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Research paper

Harmonics distortions and interactions of modern residential electrical loads

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Abstract

Driven by continuous growth in electrical energy cost and technologies developments in power electronics performance, customers have been motivated towards utilization of power electronics loads and energy-efficient appliances at their houses. Power electronics devices are one of the main harmonics sources. With high proliferation of such devices in electrical system, it is imperative to examine the harmonics profile of such houses. The purpose of this paper is to investigate and characterize the harmonics distortion level on typical Jordanian modern residential loads. A field data survey for the harmonic distortions of the individual residential loads is presented. Synchronized measurements are conducted to point out the contribution of each individual loads to the net total harmonic distortion level (THD) and to explain harmonic interaction between the loads. The results show a high level of harmonics distortion in current, reaches as high as 45%.

Keywords: *energy-efficient appliances; Harmonics Distortion; Harmonics Interaction; Non-Linear Load; Power Electronics, Field Measurement.*

1. Introduction

Due to increase dependency on electrical energy in daily life activities and increase of the sensitivity of the today's loads, the quality of delivered electrical power become a one of major priority in power system design and operation [1]-[3]. Power quality disturbance can cause several challenges and problems in electrical networks [4] [5]. One of most common power quality disturbances is the waveform distortion (Harmonics). With the existence of the harmonics contents in the electrical signals, the conventional sinusoidal waveforms of current and voltage are disturbed [6].

High harmonic distortion can negatively affect a facility's electric distribution system [6]. They generate excessive heat in motors, and might cause early failures. Heat also builds up in wire insulation causing breakdown and failure. Increased operating temperatures can affect other equipment as well, resulting in malfunctions and early failure of electrical equipment. In addition, harmonics on the power line can prompt computers and other sensitive loads to restart and adversely affect other sensitive analog circuits

Harmonic disturbances come from equipment with a non-linear voltage and current characteristic. Examples of waveform distortion sources are: the saturation of a transformer core, adjustable-speed drives, switching mode power supplies, electronic fluorescent lamp ballasts and other non-linear and time-varying loads such as arc furnaces [1]-[3]. Furthermore, nonlinear loads consumed distorted current that flows in system impedances results in a distortion of system voltage, which also affect the operation and performance of nearby linear loads in electrical systems [7].

In the past, due to low harmonic contents, harmonics investigation within household appliances was neglected; however, recent appliances are generating much harmonic distortion [1]-[3], [8], and [9]. With continuous growth of non-linear household appliances, the accumulation of harmonic distortion might affect the power systems [10]-[11]. Nowadays, large parts of loads in industrial, commercial and residential facilities are non-linear loads, making the distortion level on the low-voltage networks a serious concern. At residential facilities, for economic reasons, there is a remarkable increase in the utilization of power electronics technologies (energy-efficient appliances) worldwide. For example, the percentage share of nonlinear loads on some power systems such as US was 60% [12]. A survey has been done by the author in Jordanian residential electrical systems reveals that more than 75% of current loads are non-linear loads. With high level and the expected increase proliferation of such devices there is a need to periodically assess the harmonics pollution level and quantify the possible negative impact might appear in the power systems.

Several studies have investigated the harmonics distortion produced by residential electrical devices[11]-[19]; the impact of residential appliances on the power quality profiles was analyzed in [13], reference [14] discussed the impact of large motor starting and Loading on the power quality and harmonics distortion. A study represented in [11] exhibited that the increasing of compact fluorescent lamps (CFLs) utilization could result in an increase of voltage total harmonic distortion by 10%. In [15] a hundred of distribution network feeders were monitored and it was found that the average voltage THD reaches as high as 4.7%. A high total voltage distortion reached as high as 17% was reported in [16]. Recent studies and field data measurement revealed high harmonic distortions in European residential systems [17-18], and in North America residential systems [19].

This paper provides field measurement for electrical quantities for most common household appliances in typical Jordanian residential system. The harmonic distortions of the individual residential loads are monitored and presented. The main purpose of this study is to quantify the harmonics distortions produced by nonlinear residential loads and reveal the total distortion level at consumers' facilities. Several loads; different types of lightings lamps (incandescent light bulbs, compact fluorescent lamp (CFLs), and light emitting diodes (LEDs), televisions(TVs), modern, microwave, internet moderns, and linear loads are monitored and investigated.

2. Measurements and analyses

Harmonics are defined as sinusoidal voltage and current wave-forms at integer multiples of the fundamental power frequency (50 or 60 Hz) [4]. With the existence of the harmonics, the current and voltage waveforms are changed to non-sinusoidal waveforms, where the instantaneous current and voltage can be described as follows[5]-[6]:

$$v(t) = V_o + \sqrt{2}V_1 \sin(2\pi f_1 t + \theta_1) + \sum_{n=2}^{\infty} \sqrt{2}\, V_n \sin(2\pi n f_1 t + \theta_n)$$
$$i(t) = I_o + \sqrt{2}I_1 \sin(2\pi f_1 t + \phi_1) + \sum_{n=2}^{\infty} \sqrt{2} I_n \sin(2\pi n f_1 t + \phi_n) \quad (1)$$

Where, Io, Vo are the d.c. component of current and voltage, I_1 and V_1 are the rms values of fundamental components, In and V_n are the rms values of harmonics components, f_1 is the fundamental frequency (50 or 60 Hz), θ_1 and ϕ_1 are the phase angles of voltage and current of fundamental component, and θn and ϕn are the phase angles of voltage and current of harmonics components, respectively

The Harmonics distortions can be quantified by the well known index, total harmonic distortion level (THD). Total harmonic dis-tortion factor (THD) basically relates the r.m.s. values of harmonic components to the r.m.s. value of fundamental component and mathematically can be expressed for voltage (THD_V) and cur-rent(THD_I) as follows [5]-[6]:

$$THD\%\big|_V = \frac{1}{V_1}\sqrt{V_{rms}^2 - V_1^2} \times 100\% \quad (2)$$

$$THD\%\big|_I = \frac{1}{I_1}\sqrt{I_{rms}^2 - I_1^2} \times 100\% \quad (3)$$

Where:V1 and I1: fundamental rms voltage and current compo-nent, Vrms and Irms: the rms voltage and current of the signal.

Other useful index for evaluating the distortion level in current signal is the total demand distortion (TDD) [21]. The TDD index, compared to THD index, relates the r.m.s. values of harmonic components to the r.m.s. value of total demand current which can be described by:

$$TDD\%\big|_I = 100\% \times \sqrt{\left(\frac{I_2}{I_L}\right)^2 + \left(\frac{I_3}{I_L}\right)^2 + \left(\frac{I_4}{I_L}\right)^2 + \ldots\ldots + \left(\frac{I_n}{I_L}\right)^2} \quad (4)$$

Where I_L is the maximum demand current.

2.1. Harmonics characteristic of single phase loads

The studied system is typical modern residential loads at one of Jordanian houses. Figure 1 shows the picture of the measurement layout at the house. A single phase configuration of power quality analyzer is used to monitor the power quality parameters: current waveform, harmonics contents, total harmonics distortion (THD) and total demand distortion (TDD). Several loads are monitored: different types of lighting systems (LEDs, incandescent, and CFLs), TVs, fans, refrigerator, internet modems, microwave, vac-uum cleaner which represents the most common loads styles at Jordanian low voltages residential system.

Figures 2-10 show the current waveforms, harmonics spectrums and THD values for these individual loads. The type of the load is stated in the figure capture. As it is obvious, the major of these loads have distorted waveforms (with non-linear characteristics) which produce high harmonics levels. The only linear loads are the conventional incandescent lamp and small fans. The rests of the loads are power electronics based loads and energy-saving devices such as (CLFs, LEDs, TV, modern, microwave, internet moderns).

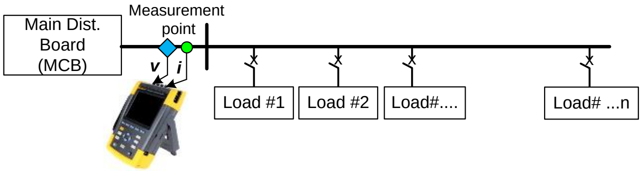


Fig. 1: Measurement Point at the Main Distribution Board.

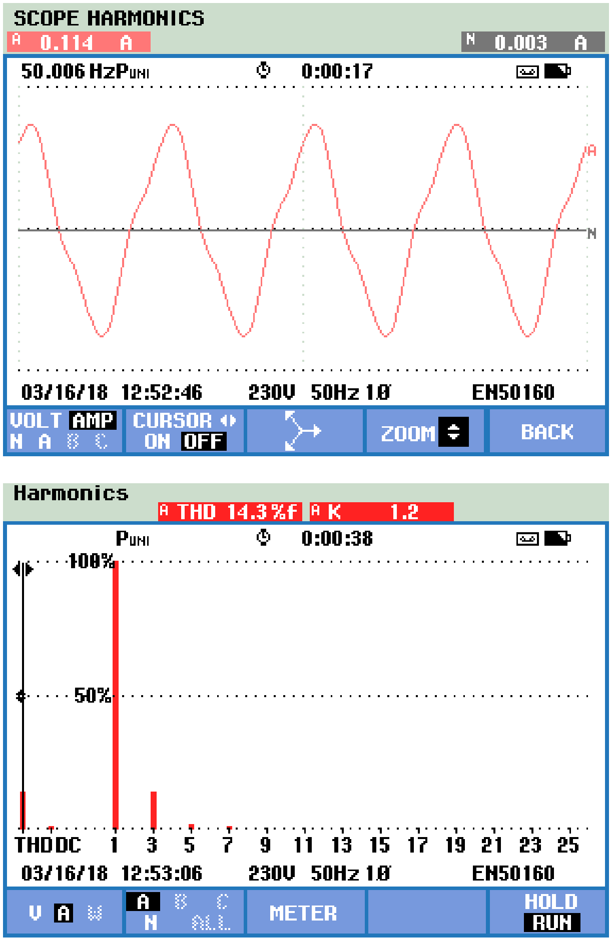
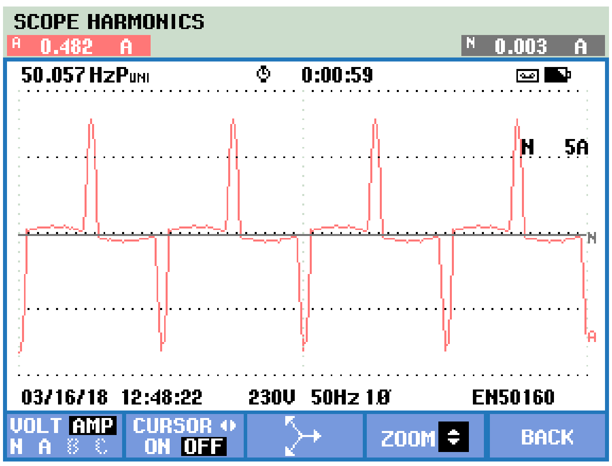


Fig. 2: Current Waveform, Harmonics Spectrum and THD (I) for Small Fan.



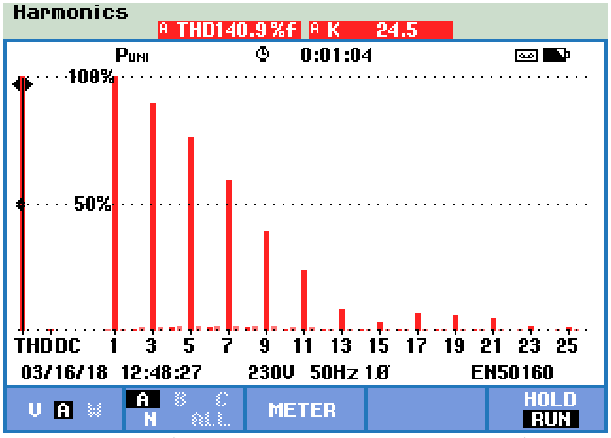
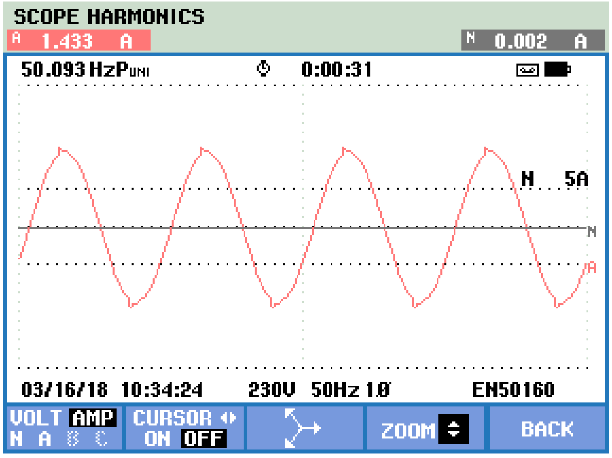


Fig. 3: Current Waveform, Harmonics Spectrum and THD (I) for LCD TV.



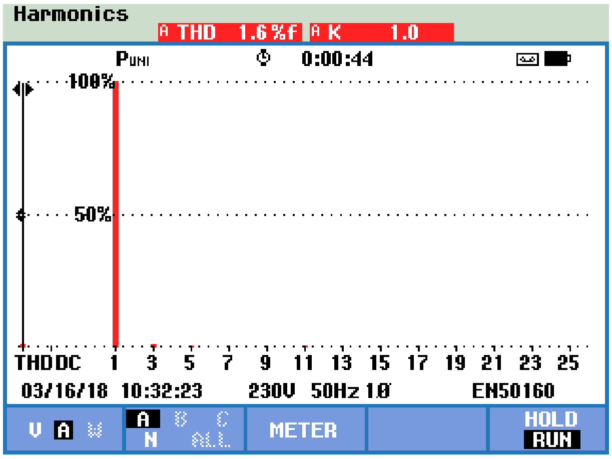
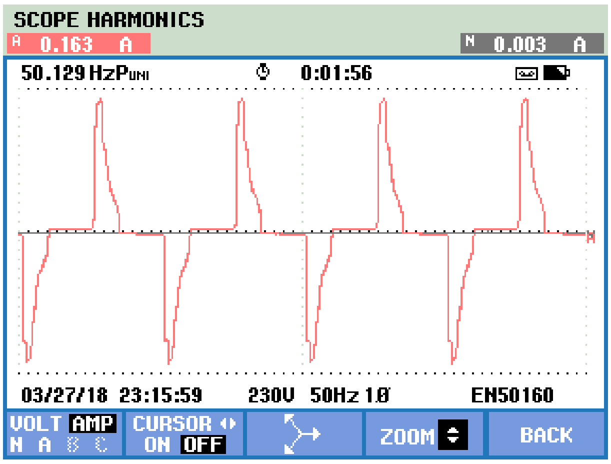


Fig. 4: Current Waveform, Harmonics Spectrum and THD (I) for Incandescent Lamp.



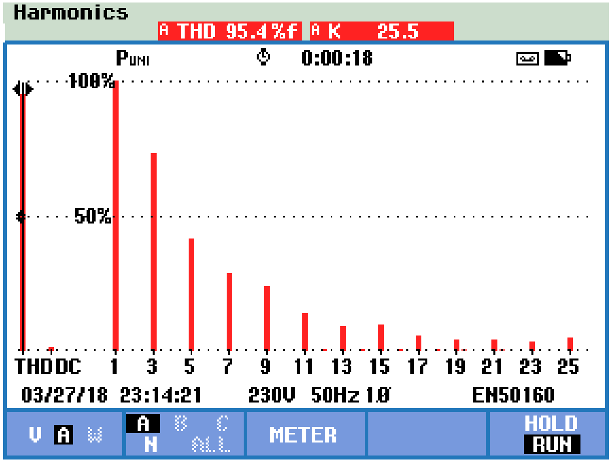
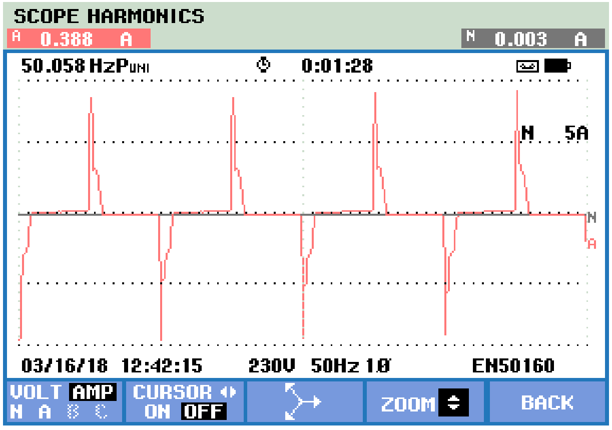


Fig. 5: Current Waveform, Harmonics Spectrum and THD (I) for CFL.



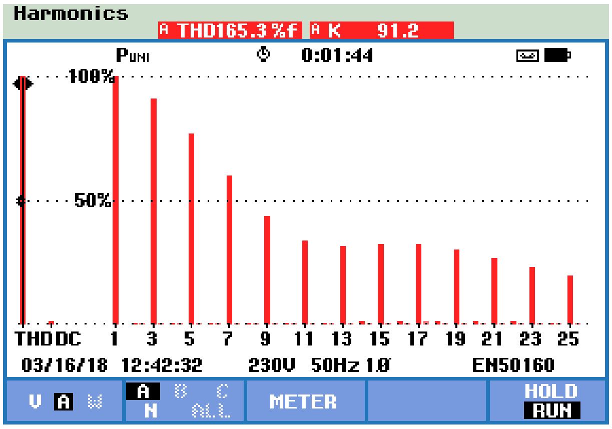
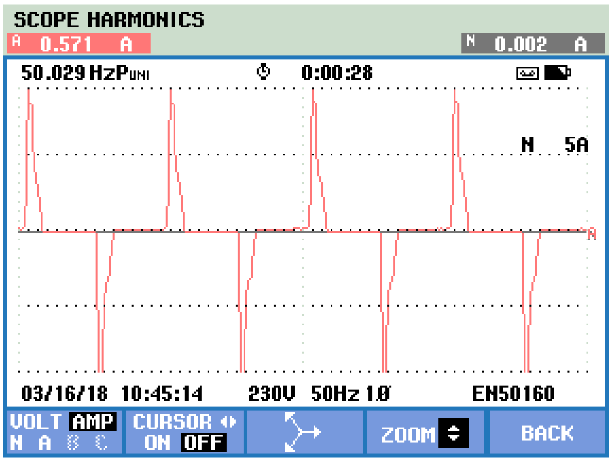


Fig. 6: Current Waveform, Harmonics Spectrum and THD (I) for Spots LED (White Color Type).



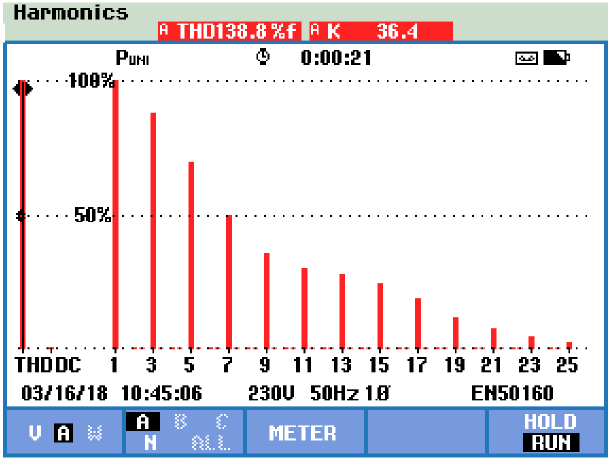
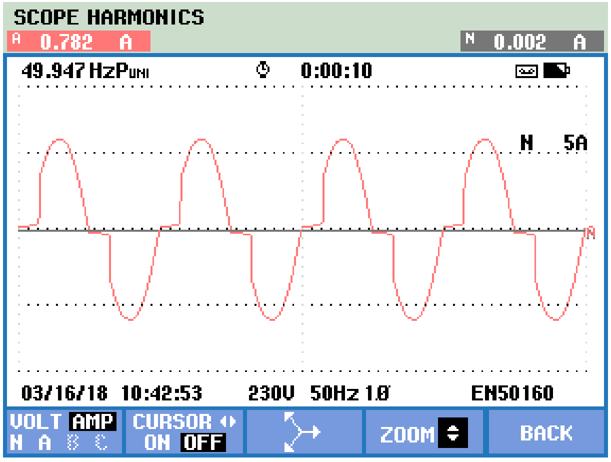


Fig. 7: Current Waveform, Harmonics Spectrum and THD (I) for Spots LED (Yellow Color Type).



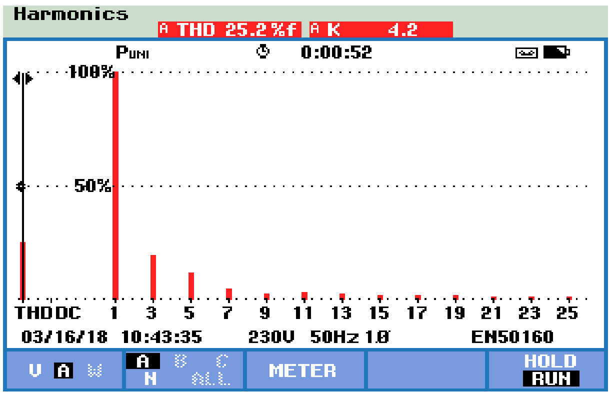
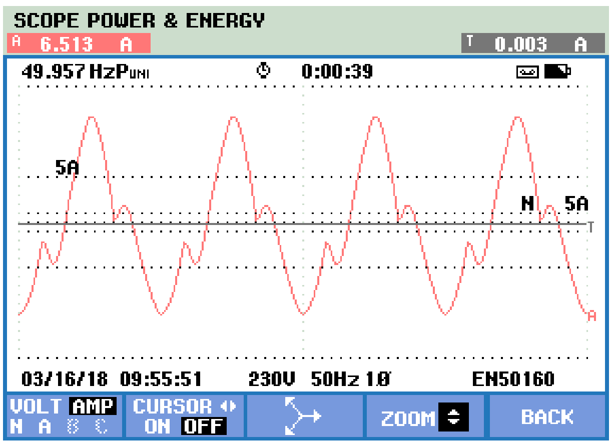


Fig. 8: Current Waveform, Harmonics Spectrum and THD (I) for Strip Type LED.



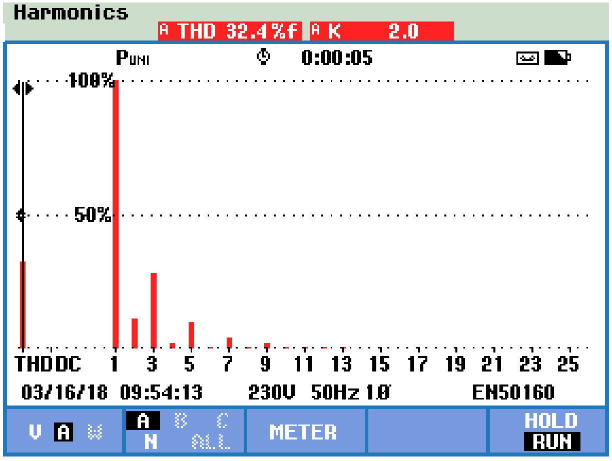
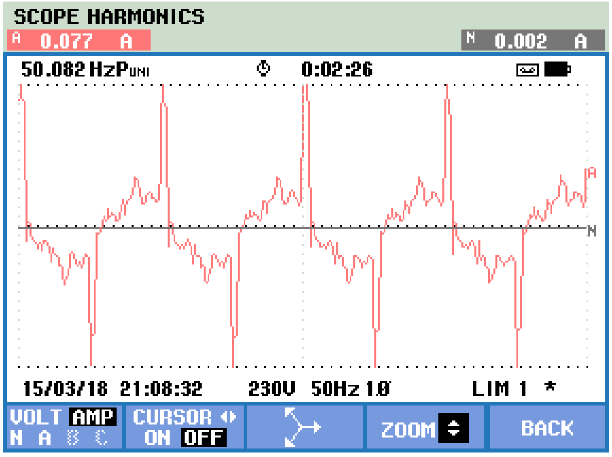


Fig. 9: Current Waveform, Harmonics Spectrum and THD (I) of Micro-wave.



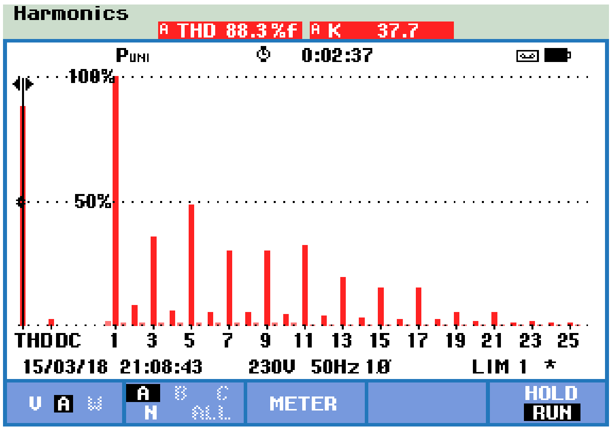


Fig. 10: Current Waveform, Harmonics Spectrum and THD (I) of Internet Modem.

2.1. Harmonics interaction between non-linear loads; CF and LED

In this subsection the harmonics interaction between non-linear loads; LED light and CFL is analyzed. Figure 11 shows the lights data and measurement point. Ten LED with 3W each and one CFL with 26 W. A synchronized measurement (between the voltage and current in order to measure the current harmonics angles) is conducted to explain the harmonic interaction between the loads.

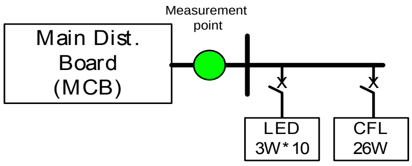


Fig. 11: Lights Data and Configuration of LED and CFL Combination.

Figure 12 shows harmonics current contents and THD for three cases: CFL alone, LED alone and combined LED and CFL. Table 1 summarise the findings of the rms and fundamental currents and it's THD for the three cases. LED alone produces THD as high as 135.3%, while THD for FCL alone reaches to 95.4%, and the THD reaches to 100.9% for the combined case. For the case both lights are switched on, it is observed that the percentage increase in fundamental component of current, due to increase in the load current, is higher than that in harmonics current. Further investigations are made to explain the change in THD profile. The variation of the harmonics current magnitudes and angles along with THD current are plotted and shown in Figures 13 and 14 respectively.

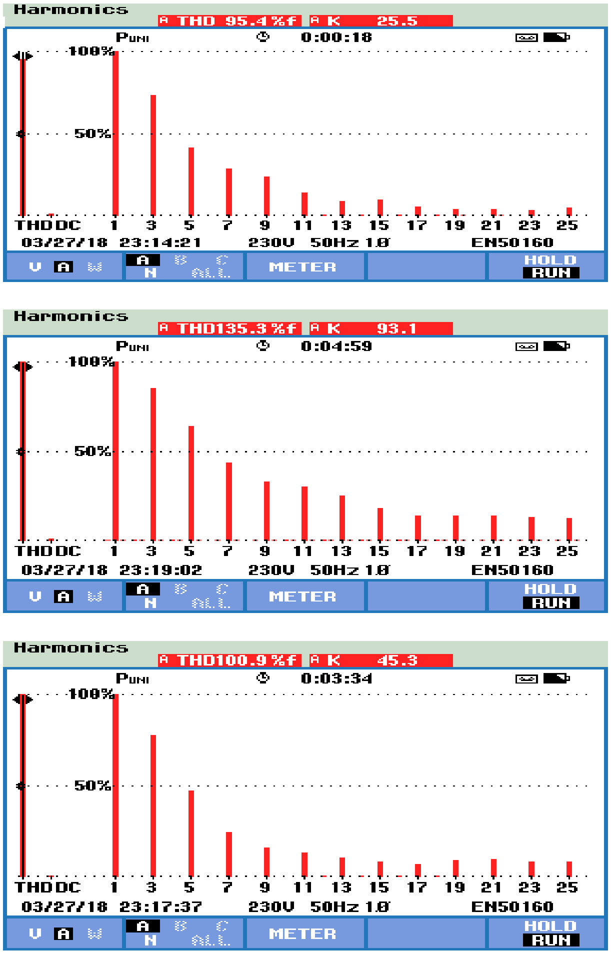


Fig. 12: Harmonics Spectrum: CFL (Upper Plot), B) LED (Middle Plot), C) CFL &LED (Bottom Plot).

By investigating the results in Figure 13, for the middle part (where both loads are switched on), the harmonic currents magnitude increases except the seventh and ninth harmonic current magnitude where decrease, hence only small increase in THD value, with addition of LED load, is observed. With further investigation on harmonics current angles, as shown in Figure 14, it is found that the angles of 7th and 9th harmonics has opposite phase angles in each load that make some sort of harmonics cancelation (partial cancelation) and therefore small change appears in the net THD value when both lights are operated. It is worth to mention that a full cancellation does not occur due to the difference in current magnitudes. No significant change is observed for harmonics order; 11th , 13th and 15th . CFL does not produce large high order harmonics (above 15th order), hence the harmonics trend, when both loads are on, is mainly governed by harmonics produced by LED.

Table 1: Current Values IRMS and I1 and THDI

Case	I_{RMS} (I_1) [A]	THD_I [%]
CFL	0.163 (0.119)	95.4
LED	0.241 (0.142)	135.3
Both	0.369 (0.259)	100.9

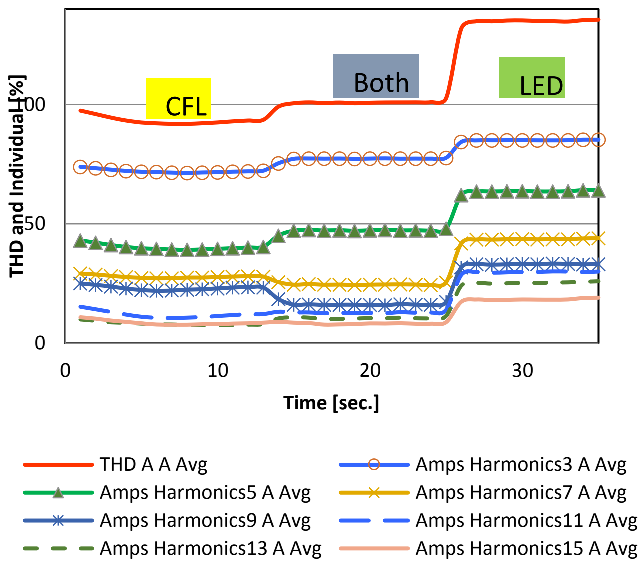


Fig. 13: Variation of Harmonics Current Magnitudes and THD.

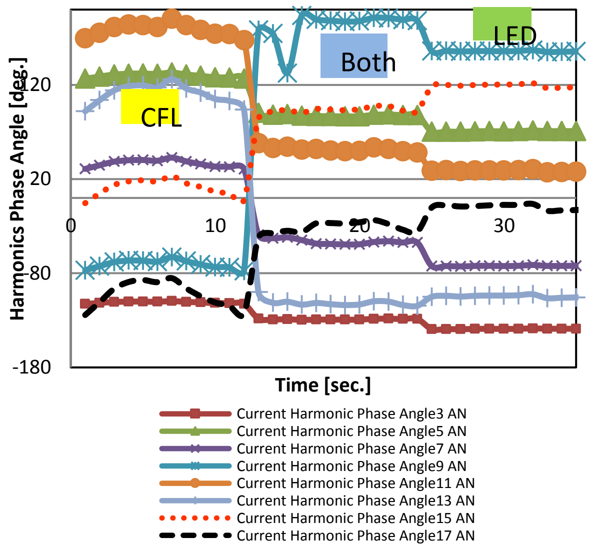


Fig. 14: Angle Variation of Harmonics Currents.

2.3. Harmonics interaction between linear and non-linear loads

In this subsection, the harmonics profile and interaction between linear and non-linear loads; incandescent lamp with two LEDs (LED Type 1 spot type, LED Type 2 strip type) are monitored and investigated. The current waveforms for the different operation conditions are shown in Figure 15.

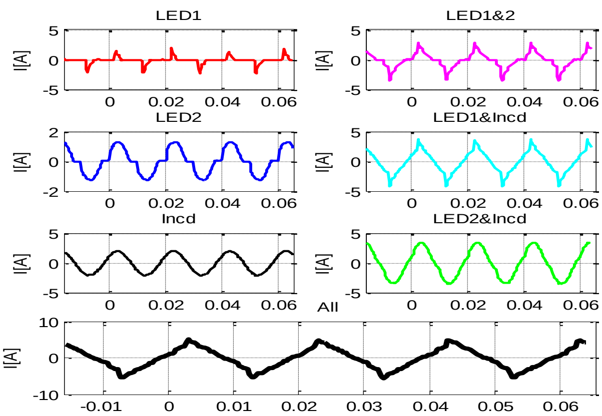


Fig. 15: The Current Waveforms for Different Load Conditions.

Table 2 illustrates the corresponding current measurement (THD_I, Irms and I_1) for the above mentioned operating cases in Figure 15. When all the lights are switched on the net THD reaches to 20.7%, among different load combinations; combining LED# Type 2 and incandescent gives the lowest THD value (8.6%) as they are almost linear loads.

Table 2: Current Values IRMS, I1 and THDI

Load condition	THD_I	I rms (I_1) [A]
LED # Type 1 (Spot type)	137.2%	0.579 (0.341)
LED # Type 2 (Strip type)	23.8%	0.838 (0.815)
Incand. Lamp	1.3%	1.44 (1.44)
LED# Type 1 and 2	48.0%	1.297 (1.17)
LED# Type 1 and Incand.	26.0%	1.895 (1.799)
LED# Type 2 and Incand.	8.6%	2.324 (2.316)
All lights	20.7%	2.750 (2.693)

Five cases are further monitored and investigated, namely: C#1: LED#1 , C#2: LED#1 and LED#2, C#3: All lights ,C#4: LED#2 and Incandescent and C#5: Incandescent alone. Figure 16 depicts the variation of active power, total rms current, fundamental current, and THD_I. The variation of the magnitudes of individual dominant harmonics orders (from 3rd to 17th) are also displayed in Figure 17. Furthermore, the angle variations of these harmonics are displayed in Figure 18.With the help of these figures it is clearly understood that the reduction in current THD for the cases is attributed to the increase in the fundamental currents. For moving from case1 to case2, the THD reduced to 48% due to increase in fundamental current added by LED#2. For case3 the THD further reduces due to large added fundamental current by incandescent. The increase in fundamental current is more than that in harmonics current which manifests as decrease in all the individual current ratio and hence THD_I.

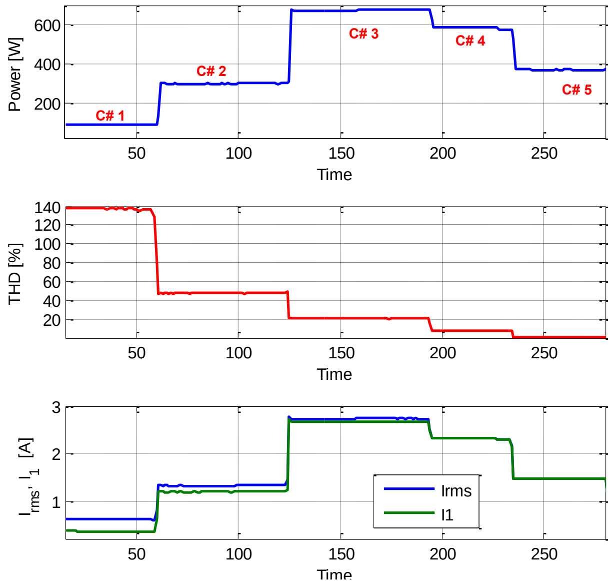


Fig. 16: Variation of Active Power, THD, Irms and I1.

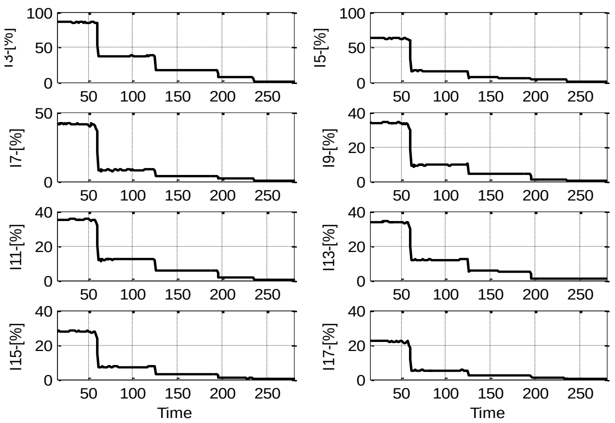


Fig. 17: Variation of Harmonics Current.

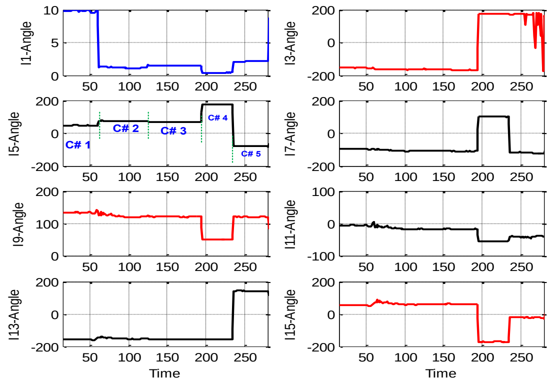


Fig. 18: Variation of Angle of Harmonics Current.

2.4. Net harmonics prolife and interaction at main house breaker

The net THD and harmonics variations at the main breaker (MCB at house distribution board) are monitored to investigate the interaction between the house loads. The measurement period is almost 14 minutes (all the loads were switched on during this period to observe the dynamic profile of harmonics contents distortion and THD). Figures 19 show the average value of harmonics voltage and it's THD_V. It is found that the voltage THD varies between 3.5% to 5.0%. The dominant harmonics is the 3rd and 5th orders. It is noticed that there is an increase in voltage THD during the period (t=680sec.) and (t=760sec.). In this period a couple of linear loads are switched on (the current THD decreases as observed in figure 20) this increase in voltage THD can be attributed to effect of distorted current that flows in system impedances results in a further distortion of voltage.

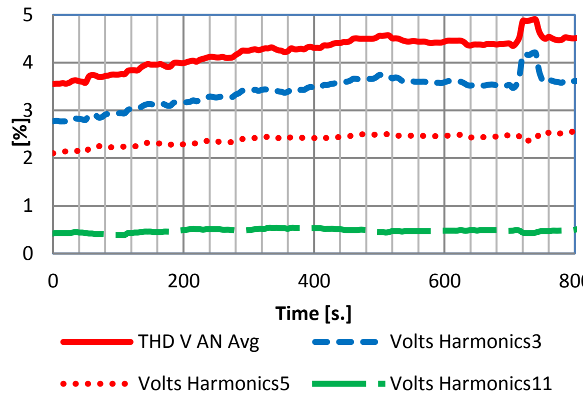


Fig. 19: THD Voltage and Harmonics Voltage at the Main MCB.

Figures 20 and 21 show the variation of rms current and its THD during the test period, respectively. Higher THD occurred at (t=70sec.) due to switching of the LED lights. Then THD drops to 20.5%, at this time the incandescent lamp was switched on. Such reduction is attributed to increase in fundamental current as explain previously. Then THD increases as the loads are added; these loads were CFLs and LEDs at different rooms. Between (t=680sec.) and (t=760sec.), linear loads were introduced (heater, fan motor and cooler) and microwave. The highest demand current value was 12.08 Amp. The THD drops to its lowest value to 11.55%. It is worth mentioning that, this THD value appears only for short time in normal house activities, as the non-linear loads are the base loads in load pattern in daily life activities.

Figure 22 shows the variation of current harmonics over the test period. It is understood that the THD is governed by the 3rd and 5th order as the dominant harmonic especially the 3rd harmonic.

Considering the MCB as the point of common coupling (PCC) between the grid and house, the TDD is estimated and shown in Figure 23. The TDD increases (starting from t=70sec.) as the non-linear loads is added, and it reaches to approximately 20.3% at t=660sec.). As the switched loads in this period are CFLs and LEDs, increase in TDD (i.e., harmonics contents) is observed. It is worth to mention that during this period the increase in harmonics contents is higher than the increase in fundamental component which explains the increase of TDD with added loads. In this period, the value of TDD reached its boundary according to IEEE519 [20]. From other side, during (t=680sec.) to (t=790sec.), the TDD reduce to the value 11.5%, as the linear loads are added in the period, which increases the fundamental component and hence reduce the TDD. The TDD value return to 20% as the linear loads are switched off.

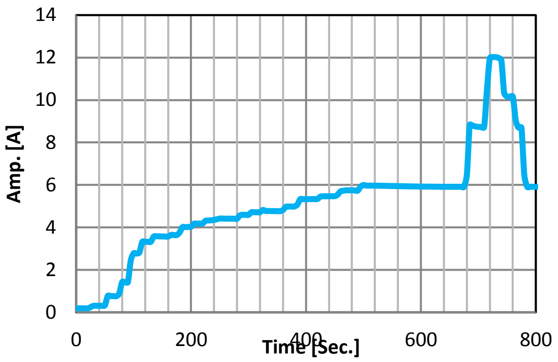


Fig. 21: Variation of RMS Current.

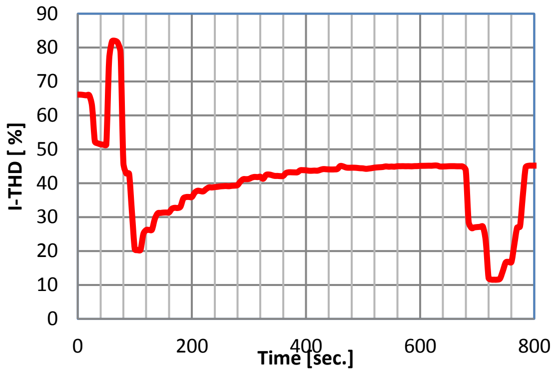


Fig. 20: Variation of THD Current.

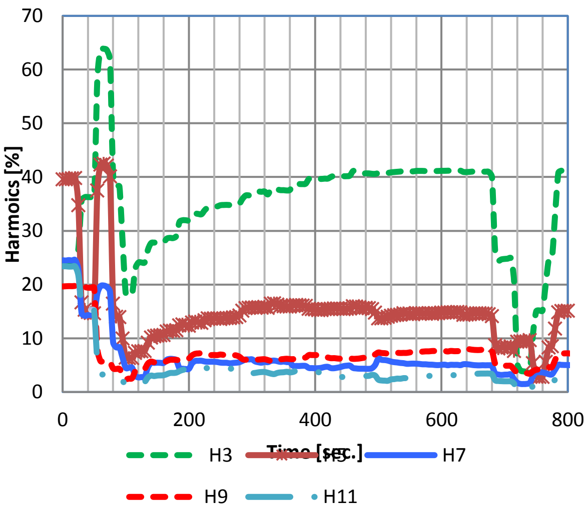


Fig. 22: Harmonics Contents Profile during the Test Period.

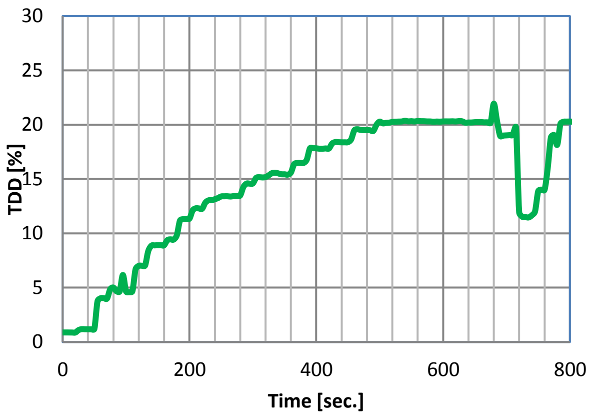


Fig. 23: Variation of TDD Current during the Test Period.

3. Conclusion

The paper has investigated the harmonics distortion profile produced by several single phase loads in typical Jordanian residential systems. The interaction between these loads and their contribution to the net harmonics distortion and THD at main distribution board has been analyzed and explained.

Mixing the loads between linear and non-linear loads reduce the current THD from one side and can negatively increase voltage distortion from other side. Non-linear current flows in system impedance increases the voltage distortion. However, the voltage distortion was within the acceptable standard limit. Harmonics cancelation and reduction are studied. Two main factors affect the level of reduction; adding more linear loads i.e., increase of fundamental currents and the appearance of opposite angles of the same harmonic content in different loads.

For the studied system, the average current THD varies between 81.8 % to 11.55%, where 3rd and 5th are the dominant harmonics orders. The TDD varies between 2% to 20.3%, the upper value reaches to limitation in IEEE519. Over the course of normal equipment operation, the average observed current THD value was 45%, where common operated home appliances are non-linear which produce high harmonics distortion.

As the current industries trend moving towards more and more utilization of power electronics technologies in modern home appliances, it is highly recommended to update the measurement of harmonics for future houses to monitor and identify the change in the power quality profile and avoid unsafe system operation. Additionally, there is a need for updating international standards to regulate the harmonics level of small home appliances as is expected that the new houses include 100% non-linear load. Furthermore, the recent Jordanian energy's regulations allow the customers to install photovoltaics system at their premises. Under these conditions there is need for harmonic investigation studies as the non-linearity in the system will increase and the harmonics pollutions in the low voltage networks might exceed it is safe limits.

Acknowledgement

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