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Measurement 30 (2001) 257–267

Measurement

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Arbitrary waveform generator for harmonic distortion tests on compact fluorescent lamps

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Received 9 September 2000; received in revised form 21 February 2001; accepted 22 February 2001

Abstract

This paper presents an experimental method to perform tests on compact fluorescent lamps operated with distorted voltage waveform conditions. The voltages used for the tests are obtained from an arbitrary waveform generator. It consists of a computer, a multifunction card and the software package. The characteristics of the voltage are entered from the computer that loads the required waveform into the card. The output of the card is driven to a voltage amplifier to supply the lamps. Samples of the voltage across the load and of the circulating current are recorded and transferred to the computer for harmonic analysis. The user supervises the tests through several virtual instruments that have been developed especially for this application. The system facilitates the performance evaluation of various appliances for distorted supply voltages. The cost of the system is very low compared with a conventional system consisting of an arbitrary waveform generator, a digital oscilloscope, a spectrum analyzer or/and a computer for harmonic analysis and a true rms multifunction meter. The experimental results show that the distribution of the harmonics of some lamp types does not alter linearly under distorted supply voltages.

Keywords: Arbitrary waveform generator; Power system harmonics; Compact fluorescent lamps; Power quality

1. Introduction

As part of energy conservation strategy, many electric power utilities are promoting modern technologies that consume less energy while providing better quality. In this category belongs the compact fluorescent lamp (CFLs). This electrical equipment is of great importance in lighting since it can provide significant energy saving and last longer than incandescent lamps.

CFLs operate at a low power factor consuming less active power, providing comparable luminous output to the incandescent lamps [1]. However, the ballasts of compact fluorescent lamps can be an important source of higher-order harmonic components of current. These lamps induce distorted current waveform, which influence the quality of the supplied power as well as the electrical appliances [2,3].

The current of the CFLs has not a purely sinusoidal waveform and it is characterised by rapid amplitude changes, a fact that among others creates distortion in the voltage waveform. The effect of CFLs on the distribution system has been investigated and found out that a low percentage of CFLs

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0263-2241/01/$ – see front matter
PII: S0263-2241(01)00017-3

may be sufficient to cause voltage distortion in excess of 5% [4]. Some CFLs have total harmonic distortion (THD) of current higher than 100%, but they have low active power compared with other high-THD sources such as personal computers. That is the reason why standards organisations have not set power quality requirements for CFLs [5,6]. ANSI defines a limit of 32% [7] as the maximum current THD of electronic lamps. This standard also specifies the limit of the amplitude of all high-order harmonics to 30% of the fundamental amplitude. The upper limit of all the higher than the 11th order harmonics is defined as 7% of the fundamental. The limit of the current THD of electronic ballasts is 20%, according to IEEE [5] and IEC [6].

The increasing use of electrical devices (computers etc.), which are sources of harmonics causes distortion in the line voltage. Consequently, it is possible for some CFL lighting systems to be installed in locations where the supply voltage is not always pure sinusoidal. In this case, the harmonic components of the line voltage may affect the performance of CFLs. The aim of this project is to develop an experimental apparatus for the investigation of the harmonic distortion and the problems that may be caused to the distribution network by CFLs as well as to the CFL's performance.

2. Experimental apparatus

2.1. General description

The voltages used for the tests are obtained from an arbitrary waveform generator. It consists of a computer, the multifunction card AT-MIO-16E-10 of National Instruments, the software package and a voltage amplifier.

The components of the voltage are entered from the computer, which loads the required waveform into the card. The analogue output of the card is driven to a voltage amplifier, where it is amplified up to 250 V, AC in order to supply the lamps. The lamps are mounted base-up as their regular burning position. The experimental apparatus is sketched in Fig. 1.

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 Lab View is very friendly for developing programmes 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 experimental procedure of this project is split into 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 been especially developed for the purposes of the project.

2.2. Arbitrary waveform generator

The characteristics of the supply voltage are defined by a VI, which simulates the panel of the physical instrument. It contains an interactive user interface that is the front panel of the arbitrary

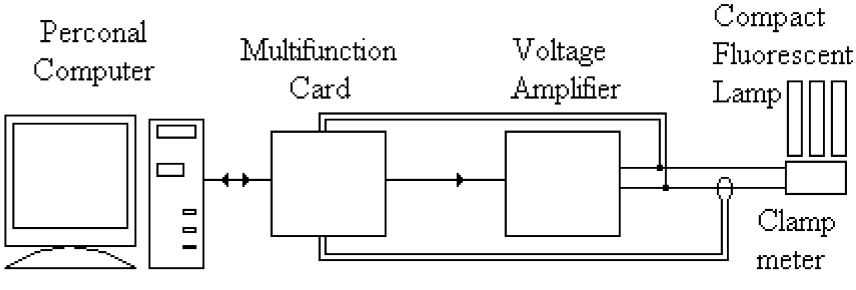

Fig. 1. Experimental apparatus.

waveform generator (Fig. 2). The user defines the frequency and the amplitude of the fundamental signal as well as the desirable harmonics and their amplitude. In this VI a spectrum analyser and an oscilloscope are present. The front panel receives instructions from a block diagram (Fig. 3) that provides a pictorial solution to the programming problem. The generator, the spectrum analyser and the oscilloscope are subVIs within the main VI (Fig. 4).

The programme calculates the THD of the voltage waveform using Fast Fourier transform. The THD is calculated as [5]:

$$\mathrm{THD}_v = \frac{\sqrt{V_2^2 + V_3^2 + \cdots + V_n^2}}{V_1} \cdot 100 \qquad (1)$$

where V_1, V_2, $V_3, \ldots, V_n$ are the magnitudes of the 1st, 2nd, 3rd, ..., nth order harmonics, respectively, of the voltage.

The digital waveform is loaded into the card that generates the analogue signal. The amplitude of the analogue signal at the output of the arbitrary generator is ±5 V. The signal is driven to the voltage amplifier where it is amplified up to 250 V in order to supply the lamps. Through this method the generated waveform by the computer is reliably converted to the supply voltage of the lamp.

2.3. Voltage amplifier

For the needs of the research about the harmonics produced by CFLs and also about the operation of CFLs under harmonic environment ($\mathrm{THD}_v \neq 1$) the design and development of a modified harmonic voltage supply system (MHVSS) is important. The general block diagram of that system is presented in Fig. 5.

As is observed from this block diagram, MHVSS is an analogue type amplifier specially designed to

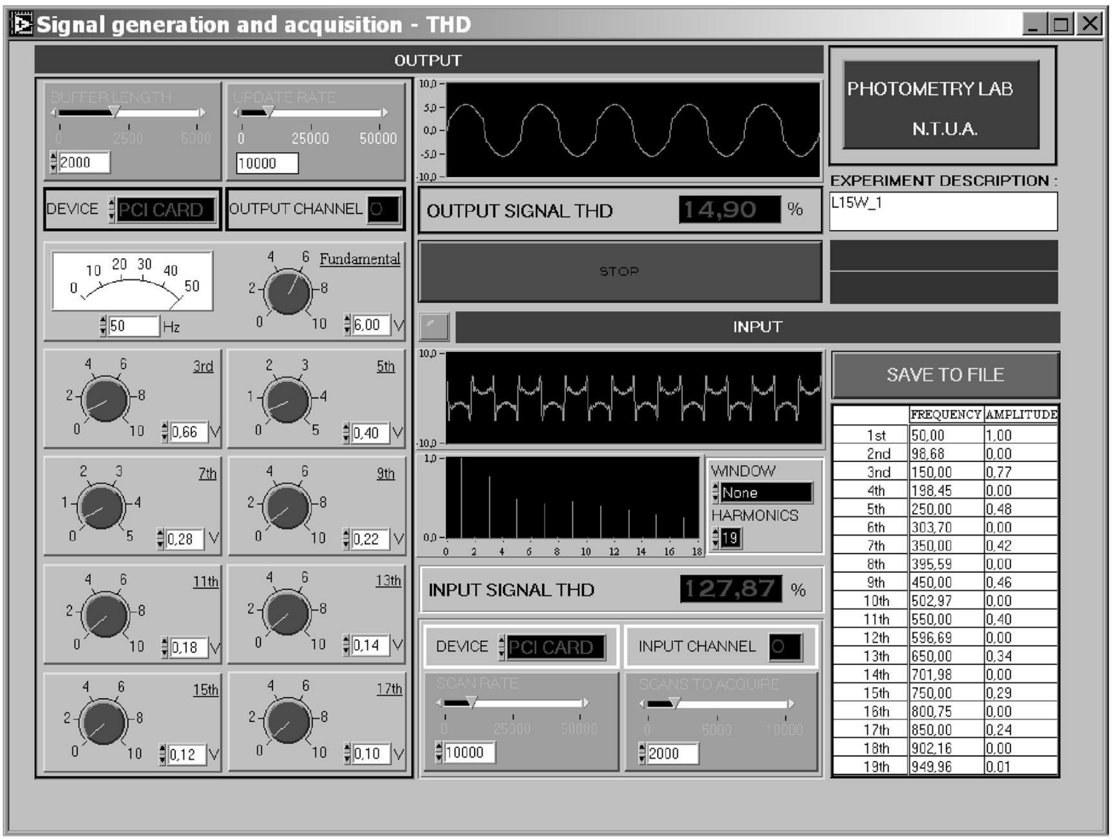

Fig. 2. Front panel of arbitrary waveform generator, spectrum analyzer and oscilloscope.

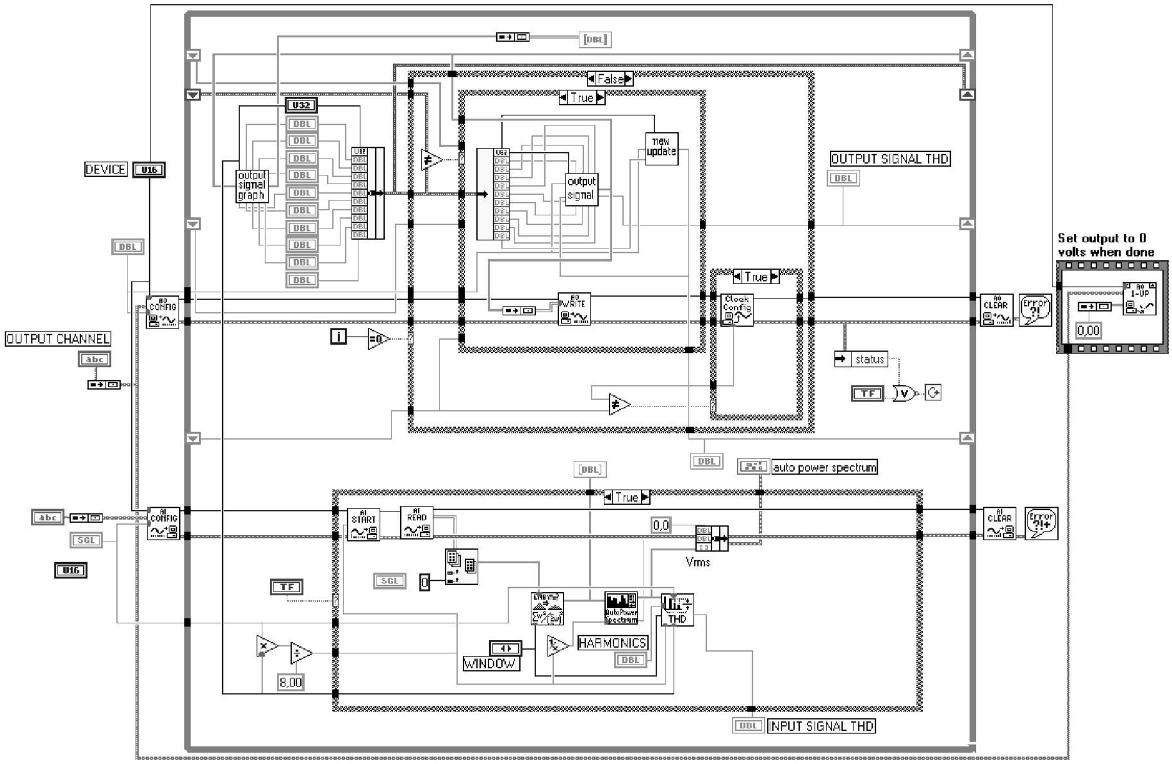

Fig. 3. Block diagram of arbitrary waveform generator, spectrum analyzer and oscilloscope.

amplify the input signal in its entire spectrum. The input signal is produced by a harmonic generator. The user defines the harmonic content of the produced voltage waveform. More specifically, he defines the value of every harmonic component (3rd, 5th, . . . , 17th). This means that the input spectrum is between 50 and 850 Hz. This signal is the input to the MHVSS, which accordingly has the responsibility to amplify the signal and to finally produce a supply voltage of 230 V with every single harmonic component equally (respectively) amplified. MVHSS is specially designed in order to achieve that goal without having any possible disturbances or problems at the output where the compact fluorescent lamps are connected and measured. MVHSS is divided in two parts.

Part A consists of two sub-parts: a 1:1 'amplification' of the input signal, the waveform of which is selectively distorted by the user and two splitter amplifiers. The first sub-part has two tasks. Firstly, it isolates the initial signal of the harmonic voltage generator from the rest of the system. In that way electrical characteristics (impedance etc.) of the generator do not influence the rest of the system. Secondly, it has the task to regulate and control the amplitude of the output of MVHSS. The second sub-part receives the output of the first sub-part and leads two splitter 1:1 amplifiers. The reason for this is to obtain one copy of the initial signal and one 180° diverted signal at the outputs of the two splitter amplifiers.

Afterwards the two 180° phase difference outputs are inputs to part B, where each one is treated separately. Part B consists of two sub-parts as well. At the beginning each signal is input to a buffer circuit and then to the power amplifier. The buffers regulate and control the voltage amplitude used as input to the power amplifier and adapt it to the load (a CFL). Then the amplification is made through Darlington type transistor circuits. The output of part B finds two amplified voltage waveforms of 180° phase difference. The first one is +115 V and the

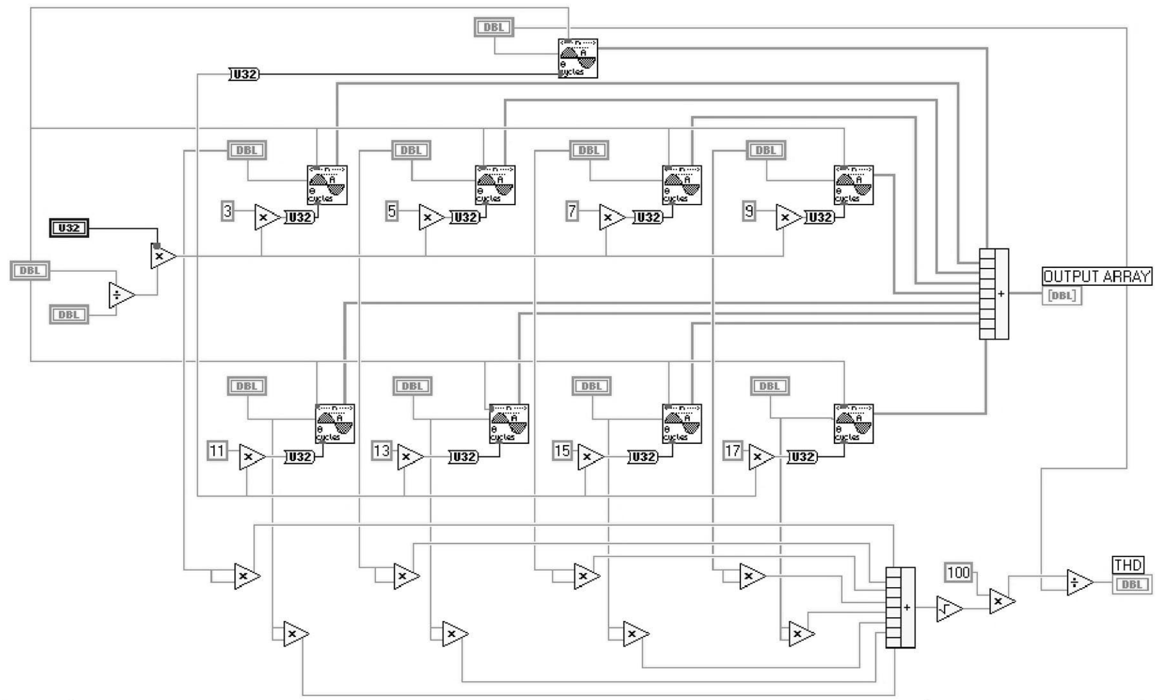

Fig. 4. Block diagram of arbitrary waveform generator (subVI).

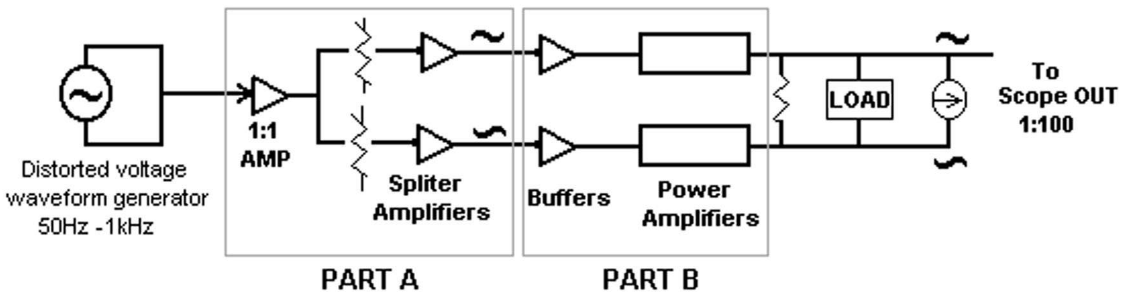

Fig. 5. Block diagram of power amplifier.

other (its twin) is −115 V. These two distorted voltage waveforms are led to the load, which is a CFL. The voltage across the load is 115 V−(−115 V)=230 V.

The special design of the MVHSS allows the reliable amplification of each harmonic component that the user decided that the supply voltage should have. This system is the major tool with which all the experiments about the harmonics produced by a CFL or about the operating characteristics of a CFL under a distorted environment are accomplished.

2.4. Data acquisition system

The data acquisition system for recording of the waveforms is again performed through an especially designed VI. The voltage and the current of the lamps are driven via the connection board, back to the card where they are recorded. A clamp meter is used for the current measurement. Voltage and current of each lamp are measured simultaneously. The recorded current is analysed in its harmonic components using FFT. The THD of the current waveform is calculated as [5]:

$$\mathrm{THD}_i = \frac{\sqrt{I_2^2 + I_3^2 + \cdots + I_n^2}}{I_1} \cdot 100 \qquad (2)$$

where $I_1, I_2, I_3, \ldots, I_n$ are the magnitudes of the 1st, 2nd, 3rd, ..., nth order harmonics, respectively. Samples of the supply voltage and the current are stored in ASCII files for further processing.

The sampling rate of AT-MIO-16E-10 card is 100 kS/s with a 12-bit resolution. The card has two output channels and eight differential (or 16 single-ended) input channels. The absolute accuracy, using the ±10 V range, is 0.056% of reading and the averaged relative accuracy (resolution) is 1.114 mV.

The card of the developed system is sampling at 100 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 50 kHz per channel. This frequency is high enough to prevent aliasing, according to Nyquist theorem, since the maximum frequency component of the generated signal is 850 Hz (17th harmonic). Therefore, an anti-aliasing filter is not required. The asynchronous sampling on two input channels causes a phase shift of 1/100 kS/s = 0.01 ms which is negligible compared even with the period of the 17th harmonic (1/850 Hz = 1.176 ms).

The buffer length is set up to 5000 samples. The maximum length of FFT is the length of the buffer. This number of samples provides a fast and accurate recording and analysis. The FFT is performed by a virtual instrument. If the number of samples is a valid power of 2, then the virtual instrument computes the fast Fourier transform by applying the split-radix algorithm. When the number of samples is not a power of 2, the virtual instrument computes the discrete Fourier transform by applying the Chirp-Z algorithm. Usually, the developed system uses 4096 samples, as FFT is faster than DFT.

The 'Window' on the front panel of the VI shown in Fig. 2 contains the following functions: (a) Blackman, (b) Blackman–Harris, (c) Exact Blackman, (d) Flat Top, (e) Hamming, (f) Hanning and (g) No window. Each time, the proper window function depends upon the application requirements [8]. If no window function is used (not recommended for an accurate THD estimation), this selector defaults to 'No window'.

3. Tests

The compact fluorescent lamps of this investigation are provided with either magnetic-core or electronic ballast. The electronic ballasts are built into lamp fixtures with E27 screw mount (self-ballasted lamp). The magnetic core ballasts are adapted for operation in a conventional socket. All these lamps are designed for the 230 V, 50 Hz electric utility systems. They operate at a very low power factor (0.4–0.5). Four types of self ballasted, electronic lamps are investigated: 9 W, 11 W, 15 W and 20 W. The lamps with the magnetic ballast are: 7 W, 9 W, 11 W, 13 W and 18 W.

The lamps are tested under four types of supply voltages. They represent waveforms of pure sinusoidal form as well as distorted signals with low, medium and high (up to 30%) total harmonic distortion. The input voltage harmonic content was chosen following scenarios based on field measurements of the harmonic content of weak electric grids of two Greek Islands Arki and Antikythira where photovoltaic (PV) stations are installed. As known, PV stations may induce significant THD because of the power electronics used for the control and inversion of the DC voltage to AC. The field measurements on these two Greek Islands are presented in Ref. [9]. The voltage THDs measured throughout the two electric grids was generally between 1.5 and 5.5%. It was observed that the variation of the three first harmonic components (3rd, 5th, 7th) while the voltage THD was rising was following — more or less — the next rules: the 3rd was rising, the 5th was changing occasionally (up or down) while the 7th was usually the same. This variation was followed to the rest of the hypothetical scenarios of 10%, 20% and 30% of voltage THD in this project. Similar voltage THD variations (4.6%, 15.5%, 36.4%) were reported in Ref. [10].

The application starts with the definition of the characteristics of the test voltage. The amplitude and the frequency of the fundamental waveform as well as the higher order harmonic components are defined using the knobs on the front panel (Fig. 2). The amplified signal at the output of the amplifier is displayed in real time mode on the front panel. The distortion in the waveform is computed by a subVI and the THD is displayed. This is the output signal on the front panel. The current of the load (i.e. lamp), which is the input signal on the front panel, is also displayed in real time mode. A sample of the waveform is analysed by the subVI and the harmonic spectrum as well as the THD are displayed (Fig. 2). Both signals are stored in the hard disk for further analysis.

Fig. 6 presents the results of another application concerning the performance of a typical 11 W self-ballasted electronic lamp when supplied with a 4% THD in the voltage waveform. As it was expected the current waveform is heavily distorted. The THD is slightly below 100%. A similar application on a typical 18 W lamp with magnetic ballast is shown in Fig. 7. Under 4% THD supply voltage the THD of the current is slightly below 10%.

4. Results and discussion

The lamps with magnetic ballasts produce the least harmonic current when supplied by pure sinusoidal voltage. The THD values of their current waveforms are on average below 10%. On the other hand, the distortion in the current of self-ballasted electronic lamps exceeds 100%.

It was expected that if the line voltage was distorted then it would add distortion to the current of the lamp. Unlike this hypothesis, the experiments show that the shape and the harmonic content of the current waveform for lamps with magnetic ballast are the least affected by changes of harmonic distortion in their supply voltage. The tests on all the investigated lamps with magnetic ballast show that increasing the supply voltage harmonics, only slight additional current distortion is observed (Fig. 8). The current THD increases slightly with the increase of the voltage THD but it does not follow the high values of voltage distortion. This is also confirmed by observing the variation of each harmonic (Fig. 9). Similar performance has been observed on a wide range of lamps for the 120 V AC, 60 Hz electrical utility system [11].

This phenomenon is more evident on the electrical performance of the lamps with electronic ballasts. The current THD vs. the THD in the supply voltage follows a 'U' curve for all the lamps of this group (Fig. 8). Previous investigations [1,10,11] experience

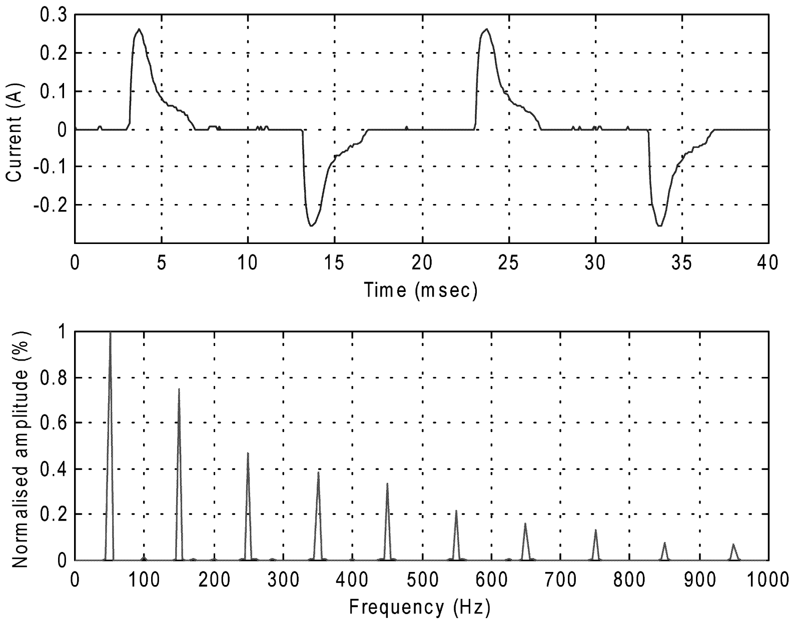

Fig. 6. Current waveform and its harmonic spectrum of an 11 W electronic lamp (THD of supply voltage, 4%; THD of current, 106.9%).

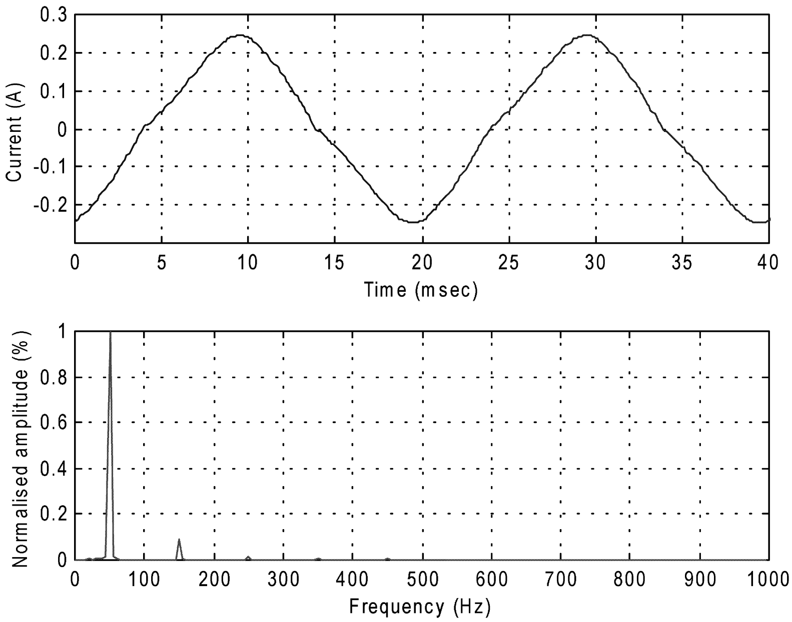

Fig. 7. Current waveform and its harmonic spectrum of an 18 W lamp with magnetic ballast (THD of supply voltage, 4%; THD of current, 9.4%).

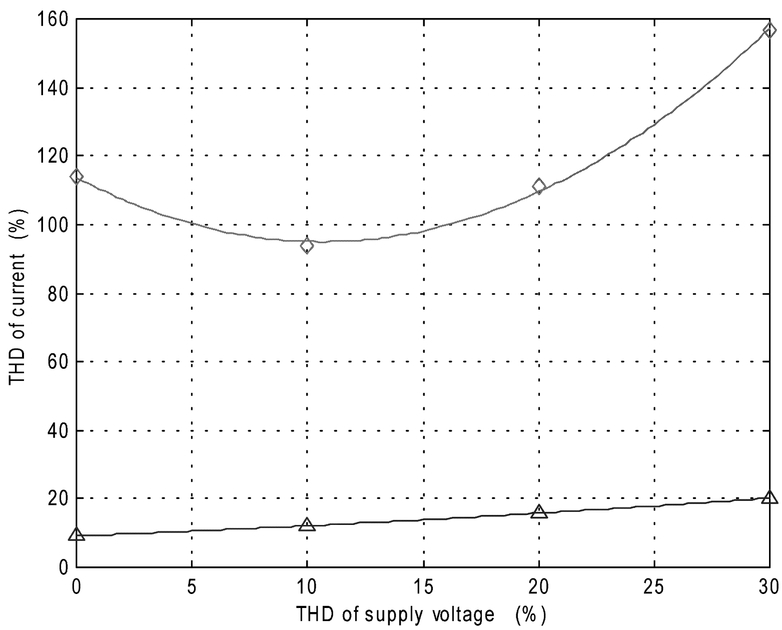

Fig. 8. Effect of changing THD of voltage on the current distortion. △, 9 W lamp with magnetic ballast; ◇, 9 W electronic lamp.

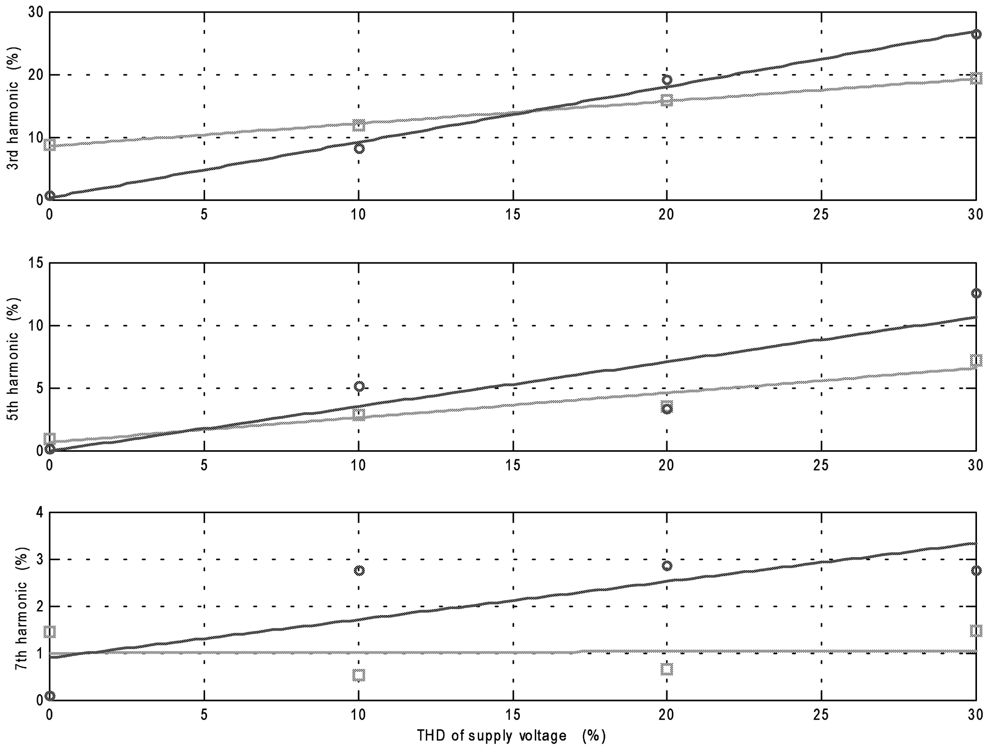

Fig. 9. Effect of changing THD of test voltage on the interaction between harmonics. 3rd, 5th and 7th harmonic of a typical lamp with magnetic ballast (current, □; voltage, ○).

THD values of current exceeding 100% when the lamps operate under pure sinusoidal voltage. However, as in the case of lamps with magnetic ballast, the increasingly distorted supply voltage does not influence the THD of current waveform in the same way. Moreover, the current distortion seems to decrease as the THD in voltage waveform increases for THD values up to 10%. Similar performance was reported on a wide range of lamps for the 120 V AC, 60 Hz electrical utility system [10,11]. Only under heavily distorted supply voltages (THD > 20%), which are not common in distribution networks, the current THD increases and exceeds the respective value of the pure sinusoidal operation. It seems that higher than the 3rd order harmonics contribute most to the 'U' form of the THD of the current waveform (Fig. 10).

5. Conclusions

Compact fluorescent lamps consume less active power and their use will result in reducing the active power demand of the electric power system. On the other hand, their low power factor requires additional reactive power from the electric utility system.

The current in circuits with the compact fluorescent lamps has only odd harmonics. These lamps, which are increasingly being used as alternatives to incandescent lamps, will likely cause problems to interference-sensitive devices because of the associated current distortion.

In recent years, the levels of harmonic distortion in power systems have been increasing steadily. It is therefore important to study the electrical performance of these new lamps for distorted voltage

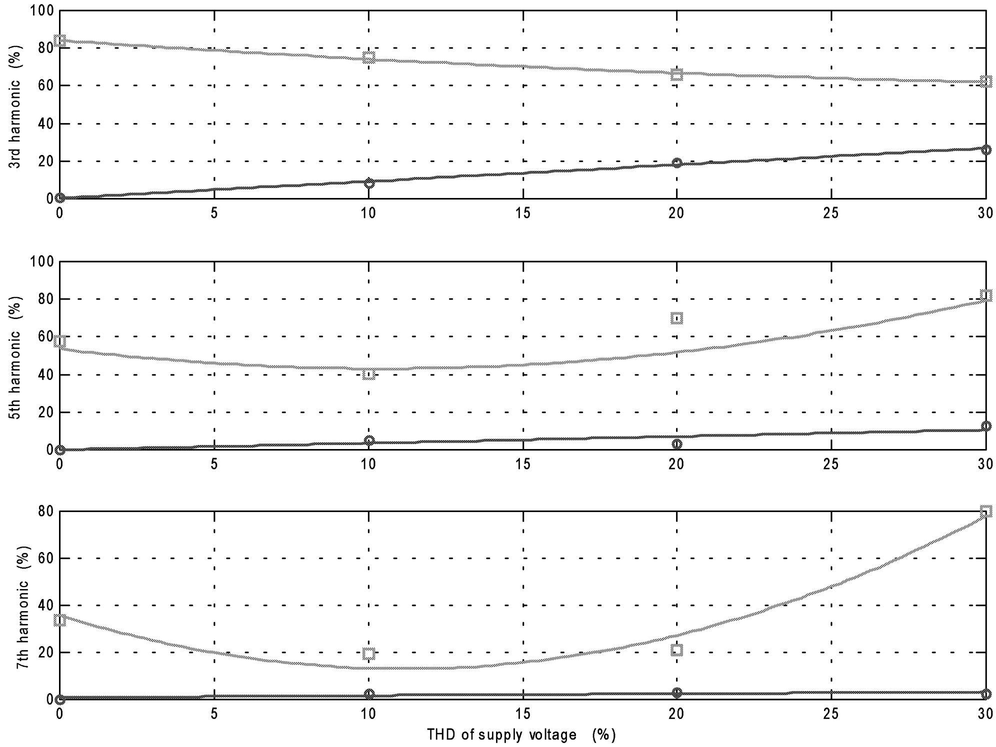

Fig. 10. Effect of changing THD of test voltage on the interaction between harmonics. 3rd, 5th and 7th harmonic of a typical electronic lamp (current, □; voltage, ○).

waveforms. The developed arbitrary waveform generator (hardware and software tools) facilitates such an experimental investigation. The cost of the system is very low compared with a conventional system consisting of an arbitrary waveform generator, a digital oscilloscope, a spectrum analyzer or/and a computer for harmonic analysis and a true rms multifunction meter. The system configuration is compact and user friendly. It can be also used for similar experiments on other low voltage equipment.

The experimental results of this project arrive at the conclusion that neither the electrical performance of CFLs will be affected in networks with low or medium harmonic problems, nor additional problems will be introduced. Unlike the hypothesis that the utilization of CFLs in networks with harmonic problems will deteriorate the power quality, it seems that the harmonic content of the current load is only slightly affected by changes of harmonic distortion in the line voltage.

Acknowledgements

The authors would like to thank Mr. John Paschalidis for his contribution to the development and testing of the power amplifier.

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