LOW-POWER AC LOADS AND ELECTRICAL POWER QUALITY

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Abstract –This paper deals with experimental study and numerical simulation of single phase AC low power loads: artificial light sources, personal computers, refrigeration units, air conditioning units and TV receivers. These loads are in such large numbers that represents the main source of disturbances (harmonic current, reactive power and unbalanced three-phase network). The obtained simulation models, verified by comparison with experimental results may be used in larger simulation models for testing and sizing the optimum parameters of active power filters. Models can also be used to study the interactions between grid elements and various loads or situations.

Keywords: modelling, renewable power sources, power quality, electrical network, AC loads.

1. INTRODUCTION

This work represents a part of the research project PN-II-RU-TE-2014-4-1761, who's aim is to design, test (simulation and experiments) and validate a distributed low power system (up to 5kW). The structure of the proposed system is presented in Fig. 1:

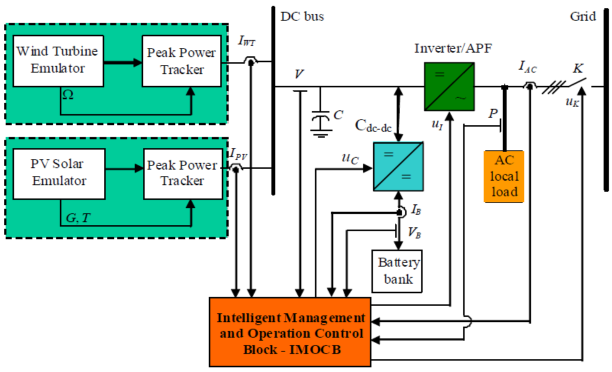

Fig. 1. Structure of the proposed distributed power system

The system is a combination of a voltage inverter, renewable energy sources and lead-acid battery, resembling some of the topologies presented in [1] or [2].

In Fig.1 the *AC local loads* represents a group of single phase electronic devices that can be connected in any possible configuration in a three phase power distribution system (between any of the phases and the common wire).The energy needed to run these loads can be provided simultaneously by one or more of the possible sources – national grid, local wind turbine, photovoltaic panels (emulator) and lead-acid battery – according to an algorithm based on cost and renewable power source availability.

The AC loads, of commercial type and mass-use, represents the main source of perturbations (current harmonics) for the national distribution grid in the rural areas. The most visible effect is the distortion of the main grid voltage, sometimes with more than 5% total harmonic content [3]. Some examples of electronic devices and associated power quality problems will be detailed in the following chapter of the paper.

Electrical loads can be grouped in linear, reactive, nonlinear and mixed. Each of these loads poses some difficulties for inverters or active power filters (APF) regardless the control strategy.

a) Linear loads are rarely used today, excepting for incandescent light bulbs (in decline), electric heaters and ovens. The problem induced in the grid consists in the high start-up current;

b) Reactive loads are AC motors, light fixtures with fluorescent or sodium lamps with classical 50/60Hz inductor, small capacitive loads – like the ones connected in switching power supplies in order to suppress high frequency commutation noise. The inductive loads have filtering effect so that current harmonics are negligible. The capacitive loads have a derivative effect, inducing in the grid current harmonics that are proportional to the distortions of the sinewave of the supplied voltage.

c) Nonlinear loads can be of various natures, but the most used kind is the uncontrolled rectifier bridge with capacitor on the DC side. It is used practically in every power supply up to 500W, from phone AC adapter to personal computers or TV receivers. The lower nominal power, component count and production costs, but the higher the content of the current harmonics is. We have even replaced the incandescent bulbs with compact fluorescent lamps (CFL) that uses a high frequency internal oscillator to minimize the size of the current limiting inductor. The oscillator is created with integrated circuits and/or transistors and it requires DC voltage in order to operate properly. This DC voltage is obtained in majority of cases with a simple bridge with rectifier diodes and capacitor for filtering the output. To obtain the same quantity of light, we have replaced the 100W incandescent bulb (negligible current harmonics added in the grid) with a 36W CFL (with a total harmonic distortions/THD of the current of 10 to 200%).

Flattening the sinewave depends on the load instantaneous current and the impedance of the grid:

farther from generator – greater the distortion for the same nonlinear load. As stated in [4], the loads will generate variable amount of perturbations, as response to the sinewave changes. Given the length of the wires in the national grid, nonsinusoidal voltage and high order current harmonics, the electro-magnetic perturbation is generated on large scale.

The *Inverter/APF* block in Fig.1 must operate in active power filter mode when loads are connected to the national grid and in inverter mode when grid is offline.

After consulting the current state of the art in active power filter domain [5], [6], [7], the control structure of the APF has been chosen as "DC side control", as designated in [8], because of the good compromise between computational effort and implicit use of the static power switches at their maximum performances. The mentioned control strategy can be applied with minimal changes both to single or multiple/three phase power distribution systems.

One of the most important steps in sizing the proposed system is to dimension the components of the inverter/APF, so that loads will function properly but without injecting current harmonics in the grid. To accomplish this, the static switches must be chosen by the maximum value of the instantaneous load current, inductors must be sized to allow the needed gradient of the current through loads, keeping in the same time the boost effect of the APF and allowing for protection circuits to function reliable. Some internal control loops needs to be calibrated in order to minimize ringing and over-voltages/currents in the power circuits. It is well known that the hardest operating point of an electric device (and grid) is the power-up moment – at this time currents are usually many times greater than the nominal ones, perturbations injected in the grid are highest, and failure is more probable.

In a previous work, [9], a single phase APF was dimensioned and validated through simulation and experiment. In this project, because loads are connected in random configuration on the phases, a good simulation model is needed before experiments.

A mixed analysis of consumer was carried out which takes into account both the internal structure of the polluting equipment and the results of experimental measurements. The internal structure of nonlinear loads is known with fairly good approximation, at least in terms of functional blocks. The voltage and current signals can be acquired in digital format using an electronic circuit specifically designed and, as digital simulation environment, Matlab / Simulink / SimPowerSystems software is used.

Sizing the electrical components of each model is obtained by comparing the simulation with experimental results in the same initial conditions. For example, it is essential to use the same voltage distorted "sinewave" in simulation as in the experiment, in order to obtain conclusive results.

2. THE DATALOG CIRCUIT

For the experimental analysis it was designed, developed and used an electronic circuit that can record in digital form two input signals: the instantaneous voltage across the load terminals and the instantaneous current. There are commercial devices, [10], capable of doing the same measurements, but at the time of experimenting, those equipments were not available.

The proposed device is based on a programmable digital signal processor (in dsPIC33F family), who performs both analog-digital conversion and writing the output values on a digital data storage support (micro SDCard). The overall structure of the device is shown in the Fig. 2 and the blocks can be identified on the physical circuit represented in Fig. 3.

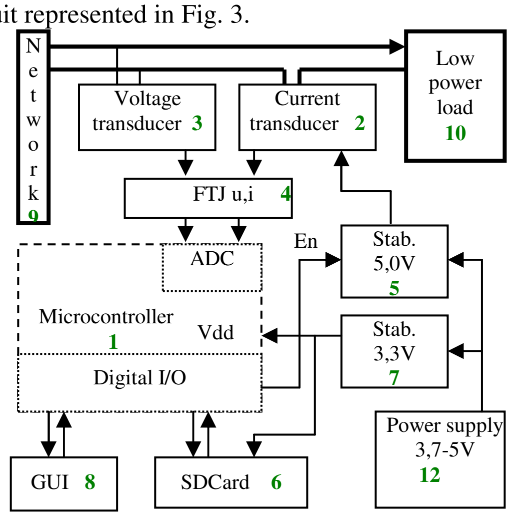

Fig. 2. Structure of the DATALOG circuit

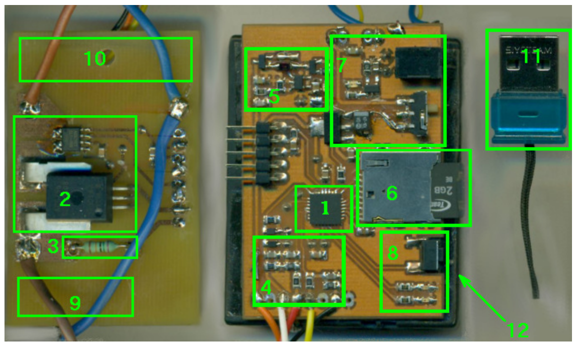

Fig. 3. Physical aspect of the DATALOG

The current transducer is obtained with a specialized Hall sensor, ACS712, which offer a sensitivity of 185mV/A, for currents up to ±12.9A, with linearity better than 0.5%. The output of the current transducer is fed to the 12 bit Analog to Digital Converter (ADC) of the signal processor, resulting a total sensitivity of 26mA/bit.

The voltage transducer consist in a simple resistive divider, that adapts the input domain of ±365V to the accepted domain of 0…3.3V for the ADC. The total sensitivity for the voltage path is 0.71V/bit.

Given the fact that the voltage transducer is connected to the mains during acquisitions, the datalog circuit is powered with isolated battery (4.2V – one standard Li-Ion battery) and no conductive parts may be touched during data logging.

For both transducers, the sampling frequency can be imposed at any value between 1 and 100 kHz, keeping in account that only one buffer of 2 x 3590 numerical values (12 bit each) can be acquired "in a single shot". During experiments, a sampling rate of 4kHz for was useful for start-up regime, and a 89kHz was used to observe the harmonic content of the signals.

Using the Datalog device was observed that the grid voltage distortions are variable in time, even in the same node as presented in Fig. 4.

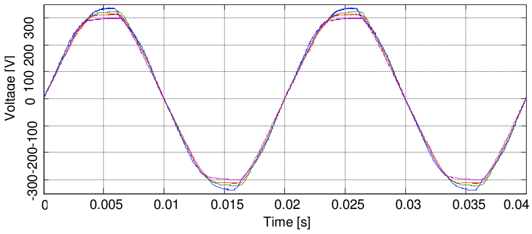

Fig.4. One phase grid voltage, at various times

By processing the most deformed curve in Fig. 4 using Matlab, the following harmonics were revealed:

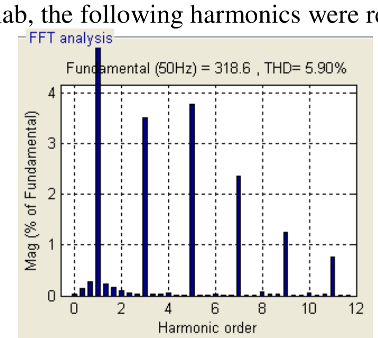

Fig. 5. Harmonics content of the grid voltage

In none of the analyzed cases, the THD (Total Harmonic Distortions) of the grid was lower than 2%, most of the time varying between 3 and 6%.

3. LOW POWER, NON-LINEAR AC SINGLE PHASE LOADS

3.1 Low power, switching mode power supplies are used in large amount among electronic devices that needs a constant voltage DC supply: from mobile phone AC adapters, to PC or TV receivers. The following analyzed devices were: notebook AC adapter, a group of 4 desktop PCs (from a small office), TV receivers, CFL bulbs (that are constant current devices, but the power quality behavior is the same).

Study as early as 1995, [11] has shown the high amount of current harmonics induced in the grid by PC power sources. Even if the circuit needed to compensate the power factor implies using three additional power components and a control circuit, Fig. 6b), the majority of present PCs still use the cheaper circuit from Fig. 6a):

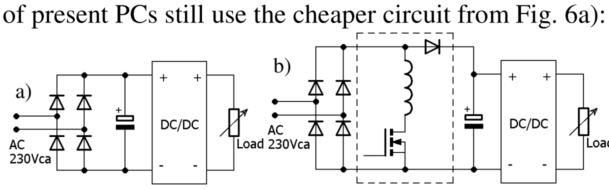

Fig. 6. AC/DC rectifier in PC power supplies a) with no power factor corrector (PFC), b) with PFC block

For a portable PC, the AC adaptor needs to be as light as possible, but still able to output the required active power. Because nominal power is low (<100W), the PFC circuit and high frequency filters are absent and the DC smoothing capacitor is of low capacity. This allows for the removal of the current limiter thermistor, generating the signals in Fig. 7.

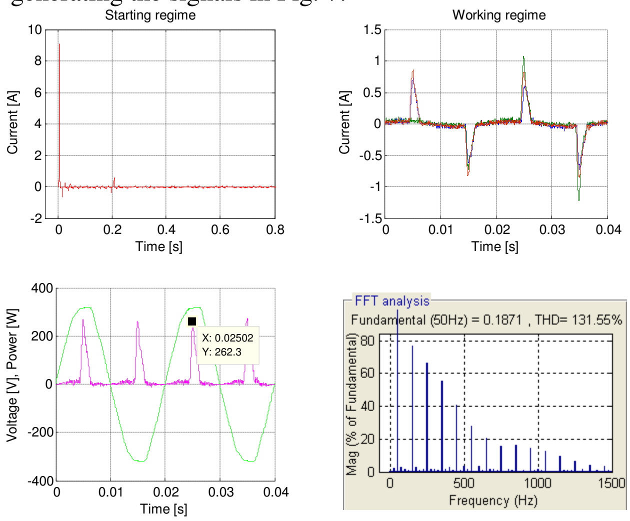

Fig.7. Signals of interest for a notebook AC adapter

No current limiter in the input circuit generates a high inrush current at the moment of inserting the plug in the outlet, electro-magnetic interference and a high popping noise together with the melting of small parts of the plug and outlet pins. During normal operation, the shape of the current is highly distorted, with step transitions denoting a very high value of the total harmonic distortion (131% in Fig. 7d). The mean active power is only 30W, but the instantaneous value oscillates between 0 and 262W, Fig. 7.c).

A simplified model for the notebook AC adapter, Fig. 8a) was tested in simulation and found to be accurate, Fig. 8b):

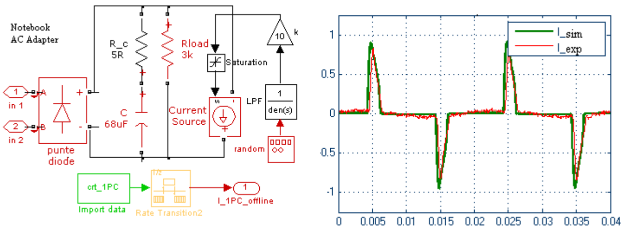

Fig. 8. a) Simulation model for notebook AC adapter, b) Comparison between experimentally measured current and the simulated one

A PC desktop uses up to 10 times more power during normal operation than the portable one. In office buildings, each room contains many workstations, each one permanently connected to the grid. Inrush current is thus much less problematic because it will appear only sporadically, usually after grid blackout or prolonged holydays (when all the systems are disconnected from grid).

Fig. 9 presents the signals associated with a modern PC with 3GHz processor, 7200RPM hard drive, DVD Writer and 19 inch display.

Multiple measurements of the input current Fig. 9b), shows that the active power varies strongly dependant of the usage, the current waveform is smoothed out and the

THD is between 90 and 100%, Fig. 9.d).

The mean active power is close to 100W, but the instantaneous value peaks 540W, Fig. 9.c).

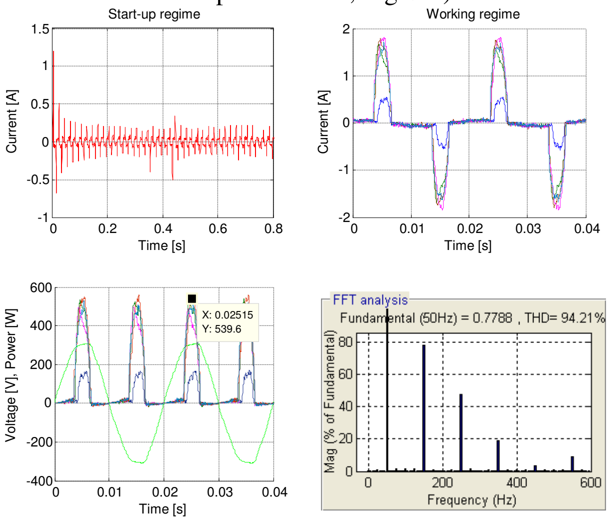

Fig. 9. Signals of interest for a desktop PC power supply

A group of 4 desktop PCs from an office were connected in the same outlet and the total current was measured. To simplify the simulation, the group was considered as a single nonlinear load, with the same internal simplified schematic as each individual PC. The values were summarized and the circuit in Fig 10 was obtained, simulated and found to approximate the experimental signals with minimal error. *Rseries* represents the inrush current limiter (a low value thermistor), the R_C represents the series resistance of the DC capacitor and the load is simulated with a fixed 130Ω resistor and a “random” current generator. The input C-L-C filter is used to filter high frequency noise from the internal inverter and generates a small hysteresis in the input current, as in Fig. 9b) and Fig. 10b).

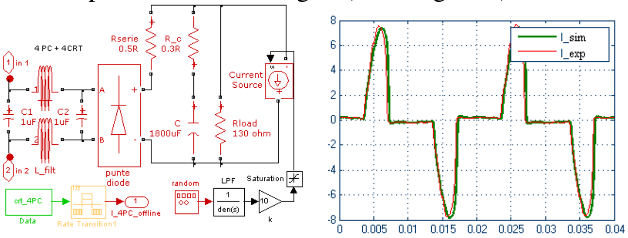

Fig. 10. a) Simulation model for a group of 4 PCs, b) Comparison between experimentally measured current and the simulated one

A Fujitsu-Siemens workstation was available and also tested. It was found to contain a PFC circuit, active during normal operation. During stand-by, the current drawn from the grid has the same shape as the previous analyzed nonlinear adapters – red wave in Fig. 11b).

From power quality concerns, the advantages of the PFC circuit are obvious: no phase difference between grid voltage and current, active power without instantaneous overvalues and negligible current harmonics injected in the grid. THD of 12% resulted mainly because the current is the lowest between all tested circuits, with values close to the signal-to-noise ratio of the measuring circuit.

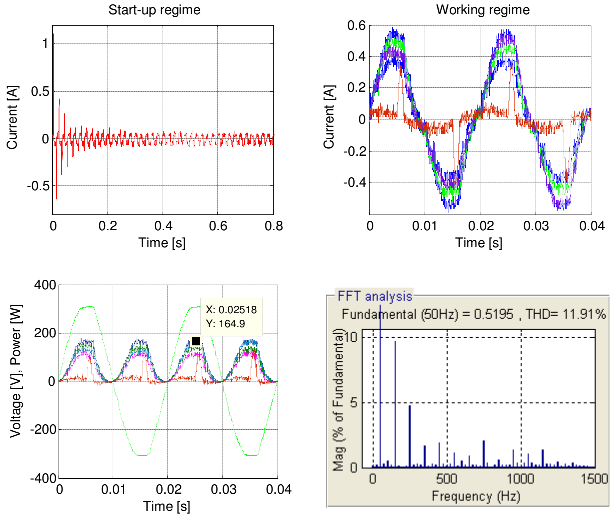

Fig. 11. Signals of interest for a PC power supply with power factor correction circuit

TV receivers are usual devices in every home. Old receivers used cathode ray tubes (CRT) and a complex power supply with energy recovering loops. Modern ones use LCD or plasma tube, fact that transforms the internal electronics towards digital signal processing, close to the structure of the PC. This way, the power supply is also simplified, resembling to those already presented.

Fig. 12 presents the signals for a 21 inch CRT TV receiver in two situations: stand-by and power-up. It is easy to conclude that the power supply still has the structure of an uncontrolled rectifier with smoothing capacitor at the output. The instantaneous power is 5 times bigger than the mean value, stand-by power is about 8W and the harmonic content of the current presents components up to the 11’th harmonic.

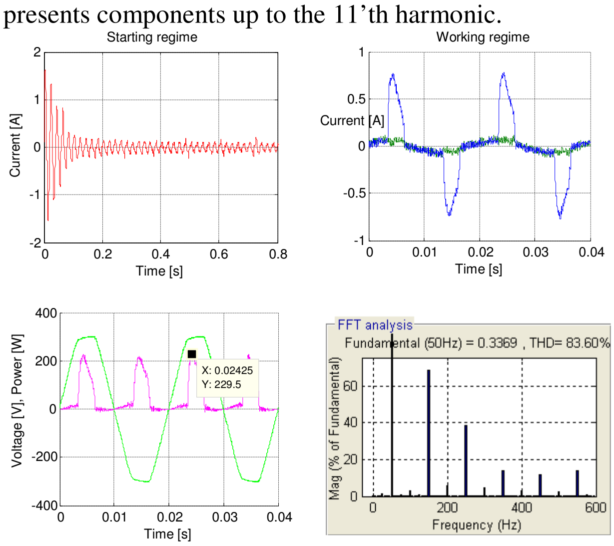

Fig. 12. Signals of interest for a CRT TV receiver

Another device in the same category of nonlinear AC loads is the compact fluorescent lamp (CFL) It is extensively studied in [12] and [13]. To replace a 75W incandescent bulb a 26W CFL is normally used to obtain the same quantity of light.

A cheap CFL induces in the grid current harmonics up to 25th order, as seen in Fig. 13, with THD for current up to 90%.

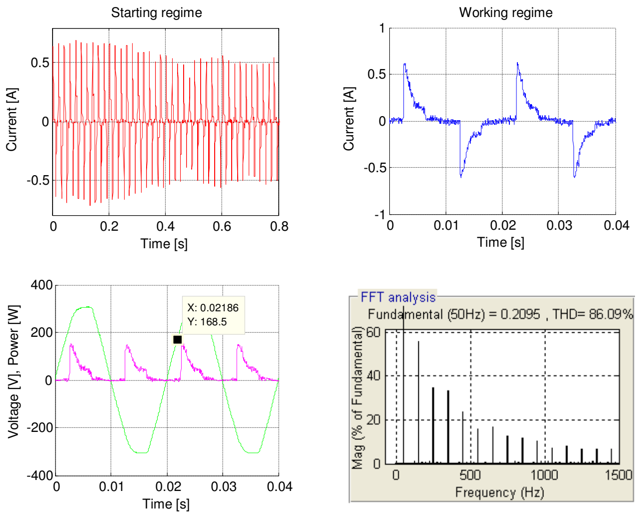

Fig. 13. Experimental signals for 26W CFL

A simulation model was also created starting from the known internal structure of the lamp. Only 4 components need to be dimensioned:

- *Rserie* represents the series resistor often used as fuse and startup current limiter;
- *R_cap* represents the series resistance of the capacitor;
- *C* represents the DC capacitor value;
- *Rload* describes the active power of the lamp.

Fig. 14 presents the proposed simplified circuit and the comparison between experimental measures current and the simulated one. Voltage waveform used in simulation is the one recorded from the real grid.

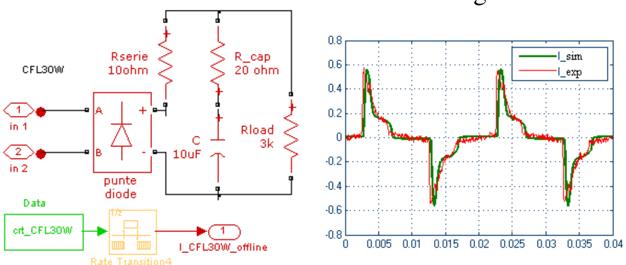

Fig. 14. Simulation model and comparison between simulation and real current waveform

3.2. Classical fluorescent lamps are still largely used because of the good reliability. When new, such lamp will generate negligible power quality problems because the filtering capacitor will compensate the inductive reactance of the current limiting inductor. In time, capacitor dries out and inductive power is generated in the grid. The Fig. 15 presents the instantaneous variations of the voltage, current and power for such device. Note the relatively low THD current value but the negative values for the instantaneous power, fact that denoted the reactive power injected in the grid.

In Fig. 16 is presented a simple simulation model is enough to estimate the behavior of these lamps.

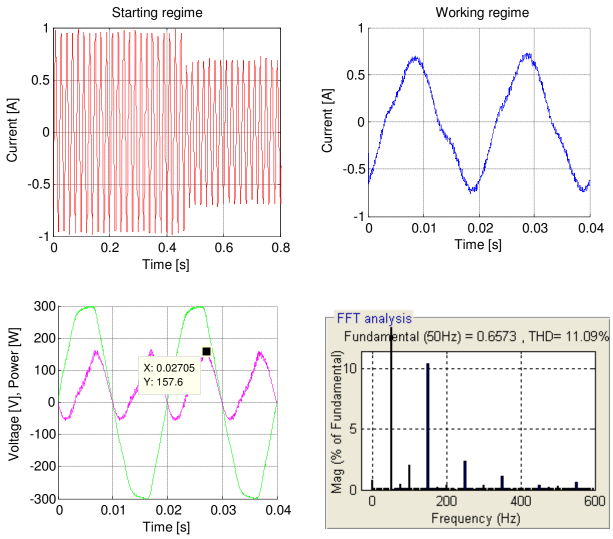

Fig. 15. Experimental signals for a 40W classical fluorescent lamp

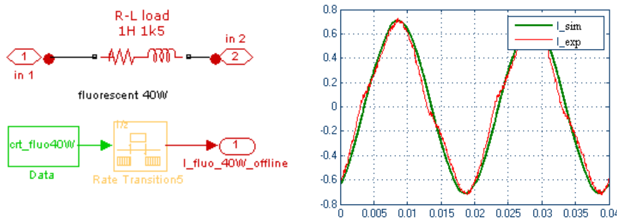

Fig.16. Schematic and comparison with experiment for the classical fluorescent lamp

3.3. Refrigeration units are another class of electronic equipment in residential area. The electrical part consists in a single phase AC motor, controlled by a thermostat. Experimental analyzes in Fig. 17, realized for two different brands, denote the fact that both reactive power and harmonic contents are still injected in the grid. Active power for such a unit is around 120W, current is almost sinusoidal and ahead of the voltage and at each start of the engine the current is 10 times bigger than the nominal one (10A versus 1A):

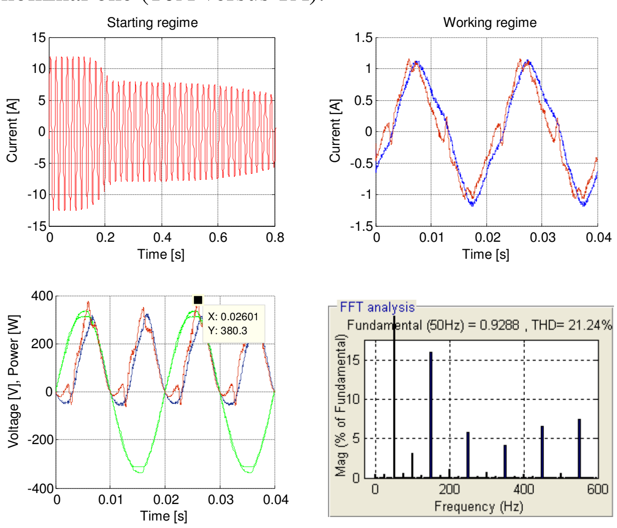

Fig. 17. Experimental signals for two refrigerators

An accurate simulation model for such device should keep in account the internal structure of the AC motor. This information is rarely available, so a model based on mimicking was adopted, as one can see in Fig. 18a). The current waveform is recorded in Matlab workspace and played in infinite loop synchronous with the reference voltage.

This way it is possible to use any current shape in Matlab / Simulink environment, but the cause-effect link between simulation voltage and current needs to be verified.

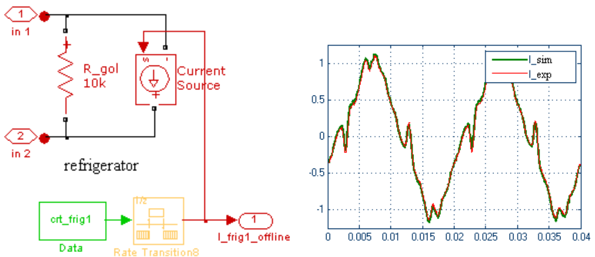

Fig.18. Simulation model and comparison with experimental signals for a refrigerator

Equipments with similar internal structure are air conditioning units and other devices with electro-mechanical compressor.

5. CONCLUSION

There are a great number of electronic devices of low power for which implementing a power factor correction circuit is not economically feasible. A power factor corrector or active power filter can be used for groups of pollutant loads, for example one for every building.

The Datalog circuit that was build and used to analyze the nonlinear character of household electric devices offer enough precision to discover harmonics up to 30th order for grid voltage and current. The acquired signals are available for offline processing in Matlab workspace and can be used in the simulation of the whole system.

During experimental analysis of the usual household AC loads proved to have strong non-linear behavior in terms of power quality.

Simplified simulation models were proposed and verified through Matlab simulation, and found to be fast and accurate enough to be used in large simulations.

The results obtained through simulations are comparable to experimental ones, due to the fact that the same voltage waveform was used both in experiment and simulation.

Other devices to be further analyzed for a greater characterization of the nonlinear loads are: dimmer with angle firing triac - used from desktop lamps to vacuum cleaners, conditioned air units – that have multiple working points, induction cooker, and washing machine.

The results presented in Table 1 shows the pollutant character of the experimentally analyzed AC loads, fact that imposes measures to improve the power quality in low power distributed systems, e.g. by using active power filters as the one presented in Fig. 1.

Table 1. Household electrical loads characteristics

	THDi [%]	Harmonic order ['th]	Active power [W]	Obs.
Portable PC	80-130	3, 5,... 25	30	Rectifier + C
Desktop PC	80-100	3, 5, 7, 9, 11	150	Rectifier + C
CFL bulb	86	3, 5, ... 25	30	Rectifier + C
Fluorescent tube	11	3, 5	46	Reactive power
Refrigerator	21	3, 5, 7, 9, 11	100	Reactive power

ACKNOWLEDGEMENT

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