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# HARMONIC CANCELLATION OF HYBRID LOADS IN RESIDENTIAL AND COMMERCIAL INSTALLATION

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## ABSTRACT

Nowadays, Non-linear loads are widely used in residential and commercial applications. This nonlinearity distort the drawn source current which injects harmonics to the electric grid. These harmonics negatively affect not only the electric grid at the point of common coupling but also affect the load itself in different ways. Harmonic currents limits are set by international standard IEC 61000 and IEEE 519 to protect the network from the high level of harmonics injected by the customer loads. These loads have low power like LED lamps, Computers, printers, TV sets, Florescent and incandescent lamps, however the residential and commercial loads represent above 70% of the total load supplied by the electric network. For this reason the overall impact on power quality indices of the network is negative.

As the loads are different in nature, the drawn current is different in terms of harmonic currents amplitude and phase shift. In some cases, this diversity may lead to natural harmonic cancellation for load combined together due to the diversity factor. By other word, Harmonic requirements for a specific load are supplied by another load connected together away from the supply leading to improved resultant source current with lower harmonic contents. In this research, power analysis for individual home appliance loads is carried out to assess and evaluate the nonlinearity nature of each load and also analysis conducted for combined or hybrid loads. Lighting lamps loads are assessed together with better power quality indices for the combination rather than the individual lighting loads. Similarly, all home appliance loads are combined together. The resultant power factor is improved and current THD is decreased due to the concept of diversity phenomena. Recommendations for the residential building electrical installation designer and load manufacturer are presented as a conclusion at the end of this paper.

**KEYWORDS**: Power Quality Indices, Total harmonic distortion, Diversity factor, distortion factor, Point of Common Coupling.

## 1. INTRODUCTION

Power electronic equipment has many applications in various residential and commercial buildings. Meanwhile, they are normally the main sources of power system harmonic distortion, which negatively affect the system. The residential and commercial loads represent 76% of Egyptian customers. The international standard IEC 61000-3-2 set the limits for harmonic currents for different types of loads. The injected harmonics affect the network in two ways; the first way is the effect on the voltage distortion of the voltage at point of common coupling; PCC affecting other neighboring loads. The second way is the effect on the load itself, increase losses in electric equipment and overheating.[1]-[7]. The loads investigated under this research are Computer, Fluorescent lamp; FL, LED lamp, Incandescent lamp, Fan, compressor of Refrigerator and TV set.

The remaining sections of this paper are organized as follows. Section 2presents the measured power quality indices for individual load stand alone to measure its own contribution for harmonic emissions and its unique fingerprint. This followed by power quality measurements for load combination in two steps; the first one hybrid lighting load, with combination of florescent lamp, LED and Incandescent lamp. The second step is combining all home appliance loads (lighting, Computer, TV, Compressor and Fan) to assess the overall effect of hybrid load of a typical home load combination. Section 3 presents the limitation of current harmonics set by IEC61000-3-2 Standard to evaluate individual load and the overall loads [8]- [9]. Section 4 outlines the analyzesfor the individual and the two hybrid loads measurements; lighting and all loads combination indicating the improvement occurred for the power quality indices resulted from hybrid load operation in both cases.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

Section 5 presents the conclusion and recommendations to obtain harmonic natural cancellation due to load mixing according to load diversity phenomena.

## 2. HARMONICS STANDARD

IEC61000 address the limits for small customers like the residential and commercial building to govern the maximum level of harmonics that can be injected by those customers which classified as class A, B, C and D [9]. The reason behind the concern of international organization to set these limits are the nature of nonlinearity of the electronic loads and the second reason is the high weight of those loads on the network, as the residential and commercial represent around 75% of the total loads on the network.

Table 1.3 represent the harmonic current limits for each individual harmonic order in terms of load level by the value of current/power in mA/W. and the value of harmonic current in A.

***Table 1. Limits for Class D Equipment***

| Harmonic order | Maximum Harmonic current per watt (mA/w) | Maximum Harmonic current (A) |
|---|---|---|
| 3 | 3.4 | 2.3 |
| 5 | 1.9 | 1.14 |
| 7 | 1 | 0.77 |
| 9 | 0.5 | 0.4 |
| 11 | 0.35 | 0.33 |
| 13 | 3.85/n | 0.21 |
| 15≤n≤39 | | 0.15*15/h |

## 3. HARMONIC MEASUREMENTS

Two measurements are taken in this research; the first one is the individual load measurement separately fed from the supply. The second one is the combined load measurements (Hybrid loads). Combined loads measurements are recorded for hybrid lighting load (Fluorescent, LED and Incandescent lamps) and other one for all loads together (lighting, TV set, Computer, Fan and Compressor). Actual measurement for home appliance have been recorded using HIOKI 3196 Power analyzer.

### 3.1 Individual load measurements:

To assess the load fingerprint and how much harmonics injected by this load and what is its contribution in the overall distortion, individual load power analysis are performed as follow:

#### *3.1.1 Florescent lamp*

Fig. 1 shows the voltage and current waveforms drawn by 40 watt florescent lamp. Phase angle between fundamental current and voltage is indicated in vector diagram Fig. 2 with lagging current. Figure 3 illustrate the harmonic spectrum of the drawn current with $THD_i$= 14.3%. Table 2 lists a summary for recorded power quality indices measured by the power analyzer.

Individual harmonic of both current and voltage are indicated in Figure 3. The distortion of the voltage at point of common coupling occurred due to the source current; $I_s$ distortion and the source inductance; $L_s$ as per the below equation:

$$V_{pcc} = V_s - (L_s.\ dI_s/dt) \qquad (1)$$

Where $V_{ppc}$ is the voltage at the point of common coupling, $V_s$ is the supply voltage.

It is noted that the voltage distortion is very low ($THD_v$ = 1.4%) due to the low current drawn by the florescent lamp and the low value of supply inductance. So the value of the ($L_s$. $dI_s$/dt) is small giving low voltage distorsion. But this distorsion will be increased at higher levels up to the distribution transformer.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

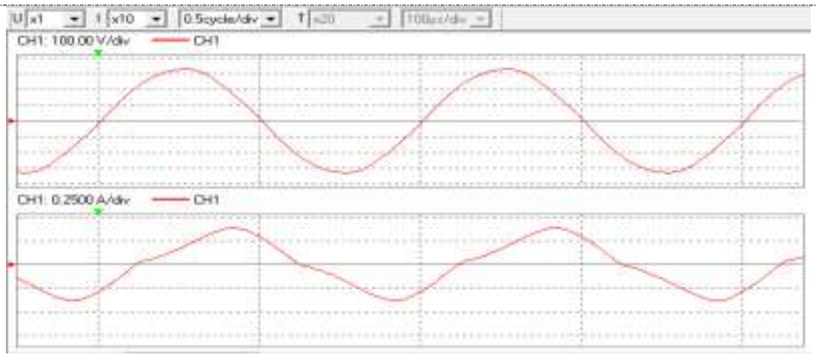


*Fig. 1 Voltage and current waveforms for F. Lamp*

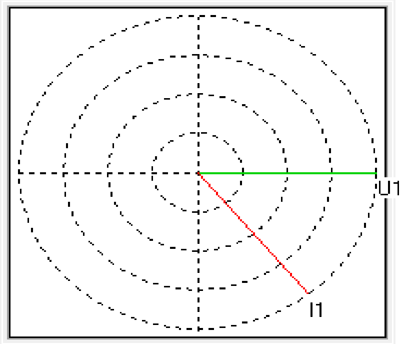


*Fig. 2 Vector diagram for F. lamp*

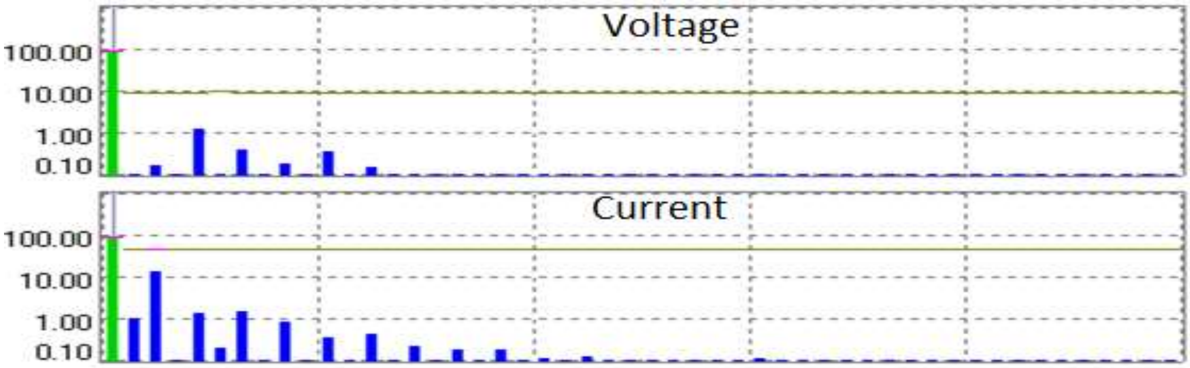


*Fig. 3 Voltage and current harmonic spectrum for F. Lamp*

*Table 2 Measured power quality indices for florescent lamp*

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 35 | U1 (V) | 232.5 | I1 | 0.24 |
| S1 (VA) | 56.7 | THD-U1 % | 1.40 | THD-I1 % | 14.3 |
| Q1 (VAR) | 44.6 | Upk+1 (V) | 328.8 | Ipk+1 (A) | 0.39 |
| PF1 | 0.62 | Upk-1 (V) | -329.0 | Ipk-1 (A) | -0.39 |

#### *3.1.2 LED lamp*

Figure 4 and 5 represent voltage/current waveforms and vector diagram for 13 watt LED lamp. Figure 6 shows the harmonic spectrum of the source voltage and current with $THD_i$= 141.8% with clear deviation against IEC standard. Table 3 lists the measured PQI's indicating poor power factor of 0.53.

From the previous measurements, it is very clear that the harmonic levels are exceeded above the IEC limits for LED and Fluorescent lamp.

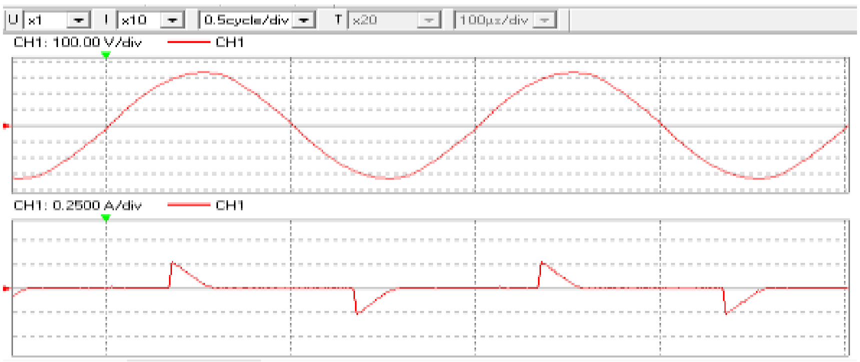


***Fig. 4 Voltage and current waveforms for LED Lamp***

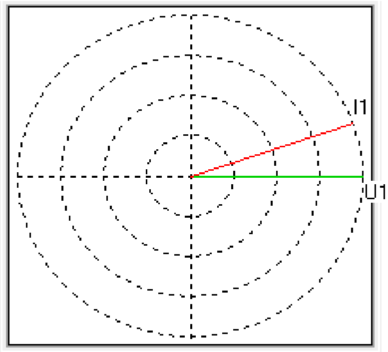


***Fig. 5 Vector diagram for LED lamp***

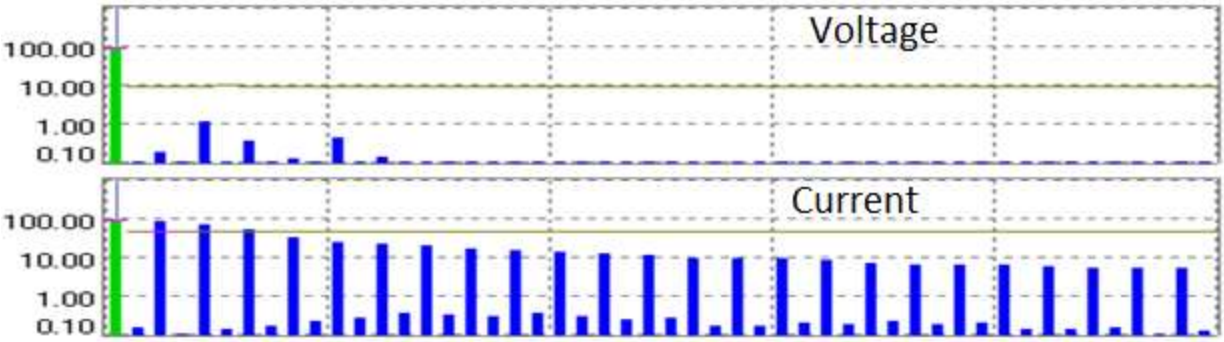


Fig. 6 Voltage and current harmonic spectrum for LED Lamp

***Table 3 Measured power quality indices for LED lamp***

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 9.3 | U1 (V) | 232.6 | I1 | 0.07 |
| S1 (VA) | 17.4 | THD-U1 % | 1.36 | THD-I1 % | 141.8 |
| Q1 (VAR) | -14.7 | Upk+1 (V) | 329.2 | Ipk+1 (A) | 0.28 |
| PF1 | -0.53 | Upk-1 (V) | -328.6 | Ipk-1 (A) | -0.27 |

### *3.1.3 Incandescent lamp*

Incandescent lamp is a linear load, with 100 watt power, pf. = 0.99 and $THD_i$ = 1.39 %. The harmonics in the current of a linear load is due to the harmonic distortion of the source voltage; $THD_v$= 1.3% because the current is pure sinewave. Figure 7 & 8 describe the voltage/current waveforms and vector diagram for incandescent lamp, while Fig. 9 shows the harmonic spectrum for voltage and current. Table 4 list PQI's measured by the analyzer.

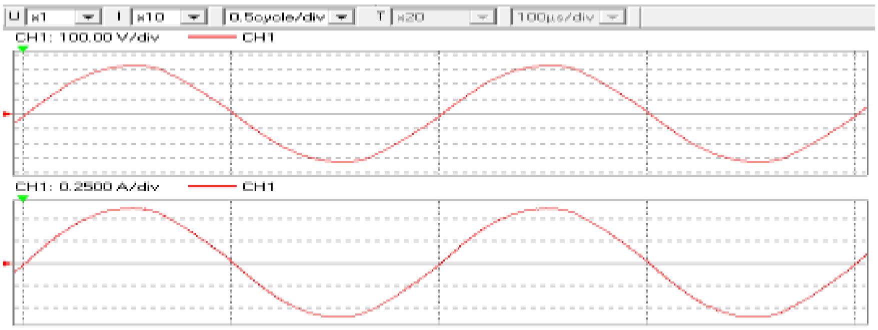


***Fig. 7 Voltage and current waveforms for incandescent Lamp***

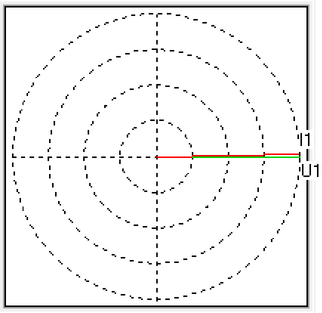


***Fig. 8 Vector diagram for Inc. lamp***


***Fig. 9 Voltage and current harmonic spectrum for incandescent Lamp***

***Table 4 Measured power quality indices for incandescent lamp***

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 99.9 | U1 (V) | 230.5 | I1 | 0.43 |
| S1 (VA) | 99.9 | THD-U1 % | 1.3 | THD-I1 % | 1.39 |
| Q1 (VAR) | - 2.8 | Upk+1 (V) | 326.4 | Ipk+1 (A) | 0.62 |
| PF1 | -0.99 | Upk-1 (V) | -326.1 | Ipk-1 (A) | -0.61 |

### *3.1.4 Refrigerator Compressor*

Refrigerator compressor motor is an inductive linear load with voltage and current waveform as shown in Fig. 10. Figure 11 describes the vector diagram indicating the lagging phase angle between current and voltage. Figure 12 illustrates the voltage and current harmonic spectrum with low harmonic content; $THD_i$ = 4.77%,

ISSN: 2277-9655
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however the measured pf. = 0.54 as listed in Table 5 because the displacement power factor is low due to the lagging current as the total power factor is governed by equation (2) as below:

$$Total\ Power\ Factor = Displacement\ Power\ Factor * Distortion\ Factor \tag{2}$$

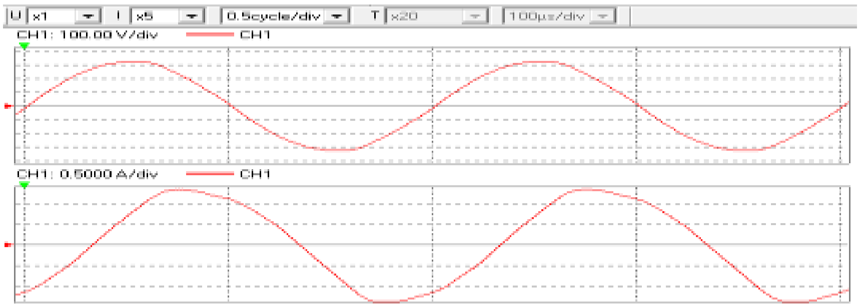


*Fig. 10 Voltage and current waveforms for Compressor*

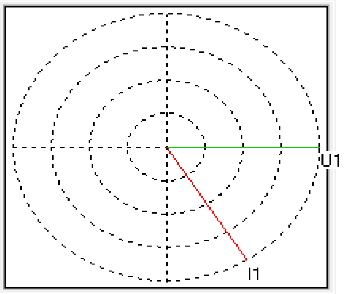


*Fig. 11 Vector diagram for Compressor*

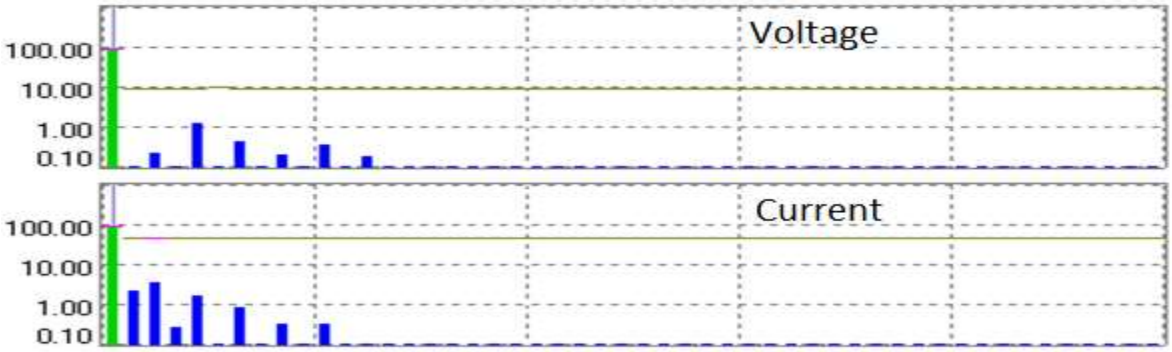


*Fig. 12 Voltage and current harmonic spectrum for Compressor*

*Table 5 Measured power quality indices for Compressor*

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 118.5 | U1 (V) | 231.2 | I1 | 0.96 |
| S1 (VA) | 222.4 | THD-U1 % | 1.40 | THD-I1 % | 4.77 |
| Q1 (VAR) | 188.2 | Upk+1 (V) | 327.5 | Ipk+1 (A) | 1.36 |
| PF1 | 0.53 | Upk-1 (V) | -327.2 | Ipk-1 (A) | -1.4 |

### *3.1.5 TV Set*

Figure 13 & 14 show the voltage/current waveforms and vector diagram indicating leading current. Figure 15 illustrate the breakdown of voltage and current versus harmonic order in the harmonic spectrum. Table 6 lists the PQI's with Power = 80 Watt, $THD_i$= 52.4% and power factor = 0.75.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

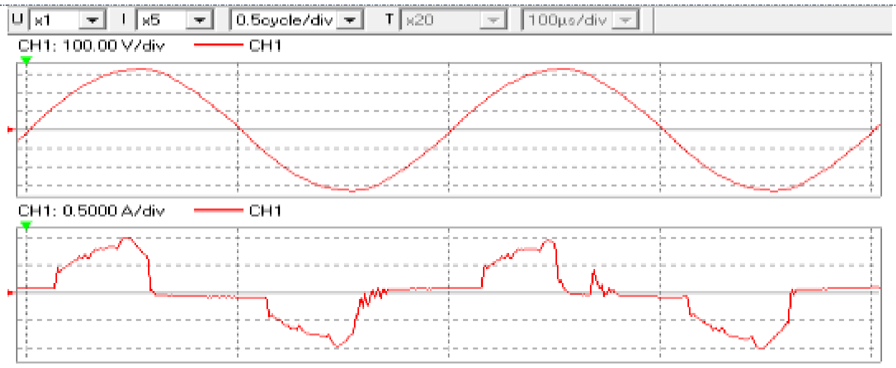


*Fig. 13 Voltage and current waveforms for TV Set*

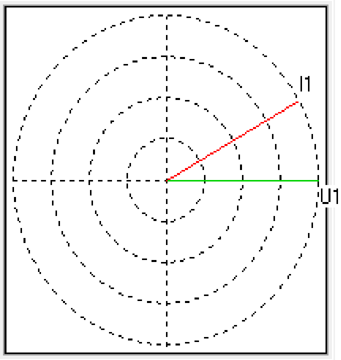


*Fig. 14 Vector diagram for TV Set*

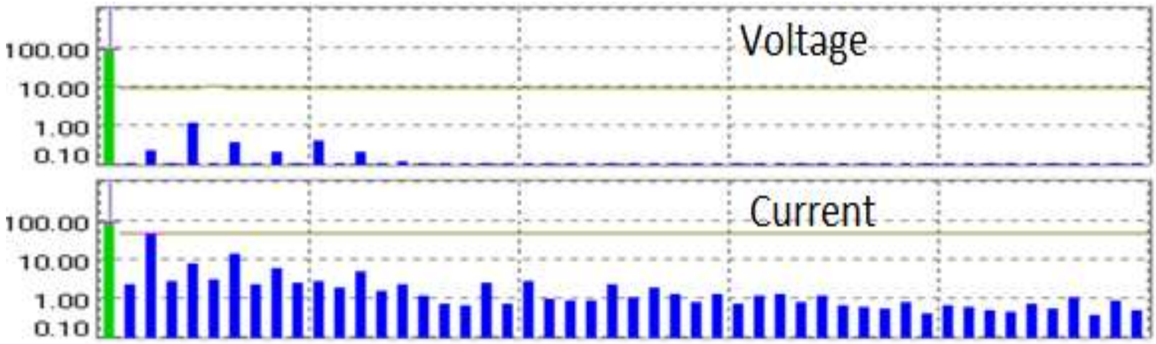


*Fig. 15 Voltage and current harmonic spectrum for TV Set*

*Table 6 Measured power quality indices for TV Set*

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 81.6 | U1 (V) | 231.9 | I1 | 0.47 |
| S1 (VA) | 108.6 | THD-U1 % | 1.36 | THD-I1 % | 52.4 |
| Q1 (VAR) | -71.7 | Upk+1 (V) | 329.2 | Ipk+1 (A) | 1.0 |
| PF1 | -0.75 | Upk-1 (V) | -328.7 | Ipk-1 (A) | -1.01 |

### *3.1.6 Computer*

Figure 16 & 17 show the voltage/current waveforms of the worth current shape and vector diagram indicating leading and distorted current at the same time, so the total power factor has the lowest value due to the low value for not only displacement power factor but also for distortion power factor according to equation (2).

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

Figure 18 presents the voltage and current harmonic spectrum. Table 6 lists the PQI's with P = 30 Watt,$THD_i$= 205.7% and total power factor = 0.42.

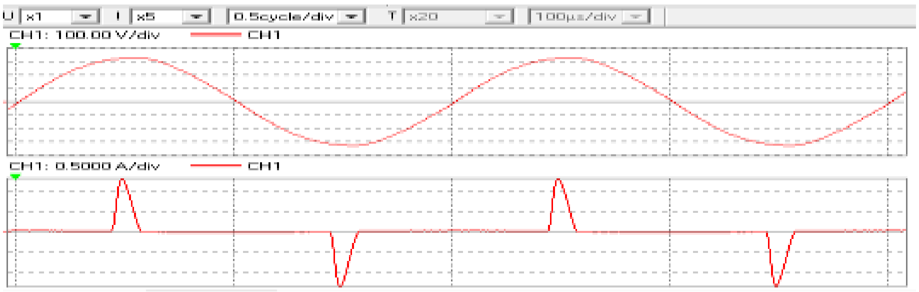


*Fig. 16 Voltage and current waveforms for Computer*

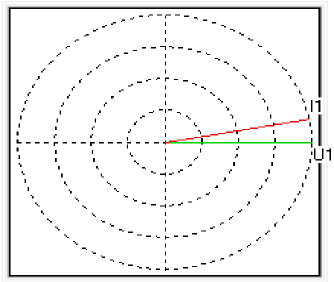


*Fig. 17 Vector diagram for Computer*

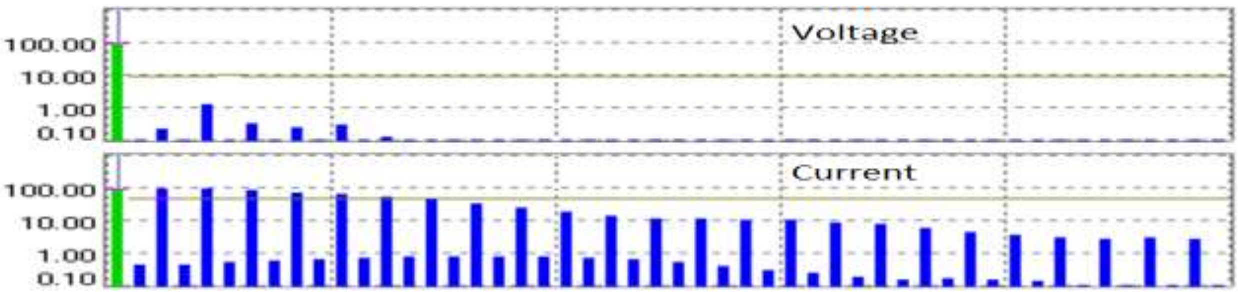


*Fig. 18 Voltage and current harmonic spectrum for Computer*

*Table 7 Measured power quality indices for Computer*

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 30.8 | U1 (V) | 232 | I1 | 0.31 |
| S1 (VA) | 72.4 | THD-U1 % | 1.36 | THD-I1 % | 205.7 |
| Q1 (VAR) | -65.5 | Upk+1 (V) | 329 | Ipk+1 (A) | 1.4 |
| PF1 | -0.42 | Upk-1 (V) | -328.6 | Ipk-1 (A) | -1.4 |

### *3.1.7 Fan*

Fan motor is a linear load with voltage and current waveform as shown in Fig. 19. Figure 20 shows the vector diagram indicating nearly in-phase current due to the effect of capacitor. Figure 21 describe the voltage and current harmonic spectrum with low harmonic content in source current; $THD_i$ = 1.6%, and the measured pf.= 0.99 and P= 75 Watt as stated in Table 8 because the displacement power factor and distortion factor are high giving good power quality indices according to equation (2).

From the previous measurements, it is very clear that the harmonic levels are exceeded above the IEC limits for LED, Fluorescent lamp, TV set, and Computer.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

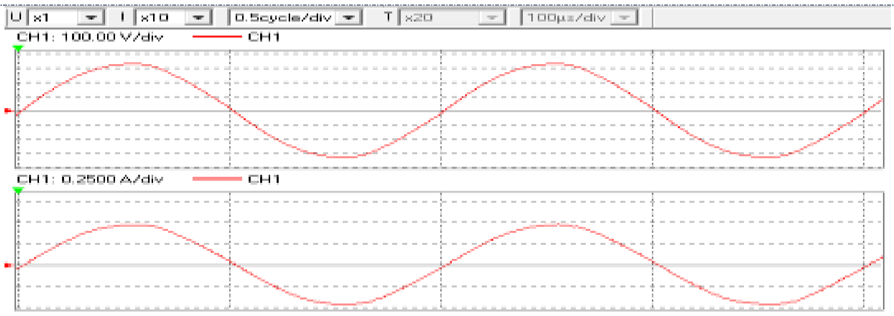


*Fig. 19 Voltage and current waveforms for Fan*

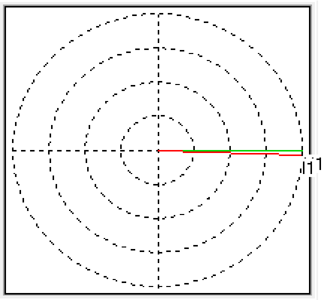


*Fig. 20 Vector diagram for Fan*


*Fig. 21 Voltage and current harmonic spectrum for Fan*

*Table 8 Measured power quality indices for Fan*

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 76.8 | U1 (V) | 233.4 | I1 | 0.33 |
| S1 (VA) | 76.8 | THD-U1 % | 1.33 | THD-I1 % | 1.6 |
| Q1 (VAR) | 3.3 | Upk+1 (V) | 330.7 | Ipk+1 (A) | 0.48 |
| PF1 | 0.99 | Upk-1 (V) | -330.4 | Ipk-1 (A) | -0.46 |

### 3.2 Combined Loads

The idea of the natural harmonic cancellation is based on feeding a specific harmonic currents from load to another load away from the supply. Because each load has its own fingerprint and current waveform has its unique shape that lead to difference not only in the harmonic current magnitude but also in its phase angle. The difference between the phase angles for a specific harmonic order, makes one load is able to feed the other one. This is defined as the diversity factor represented by equation 3 [10].

Diversity Factor =

$$Diversity\ Factor = \left|\frac{Phasor\ sum\ of\ harmonics\ currents\ (h)}{Algebric\ sum\ of\ harmonics\ currents\ (h)}\right|$$

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

$$= \left| \frac{\sum_{i=1}^{N} Ihi}{\sum_{i=1}^{N} |Ihi|} \right| (3)$$

Where $I_{hi}$ is the harmonic current h for a specific load i of N loads.

For example, considering 2 loads represented in Fig.22 , a specific harmonic order current $I_{h1}$ with angle A drawn from load 1 and $I_{h2}$ with angle B from load 2. By factorize both current vectors on X and Y axis, The attenuated resultant current; $I_{hxR} = I_{hx1} - I_{hx2}$ (4)
And $I_{hyR} = I_{hy1} - I_{hy2}$ (5)

This means that the resultant currents $I_{hxR}$, $I_{hyR}$ and $I_{hR}$ are attenuated due to the summation of both harmonic currents $I_h$ for load 1 and load 2 when the two currents lie in two opposite quadrant (1&3 or 2&4).By other word, load 1 supply the h order harmonic current to load 2 away from the supply giving better source current quality and lower total harmonic distortion. Figure 3 represents individual load; case A and parallel load operation for 2 different loads; case B. In case B, Load 1 is operating as a filter for the system as the harmonic current needs of load 1 is supplied by load 2 away from the supply. So the diversity factor gives natural harmonic cancellation due to the diversity of the footprint of the loads (in terms of harmonic current magnitude and phase angle) that connected in parallel not only on the residential but also on the industrial applications.

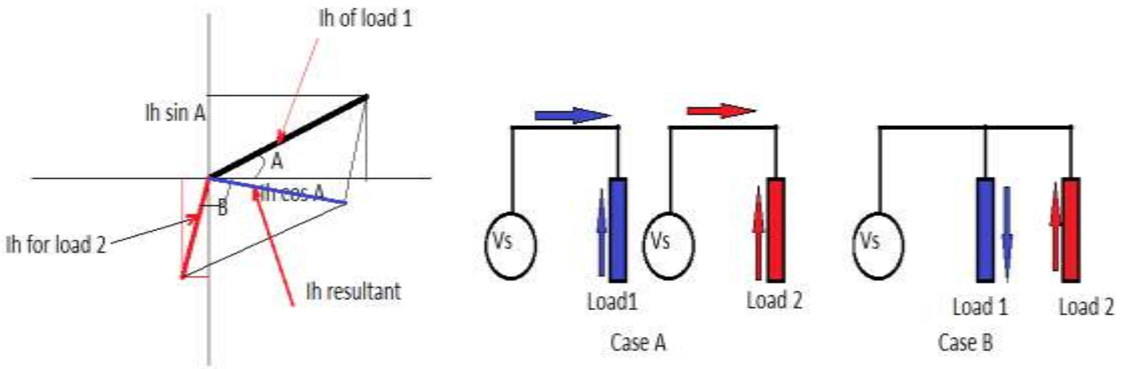


*Fig. 22 Phasor diagram and equivalent circuit to illustrate natural harmonic cancellation*

### *3.2.1 Hybrid lighting loads (FL, LED and Incandescent lamp)*

Figure 23 and 24 show voltage/current waveforms for the lighting load combined of FL, LED and Incandescent lamp. Figure 25 draws the vector diagram for the total current and Fig. 26 presents the voltage and current harmonic spectrum. From the measured PQI's in table 9, the resultant current $THD_i$ is reduced to 9.2% and the total power factor improved to 0.96. This improvement in the PQI's happened due to the diversity factor of the hybrid loads connected to the supply. Some harmonic currents are supplied from one of the loads due to the phase shift between the same harmonic order of each load as the above mentioned illustrated natural cancellation concept [11]- [16].

ISSN: 2277-9655
Impact Factor: 5.164
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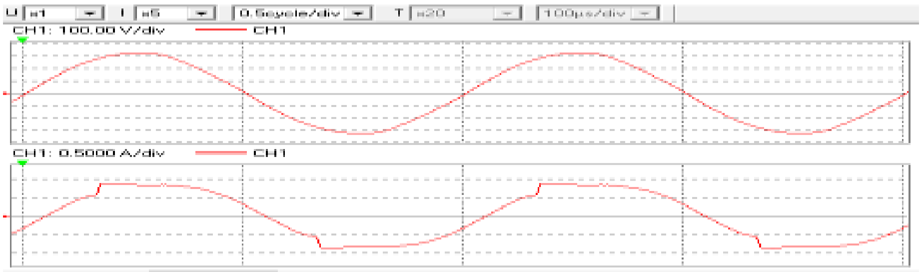


*Fig. 23 Voltage and current waveforms for hybrid lighting loads*

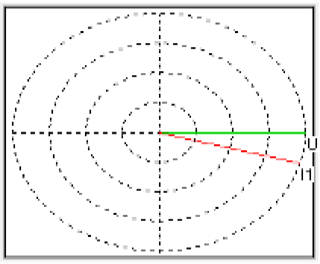


*Fig. 24 VD for hybrid lighting loads*

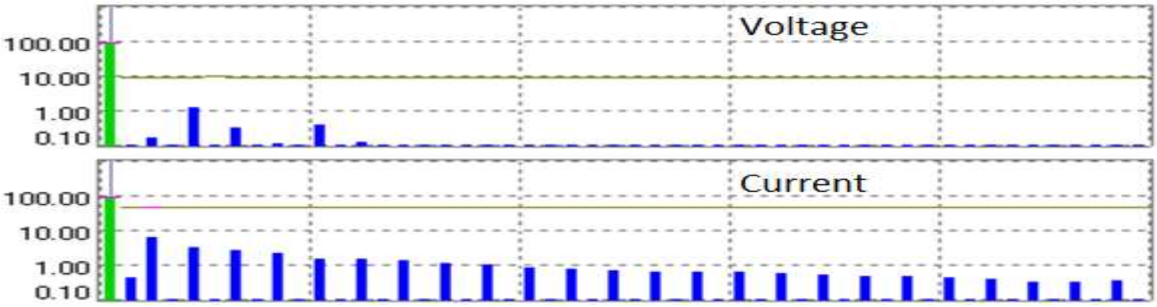


*Fig. 25 Voltage and current harmonic spectrum for Hybrid lighting loads*

Figure 26 shows the vector summation of the resultant fundamental current for both florescent lamp and LED lamp with smaller phase shift; reduced from angle; F = -51° to angle; L = -37°and accordingly improvement for power factor. On the other hand the third harmonic resultant current summation is 65.8 mA and the resultant current is 61 mA with reduction to 92% due to phase shift or diversity factor (diversity factor = 61/65.5 = 93%). Better results can be achieved if 4 LED lamps are connected with the FL at the same time. This will lead to resultant current amplitude of 57.7 mA with diversity factor 87.6%as indicated in Fig. 26; Third harmonic reduction by diversity will be improved if 4 LED lamps is connected with Florescent lamp. This means that, the proper selection for the load type and load size will directly positively impact the displacement power factor and the distortion factor due to the diversity factor based on the load nonlinearity fingerprint.

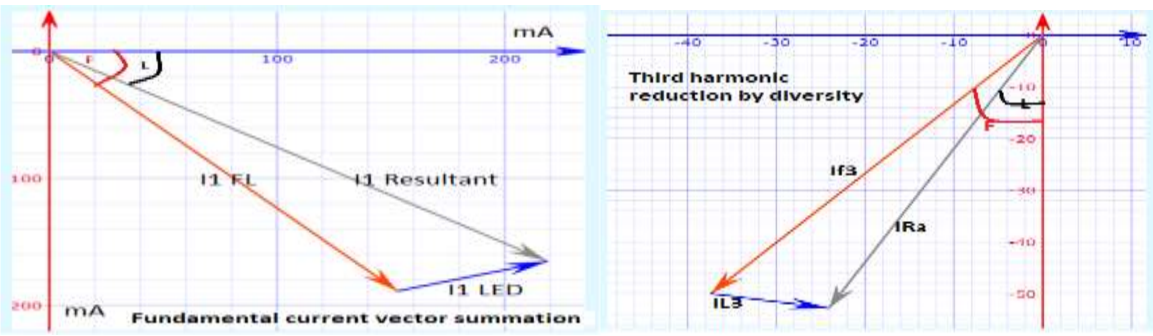


*Fig. 26 Fundamental current displacement angle improvement and third harmonic reduction due to diversity*

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

*Table 9 Measured power quality indices for Hybrid lighting loads*

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| F (HZ) | 50 | | | | |
| P1 (W) | 142.9 | U1 (V) | 230.6 | I1 | 0.64 |
| S1 (VA) | 149.0 | THD-U1 % | 1.38 | THD-I1 % | 9.2 |
| Q1 (VAR) | 42.3 | Upk+1 (V) | 326.1 | Ipk+1 (A) | 0.89 |
| PF1 | 0.96 | Upk-1 (V) | -325.7 | Ipk-1 (A) | -0.87 |

### *3.2.2 Combination of all home appliance loads together*

In this case, all loads are working together at the same time; FL, LED, Incandescent lamp, TV set, Computer, Refrigerator compressor and Fan. Figure 27 shows the resultant current and voltage waveforms for the combination of all loads working together. Figure 28 represents the vector diagram of the resultant current with improved phase angle between the resultant current and reference supply voltage.

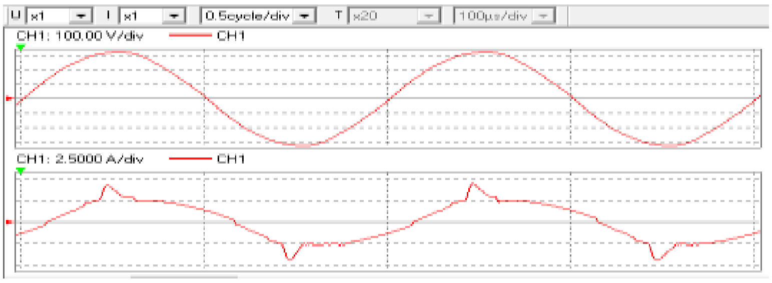


*Fig. 27 Voltage and current waveforms for hybrid all loads*

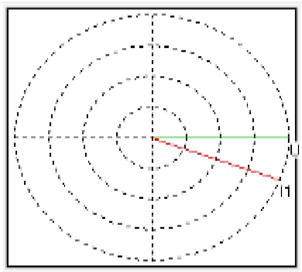


*Fig. 28 VD for hybrid all loads*

Figure 29 illustrates the voltage and resultant current harmonic spectrum with resultant current $THD_i$ = 31.4% and $THD_v$ = 1.4%. Table 10 lists the measured PQI's with improved total power factor of 0.91 due to the effect of load diversity phenomena because all loads are connected together at the same time [11]- [16].

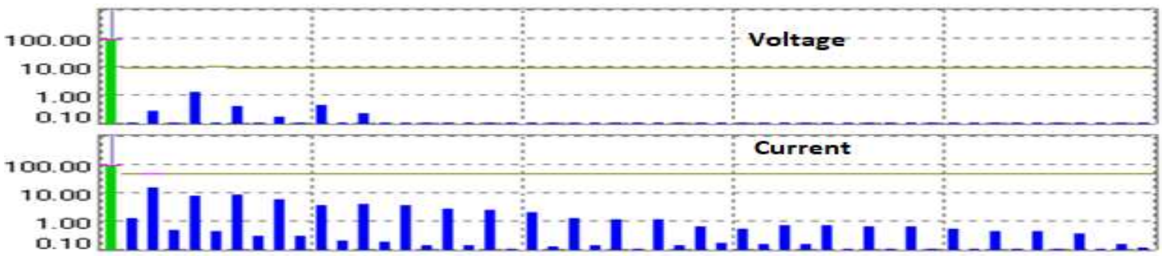


*Fig. 29 Voltage and current harmonic spectrum for Hybrid all loads*

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*Table 10 Measured power quality indices for Hybrid all loads*

| POWER | | VOLTAGE | | CURRENT | |
|---|---|---|---|---|---|
| P1 (W) | 456.2 | U1 (V) | 228.9 | I1 | 2.2 |
| S1 (VA) | 499.3 | THD-U1 % | 1.4 | THD-I1 % | 21.4 |
| Q1 (VAR) | 202.9 | Upk+1 (V) | 323.6 | Ipk+1 (A) | 4.44 |
| PF1 | 0.91 | Upk-1 (V) | -323.6 | Ipk-1 (A) | -4.47 |

## 4. CONCLUSION

In this paper, the natural harmonic cancellation for hybrid load is studied for home appliance loads in the residential application. The individual load power quality indices are measured for FL, LED, Incandescent lamp, TV set, computer, refrigerator compressor motor, and Fan. FL, LED lamps, TV Set and Computers are nonlinear loads. The measured PQI's for these loads exceed the predefined international standard limits set by IEC 61000-2-3.

Hybrid load connections are analyzed for lighting loads and another analysis is recorded for all loads connected together. The measured PQI's are summarized in Table 11. Hybrid lighting loads measurements shows a considerable improvement for the $THD_i$ and total power factor, where the $THD_i$ for LED and FL are 141.8 % and 14.3% respectively, while hybrid lighting $THD_i$ is only 9.2% with obvious improvement. Moreover the total power factor for LED and FL are 0.53 and 0.62 respectively while hybrid lighting power factor is 0.96 which is a great improvement.

The second hybrid load is all loads combined together. The individual load $THD_i$ measured for LED, FL, TV set and Computer are 141.8 %, 14.3%, 52.4% and 205.7% respectively while the total load combination $THD_i$ is 21.4%. On the other hand, the total power factor of the same individual loads are 0.53, 0.62, 0.75 and 0.42 respectively while the total power factor for hybrid load is 0.91 with a considerable improvement due to the natural cancellation of harmonics because of the load diversity.

Harmonic cancellation can be achieved by properly selecting the load combination by the designer of the electrical installation considering harmonic cancellation due to the load diversity. The information related to the load harmonics magnitude and angle delivered by the manufacturer will facilitate the job of the designer to compose the best combination of loads together fulfilling the customer needs and power quality limits at the same time. Power saving and better PQI's are the main benefits of hybrid load configuration.

*Table 11 Summery of PQI's recorded for individual and hybrid load*

| | **LED** | **FL** | **TV Set** | **Computer** | **Hybrid lighting** | **ALL loads combination** |
|---|---|---|---|---|---|---|
| **$THD_i$%** | 114,8 | 14.3 | 52.4 | 205.7 | 9.2 | 21.4 |
| **TPF** | 0.53 | 0.62 | 0.75 | 0.42 | 0.96 | 0.91 |

## 5. ACKNOWLEDGEMENT

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