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VALIDATION OF DISTRIBUTED ENERGY RESOURCES IN ACCORDANCE WITH VOLTAGE FLUCTUATION LIMITATIONS PRESCRIBED BY THE IEEE 1547-2018 STANDARD

VALIDACIJA RAZPRŠENIH VIROV ENERGIJE V SKLADU Z OMEJITVAMI NIHANJA NAPETOSTI, KI JIH PREDPISUJE STANDARD IEEE 1547-2018

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Abstract

The increased need for clean energy and global warming is among the biggest challenges of the modern age. One of the potential solutions to these challenges, which can be achieved by using existing technologies, are distributed energy resources (DER). DER can be an isolated system of different capacity and purpose, but, in most cases, it is connected to the electricity grid.

Connecting a DER system to the electricity grid is a complex task, the complexity in-creases with the number of integrated DERs. In order to regulate interoperability and interconnection of DERs with electricity grid, the IEEE 1547-2018 standard is imposed.

Among other requirements, the standard prescribes voltage fluctuation limitations induced by the DER. The analysis of voltage fluctuations – flicker assumes measurement procedures defined

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by IEEE 1453-2015 standard and implementation of digital flicker-meter described by IEC 61000-4-15 standard.

In this proceeding, the realization of virtual instrument for voltage fluctuation analysis will be presented. This function is part of more comprehensive system for DER validation.

Povzetek

Povečana potreba po čisti energiji in globalno segrevanje sta med največjimi izzivi sodobnega časa. Ena od možnih rešitev omenjenih izzivov, ki jo lahko dosežemo z uporabo obstoječih tehnologij, so razpršeni energetski viri (v nadaljevanju DER). DER je lahko izoliran sistem različnih zmogljivosti in za različne namene, vendar je v večini primerov priključen na elektroenergetsko omrežje. Priključitev sistema DER na elektroenergetsko omrežje je kompleksna naloga, katere kompleksnost se povečuje s številom integriranih DER. Za ureditev interoperabilnosti in medsebojnega povezovanja DER z elektroenergetskim omrežjem je uveden standard IEEE 1547-2018.

Med drugim standard predpisuje omejitev nihanja napetosti, ki jih povzročajo DER. Za analizo nihanja napetosti (flikerja) so predvideni postopki meritev, določeni v standardu IEEE 1453-2015, implementacija digitalnega flikermetra pa je opisana v standardu IEC 61000-4-15.
V članku je predstavljena realizacija virtualnega instrumenta za analizo nihanja napetosti, ki je del celovitejšega sistema za validacijo DER.

1 INTRODUCTION

Global warming caused by increased CO_2 emissions and increased demands for energy production are two related problems. In the last two decades, great efforts have been made to solve these issues. Approaches to solving it are different: from social and political – raising awareness of the need for more economical use of energy, to technical and technological – finding cleaner sources of energy and more energy efficient systems.

In the technical-technological domain, in addition to efforts to achieve stable nuclear fusion with a positive energy yield, most research is carried out in the field of renewable energy sources (RES). As nuclear fusion is currently beyond our practical reach, scientific and commercial interests are currently focused on RES, particularly photovoltaics (PV).

The first installations of PV were stand-alone power generation systems, which are located in remote areas where commercial electricity is not available, thus isolated from the public electricity grid. Nowadays, most common PV installations are systems that are connected to a public electricity grid [*1*]. Such installations are frequently named distributed energy resources (DER). However, the public electricity grid was originally designed for the delivery and consumption of electricity, but not for the generation and storage of energy at the end-user level. Therefore, the integration of DER into the public power grid represents a complex problem, which complexity increases with the number of installations and global needs for electricity. In order to regulate interoperability and interconnection of DERs with electricity grid, the IEEE 1547-2018 standard is passed.

The IEEE 1547-2018 [*2*] standard defines a number of power quality requirements, which can be divided into following categories: direct current injection and current distortion limitations, limitations of voltage fluctuations – flicker, reactive power capability and voltage/power control requirements.

In this proceeding, the part of the system for validation and testing of DER – virtual instrument for voltage fluctuation analysis is presented. The function of described virtual instrument is in compliance with IEEE 1453-2015 [*3*] standard and implementation is based on digital flicker-meter described by IEC61000-4-15 standard [*4*].

This paper is organized as follows: the concept of electrical flicker is defined and the specified standards are presented and discussed in Section 2. Section 3 describes an integrated system for DER validation with an emphasis on flicker-meter implementation. Section 4 concludes the paper.

2 THE VOLTAGE FLUCTUATIONS – FLICKER

Originally, term flicker refers to the rapid and repeated variation in light intensity. It is usually perceived as a quick and annoying fluctuation in the brightness of a light source, often at a frequency that is not easily detectable by the human eye. Flicker can be caused by various factors, and it can have several implications and effects. Most common cause of flicker is voltage fluctuation, i.e., variation in the voltage supplied to the lighting system. Typically, the term electrical flicker is synonymous with voltage fluctuations.

Apart from unpleasant visible effects, voltage fluctuations can negatively affect the operation of electronic devices. Therefore, voltage fluctuations are regulated by international and national standards to ensure the safe and stable operation of electrical systems and protect connected devices. Some of the key standards that regulate voltage fluctuations are IEEE 1453-2015 [*3*] and IEC61000-4-15 [*4*]. In order to regulate the interoperability and interconnection of DERs with the electric grid, the IEEE 1547-2018 standard [*2*] was proposed, which also prescribes limitations regarding voltage fluctuations produced by grid inverters. Some of the key limitations for voltage fluctuations specified by standards are:

- limitations for instantaneous voltage fluctuations P_{inst} , which are short term calculation of how human eye and brain respond to flickering incandescent lights,
- limitations for short-term voltage fluctuations P_{st} , which are the cumulative measure and statistical analysis of instantaneous fluctuations during ten minutes.
- limitations for long-term voltage fluctuations P_{lt} , which are voltage fluctuation occurring over two hours.

The IEEE 1547-2018 standard prescribes minimum individual DER flicker emission limits. During a one-week measurement period, in 95% of individual measurement cases, the short-term and the long-term flicker should not exceed the limits of 0.35 and 0.25, respectively.

3 THE SYSTEM FOR DER VALIDATION

The system for DER validation is aimed to facilitate testing and validation of DERs containing power electronic based grid inverters, necessary for MPPT (Maximum Power Point Tracking) and converting a DC voltage to AC voltage with standardized waveform, frequency and amplitude. The entire DER, which consists of PV panels connected in strings and arrays, a MPPT controller and a network inverter, must meet certain standards, both in terms of converted power and in a quality of delivered electricity. In order to verify the operation in terms of fulfilling all the specific requirements prescribed by the IEEE 1547-2018 standard, it is necessary to perform a series of measurements on the DER being tested. These measurements require different instruments and different measurement setups, and in many cases, it is not possible to perform them simultaneously. For example, for a DC injection measurement one must use an ammeter with the ability to measure direct current, for measuring current harmonics an instrument for measuring the spectrum of current up to the appropriate frequency, and for voltage quality a digital flicker-meter.

In order to leverage DER validation, shorten the necessary time and reduce the costs of purchasing special instruments, this system was developed. Based on the concept of virtual instrumentation, the system uses universal modules for the acquisition of voltages and currents, while the calculations of power quality and other related parameters are performed in software on the computer. This realization concept enables the integration of several specific instruments into one unique system. Furthermore, it enables easy addition of new capabilities, as well as simple changes in functionality in accordance with future changes in standards.

Some functions of the system, related to DER verification regarding direct current injection and higher current harmonics are presented in [*5*]. Here, functions related to measuring voltage fluctuations and validating DERs against flicker will be shown.

3.1 Hardware implementation

System's hardware consists of sensors, connection circuitry and acquisition modules with computer interface. The voltages are measured directly, using National Instruments NI9225 module, equipped with three simultaneous acquisition channels, with ±300V measurement range. The resolution is 24bit, with sampling frequency is 50kHz. The module has interface that enable connection and data transfer to a computer.

3.2 Software implementation and signal analysis

Today, digital flicker-meters are used to analyze voltage fluctuations in the power grid, as well the voltage quality of grid inverters that are an integral part of DERs. The flicker-meter is designed to comply with international standards, such as IEC 61000-4-15, to accurately assess the flicker severity and provide relevant measurements. Flickermeter has three basic functions - voltage measurement, signal processing and parameter analyses, presentation and storage obtained by measurements. Here, digital flickermeter is an integral part of the system for DER testing and validation, sharing some functions such as voltage measurement/acquisition, data presentation and storage and the measurement control and management with other parts of the system. The signal processing function implies complex signal processing algorithms to analyze the voltage waveform and extract flicker parameters. These parameters, such as the instantaneous flicker (P_{inst}), short-term flicker (P_{st}) and longterm flicker (P_{lt}) are usually calculated using numerical algorithms. The virtual instrumentation-based implementation of the signal processing function, which is an integral part of the system, will be described in detail.

According to IEC 61000-4-15, the voltage fluctuation analyses virtual instrument architecture is composed of five signal processing blocks [*4*]. Some implementations of virtual instrumentation, as well as digital based flicker-meter are presented in [*6-9*].

The first block, shown in Figure 1 conditions input voltage by removing the DC component and normalizing the input voltage to output signal independent of the input voltage amplitude, maintaining constant long-term average. Voltage DC component is removed by high pass filer. The voltage normalization is performed by dividing input voltage with half-cycle RMS sliding average calculated within 1s time interval.

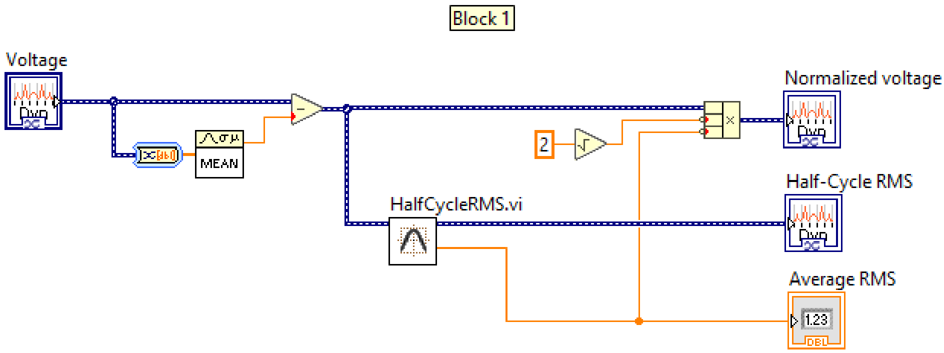

Figure 1: *First block – voltage normalization*

The input voltage is of the form

$$v_0(t) = V_{DC} + \sqrt{2}V_{rms}(1 + m(t))\cos\omega t, \tag{3.1}$$

where V_{DC} is the DC component of input voltage, V_{rms} is the voltage RMS which is a long-term constant, $m(t)$ is the voltage fluctuation and ω the mains frequency (50Hz). Voltage fluctuations can be regarded as low-frequency amplitude modulation of an input voltage.

After removing the DC component and voltage normalization performed by half-cycle RMS average, the output of the first block is the normalized signal

$$v_1(t) = (1 + m(t)) \times \cos\omega t. \tag{3.2}$$

The second block is a square multiplier (Figure 2). The output of the second block is a signal multiplied with itself, thus, of the form

$$v_2(t) = (v_1(t))^2 = (1 + 2m(t) + m^2(t)) \times \cos^2\omega t, \tag{3.3}$$

or by applying basic trigonometric transformations

$$v_2(t) = \frac{1}{2}(1 + 2m(t) + m^2(t)) \times (1 + \cos 2\omega t). \tag{3.4}$$

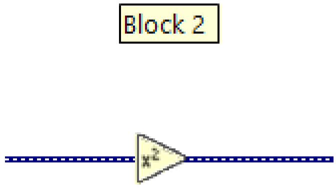

Figure 2: *Second block – square multiplier*

The third block consists of three different filters, the first two operating in combination with the square multiplier as an amplitude demodulator. The first filter is a 6th order low pass Butterworth filter, with a 3dB cutoff frequency at 35Hz. This low pass filter eliminates the double mains frequency component from the square multiplier output ($\cos 2\omega t$ term from equation (3.4)), producing a signal containing only one-time dependent term, $m(t)$. The second filter is a first order high-pass filter with a 3dB cut-off frequency at 0.05Hz, which eliminates the constant, time independent term from (1.4).

The weighting filter operates as a band-pass filter with a center frequency of 8.8Hz (Figure 3).

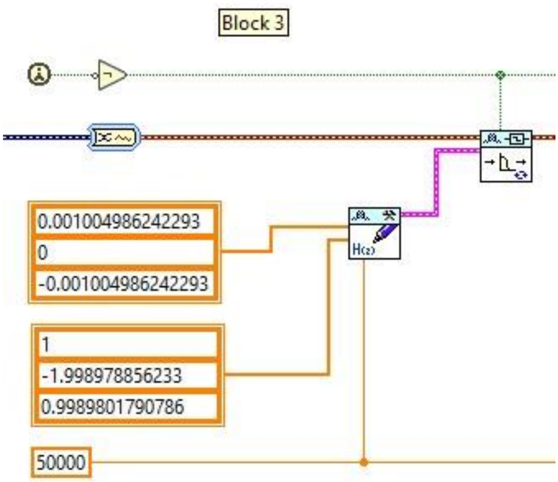

Figure 3: *The weighting filter implementation, part of the 3rd block*

The third block filter transfer function is

$$H(s) = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^2} \times \frac{1 + \frac{s}{\omega_2}}{1 + \frac{s}{\omega_3}} \times \frac{1}{1 + \frac{s}{\omega_4}}, \qquad (3.5)$$

where *s* is the complex frequency and the filter coefficients are prescribed by IEC61000-4-15 [*4*] and given in Table 1.

Table 1: *Filter coefficients for a 50Hz mains frequency*

Parameter	Value
k	1.74802
λ	2π·4.05981
ω_1	2π·9.15494
ω_2	2π·2.27979
ω_3	2π·1.22535
ω_4	2π·21.9

The output of the third block is the modulation signal

$$m(t) = M(\omega_m) \times \cos \omega_m t, \tag{3.6}$$

which contains information of the voltage fluctuation $M(\omega_m)$ and modulation frequency ω_m. The fourth block behaves similarly to the second block with parts of the third. It consists of a squaring multiplier and a first order low-pass filter with a 300ms time constant (Figure 4).

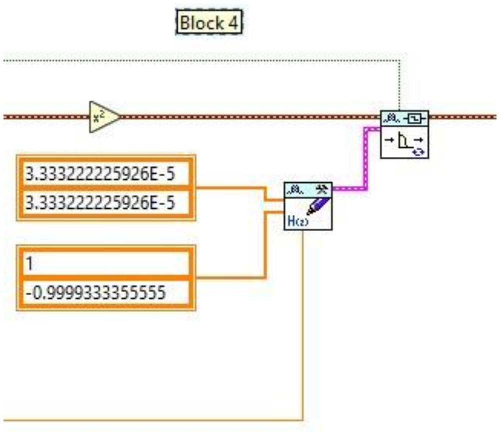

Figure 4: *The fourth block containing a squaring multiplier and first order low-pass IIR filter*

Similar to the output of the third block, the signal at the output of the fourth block has the form

$$p_{inst} \approx \left(M(\omega_M)\right)^2, \tag{3.7}$$

and represents instantaneous voltage flicker, p_{inst}.

The final, fifth block (Figure 5), performs statistical analysis, providing the short-term and long-term flicker voltage fluctuation evaluations, p_{st} and p_{lt}, respectively.

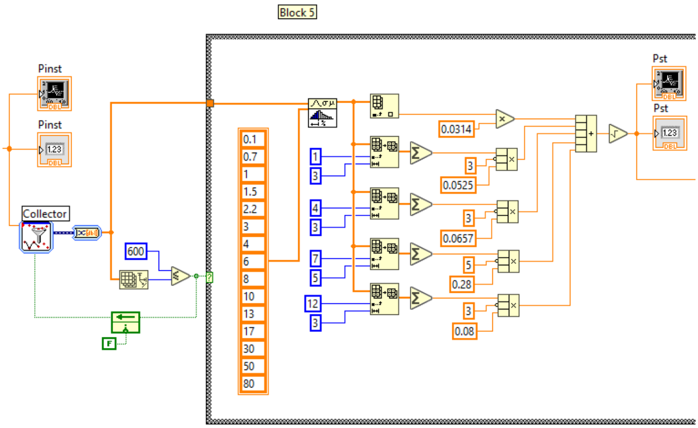

Figure 5*: Part of the fifth block, graphic code related to the short-term flicker calculation*

The instantaneous flicker values p_{inst} are grouped over 600 second intervals, in order to perform statistical analyses. 0.1%, 1%, 3%, 10% and 50% percentiles of p_{inst} are calculated for short-term flicker evaluation. The short-term flicker is calculated as the square root of a weighted sum

$$p_{st} = \sqrt{.0314 p_{0.1} + .0525 p_{1_s} + .0657 p_{3_s} + .28 p_{10_s} + .08 p_{50_s}}, \tag{3.8}$$

where index "s" in the equation suggests smoothing, i.e.

$$\begin{aligned} p_{50s} &= \frac{1}{3} \times (p_{30} + p_{50} + p_{80}) \\ p_{10s} &= \frac{1}{5} \times (p_6 + p_8 + p_{10} + p_{13} + p_{17}) \\ p_{3s} &= \frac{1}{3} \times (p_{2.2} + p_3 + p_4) \\ p_{1s} &= \frac{1}{3} \times (p_{0.7} + p_{.} + p_{1.5}). \end{aligned} \tag{3.9}$$

The long-term voltage flicker is calculated (Figure 6) at two-hour intervals using

$$p_{lt} = \sqrt[3]{\frac{1}{12} \sum_{k=1}^{12} p_{st,k}}, \tag{3.10}$$

where $p_{st,k}$ represents the collected short time flicker values during the two-hour time interval.

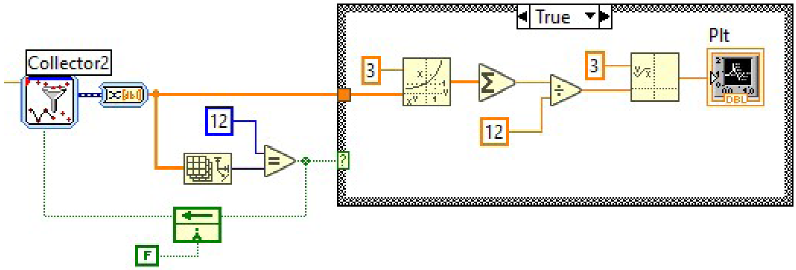

***Figure 6:** The long-term flicker calculation*

4 TESTING AND VALIDATION

The implemented part of the DER testing system, which refers to the measurement of voltage fluctuations, was tested in accordance with the IEC61000-4-15 [4] Standard. A simulated signal, a simple periodic signal modulated by a sinusoid and a square signal were used to test this function of the system,

According to the Standard, the output of the fourth block P_{inst} must be equal to unity, with a tolerance of 8%, for appropriate voltage modulations, $m(t)$. The values averaged over 600s for sinusoidal and square modulation are given in Tables 2 and 3, respectively. Only mandatory tests were conducted. The test was performed for a 50Hz, 230V electricity grid.

***Table 2:** Instantaneous flicker values for sinusoidal modulation*

Modulation frequency [Hz]	Modulation P_{inst} [%]	P_{inst}
0.5	2.325	1.041
1.5	1.067	0.933
8.8	0.25	0.932
20	0.704	1.003
25	1.037	0.993
33	2.218	1.076

***Table 3:** Instantaneous flicker values for square modulation*

Modulation frequency [Hz]	Modulation $m(t)$ [%]	P_{inst}
0.5	0.509	0.920
3.5	0.342	1.059
8.8	0.196	0.965
18	0.446	0.967
21.5	0.592	1.049
22	0.612	0.929
25	0.764	1.059
25.5	0.806	0.947
28	0.915	1.009
30.5	0.847	1.056
33.3	1.671	1.035

Preliminary tests of the system function with simulated signals showed that the function of the flicker-meter was realized in accordance with the IEC61000-4-15 [*4*] Standard. Further tests are necessary in real conditions, with measured voltages and comparison with reference instruments.

5 CONCLUSION

This paper describes one function of a comprehensive, integrated and specialized DER validation system: a virtual instrument for voltage fluctuation analysis.

This implementation of the system for DER validation has a number of advantages compared to the classical approach. The described solution integrates many functions of different instruments into one system. The described function of a digital flicker-meter is one of them.

The described function of the system is tested by means of simulation. The validation is planned by means of comparison with referent instruments.

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Nomenclature

(Symbols)	(Symbol meaning)
P_{inst}	Instantaneous flicker
P_{st}	Short-term flicker
P_{lt}	Long-term flicker
V_{DC}	Voltage DC component
V_{rms}	Voltage RMS value
ω	Mains angular frequency