Investigation of Power Quality Indices in Jordanian Distribution Grid

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Abstract: *The sensitivity and the highly connected modern power systems make Power quality problems a priority in these systems. Both utilities and consumers have essential role in dealing with these problems. It is utilities responsibility to provide a clean and reliable power. On the other hand, it is consumer's responsibility to draw power with acceptable indices. In this Paper, the type of the consumer's facility is chosen as a basis for managing power quality indices. In this paper, comprehensive power quality in Jordan Low-Voltage Electrical Power Grid is measured. The loads are divided into five categories: : (i) industrial loads, (ii) commercial loads, (iii) hospital loads, (iv) residential loads, and (v) office loads. Assuming each category will affect the grid in similar way, which will facilitate prediction of power quality problems. Also, this methodology will help proposing new regulation that governs the relation between utilities and consumers. The power quality indices considered in this paper are; THD, Crest factor, K-factor, Power factor, Harmonic to active power ratio, Voltage imbalance, and Frequency variations. The results show similar results for the loads with the same type. Also, the results show the correlation between the current total harmonic distortion and utility voltages and neutral-to-ground voltage, and between voltage and current imbalance.*

Keywords: *Power quality, Indices, harmonics, distribution grid, Jordan.*

I. Introduction

Recently, Power quality issues attracted more attention from both utilities and electrical power consumers. This attention is driven by several factors; the proliferation of nonlinear loads in power system, the increasing sensitive load equipment to supply variation, , customers awareness about power quality problems, and the probability of failure impact magnification because of network interconnection. A suitable definition of power quality problem could be any variation of voltage, current, and/or frequency that can cause failure or misoperation of electrical equipment [1].

The literature contains many publications contain proposed indices to characterize the power quality for a given site or in the electrical grid. These indices include individual harmonics, total harmonic distortion, flicker, voltage and current imbalance, slow voltage variation, frequency deviation, power factor, and mains signaling [2]–[5]. While standards and many publication measure and tackle each of power quality problems alone[2], [6]–[9], other literature tried to formulate a parameter that combine two or more power quality problems in one index [10][11]. The power quality index for a given site can be specified by two types of measurements: (i) short-term measurements which are used to identify the disturbances in the power signals. The time window for this short-term measurements is 10(12) cycles depending on the frequency of supply 50 Hz or 60 Hz, respectively[12], [13]. (ii) long-term measurements which are used to obtain statistical power quality indices[14], [15]. Till now no benchmark approach is adopted for managing power quality. While most regulatory ask utilities to comply with national or international standards within a given margin, many see the managing of the power quality should be done by deep collaboration between the customers and utilities[16]–[18]. This paper proposes the type of the customer facility as a basis for managing power quality indices. This paper is a continuation of the work presented in [19]. That work focused on just the harmonic index. In this paper a comprehensive power quality indices is measured and analyzed. This paper is organized as following: section II deal with problem formulation and research methodology. Section III is about results and discussion. Conclusions and findings are discussed in section IV.

II. Problem Formulation and Methodology

The power quality assessment in power system includes many indices such as transients, short-term duration variation, long-term duration variation, imbalance, waveform distortion, voltage fluctuation, and frequency variation [7]. The interaction between the consumer's loads and the grid power quality indices is always a controversial issue. This paper is proposed a simple methodology to assess the correlation between consumer's loads and power quality indices. The proposed method classifies the consumers into finite classes. This classification is based on the load category, assuming each load category will mostly have the same types

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of loads, and these loads will affect the grid power quality indices in similar way (i.e. inject approximately the same harmonic pollution type into the grid).

This paper classifies the loads into five distinct load categories: (i) industrial loads, (ii) commercial loads, (iii) hospital loads, (iv) residential loads, and (v) office loads.

The power quality indices used in this paper include: total harmonic distortion (voltage and current), crest factor (voltage and current), K-factor, harmonic power percentage, frequency fluctuation, and power factor.

1. Definitions of measured parameters:
- **Fundamental frequency:** Refers to the power source frequency which is usually 50 Hz or 60 Hz.
- **Total Harmonic Distortion (THD):** The ratio of the root-square for the sum of the square values of all the harmonics to the root-mean-square (rms) value of the fundamental component[6][20] .

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} * 100\%$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} * 100\%$$

Where :
n= the harmonic order
THD_V= the voltage total harmonic distortion
THD_I= the current total harmonic distortion
V_1= the voltage fundamental component.
I_1= the current fundamental component.
V_n= the nth voltage harmonic.
I_n= the nth current harmonic.

- **Voltage imbalance:** is defined as the ratio of the negative sequence component magnitude to the positive sequence component magnitude in a three-phase system, expressed as a percentage[7].

$$Imbalance\% = \frac{|V_{neg}|}{|V_{pos}|} * 100\%$$

Where:
V_{neg}, V_{pos} are the negative and positive sequence components, respectively.
- **Frequency Fluctuation:** is the difference between the grid fundamental frequency and its specified nominal value (e.g. 50 Hz, or 60 Hz) [7].
- **Crest Factor:** The ratio of the peak (max) value (Yp) to the rms value (Yrms) [21].

$$Crest\ factor = \frac{Y_P}{Y_{rms}}$$

- **K-Factor:** is an indication to the transformer capability to dissipate thermal losses under no-sinusoidal current [22]. It can be defined as:
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$$K - factor = \frac{\sum_{n=1}^{n_{max}} (nI_n)^2}{\sum_{n=1}^{n_{max}} (I_n)^2}$$

- **Active Phase Power:** $\frac{1}{N}\sum_{n=k}^{k+N} V_x(n).I_x(n)$
- **Total Active Power for Y connection:** $P_{total} = P_A + P_B + P_C$
- **Total Harmonic Power=** $\sqrt{S - S_1}$

where
S is the apparent power, S_1 is apparent power for the fundamental component
- **System power factor Y and Δ: PF = P/ S**

2. Data collection and analysis scheme
The methodology of this paper includes:
1. Collecting the Data through field measurements for the major power quality indices
The data collecting is performed as follows:
A. At first four cities are chosen these cities consume the major portion of electrical power in Jordan , the proposed cities are characterised as:
- 1(Amman): represents the city with the highest number of population
- City#2 (Karak): represents the city that includes some bulky consumers
- City#3 (Tafila): represents a city that contains an installed renewable energy projects.

- City#4 (Zarqa): represents the city with industrial base.
B. Different locations at each city are chosen in order to measure the major power quality indices. These locations will include industrial facilities, malls, residential buildings, and governmental buildings, etc. Some of these measurements are shown in Fig.1
C. Three-Phase Power recorder is used to carry out the measurements. These measurements will be through different times, days, months, and years.
2. Statistical techniques are used for data analysis. The data analysis will show the following:
A. The power quality indices considered in this paper are:
  i. THD
 ii. Crest factor
iii. K-factor
 iv. Power factor
  v. Harmonic to active power ratio
 vi. Voltage imbalance
vii. Frequency variations
B. The average values are calculated as
  i. All the samples from the same category (i.e. commercial loads) will be combined to form one big file including all collected measurements.
 ii. The sample average is calculated as:

$$\text{Average} = \frac{\sum_{i=0}^{N} x(i)}{N}$$

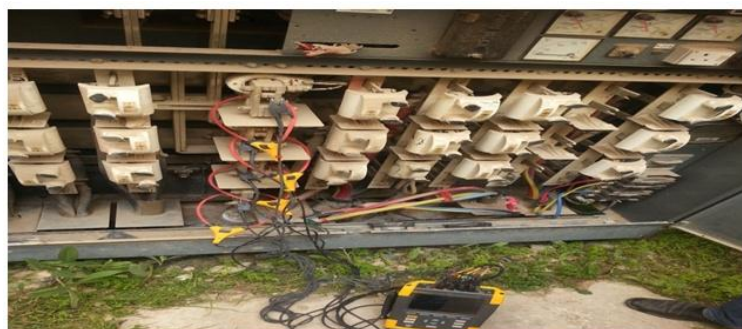Where *x(i)* is the ith sample and N is the number of samples.

Fig. 2 Some of Cites Measurements

III. Indentations and Equations (11 Bold)

All the measurements in this research is carried out by Fluke 435-II/437-II Three Phase Energy and Power Quality Analyzer.

All the harmonic analysis is based on FFT algorithm. The FFT algorithm in accordance with IEC 61000-4-7 is used to calculate the fundamental and harmonic components of each input signal over a 10 cycle (50 Hz) time window.

Table 1 shows the average voltage THD values for each load category and for the four cities. Each value represents the average of the three phase THD values. For the recorded loads all the average values are within the ranges of IEEE Std. 519-1992. Table 2 shows the average current THD values for each load category and for the four cities. The first note about these data is that a lot of these values exceed the 5% THD limit in IEEE Std. 519-1992. The industrial sector has the highest THD average value for the four cities, which is normal due to the extensive use of motor drive converters and Arc furnaces. The Office sector, which includes a lot of computer loads, CFL, and LED lighting, comes second. The commercial sector, has an interesting results. Cities #1 and #4 have similar results while cities #2 and #3 have similar results but they are relatively far from each other. This can be explained by the nature of these cities. Cities #1 and #4 are modern cities and include a lot of big malls, which have many nonlinear loads such as escalators and LEDs. On the other hand cities #2 and #3 are rural areas and have only small to medium shops.

Table 3 and Table 4 show the average crest-factor values for the voltage and current, respectively. The Ideal value for a crest factor is *1.414,* which represent a pure sinusoidal signal. While most of the measured voltage crest-factor values are close to the ideal value by *±0.1,* the current crest-factor values are above this ideal value. This indicates a deformation in the current waveform and a higher peak values comparing to the rms values, which can affect normal power supplies.

Table 1 Average phase voltage THD

Voltage THD %				
	City# 1	City# 2	City# 3	City# 4
Comm.	1.335	1.991	1.462	0.826
Office	1.304	1.177	1.174	1.532
Hosp.	1.651	1.071	1.117	1.637
Indus.	1.180	1.906	4.279	1.884
Resid.	1.334	0.938	1.619	1.701

Table 2 Average phase current THD

Current THD %				
	City# 1	City# 2	City# 3	City# 4
Comm.	7.080	4.228	4.327	7.049
Office	6.458	11.094	1.148	5.545
Hosp.	6.531	5.336	4.763	6.176
Indus.	7.908	3.882	6.536	6.824
Resid.	6.536	5.691	4.842	4.593

Table 3 Average phase voltage crest factor

Voltage Crest Factor (Average)				
	City# 1	City# 2	City# 3	City# 4
Comm.	1.422	1.410	1.410	1.425
Office	1.394	1.420	1.396	1.397
Hosp.	1.408	1.407	1.392	1.409
Indus.	1.398	1.421	1.423	1.453
Resid.	1.400	1.397	1.403	1.394

Table 4 Average phase current crest factor

Current Crest Factor (Avearge)				
	City# 1	City# 2	City# 3	City# 4
Comm.	1.483	1.512	1.487	1.457
Office	1.403	1.430	1.516	1.494
Hosp.	1.625	1.568	1.452	1.475
Indus.	1.402	1.548	1.440	1.669
Resid.	1.570	1.503	1.550	1.490

Table 5 shows the average K-factor for the three phase currents. It indicates that most values are exceeding the value for a linear load, which is one. These measured values can help the utilities in systematic dating of their working transformers. The measured line frequency is shown in Table 6. These values show the stability of frequency in Jordanian power grid. The standard deviation for these values is equal or les *0.1*. the consistency in frequency in power system is essential for the stability of these systems. Also, this value defined the fundamental frequency. Any deviation from this nominal value will affect many of the equipment connected to the grid. Voltage imbalance is shown in Table 7. All the measured voltage is within the standards limits, which limit the voltage imbalance to *2%* in the PCC. The excessive voltage imbalance can cause motors overheating and can worsen the current imbalance problem.

Table 5 Average phase voltage K-factor

Current K-Factor (Avearge)				
	City# 1	City# 2	City# 3	City# 4
Comm.	1.614	1.062	1.073	1.033
Office	1.050	1.158	1.312	1.103
Hosp.	1.261	1.262	1.362	1.158
Indus.	1.042	1.471	1.030	2.045
Resid.	1.447	1.070	1.120	1.051

Table 6 Frequency

Frequency				
	City# 1	City# 2	City# 3	City# 4
Comm.	49.955	50.056	50.067	49.847
Office	50.122	50.002	49.956	49.766
Hosp.	50.057	50.078	50.054	49.793
Indus.	49.952	49.986	50.045	50.073
Resid.	49.968	49.813	50.003	50.044

Table 7 Voltage imbalance

Voltage imbalance %				
	City# 1	City# 2	City# 3	City# 4
Comm.	0.620	0.305	0.534	0.679
Office	0.385	0.253	0.508	0.886
Hosp.	0.302	0.305	0.371	0.507
Indus.	0.353	0.581	0.431	0.359
Resid.	0.375	0.320	0.304	0.217

Table 8 shows the average power factor. As expected the residential loads have the highest power factor, since most of these loads are not highly inductive. The industrial loads have the lowest values. One important note that the power factor does not depend only on the inductive loads, also highly non-linear load could affect the power factor and this explain the low power factor for the commercial load in city#4 . Another important aspect of power quality indices is shown in table 9 which represent the ratio between the total harmonic power and the total active power as percentage. It is well known that the useful power is that obtained from the fundamental component, while the harmonic power is not useful and can cause problems such as motor and transformers overheating.

Table 8 Average power factor

Power Factor (average)				
	City# 1	City# 2	City# 3	City# 4
Comm.	0.659	0.971	0.889	0.899
Office	0.897	0.867	0.812	0.900
Hosp.	0.861	0.916	0.874	0.969
Indus.	0.791	0.894	0.842	0.850
Resid.	0.918	0.905	0.945	0.920

Table 9 Ratio between total harmonic power to total active power

Total Harmonic Power/ Total Active Power %				
	City# 1	City# 2	City# 3	City# 4
Comm.	0.056	0.060	0.176	0.020
Office	0.083	0.089	0.060	0.057
Hosp.	0.050	0.082	0.018	0.030
Indus.	0.119	0.138	0.084	0.140
Resid.	0.038	0.077	0.101	0.080

The interaction between the current harmonics and the grid voltages are also investigated. The most correlation is found between the load current and the voltage between neutral-to-ground. Fig.2 shows the THD level in the *phase A* current and THD level in neutral-to-ground voltage for a hospital load. The figure shows measured THD over one week period. The correlation coefficient between THD in Phase current and THD in neutral-to-ground voltage is *0.505* comparing to *0.1187* between THD for phase current and phase voltage. The correlation factor is *0.005* between the phase current and neutral current. A similar correlation factors are found for other load types. Another interesting finding is shown in Fig.3 which is the periodicity in the THD level in the phase voltages.Fig.3 shows the THD level in the phase voltages for the three phases. This THD is for hospital load and is measured over one week period.
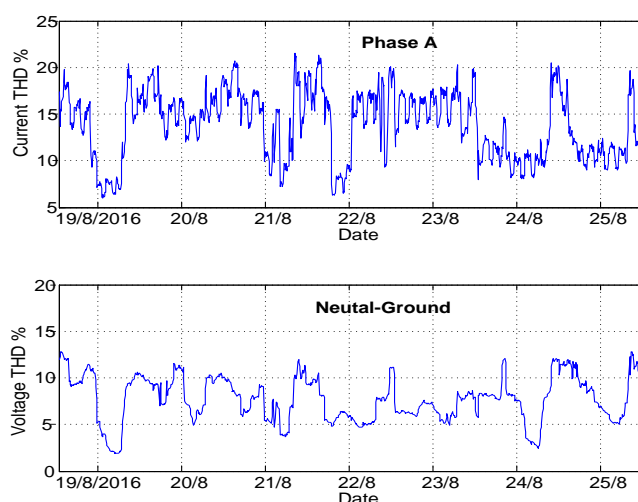

Fig.3 THD level in the *phase A* current (upper) and THD level in neutral-to-ground voltage (Lower) for a hospital load
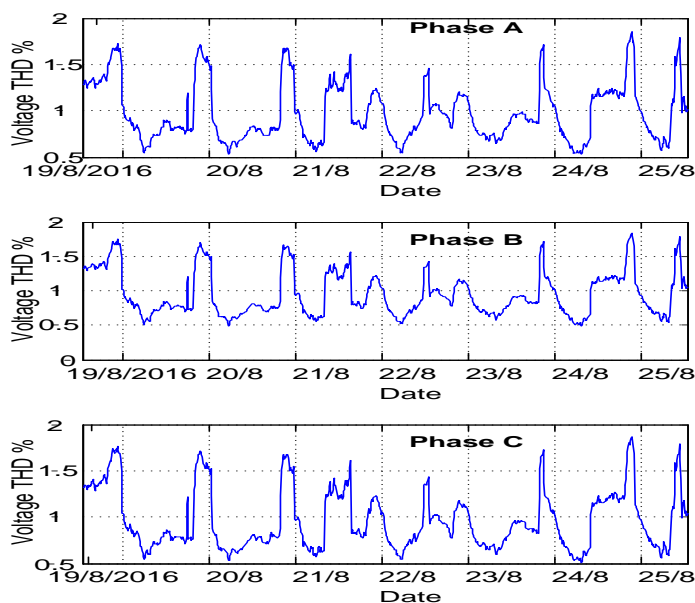

Fig.4 Time evolution for THD of the three phase voltages

Fig.4 shows the relation between the voltage and current imbalance. The upper part represents the normalized voltage and current imbalances that are calculated as the ratio between the negative and positive sequences. The lower part represents the normalized voltage and current imbalances that are calculated as the ratio between the zero and positive sequences. The correlation factors between the voltage and current imbalance is *0.7242* for the lower part comparing to *0.1241* to the lower part.
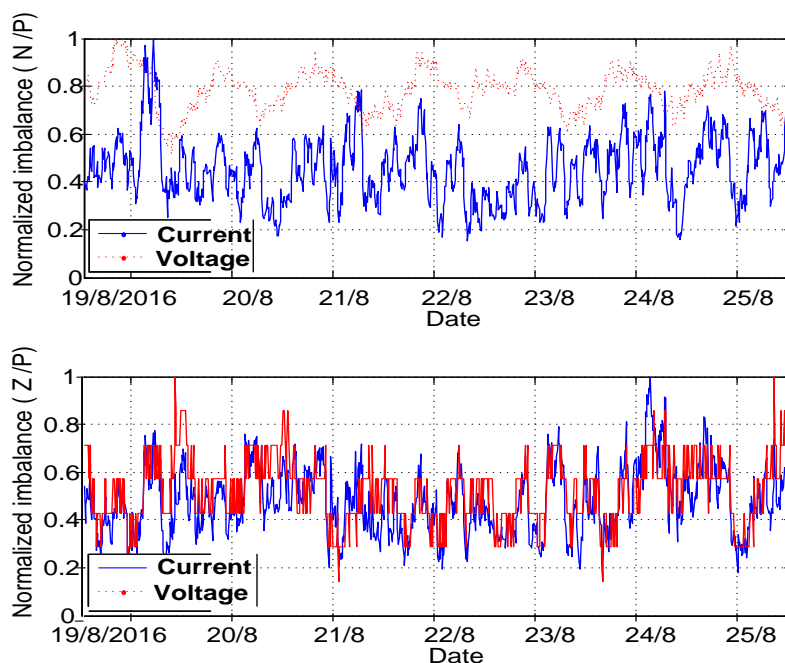

Fig. 5 Normalized voltage (solid) and current (dashed) imbalnce.

IV. Conclusion

In this Paper, power quality indices in Jordanian low-voltage power grid are investigated. Field measurements for the major electrical units in JLVEPG are carried out for different locations in multiple cities. These measurements are followed by extensive data analysis techniques in order to identify THD, Crest factor, K-factor, Power factor, Harmonic to active power ratio, Voltage imbalance, and Frequency variations. The electrical loads were categorized into five sectors which are: commercial, governmental, hospital, industrial, and residential. The results show similar results for the loads with the same type. Also, the results show high correlation between the current total harmonic distortion and utility neutral-to-ground voltage. Also, the results show the interaction between voltage and current imbalance. This paper can be used as a basis for developing new regulations that govern the relation between the utilities and the consumers.

Acknowledgements

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