Measurement of the Influence of Household Power Electronics on the Power Quality

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***Abstract* —The paper deals with the measurement of the influence of new technology household appliances on the power quality. A virtual instrument for power quality monitoring based on NI LabVIEW™ platform and simultaneous measurements of electrical voltages and currents, as well as powers, frequency, voltage variations, magnitude of rapid voltage changes, flicker severity, voltage unbalance and total harmonic distortion is described. The virtual instrument-power analyser enables measurement of power characteristics in non-sinusoidal conditions. Power measurements (*P, Q* and *D*) of household appliances are presented and discussed. The influence of the modern, domestic energy saving lighting and inverter air conditioners, as significant household consumers, on the power quality of the electrical energy is considered.**

***Keywords* — measurement, power quality, household appliances**

I. INTRODUCTION

The continual implementation of new technologies in the household appliances using power electronics: inverter air conditioners, personal computers, led lighting solutions, the inverter principle washing machines and microwave ovens, results in a rapid growth of the nonlinear domestic loads. The power demand of a single household device is low and does not cause problem in the grid, however the very big number of such devices and the very large number of households will have a significant negative influence causing distortion, dips, non-active/distortion powers and other different types of disturbances in the electricity network. One of the main problems is the flow of non-active energy caused by harmonic currents and voltages.

Dealing with this growing problem implies study of household sources of disturbances of the power quality as well as research of their interactions with the power system. That problem supposes also measurement of the all powers, active and reactive. This implies the need of continual monitoring of the power characteristics by proper instruments in compliance to the international guide IEC 61000-4-7, [1]. On the other hand the usage of the personal computers (PC) in the measurement technique and the availability of I/O modules and data acquisition cards (DAQ) enable cheap and fast creation of virtual instruments for physical measurements.

For the study and analysis of the problems connected to the power quality of the household appliances, a virtual power quality analyzer based on National Instruments™ (NI) input modules, NI USB chassis, PC and LabVIEW™ platform is developed.

II. MEASUREMENT OF ELECTRIC POWER

Concerning the measurement of the power in non-sinusoidal conditions, there are number of different approaches and definitions of reactive power. New definitions of powers have been discussed almost 50 years among the engineering community.

Budeanu [2] introduced reactive power Q and a quantity named distortion power D. The distortion power mainly consists of cross-products of voltage and current harmonics. The power in the case of non-sinusoidal conditions is presented in Figure 1, where P_{50}, Q_{50} and S_{50} are active, reactive and apparent power of the basic harmonic at network frequency f=50 Hz, D is distortion power, Q is total reactive power and S is total apparent power with influence of harmonics.

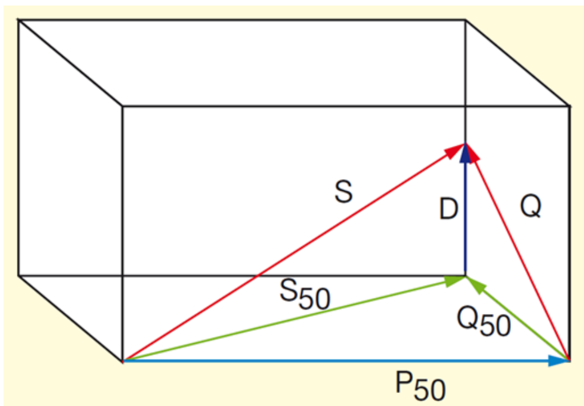

Fig. 1 Power presentation according DIN 40110.

The active power P [kW] is the arithmetic mean value of the known function

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

The apparent power S [kVA] is the peak value of the power function in (1) and presents product of effective voltage and current values

$$S = U\,I \tag{2}$$

Assuming ideal sinusoidal form of voltage and current signals, the active power is

$$P = U\,I\,cos\varphi_1 \tag{3}$$

where φ_1 is the delay/forward angle between voltage and current. It means that only for ideal sinusoidal supply power factor *PF* is equal to $cos\varphi_1$.

$$PF = P/UI = cos\varphi_1 \tag{4}$$

The disturbance power *D* [kVAr] could be expressed on two ways, as in (5) and (6)

$$D = U \cdot \sqrt{\sum_{\nu=2}^{\infty} I_\nu^2} \tag{5}$$

$$D = \sqrt{Q^2 - Q_{50}^2} = \sqrt{S^2 - P^2 - Q_{50}^2} \tag{6}$$

It is clear that (6) results from Fig. 1. Only active power is useful, working power and therefore $P=P_{50}$.

Now the power factor is

$$\lambda = \frac{U \cdot I_1 \cdot cos\varphi_1}{U \cdot I} \tag{7}$$

where φ_1 is the angle between P_{50} and S_{50} and *PF* is the angle P_{50} and *S*.

The reactive power definition proposed by S. Fryze [3] is based on a time domain analysis. Different definitions of reactive power were proposed by N. L. Kusters and W. J. M. Moore [4], by W. Shepherd and P. Zakikhani [5], by Sharon [6], by L. S. Czarnecki [7] and by IEEE working group on harmonics [8].

There is not yet available generalized power theory that can provide a simultaneous common base for energy billing, evaluation of electric energy quality, detection of the major sources of waveform distortion, theoretical calculations for the design of mitigation equipment such as active filters or dynamic compensators.

The IEEE working group on “non-sinusoidal situations” has suggested ”practical definitions for powers”, [8]. The main difference between this definition and other definitions is that it separates the fundamental quantities P_1 and Q_1 from the rest of the apparent power components. Focus is also put on revenue metering than on compensation. The new definitions were developed to give guidance with respect to the quantities that should be measured for revenue purposes, engineering economic decisions, and determination of major harmonic polluters.

The virtual instrument using computer enables accurate and versatile metering of electrical quantities defined by means of advanced mathematical models.

Measurements presented in the paper are according IEEE Std 1459/2010, IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Non-sinusoidal, Balanced, or Unbalanced Conditions [9].

In the Table I and Table II are presented the measurements of:

Power factor $$PF = \frac{P}{S} \tag{9}$$

and the total harmonic distortion *THD*.

The overall deviation of a distorted wave from its fundamental is estimated with the help of the total harmonic distortion.

The total harmonic distortion of the voltage is defined with:

$$THD_v = \frac{V_H}{V_1} = \sqrt{\left(\frac{V}{V_1}\right)^2 - 1} \tag{10}$$

The total harmonic distortion of the current is as follows:

$$THD_i = \frac{I_H}{I_1} = \sqrt{\left(\frac{I}{I_1}\right)^2 - 1} \tag{11}$$

The corresponding RMS values and squared are as follows:

$$V = \sqrt{\frac{1}{kT}\int_{\tau}^{\tau+kT} v^2 dt} \quad \text{and} \quad V^2 = V_1^2 + V_H^2 \tag{12}$$

$$I = \sqrt{\frac{1}{kT}\int_{\tau}^{\tau+kT} i^2 dt} \quad \text{and} \quad I^2 = I_1^2 + I_H^2 \tag{13}$$

where:

$$V_H^2 = V_0^2 + \sum_{h>1} V_h^2 = V^2 - V_1^2 \tag{14}$$

$$I_H^2 = I_0^2 + \sum_{h>1} I_h^2 = I^2 - I_1^2 \tag{15}$$

are the squares of the RMS values of voltage V_H and current I_H, respectively.

Today there is a wide choice of microprocessor based instruments called power analyzers or network analyzers, capable to perform FFT, necessary for non-sinusoidal power measurements, [9], [10], and [12].

For measurement of the all power quality characteristics a virtual instrument based on NI LabVIEW™ platform and simultaneous measurements of electrical voltages and currents, as well as powers, frequency, voltage variations, magnitude of rapid voltage changes, flicker severity, voltage unbalance and total harmonic distortion is developed.

The virtual instrument-power analyzer enables measurement of power characteristics in non-sinusoidal conditions. The use of computer enables accurate and versatile metering of electrical quantities defined by means of the presented advanced mathematical models.

III. Description of the Instrument

The measurement of electric power is based on current and voltage measurement.

The instrument has two modules for the Analog input:

1) NI 9225, 3-channel 300 V rms analog input module with 50 kS/s per channel simultaneous inputs for phase voltage measurement and built-in antialias filters.
2) NI 9227, 4-channel current input, 5 A rms measurement, 50 kS/s per channel simultaneous inputs and built –in antialias filters.

Other equipment used:

3) NI cDAQ-9174, compact DAQ, 4 slot chassis with USB connection. The chassis runs the Analog input modules simultaneously. The chassis has four general purpose 32 bit counter/timers built-in.

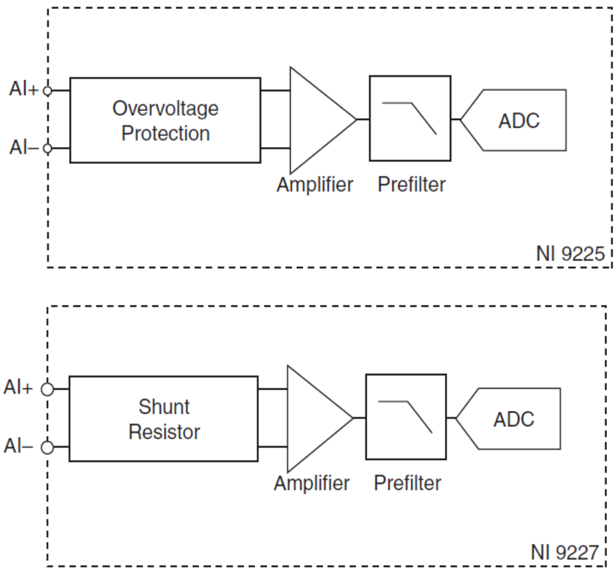

Fig. 1. Input circuits for one channel of NI 9225 and NI 9227

The input circuit for one channel of NI 9225 and NI 9227 is shown in Figure 1. The Delta-Sigma ADCs are with 24 bits. The internal master time-base is f_M=12,8 MHz. The accuracy is ±0,23 % of the read value, ±0,05 % of the range (for temperature range from -40 °C to 70 °C). The wiring diagram of the power quality analyzer for direct measurement of the phase voltages and currents is shown in Figure 2.

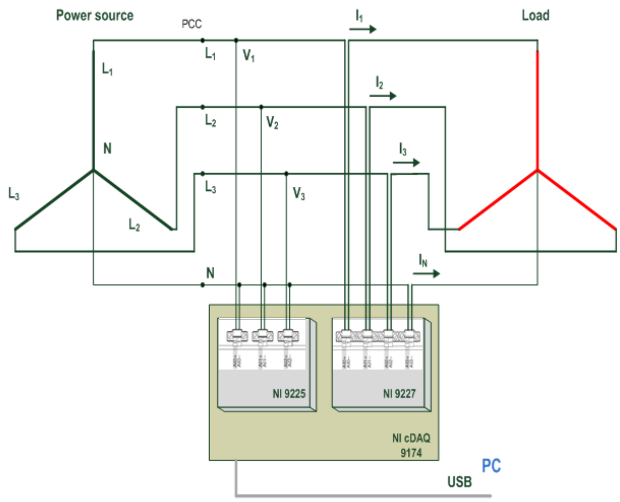

Fig. 2. Wiring diagram of the power quality analyzer.

The LabVIEW™ graphical programming language was used for creation of the virtual instrument for measurement of the power quality characteristics. The graphical source code of the virtual instrument is shown on Figure 3.

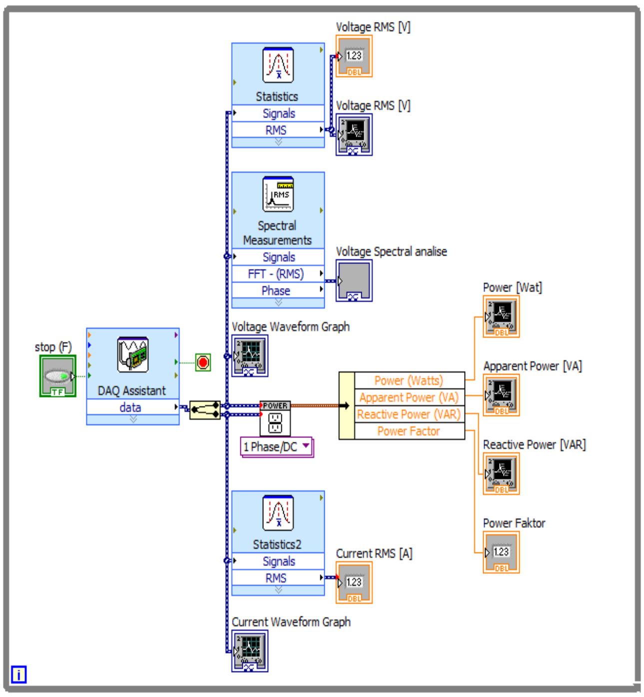

Fig. 3. Software block diagram of the PQ virtual instrument.

The virtual instrument beside the measurement of the phase voltages, phase and neutral currents, contains software modules running in parallel:

- Power monitor;
- EN 50160 voltage monitor;
- FFT analyzer;
- Vector analyzer;
- Flicker analyzer.

Before practical usage of the virtual instrument for monitoring of power characteristics, it was calibrated using the multifunctional calibrator Fluke 5500A.

IV. Measurement Results

To study the generation of power disturbances by the new household power electronic technologies, series of measurements on the inverter air conditioners, led lighting solutions, the inverter principle washing machines and microwave owns were done. Here the measurements of the influence of modern, domestic energy saving lighting and inverter air conditioners on the power quality and the price of the electrical energy are presented and discussed.

A. Laboratory Set-up

The measuring arrangement for measuring the power characteristics of different domestic appliances technologies is shown in Figure 4.

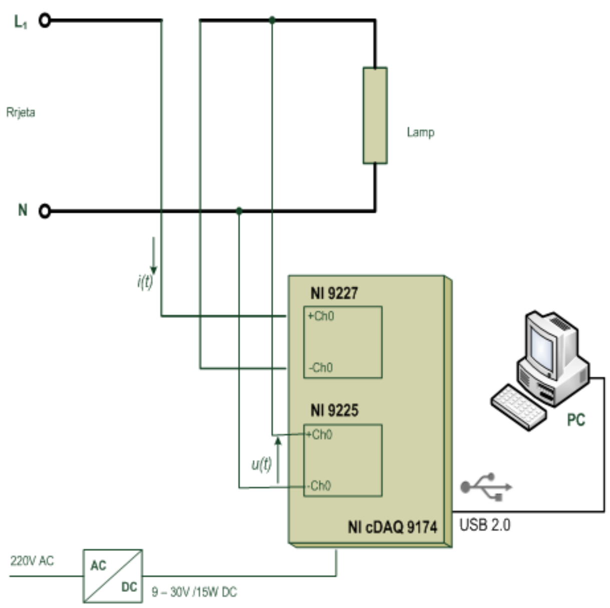

Fig. 4. Measuring scheme.

The measurements of the power characteristics were done on:

I. Different lighting technologies
1. Incandescent light bulb;
2. Fluorescent light with inductive ballast;
3. Fluorescent light with electronic ballast;
4. ECO Energy saving light, 5. LED light, and

II. Air conditioners with cooling / heating.

B. Experimental Results

The generation of harmonics from a particular light bulb may be illustrated by the distortion of the current sinusoidal form, and by the harmonic spectrum. Below in the Figures 5-9 the measured currents of different light bulbs are presented.

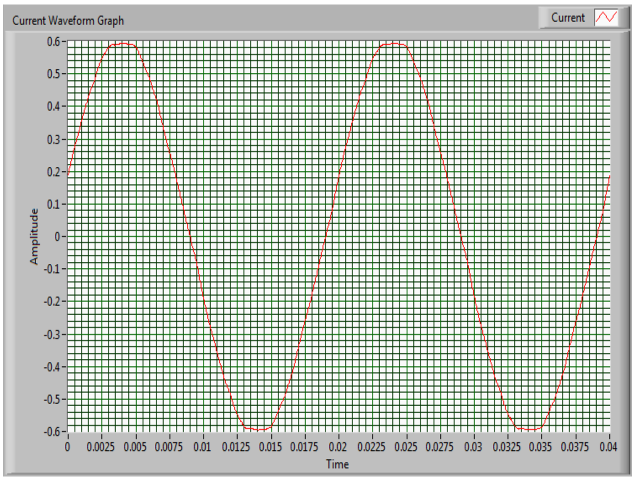

Fig. 5. Current waveform graph of Incandescent light bulb, *THDI*=1,54 %.

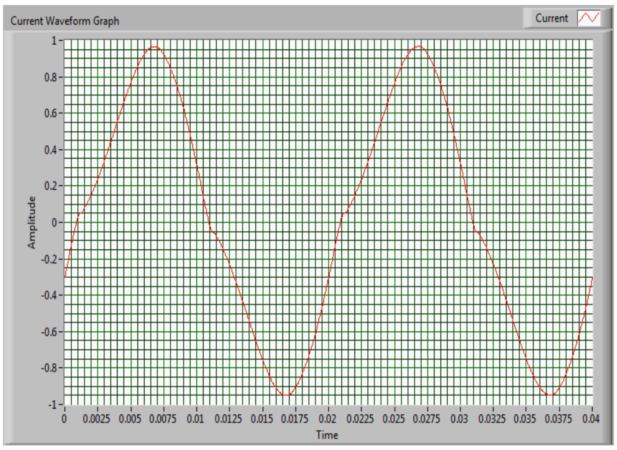

Fig. 6. Current waveform graph of Fluorescent light with inductive ballast, *THDI*=11,42 %.

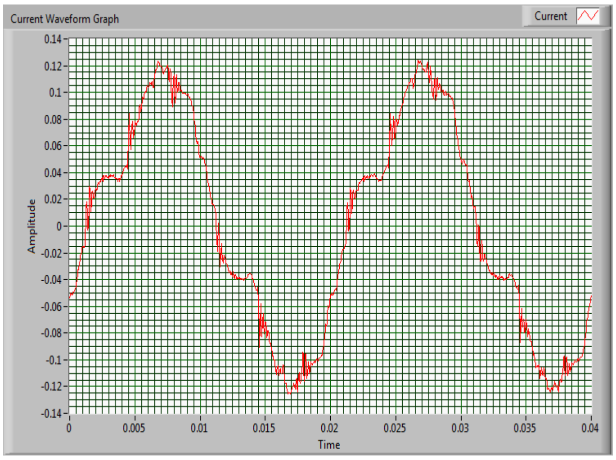

Fig. 7. Current waveform graph of Fluorescent light with electronic ballast, *THDI*=19,76 %.

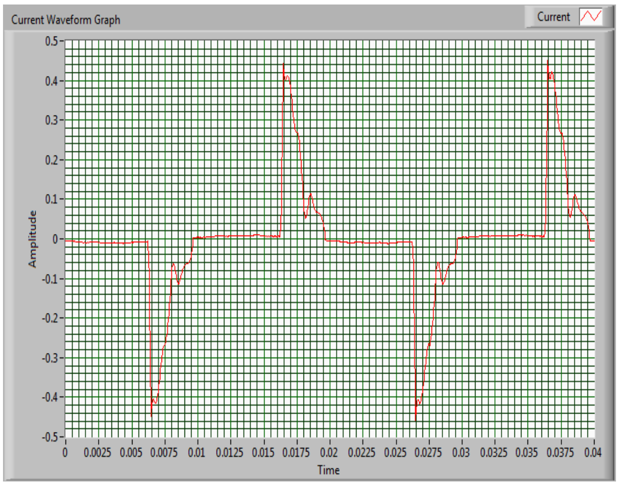

Fig. 8. Current waveform graph of ECO Energy saving light, *THDI*=113,12 %.

Fig. 9. Current waveform graph of LED light, *THDI*=15,03 %.

Comparison of the power characteristics of different lighting technologies is shown in the Table I.

TABLE I
POWER FACTOR AND DISTORTION OF DIFFERENT LIGHT TECHNOLOGIES

Light Technology	POWER FACTOR *PF* (%)	TOTAL HARMONIC DISTORTION OF THE VOLTAGE THD_V (%)	TOTAL HARMONIC DISTORTION OF THE CURRENT THD_I (%)
Incandescent light bulb	0,999	1,59	1,54
Fluorescent light with inductive ballast	0,485	1,52	11,42
Fluorescent light with electronic ballast	0,666	1,49	19,76
ECO Energy saving light	0,587	1,57	113,12
LED light	0,922	1,36	15,03

It is obvious that the power factor and the harmonic distortion vary significantly, depending on the light bulb technology. The power factor of the fluorescent light with inductive ballast, the ECO Energy saving light and the fluorescent light with electronic ballast, is rather low. The energy conversion efficiency should be considered together with the complete power characteristics of the lighting technologies.

If the numerous negative effects of the generated harmonics on the network (increased losses in the transformers and the conductors, overheating and damage to neutral conductor, etc.) are the represented by effective price of the reactive energy equal to 1/3 of the active energy price, in that case the ranking of the different lightning technologies in terms of saving of electrical energy will be different. For example, for ECO energy saving light it was measured active power *P*=18,55 W and reactive power *Q*=25,55 VAR, what would be equivalent with the price of 27,06 W.

The generation of harmonics from inverter wall split air conditioners with cooling / heating, was also measured and studied. The distortion of the current sinusoidal form, and the harmonic spectrum are shown below in the Figures 10 - 13.

Fig. 10. Current waveform graph of inverter air conditioner, Operation mode: Cooling, Line voltage RMS: 235,14 V, Load current RMS: 1,817 A, *THDI*: 49,868 %.

Fig. 11. Current waveform graph of inverter air conditioner, Operation mode: Heating, Line voltage RMS: 233,16 V, Load current RMS: 3,487 A, *THDI*: 34,368 %.

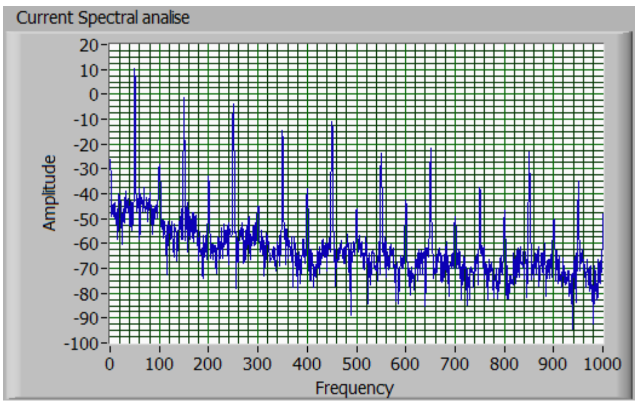

Fig. 12. Current spectrum of inverter air conditioner, Operation mode: Heating, Line voltage RMS: 233,16 V, Load current RMS: 3,487 A, *THDI*: 34,368 %.

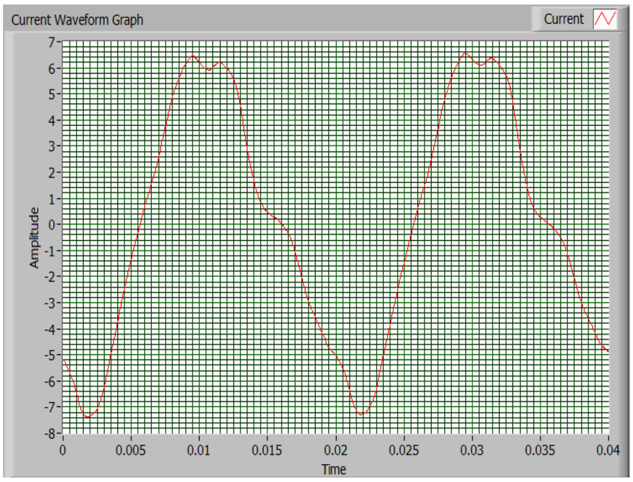

Fig. 13. Current waveform graph of air conditioner without inverter, Operation mode: Cooling, Line voltage RMS: 234.10V, Load current RMS: 4,489 A, *THDI*: 18,145 %.

Power characteristics of the air conditioners with cooling/heating for different working points are shown in the Table II.

TABLE II
POWER FACTOR AND DISTORTION OF AIR CONDITIONER DIFFERENT OPERATION MODES

Air conditioner /operation mode	POWER FACTOR PF (%)	TOTAL HARMONIC DISTORTION OF THE VOLTAGE THD_V (%)	TOTAL HARMONIC DISTORTION OF THE CURRENT THD_I (%)
AIR CONDITIONER WITH INVERTER/COOLING			
I_{rms}=1,016A	0,827	1,039	66,964
I_{rms}=1,612A	0,815	1,019	68,510
I_{rms}=2,003A	0,912	1,006	45,446
AIR CONDITIONER WITH INVERTER/HEATING			
I_{rms} =1,601A	0,813	1,063	68,035
I_{rms} =3,487A	0,945	1,008	34,368
I_{rms} =4,525A	0,954	1,019	31,308
AIR CONDITIONER WITHOUT INVERTER /COOLING			
I_{rms} =4,4895A	0,971	1,005	18,145

The inverter air conditioner with cooling/heating is an important source of harmonic distortion in the households. The power factor and the harmonic distortion vary depending of the operating point, but they should be considered in the analyses of the energy efficiency and the use of energy in the households.

V. Conclusion

The paper described a virtual instrument for power quality monitoring based on NI LabVIEW™ platform with simultaneous measurements of electrical voltages and currents, and presented the measurement of the influence of new technology household appliances on the power quality. The virtual instrument-power analyzer enables accurate and versatile measurement of power characteristics in non-sinusoidal conditions, as well as use of different advanced mathematical models.

The measurements of the generation of power disturbances by the different household appliances technologies and the comparison of their PQ characteristics have shown that their influence on the power quality may be significant. The negative effects generated by the modern home appliances may annulate the advantages of the energy saving. The conclusions about energy efficiency of particular domestic appliances technology should be reconsidered with respect of the integral power quality effects. There is need for future study of the PQ influence of different household appliances and monitoring of the influence of the clusters of appliances and households at the point of common coupling on the distribution system. Also the study of DC micro grids with local renewable sources like photovoltaics and modern generation household appliances may give new interesting energy saving solutions.

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