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Measurement of Voltage Flicker: Application to Grid-connected Wind Turbines

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1. Introduction

Electric power is an essential commodity for most industrial, commercial and domestic processes. As a product, electric power must be of an acceptable quality, to guarantee the correct behavior of the equipment connected to the power distribution system. Low-frequency conducted disturbances are the main factors that can compromise power quality. The IEC 61000-2-1 standard classifies low-frequency conducted disturbances in the following five groups: harmonics and interharmonics, voltage dips and short supply interruptions, voltage unbalance, power frequency variations and voltage fluctuations or flicker.

Voltage fluctuations are defined as cyclic variations in voltage with amplitude below 10% of the nominal value. Most of the connected equipment is not affected by voltage fluctuations, but these fluctuations may cause changes in the illumination intensity of light sources, known as *flicker*. Flicker may produce a very unpleasant visual sensation, leading to complaints from utility customers. The annoyance level depends on the type of lamp and amplitude, frequency and duration of the voltage fluctuations. Its precise quantification is a complex task that must be statistically approached to characterize adequately the perception of a large number of people. A flickermeter must characterize the behavior of the lamp-eye-brain set that represents most people and must provide an indication of the discomfort, or flicker severity. In 1986, The International Electrotechnical Commission (IEC) published the first standard describing the functional and design specifications for the measurement of flicker.

The main sources of flicker are large industrial loads, such as arc furnaces, or smaller loads with regular duty cycles, such as welding machines or electric boilers. However, from the point of view of power generation, flicker as a result of wind turbines has gained attention in recent years. Rapid variations in wind speed produce fluctuating power, which can lead to voltage fluctuations at the point of common coupling (PCC), which in turn generate flicker. The IEC 61400-21 standard establishes the procedures for measuring and assessing the power quality characteristics of grid-connected wind turbines. The section dedicated to flicker proposes a complex model for calculating the flicker coefficient that characterizes a wind turbine. This coefficient must be estimated from the current and voltage time series obtained for different wind conditions. The wind turbine being tested is usually connected to a medium-voltage network, having other fluctuating loads that may cause significant voltage fluctuations. In addition, the voltage fluctuations imposed by the wind turbine depend on the characteristics

of the grid conditions. The most relevant block of the model is responsible for simulating the voltage fluctuations on a fictitious grid with no source of flicker other than the wind turbine. This chapter is organized in two related sections. The first section deals with the IEC flickermeter. First, the main research enabling modeling of the lamp-eye-brain set is summarized. A description of the IEC 61000-4-15 standard follows, as well as a detailed account of a high-precision digital implementation of the flickermeter, after which the ability of the IEC flickermeter to assess the actual annoyance produced by flicker in people is critically analyzed. This analysis is based on field measurements obtained from analytically generated test signals and subjective experimental data obtained from a small group of people. In the second section, the IEC flickermeter is used to characterize flicker caused by wind turbines. The section contains a detailed description of the part of the IEC-61400-21 standard dedicated to flicker, together with a critical analysis of the different methods used to solve the fictitious grid. The chapter concludes by analyzing how the errors in the estimation of the fictitious grid affect the calculation of flicker severity.

2. Measurement of flicker

2.1 Historical perspective

Flicker is defined as the variation in the luminosity produced in a light source because of fluctuations in the supply voltage. Fig. 1 shows an example of rectangular fluctuation at a frequency of 8.8 Hz and an amplitude $\Delta V = 0.4$ V (i.e., $\frac{\Delta V}{V} = 40\%$), which modulates a mains signal of 50 Hz and amplitude $V = 1$ V.

Fig. 1. Example of rectangular fluctuation in voltage supply.

Variations in luminosity can annoy humans. A flicker measuring device or flickermeter must assess the annoyance, or the flicker severity, caused to people exposed to variations in luminosity. The measurement of the annoyance caused should be done starting from the supply voltage of the light source.

It is obvious that the annoyance caused is a subjective phenomenon, related to the sensitivity of each individual to light fluctuations. In this sense, the measurement of annoyance can only be performed on a statistical basis; that is, by carrying out experiments involving a large number of people. A flickermeter has to provide an acceptable model of the behavior of the lamp-eye-brain set responsible for converting the voltage fluctuations into annoyance.

The voltage fluctuations are converted in the lamp into light fluctuations. The response depends, to a great extent, on its construction, power and nominal voltage. Consequently, in order to define the specifications of a flickermeter, it is necessary to select a suitable reference lamp. The analysis of the lamp-eye system requires carrying out statistical studies to enable characterization of the behavior of the human eye when exposed to light fluctuations. Lastly, the eye-brain set constitutes a complex, nonlinear system, and its neurophysiological study also requires a statistical basis. Complex characteristics of the brain, such as its memory capacity and its inertia when faced with consecutive variations in luminosity, must be modeled. The first research into the behavior of the lamp-eye set was carried out by K. Simons (Simons, 1917). More detailed studies on the behavior of the lamp-eye set were carried out by P. Ailleret, at the end of the 1950s (Ailleret, 1957). These experiments were based on various subjective tests on representative groups of people, and they analyzed the behavior of the lamp-eye set with various lamp types. They demonstrated that the lamp-eye system has a band-pass-type response with maximum sensitivity around 10 Hz for incandescent lamps. This work also defined the response of the incandescent lamp under small variations in voltage:

$$\frac{\Delta L}{L_n} = \gamma \frac{\Delta V}{V_n}, \quad (1)$$

where V_n represents the root mean square (rms) value of the nominal voltage, L_n is its corresponding luminosity and γ is a proportionality constant. This expression leads to the conclusion that the level of annoyance calculated in flicker measurement must be proportional to the relative level of voltage fluctuation. That is, double the amplitude of voltage fluctuation corresponds to double the amplitude of luminosity fluctuation and, therefore, double the annoyance.

In a second experiment, P. Ailleret related the annoyance to the amplitude of the fluctuation and its duration. The results demonstrated that the annoyance depends on the product of two factors, the duration and square of the amplitude, according to the following expression:

$$Annoyance = f(L^2 \cdot t), \quad (2)$$

where L represents the fluctuation amplitude and t the duration.

That is, a continuous variation in luminosity with a specific voltage amplitude and frequency, during a particular interval, provokes the same annoyance as three-quarters of the interval without fluctuation and a quarter of the interval with double the amplitude.

Finally, P. Ailleret studied the combination of annoyance provoked by light fluctuations with different frequencies. He demonstrated that the combination of the amplitudes follows a quadratic law. If the annoyance at frequency f_1 has equivalent amplitude, L_1 , at 20 Hz, and at another frequency f_2 it has equivalent amplitude L_2 , the overall effect of the combined presence of the two frequencies is given by:

$$\Delta L = \sqrt{\Delta L_1^2 + \Delta L_2^2} \quad (3)$$

In parallel with the previous works, H. de Lange considered that the ambient luminosity is an important factor in the evaluation of the annoyance and characterized the response of the human eye by taking into account the influence of the illumination level of the retina. Fig. 2 shows the relation between the amplitude of the luminous fluctuation and the average ambient luminosity against frequency, at the perceptibility threshold (de Lange, 1961) for an incandescent lamp. The variation of this relationship with frequency is provided on a logarithmic scale for different illuminations of the retina. From the figure, it can be deduced that for high

levels of illumination, the frequency response of the optical system behaves as a band-pass filter, with a maximum sensitivity at a frequency of 8.8 Hz, making it the reference of sensitivity for human visual perception of flicker.

Fig. 2. Frequency characteristics of the human optical system at the threshold of perception for different illumination levels. Source: (de Lange, 1952).

Once the lamp-eye set had been studied, to complete the model of perception, it was essential to analyze the behavior of the eye-brain system. During the 1970s, a series of experiments were conducted, aimed at mathematical modeling of the neurophysiological processes caused by light fluctuations.

The first such research, undertaken by C. Rashbass, obtained the lowest intensity at which the rectangular changes of luminance of a specific duration are perceptible (Rashbass, 1970). The results demonstrated that the relative intensity decreases with increasing flash duration, with a minimum at 64 ms, supporting the band-pass characteristic postulated by H. de Lange and Ailleret.

In the second study, C. Rashbass combined two flashes of the same duration but with intensities that were not necessarily the same. The results demonstrated that the response to any combination of two intensities obeyed a quadratic law, which could be modeled using three elements:

- a. a band-pass filter coinciding with the one previously used by H. de Lange to model eye behavior;
- b. a second element reproducing the quadratic response of the system, which is modeled using a squaring circuit; and
- c. a third element to model the effect of the brain’s memory using a first-order band-pass filter and a time constant between 150 and 250 ms¹.

Fig. 3 shows the analog model of the eye-brain set produced from Rashbass’ experiments. This model constitutes the nucleus of the current specification of the IEC flickermeter (IEC-61000-4-15, 2003; IEC-868, 1986).

¹ This constant was definitively fixed at 300 ms starting from the studies of Koenderink and Van Doorn (Koenderink & van Doorn, 1974).

Fig. 3. Model of visual perception (eye-brain set) based on studies by H. de Lange and C. Rashbass. Source: (UIE, 1992).

2.2 Description of the IEC flickermeter

At the end of the 1970s, the UIE² perturbations working group started to prepare a specification for the measurement of flicker that was universally accepted. The first results of this work were presented to the international community at the 1984 UIE congress (Nevries, 1984). The definitive version was standardized in 1986 through the IEC 868 standard (IEC-868, 1986), which provided the functional and design specifications of a flicker measuring device. Currently, the standard containing the specifications of the flickermeter is IEC 61000-4-15 (IEC-61000-4-15, 2003).

Fig. 4 shows the block diagram defined by IEC 61000-4-15. The simulation of the response of the lamp-eye-brain system is carried out in the first four blocks, based on the physiological experiments described previously. In addition, the standard requires integration of the sensation experienced by the observer during a specific period in a single value. Block 5 is responsible for this, through a statistical evaluation of the output from block 4.

Fig. 4. Block diagram of the flickermeter specified in the IEC 61000-4-15 standard.

Next, a brief description is given of each block shown in Fig. 4 for 50 Hz systems. The main characteristics of a high-precision digital implementation developed as a reference for the results found in the rest of this chapter are described in the following sections.

2.2.1 Block 1: Input voltage adaptor

Given that the flicker measurement must be made from the relative fluctuations in voltage, expressed in percentages, it is necessary to guarantee the independence of the input voltage measurement. In this block, the input is scaled with respect to its average value. This operation can be done through automatic adjustment of the gain at the *rms* value of the input voltage, with a constant time of 1 min.

² International Union for Electrical Applications.

In our reference implementation, the input signal is scaled to an internal reference value proportional to the 1 min *rms* value, using a half-cycle sliding window.

2.2.2 Block 2: Quadratic demodulator

Voltage fluctuations normally appear as a modulation in amplitude of the fundamental component. Thus, the input to block 2 can be understood as a modulated signal with a sinusoidal carrier of 50 Hz. Block 2 is responsible for carrying out the quadratic demodulation of the input.

The light source chosen by IEC as reference for the construction of the flickermeter is an incandescent lamp filled with inert gas with a spiral tungsten filament and a nominal power of 60 W at 230 V for 50 Hz systems, and 120 V for 60 Hz systems.

The processing required by this block is simply to square the samples from the signal obtained in block 1. This operation generates a signal containing frequency components corresponding to the fluctuation in luminosity and other frequencies that have to be suitably eliminated.

2.2.3 Block 3: Demodulation and weighting filters

To select the frequency components that generate flicker from the output of block 2, it is necessary to suppress the continuous and 100 Hz components generated in the demodulation process. This is done through the demodulation filters, which consist of the cascade connection of:

- a. a first-order high-pass filter with a cutoff frequency of 0.05 Hz; and
- b. a sixth-order low-pass Butterworth filter with a cutoff frequency of 35 Hz, which introduces an attenuation of 55 dB at 100 Hz.

The human eye has a selective, frequency-dependent behavior toward variations in luminosity. For this reason, the second stage of filtering consists of a weighted band-pass filter that follows the frequency response of the lamp-eye set. This filter is based on the threshold curve of perceptibility obtained experimentally by H. de Lange (de Lange, 1952; 1961). The standard provides the transfer function in the continuous domain of this filter. With respect to attenuation, at 100 Hz, this filter adds 37 dB to what has already been achieved using the band-pass demodulation.

Finally, block 3 contains a measurement scale selector that determines the sensitivity of the instrument. It modifies the gain depending on the amplitude of the voltage fluctuation to be measured. The scales, expressed as the relative changes in voltage, $\frac{\Delta V}{V}(\%)$, for a sinusoidal modulation of 8.8 Hz, are 0.5%, 1%, 2%, 5% and 10%, the 20% scale being optional.

For the discrete implementation of the filters, Infinite Impulse Response (IIR) systems were selected. The demodulation filters were designed through the impulsive invariance method, and the weighting band-pass filter using bilinear transformation. All the filters were implemented using the direct-form II transpose.

The reference flickermeter works with sampling frequencies (f_s) of 1600, 3200, 6400, 12800 and $25600 \frac{\text{samples}}{\text{s}}$, and demodulation filters were designed for these frequencies.

Given that the bandwidth of the output signal of the low-pass demodulation was practically reduced to 35 Hz, maintaining such high sampling rates is not necessary. For this reason, a decimation process is implemented at the output of the low-pass demodulation filter, which reduces f_s to $f_p = 800 \frac{\text{samples}}{\text{s}}$. This decimation process does not require low-pass filtering, as the signal to be decimated is band limited. In this way, the weighting filter designed for f_p is the same for all the input sampling frequencies.

2.2.4 Block 4: Nonlinear variance estimator

To complete the model of visual perception defined by C. Rashbass, it is necessary to add two new functions: the modeling of the nonlinear perception of the eye-brain set and the effect of the brain's memory. These two functions are introduced using a quadratic multiplier and a first-order sliding low-pass filter with a time constant of 300 ms.

As for the low-pass filter in block 3, this filter has also been designed using the impulsive invariance method for $800 \frac{\text{samples}}{s}$, and it was also implemented in the transposed form of the direct II form.

The output of this block represents the instantaneous sensation of flicker. It should be stressed that this signal must not be evaluated as an absolute indicator. On the contrary, it must be referred to the unit, taking this as the maximum value of the output of this block if the supply voltage is modulated by a sinusoidal frequency fluctuation of 8.8 Hz and an amplitude 0.25%, corresponding to the threshold of perceptibility.

2.2.5 Block 5: Statistical evaluation

Block 5 has the aim of assessing the level of annoyance starting with the values of the instantaneous sensation of flicker that are exceeded during a certain percentage of the observation time. It is important to choose a suitable assessment period that is characteristic of the reaction of an observer confronted with different types of light fluctuations. Because of the disparity in the characteristics of flicker-generating loads, the standard defines two observation periods:

- a. short term, normally fixed at 10 min, during which short-term flicker severity, P_{st} , is assessed; and
- b. long term, usually 2 h, during which long-term flicker severity, P_{lt} , is assessed.

It should be noted that the annoyance threshold corresponds to $P_{st} = 1$. When $P_{st} > 1$, the observer is understood to suffer annoyance; when $P_{st} < 1$, the light fluctuations may be perceivable but not annoying.

2.2.5.1 Evaluation of short-term flicker severity, P_{st}

Because of the random nature of flicker, it must be assumed that the instantaneous sensation of flicker may be subject to strong and unpredictable variations. For this reason, not only the maximum value reached but also the levels exceeded during specific parts of the observation period must be taken into account. Therefore, it seems best to design a method based on a statistical evaluation of the instantaneous sensation. The standard specifies a multipoint adjustment method according to the following expression:

$$P_{st} = \sqrt{k_1 P_1 + k_2 P_2 + \dots + k_n P_n}, \quad (4)$$

where k_n are weighting coefficients and P_n are levels corresponding to the percentiles ³ 1, 2, ..., n of the output of block 4. The values k_n and P_n were adjusted starting with the annoyance threshold curve or $P_{st} = 1$ curve, obtained experimentally from a large group of people undergoing rectangular light fluctuations at more than one change per minute (cpm). The results providing values lower than 5% for all cases were as follows:

³ Level of instantaneous sensation of flicker that is surpassed during a specific part of a time period.

$$\begin{aligned}
k_1 &= 0.0314 & P_1 &= P_{0.1} \\
k_2 &= 0.0525 & P_2 &= P_{1s} = \frac{P_{0.7} + P_1 + P_{1.5}}{3} \\
k_3 &= 0.0657 & P_3 &= P_{3s} = \frac{P_{2.2} + P_3 + P_4}{3} \\
k_4 &= 0.2800 & P_4 &= P_{10s} = \frac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \\
k_5 &= 0.0800 & P_5 &= P_{50s} = \frac{P_{30} + P_{50} + P_{80}}{3}
\end{aligned} \tag{5}$$

The index s refers to values or averages, and $P_{0.1}$ is the value of the instantaneous sensation of flicker exceeded during 0.1% of the observation time.

For implementation of this block, the standard specifies sampling the output of block 4 at a constant frequency of 50 Hz or above. The statistical analysis starts by subdividing the amplitude of the output of block 4 into an appropriate number of classes. For each sample, the counter of the corresponding class increases by one. Using the classified samples, at the end of the observation period, the curve of accumulated probability of the instantaneous sensation of flicker, which provides the appropriate percentiles, is obtained. Nevertheless, it should be taken into account that the classification introduces errors, basically because of the number of classes utilized and the resolution of the accumulated probability function within the range of values corresponding to each class.

In the reference flickermeter, the classification is not carried out, but the accumulated probabilities are calculated starting with all the stored samples of the output of block 4 during the 10 min evaluation of P_{st} . This procedure provides total precision in the measurement of P_{st} , given that the errors derived from the classification of the samples are avoided.

2.2.5.2 Evaluation of long-term flicker severity, P_{lt}

The method for calculating P_{lt} is based on the cubic geometric average of the 12 values of P_{st} in a period of 2 h, according to the expression:

$$P_{lt} = \sqrt[3]{\frac{1}{12} \sum_{i=1}^{12} P_{st,i}^3} \tag{6}$$

2.3 A deep review of the annoyance assessment by the IEC flickermeter

Over the last 25 years a very few studies have reported doubts about the goodness of the IEC flickermeter's annoyance assessment. The main problems described are related to the accuracy requirements specified by the standard. In this sense, it has been reported that different flickermeters, all compliant with IEC 61000-4-15, report different P_{st} values for the same input signal (Key et al., 1999; Szlosek et al., 2003). These deviations are a result of the limited number of accuracy requirements specified by the standard (WG2CIGRÉ, 2004). They should be solved with the new edition of the standard, planned for 2010, which includes a higher number of accuracy requirements. Other studies have analyzed the nonlinear behavior of the IEC flickermeter when subject to rectangular voltage fluctuations (Ruiz et al., 2007).

We have analyzed the annoyance assessment performed by the IEC flickermeter by means of P_{st} . We have considered three aspects of the question. Firstly, we analyzed several reports providing field measurements on domestic lines to study the relation between flicker

severity levels and the existence of complaints from the users. Secondly, we studied the behavior of block 5 when the IEC flickermeter was subjected to nonuniform rectangular voltage fluctuations. Finally, because it is not easy to find a consistent relationship between the true annoyance and flicker severity, we performed some laboratory tests to correlate the values provided by the IEC flickermeter and the sensation that was experienced by several people, previously trained and qualified.

2.3.1 Field measurements vs complaints

Power quality objectives must be based on statistical limits defined by the regulators according to long-term measurements. In the context of the European electricity market, the standard EN 50160 specifies the index to be used as the weekly P_{lt} for 95% of the time, $P_{lt,95}$. The objective for this index is a value of $P_{lt,95} < 1$. Standard IEC 61000-4-30 also establishes that the minimum measurement period should be one week, defining limits for $P_{st,99} = 1$ and $P_{lt,95} = 0.8$.

There have been very few studies contrasting field measurements of flicker and the level of annoyance perceived by people. The work (Arlt et al., 2007) compares the international planning levels for flicker in high-voltage networks and the flicker requirements that must be fulfilled by customers running flicker-generating equipment. They show that in many cases, the real flicker values in high-voltage networks, which are supplying towns with industrial areas, are much higher than the planning levels without causing complaints by residential customers who are supplied via medium voltage and low voltage from these systems. However, other industrial loads that produce P_{st} levels quite similar to previous examples, but clearly over the planning levels, generate complaints by customers and require corrective actions.

Another study of this issue was elaborated by the joint working group CIGRE C4.07/ CIRED and presented in their report (WGC4CIGRÉ, 2004). This group was formed in 2000 to research available power quality measurement data with the intention of recommending a set of internationally relevant power quality indices and objectives. One of the sections is, obviously, dedicated to the analysis of the flicker indices. In many sites, characterized by strong and meshed networks, the actual flicker disturbance is sometimes more than double the planning levels without known problems. Some studies suggest as causes of this divergence the conservative character of the objectives defined by the regulatory standards, or the decreasing use of incandescent lamps. However, we wanted to study the next hypothesis: that the short-term flicker severity assessment made by block 5 of the IEC flickermeter may not be the most appropriate way to characterize the annoyance.

2.3.2 Behavior of block 5 when subject to nonuniform rectangular voltage fluctuations

The multipoint algorithm for P_{st} assessment (see Equation 6) was adjusted by the standard to provide the flicker severity caused by rectangular voltage fluctuations that remained completely uniform throughout the 10 min period. In this section we will analyze the P_{st} assessment when the rectangular voltage fluctuation is not homogeneous; that is, when there are several voltage fluctuations with different frequencies and amplitudes during the observation period.

Next, we will describe the experiments that we carried out to analyze the behavior of the IEC flickermeter when subject to nonuniform rectangular voltage fluctuations.

2.3.2.1 Experiment 1

Fig. 5 shows the type of fluctuation used for this case. During a certain period t_1 , in seconds, we applied to the reference flickermeter a rectangular fluctuation of frequency f_1 cpm and amplitude $A_1 = \frac{\Delta V}{V}|_{P_{st}=2}$; that is, the amplitude that would produce $P_{st} = 2$ for the frequency f_1 if it were applied during the complete 10 min period. For the rest of the time up to 10 min, the input signal is a 50 Hz sinusoidal without fluctuations.

Fig. 5. Outline of the fluctuation used in Experiment 1.

Because A_1 is the fluctuation amplitude that produces $P_{st} = 2$ for the frequency f_1 , the assessment of the annoyance should not depend on f_1 for different values of t_1 . Considering Equation 2, the diagram of Fig. 5 is equivalent to a fluctuation applied during the whole 10 min period, of frequency f_1 and amplitude:

$$A = A_1 \cdot \sqrt{\frac{t_1}{600}} . \tag{7}$$

Because the amplitude A_1 applied during 10 min produces $P_{st} = 2$, the flicker severity value corresponding to the situation showed in Fig. 5 should follow:

$$P_{st} = 2 \cdot \sqrt{\frac{t_1}{600}} . \tag{8}$$

According to Equation 8, Table 1 provides the theoretical P_{st} values for the values of t_1 used in this experiment.

t_1	P_{st}	t_1	P_{st}	t_1	P_{st}
5	0.183	50	0.577	120	0.894
10	0.258	55	0.606	180	1.095
15	0.316	60	0.632	240	1.265
20	0.365	65	0.658	300	1.414
30	0.447	70	0.683	360	1.549
35	0.483	75	0.707	420	1.673
40	0.516	80	0.730	480	1.789
45	0.548	90	0.775	540	1.897

Table 1. Theoretical P_{st} values for Experiment 1.

Fig. 6 shows the results that were obtained with the IEC reference flickermeter for the values of t_1 compiled in Table 1 and values of f_1 from $f_{1,min}$ to 2400 cpm. The value of $f_{1,min}$ depends on t_1 and was adjusted to generate a rectangular fluctuation with at least five voltage changes during the period t_1 .

The analysis of Fig. 6 reveals three main conclusions, all of them contrary to the expected results.

- a. The P_{st} values depend on the fluctuation frequency, f_1 , basically up to 800 cpm.

Fig. 6. P_{st} values obtained with the reference flickermeter for Experiment 1.

- b. The P_{st} values for each t_1 show an important deviation from the theoretical values compiled in Table 1.
- c. Additionally, regarding the relation between the annoyance and the duration of the fluctuation, it is possible to distinguish abrupt variations in P_{st} as a function of t_1 .

The origin of the discrepancies between the experimental and the expected results for the above experiment is located in block 5 of the IEC flickermeter. The multipoint algorithm, assessing the P_{st} by the calculation of the percentiles of the instantaneous flicker sensation, provides accurate results when the rectangular fluctuation is applied uniformly during the whole period of 10 min. When the fluctuation is not applied in that way, the evolution of the percentiles becomes unpredictable, and P_{st} presents abrupt changes in terms of the duration of the fluctuation, t_1 .

2.3.2.2 Experiment 2

Fig. 7 shows the fluctuations used for this case. During the first 5 min, the amplitude of the rectangular fluctuation is A_1 and the frequency is f_1 , whereas for the last 5 min, the amplitude is A_2 and the frequency is f_2 . Both A_1 and A_2 correspond to the amplitudes that would produce $P_{st} = 2$ for the frequencies f_1 and f_2 respectively if they were applied independently during the complete 10 min period.

Fig. 7. Outline of the fluctuation used in Experiment 2.

It is obvious that the expected flicker severity value when computing the whole period should be $P_{st} = 2$, independently of f_1 and f_2 . Fig. 8 shows the percentage of the P_{st} deviation from the theoretical value of 2 for $f_1 = 1, 2, 3, 5, 7, 10$ and 20 cpm and a range of f_2 from 30 to 2400 cpm.

The deviations become quite important for small values of f_1 and large values of f_2 . For $f_1 = 1$ cpm and $f_2 = 1000$ cpm, the deviation is 22%. This means that the IEC flickermeter does not compute the annoyance properly when the rectangular fluctuations consist of two

Fig. 8. P_{st} deviations calculated with the reference flickermeter for Experiment 2.

frequencies during the 10 min period. The origin of this error is located in the multipoint algorithm that is implemented in block 5.

2.3.2.3 Experiment 3

In this experiment, we worked with rectangular voltage fluctuations following the diagram outlined in Fig. 9. The fluctuation frequency, f , is the same for the 10 min period. During the first 5 min, t_1 , the fluctuation amplitude is A_1 , and A_2 for the rest of the time, t_2 . Both A_1 and A_2 correspond to the amplitude of the fluctuations that would produce P_{st1} and P_{st2} for the complete 10 min period, respectively.

Fig. 9. Outline of the fluctuation used in Experiment 3.

The annoyance produced by a 5 min fluctuation of frequency f and amplitude A_1 is equivalent to the annoyance produced by a 10 min fluctuation of the same frequency and amplitude $A_{1e} = A_1 \cdot \sqrt{\frac{1}{2}}$. In the same way, the annoyance corresponding to the last 5 min is equivalent to the annoyance produced by a 10 min fluctuation of frequency f and amplitude $A_{2e} = A_2 \cdot \sqrt{\frac{1}{2}}$. By applying the amplitude quadratic composition of Equation 3, the fluctuation equivalent amplitude would be:

$$A_{eq} = \sqrt{A_{1e}^2 + A_{2e}^2} = \sqrt{\frac{A_1^2 + A_2^2}{2}}, \tag{9}$$

and therefore the equivalent flicker severity for the complete 10 min period would be:

$$P_{st_{eq}} = \sqrt{\frac{P_{st1}^2 + P_{st2}^2}{2}}, \tag{10}$$

independently of the fluctuation frequency, f .

We carried out simulations for values of A_1 and A_2 corresponding to the values of P_{st_1} and P_{st_2} compiled in Table 2 and for a range of the fluctuation frequency, f , from 1 to 2400 cpm.

P_{st_1}	P_{st_2}	$P_{st_{eq}}$
1	2	$\sqrt{2.5} = 1.581$
1	3	$\sqrt{5} = 2.236$
1	4	$\sqrt{8.5} = 2.915$
1	5	$\sqrt{13} = 3.606$
1	6	$\sqrt{18.5} = 4.301$

Table 2. Values of the total P_{st} for different combinations of P_{st_1} and P_{st_2} .

Fig. 10 shows the results of this experiment. Each curve of the figure reveals that the total P_{st} value depends on the fluctuation frequency in the interval from 1 to approximately 200 cpm. Additionally, the P_{st} values are always far from the expected ones, detailed in Table 2. In general, all the results are closer to the P_{st_2} value, although for 50% of the time, the fluctuation amplitude corresponds to P_{st_1} . Once again, the reason for this behavior is located in Block 5 of the IEC flickermeter.

Fig. 10. P_{st} values obtained with the reference flickermeter for Experiment 3.

2.3.3 Laboratory subjective experiments using field registers

To quantify the relationship between P_{st} and the true annoyance perceived by people, we performed some laboratory tests using actual registered signals that were applied to a group of 11 people. These experiments do not try to be statistically significant but are intended to point out an agreement or discrepancy with the measurements carried out by the IEC flickermeter. The experiment consisted of two main tasks, training and assessment, based on a digital-to-analog conversion system that reproduced very accurately the voltage fluctuations corresponding to analytical signals or to field-registered signals.

Fig. 11 shows the physical layout of the laboratory. The luminance conditions were quite similar to those used for the characterization and specification of the IEC flickermeter (Cornfield,

1988). Those experiments were performed by using incandescent lamps of 60 W and a luminance of 125 lx. We used the same type of lamp, covered by a light diffuser that generates an average luminance of 125 lx over the table where the subjects spent most of the time during the experiments reading newspapers that were laid flat on the desk in front of them.

Fig. 11. The subjective experiments laboratory during the performance of the tests.

The main purpose of these experiments was to create a group of people with the ability to quantify the annoyance when subjected to light fluctuations produced by actual voltage signals. To achieve that objective, it was first necessary to perform a training task so that the 11 subjects could identify a numeric level of annoyance in particular light fluctuations.

The training task was carried out using rectangular voltage fluctuations, generated analytically by the reproduction system. The frequencies of the fluctuations were 1, 10, 100 and 1000 cpm with amplitudes corresponding to $P_{st} = 0.5, 1, 1.5, 2, 2.5$ and 3.

Originally, the assessment task was designed to evaluate a single value of annoyance for a 10 min period. This objective was not fulfilled because all the subjects reported the impossibility of averaging the annoyance over such a long period. Because of that, the assessment period was redefined to 1 min, maintaining the 10 min period for the complete duration of each test. We selected eight windows of 10 min from the field registers. The selection was carried out in terms of the P_{st} values and the distribution of the annoyance during the 10 min. The results obtained during the laboratory subjective experiments are presented in Fig. 12. Each figure corresponds to a 10 min interval and shows, by using circles as the plot symbols, the average of the annoyance assessed by the 11 subjects for each minute and the flicker severity calculated by the IEC flickermeter with a short-term period of 1 min, $P_{st,1min}$. The solid lines in the figures show the flicker severity assessed by the IEC flickermeter for the usual short-term period of 10 min, $P_{10,min}$, and the subjective annoyance for the 10 min period, calculated by applying Ailleret's quadratic laws (see Equations 2 and 3) to the 1 min average values evaluated by the 11 subjects. The graphics have been organized for increasing P_{st} values, from $P_{st} = 0.9$ in case of Test 1 to $P_{st} = 3.8$ in case of Test 8. The distribution along the interval of the $P_{st,1min}$ values is quite regular for the tests 1, 2, 3 and 5. However, the rest of the tests show sudden changes for the $P_{st,1min}$ values.

The figures demonstrate that the $P_{st,1min}$ values were clearly larger than the subjective annoyance for the eight tests. Moreover, $P_{st,10min}$ is quite dependent on the largest $P_{st,1min}$ values.

Fig. 12. Results for the laboratory subjective experiments.

This fact produces, for all the flicker levels, the important difference between the $P_{st,10min}$ and the average of the 10 min subjective annoyance. This difference becomes more important when the annoyance during the 10 min period is not uniform.

As a summary, in realistic conditions, when the voltage fluctuations are not uniform but have varying frequency and amplitude, the multipoint algorithm does not assess the true flicker annoyance precisely.

We think it is not possible to obtain a correct assessment by using a method based on the percentiles of the output of block 4. Another relevant conclusion refers to the observation period used for the calculation of the P_{st} . The standard established this time considering the duty cycles of the loads generating flicker. Our experiments proved that the human optical system does not average properly the annoyance caused by nonuniform fluctuations during the 10 min period. An alternative short-term period could be obtained from studies related to the assessment of the flicker annoyance by the people. From this perspective, our work suggests a short-term period of 1 min approximately.

3. Measurement of flicker in grid-connected wind turbines

3.1 Introduction. IEC 61400-21 Standard

Wind energy can be considered the source of a series of perturbations that alter the ideal form of the voltage signal at the common connection point. This is because of the relation between the wind speed and the power generated by the wind system, as well as the technical characteristics of the turbine itself.

Among the perturbations generated by the wind turbines, the fluctuations in voltage (Ackermann, 2005) are the most notable. These fluctuations in voltage and the associated flicker are linked to the connection and disconnection operations; the tower shadow effect; errors in the angle of incidence of the sail; yaw errors; wind shears and slight fluctuations in the wind.

The definitions, rules and procedures for the characterization of waveform quality in a wind turbine connected to the grid are defined by IEC 61400-21 (IEC-61400-21, 2001). This standard aims to define and specify the magnitudes that need to be determined to characterize wave quality; the measurement procedures to quantify the characteristics; and the procedures to assess the fulfillment of supply quality requirements.

The application framework of the standard is focused on individual wind turbines connected to the grid at medium or high voltage, that can regulate to a sufficient extent the active and reactive power.

With respect to the measurement of flicker, the standard requires that the wind turbine be characterized for the following situations:

- a. Continuous operation: the specifications establish a processing and statistical evaluation scheme to obtain the flicker coefficients defining the wind turbine being studied. The phase-to-neutral voltage and the line current, $u_m(t)$ and $i_m(t)$, need to be processed for at least 10 registers of 10 min duration for each wind velocity between the cut-in of the wind turbine and $15 \frac{m}{s}$.
- b. Switching operations: the specifications establish an alternative processing and statistical evaluation scheme to assess the consequences of the start-up and shut-down maneuvers of the wind turbine. In this case, signals $u_m(t)$ and $i_m(t)$ need to be processed during these connection operations.

For both the continuous operation and the switching operations, the specifications establish a model to make the results independent of the characteristics and conditions of the grid to

which the wind turbine is connected. This model is based on a fictitious grid that enables evaluation of voltage fluctuations caused exclusively by the wind turbine.

Fig. 13. Fictitious grid used to define $u_{fic}(t)$ for flicker measurements in wind turbines.

The fictitious grid is shown in Fig. 13. The turbine is represented by a current generator with a value of $i_m(t)$ (phase current of the turbine), and the grid to which it is connected is represented by the equivalent Thevenin, which is made up of the following components.

- a. An ideal voltage supply $u_0(t)$, neutral-phase voltage with no fluctuation:

$$u_0(t) = \sqrt{\frac{2}{3}} U_n \sin(\alpha_m(t)) , \tag{11}$$

where U_n is the *rms* nominal voltage, $\alpha_m(t)$ is the instantaneous phase of the fundamental component of the voltage and $u_m(t)$ is the phase-to-neutral voltage, measured in the turbine’s terminals.

- b. A fictitious impedance composed of the values R_{fic} and L_{fic} . The standard specifies angles of 30°, 50°, 70° and 85° for this grid impedance.

With this model, the fluctuations in voltage resulting from the turbine will be represented by the fictitious voltage fluctuations obtained using the following expression.

$$u_{fic}(t) = u_0(t) + R_{fic} \cdot i_m(t) + L_{fic} \cdot \frac{di_m(t)}{dt} , \tag{12}$$

The flicker measurement procedure established in the IEC 61000-4-15 standard is applied to this fictitious voltage, the first step being the calculation of its P_{st} . The value of $u_{fic}(t)$ determines the value of P_{st} . The main error source in the calculation of $u_{fic}(t)$ appears because $u_0(t)$ is obtained from $u_m(t)$. For this reason, the different techniques for obtaining $u_0(t)$ are described next.

3.2 Techniques for estimation of $u_0(t)$

The voltage $u_0(t)$ must be composed only of the fundamental component of the voltage in the terminals of the turbine, $u_m(t)$, suitably scaled. The estimation of $u_0(t)$ requires two operations:

- a. Calculation of the instantaneous phase of the fundamental component of $u_m(t)$.
- b. Adjustment of the amplitude of $u_0(t)$ in agreement with the nominal voltage of the turbine, U_n .

A small error in the estimation of the phase of the fundamental component of $u_m(t)$ can generate important changes in $u_{fic}(t)$ that significantly affect the P_{st} value calculated (Gutierrez et al., 2008).

To calculate the instantaneous phase of the fundamental component of $u_m(t)$, it is important to understand that this signal is limited in band and that most of its power is concentrated around its fundamental component of frequency, which is equal or very close to 50 Hz. Under this hypothesis, four techniques for obtaining the instantaneous phase of $u_m(t)$ are described next.

3.2.1 Techniques for calculating the instantaneous phase of $u_m(t)$

3.2.1.1 Zero-Crossing Method

The estimation of the frequency of the power system using the zero-crossing technique has been well known for a long time (Lee & Devaney, 1994). Starting with the frequency or period of each cycle of $u_m(t)$, constructing the instantaneous phase of the signal $u_m(t)$ is straightforward.

Working in the discrete domain, the algorithm searches for the positions of the contiguous samples of $u_m(t)$ that mark a transition of values from positive to negative. To achieve a more precise approximation to the zero-crossing point, a linear interpolation between the points of the transition is used, as is shown in Fig. 14.

Fig. 14. The zero-crossing scheme.

The fraction of the sampling period that places the zero-crossing can be obtained from the following expression:

$$\Delta_n = \frac{Y_1}{Y_1 - Y_2} \quad (13)$$

Knowing the number and the fraction of the samples that make up a period, reconstruction of the instantaneous phase of the fundamental component is done, sharing the 2π radians uniformly for each sampling instant.

3.2.1.2 Hilbert Transform

If $u_m(t)$ is considered to be a band-pass signal, the estimation of the instantaneous phase of its fundamental component can be approached using the Hilbert transform (Gabor, 1946). In the

context of signal processing and communications, the analytical representation of real signals facilitates some mathematical manipulations of the signal (Oppenheim & Shafer, 1999; Proakis & Manolakis, 2006). Given a band-pass signal, $u_m(t)$, it is possible to obtain the positive analytical signal corresponding to $u_m(t)$ in terms of its Hilbert transform with the composition:

$$u_{m+}(t) = u_m(t) + j\hat{u}_m(t), \quad (14)$$

where $\hat{u}_m(t)$ represents the Hilbert transform of $u_m(t)$.

Starting from the analytical representation, the instantaneous phase of the signal can be obtained as:

$$\alpha_m(t) = \arg\{u_{m+}(t)\} \quad (15)$$

3.2.1.3 Short Time Fourier Transform (STFT)

To obtain the instantaneous phase of $u_m(t)$, a spectral estimation technique such as the short-time Fourier transform that is very widely applied in digital signal processing can be used. Basically, it consists in windowing the signal $u_m(t)$ and calculating the fundamental component at 50 Hz using the DFT (discrete Fourier transform) of the windowed signal. The window duration establishes the trade-off between time and frequency resolution. The minimum window necessary to characterize the fundamental component correctly is of 1 cycle and the maximum corresponds to the 10 min of $u_m(t)$.

When using 1 cycle windows, a very high time resolution can be achieved, and if advancing the window sample by sample, the apparition of sudden phase changes can be minimized. This method implies a large computational load and has a large associated spectral leakage, so it is possible that interharmonic components present in $u_m(t)$ close to the fundamental component distort the phase estimation. To improve the precision in these cases, spectral leakage can be reduced by increasing window length. In the extreme case of using a 10 min window, the frequency resolution between two points of the DFT would be 1.6 mHz, but a single average value of the phase of the fundamental component would be obtained. This means that the instantaneous phase of $u_m(t)$ is not followed; instead, its average value over 10 min is obtained.

3.2.1.4 Digital Phase-Locked Loop (DPLL)

A DPLL is based on the fundamentals of analogue systems that enable the synchronization of the reference signal generated by an oscillator, and with a specific input signal in both frequency and phase.

The working principle of a PLL is based on a feedback loop that can lock two waveforms in frequency and phase. The block diagram of the PLL is composed of three basic functional blocks: Phase Detector, Loop Filter+Amplifier and Voltage Controlled Oscillator (VCO). A block diagram of the PLL system is shown in the figure.

The PLL system generates a reference signal in phase with the fundamental component of $u_m(t)$, but it does not have a constant amplitude as required by $u_0(t)$. Therefore, it is necessary to complement the PLL system with an automatic gain control (AGC) at the VCO output, as shown in Fig. 15.

The loop filter output generates small phase errors in stationary working conditions all the time; therefore, the model's closed-loop transfer function can be linearized and its discrete implementation simplified through a DPLL system.

If the measured voltage, $u_m(t)$, was a single component at 50 Hz with variable amplitude, any one of the four aforementioned methods would enable the calculation of the voltage $u_0(t)$

Fig. 15. The phase-locked loop scheme.

practically without error. However, the signal $u_m(t)$ can contain harmonic and interharmonic components, and its fundamental component may not be exactly 50 Hz. In this case, errors will be produced in the estimation of $u_0(t)$ that depend on the technique used. To minimize these errors, the $u_m(t)$ signal can be filtered using a very narrow band-pass filter that only selects its fundamental component. Given that this filtering step is critical from the precision viewpoint, it will be analyzed in more detail in the next subsection.

3.2.2 Filtering of the fundamental component of $u_m(t)$

When a signal has very narrow band interference, the traditional method of eliminating it consists in filtering the signal using a notch filter. Our case is the inverse, given that the objective is the fundamental component of the signal $u_m(t)$. Working in a discrete domain, a very narrow band-pass filter needs to be designed around the discrete pulsation corresponding to the fundamental frequency $\Omega_0 = 2\pi \frac{f_0}{f_s}$ with $f_0 = 50$ Hz.

In this section, the narrow band-pass filter design is analyzed first through an adaptive scheme based on the LMS⁴ algorithm. This design enables the fundamental component at 50 Hz to be obtained without distortion and without any delay at the output with respect to the input. Nevertheless, when the fundamental component is at a frequency close to, but not exactly 50 Hz, the response of the filter is delayed a few samples with respect to the fundamental component of $u_m(t)$. This delay causes an error when calculating the P_{st} of $u_{fic}(t)$. To solve this problem, a zero-phase IIR filter implementation is used.

3.2.2.1 Adaptive Design of a Narrow Band Pass Filter

The adaptive interference canceller is a classical application of the adaptive filter, LMS (Widrow & Stearns, 1985). It is designed to eliminate an undesired sinusoidal interference. In reality, it implements a notch filter with the advantages of offering easy control of bandwidth and capacity to adaptively follow the frequency and phase of the interference. The Fig. 16 shows a discrete implementation of the adaptive interference canceller.

Fig. 16. The Adaptive Interference Canceller scheme.

⁴ Least Mean Square

The transfer function of this output scheme $e[n]$ with respect to $u_m[n]$ is given by:

$$H_1(z) = \frac{E(z)}{U_m(z)} = \frac{z^2 - 2z \cos(\Omega_0) + 1}{z^2 - 2(1 - \mu C^2)z \cos(\Omega_0) + 1 - \mu C^2} \quad (16)$$

It can be observed that this function does not depend on the phase of the reference signal, and that the amplitude of the reference signal, C , and the step-size of the algorithm LMS, μ , are interchangeable values given that $H_1(z)$ only depends on the product μC^2 . The frequency response of $H_1(z)$ corresponds to a notch filter with a 3 dB bandwidth $BW = 2\mu C^2 \text{ rad} = \frac{f_s \mu C^2}{\pi} \text{ Hz}$.

In the same scheme, if the transfer function of the adaptive filter output, $y[n]$, is calculated with respect to the input, $u_m[n]$, the following expression is obtained:

$$\begin{aligned} H(z) &= \frac{Y(z)}{U_m(z)} = \frac{U_m(z) - E(z)}{U_m(z)} = 1 - H_1(z) \\ &= 2\mu C^2 \cdot \frac{z \cos(\Omega_0) - 1}{z^2 - 2(1 - \mu C^2)z \cos(\Omega_0) + 1 - \mu C^2} \end{aligned} \quad (17)$$

The frequency response $H(\Omega)$ corresponds to a narrow band-pass filter that enables obtaining the fundamental component of $u_m[n]$. When working with $C = 1$, $f_s = 3200$ and $\mu = 0.0003$, a bandwidth of approximately 0.3 Hz is found around the 50 Hz component. The Fig. 17 shows the module and the phase delay $\tau_f(\Omega) = \frac{-\phi(\Omega)}{\Omega}$ of $(1 - \mu C^2)H_1(\Omega)$ and $H(\Omega)$ scaling the axis of frequency in Hz.

The main problem of $H(z)$ in obtaining the fundamental component of $u_m[n]$ centers on the abrupt behaviour of the phase delay around 50 Hz. If the fundamental component of $u_m[n]$ were of 50.05 Hz, the output of $H(z)$ would be displaced with respect to the input by three samples. This causes an appreciable error in the P_{st} of $u_{fic}(t)$. To solve this problem, the Anticausal Zero-Phase Filter Implementation can be used.

3.2.2.2 Anticausal Zero-Phase Filter Implementation

For IIR filters, such as $H(z)$, the phase distortion is usually highly nonlinear. To eliminate phase distortion, anticausal zero-phase filter implementation can be used. Consider the processing scheme in Fig. 18.

After filtering in the forward direction, the filtered sequence is reversed and run it back through the filter. The result has exactly zero-phase distortion. In fact, in the frequency domain, $Y(\Omega) = U_m(\Omega) \cdot |H(\Omega)|^2$. The magnitude is the square of the filter's magnitude response, and the filter order is double the order of $H(z)$.

This implementation can only be used in cases such as ours, in which $u_m[n]$ is a finite duration signal known before being filtered. From the signal obtained, $y[n]$, it is necessary to eliminate the transitory at both its ends.

3.3 Results

3.3.1 Results Using Test Signals

A comparison was made of different methods of estimation of $u_0(t)$ under the same test signals. To do this, analytical signals were defined corresponding to $i_m(t)$ and $u_m(t)$. Moreover, the nominal working conditions of the wind turbine defining the parameters making up the fictitious grid were established:

Fig. 17. Frequency responses of the notch and band-pass filters.

Fig. 18. The anticausal zero-phase filter scheme.

Parameters of the wind turbine.

The characteristic parameters of the wind turbine affect the fictitious grid and the waveforms of the test signals. In this sense, a turbine with a rated apparent power of $S_n = 600$ kVA and nominal voltage of $U_n = 690$ V were considered. Furthermore, a ratio between the short-circuit apparent power of the fictitious grid, S_{kfic} and S_n of 20 and a grid angle $\psi_k = 85^\circ$ was considered.

Test voltage, $u_m(t)$

To model an analytical voltage at the terminals of the wind turbine, $u_m(t)$, near real conditions, different studies into the measurement of perturbations produced by wind turbines (Sørensen, 2001; Vilar et al., 2003) were analyzed and a test voltage was configured according to the following analytical expression.

$$u_m(t) = \sqrt{\frac{2}{3}}U_n \cos \left(2\pi f_0t + 2\pi \frac{\Delta f}{2} \sin(2\pi f_rt) \right) + \sqrt{\frac{2}{3}}U_n \sum_{i=1}^N a_i \cos(2\pi f_it)$$

(18)

In this way, the test voltage is made up of a fundamental component of frequency f_0 that undergoes a sinusoidal variation with a rate $f_r = \frac{1}{60} \frac{\text{Hz}}{\text{s}}$ and a range $\Delta f = 0.2$ Hz. Furthermore, N frequency components of amplitude a_i and frequency f_i were added including, 3^{rd} , 5^{th} , 7^{th} , 9^{th} and 11^{th} harmonic components of f_0 with $a_i = 0.5\%$ of the fundamental's amplitude and, the interharmonic components from 40 to 60 Hz, with 1 Hz separation and with amplitudes $a_i = 0.1\%$ of the fundamental's amplitude.

Test current, $i_m(t)$

From the same bibliographic analysis used for $u_m(t)$, a test current was configured and derived from the following expression:

$$i_m(t) = \sqrt{2}I_n \cos \left(2\pi f_0 t + 2\pi \frac{\Delta f}{2} \sin(2\pi f_r t) + \alpha_{iu} \right) + \sqrt{2}I_n \sum_{k=1}^M b_k \cos(2\pi f_k t)$$

(19)

The configuration of the fundamental component is identical to the $u_m(t)$ case, except for the inclusion of phase α_{iu} . This is calculated after considering a power factor of 0.95. In this case, M interharmonic components different from those of $u_m(t)$ were added including the 3^{rd} , 5^{th} , 7^{th} , 9^{th} and 11^{th} harmonic components of f_0 with $b_k = 1.5\%$ of the fundamental's amplitude; the 20^{th} , 21^{th} , 22^{th} , 23^{th} , 24^{th} and 25^{th} harmonic components of f_0 with $b_k = 1.75\%$ of the fundamental's amplitude and, the interharmonic components from 1025 to 1225 Hz, with 50 Hz separation and with amplitude $b_k = 1.75\%$ of the fundamental's amplitude.

Results

Starting from the test signals and the wind turbine parameters, the theoretical $u_{fic}(t)$ and the P_{st} produced were calculated, giving a value of $P_{st,fic_{ref}} = 0.536$ for a fundamental frequency $f_0 = 50$ Hz and $P_{st,fic_{ref}} = 0.535$ for a frequency $f_0 = 50.05$ Hz. This value is taken as the reference for the comparison of all of the methods of estimation of $u_0(t)$ described previously. On the other hand, starting from the same test signals and wind turbine data, a different $u_0(t)$ was estimated for each method described, and the corresponding $u_{fic}(t)$ and their P_{st} were calculated. Tables 3 and 4 show the results for each method in relation to the reference values. In all cases, a sampling frequency of $f_s = 3200 \frac{m}{s}$ was used. Both tables give details about the value of $P_{st,fic_{est}}$ obtained for the $u_{fic}(t)$ calculated from the estimation of $u_0(t)$, as well as the error with respect to the theoretical reference value.

Table 3 corresponds to the phase estimation techniques without filtering $u_m(t)$, whereas table 4 shows the results for the methods that use a band-pass filter before estimating the phase.

Method	50 Hz		50.05 Hz	
	$P_{st,fic_{est}}$	Error (%) ¹	$P_{st,fic_{est}}$	Error (%) ²
Zero-Crossing	0.548	2.24	0.547	2.24
Hilbert Transform	0.553	3.12	0.552	3.12
STFT 1 cycle	0.556	3.78	0.555	3.66
DFT 10 min	0.546	1.78	0.651	21.70
PLL	0.592	10.42	0.585	9.21

¹ Percentage deviation from $P_{st,fic_{ref}} = 0.536$

² Percentage deviation from $P_{st,fic_{ref}} = 0.535$

Table 3. Simulated results for analytical signals by non-filtering methods.

Method	50 Hz		50.05 Hz	
	$P_{st,fic_{est}}$	Error (%) ¹	$P_{st,fic_{est}}$	Error (%) ²
LMS+ Zero-Crossing	0.537	0.22	0.564	5.36
Zero-Phase filter+ Zero-Crossing	0.536	0.00	0.535	0.00

¹ Percentage deviation from $P_{st,fic_{ref}} = 0.536$

² Percentage deviation from $P_{st,fic_{ref}} = 0.535$

Table 4. Simulated results for analytical signals by band-pass filtering methods.

It can be observed that the phase estimation of $u_m(t)$ is affected by the presence of interharmonic content, which causes errors in the calculation of $P_{st,fic_{est}}$. These errors are appreciable in the techniques that do not eliminate those components through filtering (less than 3.5% in the zero-crossing case and Hilbert and reaching 4% and 10% in the STFT and PLL cases, respectively). However, most of these techniques are not substantially affected by the deviation of the fundamental frequency f_0 . Most of them provide values quite similar for both frequencies, except in the case of DFT with 10 min window that provides an error over the 21% when the fundamental frequency corresponds to 50.05 Hz. Moreover, it can be seen that the phase estimation using zero-crossing or Hilbert provides practically identical results in all cases. Table 4 shows how the errors in the estimation of $u_0(t)$ are drastically reduced by applying a narrow band-pass filter. Nevertheless, the deviation in $f_0 = 50.05$ Hz produces important errors (more than 5%) as a result of the nonlinear phase of the narrow band filter. The problem of the nonlinear phase can be solved by applying a band-pass filtering using a zero-phase IIR filter, thus obtaining a very precise estimation of $u_0(t)$ and leaving the errors in P_{st} practically nil.

3.3.2 Results using real signals

To finalize the study, a comparison of the most relevant techniques brought to light in the previous analysis was carried out using the signals from the real registers. To achieve this, several measurements were performed on two different wind turbines⁵. The first corresponds to a machine with a double speed asynchronous generation system (4 and 6 poles); fixed sail passage and a fixed generator velocity; nominal power of 600 kW and nominal voltage of 690 V. The second machine has a four-pole, synchronous generation system and electronic power control; variable sail passage and variable generator velocity, and provides a nominal power of 800 kW and a nominal voltage of 1000 V. A total of three-phase 45 registers were taken of voltage, current and wind velocity with a duration of 10 min in the first machine and 25 registers in the second. These registers were used for the comparison of the four most relevant methods for estimation of $u_0(t)$ through the calculation of the P_{st} of the $u_{fic}(t)$. The techniques employed for the comparison of the real registers were zero-crossing, STFT with a 1 cycle window, zero-crossing after narrow band filtering using LMS and zero-crossing after filtering using a zero-phase filter. For comparison purposes, the values of P_{st} obtained with the zero-crossing method after filtering using a zero-phase filter were used as reference.

⁵ The authors would like to thank SOTAVENTO GALICIA S.A. (Spain) for making the signals available free of charge for the purpose of this work.

Fig. 19 shows the results for the first machine. This figure shows the percentage deviation in the P_{st} for each register corresponding to the different techniques selected with respect to the reference value, as a function of the corresponding mean power of each 10 min register. It can be observed that the average percentage of deviation is not excessive at less than 2%, when techniques without filtering are used. However, on filtering the fundamental component of $u_m(t)$ using a narrow band-pass filter, LMS, the average percentage of variation is greater than 5%, and even in numerous cases over 10%. This is the result of the variability of the fundamental component f_0 of $u_m(t)$ in the generation of the first machine. In these cases, the application of a nonlinear filtering of phase causes errors in the estimation of the phase of $u_m(t)$, which affect the formation of $u_{fic}(t)$ and thus the calculation of the P_{st} .

Fig. 19. Results for actual registers in first turbine of Sotavento wind farm.

Fig. 20 shows the results for the second machine. This figure shows the values of P_{st} obtained for each register corresponding to the different techniques selected, as a function of the corresponding mean power of each 10 min register. It can be observed in this case that the zero-crossing without filtering provides very large variations with respect to the other methods as a result of the important interharmonic components present in $u_m(t)$. As the frequency of the fundamental component of $u_m(t)$ in this machine varies only slightly with respect to its nominal value, the LMS, narrow-band filtering does not generate as many variations as in the first machine, fitting with the reference method very precisely.

4. Conclusion

This chapter dealt with the voltage flicker and the current investigations around the main instrument used to characterize the annoyance produced by the light flicker, the IEC flicker-

Fig. 20. Results for actual registers in the second turbine of the Sotavento wind farm.

meter. After a brief description of the IEC 61000-4-15 standard we have critically analyzed the ability of the IEC flickermeter to assess the actual annoyance produced by flicker in people. All the studies we presented lead to the same conclusion. The assessment of flicker severity performed by the IEC flickermeter does not match the true flicker annoyance. Block 5 of the IEC flickermeter calculates the annoyance accurately only for uniform fluctuations during the 10 min period. In realistic conditions, when the voltage fluctuations are not uniform but have varying frequency and amplitude, the multipoint algorithm does not assess the true flicker annoyance precisely. We think it is not possible to obtain a correct assessment by using a method based on the percentiles of the instantaneous flicker sensation. Moreover, the introduction of a higher accuracy for the adjustment of the multipoint algorithm does not seem to be a proper solution.

In the last section, the IEC flickermeter is used to characterize flicker caused by wind turbines. The section contains a description of the part of the IEC-61400-21 standard dedicated to flicker. We demonstrated the sensitivity of the P_{st} of the fictitious voltage when $u_0(t)$ is estimated by different discrete techniques. Our results show, using both analytical signals as real signals, how the filtering of the measured voltage, $u_m(t)$, is essential for an accurate estimation of the phase of the fundamental component of $u_m(t)$. Moreover, a typical band pass filter could not be efficient enough to obtain good results in some real conditions. These filtering techniques produce small phase delays in the estimation of $u_0(t)$ that could cause appreciable errors in the P_{st} of $u_{fic}(t)$. To solve this problem, the Anticausal Zero-Phase Filter Implementation can be used, eliminating the phase distortion.

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