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Virtual Instrument as a Tool for Teaching Power Quality

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Abstract. The course(s) in the field of power quality (PQ) for postgraduate even for undergraduate curriculums in power engineering is becoming necessity. The importance of this field and general public awareness of the subject is growing. Teaching and presenting this complex field to the students, which by its nature is multidisciplinary between various branches in electrical engineering, is not an easy task. The objective of this paper is to propose modern approach for teaching the PQ using low cost data acquisition cards.

Key words

Power quality parameters, flicker, sampling theorem, data acquisition cards, virtual instrument.

1. Introduction

The increased use of industrial and consumer equipment with nonlinear characteristics, loads that need reactive power and other causes, generate power quality disturbances. The loses of industry produced of voltage interruptions or equipment failures due to unwanted PQ disturbances has been estimated to tens of thousand to millions of dollars, worldwide.

Considering the education in PQ, theoretical classes are not enough for real understanding of the subject. Experimental classes where measurements of PQ parameters will be demonstrated are essential for comprehensive education in the field.

The paper is presenting one approach of teaching PQ parameters using a virtual instrument that can carry out measurements in the laboratory. The designed virtual instrument (fig. 1) are consisting of signal conditioning circuitry for voltage and current, PCI data acquisition card and software developed on LabVIEW platform. The designed instrument is based on the standards EN 50160 and IEC 61000-4-15.

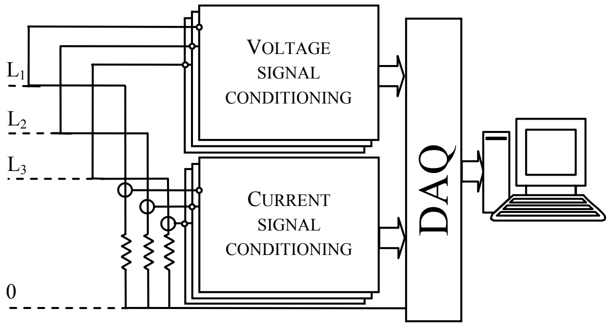

Fig. 1. Principal structure of measuring instrument

The paper is organized as follows. First, the short overview of power quality (PQ) parameters is given according the CENELEC EN 50160 standard. Third paragraph explains the sampling theorem considerations and aliasing problem. In section 4 the hardware solution for signal conditioning module of the virtual instrument is presented. The development of software using LabVIEW program for digital flicker meter are given in section 5. The proposed model is consisting of two parts, the first one is simulating the lamp-eye-brain chain and the second part is used for statistical calculation of the measured data. The validation of the flicker meter is given in 6 and the experimental results in section 7. Conclusions are given in section 8.

2. Power Quality Parameters

The ideal supply voltage is pure sinusoidal voltage with nominal frequency and nominal amplitude. Any variation from this is considered as power quality event or a disturbance. In general the parameters could be divided in two groups voltage amplitude variations and wave-form distortion. A short classification of PQ parameters is given in Table I.

TABLE I. Power Quality Parameters

Variation of	*Parameter*
Frequency	*Variation of power frequency*
Voltage	*Variation of magnitude of supplied voltage* *Rapid voltage changes* *Supply voltage dips and swells* *Voltage interruptions* *Flicker (voltage fluctuation)* *Supply voltage unbalance*
Waveform	*Transient overvoltages* *Voltage harmonics* *Voltage interharmonics* *Mains signaling voltage on the supply voltage* *Notching* *Noise*

3. Signal Processing Considerations

In mathematics the method for taking samples could be represent as multiplication of the signal itself and Dirac delta impulse $\delta(x)$, uniformly sampled signal can be expressed as:

$$x^*(t) = \sum_{n=-\infty}^{\infty} x(n\Delta)\delta(t - n\Delta), \qquad (1)$$

where: $\Delta \le \pi / \omega_u$ and ω_u is the upper angular frequency of the sampled signal spectrum.

This method is also known as δ – modulation, which can be seen as a multiplication with an impulse train:

$$x^*(t) = x(t) \cdot I_\Delta(t) \;, \qquad (2)$$

$$\text{with } I_\Delta(t) = \sum_{n=-\infty}^{\infty} \delta(t - \Delta n). \qquad (3)$$

Though a δ - modulation signal takes non-zero values, at the sampling times only, it is still a continuous time signal, allowing the use of Fourier transformation. This enables to relate the spectrum of a sampled signal to its original spectrum. Using Fourier transformation and Poisson summation formula one can obtain:

$$X^*(\omega) = \frac{1}{\Delta} \sum_{n=-\infty}^{\infty} X\left(\omega + n\frac{2\pi}{\Delta}\right). \qquad (4)$$

The spectrum of the sampled signal consists of duplications of the original frequency spectrum, shifted in frequency. If the signal is band limited to $[-\omega_u, \omega_u]$ and sampled at the Nyquist rate $\Delta = \pi / \omega_u$, the different duplicates do not overlap. In this case the spectrum $X(\omega)$ can be easily retrieved by filtering with an ideal low-pass filter.

According the Nyqist criterion, the sampling frequency f_s should not be lower than twice the upper frequency f_u of the sampled signal spectrum: $f_s \ge 2 f_u$. If the Nyquist criterion is not met, either by sampling a non-band limited signal, or by choosing the sampling frequency too low (under sampling), the reconstruction process yields a special kind of error which is called aliasing.

If the signal contains frequencies bigger than π / Δ the duplicates of the original signal are overlapping and the original spectrum can no longer be retrieved. To prevent aliasing, a signal can be filtered prior to sampling. If an ideal low-pass filter is used, the signal becomes band limited and can be sampled properly, this filter is called an anti-aliasing filter (Fig. 2).

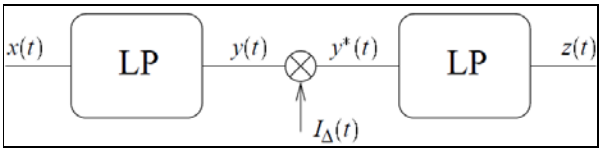

Fig. 2. Sampling and anti-aliasing filter

In the practice the sampling frequency f_s is 5 to 10 times higher than frequency f_u. Figures 3.a and 3.b are illustrating experiment with two different sampling

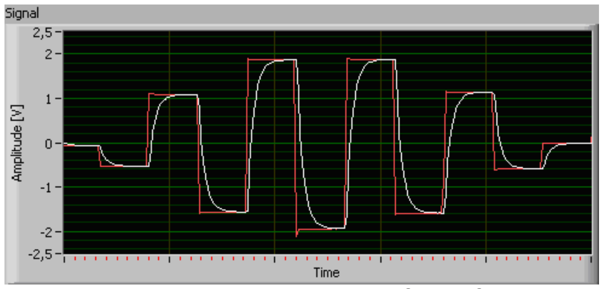

Fig. 3.a. Sampling with $f_s = 2 f_u$

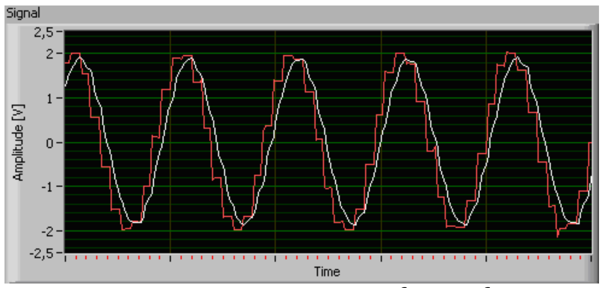

Fig. 3.b. Sampling with $f_s = 10 f_u$

frequencies $2 f_u$ and $10 f_u$. The red signals are after sample and hold circuit and white signals are reconstructured signals with third order filter. It is clear that with sampling frequency $10 f_u$ (Fig. 3.b) reconstructured signal is sinus.

Period of observation of the signals $u(t)$ and $i(t)$ should contain integer multiples of the signal periods, otherwise in case of unsynchronized sampling conditions interpolation algorithm has to be employed.

4. Hardware Solution for Virtual Instrument

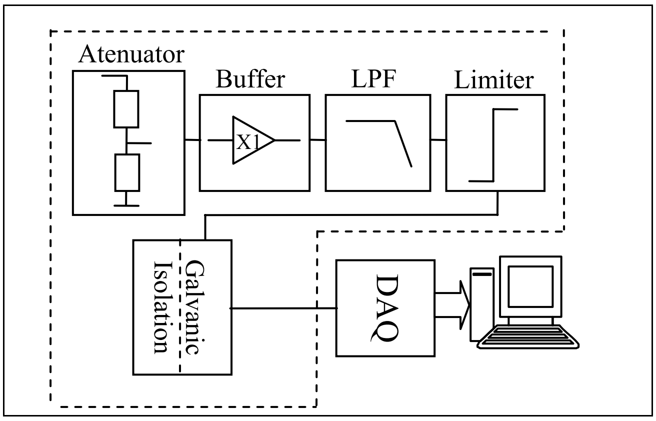

Fig. 4. Block diagram of signal conditioning module

The module for signal conditioning is given on Fig.4. The conditioning system should provide few functions like: galvanic isolation from supply network, attenuation of measured signals, protection of DAQ card and noise suppression. The input attenuator is adapting the signal for the measurement range of analog-to-digital converter (ADC). Between the attenuator and the low pass filter there is a buffer for adapting their impedances. Also, fast circuits for limiting the input voltage to range 0 to 5 V have been designed. Sixth order anti-aliasing filter has been designed with cut-off frequency of 6 kHz and near flat amplitude-frequency and phase-frequency characteristics. The used data acquisition card is with galvanic isolated inputs.

5. Virtual instrument for flicker measurement

A model of virtual flicker meter is proposed which is further used for evaluation of the short-time flicker level P_{st}. The model is divided in two parts:

- input signal scaling and simulation of the response of the lamp-eye-brain chain blocks 1 to 4 (Fig.5) and
- statistical evaluation of the flicker level, block 5.

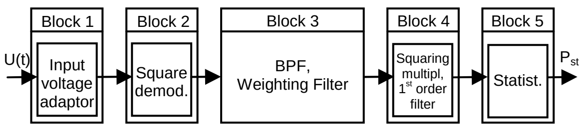

Fig. 5. Block diagram of digital flicker meter

The block 1 represents the signal conditioning circuit for filtering and attenuation of the input signal down to an appropriate reference level, explained in the previous chapter. The block 2 represents a squaring demodulator for reconstruction of the envelope of the voltage fluctuations, and simulation of the lamp behavior. The block 3 is a cascade of two filters. The first filter can be further divided on two filters forming a band pass filter:

- 3^{th} order high pass filter for DC removal with cut-off frequency of 0.05Hz,
- 6^{th} order low pass filter with cut-off frequency of 42Hz.

The second filter of block 3 is a weighting filter which simulates the frequency response of a lamp and human visual system caused by voltage fluctuations. The transfer function of this filter with maximum on 8.8 Hz is expressed with:

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

where: $\omega_1=2\pi 9.2$, $\omega_2=2\pi 2.27$, $\omega_3=2\pi 1.22$, $\omega_4=2\pi 21.9$ and $k=1.74$, $\lambda=2\pi 4.06$.

The method of bilinear transformation is used for conversion of the transfer function in z-domain. The results in a form of poles and zeroes are used for design of appropriate digital filter.

The block 4 contains squaring multiplier and a first order low pass filter with cut-off frequency of 0.54 Hz. On the output of this filter the level of instantaneous flicker is obtained.

The last block is used for statistical analyzes of the measurement results, where the amplitude of the instantaneous flicker is divided in minimum 64 classes defined by IEC standard. This classification is further used for obtaining the cumulative probability function and calculation of the short-term flicker P_{st}. The short-time flicker is calculated over observation interval of 10 minutes according the relation:

$$P_{st} = \sqrt{0.031P_{0,1} + 0.052P_{1s} + 0.065P_{3s} + 0.28P_{10s} + 0.08P_{50s}}$$

$$\begin{aligned} P_{50s} &= (P_{30} + P_{50} + P_{80})/3 \\ P_{10s} &= (P_6 + P_8 + P_{10} + P_{13} + P_{17})/5 \\ P_{3s} &= (P_{2.2} + P_3 + P_4)/3 \\ P_{1s} &= (P_{0.7} + P_1 + P_{1.5})/3 \end{aligned} \qquad (6)$$

where: $P_{0,1}$, P_1, P_3, P_{10} и P_{50} are the flicker levels exceeded for 0,1; 1; 3; 10 and 50 % of the time during the observation period.

In the process of virtual instrument design it is very important to determine the appropriate sampling frequency and observation interval. Lower sampling frequency decreases the quality of the modulation signal envelope, and higher sampling frequency expands the calculation period. Having in mind the concepts in the introduction of this paper and experimental analyzes, 1kHz sampling frequency and 2 sec averaging interval is chosen. The process is simplified with reduction of the number of data records for statistical analyzes. The instantaneous flicker signal is resampled with sampling frequency of 100 Hz. The values of the resampled signal are stored in textual files for a period of 10 min, and are further used for calculation of the short-time P_{st} and long-time P_{lt} flicker.

The block diagram of the virtual flicker meter is shown on Fig. 6.a and front panel on the Fig. 6.b.

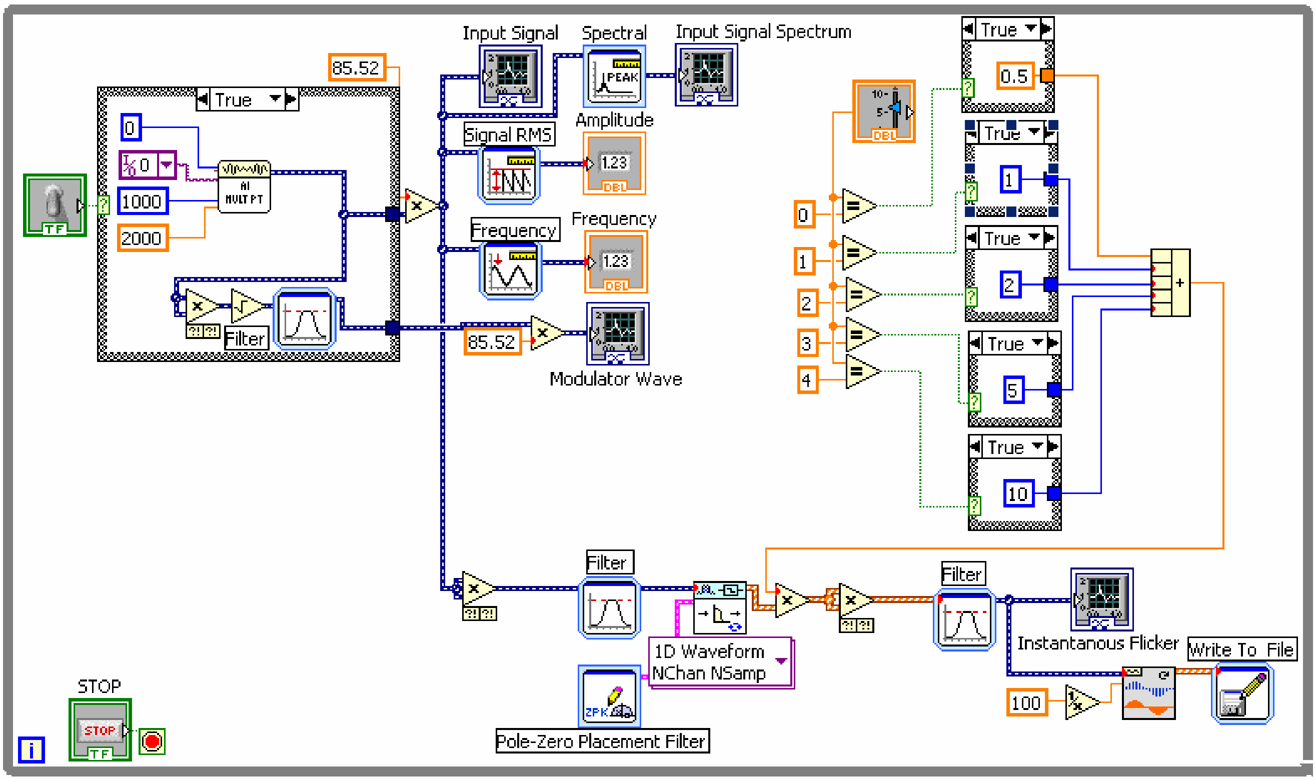

Fig. 6.a. Block diagram of the virtual instrument

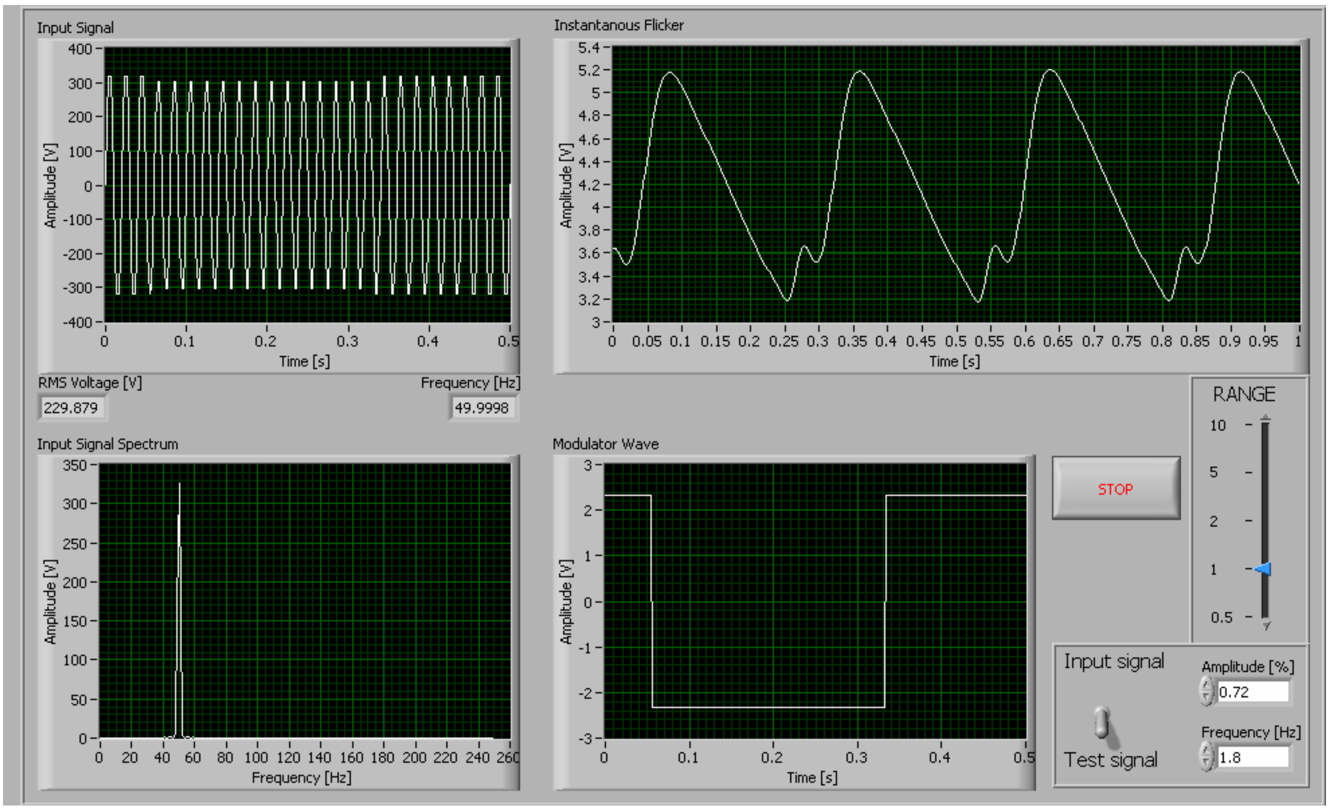

Fig. 6.b. Front panel of the virtual instrument

6. Testing of the virtual instrument

The IEC-6100-4-15 describes measuring procedures for validation testing of the flicker meters. The standard defines a set of values for amplitude and frequency voltage fluctuations for sinus and square wave shapes (Fig. 7), at which the short-time flicker is equal to 1. The errors of the measurement results should be between ±5%.

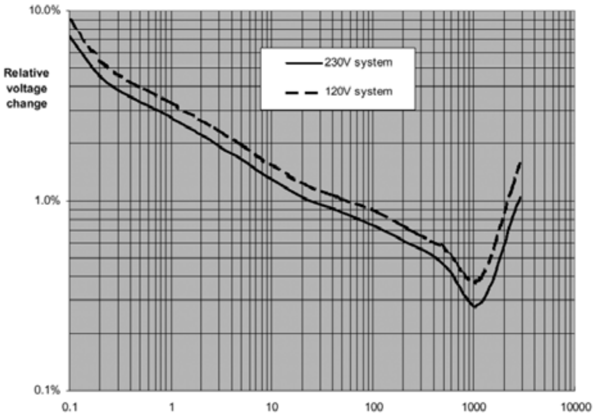

Fig. 7 Number of voltage changes per minute (rectangular)

The validation of the flicker meter is tested by doing series of experiments for signals with square wave shapes and frequencies in a range of 1 Hz to 40 Hz and resolution of 5 Hz, the tests are shown in Fig. 8.

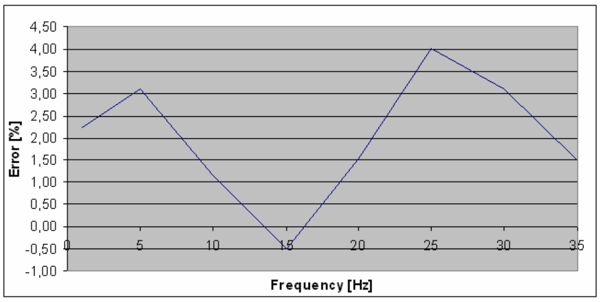

Fig. 8. Validation tests

For the short-term flicker performance evaluation tests (Fig.8), it can be stated that all the found values are within the Pst thresholds of 0,95 and 1,05 and the errors lie within the prescribed accuracy. Maximum errors of approximately 4% are obtained for frequencies around 25Hz.

7. Experimental measurements

The measured data of the flicker are in the form of text files, taking into consideration the frequency of sampling of 100 Hz in ten minutes interval 60.000 records are obtained. Those data are input parameters in the last block of digital flicker meter, which is for statistical analyzes (Fig. 5).

The input signal for digital flicker meter has been obtained from the simulator of power quality parameters (Metrel MI 2191). Obtained results are given in Fig. 9 and Fig. 10. Flicker with square distribution with different amplitudes are presented on Fig. 9.a and Fig. 9.b and sinusoidal distribution with different amplitudes are given on Fig. 10.a and Fig. 10.b, respectively.

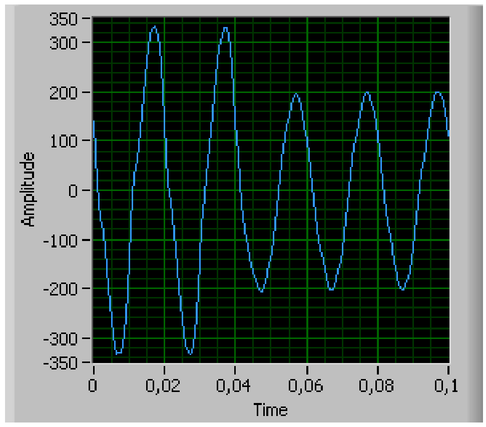

Fig. 9.a. Flicker with square distribution

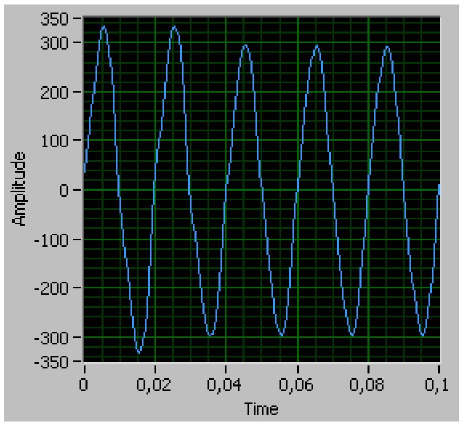

Fig. 9.b. Flicker with square distribution

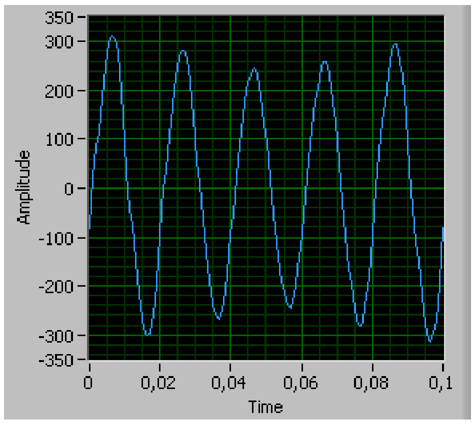

Fig. 10.a. Flicker with sinusoidal distribution

The tasks of the students are to set up the whole experiment, perform measurements and make statistical analyzes, which is the most time consuming part of the exercise. The statistical analyze are performing using some mathematical tool like MATHLAB or C language. Doing this experiment student get practical feeling and basic knowledge about this comprehensive subject.

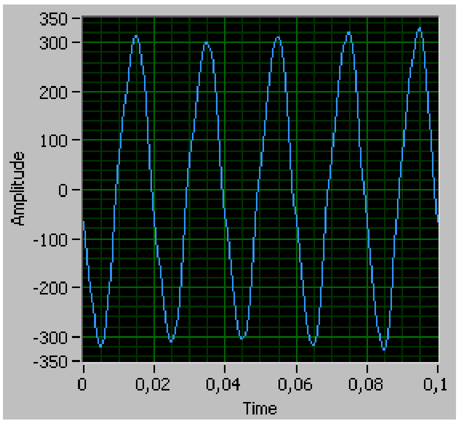

Fig. 10.b. Flicker with sinusoidal distribution

8. Conclusions

The objective of the paper is to introduce the background needed for electrical engineering students in understanding the power quality parameters using graphical programming. The low cost data acquisition cards together with powerful software (for example LabVIEW) offers good basis for building virtual instruments that could be easily implemented at academia. The aim of this technique is to improve teaching capabilities and make power quality field understandable to students and young engineers.

In the paper brief overview of the sampling theory is given. An experiment is presented showing that in order to prevent aliasing problem sampling frequency must be higher than the frequency defined by Nyquist criterion.

A solution for virtual digital flicker meter based on data acquisition card and LabVIEW software is presented. The input conditioning module has been developed, which can be used for measurement of all power quality parameters. The validation of the flicker meter is tested with square wave shape signals with frequencies in the range from 1 Hz to 40 Hz.

The aim of this project is to make understandable the power quality filed to the students through laboratory experiment(s). In this project students are getting familiar not only with power quality but also with data acquisition cards and virtual instruments, which are modern tools in engineering education.

The future tasks are to develop virtual instruments for measuring not only the flicker but all power quality parameters.

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