

A Virtual Energy Analyser For Harmonic Measurements On Discharge Lamps

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Abstract- This paper presents an energy analyser with the required specifications for the investigation of the electrical performance of non-linear loads and especially of discharge lamps. The instrument is a virtual digital oscilloscope and a spectrum and energy analyser but the emphasis is given to record the energy. It has been developed using a graphical programming language. All the necessary measurements are taken in real time, on line. A DAQ board through two analogue input channels samples the voltage and current waveforms. Their frequency spectra are determined using FFT and DFT. Moreover, the system performs energy analysis. So the total active and reactive energy is recorded, as well as the similar energies of each harmonic component. The energy is recorded in time bands that are independent each other so can be overlapped. Also there is no limit of the number of bands that can be used. A time band can last from less than a second to years. The recording can be chosen to take place in every iteration of the programme, several seconds or hours. Within the bands all the power related parameters are recorded. The maximum and minimum values of them are also taken.

Key words: virtual instrument, power measurement, energy measurement, power quality, energy analyzer

I. Introduction

In the last few years, there has been an increasing concern about harmonic distortion and the effects of harmonics on the power system. Nonlinear loads (such as electronic power supplies, lighting ballasts, battery chargers, motor drives and UPS systems) are the primary source of harmonic currents. Non-linear loads inject harmonic currents into power systems. Even if assumed that the source bus contain only fundamental frequency voltage the harmonic currents passing through the impedance of the system cause a voltage drop for each harmonic. This results in voltage harmonics appearing at the load bus. Surveys [1] report that the 95% probability level for the 5th harmonic voltage sustained a steady increase from 3% to 5% i.e. 1.67% per 10 years.

The discharge lamps (fluorescent, sodium vapour, and mercury vapour) are such a non-linear loads. These lamps characterized by their high luminous efficiency, provide significant energy saving and last longer than incandescent lamps. They operate at low power factor consuming less active power, providing comparable luminous output to the incandescent lamps [2]. However, their ballast as well as their arc tube can be an important source of higher-order harmonic components of current. They induce distorted current waveform, which influence the quality of the supplied power as well as the electrical appliances [3].

Some instruments and on line monitoring equipment include the capability to sample waveforms and perform FFT calculations for the record of the harmonic deviation. The capabilities of these instruments vary widely and the user must be careful that the accuracy and information obtained is adequate for the investigation [4]. The aim of this project is to develop an adequate experimental instrument for recording the consumed energy by the discharge lamps. The cost for the development of such a system is very low compared with conventional ones, which consist of digital oscilloscopes, spectrum and energy analyzers as well as several measuring instruments. The configuration of the system is compact and user friendly.

II. Experimental apparatus

A. Harmonic analyzer

The following are some basic requirements [5] for harmonic measurements used to investigate a problem:

a) Capability to measure both voltage and current simultaneously so that harmonic power flow information can be obtained. b) Capability to measure both magnitude and phase angle of individual harmonic components (also needed for power flow and energy calculations). c) Synchronization and a high enough sampling rate for accurate measurement of harmonic components up to at least the 37th

harmonic (this requirement is a combination of a high sampling rate and a sampling interval based on the 50 Hz fundamental).

The harmonic energy analyzer consists of a computer, a data acquisition multifunction card PCI-1200 of National Instruments and the LabView software package. The supply voltage and the current waveforms are recorded and transferred to the computer through analogue inputs of the card. Both waveforms are analysed [6] and their harmonic components are computed.

The computer controls the experimental procedure using LabView software package. LabView is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine program execution, LabView uses dataflow programming, where the flow of data determines execution. In LabView, the user builds the interface by using a set of tools and objects. The user interface is known as the front panel. Then the code is added using graphical representations of functions to control the front panel objects.

The block diagram contains this code. In some ways, the block diagram resembles a flowchart. It has extensive galleries of functions and subroutines for most programming tasks including data acquisition. Virtual Instruments (VIs) imitate actual instruments. The developed VI simulates the panel of three physical instruments: an oscilloscope, a spectrum analyzer and an energy analyzer. A number of VIs have especially been developed for the purposes of the project.

B. Data acquisition card

The DAQ board is a PCI-1200 card with maximum sampling rate 100 kS/s. The card has 2 output channels and 8 differential (or 16 single-ended) input channels. The voltage-input range is software programmable for 0-10V (unipolar) or ± 5 V (bipolar). The card is sampling at 25 kHz on two input channels for the recording of the applied voltage to the lamp and of the current of the lamp. This means that the sampling frequency is 12.5 kHz per channel. This frequency is high enough to prevent aliasing, according to Nyquist theorem, since the maximum harmonic frequency of the measured signals is 1950 Hz (39th harmonic). The asynchronous sampling on two input channels causes a time delay of $1/25\text{ms}=0.04$ ms. This is not a problem because from field measurements harmonics up to 7th order have been detected in the utility voltage. In that case the period of 7th harmonic is 2.86 ms so the introduced by the asynchronous sampling error in the phase displacement between the voltage and current harmonics of 7th order is only 5°.

C. Software

. Sampling starts after an analogue trigger from the software. A specified number of samples of voltage and current waveforms are retrieved through two analogue input channels. A triggered acquisition can start multiple time while is avoided the overhead of configuration and the buffer allocation each time. This is a timed acquisition, meaning that a hardware clock is used to control the acquisition rate for fast and accurate timing. It is also a buffered acquisition because the data are stored in an intermediate memory buffer after they have been acquired from the DAQ board.

Since an analogue trigger is used from the software, data are continuously acquired while the program is checking whether the intermediate buffer for the analogue trigger specifications is being met. Once met the program retrieves and displays data from that buffer after the appropriate amount of data have been acquired before and after the trigger. After each iteration the program waits for the next trigger, it reads then the same amount of data again from the same channels at the same rate.

The user can set up the trigger channel, the polarity of the slope (positive or negative), the hysteresis around the trigger level within which variations in the analog signal level do not cause triggers. He can also set the time delay for the trigger and the number of scans as well as the number of pre-trigger scans i.e. the number of scans before the trigger.

The samples of voltage and current return to a $2 \times N$ array that is split into two $1 \times N$ arrays, one for the samples of voltage waveform and the other for the current waveform. Each vector of samples is scaled in order to be in accordance with the real values.

When using FFT or DFT the digital signal is modified to integer number of periods in order to avoid leakage of spectral information. The number of periods is always greater than three. Additionally, the user may apply smoothing windows such as Hanning, Hamming, Blackman, Blackman-Harris, Exact Blackman, Flat Top, General Cosine (4 Term B-Harris, 7 Term B-Harris) to improve the spectral characteristics of the sampled signals [7]. After that, both of the digital signals are analysed in the time and frequency domain. If the number of samples is a valid power of 2, then the subroutine performs FFT to reduce the number of calculations to $3n \cdot \log_2 n$. The maximum length of FFT is the length of the buffer. The buffer length is set up to 4096 samples. FFT is performed by applying the Split-Radix algorithm, which is similar to the Radix-4 algorithms in addition to the efficiency of Radix-8 algorithms. The Split-

Radix algorithm requires the least number of multiplications among the Radix-2, Radix-4 and Mixed-Radix algorithms [7]. If the number of samples is not a valid power of 2, then the program computes the DFT calling an efficient DFT routine. However, DFT is slower and uses more memory than FFT.

III. Harmonic power and energy measurements

A. Spectrum analysis

The system records the voltage and current waveforms as it is shown on the front panel oscilloscope page of the instrument (Fig.1). Then it calculates their effective values in the time domain:

$$Y = \sqrt{\frac{1}{T} \int_0^T y^2(t) dt} \quad (1)$$

where $y(t)$ represents the voltage or current signal $v(t)$, $i(t)$ and Y their effective (rms) values V and I respectively. For better accuracy, this procedure is repeated for several periods and the mean values are determined.

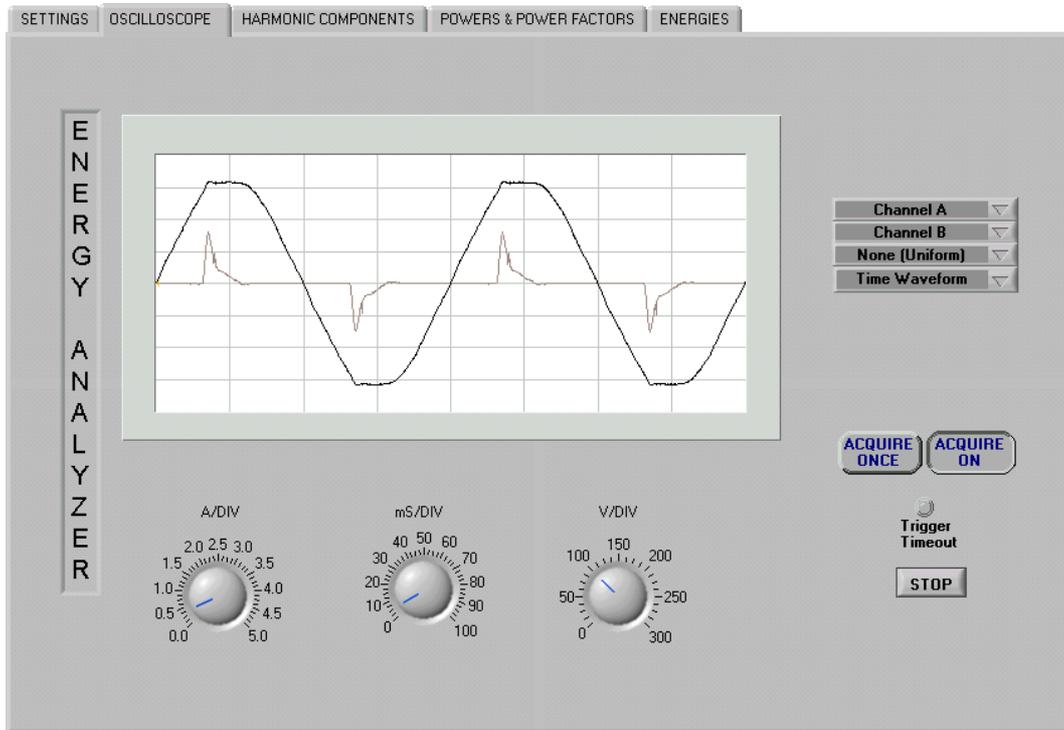


Figure1. Voltage and current waveforms of a 15 W compact fluorescent lamp.

The FFT (or DFT) analysis of the signals gives their frequency spectra i.e. the effective (rms) values of their harmonic components Y_n . Therefore, the effective value Y of the signal is calculated again with harmonic representation:

$$Y = \sqrt{\sum_{n=0}^N Y_n^2} \quad (2)$$

Y_0 is the DC offset, Y_1 the amplitude of the fundamental, Y_n the amplitude of the harmonic of n^{th} order and N the highest harmonic order.

The individual harmonic rate H_n of each component is calculated according to the CIGRE definition:

$$H_n = \frac{Y_n}{Y_1} \cdot 100\% \quad (3)$$

Last but not least, the total harmonic distortion (THD) of the recorded signal $y(t)$ is calculated according to the IEEE definition[8]:

$$THD = \frac{\sqrt{\sum_{n=2}^N Y_n^2}}{Y_1} \cdot 100\% \quad (4)$$

The crest factor is also defined as the ratio of the peak value of the waveform to its rms amplitude. The waveform is distorted if this ratio is not equal to $\sqrt{2}$ [4]. For a distorted signal it is important to determine its harmonic content. The waveform should be cleared off the fundamental component and the DC offset. This results to a signal that is purely the distortion of the waveform. The effective value of the total harmonic content Y_H is calculated as follows:

$$Y_H = \sqrt{\sum_{n=2}^N Y_n^2} \quad (5)$$

B. Power analysis

The active power of the individual harmonics -including the fundamental- is determined from the effective amplitudes V_n , I_n of their voltage and current:

$$P_n = V_n \cdot I_n \cdot \cos \varphi_n \quad i=1, 2, 3, \dots, N. \quad (6)$$

where $\cos \varphi_n$ is the phase displacement between them. This is the power factor of each individual harmonic that is also calculated:

$$PF_n = \cos \varphi_n \quad (7)$$

The total active power is the sum of the active powers P_n of the respective harmonics plus the DC power P_0 :

$$P = \sum_{n=0}^N P_n \quad (8)$$

The active power of the recorded signals is also calculated in the time domain. First, the instantaneous power $p(t)=v(t) \cdot i(t)$ is calculated and it is derived the integral of it. The mean value of the instantaneous power is the total active power:

$$P = \frac{1}{T} \int_0^T v(t) \cdot i(t) \cdot dt \quad (9)$$

The reactive power of the harmonics is determined using the same as previous method:

$$Q_n = V_n \cdot I_n \cdot \sin \varphi_n \quad i=1, 2, 3, \dots, N. \quad (10)$$

As for the total reactive power Q , there is a disagreement between the analysts on how to define it in the presence of harmonics. Most of them agree that Q is the sum of reactive powers at each frequency. In this concept the total reactive power is be calculated as:

$$Q = \sum_{n=1}^N Q_n \quad (11)$$

Apparent power is defined as the capacity of the power system required to deliver active power P and according to the IEEE definition [8] it is given as the product of the rms values of voltage and current:

$$S = V \cdot I \quad (12)$$

Substituting the equivalent expressions of V and I from Eq.(2) to Eq.(12) results the following form for the apparent power:

$$S^2 = \sum_{n=1}^N V_n^2 \cdot I_n^2 + \sum_{n=1}^N \sum_{\substack{k=1 \\ k \neq n}}^N V_n^2 I_k^2 \quad (13)$$

Working similarly with Eq.(6), (8) results the following form for the active power:

$$P^2 = \sum_{n=1}^N (V_n \cdot I_n \cdot \cos \varphi_n)^2 + 2 \sum_{n=1}^N \left(V_n \cdot I_n \cdot \cos \varphi_n \cdot \sum_{k=n+1}^N V_k \cdot I_k \cdot \cos \varphi_k \right) \quad (14)$$

A similar formula is obtained from Eqns.(10), (11) for the reactive power:

$$Q^2 = \sum_{n=1}^N (V_n \cdot I_n \cdot \sin \varphi_n)^2 + 2 \sum_{n=1}^N \left(V_n \cdot I_n \cdot \sin \varphi_n \cdot \sum_{k=n+1}^N V_k \cdot I_k \cdot \sin \varphi_k \right) \quad (15)$$

Observing Eq.(13)-(15) becomes obvious that the sum P^2+Q^2 is not equal to S^2 for distorted signals $v(t)$ and $i(t)$. This would be true only in case of pure sinusoidal voltage and current waveforms i.e. without harmonics. For distorted signals the apparent power consists not only of active and reactive power but also of a new quantity that shall be added in order to fulfil the equation:

$$S^2 = P^2 + Q^2 + D^2 \quad (16)$$

This quantity is equal to the sum of the cross products of the harmonics of different order $V_n \cdot I_k$ ($n \neq k$). It is called distortion power D since these harmonics do not produce work and yield no average power. D is calculated from the following formula that is obtained from Eq.(13)-(16):

$$D = \sqrt{\sum_{n=1}^N \sum_{k=n+1}^N (V_n \cdot I_k \cdot \cos \varphi_n - V_k \cdot I_n \cdot \cos \varphi_k)^2 + \sum_{n=1}^N \sum_{k=n+1}^N (V_n \cdot I_k \cdot \sin \varphi_n - V_k \cdot I_n \cdot \sin \varphi_k)^2} \quad (17)$$

Finally, the power factor is determined using the well-known expression:

$$PF = \frac{P}{S} \quad (18)$$

The variation of the instantaneous and average value of each power-related parameter in a time band is also displayed as well as the minimum and maximum values.

The panel with the measurements of the power-related parameters is shown in Fig. 2.

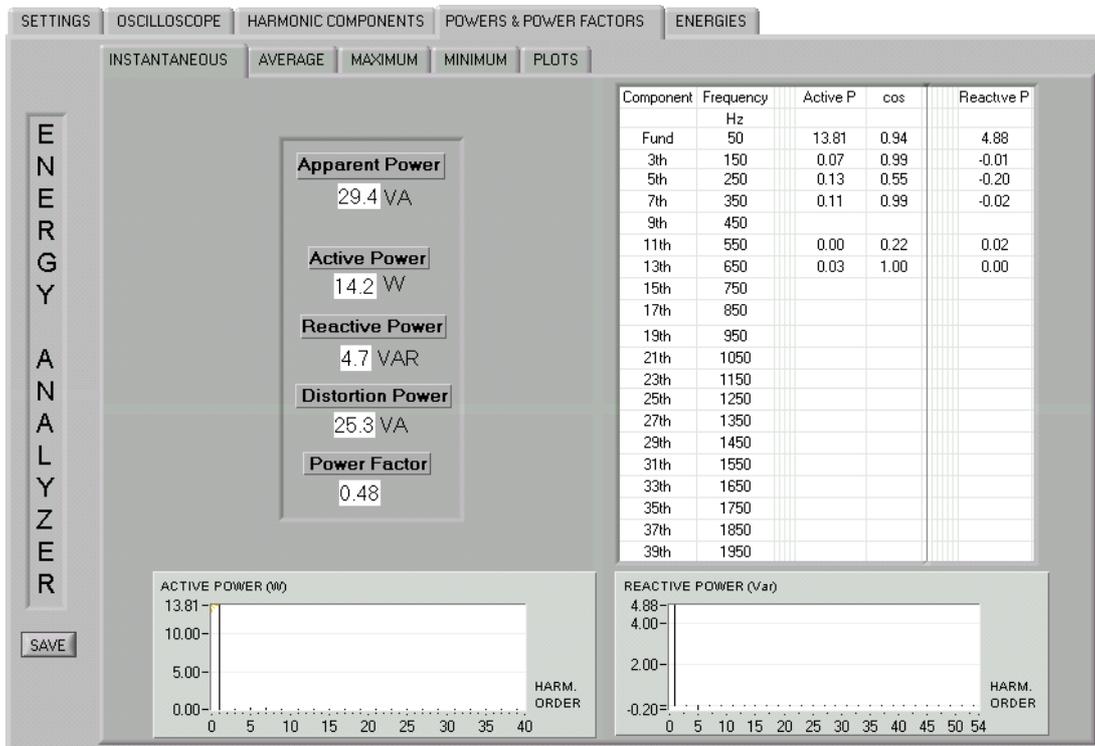


Figure 2. Instantaneous powers of a 15 W compact fluorescent lamp

C. Energy analysis.

The instrument can measure the active and reactive energy that consumed due to the voltage and current waveforms as well as their common harmonic components. For the calculations is used the general formulae:

$$\text{Energy} = \Sigma(\text{Power} \times \Delta\text{time})$$

The time interval of a program execution cycle is always considered as Δtime .

The energies as well as the powers are recorded in time bands. The user can select so many time bands he wants for his experiment without limit. Also there is not limit about the duration of a time band that can be less than a second up to years. The time bands can be overlapped (Figure 3). Thus the user can take information for the variation of the variables in a time band that is included in other or there is common time with another. There is Boolean indication for the status of the time bands (recording or not)

The user has also the possibility to choose the frequency of recording. It can be every 1, 2, 3, 4, 5, 10, 30 seconds, 1, 15, 30 minutes, 1, 6, 12, 24 hours and so on. Thus is given the possibility to be recorded simultaneously hundred of variables. For example: Investigating the behavior of a discharge lamp feed by a slightly distorted voltage there are about 14 plots that can drawn. 7 plots display the variation of the total active power and the active power of the harmonics while the other 7 display the total reactive power and the reactive power of the harmonics. 28 energy parameters are plotted per time band. Finally 112 plots are drawn for recording them in 4 time bands. In general there is no limit from the program but only from the capability of the computer. Reducing the recording frequency diminishes the necessary computer capability. All the above mentioned plots can be in one graph. The user has the possibility to choose those that he wants to examine.



Figure 3 Energies consumed by a 15W compact fluorescent lamp recorded in 4 overlapped time bands.

IV. Conclusions

The developed virtual instrument (hardware and software tools) facilitates experiments on energy harmonic analysis. The main feature of this instrument is the given possibility to the user to choose the time bands without restrictions of the number of them, the duration and permitting the overlapping. The advantage of this instrument as a virtual one is its expandability. It is easy to modify the software if it is required to measure a new quantity during the investigation of the behaviour of a non linear load. The cost of the system is very low compared with a conventional one consisting of a number of meters as oscilloscope power and energy analyser etc. The system facilitates the performance evaluation of various appliances for distorted supply voltages.

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