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Implementation and Testing of a Flicker Meter Using IEC 61850-9-2 Sampled Values

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SUMMARY
Providing uninterrupted and undistorted power supply is essential due to increasing use of sensitive electronic devices which could malfunction under poor quality of power supply. Voltage flicker is one power quality issue which can arise due to fluctuating electrical loads or due to intermittent power sources such as solar and wind energy systems. Voltage flicker can manifest as repeated fluctuations in indoor light intensity which can cause health issues. Voltage flicker can also lead to malfunction of sensitive electronic equipment. Measurement of flicker is important to design flicker mitigation methodologies and to verify the effectiveness of the implemented flicker mitigation steps. International Electro Technical Commission (IEC) 61000-4-15 standard defines a method to quantify and measure the flicker level.

In order to continuously monitor the flicker level, power utilities install Flicker meters. In modern digital substations that follow IEC 61850 standard for substation automation, the conventional analog electrical signals are replaced with digitized sample values as defined in IEC 61850-9-2 standard. Hence, a Flickermeter installed in such a substation need to rely on sampled values instead of the analog voltage signals from instrument transformers.

This paper investigates the possibility of implementing an IEC Flickermeter based on IEC 61850-9-2 sampled values. The Flickermeter was successfully implemented on a RTDS™ real time simulator with GTNET™ card, and its performance was confirmed using the standard test signals prescribed in the IEC 61000–4–15 standard. The effects of the merging unit and the communication network performance on flicker calculation were evaluated. The tests showed that the bit resolution of the merging unit analog to digital converter and the packet losses in the communication network have significant impact on the accuracy of the Flickermeter. Flickermeter implemented on the real time digital simulator was used to analyze the flicker contribution from an arc furnace to a simple power system. The investigation presented in this paper shows that a Flickermeter based on sampled values can perform satisfactorily with commercial merging units and a reliable communication network.

KEYWORDS

Flickermeter, IEC 61000-4-15, IEC 61850, Power Quality, Real Time Digital Simulator, Sampled Values

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INTRODUCTION

With the wide usage of nonlinear electrical loads and rapid increase in distributed energy resources which utilize power electronic equipment, power quality has become a concern for both the utility and electricity customers. This is mainly due to the increasing use of sensitive electronic equipment which are susceptible for malfunction due to poor quality of power supply. Voltage flicker is one such power quality issue, which arises due to fluctuating loads or due to the intermittent nature of some distributed generators. Even though voltage flicker is normally not an issue at the transmission level, it surfaces in weak distribution feeders creating problems to the consumers. If not mitigated, voltage flicker can manifest as repeated fluctuations in the intensity provided by artificial lighting, leading to people being affected by health issues such fatigue, migraine, lack of concentration [1]. Voltage flicker can also cause malfunction of protection relays and other sensitive electronic equipment [2].

In order to design voltage flicker mitigation measures, it is necessary to understand the severity of the problems and the sources of flicker. Also, when a mitigation measure is implemented, it is necessary to verify that the measure is effective. Both these require a method for measurement of flicker, and IEC 61000–4–15 standard [3] defines two indices, the Short Term Flicker (PST) and the Long Term Flicker (PLT). The Flicker indices attempt to capture the human eye-brain response to the fluctuating light intensity of an incandescent lamp. The standard also provides specifications for a standard Flickermeter and test waveforms to validate the accuracy of a Flickermeter.

Power utilities often install power quality meters, including Flickermeters, in substations for continuous monitoring and recording various power quality events and indices. Modern substations are equipped with substation automation systems (SASs) which greatly enhance the real-time observability, protection, automation, and controllability. Improved event detection and recording are one of the many benefits of substation automation. IEC 61850 standard [4], which was introduced in the early 2000s, is a relatively new standard that facilitates non-proprietary communication for power system automation [5]. Reduction in project cost, ease of maintenance, better safety, and isolation, interoperability and interchangeability are some of the many advantages of IEC 61850 standard. One major feature of IEC 61850 standard is the replacement of analogue electrical signals transmitted over numerous copper wires that connect instruments transformers in the yard with protection and control equipment in the substation building, with digitized sample values communicated over fibre optic communication network. The specifications for implementation of sampled values (SV) is provided in IEC 61850–9–2 [6]. Due to many advantages of IEC 61850 standard, Intelligent Electronics Device (IED) vendors are quickly adopting their equipment to be compatible with this standard. A Flickermeter installed in such a substation would be provided with sampled values, rather than with the typical analogue voltage signals.

Many studies that investigate different implementations of the IEC 61000–4–15 Flickermeter have been reported in literature [7]–[10]. However, none of them have considered IEC 61850 –9–2 sampled values in implementing the Flickermeter. Since the industry is rapidly adopting the concept of digital substations based on IEC 61850 standard, it is essential to understand how would a typical Flickermeter perform when input with IEC 61850-9-2 SVs. Although it appears straight forward, the performance can be affected by the implementation of samples values, particularly the analogue to digital converter (ADC) resolution and sampling rates, which are outside the Flickermeter control and change from substation to substation. In a traditional Flickermeter, these are known parameters and not expected to change. The performance, can also be affected by the performance of the communication network that deliver the sample values (referred to as process bus in IEC 61850 standard).

This paper reports the implementation and evaluation of the performance of an IEC 61000–4–15 standard Flickermeter that uses IEC 61850–9–2 sampled values. The Flickermeter was implemented on a real-time digital simulator. The performance was assessed using the standard test signals provided in the IEC 61000–4–15 standard. Effects of the merging unit analogue to digital converter resolution, sampling rate, and the performance of the communication network in the substation in calculating the flicker level was investigated. After evaluating the performance the implemented Flickermeter using standard test signals, its application to evaluate the flicker contribution from an Arc Furnace was demonstrated.

METHODOLOGY

The overall methodology involves implementation of the standard Flickermeter defined in the IEC 61000–4–15 with the voltage measurements are input in the form of IEC 61850–9–2 sampled values, and evaluating it using the standard test cases defined in the IEC 61000–4–15 standard. In this research, the standard Flickermeter is implemented in a RTDS™ real-time digital simulator [11], which is equipped with hardware and software required to publish and subscribe to IEC 61850–9–2 sampled values. The RTDS™ simulator consists of the units called racks, which can operate as independent simulators or combined to form a larger simulator with more computing resources. The setup used in this research consisted of two racks: The Flickermeter was implemented on one rack while the other was used to generate test signals and publish the signals as sampled values through a merging unit modeled in the simulator. The two racks communicated through an external network as illustrated in Figure 1. The GTNET cards [12] installed on each rack facilitated the publishing and subscribing of SVs through network ports on them. The two racks were independently synchronized to a GPS clock via GTSync [13] cards on each of the racks, and therefore operated as two completely independent units.

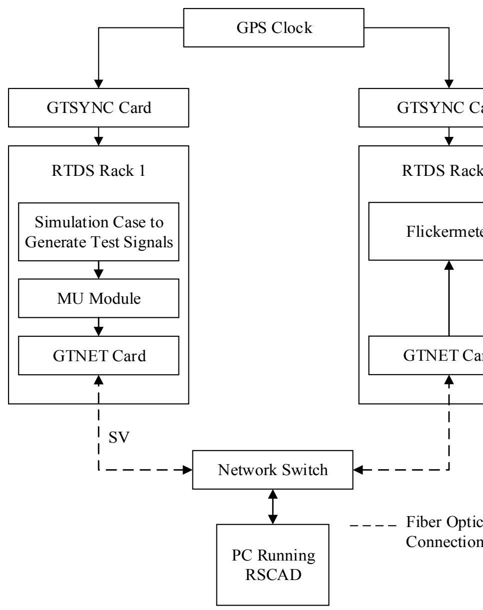


Figure 1 – The laboratory setup that include two RTDS™ racks and a local area network.

IEC 61000 – 4 – 15 Flickermeter

The IEC 61000 – 4 – 15 standard divides the Flickermeter into five blocks as shown in Figure 2. The input voltage adaptor circuit which is the first block in the Flickermeter model is used to scale the input voltage level to an internal reference level. Scaling enables the Flickermeter calculation independent of the system voltage level. The scaled output is squared in the next block in order to simulate the behavior of an incandescent lamp. The squared voltage output is sent through a filtering block consisting of three cascaded filters. The first two filters are employed to eliminate the dc component and to eliminate the signal component at twice the mains frequency, which is usually present at the output of the squaring demodulator. The first filter is a first order high pass filter with a 3 dB cut off frequency of 0.05 Hz. The second filter is a 6^{th} order low pass Butterworth filter which has a 3dB cut off frequency of 35 Hz for a 50 Hz system and 42 Hz cut off frequency for a 60 Hz system. The third filter is a weighting filter, which simulates the frequency response of the human visual system to voltage fluctuations. The weighting filter is implemented as two cascaded second-order filters. The transfer function for the weighting filter is given in the IEC 61000–4–15 standard [3].

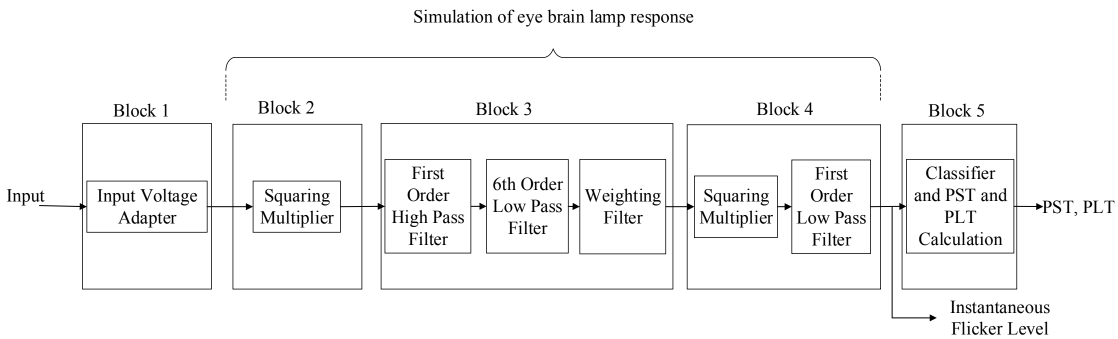


Figure 2 – Functional Diagram of Flickermeter [3]

After the filtering process, the output is squared to simulate the nonlinear eye-brain perception. The squared signal is sent through a first order resistive-capacitive low pass filter with a time constant of 300 ms to simulate the storage effect of the brain. The output from this block is defined as the instantaneous flicker severity by the IEC standard. The output of this block has to be calibrated such that the maximum output is unity when a 50 Hz/60 Hz sine wave modulated signal with a modulation frequency of 8.8 Hz and modulation amplitude of 0.25 % is applied.
Then the generated instantaneous flicker level signal is sent through the statistical analysis block, which is the final block in the system. Inside the statistical analysis block, the short term and long-term flicker severity levels are evaluated. To calculate the short-term flicker severity the instantaneous flicker level was recorded for 10 minutes and it is derived from the time at level statistics obtained from the classifier using equation (1).

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \quad (1)$$

Where the percentiles $P_{0.1}, P_1, P_3, P_{10}$, P_{50} are the flicker levels exceeded 0.1 %, 1 %, 3% , 10% and 50 % of the time during the observation period. The suffix 's' means smoothed values are used in the equation. Smoothing is done using the equations provided in the standard. The long-term flicker severity is evaluated by recording 12 consecutive P_{st} values (total recording time of 2 hours) and getting the cube root of the averaged sum of the cubes of the 12 P_{st} values. The purpose of the long-term flicker severity level is to analyze the combined effect of the several randomly operating loads or to analyze the effect of the loads with long and variable duty cycles.
The Flickermeter shown in Figure 2 was assembled in RSCAD (the software interface of RTDS simulator) using its library components. However, algorithms required to calculate PLT was not available as a library component, and therefore, a custom component was built using the RSCAD C-builder suite.

Standalone Merging Unit

Standalone merging units (SAMU) are connected to the secondary terminals of the instruments transformers. These SAMUs gather phase voltages and currents from instrument transformers. The analog values obtained from instrument transformers are converted to digital and merged into data packets formatted according to IEC 61850–9–2 standard. These data packets are known as sample value packets. Digitized data packets are published to IEDs that subscribe to the SV data stream. The IEDs carry out calculations and issue control signals based on the received sampled values. In this setup, the IED is the Flickermeter simulated in RTDS rack-2.
The input to a merging unit is typically coming from an instrument transformer, which converts the system voltages to voltage levels, which are safe to use in electronic circuits. The low-level voltage signal is then sent through an anti-aliasing filter. In the experiments, a 6^{th} order low pass Butterworth filter with a cut-off frequency set at half of the sampling frequency was used. Then it undergoes periodic sampling and analogue to digital conversion. Digital filtering and calibration are carried out to remove delays and non-linearities in the signal. Finally, the merging unit may resample the digital

data at appropriate sampled values rates [14]. In the base case, the voltage signals were sampled at 256 samples/cycle and an analog to digital converter (ADC) with 24 bit resolution was considered. The ADC resolution for a 24 bits ADC can be determined as follows:

Expected maximum voltage level = $69\sqrt{2}$ V

Number of bits available to represent the voltage signal after 1 bit is reserved for the sign = 23 bits

Resolution of the voltage = $\frac{69\sqrt{2}}{2^{23}} = 1.163 \times 10^{-5}$ V

The model of SAMU was implemented on RSCAD using standard library components.

Communication Network

A local area network was implemented in the lab using a substation grade RuggedCom™ RSG2288 [15] switch, which supports fiber optic as well as CAT 5 connection. The switch allows data rates of 1 Gbps over optical fiber connections and 1000 Mbps over CAT 5 connections. The switch also support IEEE 1588 [16] precision time protocol. SV publishing and subscribing was configured through the options of GTNET card interface in RSCAD.

EVLAUTION OF FLICKERMETER

Standard Test Results

IEC 61000–4–15 standard provides several test scenarios to test and calibrate the digital Flickermeter. The tests required for general purpose power quality meters were carried out to verify the performance of the Flickermeter implemented on RTDS™ simulator. These tests include (a) instantaneous Flicker response for sinusoidal voltage variation, and (b) rectangular voltage changes and performance test.

a) Instantaneous Flicker response for sinusoidal voltage variation

This test evaluates the response characteristic of the filters and scaling parameters of the Flickermeter. The test signal is generated by modulating the amplitude of the power frequency signal in the form of:

$$u(t) = 1 \times \sin\left(2\pi f_{sys} t\right) \times \left\{1 + \frac{a}{100} \times \frac{1}{2} \times \sin(2\pi f_{mod} t)\right\} \quad (2)$$

Where, f_{sys} is the system frequency, a is the voltage fluctuation percentage, f_{mod} is the modulation frequency.

The amplitude and frequency of modulating signal were varied as in Table 1 during the test. For each case, the expected value of maximum instantaneous flicker level (Pinst) is 1.00 with a tolerance of ±8%. Table 1 shows the test points and the corresponding maximum instantaneous flicker level and the error percentage. The maximum instantaneous flicker level for all standard test points lie within the tolerance level. The results verify the accurate response of the filters and scaling parameters.

Table 1: Pinst values for sinusoidal voltage changes

Frequency / Hz	Amplitude (%)	Max Pinst	Error
0.500	2.453	1.007	0.696%
1.500	1.126	1.007	0.689%
8.800	0.321	1.006	0.588%
20.000	0.977	1.004	0.404%
25.000	1.464	1.006	0.572%
33.330	2.570	1.007	0.681%
40.000	4.393	1.006	0.553%

b) Rectangular voltage changes and performance test

The second standard test is the rectangular voltage changes and performance test, which tests the classifier and statistical evaluation algorithms of the Flickermeter. The test signal is generated by modulating the amplitude of the power frequency signal in the form of:

$$u(t) = 1 \times \sin(2\pi f_{sys} t) \times \left\{ 1 + \frac{a}{100} \times \frac{1}{2} \times \text{signum}[\sin(2\pi f_{mod} t)] \right\} \quad (3)$$

Where, f_{sys} is the system frequency, a is the voltage fluctuation percentage, f_{mod} is the modulation frequency. The function 'signum ()' represents:

$$\text{signum}(x) := \begin{cases} -1 & \text{if } x < 0 \\ 0 & \text{if } x = 0 \\ 1 & \text{if } x > 0 \end{cases} \quad (4)$$

The frequency (specified as the rectangular changes per minute) and the amplitude modulation signal are varied as per the values given in Table 2. In Table 2, 4800 rectangular changes per minute correspond to a square wave modulation frequency of 40 Hz. The short-term flicker level (Pst) is the value under test, and its expected value is 1.00 with a tolerance of ±5% for all the test points. The PST value obtained during the test and the error percentages are given in Table 2.

Table 2: Rectangular voltage changes and performance testing test results

Rectangular Changes Per Minute	Amplitude	PST	Error
1	3.181	0.9995	0.05%
2	2.564	1.016	1.60%
7	1.694	1.02	2.00%
39	1.04	1.011	1.10%
110	0.844	1.003	0.30%
1620	0.548	1.012	1.20%
4800	4.837	1.012	1.20%

The Pst value does not exceed the standard threshold value for all the test points. This verifies the accurate performance of the classifier and statistical evaluation algorithms.

Effect of the sampling rate and bit resolution of the merging unit

In the next test, the effects of SAMU sampling rate and bit resolution was examined. The sampling rate was varied as 256 samples/cycle, 128 samples/cycle, 96 samples/cycle, 64 samples/cycle, and 32 samples/cycle. The sampled voltage signals were digitized using bit resolutions of 24 bits, 18 bits, 16 bits, 12 bits, and 8 bits.

A test waveform with sinusoidal amplitude variation was used. The frequency and magnitude of the modulation signal were 8.8 Hz and 0.321 %. This frequency was selected because it is the most sensitive flicker frequency for human eye. The instantaneous flicker level was recorded for 180 cycles (3 seconds) and the maximum instantaneous flicker level was evaluated. The standard maximum flicker level for the given input signal is 1.00 with ±8% tolerance level. The error percentages observed for different bit resolutions and sampling rates are given in Table 3.

Table 3: Percentage error in the maximum instantaneous flicker level at different sampling rates and bit resolutions

Sampling rate samples/cycle	Bit Resolution				
	8 bit	12 bit	16 bit	18 bit	24 bit
32	54.704%	0.611%	0.169%	0.292%	0.289%
64	23.778%	1.310%	0.203%	0.172%	0.059%
96	8.045%	0.113%	0.086%	0.019%	0.019%
128	9.574%	0.549%	0.051%	0.019%	0.019%
256	9.434%	0.251%	0.047%	0.059%	0.059%

Considering the results obtained from the test, it is clear that the accuracy is not much affected by the sampling rate, however, bit resolution plays a major part in accurate calculation of Flicker level. Since most commercial merging units use ADCs with bit resolutions in the range of 16 to 20 bits [17], [18], from the above results it can be concluded that a Flickermeter that use SVs from a commercial SAMU will operate satisfactorily.

Effect of packet loss on Flicker calculation

The GTNET-SVse [19] model available in the RSCAD software has the capability to suppress a specific amount of data packets specified by the user. Using this feature, in this test, publishing of several SV packets was suppressed at the beginning of each cycle of power frequency waveform. The merging unit sampling rate and bit resolution were kept constant at 256 samples/cycle and 24 bits. The standard test waveform used to analyze the effect of bit resolution of the merging unit was used as the input to the Flickermeter. Instantaneous flicker level was recorded for 180 cycles (3 seconds) and the maximum instantaneous flicker level was evaluated from the recorded data. The maximum instantaneous flicker levels and the error percentages observed after the loss of varying number of consecutive packets are given in Table 4.

Table 4: Maximum instantaneous Flicker level under packet loss scenario

Number of Packets Lost	Pinst Max without packet loss	Pinst Max with packet loss	Error %
1	1.006	1.030	2.970%
2	1.006	1.041	4.134%
3	1.006	1.081	8.139%
4	1.006	1.169	16.885%

According to the IEC standard, the error should be less than 8%. When three consecutive SV packets are lost, the error exceeds the standard error limit. The results show that packet losses can have significant impact on the accuracy of the Flickermeter. The GTNET-SVse model only allows suppressing of SV packets at the beginning of power frequency cycle, and therefore, the impact of packet loss at random places could not be tested.

APPLICATION EXAMPLE

The tested Flickermeter was used to analyze the flicker contribution from an electric arc furnace (EAF) simulated in the real time simulator. The electric arc furnace is fed from a 230 kV grid by a 100 MVA transformer which steps down the voltage to 69 kV. The EAF is connected to the 69 kV bus through a 69 kV/4 kV 100 MVA step down transformer. The arc furnace model available in RSCAD standard library was used with the default parameter values. The test setup is depicted in Figure 3.

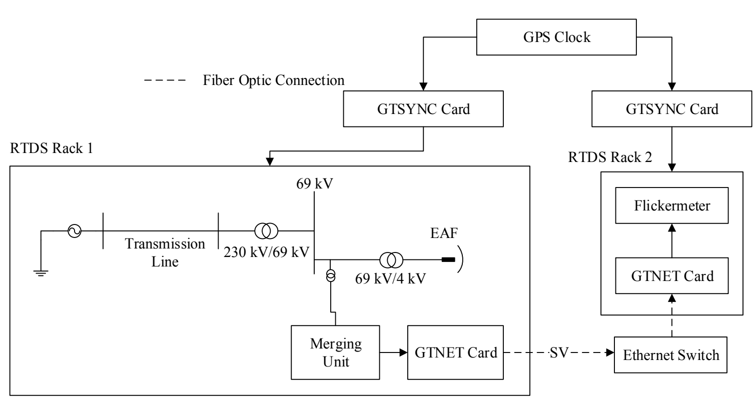
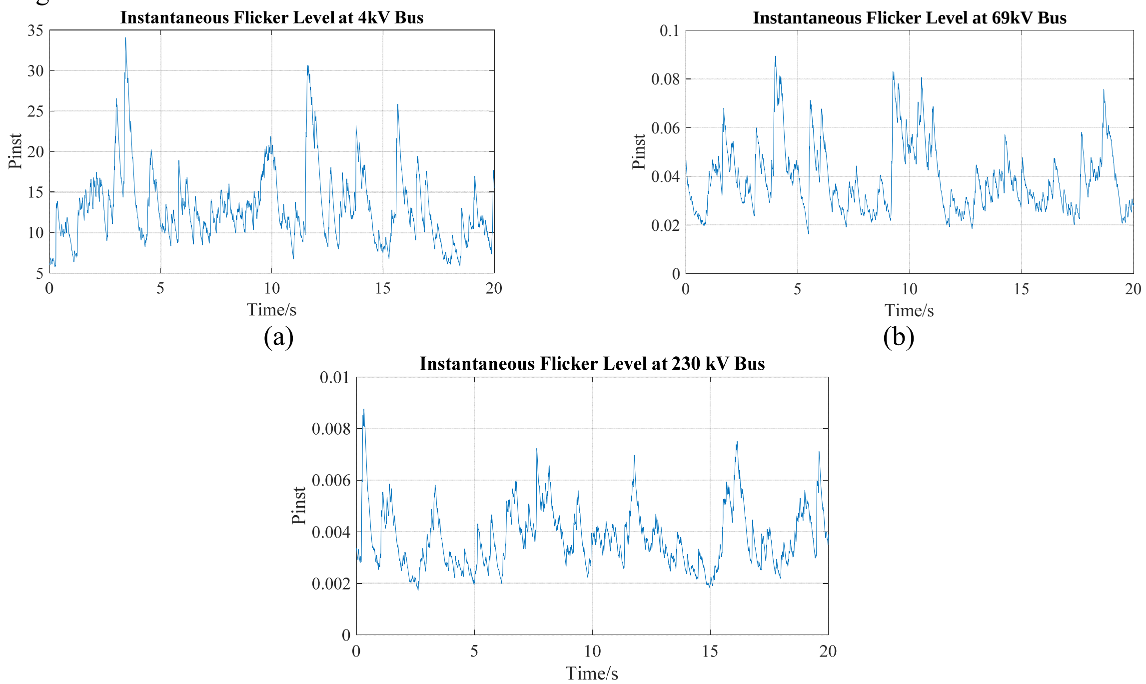


Figure 3 – Power System with an Arc Furnace Simulated in RTDS™

Arc Furnace Flicker contribution

Flicker contribution from the electric arc furnace at various locations of the power system was calculated using the developed Flickermeter that use sampled values. The merging unit sampling rate and bit resolution were 256 samples/cycle and 24 bits. Instantaneous and short term flicker levels were calculated. The short term flicker level (PST) for the recorded period was 0.1644 per unit.
Figure 4 shows the variation of the instantaneous flicker level at 4 kV, 69 kV, and 230 kV buses during a 20 s interval. The results agree with the general expectation. The long term flicker severity index at 69 kV bus was observed using the custom built component for 10 hours and it is depicted in Figure 5.



(c)

Figure 4 - Instantaneous Flicker Contribution from the Arc Furnace at (a) 4kV, (b) 69kV and (c) 230kV Buses Recorded for 20 s

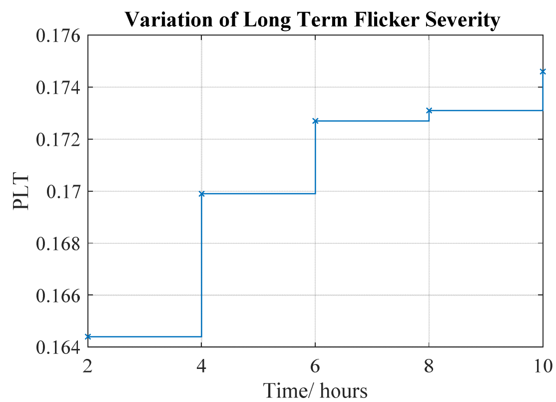


Figure 5 – Long Term Flicker Severity Observed at 69 kV Bus During a 10 Hour Period

CONCLUSION

This paper investigated the possibility of implementing an IEC Flickermeter based on IEC 61850-9-2 sampled values. The Flickermeter was successfully implemented on a RTDS™ real time simulator with GTNET™ card, and its performance was confirmed using the standard tested signals prescribed in the IEC 61000–4–15. The effects of the merging unit and the communication network performance on flicker calculation was evaluated. The tests showed that the bit resolution of the merging unit analog to digital converter and the packet losses in the communication network have significant impact on the accuracy of the Flickermeter. The investigation presented in this paper shows that a Flickermeter based on sampled values can perform satisfactorily with commercial merging units and a reliable communication network.

BIBLIOGRAPHY

[1] A. Wilkins, J. Veitch, and B. Lehman, "LED Lighting Flicker and Potential Health Concerns : IEEE Standard PAR1789 Update," in *2010 IEEE Energy Conversion Congress and Exposition*, 2010, pp. 171–178.

[2] "Voltage Fluctuations, Flicker And Power Quality | Fluke." [Online]. Available: https://www.fluke.com/en-ca/learn/best-practices/measurement-basics/power-quality/voltage-fluctuations-flicker-and-power-quality-2. [Accessed: 05-Feb-2019].

[3] I. E. Commission, *Electromagnetic compatibility (EMC). Compatibilité électromagnétique (CEM). Part 4-15, Partie 4-15, Part 4-15, Partie 4-15,*. Geneva: International Electrotechnical Commission, 2015.

[4] "IEC standard for Communication networks and systems for power utility automation," Geneva, 2013.

[5] S. Kariyawasam, "Implementation of an IEC 61850 Sampled Values Based Line Protection IED with a New Transients-Based Hybrid Protection Algorithm," 2016.

[6] "IEC standard for Communication networks and systems for power utility automation, Part 9-2: Specific communication service mapping (SCSM) – Sampled values over ISO/IEC 8802-3, IEC 61850-9-2, Second Edition," 2011.

[7] D. Fregosi, L. W. White, E. Green, J. Watterson, and S. Bhattacharya, "Digital Flickermeter design and implementation based on IEC standard," in *2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings*, 2010.

[8] D. Gallo, C. Landi, and N. Pasquino, "Design and calibration of an objective flickermeter," *IEEE Trans. Instrum. Meas.*, 2006.

[9] L. W. White and S. Bhattacharya, "A discrete matlabsimulink flickermeter model for power quality studies," *IEEE Trans. Instrum. Meas.*, 2010.

[10] T. Keppler, N. Watson, and J. Arrillaga, "Computation of the short-term flicker severity index," *IEEE Trans. Power Deliv.*, 2000.

[11] "REAL TIME POWER SYSTEM SIMULATION • RTDS Technologies Inc." [Online]. Available: https://www.rtds.com/real-time-power-system-simulation/. [Accessed: 06-Jun-2019].

[12] RTDS Technologies Inc., "RTDS Hardware Manual - GTNET Network Interface Card."

[13] RTDS Technologies Inc., "RTDS Hardware Manual - GTSYNC Synchronization Card," vol. rev 04, no. March, 2015.

[14] Q. Yang, D. Keckalo, D. Dolezilek, and E. Cenzon, "Testing IEC 61850 Merging Units," *44th Annu. West. Prot. Relay Conf.*, pp. 1–9, 2017.

[15] Siemens, "RUGGEDCOM RSG2288 - Installation Guide," 2019.

[16] "IEEE Std . 1588 Precision Time Protocol in Power System Applications," 2008.

[17] "Multi-Timeframe Power System Recorder and Monitor PMU for Wide Area Monitoring CDR (Continuous Disturbance Recorder)."

[18] "PCS-221 Merging Unit- NR Electric." [Online]. Available: http://www.nrec.com/en/product/PCS-221.html. [Accessed: 15-Apr-2019].

[19] RTDS Technologies Inc., "RTDS Component Manual - GTNET SV Special Edition," no. August, pp. 1–2, 2012.