Evaluation of Power Quality of Wind Turbines for AL Maqrun city in Libya

Nafaa Albohli
University of Zawia, Faculty of Engineering,
Sabrath, Libya
E-mail: nafaa.albohli@yahoo.com

Wedad Elosta
Center for Solar Energy Research and Studies
Tripoli, Libya
E-mail: e_wedad@hotmail.com

ABSTRACT

The operation of wind turbines has an impact on the power quality of the electrical grid. The term power quality refers to voltage stability, frequency stability, and the absence of various forms of electrical noise (e.g., flicker and harmonic distortion) on the electrical grid. The power quality will vary from location to location, depending on the nature of the wind resource, the turbine/generator technology used, and the condition of the local electrical grid. The power will fluctuate due to wind speed variations. Power fluctuation is affected by the number of wind turbines and power control technology (pitch and stall regulation).

It is important to study power fluctuations in order to reduce these fluctuations that could affect electrical networks, and therefore to choose a proper wind turbine. Power fluctuations from wind turbine generators can be predicted using two methodologies. The first method is the turbulence intensity in the power output of wind turbines, and the second method uses statistical data to analyze power output of wind turbines.

In this paper the above mentioned parameters are studied through a statistical model using the above two methodologies. Wind data for AL Maqrun city in Libya was used for the analysis. This data was of ten minutes average for the year 2003.

The results show that using two wind turbines instead of one turbine will improve the power quality. Similar results are noticed for pitch controlled against stall controlled.

The results were compared with results available in the literature showing a good agreement.

KEYWORDS: Wind turbine, Wind data, Power quality, power turbulence, Power fluctuations.

1. INTRODUCTION

1.1 Background

During the last decade the wind energy technology has advanced and the wind industry has expanded remarkably. Increased efficiency of the wind turbine generator system, higher energy prices and environmental aspects are some of the reasons for the ongoing wind power boom. However, wind turbines are among utilities considered as potential sources for bad power quality [1].

The difficulty with wind power is not only uneven power production or the different types of grids used; there are also different types of wind turbines available on the market. The turbine can be stall regulated or pitch controlled. The different types of wind turbines each have their advantages and disadvantages. They also have an impact on power quality in some way, either by improving power quality or by making it worse [2].

During 2010 and 2011 more than half of all new wind power was added outside of the traditional markets of Europe and North America, mainly driven by the continuing boom in China which accounted for nearly half of all of the installations at 18,000 MW in 2011. At the end of 2014, China had 114,763 MW of wind power installed [3].

1.2 Literature review

A literature review of power quality is presented in the subsequent paragraphs.

J.G.Keller (1994) used two mathematical methodologies to develop and analyze wind turbine power data. The first method compares the power output much like turbulence in wind measurements. Power “Turbulence” is calculated from one second power data. The second statistical method was developed to analyze power data. He developed a software to calculate the probability of a quantitative decrease or increase in terms of both magnitude and time for the test periods and produced the output results in a form of tables [4].

L. MacGill (2005) illustrated the power output (percentage of rated power) for two wind farms, 80Km apart, and their combined output, It was obvious that there is some smoothing effect in the power fluctuations for combined output [5] .

E.Muljadi and C.P.Butterfield (2006) compared two graphs; first graph is a one group of turbines has the same time series and a second graph is sixteen different groups of wind turbines. It was obvious that there is some smoothing effect in the power fluctuations for the wind power plant consisting of sixteen different groups of wind turbines [6].

2. Mathematical Model

The main primes of this model are to evaluate power quality of wind turbines, for AL Maqrun city in Libya as shown in figure (1) [7]. Wind speed data of ten minutes average for the year 2003 at 10m height above ground level (a.g.l.) was used in this study [8], surface roughness length ($Z_0 =$ 0.1m) was selected to represent site. Two mathematical methodologies were used to evaluate the power quality and to simulate the power output of the wind turbines used in this study. The first method is the turbulence intensity in the power output of wind turbines

[9], and the second method uses statistical data to analyze power output of wind turbines. The above mentioned surface roughness length ($Z_0 = 0.1$m) had been applied to wind turbines of different specifications as shown in table (1) [10].

Figure (1) AL Maqrun city – Libya

Table (1) Characteristics of the horizontal axis wind turbines (HAWTs)

Manufacturer	Wind Turbine	P_{rated} KW	D m	H_{hub} m	V_{ci} m/s	V_{co} m/s	V_r m/s	Power Control Technology
Repower	Repower MM82	2000	82	82	4	25	13	Pitch
Suzlon	S.64/1000	1000	64	72	3	25	11	Pitch
Gamesa Eolica	G52-800KW	800	52	63	4	25	15	Pitch
Nordex	N50/800	800	50	63	4	25	13.9	stall

Where ($\mathbf{P}_{rated}$) is rated power, (**D**) is rotor diameter, ($\mathbf{H}_{hub}$) is hub height, ($\mathbf{V}_{ci}$) is cut in wind speed, ($\mathbf{V}_{co}$) is cut out wind speed and ($\mathbf{V}_r$) is rated wind speed.

2.1 Determining the power output from wind turbines

The following steps were used to find power output from wind turbines:

2.1.1 Extrapolation of wind speeds from the anemometer height to the hub height of the wind turbine by using logarithmic function (Log law) [11].

$$\frac{V_{(Z)}}{V_{(Z_r)}} = Ln\left(\frac{Z}{Z_0}\right) \Big/ Ln\left(\frac{Z_r}{Z_0}\right) \qquad (1)$$

Where $V_{(Z)}$ is the wind speed at height Z, $V_{(Z_r)}$ is the wind speed at reference height Z_r and Z_0 is the surface roughness length. Terrain Description for the value of ($Z_0 = 0.1$m) is Villages, countryside with trees and hedges which was used in this study [11].

2.1.2 Extrapolation of wind speeds at hub height to power output for each wind turbine type, could be determined from the power curve of each wind turbine. It can be interpolated linearly, as follows:

$$\begin{array}{ll} V_1 & P_1 \\ V_{(t)} & P_{(t)}? \\ V_2 & P_2 \end{array}$$

$$P_{(t)} = P_1 + (P_2 - P_1)(V_{(t)} - V_1)/(V_2 - V_1) \qquad (2)$$

Where $V_1 \& V_2$ are wind speeds from the power curve for each wind turbine, $P_1 \& P_2$ are the power output from the power curve for each wind turbine, $V_{(t)}$ is the wind speed data at time t ($t = 1$ to number of data) and $P_{(t)}$ is the power output from wind turbine at $V_{(t)}$. The power output $Power_{(t)}$ from one or more wind turbine, for each type, is calculated from equation (3).

$$Power_{(t)} = number\ of\ units * P_{(t)} \qquad (3)$$

2.2 Determining total rated power (TRP)

Total rated power for each wind turbine type is calculated from equation (4).

$$TRP = number\ of\ units * rated\ power \qquad (4)$$

2.3 Evaluation of the power quality of wind turbines

To evaluate the power quality of wind turbines, two mathematical methodologies were used to analyze wind turbines power data, as follows:

2.3.1 The power turbulence (PT) of wind turbines is defined by the ratio of the standard deviation of the power output from wind turbines to the mean in percent in twenty four hours intervals. These twenty four hour values are averaged over the test period and could be used for comparison with values calculated for different wind turbines. This method has the advantage of comparing wind turbines of different rating in a non-dimensional way. It does not however describe the magnitude nor rate of power fluctuations occurring. To solve this problem, a second method uses statistical data to analyze power output of wind turbines was used. The percentage of power turbulence is defined by [9]:

$$\%\,PT = \frac{\sigma_P}{\bar{P}} * 100 \qquad (5)$$

Where σ_P is the standard deviation of the power and $\bar{P}$ is the average power. It can be determined from the following equation:

$$\sigma_P = \sqrt{\frac{1}{N_{total}-1}\left[\sum_{t=1}^{N_{total}} \left(Power_{(t)}\right)^2 - N_{total} * (\bar{P})^2\right]} \qquad (6)$$

$$\bar{P} = \frac{1}{N_{total}} \sum_{t=1}^{N_{total}} Power_{(t)} \qquad (7)$$

2.3.2 The power fluctuation for wind turbines are calculated from the following steps:

2.3.2.1 The computer program reads the power data for each wind turbine, searching for all of the peaks and valleys, as shown in figure (2) and then calculates the difference of the power and time, between every two points, as shown in figure (2), using equation (8) and (9), and then normalizes equation (8) to percentage value of total rated power for each wind turbine type, as shown in equation (10).

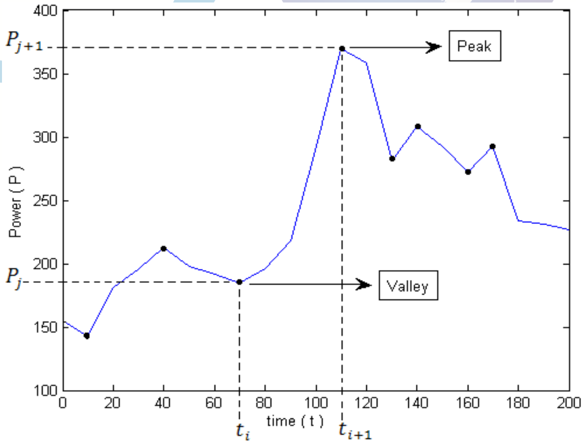

Figure (2) Peaks and valleys for power output from wind turbine

From figure (2), hence:

$$\Delta P = P_{j+1} - P_j \qquad (8)$$

$$\Delta T = t_{i+1} - t_i \qquad (9)$$

$$\%\,\Delta P = \frac{\Delta P}{TRP} * 100 \qquad (10)$$

Where ΔP is power difference, ΔT is time difference, t_i is time at point (i), t_{i+1} is time at point (i+1), P_j is power at point (j), P_{j+1} is power at point (j+1), (i) is iteration of time at x-axes and (j) is iteration of power at y-axes.

2.3.2.2 The computer program produces simplified tables showing the probability of a quantitative decrease and increase together in terms of both magnitude and the time for the test period. The computer program calculates the number of power shifts (as a percentage of rated power) in bins, each bin is 10%, occurring in the time period between: (0-20), (20-40)……(120-140) minutes, during the year and four tests period runs, are illustrated in results.

2.3.2.3 The computer program also produces simplified tables for each wind turbine to calculate increasing or decreasing turbine power shift, between (0-20), (20-40) …….. (100-120) and (120-140) minutes and then calculates the total count for increasing and decreasing turbine power shift (as a percentage of rated power) to see if wind turbine power output is symmetric, during the year and one test period runs, are illustrated in results.

3. Results

A computer program was developed to investigate the power quality of wind turbines and simulate the power output of the wind turbines used in this study. The investigation included the effect of number of wind turbines and power control technology of wind turbines (pitch regulation and stall regulation). Surface roughness length (0.1m) was used, during the year run (general case) and one test period run is a one month data (April month). The results of the computer program included the following:

1- The power output from each wind turbine.

2- Percentage of power turbulence for each wind turbine.

3-The power fluctuation, which included the turbine power shift (percentage of rated power), decreasing and increasing together in terms of magnitude and time, which occurred during (0-20), (20-40) … (120-140) minutes.

4-The power fluctuation for each wind turbine, which included the increasing and decreasing turbine power shift for each turbine, during (0-20), (20-40) … (120-140) minutes, to see if wind turbine power output is symmetric, that is, to see if the probability of a sudden power decrease is the same as that of a power increase.

3.1 Effect of the number of wind turbines

The selection of wind turbines was according to the average size available at the global market (1.5-2.5MW). One wind turbine has a rated power of 2MW which was compared with two combined wind turbines of rated power 2MW. The selected wind turbines are shown in table (2).

Table (2) Effect of the number of wind turbines

Name of turbine	Rated power (KW)	No. of units	Hub height (m)
*REpower_2MW_82m	2000	1	82
**Suzlon_1MW_64m	1000	2	72

*Turbine#1, **Turbine#2

3.1.1 The power output for wind turbines.

The power output from turbine#1 and turbine#2 for the test period of April every ten minutes, are shown in tables (3). It could be noticed that the power output of the two wind turbines is more than that of one wind turbine.

Table (3) Power output from wind turbines for the test period of April at Z_0 =0.1m

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Test period No (2) Start from (01.04.03) to (30.04.03)

No	Date	Hour	*Speed (m/s)	Power (KW) Turbine#1	 Turbine#2
1	01.04.03	0:00:00	4.99	526.79	616.33
2	01.04.03	0:10:00	6.04	925.12	1146.11
.	.	.	.	.	.
.	.	.	.	.	.
4319	30.04.03	23:40:00	4.32	332.77	398.43
4320	30.04.03	23:50:00	4.19	298.11	359.75

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*Wind speed at 10m

3.1.2 Power turbulence for wind turbines:

Power turbulence for turbine#1 and turbine#2 for April month are shown in figure (3). It could be noticed that turbine#1 and turbine#2 show similar curves, because the capacity of wind turbines are the same, but generally, the power turbulence for turbine#2 are less than turbine#1. From figure (3), it could be noticed that the best power turbulence is day 16, which is equal to 14.84% and 12.16% for turbine#1 and turbine#2 respectively at Z_0 =0.1m. The worse power turbulence is day 7, which is equal to 125.05% and 122.84% for turbine#1 and turbine#2 respectively at Z_0 =0.1m. From figure (3) it could be noticed that the power turbulence decreases with the increase of number of wind turbines.

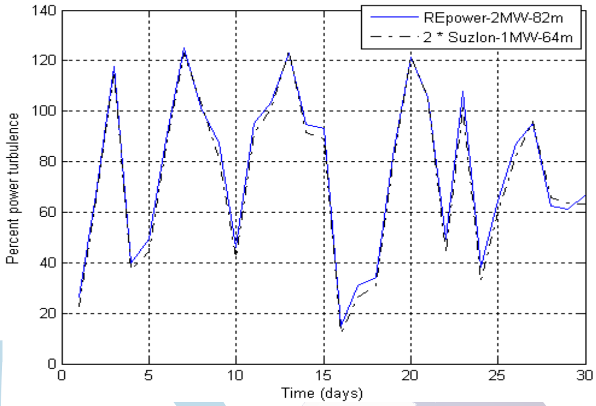

Figure (3) Power turbulence for wind turbines for April, at Z_0 =0.1m

3.1.3 The power fluctuation as power shift.

The data was analyzed, to study the power fluctuations occurring in an interval time of 20 minutes. Tables (4 and 5) illustrate the power shift for turbine#1 and turbine#2. It could be noticed that the power shifts have similar characteristics, because the capacity of turbine#1 is equal to that of turbine#2, but the magnitude of power shifts for turbine#1 is greater than that of turbine#2. This finding agrees with results obtained from power turbulence analyses in the previous section (3.1.2). From tables (4 and 5) it could be noticed that the power quality is not bad, because the power shifts (percentage of rated power) for values more than 40% are not large number of counts.

Table (4) Power fluctuation for general case for wind turbines at Z_0 =0.1m

Turbine power shift (% of rated), occurring between (0- 20) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	8207	849	168	42	25	14	6	9	5	1	39
Turbine#2	7515	867	262	80	20	22	14	9	5	2	29

Turbine power shift (% of rated), occurring between (20- 40) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	4036	1777	563	192	100	63	33	32	20	7	3
Turbine#2	3896	1532	650	272	126	66	52	40	24	30	4

Turbine power shift (% of rated), occurring between (40- 60) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	450	516	346	182	98	47	34	23	18	7	5
Turbine#2	516	458	274	177	130	82	42	42	28	15	4

Turbine power shift (% of rated), occurring between (60- 80) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	35	122	98	98	81	31	17	14	13	0	6
Turbine#2	58	130	77	66	62	51	34	11	19	11	5

Turbine power shift (% of rated), occurring between (80-100) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	2	17	26	23	29	18	10	11	9	4	0
Turbine#2	7	21	22	28	16	20	15	14	7	10	2

Turbine power shift (% of rated), occurring between (100-120) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	2	10	8	6	8	9	7	3	1	3
Turbine#2	0	4	5	4	7	6	4	8	5	6	2

Turbine power shift (% of rated), occurring between (120-140) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	0	3	3	5	4	3	3	0	7	0
Turbine#2	0	1	3	3	3	5	4	3	5	4	0

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Table (5) Power fluctuation for test period of April for wind turbines at Z_0 =0.1m

Turbine power shift (% of rated), occurring between (0- 20) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	697	86	19	2	1	0	1	1	1	0	0
Turbine#2	604	90	29	9	1	2	1	1	1	0	0

Turbine power shift (% of rated), occurring between (20- 40) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	283	146	59	16	7	5	2	3	1	1	0
Turbine#2	259	116	64	24	10	2	7	3	2	2	0

Turbine power shift (% of rated), occurring between (40- 60) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	27	35	34	24	8	4	2	1	2	0	0
Turbine#2	32	26	24	17	10	6	5	6	3	0	0

Table (5) Power fluctuation for test period of April for wind turbines at Z_0 =0.1m (Continued)

Turbine power shift (% of rated), occurring between (60- 80) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	5	10	5	5	5	4	2	3	2	0	0
Turbine#2	4	13	7	4	1	3	2	2	3	0	0

Turbine power shift (% of rated), occurring between (80-100) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	1	2	3	4	4	1	3	1	2	0	0
Turbine#2	2	1	2	3	3	3	1	3	1	2	0

Turbine power shift (% of rated), occurring between (100-120) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	0	0	0	0	0	1	1	0	0	1
Turbine#2	0	0	0	0	0	1	0	1	1	1	1

Turbine power shift (% of rated), occurring between (120-140) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	0	1	0	1	0	0	1	0	2	0
Turbine#2	0	0	0	1	0	0	2	0	0	1	0

3.1.4 The power fluctuation as increase and decrease of power shift:

Tables (6 and 7) display the results of the computer program, which show that the power fluctuations of turbine#1 and turbine#2 are not perfectly symmetric. The changes of power shifts for turbine#1 occurring in less than forty minutes are higher for increases in power shifts than decreases in power shifts and the opposite is true for power shifts occurring in greater than forty minutes, while the changes of power shifts for turbine#2 occurring in less than twenty minutes are higher for power shift increases than power shift decreases and the opposite is true for power shifts occurring in greater than twenty minutes.

Table (6) Power fluctuation for each wind turbine, for general case, for wind turbines, at Z_0 =0.1m

Turbine#1

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	4161	422	86	22	17	9	5	8	4	0	20
20- 40	1995	902	280	106	51	37	19	18	13	5	2
40- 60	223	250	163	81	39	25	19	10	9	5	3
60- 80	12	52	45	50	34	10	8	6	7	0	2
80-100	1	5	10	7	13	11	6	6	7	3	0
100-120	0	0	2	2	1	3	2	0	2	1	2
120-140	0	0	2	1	3	1	1	1	0	5	0

*The total count is 9333

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	4046	427	82	20	8	5	1	1	1	1	19

Table (6) Power fluctuation for each wind turbine, for general case, for wind turbines, at z_0 =0.1m (Continued)

Turbine#1

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
20- 40	2041	875	283	86	49	26	14	14	7	2	1
40- 60	227	266	183	101	59	22	15	13	9	2	2
60- 80	23	70	53	48	47	21	9	8	6	0	4
80-100	1	12	16	16	16	7	4	5	2	1	0
100-120	0	2	8	6	5	5	7	7	1	0	1
120-140	0	0	1	2	2	3	2	2	0	2	0

*The total count is 9333

Turbine#2

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	3842	436	142	44	12	14	11	4	4	1	15
20- 40	1930	764	312	130	76	30	23	24	17	22	2
40- 60	232	211	140	80	58	40	22	21	15	8	4
60- 80	24	55	40	28	34	24	15	3	11	5	2
80-100	4	10	6	9	5	11	5	7	2	7	2
100-120	0	1	4	0	0	2	1	3	0	4	1
120-140	0	0	1	1	2	1	2	1	1	2	0

*The total count is 9022

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	3673	431	120	36	8	8	3	5	1	1	14
20- 40	1966	768	338	142	50	36	29	16	7	8	2
40- 60	284	247	134	97	72	42	20	21	13	7	0
60- 80	34	75	37	38	28	27	19	8	8	6	3
80-100	3	11	16	19	11	9	10	7	5	3	0
100-120	0	3	1	4	7	4	3	5	5	2	1
120-140	0	1	2	2	1	4	2	2	4	2	0

*The total count is 9031

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Table (7) Power fluctuation for each wind turbine, for test period of April, for wind turbines, at z_0 =0.1m

Turbine#1

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	358	42	12	2	0	0	1	0	1	0	0
20- 40	135	79	25	7	3	3	1	2	1	0	0
40- 60	17	13	10	10	4	2	1	1	1	0	0
60- 80	3	3	1	3	4	2	2	0	1	0	0
80-100	0	1	1	2	1	1	1	1	2	0	0
100-120	0	0	0	0	0	0	0	0	0	0	1
120-140	0	0	1	0	1	0	0	1	0	2	0

*The total count is 766

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	339	44	7	0	1	0	0	1	0	0	0
20- 40	148	67	34	9	4	2	1	1	0	1	0
40- 60	10	22	24	14	4	2	1	0	1	0	0
60- 80	2	7	4	2	1	2	0	3	1	0	0
80-100	1	1	2	2	3	0	2	0	0	0	0
100-120	0	0	0	0	0	0	1	1	0	0	0

Table (7) Power fluctuation for each wind turbine, for test period of April, for wind turbines, at Z_0 =0.1m (Continued)

Turbine#1

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
120-140	0	0	0	0	0	0	0	0	0	0	0

*The total count is 772

Turbine#2

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	309	47	19	6	1	1	1	0	1	0	0
20- 40	124	59	30	10	4	1	3	2	2	1	0
40- 60	18	12	9	5	3	3	3	3	2	0	0
60- 80	2	3	2	0	1	3	2	0	1	0	0
80-100	1	1	0	2	1	1	0	1	1	2	0
100-120	0	0	0	0	0	0	0	0	0	1	1
120-140	0	0	0	1	0	0	2	0	0	1	0

*The total count is 709

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	295	43	10	3	0	1	0	1	0	0	0
20- 40	135	57	34	14	6	1	4	1	0	1	0
40- 60	14	14	15	12	7	3	2	3	1	0	0
60- 80	2	10	5	4	0	0	0	2	2	0	0
80-100	1	0	2	1	2	2	1	2	0	0	0
100-120	0	0	0	0	0	1	0	1	1	0	0
120-140	0	0	0	0	0	0	0	0	0	0	0

*The total count is 716

* * *

3.2 Effect of power control technology of wind turbines

Two different types of power regulation were used; stall regulation and pitch regulation to investigate the effect of power control technology of wind turbines, on the power quality. Two wind turbines were chosen each has a rated power of 800KW, one uses pitch regulation, and the other wind turbine, uses stall regulation. Wind turbines have the same cut-in wind speed and cut-out wind speed. Type of wind turbines are shown in table (8).

Table (8) Power control technology of wind turbines

Name of turbine	Rated power (KW)	No. of units	Hub height (m)	Power regulat-ion
*Gamesa_800KW_52m	800	1	63	Pitch
**Nordex_800KW_50m	800	1	63	Stall

*Turbine#1, **Turbine#2

3.2.1 The power output for wind turbines:

The power output from turbine#1 and turbine#2 are shown in tables (9). It could be noticed that the power output for pitch control wind turbine is greater than that stall controlled wind turbine.

Table (9) Power output from wind turbines, for two power control technologies, for test period of April, at Z_0 =0.1m

Test period No (2) Start from (01.04.03) to (30.04.03)					
No	Date	Hour	*Speed (m/s)	Power (KW)	
				Turbine#1	Turbine#2
1	01.04.03	0:00:00	4.99	188.07	163.83
2	01.04.03	0:10:00	6.04	341.49	303.31
.	.	.	.	.	.
.	.	.	.	.	.
4319	30.04.03	23:40:00	4.32	108.45	93.49
4320	30.04.03	23:50:00	4.19	97.08	85.53

*Wind speed at 10m

3.2.2 Power turbulence for wind turbines.

Power turbulence for turbine#1 and turbine#2 for April month are shown in figure (4). It could be noticed that turbine#1 and turbine#2 show similar curves, because the capacity of wind turbines are the same, but generally the power turbulence for turbine#1 are less than that of turbine#2, because turbine#1 uses pitch regulation and turbine#2 uses stall regulation. From figure (4) and, it could be noticed that the best power turbulence is day 16, which is equal to 15.55% for turbine#1 and 18.39% for turbine#2 at Z_0 =0.1m, The worse power turbulence for turbine#1 is day 13, which is equal to 134.72% at Z_0 =0.1m, and the worse power turbulence for turbine#2 is day 7, which is equal to 130.09% at Z_0 =0.1m. From figure (4), it could be noticed that the power turbulence decreases in case of pitch controlled compared to stall controlled.

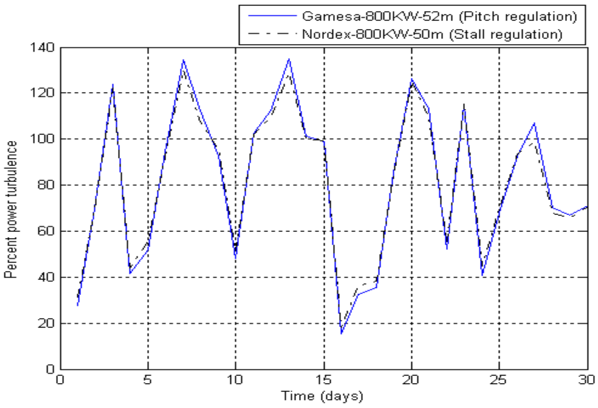

Figure (4) Power turbulence for two power control Technologies, for test period of April, at Z_0 =0.1m

3.2.3 The power fluctuation as power shift.

The data was analyzed, to study the power fluctuations occurring in an interval time of 20 minutes. Tables (10 and 11) illustrate the power shift for turbine#1 and turbine#2. It could be noticed that the power shifts have similar characteristics, because the capacity of turbine#1 is equal to turbine#2, but the magnitude of power shifts for turbine#1 is greater than that of turbine#2. From tables (10 and 11) it could be noticed that the power quality is not bad, because the power shifts (percentage of rated power) for values more than 40% are not large number of counts

Table (10) Power fluctuation for general case for two power control technologies, at Z_0 =0.1m

Turbine power shift (% of rated), occurring between (0- 20) minutes, during the test period											
Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	9036	801	162	40	21	11	7	6	4	1	19
Turbine#2	9776	795	122	36	22	9	7	3	0	12	0
Turbine power shift (% of rated), occurring between (20- 40) minutes, during the test period											
Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	4752	1676	549	197	96	59	35	31	18	6	1
Turbine#2	5346	1749	485	168	101	47	36	17	14	14	2

Table (10) Power fluctuation for general case for two power control technologies, at Z_0 =0.1m (Continued)

Turbine power shift (% of rated), occurring between (40- 60) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	567	508	330	182	102	54	31	28	18	16	2
Turbine#2	655	572	330	164	81	42	36	18	13	11	4

Turbine power shift (% of rated), occurring between (60- 80) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	55	123	100	98	73	32	23	12	15	7	0
Turbine#2	77	127	107	108	62	27	16	12	7	7	2

Turbine power shift (% of rated), occurring between (80-100) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	5	15	32	22	34	18	11	9	11	3	0
Turbine#2	5	23	34	36	24	16	12	7	6	0	1

Turbine power shift (% of rated), occurring between (100-120) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	6	6	9	5	7	11	5	3	6	0
Turbine#2	1	4	11	7	8	11	6	3	2	2	2

Turbine power shift (% of rated), occurring between (120-140) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	0	2	4	6	4	3	5	0	7	0
Turbine#2	0	1	3	3	5	6	4	1	6	3	0

* * *

Table (11) Power fluctuation for test period of April for two power control technologies, at Z_0 =0.1m

Turbine power shift (% of rated), occurring between (0- 20) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	788	89	22	1	1	0	1	1	1	0	0
Turbine#2	878	84	17	1	0	1	1	0	0	1	0

Turbine power shift (% of rated), occurring between (20- 40) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	342	144	52	14	7	6	3	2	0	0	0
Turbine#2	432	148	49	14	7	5	2	0	1	0	0

Turbine power shift (% of rated), occurring between (40- 60) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	38	39	33	18	8	4	3	2	1	2	0
Turbine#2	47	41	43	12	7	4	1	1	1	2	0

Turbine power shift (% of rated), occurring between (60- 80) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	4	13	7	7	6	2	3	3	1	1	0
Turbine#2	8	11	7	5	7	4	3	0	1	2	0

Turbine power shift (% of rated), occurring between (80-100) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	2	1	2	4	5	1	3	1	2	0	0
Turbine#2	3	1	5	5	1	4	1	1	1	0	0

Table (11) Power fluctuation for test period of April for two power control technologies, at Z_0 =0.1m (Continued)

Turbine power shift (% of rated), occurring between (100-120) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	0	0	0	0	0	1	1	0	2	0
Turbine#2	0	0	0	0	0	1	1	0	1	0	0

Turbine power shift (% of rated), occurring between (120-140) minutes, during the test period

Turbine	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
Turbine#1	0	0	1	0	1	0	0	1	0	2	0
Turbine#2	0	0	1	0	1	0	0	1	2	1	0

****

3.2.5 The power fluctuation as increase and decrease of power shift:

Tables (12 and 13) display the results of the computer program, which show that the power fluctuations of turbine#1 and turbine#2 are not perfectly symmetric. The changes of power shifts for turbine#1 and turbine#2 occurring in less than forty minutes are higher for increases in power shifts than decreases in power shifts and the opposite is true for power shifts occurring in greater than forty minutes.

Table (12) Power fluctuation for each wind turbine, for general case, for two power control technologies, at Z_0 =0.1m

Turbine#1

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	4575	396	84	19	14	6	6	5	4	0	10
20- 40	2362	850	283	101	52	33	19	17	12	4	0
40- 60	272	252	156	79	50	28	14	16	8	11	2
60- 80	23	49	49	51	30	10	13	5	7	3	0
80-100	2	4	11	7	17	11	6	5	7	2	0
100-120	0	2	0	2	1	3	2	0	3	4	0
120-140	0	0	1	1	3	1	1	1	0	5	0

*The total count is 10082

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	4461	405	78	21	7	5	1	1	0	1	9
20- 40	2390	826	266	96	44	26	16	14	6	2	1
40- 60	295	256	174	103	52	26	17	12	10	5	0
60- 80	32	74	51	47	43	22	10	7	8	4	0
80-100	3	11	21	15	17	7	5	4	4	1	0
100-120	0	4	6	7	4	4	9	5	0	2	0
120-140	0	0	1	3	3	3	2	4	0	2	0

*The total count is 10071

Turbine#2

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	4936	393	64	18	15	5	6	3	0	6	0
20- 40	2683	872	241	95	47	28	21	12	7	8	1
40- 60	314	289	155	74	42	19	17	8	10	7	3
60- 80	31	55	49	59	23	9	9	7	4	4	0
80-100	1	8	11	13	15	10	6	4	4	0	1
100-120	0	2	1	1	4	2	0	2	2	1	1

Table (12) Power fluctuation for each wind turbine, for general case, for two power control technologies, at Z_0 =0.1m (Continued)

Turbine#2

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
120-140	0	0	2	1	2	2	1	0	3	3	0

*The total count is 10752

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	4840	402	58	18	7	4	1	0	0	6	0
20- 40	2663	877	244	73	54	19	15	5	7	6	1
40- 60	341	283	175	90	39	23	19	10	3	4	1
60- 80	46	72	58	49	39	18	7	5	3	3	2
80-100	4	15	23	23	9	6	6	3	2	0	0
100-120	1	2	10	6	4	9	6	1	0	1	1
120-140	0	1	1	2	3	4	3	1	3	0	0

*The total count is 10740

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Table (13) Power fluctuation for each wind turbine, for test period of April, for power control technologies, at Z_0 =0.1m

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Turbine#1

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	400	46	15	1	0	0	1	0	1	0	0
20- 40	171	76	24	4	4	4	1	1	0	0	0
40- 60	15	16	12	4	5	1	2	2	1	1	0
60- 80	2	4	3	4	4	2	2	0	0	1	0
80-100	1	0	1	2	2	1	1	1	1	0	0
100-120	0	0	0	0	0	0	0	0	0	2	0
120-140	0	0	1	0	1	0	0	1	0	2	0

*The total count is 847

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	388	43	7	0	1	0	0	1	0	0	0
20- 40	171	68	28	10	3	2	2	1	0	0	0
40- 60	23	23	21	14	3	3	1	0	0	1	0
60- 80	2	9	4	3	2	0	1	3	1	0	0
80-100	1	1	1	2	3	0	2	0	1	0	0
100-120	0	0	0	0	0	0	1	1	0	0	0
120-140	0	0	0	0	0	0	0	0	0	0	0

*The total count is 852

Turbine#2

Increasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	445	43	11	0	0	1	0	0	0	1	0
20- 40	216	79	20	4	3	3	2	0	0	0	0
40- 60	24	15	16	6	3	1	1	1	1	1	0
60- 80	4	4	2	4	5	2	0	0	1	1	0
80-100	1	0	2	2	1	2	1	1	0	0	0
100-120	0	0	0	0	0	0	0	0	1	0	0
120-140	0	0	1	0	1	0	0	1	2	1	0

*The total count is 937

Table (13) Power fluctuation for each wind turbine, for test period of April, for power control technologies, at Z_0 =0.1m (Continued)

Turbine#2

Decreasing turbine power shift (% of rated)

Time	00-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110
0- 20	433	41	6	1	0	0	1	0	0	0	0
20- 40	216	69	29	10	4	2	0	0	1	0	0
40- 60	23	26	27	6	4	3	0	0	0	1	0
60- 80	4	7	5	1	2	2	3	0	0	1	0
80-100	2	1	3	3	0	2	0	0	1	0	0
100-120	0	0	0	0	0	1	1	0	0	0	0
120-140	0	0	0	0	0	0	0	0	0	0	0

*The total count is 942

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4. CONCLUSIONS

The most important outcomes of this study can be summarized as follows:

1. Two wind turbines gave less power turbulence than one wind turbine. Same results were obtained when using pitch control compared to stall controlled.

2. The power fluctuation as power shift has improved (i.e. less power fluctuation) when using two wind turbines compared to one wind turbine and when using pitch control compared to stall controlled.

3. Power fluctuations as increase and decrease of power shift are not perfectly symmetric; it depends on the wind data.

4. Power shifts (percentage of rated power) for values more than 40% are not large number of counts.

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