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A strategy for improving the accuracy of flicker emission measurement from wind turbines

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ABSTRACT

The paper analyzes the flicker measurement procedure defined in the IEC 61400-21 standard to identify the sources of inaccuracy and divergence in the results. The analysis is focused on the estimation of the electrical angle of the fundamental frequency of the voltage measured in a wind turbine. The sensitivity to possible disturbances in the voltage signal was studied for different estimation methods. The harmonic and interharmonic pollution, as well as variations in the fundamental frequency, were demonstrated to be a source of error in flicker measurement. A narrow-band zero-phase filtering strategy is proposed to obtain accurate results with any of the estimation methods. The strategy has been validated using both simulated waveforms and an extensive set of recordings from a real wind turbine. The work highlights the need to define additional requirements in the IEC 61400-21 standard to guarantee accurate and convergent results of flicker emission from grid-connected wind turbines.

1. Introduction

The International Electrotechnical Commission (IEC) 61400-21 standard [1] provides methods for the measurement and assessment of conducted disturbances generated by a grid-connected wind turbine (WT). Meanwhile, the international network for harmonized and recognized measurements in wind energy, Measnet, has developed a power quality measurement procedure [2] that is based on the standard [1]. The work of Measnet is aimed at ensuring high quality and uniform measurements among the different power quality monitoring agents.

Among the conducted disturbances, special attention has been paid to the assessment of the flicker emission of a WT [3–5]. The procedure of measurement of flicker emission is complex, because it is required to be as non-site specific as possible to minimize the effect of flicker sources other than the WT. To that end, the standard defines a procedure that, based on the measured current and voltage time series, simulates the voltage fluctuations in a fictitious grid in which the single source of perturbance producing flicker is the WT. Flicker severity has to be measured on that fictitious voltage by means of the IEC flickermeter, specified by the IEC 61000-4-15 standard [6].

Currently, the IEC Maintenance Team TC88/MT21 is working on a new revision of the IEC 61400-21 standard [7]. The standard revision has two main objectives, namely to match the technology development, aligning with the upcoming standards that will specify dynamic electrical simulation models for wind power generation [8,9], and to provide uniform procedures that will ensure consistency and accuracy in the testing and assessment of the electrical characteristics of grid-connected WTs. Regarding flicker, the complexity of the procedure may lead to different digital implementations that may involve inconsistency in the results. The comparisons carried out by Measnet reveal that measurements performed by different members on the same current and voltage time series do not always converge to the same results. Furthermore, the Maintenance Team TC88/MT21 points to the simplification of the flicker measurement procedure and the definition of a test protocol aimed at improving the consistency of the results.

The flicker measurement results depend strongly on two aspects of the measurement procedure: the implementation of the IEC flickermeter and the resolution of the fictitious grid. Regarding the IEC flickermeter, the use of class F1 implementation guarantees high accuracy in the calculation of flicker severity values [6]. However, regarding the second aspect, the IEC 61400-21 standard does not define any limitation on the degrees of freedom allowed in the solution of the fictitious grid with the purpose of making the measurements converge. Several publications reflect this need, suggesting that the measurement variability is caused by the diversity of options available for the various digital implementations used to solve and implement the fictitious grid [5,10–12].

The present work cautions that the procedure for measuring WT flicker emission is sensitive to the implementation of the fictitious

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grid, more specifically to small errors in the estimation of the electrical angle of the measured voltage. In view of this problem, this work proposes an alternative strategy, verified in real scenarios, that reduces the error in the estimation of the electrical angle, and consequently minimizes the divergences in flicker measurement results.

The flicker measurement procedure described in the IEC 61400-21 standard is summarized in Section 2. Section 3 presents three possible digital implementations for the estimation of the electrical angle of the measured voltage, as well as the potential sources of inaccuracy. Experiments performed with simulated waveforms confirm the inaccuracy of the three methods under a disturbed measured voltage. A new strategy to enhance the results is proposed in Section 4. Section 5 reproduces the divergence and inaccuracy of the results in an extensive set of recordings from an actual WT using the same three digital implementations, and confirms the solution to the problem with the proposed strategy. Conclusions are presented in Section 6.

2. Procedure for flicker measurement in a grid-connected WT

The standard IEC 61400-21 [1] specifies two procedures for measuring voltage fluctuations by a WT, depending on whether its functional status is continuous or switching operation. Both procedures use current and voltage time series measured at the WT terminals, line current $i_m(t)$ and phase-to-neutral voltage $u_m(t)$ respectively. This paper focuses on the part of the procedures that is common to both functional states of the WT, as shown in Fig. 1.

The WT under test is connected to a grid that usually has other fluctuating loads. Block 1 defines a fictitious grid that represents the interaction between the WT and the grid. The output voltage of the fictitious grid, $u_{fic}(t)$, is affected exclusively by disturbances injected by the WT. The standard specifies that $u_{fic}(t)$ must be obtained for different grid impedances (R_{fic}, L_{fic}), determined by the grid impedance phase angle ψ_k and the short-circuit apparent power $S_{k,fic}$ of the fictitious grid.

Specifically, the voltage $u_{fic}(t)$ must be obtained according to:

$$u_{fic}(t) = u_0(t) + R_{fic} \cdot i_m(t) + L_{fic} \cdot \frac{di_m(t)}{dt}. \tag{1}$$

The electrical angle of $u_0(t)$, $\alpha_m(t)$, must be the same as that of the fundamental of the measured voltage $u_m(t)$, according to:

$$\alpha_m(t) = 2\pi \cdot \int_0^t f(t)\,dt + \alpha_0, \tag{2}$$

where $f(t)$ is the instantaneous frequency of the fundamental component and α_0 is its initial electrical angle at $t = 0$. From the electrical angle, $\alpha_m(t)$, $u_0(t)$ must be constructed as:

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

where U_n is the nominal phase-to-phase voltage. Therefore, $u_0(t)$ is an ideal voltage without amplitude fluctuations.

Block 2 first calculates the flicker severity value, $P_{st,fic}$, for each $u_{fic}(t)$ by means of the IEC flickermeter, and finally obtains the flicker coefficient $c(\psi_k)$ normalizing each $P_{st,fic}$ value by applying:

$$c(\psi_k) = P_{st,fic} \cdot \frac{S_{k,fic}}{S_n}, \tag{4}$$

where $S_{k,fic}$ is the short-circuit apparent power of the fictitious grid and S_n is the rated apparent power of the WT. The standard suggests that values for the short-circuit power ratio, $S_{k,fic}/S_n$, should be between 20 and 50.

3. Inaccuracy of the flicker measurements in a grid-connected WT

The complexity of the procedure for flicker measurement in a grid-connected WT may lead to errors in its digital implementation that may result in the lack of consistency and accuracy of the flicker emission measurement results.

The implementation of the fictitious grid and the IEC flickermeter (see Fig. 1) could be a source of errors. The implementation of the IEC flickermeter could generate errors because of two main aspects. On the one hand, some studies have reported relevant discrepancies between the results of different IEC flickermeters when subject to the same input voltage [13,14]. The last edition of the IEC 61000-4-15 standard, 2.0, includes an additional type testing to enclose the margin of the implementations, classifying the instruments in terms of their accuracy. On the other hand, the application of the IEC flickermeter in the IEC 61400-21 standard requires it to measure very low $P_{st,fic}$ values, close to the bottom of the flickermeter measurement range. Therefore, an accurate implementation of the IEC flickermeter needs to be used that passes the functional tests at that low range.

When the accuracy of the IEC flickermeter implementation is guaranteed, the potential sources of errors must lie within the implementation of the fictitious grid (block 1 of Fig. 1), i.e. the calculation of $u_{fic}(t)$. The procedure to calculate $u_{fic}(t)$ requires two main tasks according to (1), namely the differentiation of the measured line current $i_m(t)$ and the construction of the $u_0(t)$ voltage. Regarding the first aspect, Redondo et al. reported that in exceptional circumstances the differentiation of $i_m(t)$ may lead to important errors [15,12]. With regard to the second task, the IEC 61400-21 standard does not specify the signal processing method that should be used to estimate $\alpha_m(t)$ from $u_m(t)$. Therefore, different digital implementations may lead to inconsistent results. This paper focuses on the errors associated with the estimation of the electrical angle $\alpha_m(t)$ of the measured voltage $u_m(t)$ that is needed to construct $u_0(t)$.

3.1. *Methods for* $u_0(t)$ *estimation*

Next, three methods that are traditionally used to estimate the instantaneous angle from a discrete signal are explained. The methods provide an accurate estimation with signals in which the fundamental frequency is the only relevant component. Recent works have reported the presence of other frequencies, such as harmonics and interharmonics, for type-3 and type-4 WT [16,17]. The presence of such disturbances may affect the accuracy of the estimation method. Besides the description of the methods, the disturbances in $u_m(t)$ that could affect their reliability are also noted.

3.1.1. *Zero-Crossing Detection*

The Zero-Crossing Detection (ZCD) technique is a well-known method to estimate the fundamental frequency of the power system [18]. The principle of the technique is to identify the cycles of a periodic signal. Working in the discrete domain, the algorithm searches for the positions of the contiguous samples of the signal that mark the transition from positive to negative values. To achieve a more precise estimation of the zero-crossing point, linear interpolation between the two samples can be used. The following expression calculates the fraction of the sampling period, $\Delta t/T_s$, corresponding to the interpolated positive-to-negative zero-crossing point:

$$\frac{\Delta t}{T_s} = \frac{v_p}{v_p - v_n}, \tag{5}$$

where v_p and v_n are the amplitude values of the positive and negative samples, respectively and T_s is the sampling period. To calculate