The influence of home nonlinear electric equipment operating modes on power quality

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Abstract: - The proliferation of nonlinear electronic loads is increasing day by day, and it can anticipate an influx of newer technologies in this domain in the future. This article focuses on the impacts of various home nonlinear electric equipment on the power quality of electrical distribution system. It was studied the influence of operating mode on the harmonic pollution generated by nonlinear home appliances operating in an isolated mode, using the *CA 8334B* three-phase power quality analyzer. Although home electric appliances are low power receivers, the cumulative effect produced by a large number of small harmonic sources can be substantial.

Key-Words: -disturbances, harmonics, nonlinear equipment, operating mode, power quality

1 Introduction

Harmonic distortions are the major cause for power quality problems [1, 2].

In recent years many studies have as subject the power quality problems caused by nonlinear loads on the electric power grid. When fed directly from the utility power system, nonlinear loads generally have non-sinusoidal harmonic currents [2].

Power electronics equipment, such as adjustable speed drives, controlled rectifiers, cyclo-converters, arc furnaces, induction heating equipment,electronically ballasted lampsand clusters of personal computers, represent major nonlinear and parametric loads proliferating among industrial and commercial customers [3-16]. In addition, the proliferation of nonlinear home electric appliances is increasing day by day.

Nonlinear loads have the potential to create disturbances for the utility and the end-user's equipment. Non-sinusoidal harmonic currents can lead to significant line voltage distortion [17-21]. Also, harmonics can interfere with control, communication or protection equipment, causing energy meter inaccuracy, additional losses and decreasing the equipment lifetime. Harmonic distortion degrades the power factor. The flow of non-active energy caused by harmonic currents and voltages became a great problem today [1, 2,17].

Home electric appliances, although they are relatively low-power receivers, summed can represent an important source of harmonic distortion, because it can be used at the same time a large number of receivers over long periods of time.

For example, measurements carried out on a sample of 50 power substations in France during one day, show that the highest rate of 5^{th} voltage harmonic order is, in general, between 12-14 hours and 20-22 hours, due to home nonlinear electric equipment [22].

During the last years large numbers of compact fluorescent lamps (*CFL*s) penetrate the market place. *CFL*s provide significant energy saving comparable with incandescent lamps. But, *CFL*s create harmonics on the supply system because of the control systems limiting the plasma current, which produces light [17, 23]. Electronic ballast has a switched mode power supply (*SMPS*) to convert the fundamental frequency to a higher frequency, usually around 25-40 *kHz* [24]. A small inductor is also used in the electronic type to limit the current.

Several studies reveal that the distortion level depends on the type of *CFL* used and the distribution parameter. The currents distortion for the *CFL* may be very high, even when *CFL* is 10% of the total load, can result an unacceptable voltage distortion at the point of common coupling (*PCC*) [23, 24].

Within the next 10 years the displacement of *CFL*s by solid state lamps (*SSL*s) is most likely. Also, electric vehicles are expected to be part of distribution systems at a massive scale. Therefore, the study of harmonic pollution must predict the impact of new power electronic equipment in the electric power grid, because the harmonic distortion may become critical.

When several identical loads share the same source impedance may appear the effect of attenuation, consisting of reduction in harmonic magnitude, and change in phase angle. The effect of diversity describes a reduction, or even cancellation of harmonics due to loads of different levels, or connected through different impedances, presenting differing phase angles to the supply [25, 26].

This article presents the influence of operating mode on the power quality disturbances of home nonlinear equipment, especially harmonic pollution. It was studied the impacts of various home nonlinear electric equipment operating in an isolated mode. Further study is required to establish the impacts of these loads operating together.

2 Laboratory measurements

In order to comply with *EMC* standards the end-users have to guarantee current absorptions with adequate power factor (*PF*) and reduced harmonic current [1, 2]. An inadequate *PF* (lower than neutral value) increase very much the power losses in the distribution grid, the voltage drop and the voltage distortion [2].

Typical nonlinear home appliances contain electromagnetic devices, such as motors and transformers (e.g. refrigerators and air-conditioning devices). The current distortion depends on the motor's design and varies with the voltage level. These nonlinear loads should be modeled by harmonic current sources [18, 19].

Other nonlinear loads should be modeled by harmonic voltage sources. Among such loads are diode rectifiers with capacitive output (*DC*) filters, which are the usual interface between electronic loads and the *AC* feeder. This kind of circuit (*SMPS*) is present in almost all residential and commercial nonlinear loads, such as computers, monitors, TV sets, electronic ballasts for fluorescent lamps, battery chargers, etc. [19].

The laboratory measurements were made using a power quality analyzer *CA 8334B*. To measure the current was used current probes *MN 93A* (5 *A* and 200 *A*) [27].

The main parameters measured by *CA 8334B* analyzer were: *True RMSAC* phase voltages and *True RMSAC* line currents; peak voltage and current; active, reactive and apparent power per phase; power factor, displacement power factor; harmonics for voltages and currents up to the 50th order; Fresnel diagrams.

Below are presented the results of measurements for the following home nonlinear equipment: refrigerator, microwave oven, induction heat plate, personal computer, laptop, laser printer,air-condition device, compact fluorescent lamps, operating in an isolated mode.

2.1 Refrigerator

In the laboratory measurements was used a low-power refrigerator.

Fig.1 shows the supply voltage and current from a refrigerator. Voltage waveform is very close to the sinusoidal; this is confirmed by harmonic spectrum from Fig.2, total harmonic distortion (THD_U) of supply voltage being 4.9%, according to *EMC* standards [28, 29].

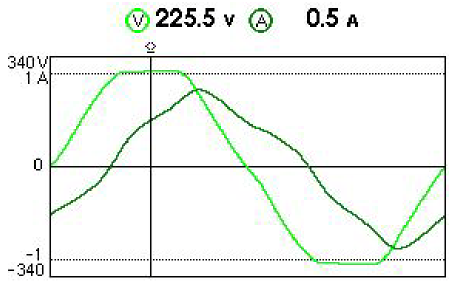


Fig.1 Refrigerator's voltage and current.

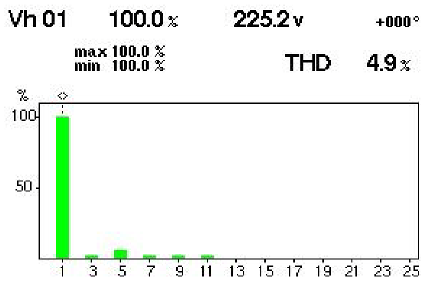


Fig.2 Harmonic spectrum of supply voltage.

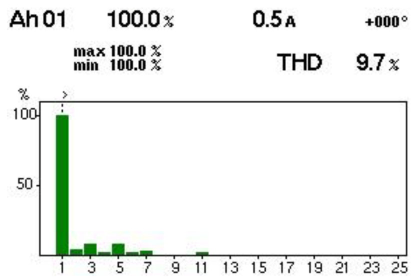


Fig.3 Harmonic spectrum of refrigerator's current.

THD of the refrigerator current is 9.7% (Fig.3), and exceed the compatibility limits. Also, the 3rd and 5th harmonics exceed the compatibility limits.

In the case of refrigerator, the average value of power factor*PF*(defined as ratio of the active power to the apparent power) is very poor (PF_{avg}=0.57, maximum value being PF_{max} =0.679).

Also, displacement power factor *DPF* (defined as the cosine of the angle between the fundamental components of the voltage and the current) is very small and approximately equal to *PF* ($DPF_{avg}=0.573$ and $DPF_{max}=0.685$). This indicates a very high reactive power consumption and relatively low harmonic current distortion.

2.2 Microwave oven

2.2.1 No-load operation

When microwave oven operating without load, the supply voltage is very close to sine wave; THD_Udoes not exceed the compatibility limits (Figs.4, 5). Operation time was 30 *s*.

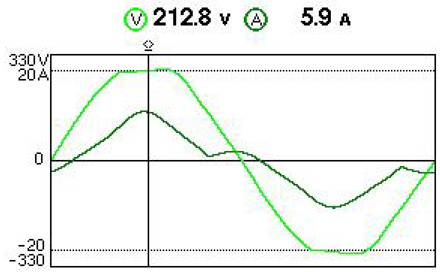


Fig.4 Microwave oven's voltage and current (no-load operation).

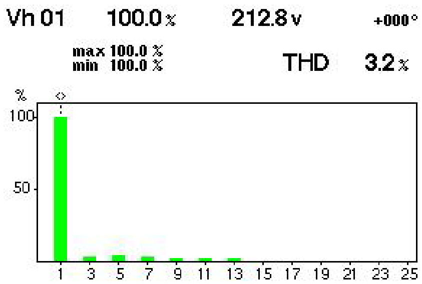


Fig.5 Harmonic spectrum of supply voltage.

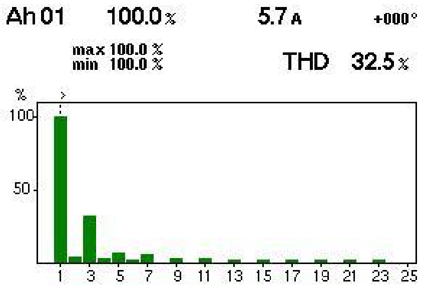


Fig.6 Harmonic spectrum of microwave oven's current (no-load operation).

The current waveform from microwave oven in no-load operation is highly distorted as compared to ideal sine wave and has a THD_Ivalue of 32.5 *%*. The 3rd, 5th, 7th harmonics have values higher than the maximum standard values.

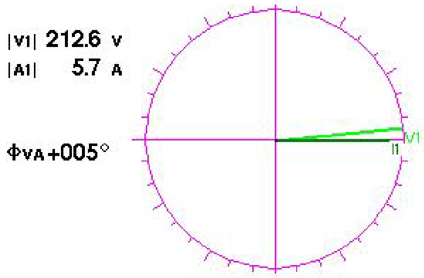


Fig.7 Fresnel diagram for voltage and current (microwave ovenno-load operation).

Fresnel diagram (Fig.7) indicates the inductive nature of microwave oven and a very small phase angle deviation (5°) between voltage and current is present. Therefore power factors are very good and exceed the neutral value (*PF=0.951* and *DPF=0.999*). The difference between *PF* and *DPF* indicates a large deviation from sinusoidal waveform of current.

2.2.2 Load operation

Measurement results when microwave oven was in load operation are presented in Figs.8, 9 and Table 1. Operation time was 30 *s*.

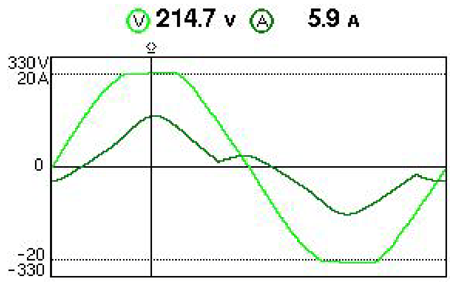


Fig.8 Microwave oven's voltage and current (load operation, 4 pancakes).

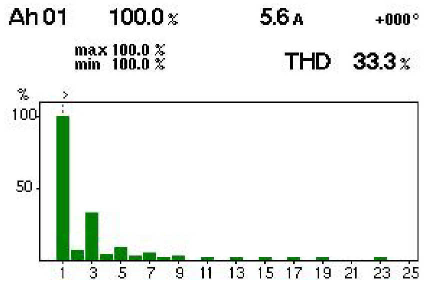


Fig.9 Harmonic spectrum of microwave oven's current (load operation, 4 pancakes).

It is found that microwave load influence very little its operation (Table 1). When the oven load increases, the current and voltage harmonic distortions slightly increase, and power factors slightly decrease.

In all situations $THD_I$and 3rd, 5th, 7th harmonics levels exceed the compatibility limits, but THD_U is small; powers factor exceed the neutral value.

Table 1 - Load operation of microwave oven

Load	THD_U [%]	THD_I [%]	*PF* [-]	*DPF* [-]
1 pancake	2.9	30.8	0.95	0.999
2 pancakes	2.9	31	0.948	0.997
4 pancakes	3.2	33.3	0.928	0.985
mashed potatoes	3.3	33.2	0.932	0.987
empty vessel	3.2	30.4	0.952	0.997

2.3 Induction heat plate

The loads of induction heat plate were two steel kettles with different amounts of water. The first kettle had a base diameter of 8 cm; the second kettle (stainless steel) had a diameter of 12 cm.

2.3.1 Load operation

Figs. 10-17 and Table 2 present the results of measurements for an induction heat plate at various loads. Active power was set at 1600 *W*.

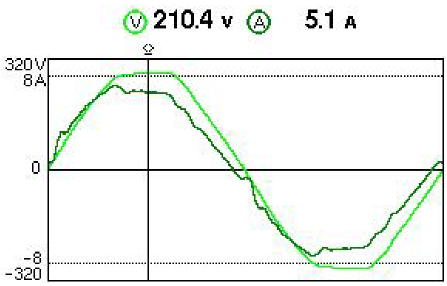


Fig.10 Induction heat plate's voltage and current(load operation,first kettle, 470 *ml* water).

Supply voltage and current are very close to sine wave when induction heat plate has the first steel kettle with 470 *ml* water as load. Total harmonic distortions are very small (THD_U=2.6 %,THD_I=6.2 %); all harmonics have values smaller than the maximum standard values.

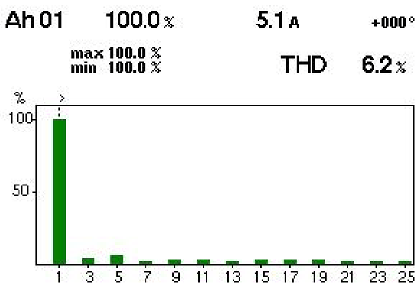


Fig.11 Harmonic spectrum of induction heat plate's current (load operation, firstkettle, 470 *ml* water).

Fresnel diagram (Fig.12) shows the capacitive nature of induction heat plate and a small phase angle deviation (10°) between voltage and current is present. Power factors exceed the neutral value (*PF*=0.985, *DPF*=0.986), and are approximately equal (due to low harmonic distortion of current and voltage).

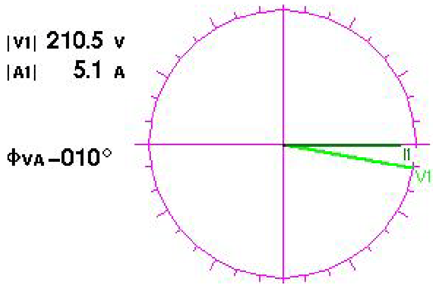


Fig.12 Fresnel diagram for induction heat plate's voltage and current (load operation, first kettle, 470 *ml* water).

Fig.13Induction heat plate's voltage and current (load operation, secondkettle, 470 *ml* water).

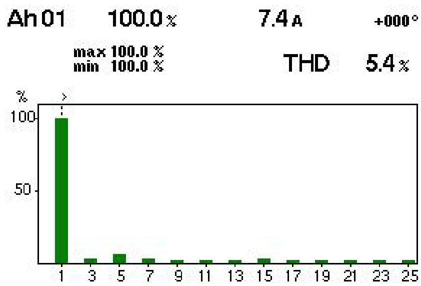


Fig.14 Harmonic spectrum of induction heat plate's current (load operation, second kettle, 470 *ml* water).

Figs. 13, 14 show that although stainless steel kettle (12 *cm*) had the same amount of water as that of steel (8 *cm*), the current (*RMS* value) from induction heat plate is much higher than in the previous case (7.4 *A*). Total harmonic distortion of the voltage increases slightly, but in the case of current decreases (THD_U=2.8 %,THD_I=5.4 %). It also decreases the phase difference between voltage and current (6°), and power factors are higher than in the previous case (*PF* = 0.993, *DPF* = 0.994).

In conclusion, the load of the induction heat plate depends on cooking vessel and does not depends on vessel's contents, which is evident by Table 2.

In Table 2 the load was stainless steel kettle (12 *cm*) with various amounts of water. Content of the kettle influence insignificant the induction heat plate's current, active, reactive and apparent powers (*P*, *Q*, *S*), THD_U, THD_I, *PF* and *DPF*.

Table 2 - Load operation of induction heat plate

Stainless steel kettle	940*ml* water	705 *ml* water	470*ml* water	235*ml* water
P [*W*]	1550	1553	1549	1547
Q [*VAR*]	179	179	179	179
S [*VA*]	1564	1556	1559	1558
PF [-]	0.993	0.993	0.993	0.993
DPF [-]	0.994	0.994	0.994	0.994
THD_U [%]	2.8	2.8	2.8	2.6
THD_I [%]	5.4	5.4	5.4	5.3
t [*s*]	150	110	70	42

Table 2 shows the great efficient of induction heat plate, time required for boiling water (*t*) in each case being very small.

2.3.2 Stand-by operation

Although the induction heat plate at load operation is compatible electromagnetic, after pressing stop switch (stand-by operation) it was find a pronounced distortion of the current (Figs.15, 16).

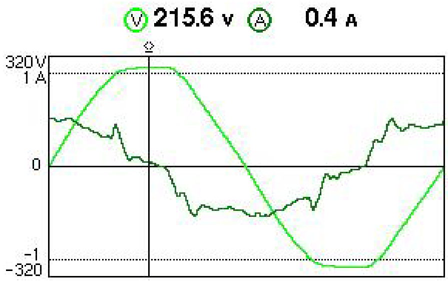


Fig.15 Induction heat plate's voltage and current (stand-by operation).

In stand-by, the harmonic distortion of supply voltage remains very low (THD_U=2.6 %), but THD_Ihas a high value, equal to 17.7%; 3rd, 5th, 7th, 9th, 13th, 15th, 17th, 19th, 21st, 23rd, 25th current harmonics breaching the standard limits. Active, reactive, apparent powers and power factors in stand-by operation were: *P*=6.4 *W*, *Q*=82.2 *VAR*, *S*=22.5 *VA*,
PF=0.078, *DPF*=0.078.

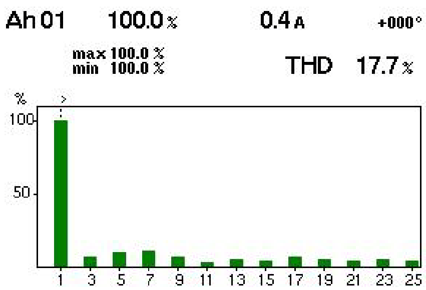


Fig.16 Harmonic spectrum of induction heat plate's current (stand-by operation).

2.4 Personal computer

Personal computers (*PC*s) impacts on power quality due to the using of *SMPS* for converting single phase *AC* into low voltage *DC* for supplying electronics devices [30].

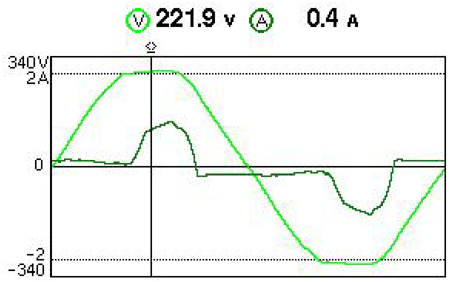


Fig.17 PC and monitor's voltage and current (idle mode).

Because the capacitor of *SMPS* is charged only during the peak of the voltage waveform, large current pulse appears in the current from *PC* at the peak of the voltage waveform [23].

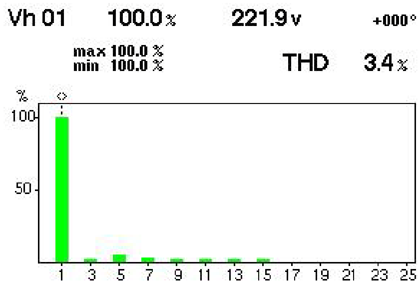


Fig.18 Harmonic spectrum of voltage supply (idle mode).

The current from *PC* (*Dell*) and *LCD* monitor is highly distorted (THD_I=91.5 %); 3rd, 5th, 7th, 9th, 11th, 13th, 15th, 17th, 19th, 21st, 23rd, 25th current harmonics exceed the standard limits (3rd harmonic level exceeds 80%). $THD_U$is in the acceptable standard limit, being equal to 3.4%.

Average values of active, reactive, apparent powers and power factors in idle mode of *PC* were: *P*=72.3 *W*, *Q*=66.2 *VAR*, *S*=98 *VA*, *PF*=0.738, *DPF*=0.993.

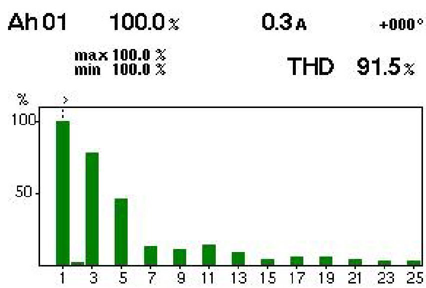


Fig.19 Harmonic spectrum of *PC* and monitor's current (idle mode).

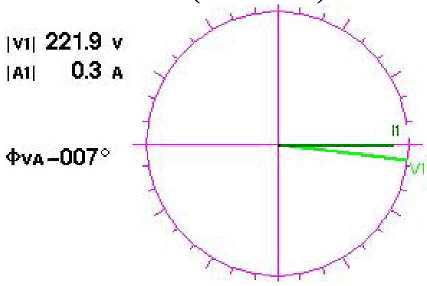


Fig.20 Fresnel diagram for *PC* and monitor's voltage and current (idle mode).

Fresnel diagram (Fig.20) indicates the capacitive nature of *PC* and monitor in idle mode operation.

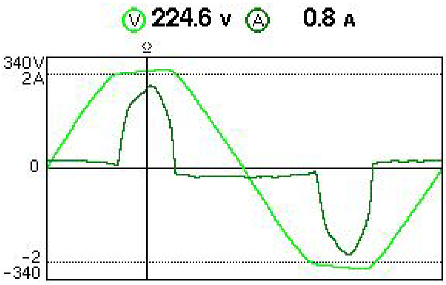


Fig.21*PC* and monitor's voltage and current (hard disk drive access).

Fig.21 shows the waveforms of *PC* and monitor's voltage and current when a small file is reading on local hard disk (*HD*). In this operational mode (*HD* drive access) the *RMS* value of current drawn by *PC* and monitor increases compared to idle mode operation.

Large concentrations of *PC*s are increasingly found in high density residential areas, offices, classrooms, etc. Several studies have shown that the current harmonics from a single *PC* differed considerably to the harmonics generated collectively by several *PC*s of the same type [31-33]. For example, when many *PC*s are operating in parallel from the same bus a significant reduction in line current harmonics may occurs (diversity effect).

2.5 Laptop

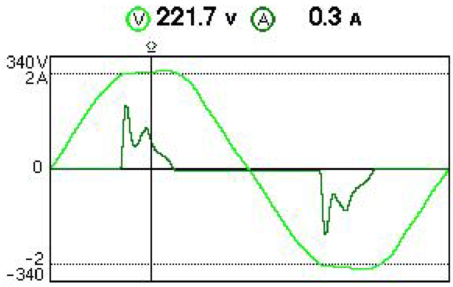


Fig.22 Laptop's voltage and current (charging mode).

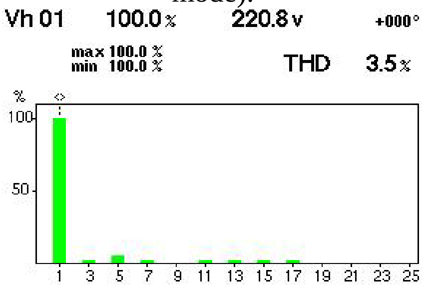


Fig.23 Harmonic spectrum of voltage supply (charging mode of laptop).

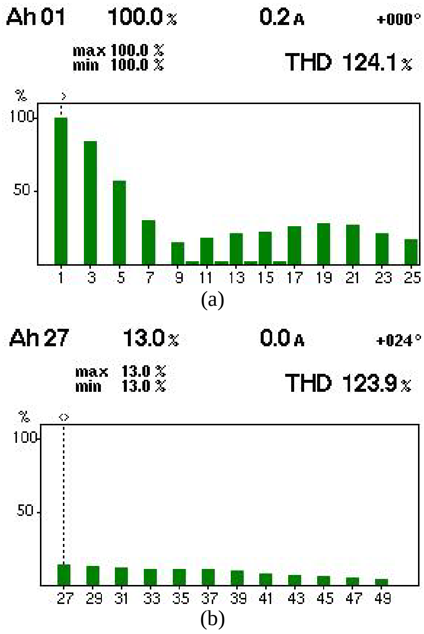


Fig.24 Harmonic spectrum of laptop's current (charging mode).

In the charging mode of laptop (*Lenovo*) THD_U is less the acceptable standard limit (THD_U=3.5%).THD_I has an alarmingly high value, equal to 124%.

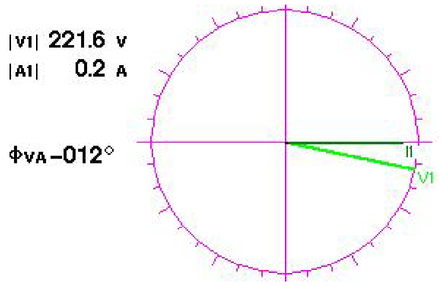


Fig.25 Fresnel diagram for laptop's voltage and current (charging mode).

In charging mode of laptop all odd harmonics of the current exceed the standard limits (3rd and 5th harmonic levels exceed 80%, respectively 60%).

Fresnel diagram (Fig.25) indicates the capacitive nature of laptop in charging mode. Average values of active, reactive, apparent powers and power factors in charging mode of laptop were: P=44.2 W, Q=59.1 VAR, S=73.8 VA, PF=0.598, DPF=0.976. Power factor is very small, less than neutral value.

In operating mode of laptop the *RMS* value of current increases compared to charge mode (Fig.26).

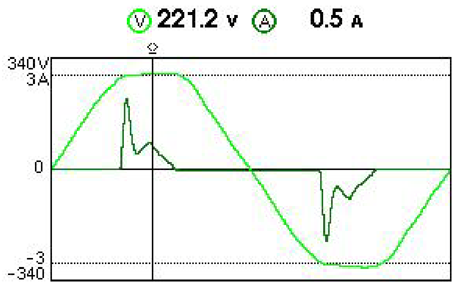
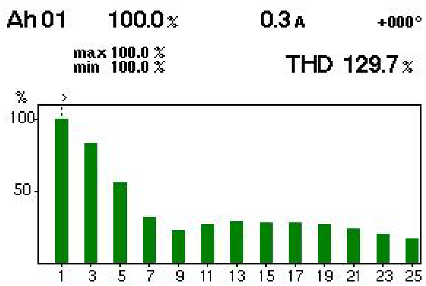
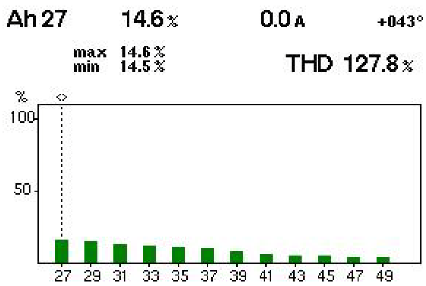


Fig.26 Laptop's voltage and current (operating mode).



(a)



(b)

Fig.27 Harmonic spectrum of laptop's current (operating mode).

Voltage waveform remains very close to the sinusoidal (THD_U=3.5%); THD_Iincreases even more compared to charging mode, being equal to 129.7%; all odd harmonics of the current exceed very much the standard limits in this case (Fig.27).

Average values of active, reactive, apparent powers and power factors in operating mode of laptop were: P=61.2 W, Q=89.9 VAR, S=108.9 VA, PF=0.563(capacitive), DPF=0.973. Power factors slightly decrease compared to charging mode. *PF* has an inadequate value. The large differencebetween *PF* and *DPF* indicates the highly distorted current drawn by laptop.

2.6 Laser printer

Figs.28-30 show that voltage supply does not exceed the compatibility limits in the idle mode of laser printer (THD_U=4.8%),but current waveform is highly distorted (THD_I=89.8%); all odd harmonics exceed very much the standard limits.

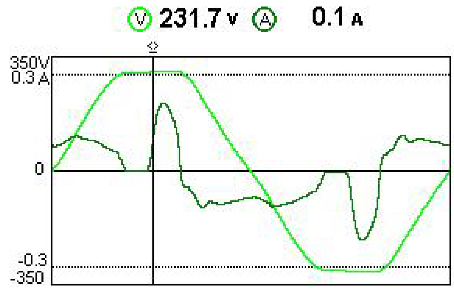


Fig.28 Laser printer's voltage and current (idle mode).

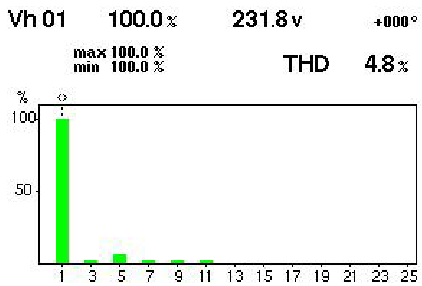


Fig.29 Harmonic spectrum of voltage supply (laser printer in idle mode).

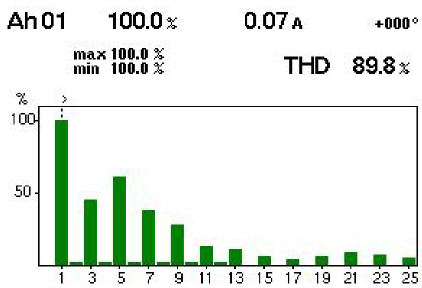


Fig.30 Harmonic spectrum of laser printer's current (idle mode).

3rd, 5th, 7th, 9th, 11th, 13th harmonics have very large levels: 45%, 60%, 37%, 29%, 14%, 12%.Average values of active, reactive and apparent powers in idle mode of laser printer were: P=73.4 W, Q=210.2 VAR, S=222.7 VA. Power factors are very small, less than neutral value(PF=0.329, DPF=0.441).

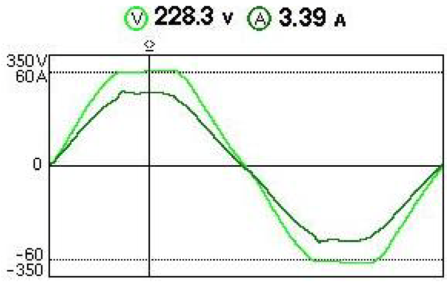


Fig.31 Laser printer's voltage and current (printing mode).

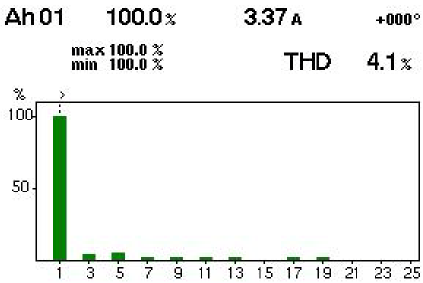


Fig.32 Harmonic spectrum of laser printer's current (printing mode).

Supply voltage and current are very close to sine wave in the printing mode. In this mode the printer works as a resistive load. Voltage and current distortions are within the acceptable standard limits in this case (THD_U=4.8%, THD_I=4.1%).

2.7 Air-condition device

Fig.33 Air-condition device's voltage and current (stand-by mode).

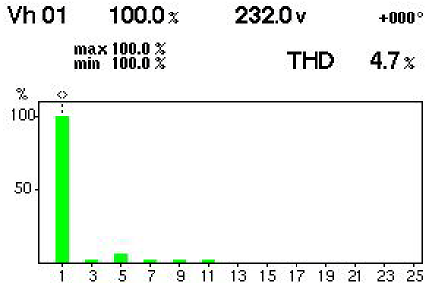


Fig.34 Harmonic spectrum of voltage supply (air-condition device in stand-by).

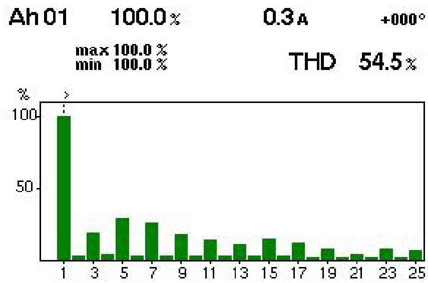


Fig.35 Harmonic spectrum of air-condition device's current (stand-by mode).

In stand-by mode of air-condition device

waveform of voltage supply is very little distorted (THD_I=4.7%), but current waveform is very high distorted (THD_I=54.5%). All odd current harmonics exceed the compatibility limits.

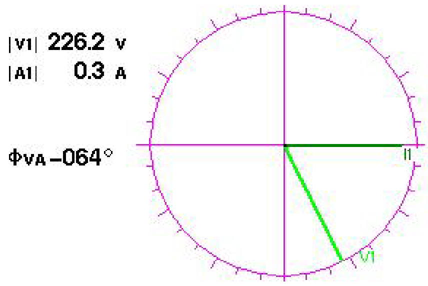


Fig.36 Fresnel diagram for voltage and current (air-condition device in stand-by).

Average values of active, reactive and apparent powers in stand-by mode of air-condition device were: P=121.4 W, Q=210.6 VAR, S=235.3 VA. Fresnel diagram (Fig.36) indicates the capacitive nature of air-condition device in stand-by mode. Power factor are very poor and less than neutral value(PF=0.516). The large difference between PF and DPF indicates the highly distorted current drawn by air-condition device in this case (DPF=0.941).

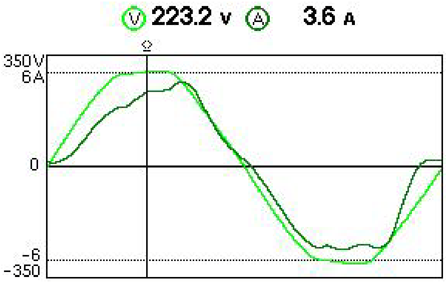


Fig.37 Air-condition device's voltage and current (heating mode).

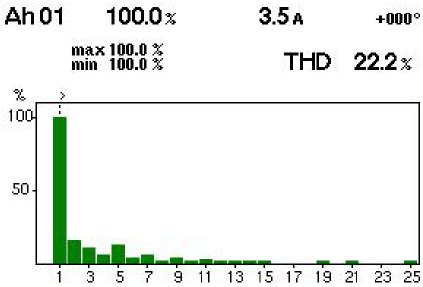


Fig.38 Harmonic spectrum of air-condition device's current (heating mode).

In heating mode of air-condition device waveform of voltage supply remain approximately sinusoidal (Fig.37); current distortion is significantly reduced in this mode of operation (Fig.38, THD_I=22.2%). Fresnel diagram (Fig.39) shows the inductive nature of air-condition device in heating mode, and a small phase angle deviation (4°) between voltage and current.

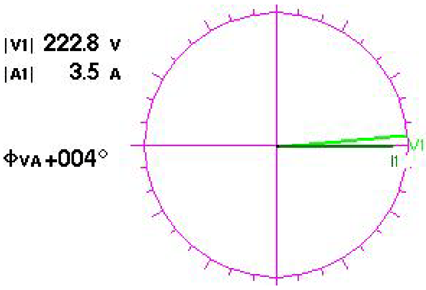


Fig.39 Fresnel diagram for air-condition device's voltage and current (heating mode).

2.8 Compact fluorescent lamps (CFLs)

Were analysed three CFLs with rated power of 15W (two CFLs) and 20W connected in parallel.

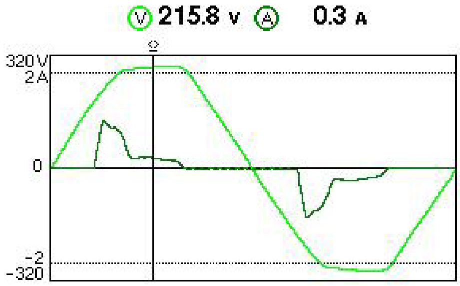


Fig.40 CFLs supply voltage and current.

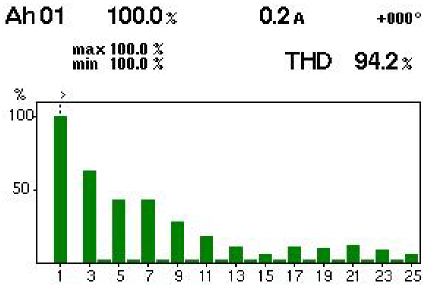


Fig.41 Harmonic spectrum of CFLs current.

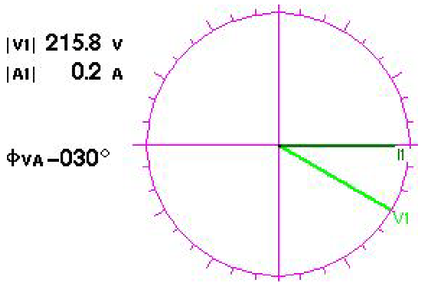


Fig.42 Fresnel diagram for voltage and current of CFLs.

Total current absorbed by CFLs is highly distorted (THD_I=94.2%); all odd harmonics of the current exceed the standard limits (3rd, 5th, 7th, 9th harmonic levels exceed 60%, 40% and 25%).

Fresnel diagram (Fig.42) indicates the capacitive nature of CFLs. Average values of active, reactive and apparent powers were: P=48.2W, Q=55.5VAR, S=73.5VA. Power factors are very small(PF=0.656, DPF=0.894), less than neutral value.

3 Conclusion

Most of the nonlinear electric equipment highly distorted current waveforms which produces high levels of harmonic distortions when connected to a distribution system.

*SMPS*is present in almost all home and commercial nonlinear loads, such as computers, monitors, laptops, electronic ballasts for fluorescent lamps, etc. From all house nonlinear electric equipment, these type of loads show the most current harmonic distortion.

SMPS's current has a significant amount of multiply 3rd harmonics order (3rd, 9th, 15th, etc.). Multiply 3rd order harmonics are zero sequence. These harmonics add algebraically through neutral conductor.

So, in three-phase power systems that have a neutral conductor and a large number of single-phase *SMPS* loads, even if the loads are balanced (on the three phases), will circulate an important neutral current, that can not be eliminated or reduced.

Current harmonic distortion is influenced by operation mode for almost analysed nonlinear loads, with the exception of the microwave oven.

Induction heat plate generates harmonics only in stand-by mode, the laser printer only in idle mode and the air condition devices, especially in stand-by mode. Due to the nonlinear electronics equipment show that harmonic voltage distortion is up 4.9 *%*.

In these conditions the following adverse effects may occur:

-losses in power transformer from power station may increase at 25%;

-available power of power station may be reduced by approximately 10-15%.

The cumulative effect produced by a large number of small nonlinear electric equipment (harmonic sources) can be substantial, because the total harmonic distortion current (THD_I) can reach up to 130% at the terminals of these electric loads, generating additional power and energy losses in electric networks.

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