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Impact Study of Wind Generation on power quality of Electrical Power Grid (Jordan Wind Farm Case Study)

Malik K. Alkasasbeh[1], Eyad K.Almaita[2]
[1]Electrical power and Mechatronics engineering departments /Tafila technical university, Jordan
[2] Electrical power engineering department / Tafila technical university, Jordan

Abstract *Renewable Energy becomes a vital part in modern power system because of; continuous increase of energy demand, global regulations about Co2 emissions, and the slash of the renewable energy prices. Wind energy is a great choice for it is reliability and sustainability. Jordan is a small and ambitious country trying to embrace renewable energy. Jordan Wind Farm (JWF) is the first wind power generation project in Jordan was carried out in Tafilah city. JWF consists of 38 ×3 MW and is connected to 132kV network. Wind energy projects are expected to grow rapidly to fulfill the increasing demand on energy in Jordan. Modern wind turbines are equipped with power converters and permanent magnetic synchronous generators (PMSG). These converters will affect the power quality and harmonic content, which can affect the operation and the reliability of the electrical grid. This paper will study the impact of installing and operating type 4 wind turbines on power quality indices at 132 kv side. Field measurements of power quality indices in JWF substation at Point of Common Coupling, data analysis, and comparison between the measurements and internationals and national standards are carried out. This paper considers several indices such as THD, Crest 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*Wind turbine, Renewable energy, Harmonics, Power quality, Jordan.*

I. Introduction

Conventional energy resources (fossil fuels, natural gas and shale oil) will not sustain forever. With the expected increasing demand, gap between energy demand and the available supply of traditional resources will expand, High energy prices are expected to stay, and negative effects from burning of fossil fuels are playing a significant role in the global climatic change. Effective mitigation of the climatic change necessary requires a huge reduction in the greenhouse gas emissions. The use of cost effective and reliable low carbon electricity generation sources becomes an important aim of energy policy in around world'scountries [1][2].

*Renewable Energy resources like solar radiation and wind energy are desirable for environmental causes (e.g. greenhouses gas reduction) and it considered great alternatives to conventional power resources. Wind turbine farms, which use wind energy, is expected to grow rapidly to fulfill the increasing demand on energy the fastest growth rate of any form of electricity generation with Continuous improvements in turbine efficiency and lower price production with higher fuel prices, Wind power become more economical with respect to conventional power production, at sites with high wind speeds on land. its development simulated by the concerns of climate change, energy security and diversity of supply in past few decades[3][4].

One of the major concerns of adding wind energy projects to the existing power grid is the impact of these projects on the power quality. In literature, there were many researches that observed the impact of wind energy project on power quality indices. In [3] the generator type of wind-power is investigated. The main distinction among them is made between fixed speed and variable speed wind turbine generator concepts. In the early stage of wind power development, induction generators and fixed-speed wind turbines were often used in wind farms. But the limitations of such generators, e.g. poor power quality and low efficiency adversely influence their further application. Wind farms are used in large-scale integration and exploration of wind sources, variable speed wind turbine generators, such as permanent magnetic synchronous generators (PMSGs) and doubly fed induction generators (DFIGs) are emerging as the preferred technology. In paper [6][7] although variable speed wind turbines have better performance in comparison with fixed speed wind turbines, mitigation and compensation may still become necessary as the wind power penetration level increases. The topology and type of power converter used in wind generators have a big impact on power quality. There are many advantages for using voltage source converter (VSC) based STATCOM technique such as; relative independent from the voltage at the connection point, faster response, flexible voltage control, and smooth reactive power control. The converter will produce smooth current with low harmonic content by using high frequency PWM (Pulse Wide Modulation). Other areas in the literature are the power quality indices and the location of measurements. According to [1], power quality issues of wind plants at the Point of Common Coupling (PCC) with the HV transmission network were investigated. Voltage, current, frequency, active, reactive and apparent power, evaluation and analysis of power factor and harmonics were based on IEEE 519-1992. The investigation figured out that the harmonic values of wind plants have a slightlynegative impact on variationin frequency, dip Voltage and current Harmonics. The analysis for power quality indices at medium voltage level of transmission network shows slightly impact from harmonic while the other parameters were mainly good.[8]

The effect of harmonics injected by wind turbine on transformers insulation was investigated In [9]harmonic magnitude increases transformer losses and affects to transformer winding temperature. This will lead to increase H2 content recorded instead of Conventional electromagnetic methods. Then insulation degradation since the insulation nature directly consumes heat from winding. Insulation degradation process indicated by DGA (Dissolved Gas Analysis) test that shows high value of CO & CO2 and H2.but it still in standard range because it happened in short time. Further, it should be considered that the harmonic trending and gas growth to define correlation between harmonic occurred and transformer insulation degradation based on DGA view. Related to study[10]The grid interferences have different causes, which are mostly turbine-specific. Average power production, wind shear and turbulence intensity refer to causes that are determined by meteorological and geographical conditions. However, the technical performance of the wind turbine may also have an influence on grid interferences.

This paper will study the impact of installing and operating for variable speed PMSG -wind turbines on power quality indices at 132 kV side at PCC. A comprehensive power quality indices are measured and analyzed in JWF substation and these values will be compared with international standards and national transmission grid code This paper will consider harmonics, flicker, power frequency, crest factor, and unbalance voltage as power quality indices to assess the impact from wind turbines on local electric power grid and transmission grid.

II. Background and methodology

A. WIND TURBINE CONCEPTS

the wind power is considered to be fully viable as mention in equation (1)[5].

$$\text{output power of turbine (P)} = \frac{1}{2}\rho A C_P V^3 \quad (1)$$

$$T = \frac{P}{W_S} \quad (2)$$

Where $\rho = \text{airdensity}(\text{kgm}^{-3})$,$V = \text{windspeed}(\text{ms}^{-1})$, A=swept area, Cp=performance coefficient

T = mechanical torque and Ws = rotor speed of wind turbine.

There are different types and concepts of the generators used and developed up to now of wind-power application. The major distinction among them is made between fixed speed and variable speed wind turbine generator concepts. In the basic concept of wind power development, fixed-speed wind turbines and induction generators as shown in Fig 1 were often used in wind farms, the limitations of such generators, e.g. poor power quality and low efficiency adversely influence their further application[11].

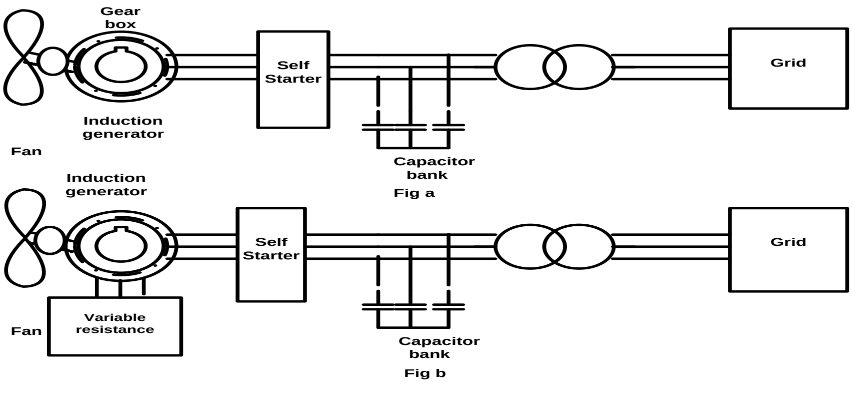


Fig 1 (a) fixed speed wind turbine with Induction Generators (IG)(b) variable speed wind turbine with (WRIG)

Both models and types in Fig 1 are vanished and not used in wind farms the variable speed has become the common type installed and this type is using wound rotor induction generator (WRIG), the limited variable speed wind turbines are designed to improve and extract maximum energy and efficiency .The dominant generators are used in this type induction or synchronous and connected to the grid through power converter ,With large-scale exploration and integration of wind sources, variable speed wind turbine generators, such as doubly fed induction generators (DFIGs) and permanent magnetic synchronous generators (PMSGs) are commonly used as the preferred technology as shown in Fig 2.a and Fig 2 b[12].

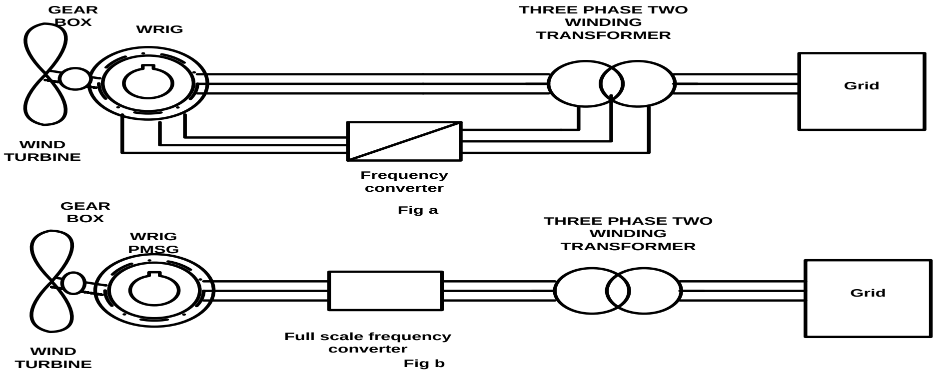


Fig 2(a) frequency converter with double fed induction generators (b) Full scale frequency converter with PMSG or WRSG or WRIG

The main advantage for this type the PMSG doesn't need external excitation current that means less losses and good efficiency and reduced maintenances and increased reliability and WT is the total decoupling between the generator and AC grid and the main disadvantage for this type not only higher cost with respect to others WT type, but also injects more harmonics than WT DFIG [13].Both models in Fig 3and 4 are commonly used in wind farm and full scale frequency converter with PMSG are used in Jordan wind farm in Al Tafilah city

B. POWER QUALITY INDICES

1) Harmonicsdefinitions And Impact

Harmonic distortion, in voltage as well as in current, is due to the presence of nonlinear components in the power system. Even whenthe voltage is sinusoidal, the resulting current could be non-sinusoidal for a nonlinear element

The harmonic sources are divided into three categories (i) small nonlinear components in the power system, e.g. televisions, personal computers, and fluorescent lamps. (ii) diode bridge rectifiers acting as DC current source or DC voltage source [14]. (iii) Large power electronic converters connected to the grid. Power-electronic converters for high voltage direct current (HVDC) transmission have been known as a common source of harmonics for many years. A recent addition to this: are wind power generation systems. The presence of power-electronic converters produces that the harmonic emissions of individual wind turbines and of overall wind parks consisting of multiple turbines have become issues of concern for network operators as well. [15]

Magnetic saturation in power transformer is another source of harmonic another source of harmonics. Power and current Transformers are usually designed to operate very near to the saturation point. When the relation between current and voltage are nonlinear in this case harmonics generate especially when the transformer is operated in an over voltage condition .in the transformer delta winding and in WT the Odd harmonics and triplen harmonics are blocked and can be neglected , then the harmonics being generated are of the orders 5th, 7th, 11th, 13th, 17th, 19th, and so on—i.e., those of orders 6k ± 1, where k is an integer [16]. The several harmonic indices available like total harmonic distortion (THD) where THD is ratio value of the sum of all harmonics components to value of the fundamental components and total demand distortion (TDD). Mathematically formulations represented in equation (3),(4)and (5)[1][17] .

$$\boldsymbol{THD_V = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1}} \qquad (3)$$

$$\boldsymbol{THD_i = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1}} \qquad (4)$$

$$\boldsymbol{TDD = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_R}} \qquad (5)$$

The main impact when the distortion of a voltage or current waveform exceeds certain levels with respect to international standards (IEC, IEEE and EN50160) is failure or damage in equipment. The distorted voltage affects shunt-connected network components (e.g. capacitor banks) and end-user equipment (like compact fluorescent lamps or induction motors); while the distorted current affects series-connected network components (e.g. transformers)and High levels of voltage harmonics may damage capacitors and cause shorter lifespan for capacitor and other equipments. The displacement current through a capacitor increases with frequency, so especially high frequency voltage harmonics may result in overheating and damage of capacitors.Harmonics lead to increase thermal and dielectric stress with capacitors. The thermal stress is proportional to the square of the frequency and the dielectric stress is related to the amplitude of the voltage peak.

All shunt-connected capacitors are impacted by voltage harmonics, Capacitors in the grid, capacitors in wind parks, and also capacitors in end-user equipment [14][15]

Voltage harmonics also increase the thermal dielectric stress of underground cables. High levels of voltage harmonics, especially at higher frequencies, will therefore also result in loss of life-time for cables [18]

- Heating of electrical motors due to voltage harmonics. High levels of especially fifth and seventh harmonic voltage results in currents through induction and synchronous motors that cause overheating and hot spots [19]
- Incorrect operation of protection due to current and voltage distortions , They may result in incorrect operation of protection, especially in unwanted tripping of a protect relay. The consequence of this is that customers experience unnecessary interruptions of the supply [19].
- Failure of electronic equipment. An indirect example is that, the high frequency voltage couples to the electronic or logic circuit, leading to malfunction [19].

2) Flickers

Fickler can be defined as Impression of unsteadiness of visual sensation induced by a light stimulus whose spectral or luminance distribution fluctuates with time [20] or the flicker is the repaid change in fluctuating loads which result in visual sensation as induced by a light stimulus whose spectral or luminance distribution fluctuates with time. the IEC standard provides limit flicker levels in HV system must not exceed certain value as mention in standard [20]or NEPCO transmission grid code .

there are two concepts of flicker the first one is the short term flicker for 10 minutes (Pst) and the second long term flicker (Plt) and they are defined as equation (6) and (7) respectively

$$Pst\Sigma = Plt\Sigma = \frac{1}{S_k} \times \sqrt{\sum_{i=1}^{N}(ci(\psi_k, v_a) \times S_{n,i})^2} \quad (6)$$

$$(Plt) = \sqrt[3]{\frac{\sum_{i=1}^{n} Pst^3}{N}} \quad (7)$$

$$c_i(\psi_k, v_a) = p_{st}\frac{s_k}{s_n}$$

Where $c_i(\psi_k, v_a)$ is a flicker coefficient of the wind turbine for the given network impedance per phase $\psi_k$and for given annual average wind speed v_a at hub height of the wind turbine at the site, $s_n$is the related apparent power of the wind turbine and s_k is short circuit apparent power [20], Flicker limits values are mention in table 3, the flicker effect in some paper and study can be cancellation of fluctuations [21].

Table 1 acceptable limit for flicker

Flicker	**Acceptable limits**
Pst	3%
Plt	1%

3) Power Frequency:

Power frequency is the nominal frequency of the oscillation of Alternating Current (AC) in an electric power grid transmitted from power generation station to the end –user and the frequency in the range used for alternating currents supplying power (commonly 50 or 60 Hz or cycles per second)[22]. The standards provides strict limit of frequency in HV system .table 1 shows the national standard adopted in Jordan according to National transmission grid code [23].

Table2 acceptable frequency

Under **normal operation** and interconnected with other systems	49.95Hz to 50.05 Hz
Under **normaloperation** but not interconnected with other systems	49.95Hz to 50.05Hz
Under **system stress**	48.75Hz to 51.25Hz
Under extreme system fauult conditions all **generating units** should have disconnected by these (high or low) frequencies unless agreed otherwise in writing with the TSO(Trassmission system operator)	By a frequency greater than or equal to 51.5Hz By a frequency less than or equal to 47.5Hz

4) Crest Factor:

Is defined as the ratio of instantaneous peak value to Root Mean Square (R.M.S) value of voltage or current waveform it is a numerical value without any units, the Crest Factor for normal sinusoidal wave is 1.414 [24].

$$\mathbf{CF}=\frac{peakamplitude}{rootmeansquare} \quad \mathbf{(9)}$$

5) Voltage Unbalance (imbalance)

Is defined the ratio of the negative (V_n) or zero(V_z) sequence component to the positive sequence component, the negative and zero sequence voltage in power system result from unbalance loads[25][22].

$$\text{Voltage unbalance} = \frac{\text{max deviation from average voltage}}{averagevoltage} \qquad (10)$$

$$\text{max deviation from average voltage} = \text{max value} - \text{average value}$$

Table 3 Voltage unblance standard and threshold values

No.	Standard	Max.value
1	ANSI (American National Standards Institute)	3.0%
2	NEMA(national equipment manufacturers association)	1%
3	NEPCO(national electrical power company)transmissionGrid Code	1% under

Table 4 acceptable value for voltage harmonics distortion levels

Voltage Level	**Acceptable Voltage Harmonic Distortion Levels**
33 Kv	THD of 6.5% with no individual harmonic greater than 5%
132 kV and higher	THD of 2% with no individual harmonic greater than 1.5%

I. Jordan wind farm layout

Fig.3 shows the Jordan wind farm structure and its location with respect to another substation and these substations connected to the load and factory to consume the power from wind farm. The Jordan wind farm consists of 38 units of V112-3.075 MW, 50 Hz with total installed active power 116.85MW wind turbines farm arranged in eight clusters, each cluster consists of 5 or 4 wind turbines, wind turbine has a 0.65/33 kV transformer which feeds the power into 33KV cable after that export power to two step-up transformer 33/132 KV each transformer connected to the grid during circuit break (C.B), voltage transformer (VT), current transformer and insulators as shown in Fig. 5. All substations are connected together by overhead transmission line as shown in Fig.6.The bus section 33KV remains opened under normal operating conditions with each MV bus bar consisting of 19 of turbines and functioning as two separate power plants.

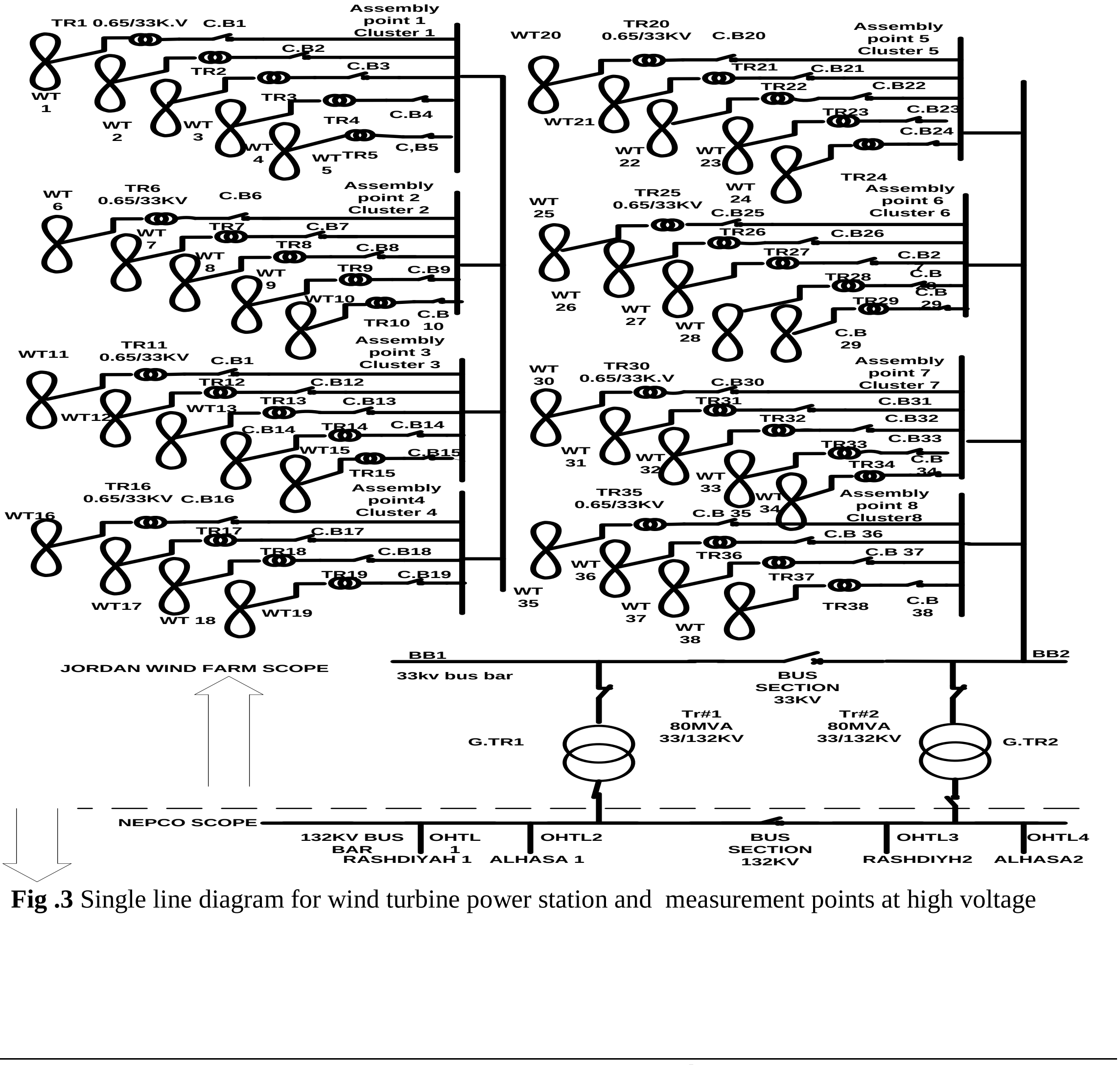


Fig .3 Single line diagram for wind turbine power station and measurement points at high voltage

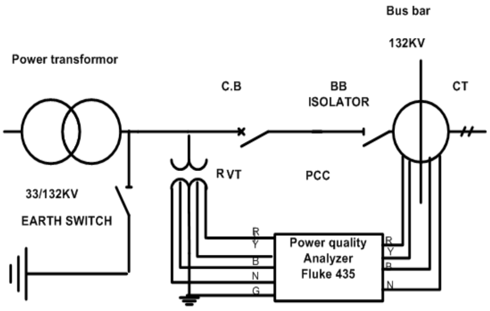


Fig 4 Single line diagram configuration to Substation

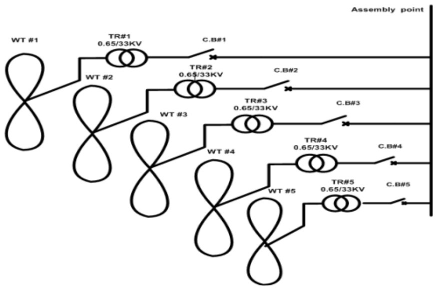


Fig5 Wind turbine cluster

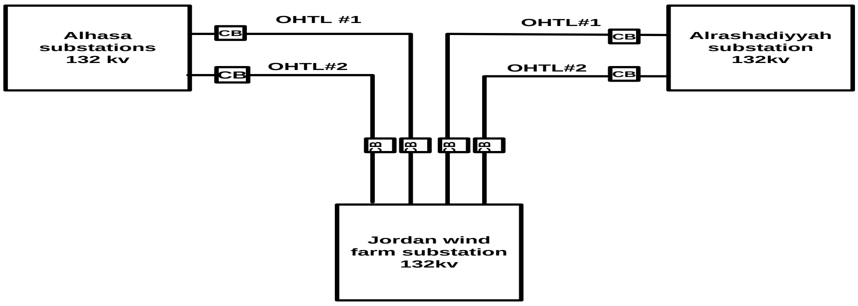
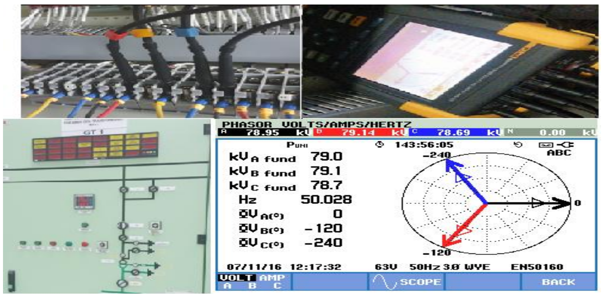


Fig 6 Jordan Wind Farm Location in Electrical Grid

III. Measurement system:

The measurements were performed in order to determine power quality indices like harmonics and flicker and dips in transmission networks.The measurement periods are determined according to EN50160 which is one week long.The measurements were carried out twicein November 2016.The measurement is carried out by power quality and energy analyzer at the PCC of the transmission network with step- up Transformer 33/132 KV in the substation. In the first step for case study is measure the all indices parameters at point one as shown in the Fig 5 for one week the measurement devise will record all values every 10 minutes as a period for recording values and after that we will repeat first step at PCC The measurement results were recorded by power quality analyzer device (fluke 435), the parameters were determined by technique reports and transmission grid code company at Point of common coupling (PCC) as demonstrate in figure 5 at PCC. Some of these measurement picture are shown in Fig7 show that the substation and one of wind turbine from the substation at the site, Fig 8 show the arrangement and type of power quality analyzer was used to measure and Fig 9 show the type of current clamps (i5s) are used to measure the current during the case study.

Fig.7 Wnd substation and Wind Turbine



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PHASOR  VOLTS/AMPS/HERTZ
A    78.95  kV  B    79.14  kV  C    78.69  kV  N    0.00  kV
      PUNI              143:56:05                     ABC
kV A fund    79.0
kV B fund    79.1
kV C fund    78.7
Hz           50.028
ΦV A(°)      0
ΦV B(°)      -120
ΦV C(°)      -240
07/11/16  12:17:32      63V   50Hz 3Ø WYE      EN50160
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Fig.8 Measurement Devise(FLUKE 435-II) and Wiring Configuration

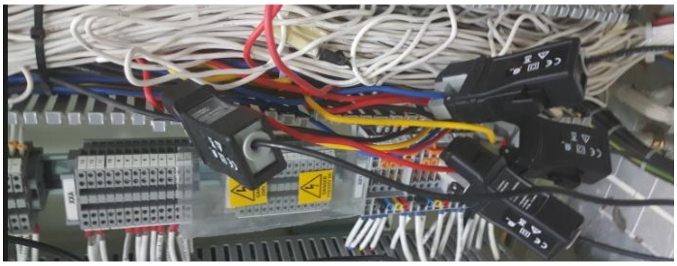

Fig. 9 i5s Current Clamps

IV. Results and discussion

Fig. 10 shows the histogram of the measured phasevoltage to neutral values.These measurements were record between 13-20/11/2016.The maxium and minimum value 80520 and 76908 V, respectively.**.**Fig11 showsthe measured frequency variation over a period of one week.Thevalue of the frequencyis spanned between (49.45-50.46).These values are acceptable and within the limits according to Jordanian national code. Fig 12 shows the measured flicker values parameters over one week. The maximum values for the flicker’s parameters are shown in table 5. Both short and long term flicker are within the acceptable limits.Fig13 shows the harmonics order and their values as percentage from the fundamental component. It is clear that the dominant harmonic is the fifth harmonic and all the individual harmonic values are less than 1.5%..Fig 14 shows THD is less than 1.3% at 132 kV. Fig 15shows the relationship between the active power and wind speed and the estimation relationship using basic fitting in mat lab measurements in Jordan Wind farm substation at NEPCO side. Table 4 shows the acceptable value for total THD or as total harmonic distortion in different level, the study case will deal at 132 KV and higher so the acceptable value are 2% for THD and 1.5% for individual harmonic , and the flicker value less than acceptable limit values .

Table 5 measured values for flicker

Flicker	**Max. Measured value**
Pst	1.965
Plt	0.861

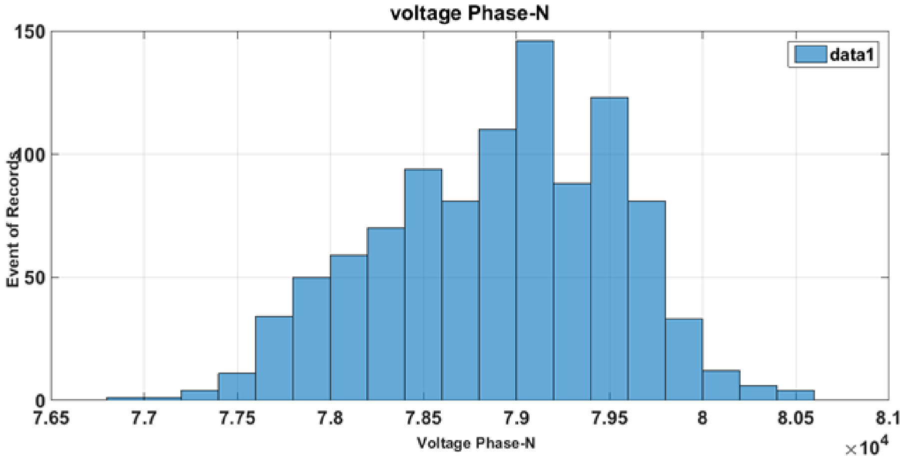

Fig 10 statics analysis for measurements for voltage at PCC

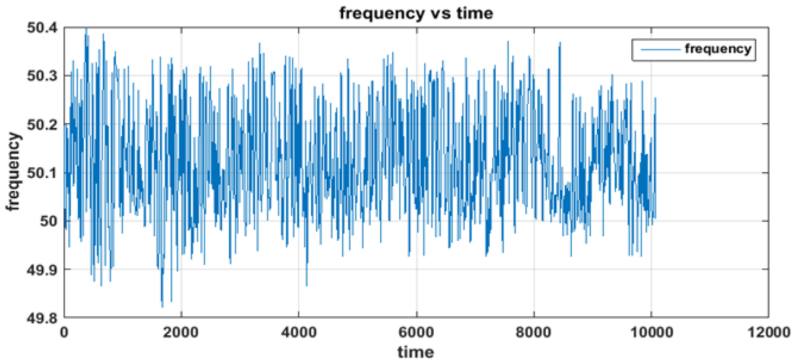

Fig11 frequency value

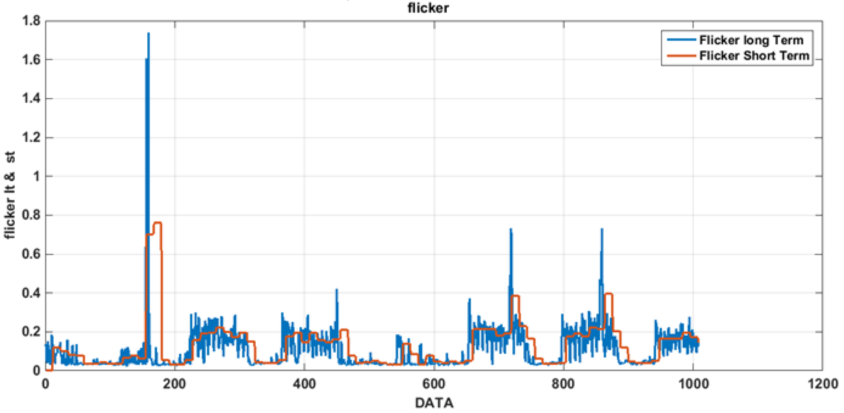

Fig12 flicker parameters

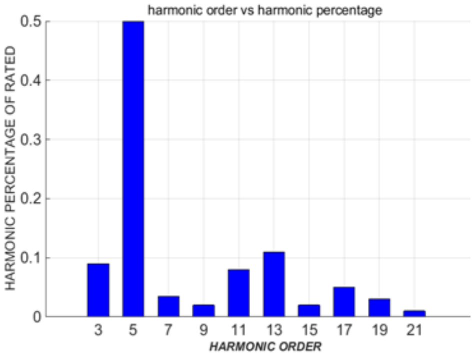

Fig13 measurement results of harmonic on the 132 kV bus bar

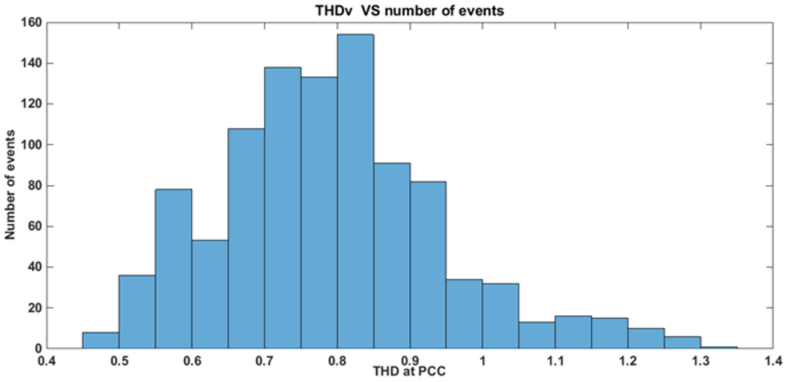

Fig 14 THD mesurment at 132 KV

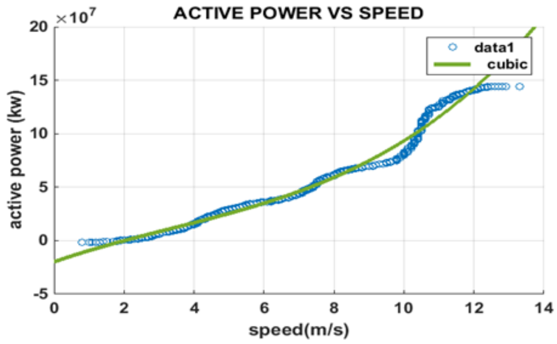

Fig15 active power variation with wind speed

Fig 16 shows inverse relationship between the in current and the active power. it is clearas active power increases the currenttotal harmonic distortion decreases. Fig 17shows the crest factor for wind turbine in Jordan Wind Farm (JWF) is near for sinusoidal wave or equal 1.414 and Fig 18 shown the unbalance for both variable negative sequence (Vn) and zero sequence (Vz) and both of these values are below 1% as pervious mention in table 3

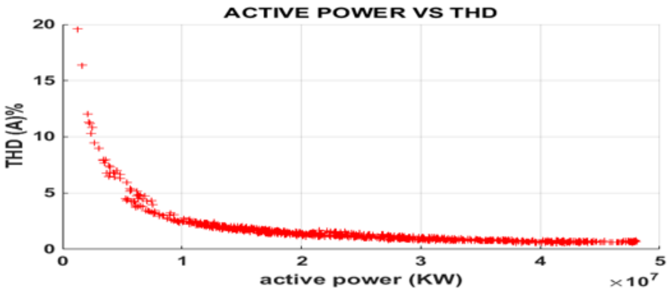

Fig 16 THDA variation with active power for three phase voltage

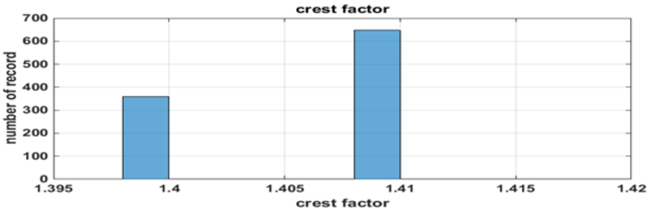

Fig 17 crest factor for phase voltage for wind turbine

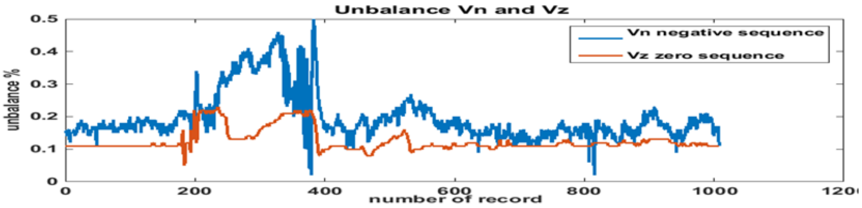

Fig 18 unbalance for wind system

V. Conclusion

In this paper the impact of installing wind energy farm on the power quality of the transmission grid was investigated. The measurements are carried out at point of common coupling. Comprehensive power quality indices comprises of total harmonic distortion, individual harmonics, imbalance voltage, frequency, flicker, and active power. All the obtained results were compared with the national transmission grid code and international standards. The results show that all the major power quality indices are within the standards limits. Total harmonic distortion, individual harmonics, voltage imbalance are within the limits. The results also show that the THD could exceed the acceptable limits in the case of low output power. Future work could include more dynamic analysis of the wind energy farm performance. Also, the JWF farm is the first wind farm in Jordan. In the future the interaction between different wind energy farms may be considered.

Acknowledgements

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