Power Quality Assessment and Analysis for Low Voltage Distribution Networks

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Abstract— Due to high application of non-linear loads and energy-saving devices at low voltage networks, power quality (PQ) assessment and investigation becomes an important requirement for electrical systems. Such a step is required to reveal the current situation of power quality, identify the margin from the unsafe boundary and take necessary remedial actions. The purpose of this paper is to investigate and assess the current situation of power quality of a low voltage distribution system within the Jordanian electrical system. The study was conducted for aggregated commercial and residential facilities. Several power quality parameters are monitored: Voltage distortion, current distortion, and power factor. Detailed measurement results and analysis are presented and explained. Among different power quality disturbances, load unbalance and distorted waveform of the current are observed. The results show that current unbalance reaches as high as 56% of the phase current. High total harmonic distortion (THD) level in the current is also observed. Its maximum value reaches 30.36%, while the Total Current Demand Distortion (TDD) level reaches as high as 10%.

Keywords— Harmonics distortion, non-linear loads, online measurement, power quality.

I. INTRODUCTION

In recent years, there has been an increased concern and emphasis on the quality of power delivered to factories, commercial establishments, and residences [1]-[6]. This is due to continuous increase and high penetrations of non-linear loads and power electronics based loads such as: adjustable-speed drives, switching power supplies, arc furnaces, electronic fluorescent lamp ballasts and other harmonic-generating equipment. Further, utility switching and fault clearing produce disturbances that affect the quality of the delivered power. Poor power quality can affect the accuracy of utility metering, protective relays to malfunction, equipment downtime and/or damage, resulting in a loss of productivity, problems with electromagnetic compatibility and noise [7]-[8]. Nonlinear loads are most often based on power electronics. The share of such loads is growing rapidly worldwide. It has been estimated that by 2016, the residential and commercial loads (with highly nonlinear loads) on the Jordanian electrical system reaches as high as 50% [9].

The common power quality definition can be divided into two parts[7]-[8]: from a customer's prospective, the ability of a power system to operate loads without disturbing or damaging them is mainly concerned with voltage quality at points of common coupling between customers and utilities; and from utility prospective, the ability of loads to operate without disturbing or reducing the efficiency of the power system is mainly but not exclusively concerned with the current quality of the load’s waveforms.

In literature, many studies and projects addressed the problem of PQ and power losses in a low voltage distribution network. The IEEE Std. 1100 defined Power quality as “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment” [10]. It is a set of electrical boundaries that ensures a piece of equipment to

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operate normally without a significant loss of performance or life expectancy. One of the main issues of PQ is the mitigation of disturbances resulting from the harmonic components of the current and voltage waveforms. The aim of distribution companies is to supply consumers with more reliable, sustainable and high quality electrical energy. In [11], the optimal operation of distribution networks is visualized under the influence of harmonics. In [12], the influence of harmonics on a medium voltage distribution system is studied with nonlinear residential loads. Some studies show that in many countries the growth in energy systems does not match the growth in power quality awareness [13]. In [14], the severity of PQ disturbance is investigated.

The financial cost caused by the PQ problems is very huge; therefore, the sustainability and efficiency of the power system essentially require understanding and analyzing the PQ phenomena based on measurements.

There are many classifications of PQ disturbances. According to the Institute of Electrical and Electronic Engineers (IEEE 1159), power quality disturbances are classified into categories [15]: Transients, short duration variations (short interruptions and voltage dips or voltage sags) and long-duration variations. The category of long-duration variations is added to deal with and include long interruptions, undervoltages and overvoltages, voltage unbalances, voltage fluctuations, power frequency variation and waveform distortions. Among these disturbances, waveform distortions (harmonics) are most common in low voltage networks.

II. HARMONIC ANALYSIS AND DECOMPOSITION OF DISTORTED WAVEFORM

Any periodic waveform can be deconstructed into a sinusoid at the fundamental frequency with a number of sinusoids at harmonic frequencies. Depending on the kind of waveform, these coefficients may or may not exist. A d.c. component may complete these purely sinusoidal terms. This concept can be explained by the following equation [7]-[8]:

$$f(t) = \frac{a_o}{2} + \sum_{n=1,2,3...}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \quad (1)$$

Where *f(t)* is a generic periodic waveform; a_o is the d.c. component; a_n, b_n are the coefficient of the series; and *n* is an integer number between 1 and infinity.

The coefficients of the series can be calculated as follows:

$$a_o = \frac{1}{(T)}\int_0^T \sqrt{2}V_p \sin\omega t \, d(\omega t)$$

$$a_n = \frac{1}{(T/2)}\int_0^T v_s \cos n\omega t \, d(\omega t) = \frac{1}{(\pi)}\int_0^{2\pi} V_p \sin\omega t \cos n\omega t \, d(\omega t)$$

$$b_n = \frac{1}{(T/2)}\int_0^T v_s \sin n\omega t \, d(\omega t) = \frac{1}{(\pi)}\int_0^{2\pi} V_p \sin\omega t \sin n\omega t \, d(\omega t)$$

$T=2\pi$ is the period. Harmonic pollution on a power line can be quantified by a measure known as total harmonic distortion or THD [1]. THD is the ratio of the rms value of harmonic components to the rms value of fundamental component.

The total harmonic current distortion factor (THD_I) can be calculated by:

$$THD\%\big|_I = 100\% \times \sqrt{\sum_{h\neq 1}\left(\frac{I_h}{I_1}\right)^2} \tag{2}$$

where I_1 is fundamental rms current component; I_h is harmonics rms current component.
The total harmonic voltage distortion factor (THD_V) can be calculated by:

$$THD\%\big|_V = 100\% \times \sqrt{\sum_{h\neq 1}\left(\frac{V_h}{V_1}\right)^2} \tag{3}$$

where V_1 is fundamental rms voltage component; V_h is harmonics rms voltage component.
Another useful index for the current is the Total demand distortion (TDD). Equation (4) describes this index. In this index, the sum of the harmonics is compared to the demand current not to the fundamental current as in (THD):

$$TDD\%\big| = 100\% \times \sqrt{\sum_{h\neq 1}\left(\frac{I_h}{I_L}\right)^2} \tag{4}$$

where I_L is the demand current during the test period.
TDD(I)=Total Current Demand Distortion calculates harmonics current distortion against the full load (demand) level of the electrical system.
With the existence of harmonics, power factor (PF) is also affected. PF can be computed by two methods: displacement power factor (DPF) and apparent (true) PF. Both give identical results for sinusoidal (non-distorted) voltage and current waveforms. However, they are different under distorted voltage and/or current waveforms. The DPF is based on the fundamental component of line frequency, while harmonics contents are considered for the calculation of true PF. The relationship between PF and DPF can be expressed as follows:

$$\left.\begin{aligned} V_{rms} &= V_1\sqrt{1+THD_V\,\%} \\ I_{rms} &= I_1\sqrt{1+THD_I\,\%} \end{aligned}\right\} \tag{5}$$

$$PF = \frac{P}{S} = \frac{P}{V_{rms}\times I_{rms}} = \frac{P}{V_1\sqrt{1+THD_V\,\%}\,I_1\sqrt{1+THD_I\,\%}} \approx \frac{P}{V_1 I_1\sqrt{1+THD_I\,\%}}$$

$$PF = DPF \times \frac{1}{\sqrt{1+THD_I\,\%}} \tag{6}$$

III. System Information and Measurement Setup

Fig. 1 below shows a single line diagram for the electrical system under the study. This system is an aggregated commercial (university school) and residential buildings. This site is supplied, from the Electricity Distribution Company (EDCO) 33-kV network through a power transformer 33/0.4 kV. The loads at this site are mixed of typical home single phase appliances, some three phase systems, electronics loads, motors, and lighting systems. The measurements were conducted at the main distribution board (MDB) as depicted in Fig. 1.

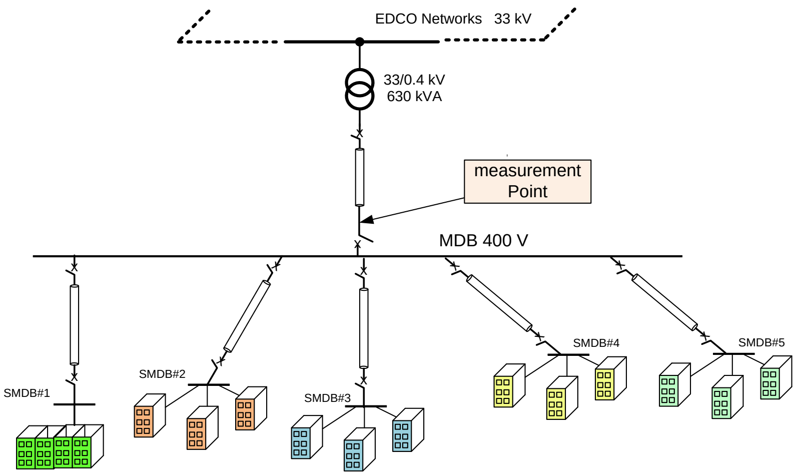


Fig. 1. Single line diagram for the system under the study

IV. MONITORING RESULTS AND ANALYSIS

The voltage, current, power factor, THD and harmonics contents are monitored -as the typical required measurements qualities for power quality investigation- at this site. The measurements are conducted by three phase power recorder Fluke 435-II over almost twenty days.

A) Voltage Profile and Quality

The conducted field measurements show a variation of three phase voltages. This is mainly due to large single-phase loads which account for the majority of power consumption in low voltage residential and/or commercial networks. Plots in Fig. 2 show the variation of three phase voltages. The plots show three values: minimum, average and maximum. As shown in the figure, phase voltages are lightly different from each other. The maximum voltage was 241.45V occurring at phase (B); and the minimum voltage occurred at phase (C) with values of 225.05V. The found average unbalance voltage was less than 2%. The average value of the voltage is within the acceptable value. However, efforts should be made, wherever possible, for uniform distribution of the single-phase loads over three phases to ensure that the expected values of the loads in each phase will be approximately equal.

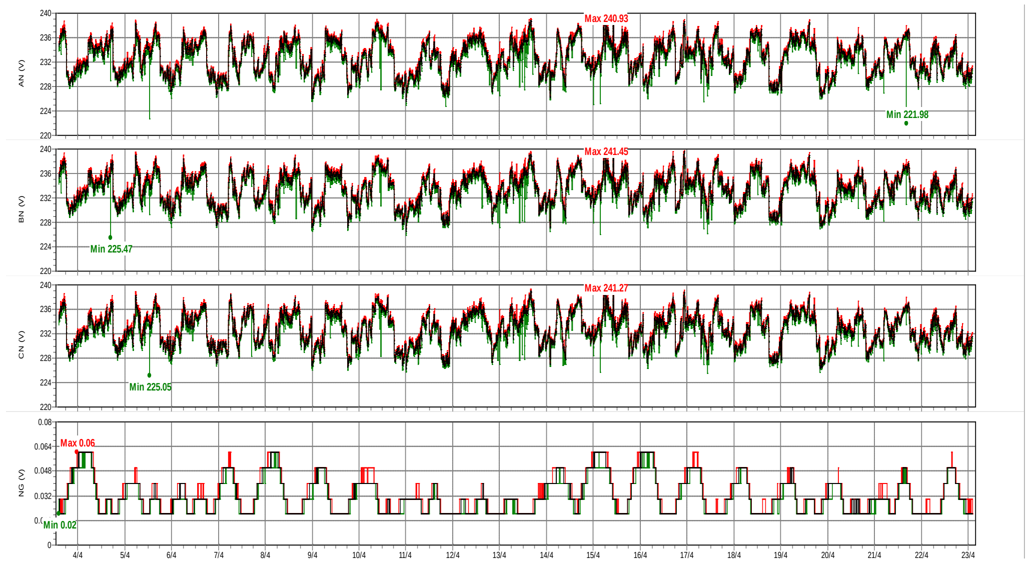


Fig. 2. Voltage profile during the test period: (red line: maximum value; green line: minimum value; black line: average value)

Plots in Fig. 3 represent a variation of the THD and harmonics spectrum for output voltages. The recorded measurement shows that the voltage THD reaches to 2.7%. The dominant harmonics contents in the phase are the 5th and 7th and in the neutral are 3rd, 9th and 15th orders (triplen harmonics). The value of THD is within the acceptable range.

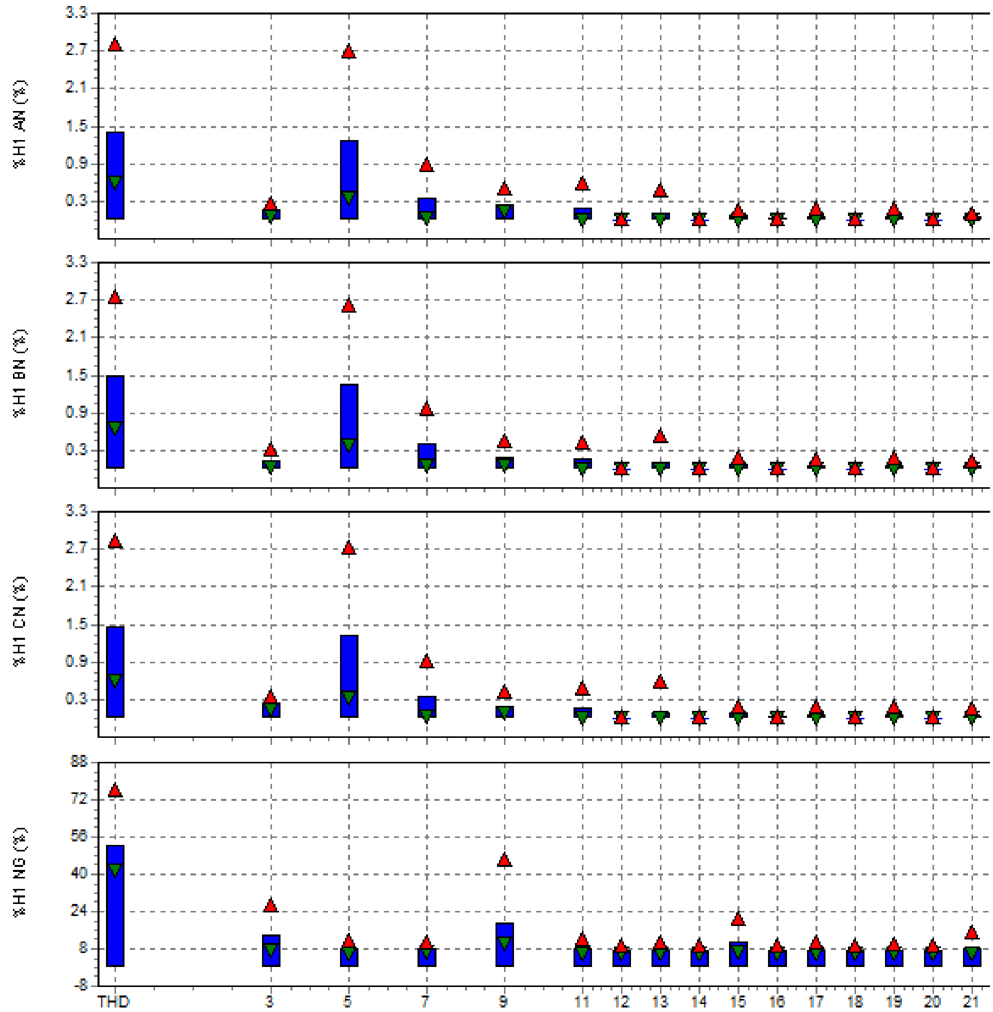


Fig. 3. Harmonics spectrum and THD for phase voltages: (red triangle: maximum value; green triangle: minimum value; blue bar: average value)

B) Current Profile and Current Quality

Plots in Fig. 4 represent the rms currents pattern during the twenty days test period. The plots show the variation of three values of phase currents: minimum, average and maximum. As shown in the figure, phase currents are highly unbalanced; and the maximum and minimum values for phases A, B, C are as follows: 197.6A/22.1A, 185A/17.8A, 179.7A/17.8A, respectively. The neutral current reached as high as 106.4 A where its minimum was 6.9A. The unbalanced current reached as high as 56.63% as shown in Fig. 5. This high unbalance could be attributed to unequal loads distribution on the phases at the installed stage, dynamics operation of the loads or to both conditions.

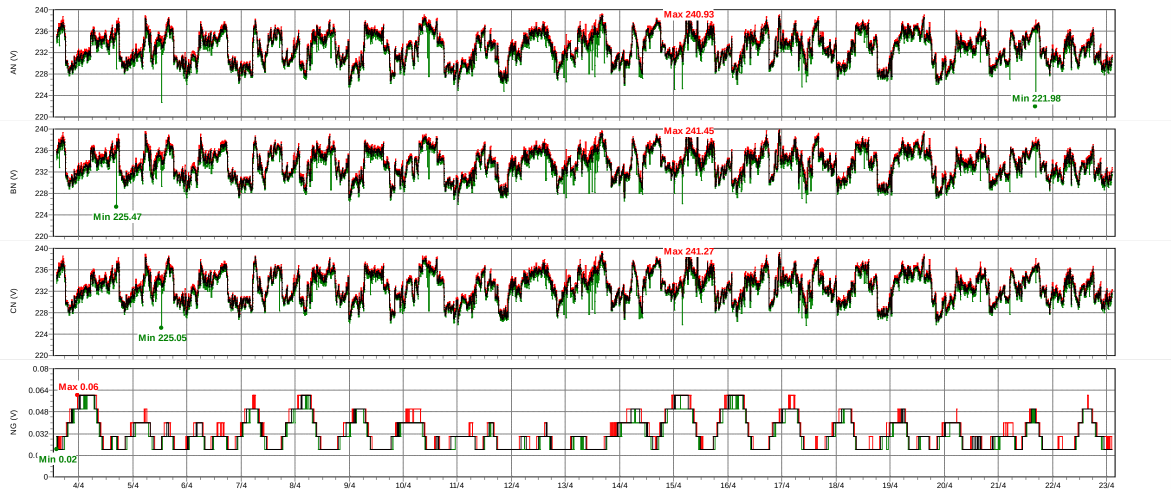


Fig. 4. Current profiles during the test period

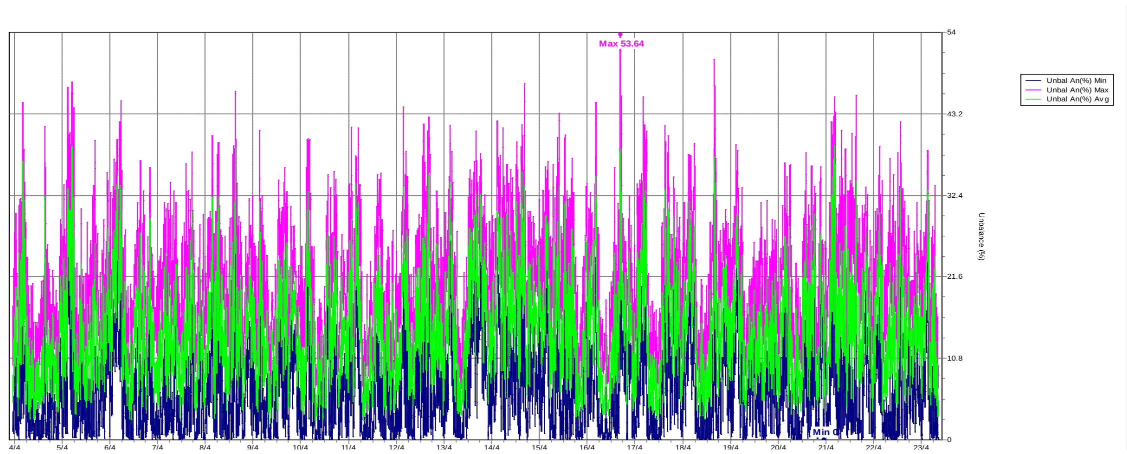


Fig. 5. Unbalanced Current profile during the test period

Plots in Fig. 6 represent THD and harmonics spectrum for the output currents. These values are the maximum, average, and minimum of THD and harmonics contents during the test period. The recorded measurement shows that the current THD reaches to 21.08%, 30.36%, and 31.29% for phase A, B and C, respectively. The recorded average THD values were 8.94%, 11.02%, 11.64%. The dominant harmonics contents in a phase are the 3^{rd}, 5^{th}, 7^{th}, 9^{th}, 11^{th} orders; while 3^{rd} and 9^{th} orders are in neutral.

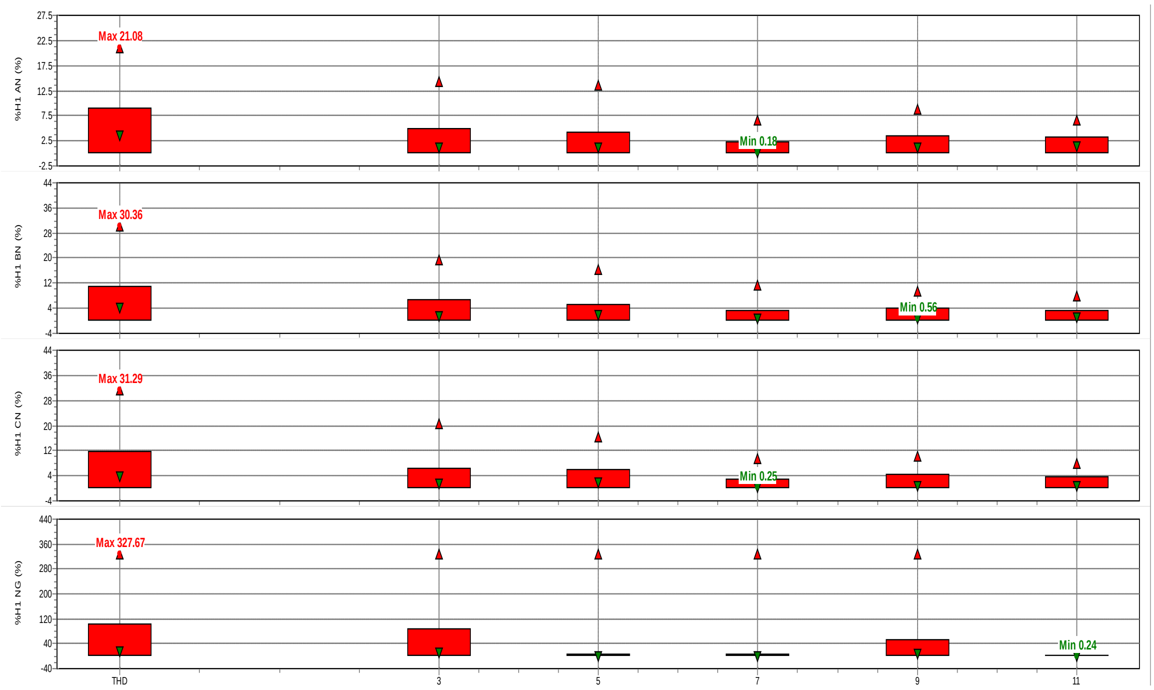


Fig. 6. Harmonics Spectrum and THD for phase currents: red triangle: maximum value; green triangle: minimum value; red bar: average value

For further investigation on the trend of harmonics, Figs. 7 and 8 display the profile of current THD and dominant harmonics order during the test period. The general trend for THD profile is that the recorded high THD was observed between 1.0PM till 6PM. As observed, the phases are rich of 3rd and 5th harmonics. As the measurement point is close to loads location, it is expected to see such orders. The majority of house appliances generate such harmonics. Further investigations are made to observe the TDD profile. High THD occurs actually at light load periods; therefore, using THD index is misleading under this case. For this reason, a more representative harmonics index needs to be used as defined by IEEE 519. Total harmonics distortion (TDD) indicates the moving average of THD. The maximum fundamental load current for phases A, B, and C are 197.4A, 185A, and 179.6A, respectively. TDDs are calculated and shown in Fig. 9. The maximum TDD values for phases A, B, and C are 9.5%, 8%, and 10%, respectively. This, according to IEEE519, is within the acceptable level.

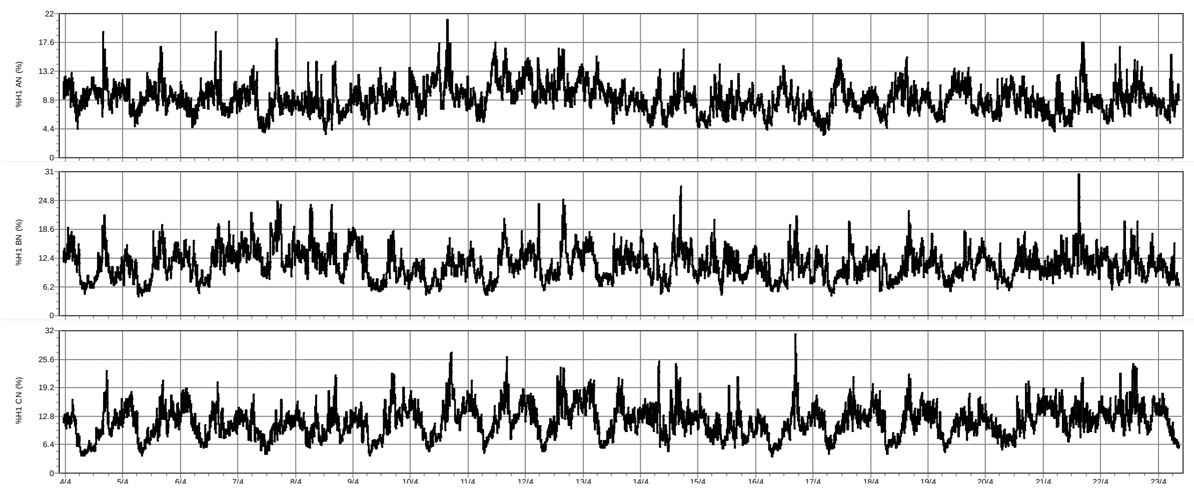


Fig. 7. THD variations for phase currents

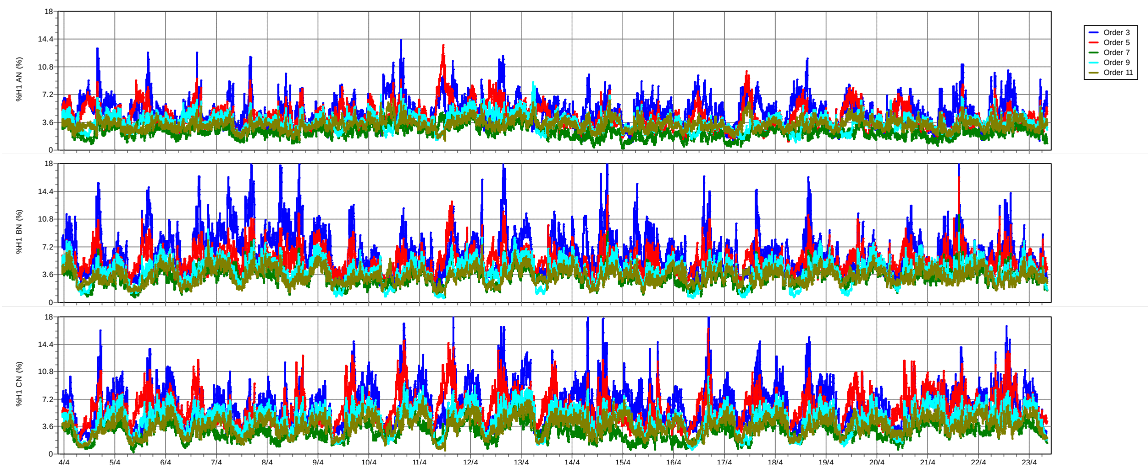
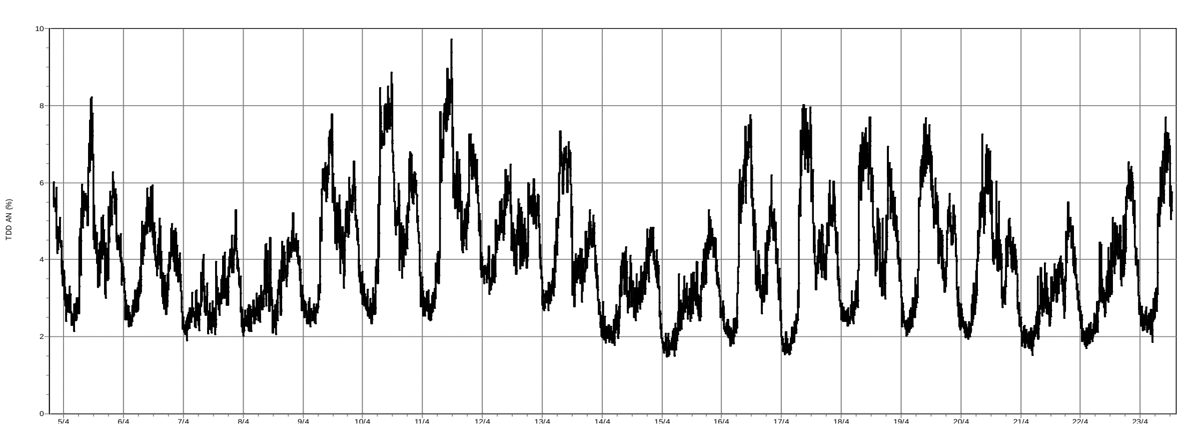
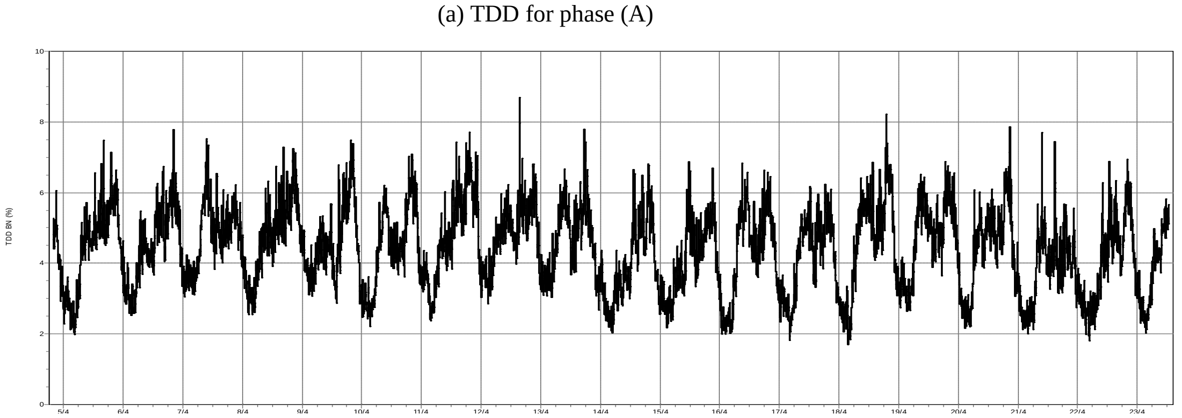


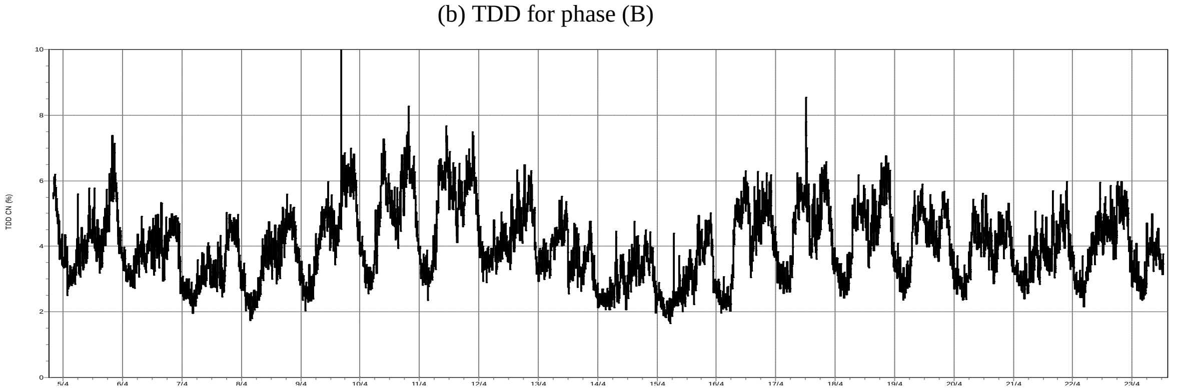
Fig. 8. Variations of dominant harmonics for phase currents



(a) TDD for phase (A)



(b) TDD for phase (B)



(c) TDD for phase (C)

Fig. 9. TDD variations for phase currents: a) phase (A), b) phase (B), and c) Phase (C)

V. DISCUSSION

In this paper, the harmonics at a low voltage distribution system within Jordanian electrical system has been investigated. The monitored parameters are: voltage distortion, current distortion, and power factor. The results obtained agree with the results obtained in similar case studies in literature such as in [12].

Different common solutions are available to mitigate harmonic emissions in a low voltage distribution system. The selection of the best-suited solution for a particular case is not always an easy process. Many options staring from the relocation of loads to a better balance of the system are available. Passive harmonic filters are traditionally used to absorb harmonic currents for their low cost and simple robust structure. On the other hand, active harmonic filters provide multiple functions such as harmonic reduction, isolation, damping and termination, load balancing, PF correction, and voltage regulation [17].

The power factor profile is depicted in Fig. 10. The recorded average PF varies between 0.97 and 0.75, whereas DFP varies between 0.99 and 0.77. Fig. 11 shows the zoom for two days. A low power factor (below 0.85) occurs overnight (12AM till 6AM). A high difference between PF and PDF (hence, more harmonics exists) occurs between 6 AM and 6 PM. The majority of the loads in this period are used for lighting, TVs and other electronics devices. Low true power factor (0.75) needs to be considered for a further discussion between customers and utility.

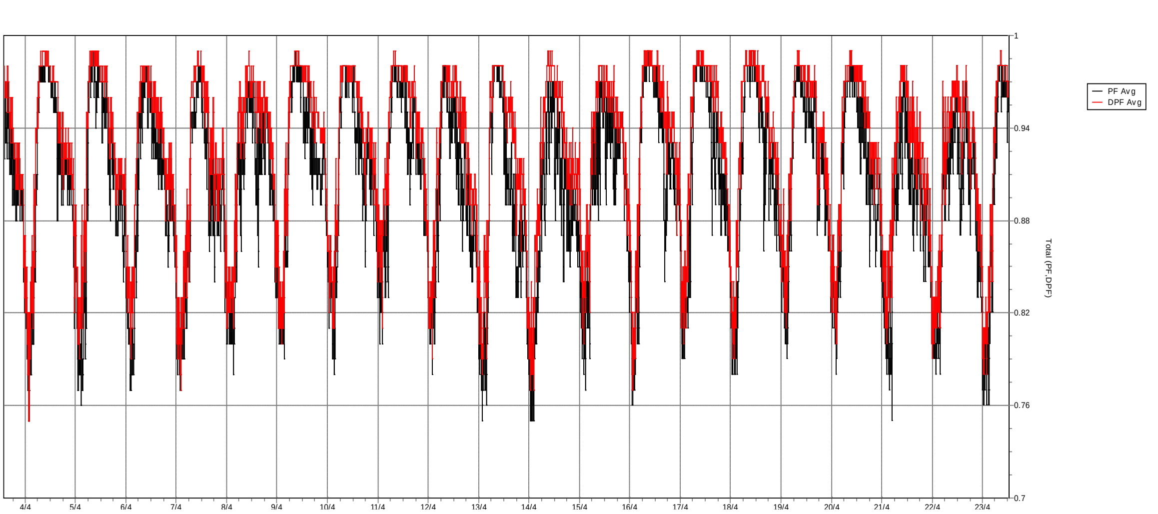


Fig. 10. Variations of PF and DPF

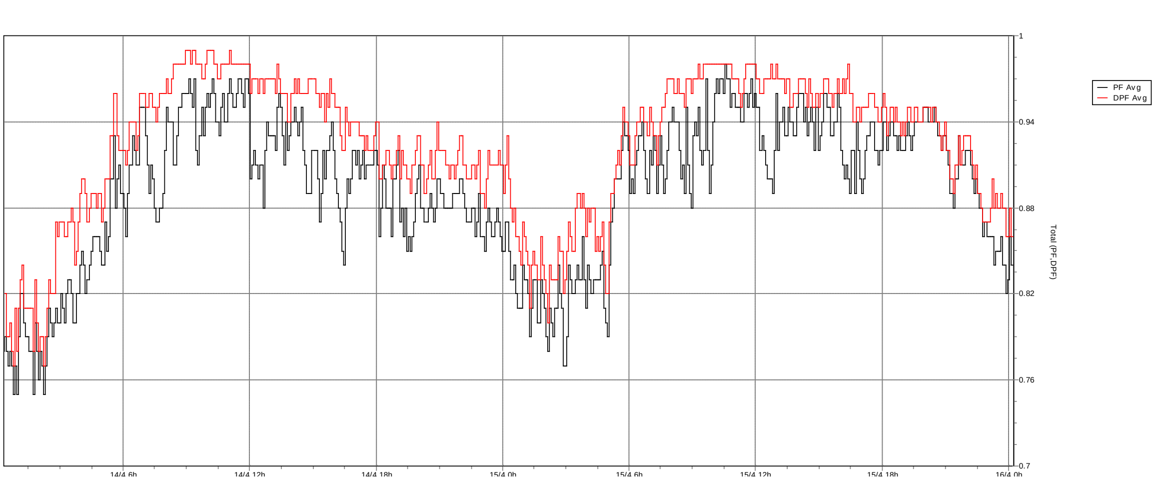


Fig. 11. Variations of PF and DPF for Two days

VI. CONCLUSION

This paper has presented a power quality assessment and investigation for a low voltage distribution system within the Jordanian electrical system, for aggregated commercial and residential facilities. Detailed measurement results and analysis for power quality parameters are presented and explained. The recorded measurements show that the voltage has a good quality in terms of voltage stiffness and distortion level (THD reaches to 2.7%, and 2% voltage variation). The load unbalance and distorted waveform in the current are observed. The results show high current unbalance reaches as high as 56% of the phase current. A high THD level in the current that is also observed; its maximum value reaches to 30.36%, while the TDD level reaches as high as 10%. However, these harmonics contents are still within the acceptance international standards. The low power factor is also observed. The recorded true power factor reached as low as 0.75. Such a value needs to be considered for a future discussion between customers and utility.

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