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

Marko DIMITRIJEVIĆ[1] and Milutin PETRONIJEVIĆ[2]

Abstract: The increased need for clean energy and global warming are 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, which complexity increases 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 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.

Keywords: Distributed energy resources, voltage fluctuations, flicker.

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.

THE VOLTAGE FLUCTUACTIONS – 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

[1] University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia, e-mail: marko.dimitrijevic@elfak.ni.ac.rs
[2] University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia, e-mail: milutin.petronijevic@elfak.ni.ac.rs

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.

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.

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.

Software implementation and signal analysis

Today, digital flicker-meters are used to analyze voltage fluctuations in the power grid, as well as 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. Flicker-meter has three basic functions - voltage measurement, signal processing and parameter analyses, presentation and storage obtained by measurements. Here, digital flicker-meter 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 are usually calculated using numerical algorithms, such as the instantaneous flicker (P_{inst}), short-term flicker (P_{st}) and long-term flicker (P_{lt}). 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]. The implementations of virtual instrumentation, as well as digital based flicker-meter are presented in [6-9].

The first block 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 interval (Figure 1).

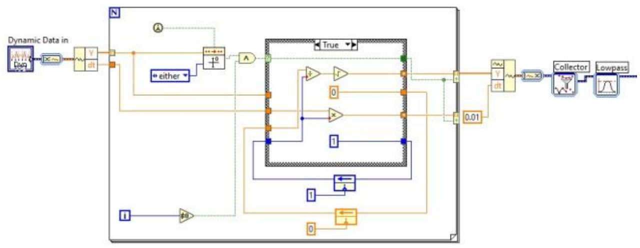

Fig.1 – *Voltage normalization block – half-cycle RMS and averaging function.*

The input voltage is of the form

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

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

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

$$v_1(t) = \left(1 + m(t)\right) \cdot \cos\omega t \,. \qquad (2)$$

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

$$v_2(t) = \left(v_1(t)\right)^2 = \left(1 + 2m(t) + m^2(t)\right) \cdot \cos^2 \omega t \,. \qquad (3)$$

or by applying basic trigonometric transformations

$$v_2(t) = \frac{1}{2}\left(1 + 2m(t) + m^2(t)\right) \cdot \left(1 + \cos 2\omega t\right). \qquad (4)$$

The third block consists of three different filters, first two operating in combination with the square multiplier as amplitude demodulator. The first filter is 6th order lowpass Butterworth filter, with 3dB cutoff frequency at 35Hz (Figure 2). This lowpass filter eliminates double mains frequency component from square multiplier output ($\cos 2\omega t$ term from equation (4)), producing signal containing only one time dependent term, $m(t)$. The second filter is first order high-pass filter with 3dB cut-off frequency at 0.05Hz, which eliminates constant, time independent term from (4).

The weighting filter operates as band-pass filter with a centre frequency of 8.8Hz (Figure 2).

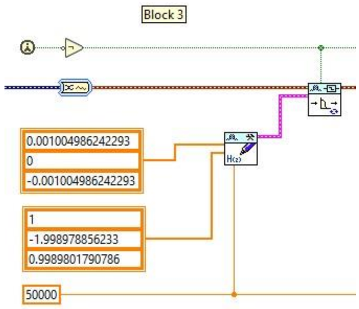

Fig.2 – *The weighting filter implementation, part of 3rd block.*

The third block filter transfer function is

$$H(s) = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^2} \cdot \frac{1 + s/\omega_2}{1 + s/\omega_3} \cdot \frac{1}{1 + s/\omega_4} \qquad (5)$$

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

Table I

Filter coefficients for 50Hz mains frequency

Parameter	Value
k	1.74802
λ	$2\pi \cdot 4.05981$
ω_1	$2\pi \cdot 9.15494$
ω_1	$2\pi \cdot 2.27979$
ω_1	$2\pi \cdot 1.22535$
ω_1	$2\pi \cdot 21.9$

The output of the third block is modulation signal

$$m(t) = M(\omega_m) \cdot \cos\omega t \,, \qquad (6)$$

which contains information of 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 first order low-pass filter with 300ms time constant (Figure 3).

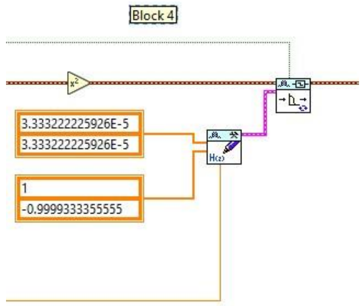

Fig.3 – *The fourth block containing squaring multiplier and first order low-pass IIR filter.*

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

$$p_{inst} \approx \left(M(\omega_M)\right)^2 , \qquad (7)$$

and represents instantaneous voltage flicker, p_{inst} .

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

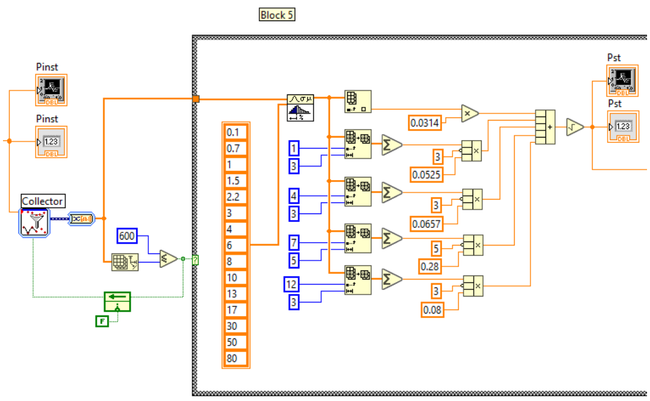

Fig.4 – *Part of the fifth block, graphic code related to short-term flicker calculation* p_{st} .

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

$$p_{st} = \sqrt{.0314 p_{0.1} + .0525 p_{1s} + .0657 p_{3s} + .28 p_{10s} + .08 p_{50s}} \,, \qquad (8)$$

where index “s” in equation suggests smoothing, i.e.

$$\begin{aligned} p_{50s} &= 1/3 \cdot (p_{30} + p_{50} + p_{80}) \\ p_{10s} &= 1/5 \cdot (p_6 + p_8 + p_{10} + p_{13} + p_{17}) \\ p_{3s} &= 1/3 \cdot (p_{2.2} + p_3 + p_4) \\ p_{1s} &= 1/3 \cdot (p_{0.7} + p + p_{1.5}). \end{aligned} \qquad (9)$$

The long-term voltage flicker is calculated (Figure 5) on two-hour intervals using

$$p_{lt} = \sqrt[3]{\frac{1}{12}\sum_{k=1}^{12} p_{st,k}}\,, \qquad (10)$$

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

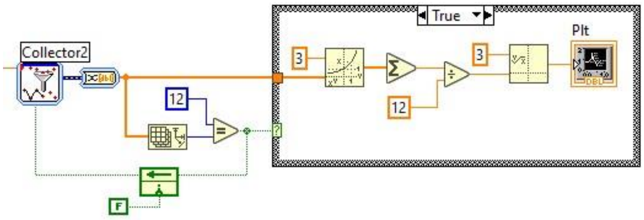

Fig.5 – *The long-term flicker calculation.*

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. To test this function of the system, a simulated signal, a simple periodic signal modulated by a sinusoid and a square signal was used.

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, $m(t)$. Values averaged over 600s for sinusoidal and square modulation are given in Tables II and III, respectively. Only mandatory tests are conducted. The test is performed for 50Hz, 230V electricity grid.

Table II
Instantaneous flicker values for sinusoidal modulation

Modulation frequency [Hz]	Modulation $m(t)$ [%]	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 III
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 show that the function of the flicker-meter is realized in accordance with the IEC61000-4-15 [4] standard. Further tests in real conditions, with measured voltages and comparison with reference instruments are necessary.

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 classical approach. The described solution integrates many functions of different instruments into one system. The described function of digital flicker-meter is one of them.

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

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