Harmonic power measurements on discharge lamps

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ABSTRACT: This paper presents an experimental method to perform harmonic power measurements on discharge lamps (metal halide, fluorescent etc). A virtual instrumentation system has been developed using the LabView graphical programming language. The system is actually a spectrum & power analyser. It also includes an arbitrary waveform generator in order to perform measurements with distorted supply voltages. This virtual instrument has also been developed in the LabView environment. The experimental apparatus includes voltage and current probes to take the measurements and a specially designed power amplifier to supply the loads with a user-defined waveform. The voltage and current signals are recorded in real time and then analysed using FFT and DFT in order to determine their frequency spectra. The magnitude and the phase angle of the harmonic components are computed as well as the THD. Moreover, the system performs power analysis of the individual harmonics and of the recorded voltage and current signals in the time domain. Therefore their power parameters are determined (apparent, active, reactive and distortion power). An important advantage of the system is that the virtual instruments allow simple modifications by the user in order to perform additional measurements for new quantities while the measurement of the non-linear load is in progress.

Keywords: Power quality, harmonics, harmonic analyser, virtual instrument, current distortion, discharge lamps

I. INTRODUCTION

Discharge lamps (fluorescent, high intensity discharge etc.) are characterised by a high luminous efficiency and provide significant energy saving if compared to the incandescent lamps. These lamps inject harmonic currents into power systems as all non-linear loads. Their ballast and their arc tube can be an important source of higher-order harmonic components of current [1]. The harmonic currents pass through the impedance of the system and cause a voltage drop for each harmonic. This results in voltage harmonics appearing at the load bus and consequently it influences the quality of the supplied power as well as the electrical appliances [2, 3]. Surveys [4, 5] report that the 95% probability level for the 5th harmonic voltage sustained a steady increase from 3% to 5% i.e. 1.67% per ten years.
The compact fluorescent lamps (CFL) exhibit the highest harmonic distortion among the discharge lamps. Their total harmonic distortion (THD) is usually higher than 100%.

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The international standard IEC 61000-3-2 requires that the 3rd and the 5th current harmonic shall not exceed 86% and 61% of the fundamental respectively [6]. ANSI defines a limit of 32% [7] as the maximum current THD of lamps with electronic ballast. This standard also specifies the limit of the magnitude of all high-order harmonics to 30% of the fundamental magnitude. The upper limit is defined as 7% of the fundamental for all higher than the 11th order harmonics. The limit of the current THD of electronic ballasts is 20%.
Harmonic measurements require instruments that are designed for spectral analysis. They shall have the capability to measure simultaneously voltage and current in order to obtain the harmonic power flow. For the same reason it is required to measure both magnitude and phase angle of individual harmonic components. Synchronization is also essential and fast sampling rate to obtain accurate measurements of harmonic components at least up to the 39th harmonic.
This paper presents an experimental apparatus with the required specifications for the investigation of the electrical performance of non-linear loads and especially of discharge lamps. The configuration of the system is compact and user friendly. The cost for the development of such a system is very low compared with conventional ones, which consist of digital oscilloscopes, spectrum analysers, and several measuring instruments.

II. DEFINITIONS

The power and harmonics analysis of this paper is performed using the voltage and current waveforms of the discharge lamp. Both of these waveforms are recorded simultaneously in the time domain. Their effective (rms) value is calculated from the formula:

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

where y(t) represents the waveform of voltage v(t) or current i(t) and Y the respective effective value V and I. This formula is valid for every periodic signal, sinusoidal or distorted. If the signal is distorted by harmonics then an FFT (or DFT) analysis is required to obtain the frequency spectrum and consequently the effective values of the harmonic components. In this case the effective value of the signal is calculated with harmonic representation as:

$$Y = \sqrt{\sum_{n=0}^{N} Y_n^2} \tag{2}$$

where Y_0 is the DC offset, Y_1 the amplitude of the fundamental, Y_n the amplitude of the harmonic of nth order and N the highest harmonic order.

A simple method to determine whether a signal is distorted is to calculate the crest factor that is defined as the ratio of the peak value of the waveform to its rms amplitude:

$$Y_{CF} = \frac{Y_{peak}}{Y} \tag{3}$$

If this ratio is not equal to $\sqrt{2}$ then the waveform is distorted. Usually the harmonic components are expressed with respect to the effective value of the fundamental. This is known as the individual harmonic rate H_n of the component. It is given by the following formula according to the CIGRE definition:

$$H_n = \frac{Y_n}{Y_1} \cdot 100\% \tag{4}$$

For distorted signals it is very useful to determine the effective value Y_H of the harmonic content. The waveform should be cleared off the fundamental component and the DC offset:

$$Y_H = \sqrt{\sum_{n=2}^{N} Y_n^2} \tag{5}$$

The magnitude of the distortion is usually expressed with respect to the rms value of the fundamental or in some cases to the rms value of the signal. According to the IEEE definition the total harmonic distortion (THD) of a signal is the ratio of the harmonic content to the magnitude of the fundamental:

$$THD = \frac{Y_H}{Y_1} \cdot 100\% \tag{6}$$

The total active power that is produced by v(t) and i(t) is the mean value of the instantaneous power:

$$P = \frac{1}{T} \int_0^T v(t) \cdot i(t) \cdot dt \tag{7}$$

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 respectively:

$$P_n = V_n \cdot I_n \cdot \cos\varphi_n \quad \text{i=1, 2, 3, …, N.} \tag{8}$$

where $\cos\phi_n$ is the phase displacement between them. This is the power factor of each individual harmonic:

$$PF_n = \cos\varphi_n \tag{9}$$

Therefore, the sum of the active powers P_n of the harmonics -plus the DC power P_0- will give the total active power:

$$P = \sum_{n=0}^{N} P_n \tag{10}$$

Obviously the results from Eq.(7) and (10) shall be equal.
The reactive power of the harmonics is determined using the same method as above:

$$Q_n = V_n \cdot I_n \cdot \sin\varphi_n \quad \text{i=1, 2, 3, …, N.} \tag{11}$$

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

$$Q = \sum_{n=1}^{N} Q_n \tag{12}$$

Apparent power is defined as the capacity of the power system required to deliver active power P. According to the IEEE definition it is given as the product of the rms values V, I of voltage and current:

$$S = V \cdot I \tag{13}$$

Substituting the equivalent expressions of V and I from Eq.(2) to Eq.(13) results the following form for the apparent power:

$$S^2 = \sum_{n=1}^{N} V_n^2 \cdot I_n^2 + \sum_{n=1}^{N} \sum_{\substack{k=1 \\ k \neq n}}^{N} V_n^2 I_k^2 \tag{14}$$

Working similarly with Eqns.(8), (10) the following form for the active power is derived:

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

A similar formula is obtained from Eqns.(11), (12) for the reactive power:

$$Q^2 = \sum_{n=1}^{N} (V_n \cdot I_n \cdot \sin\varphi_n)^2 + 2\sum_{n=1}^{N} \left(V_n \cdot I_n \cdot \sin\varphi_n \cdot \sum_{k=n+1}^{N} V_k \cdot I_k \cdot \sin\varphi_k \right) \tag{16}$$

Observing Eqns.(14), (15) and (16) 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:

$$S^2 = P^2 + Q^2 + D^2 \tag{17}$$

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 may not be referred as power since it does not flow through the system as power is assumed to do. D is calculated from the following formula that is obtained from Eqns.(14)-(17):

$$D^2 = \sum_{n=1}^{N} \sum_{k=n+1}^{N} \left(V_n \cdot I_k \cdot \cos\varphi_n - V_k \cdot I_n \cdot \cos\varphi_k \right)^2 + \sum_{n=1}^{N} \sum_{k=n+1}^{N} \left(V_n \cdot I_k \cdot \sin\varphi_n - V_k \cdot I_n \cdot \sin\varphi_k \right)^2 \tag{18}$$

Special attention should also be paid to power factor. For non-distorted signals it is equal to the phase displacement factor $\cos\varphi$ between v(t) and i(t). However, this is not true for distorted signals. In this case the value of phase displacement diverges from the value of the power factor. The divergence becomes high when the signals are considerably contaminated. In any case the power factor should always be determined as the ratio of the active power P to the apparent one S:

$$PF = \frac{P}{S} \tag{19}$$

III. HARMONIC POWER ANALYZER

For the purposes of this investigation a harmonic power analyser was developed which consists of a computer, a data acquisition multifunction card PCI-1200 of National Instruments and the software package LabView. The system also includes a resistive divider for the measurement of voltage and a clamp meter with analogue output for the measurement of current. The supply voltage and the current waveforms are recorded and transferred into the computer through analogue inputs of the card. Both waveforms are analysed and their harmonic components are computed.

The computer controls the experimental procedure using Lab View software package. The environment of LabView is very friendly for developing programs using graphical programming language. It uses terminology, icons and ideas familiar to scientists and engineers and relies on graphical symbols rather than textual language to describe programming actions. 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 analyser and a power analyser. It contains an interactive user interface that is the front panel of the analyser (Fig.1).

The experimental procedure of this project is divided in a series of tasks that can be divided again until the complicated application becomes a series of simple subtasks. The tasks and the subtasks are performed by the user of the computer via several VIs that have especially been developed for the purposes of the project.

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). A software programmable gain amplifier has gain selection 1, 2, 5, 10, 20, 50, 100. The PCI-1200 has a 12-bit ADC with analogue resolution of 2.44 mV at a gain of 1.

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 (39^{th} harmonic). Therefore, an antialising filter is not required. The asynchronous sampling on two input channels causes a time delay of 1/25 KS/s=0.04 ms. This is not a problem because from field measurements harmonics up to 7^{th} order have been detected in the utility voltage. In that case the period of 7^{th} harmonic is 2.86 ms. Hence, the introduced asynchronous sampling error in the phase displacement between the voltage and current harmonics of 7^{th} order is only 5^{o}. This means that the maximum introduced error in the measurement of power factor does not exceed 8.7%.

The front panel receives instructions from a block diagram that provides a pictorial solution to the programming problem. 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. The program waits after each iteration for the next trigger then it reads 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 analogue 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 2xN array which is split into two 1xN 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 at least four. 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 [8]. 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 [8]. 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.

The measured signals and their harmonic and power analysis are displayed on the main window of the front panel of the instrument (Fig.1) while several other windows are available for the representation of various parameters of the measured quantities.

IV. EXPERIMENTS

The experimental results which, are presented below, demonstrate the capabilities of the developed virtual instrument for harmonic analysis and power measurements. The selected lamps for the experiments represent two categories of discharge lighting: compact fluorescent with electronic gear (CFL) and metal halide (MH). A more extensive investigation of other types like mercury and sodium vapor is out of the scope of this paper. Actually it is the subject of a special paper dealing exclusively with the electrical characteristics of discharge lamps. Such an investigation is currently in progress and the results will be presented in the near future. The CFLs of this investigation are fitted with electronic ballast which is built into the lamp fixture. Their mount is E27 screw. All of them are designed for the 230 V, 50 Hz electric utility systems. Three groups of such CFLs have been tested from three different brands. Each brand with wattages 15 W, 20 W and 23 W.

The bulb of the MH lamps is a two-pin compact type. They require external magnetic ballast and starter and operate at 230 V, 50 Hz supply voltage. Two groups have been tested with wattages 70 W and 150 W.

The current waveform and the harmonic spectrum of a typical 20W CFL is presented in Fig. 2. A significant distortion is evident in the current of the lamp. All the investigated CFLs exhibit a highly distorted current. It is very important to observe in Table 1 that the 3rd harmonic in six out of nine CFLs exceeds the limit of 86% that is set by IEC 61000-3-2 [6]. On the other hand the 5th harmonic of these lamps also exceeds the limit of 61% that is set by IEC 61000-3-2.

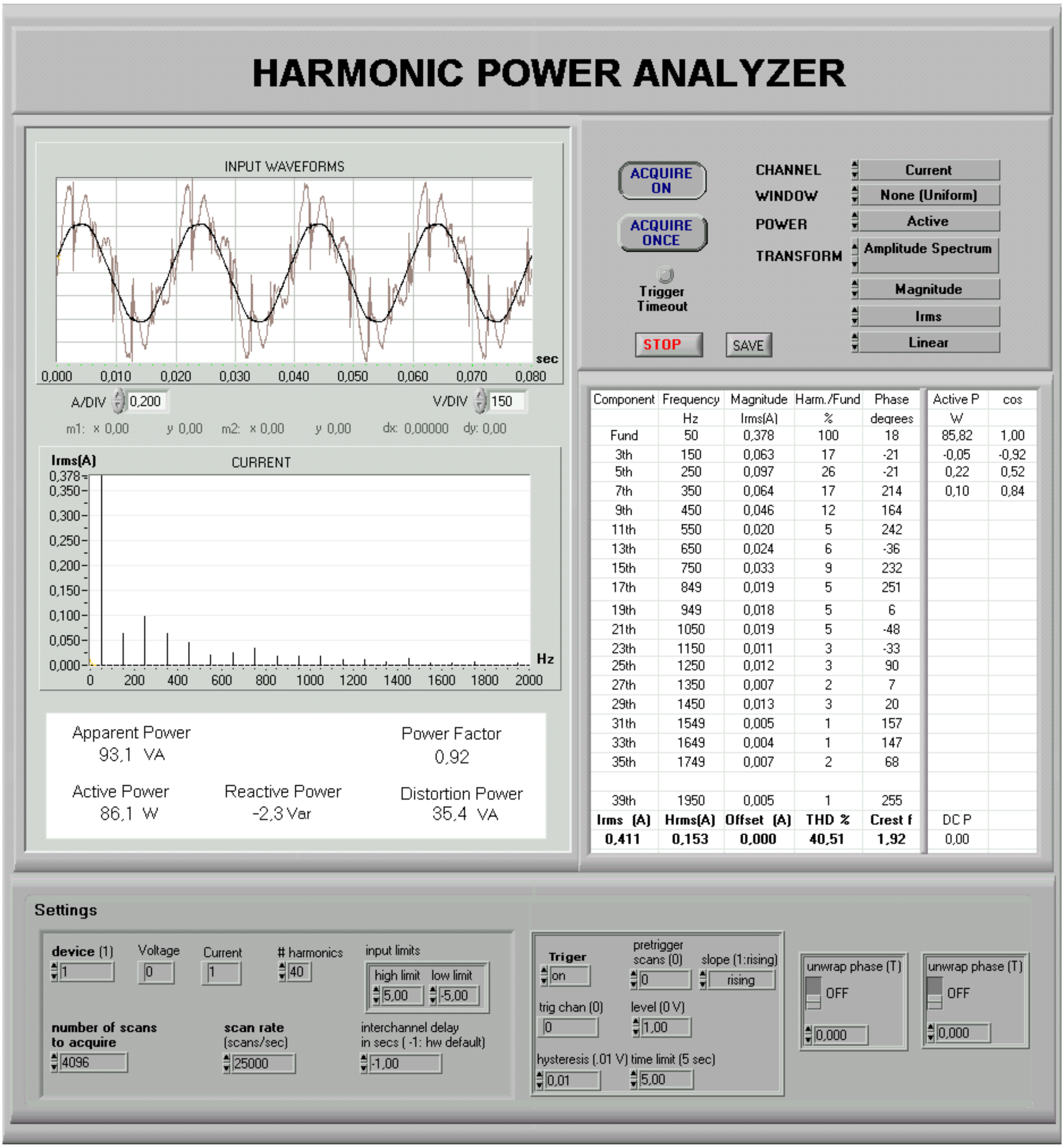

Fig.1 Harmonic power analysis of a 70W metal halide lamp (with ballast) on the front panel of the analyser.

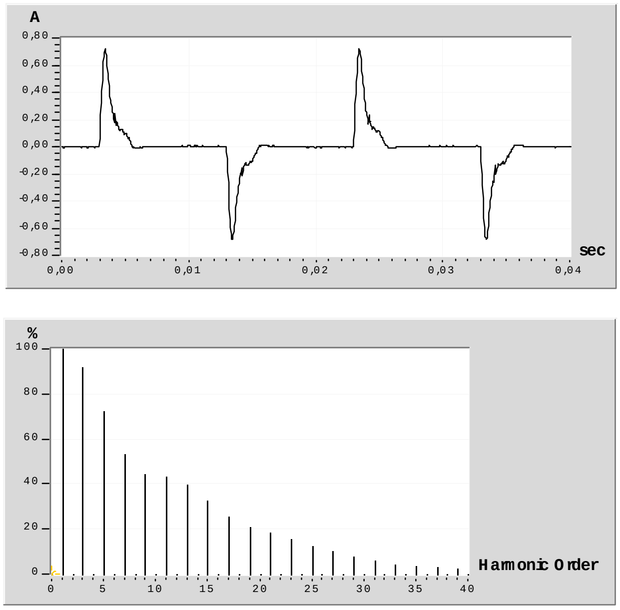

Fig.2 Current waveform and harmonic spectrum of a 20W CFL.

Table 1 Amplitude of current harmonics (% of the fundamental). The letters a, b, c denote the three different brands

	Lamp	CFL15W/a	CFL15W/b	CFL15W/c	CFL20W/a	CFL20W/b	CFL20W/c	CFL23W/a	CFL23W/b	CFL23W/c	MH70W/b	MH150W/b
Harmonic order	3	86	97	93	85	97	92	93	95	82	17	17
	5	56	77	69	58	76	72	70	74	54	26	20
	7	40	57	55	43	58	53	54	56	46	17	19
	9	34	47	50	39	49	45	49	49	39	12	16
	11	24	44	42	31	47	43	46	47	28	5	11
	13	14	42	33	21	45	40	38	43	23	6	12
	15	12	38	26	15	38	33	30	35	18	9	16
	17	9	33	21	12	31	25	25	28	13	5	10
	19	7	29	15	8	27	21	22	25	14	5	6
	21	7	26	11	7	24	18	19	23	11	5	11
	23	6	22	11	6	21	16	15	18	11	3	8
	25	6	18	9	5	17	12	12	14	12	3	6
	27	5	15	9	6	13	10	9	10	10	2	2
	29	4	13	10	6	10	8	6	8	9	3	3
	31	3	11	10	5	8	6	5	6	8	1	2
	33	3	9	10	4	7	4	4	5	6	1	1
	35	3	8	9	3	5	3	3	4	5	2	2
	37	2	7	9	2	5	3	3	3	4	0	1
	39	2	6	7	2	4	2	3	2	4	1	0

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 in the time domain that is purely the distortion of the waveform (Fig.3). The current of all tested lamps is heavily distorted. The harmonic current is comparable to the

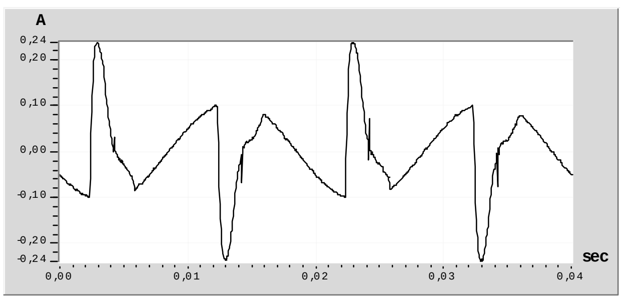

Fig.3 Waveform of the total harmonic content of a 15W CFL.

fundamental one and in some cases almost equal to it (Table 2). As expected the THD value is quite high especially the one of CFLs that exceeds 100%. The crest factor also diverges from the ideal value of 1.41.

Table 2 Amplitude of distortion.

Lamp	Total current (A)	Harmonic current (A)	THD (%)	Crest factor
CFL15W/a	0.112	0.086	121.07	3.05
CFL15W/b	0.126	0.109	173.59	4.84
CFL15W/c	0.119	0.100	155.75	3.71
CFL20W/a	0.147	0.115	126.44	3.28
CFL20W/b	0.148	0.128	174.03	4.66
CFL20W/c	0.165	0.139	158.02	4.36
CFL23W/a	0.188	0.159	159.44	4.25
CFL23W/b	0.173	0.148	167.48	4.45
CFL23W/c	0.136	0.107	126.49	3.67
MH70W/b	0.411	0.153	40.51	1.92
MH150W/b	0.781	0.338	48.20	1.76

One of the features of the virtual analyser is the determination of the phase displacement of each harmonic with respect to a reference point. Generally this point is the start of the voltage waveform in order to get the phase displacement between supply voltage and current harmonics. The window with the phase angles of the current harmonics of a 15W CFL is displayed in Fig.4.

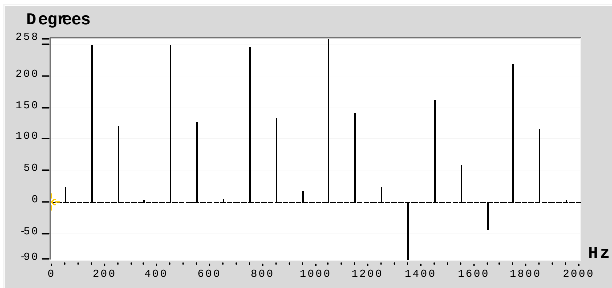

Fig.4 Phase angle of individual current harmonics of a 15W CFL.

It may be observed in Fig.4 that the phase angle of the fundamental current is quite low. This remark confirms the conjecture that all of the commercially available electronic CFLs are fitted with a compensation circuit, which corrects the phase displacement between the supply voltage and the fundamental current. Actually, all of the tested CFLs are characterised by a quite high cosφ at the fundamental frequency, usually in the range of 0.90-0.95 (Table 3).

The presence of reactive power at all frequencies is justified due to the phase angle between supply voltage and current harmonics. The reactive power of some harmonics is negative due to their capacitive phase displacement.

For non-distorted supply voltage there is no active power at frequencies higher than the fundamental, since the mean value of the instantaneous power is zero in that case. However, the slight distortion of voltage causes active power consumption at the frequencies of the respective harmonics.

Further to the harmonic analysis, the instrument also performs a power analysis of the recorded waveforms. It computes the instantaneous active power and the integral of it over a specified number of periods (mean value) that defines the active power (Fig.5). The other power parameters (reactive, apparent and distortion power) are also calculated using the methodology described in §II

(Table 4). It seems that the CFLs operate at very low power factor as it was expected while the power factor of the MHs is much better.

Table 3 Power characteristics of lower order components.

Lamp	Harmonic order	P (W)	Q (Var)	cosφ
CFL 15W/a	1	14.54	7.76	0.88
	3	0.05	0.02	0.95
	5	0.21	0.02	1.00
	7	0.04	0.04	0.71
CFL 15W/b	1	13.65	4.82	0.94
	3	0.07	-0.01	0.99
	5	0.13	-0.20	0.55
	7	0.11	-0.02	0.99
CFL 15W/c	1	13.28	6.88	0.89
	3	-0.01	0.02	-0.44
	5	0.33	-0.07	0.98
	7	0.05	0.06	0.66
CFL 20W/a	1	19.08	8.92	0.91
	3	0.05	-0.03	0.86
	5	0.27	-0.11	0.93
	7	0.08	0.04	0.88
CFL20W/b	1	15.7	6.34	0.93
	3	0.10	0.02	0.99
	5	0.23	-0.23	0.71
	7	0.12	0.01	1.00
CFL20W/c	1	19.04	7.29	0.93
	3	0.05	-0.03	0.83
	5	0.28	-0.23	0.78
	7	0.13	-0.01	1.00
CFL23W/a	1	21.17	9.24	0.92
	3	0.23	-0.04	0.98
	5	0.38	-0.33	0.76
	7	0.24	0.06	0.97
CFL23W/b	1	18.82	8.05	0.92
	3	0.13	-0.01	1.00
	5	0.34	-0.21	0.86
	7	0.15	0.03	0.98
CFL23W/c	1	17.55	8.36	0.90
	3	0.08	-0.07	0.79
	5	0.24	-0.17	0.81
	7	0.07	0.10	0.55
MH70W/b	1	85.82	-2.68	1.00
	3	-0.05	-0.02	-0.92
	5	0.22	0.36	0.52
	7	0.10	0.07	0.84
MH150W/b	1	161,87	-6.19	1.00
	3	-0.15	-0.02	-0.99
	5	0.28	0.47	0.51
	7	0.21	0.15	0.82

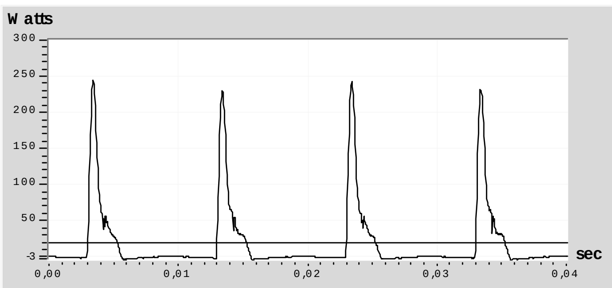

Fig.5 Instantaneous power and active power (straight line) of a 23W CFL

V. CONCLUSIONS

The developed virtual instrumentation system (hardware and software tools) facilitates experiments on power and harmonic analysis. The user supervises the tests through the virtual instruments that have been developed especially for this application. The cost of the system is very low compared with a conventional one consisting of a digital oscilloscope, a spectrum analyser and several measuring instruments such as voltmeters, ammeters or power analysers. The system configuration is compact and user friendly. It has been developed to perform measurements on discharge lamps but it can also be used for similar experiments on other low voltage equipment. The system facilitates the performance evaluation of various appliances for distorted supply voltages.

Table 4 Power analysis of the investigated lamps.

Lamp	Power				Power factor
	Active (W)	Reactive (Var)	Distortion (VA)	Apparent (VA)	
CFL15W/a	14.84	7.84	19.69	25.87	0.57
CFL15W/b	13.96	4.59	24.99	28.99	0.48
CFL15W/c	13.65	6.89	23.18	27.77	0.49
CFL20W/a	19.48	8.82	26.33	33.92	0.57
CFL20W/b	16.15	6.14	29.23	33.95	0.48
CFL20W/c	19.50	7.02	31.94	38.07	0.51
CFL23W/a	22.02	8.93	36.32	43.40	0.51
CFL23W/b	19.44	7.86	33.95	39.90	0.49
CFL23W/c	17.94	8.22	24.41	31.39	0.57
MH70W/b	86.09	-2.27	35.43	93.12	0.92
MH150W/b	162.1	-5.59	76.51	179.3	0.90

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