25th Iranian Conference on Electrical Engineering (ICEE2017)

The Effect of Turbulence and Wake on the Power Fluctuation in the Wind Farms

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Abstract—**The intermittency in wind power can face electrical network with some challenges such as power quality, frequency deviation and reliability of the system. So estimated power fluctuation in wind farm has to be known in order to reach to the grid integration requirements. In this paper the wind farm power fluctuation is investigated by considering the three factors; wake effect, turbulence and spatial smoothing, simultaneously. The wake effect is investigated for the mean value and turbulence part of the wind speed separately because of different effects of the wake. The engineering models in fluid mechanics is used for analyzing the wake effect and spatial smoothing. The proposed approach is sued for a 160 MW wind farm as a case study.**

Keywords- wind speed; power intermittency; spatial smoothing; turbulence; wake effect; wind farm.

I. Introduction

Among the renewable energies, the wind power is more interested. There are some countries in which the wind power constitutes up to 40 percent of the total energy. But the intermittency in wind power can face electrical network with some challenges such as power quality, frequency deviation and reliability of the system [1].

The power fluctuation of wind turbine is due to intermittency in wind speed profile. Temporal variations in wind speed may be in the range of year, seasonal, month, day or several hours, because of atmospheric variations such as differential heating of the earth's surface during the daily relation cycle. In addition, there is small time scale variations in wind because of boundary layer conditions that includes turbulence in wind [2]. On the other hand a wind farm includes several wind turbines, the output powers of which are gathered to form the total farm power. The wind speed profiles over the different locations are not same and the correlation factor is not unit, so consequently the power profiles for individuals wind turbine have not the same variations. Therefor the total power of wind farm, that is the summation of uncorrelated profiles, has less fluctuation compared to summation of correlated profiles. This phenomena is known as spatial smoothing i.e. the power smoothing because of space distribution of wind turbines over a farm [3, 4]. In addition to temporal variation and turbulence in wind speed, there is another factor that affects the wind speed profile over the wind farm. A wind turbine extracts energy from the wind and consequently slows down the wind field behind the turbine. Another turbine positioned in the wake of the first one will generate less energy for a given free stream wind speed [5]. The wake behavior is different for average wind speed and turbulence so that there is an increment in the turbulence level together whereas the mean wind speed is decreased in wake. Therefore, it leads to significantly larger turbulence intensities in comparison with free flow [6]. Therefore wake effect can effect power fluctuation in wind farm because of changing the turbulence level in different locations.

There are a few papers that consider short time variations in the wind power, e.g. [7], which only analyzes the effect of turbulence on available power of a single wind turbine. In the present paper, not only the dynamic model of wind speed is used, but also the wake effect on mean wind speed and the turbulence part are analyzed and the effect of instantaneous wind profile on the wind farm power fluctuations is investigated simultaneously. In fact in this paper the effect of three factors; wind speed turbulence, wake effect and spatial smoothing, on the output power of a wind farm are investigated, simultaneously.

In section II the principles of wind and wake effect are presented. Then in section III the wind farm power is analyzed. In section IV the results are shown and the average wind speed mode is compared with instantaneous mode. Finally in section V the conclusion is presented.

II. Wake Effect

In this section, first the wind speed profile is surveyed and then the wake effect for mean and turbulence speed is analyzed according to the engineering model in fluid mechanics.

978-1-5090-5963-8/17/$31.00 ©2017 IEEE

A. Wind

Global winds are created by pressure difference across the earth surface due to uneven heating of the earth by solar radiation. The spatial variation in heat transfer to earth's atmosphere create variation in the atmospheric pressure field that causes air to move from high to low pressure. Atmospheric motions vary in time and space. It is dependent on local topographical and ground cover variations. Of course, in this paper a flat terrain is assumed and the variation due to the topographical condition is neglected. Temporal variations may be in the range of year, seasonal, month, day or several hours, because of atmospheric variation such as differential heating of the earth's surface during the daily relation cycle. In addition, there is small time scale variations in wind because of boundary layer conditions that includes turbulence in wind.

Turbulence is a random variation that is imposed on the average wind speed. A wind speed can be considered as two terms; average ($\bar{V}$) and turbulence ($\tilde{v}$) speed:

$$V = \bar{V} + \tilde{v}(1)$$
$$\bar{V} = \frac{1}{\Delta t}\int_0^{\Delta t} V(t)dt \quad (1)$$

The time period Δt is usually taken as 10 minutes [2]. The basic definition of turbulence is related to the turbulence intensity, the ratio of standard deviation of the wind speed to its mean value (2).

$$I = \frac{\sigma}{\bar{V}} \quad (2)$$

The wind turbulence can be considered as a random variable with normal distribution [2], so the probability density function for wind speed can be written as below:

$$p(v) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(v-\bar{V})^2/2\sigma^2} \quad (3)$$

B. Wake Effect

Wind turbine extracts energy from the wind and consequently slows down the wind field behind the turbine. Another turbine positioned in the wake of the first one will generate less energy for a given free stream wind speed [5]. Exact study of the wake effect needs to numerical calculations such as computational fluid dynamic (CFD) code. Fortunately there are some useful works, done before, which expresses some engineering relationships to quantify the wake effect. The wake effect is different for average wind speed and turbulence, so that, there is an increment in the turbulence level, whereas the mean wind speed is decreased by wake. Therefore, it leads to significantly larger turbulence intensities in comparison with free flow [6]. In addition, the wake behavior varies with distance behind the turbine, so that basically two regions are defined as near and far wake [8]. The near wake research is concentrated on the performance of one wind turbine, but the far wake is focused on mutual influence of wind turbines in wind farms. In this paper it is focused on the far wake effect because in a wind farm the distance between the wind turbines is in the far region.

Several wake models have been developed for average wind speed deficit in wake such as, Katic model, Larsen model, Ainslie model. Also for turbulence model there are several models such as, Quarton model, Larsen model, Frandsen model, IEC 61400 model [9] and Crespo model [10]. These models have been compared in [8]. In this paper, Katic and Crespo models are employed, respectively for average and turbulence wake.

1) Wind speed deficit

Velocity deficit in Katic model for one wind turbine is described in the following relationship [5].

$$1 - \frac{V}{V_\infty} = \frac{\left(1 - \sqrt{1 - C_t}\right)}{\left(1 + \frac{2kx}{D}\right)^2} \quad (4)$$

In which, V_∞ is the free wind speed, V is the wind speed at distance (x) behind the turbine, C_t is the trust coefficient, and the coefficient k varies according to the surface type from 0.04 for offshore surface to 0.075 for onshore surface [9]. For multiple wind turbines in a wind farm, the wake effect on the second turbine along the wind direction has the most deficit, but for other wind turbines, because of merging with atmosphere layer, the wake effect would be less, and the wind speed remains almost constant. The wind speed due to mutual wakes in Katic model is defined as below.

$$(1 - \frac{V_j}{V_\infty})^2 = \sum_{i=1}^{n}(1 - \frac{V_{ij}}{V_\infty})^2 \quad (5)$$

In which V_j is wind speed at jth wind turbine, with the wakes of former wind turbines taken into account.

2) Turbulence intensity

It is assumed that the wind turbine creates an additional turbulent kinetic energy that should be added to the ambient turbulence (I_∞) [8]. It is defined as turbulence intensity variation (ΔI).

$$\Delta I = \sqrt{I^2 - I_\infty^2} \quad (6)$$

The expression for added turbulence in Crespo model is defined as below [10]:

$$\Delta I = 0.73a^{0.83} I_\infty^{0.0325} (D/x)^{0.32} \quad (7)$$

In which a is the induced velocity factor, D is the rotor diameter and x is the distance between wind turbines. This model is an experimental relationship that is obtained from CFD model. Of course there are some other models that considered the turbulence due to adjacent turbines [11], but in this paper the (7) is used for simplification. So using (6), (7) and (2), the standard deviation of wind speed in the wake can be calculated.

Therefore, the wake effect can be calculated for mean and turbulence part of wind speed separately.

III. WIND FARM

The wind farm includes several wind turbines, the output powers of which are gathered to form the total farm power. In this section, first the turbine output characteristics is expressed and then, the wind farm power is analyzed.

A. Wind Turbine Power

The wind power is related to the wind speed by:

$$P_w = 0.5\rho S C_p(\lambda,\beta) V_w^3 \quad (8)$$

In which, ρ is air density, S is the area swept by turbine blades of radius R, λ is tip speed ratio ($\lambda = \frac{Rw_r}{V_w}$) and C_p is a nonlinear wind power coefficient. At maximum power condition the power coefficient is set to the maximum value and the power, in per unit, can be written as:

$$P_g = V_w^3 \quad (9)$$

The intermittent wind speed causes fluctuated output power in each wind turbine. Of course it depends on wind speed region. For above rated speed, since the output power must be limited to the rated value, the wind fluctuations can be compensate by pitch angle and rotor speed control. But for below rated speed, the maximum power point tracking (MPPT) strategy is employed, so fluctuations will appear in the output power. For below the cut-in and above the cut-out speeds, the output power is zero. Therefore, although the wind speed turbulence has a normal distribution but the output power is not necessary normally distributed. Based on the above discussion, the speed-power relationship can be described as follows:

$$P_w = \begin{cases} 0, & V_w \le V_{cut-in} \\ V_w^3, & V_{cut-in} < V_w \le V_r \\ P_r, & V_r \le V_w < V_{cut-out} \\ 0, & V_w \ge V_{cut-out} \end{cases} \quad (10)$$

According to (3) and (10), an improved probability density function can be extracted for wind speed from the viewpoint of power generation, as expressed in (11).

$$p_{new}(v) = \begin{cases} 0, & V_w < V_{cut-in} \\ \alpha * \delta(v = V_{cut-in}), & V_w = V_{cut-in} \\ p(v), & V_{cut-in} < V_w < V_r \\ \beta * \delta(v = V_r), & V_w = V_r \\ \gamma * \delta(v = V_{cut-out}), & V_w = V_{cut-out} \\ 0, & V_w > V_{cut-out} \end{cases} \quad (11)$$

In which:

$$\alpha = p(V_w \le V_{cut-in}) = \int_0^{V_{cut-in}} p(v)dv$$

$$\beta = p(V_r \le V_w \le V_{cut-out}) = \int_{V_r}^{V_{cut-out}} p(v)dv\,,$$

$$\gamma = p(V_w \ge V_{cut-out}) = \int_{V_w \ge V_{cut-out}} p(v)dv$$

.

Considering (10) and (11), the mean value and standard deviation of power can be calculated as follows:

$$\overline{P} = \int P_w\, p_{new}(v)dv = \int_{V_{cut-in}}^{V_r} v_w^3 * p(v)dv + P_r * \beta$$

$$\sigma^2 = \int \left(P_w - \overline{P}\right)^2 * p_{new}(v)dv = \overline{P}^2 * \alpha + \int_{V_{cut-in}}^{V_r} (v_w^3 - \overline{P})^2 * p(v)dv + \left(P_r - \overline{P}\right)^2 * \beta + \overline{P}^2 * \gamma \quad (12)$$

According to (12), the power fluctuation depends on the wind speed range. Different wind speed ranges are shown in Fig.1. For ranges 1,5 and 7 the output power is constant and power fluctuation level is zero. The most power fluctuation may happen in range 6, when the output power is switched between zero and rated value for wind speed variation. However, since the wind speed rarely fluctuates around the cut-out speed, so it can be ignored in the following discussion. In the ranges 2 and 4, fluctuation is partly cancelled and the fluctuation level is moderate. In range 3 the entire wind speed fluctuation is transferred into the power, so the most power fluctuation happens in this range.

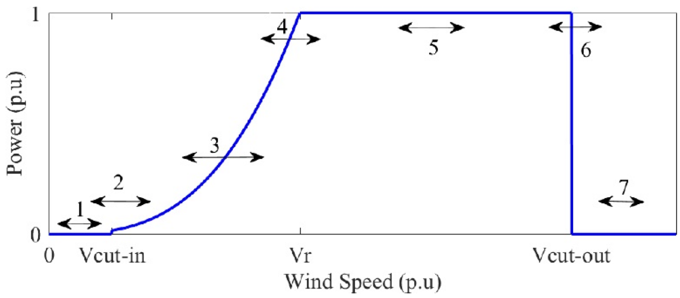

Fig.1. Speed-Power curve and different wind speed ranges

According to the wind speed characteristics and (12), the characteristics of the output power; mean and standard deviation for each individual wind turbine can be obtained.

B. Wind Farm Power

The output power of a wind farm is the sum all wind turbines power. So the total power deviation depends on power deviation in individual wind turbines and the amount of correlation between their profiles. One of the correlation analyzing methods is using coherence in frequency domain [12]. In frequency domain, the fluctuation is expressed as power spectra density (psd) function. In fact the amount of power spectra is equal to the energy in each frequency. On the other hand, the total energy in the turbulence is equal to total variance, so this concept can be expressed as the below relationship [12].

$$\int_0^\infty S(f)df = \sigma^2 \quad (13)$$

In which $S(f)$ is the power spectra density function of output power. In addition, a cross spectra density function is defined to state the correlation between the power fluctuations of individual wind turbines ($S_{ij}(f)$) [12].

Finally the power spectra for total deviation in turbulence range can be written as below [12].

$$S_\Sigma(f) = \sum_i \sum_j S_{ij}(f) \quad (14)$$

In which $S_{ij}(f)$ is the cross spectra density for a pair of wind turbines. The cross spectra can be stated in terms of coherence and individual spectra densities [12] as.

$$\gamma_{ij}(f) = \frac{|S_{ij}(f)|^2}{S_i(f) * S_j(f)} \quad (15)$$

The exponential coherence function is often used in micro metrology [12]. This function is defined as below:

$$\gamma_{ij}^2(f) = e^{-a\frac{x_{ij}}{V}f} \quad (16)$$

In which a is the decay constant (usually it taken 50 [14]), x_{ij} spacing between points i and j, V is the mean wind speed, and f is the frequency. In addition, the [13] shows that the wake does not affect the coherence for far wake region. So the coherence in the far wake can be expressed as (16).

In fact this function estimates the amount of coherence in wind speed for different frequencies between different locations. On the other hand, for the low speed region (region 3 in Fig. 1), the correlation between power profiles can be assumed as the correlation between wind speed profiles, so (16) can be used for power profiles coherence. In a typical wind farm, usually the distance between wind turbines is around several times the wind turbine diameter. For example the Horns Rev 1 offshore wind farm that is used as a case study in this paper, has an area equal to $20km^2$, with 80 turbines (in 8*10 array) [14]. The distance between wind turbines is around $500m$. Therefore, for the wind speed $16m/s$ and turbulence length scale of 500m, the coherence function vs frequency is shown in Fig.2.

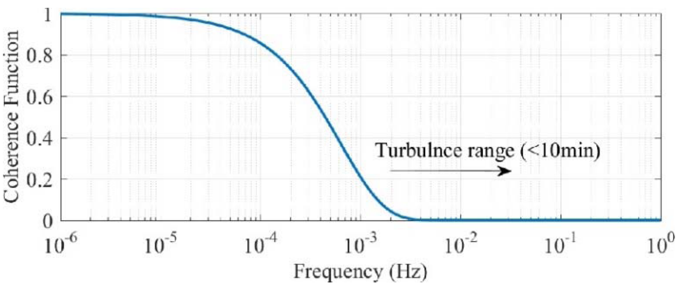

Fig.2. Coherence function for wind power profile in blow the rated speed region

As it is seen, the coherence for turbulence range is almost zero, so according to (14) the cross spectra density for frequencies in turbulence range would be zero ($S_{ij}(f) = 0\ i \neq j$), consequently, the power spectra for total wind farm power can be expressed as follows:

$$S_\Sigma(f) = \sum_i S_{ii}(f) \quad (17)$$

In which $S_{ii}(f)$ is individual power spectra density. Finally the power deviation for total wind farm power is obtained from (13).

$$\sigma_t^2 = \int S_\Sigma(f)\, df = \int \sum_i S_{ii}(f)\, df = \sum_i \int S_{ii}(f) df = \sum_i \sigma_i^2 \quad (18)$$

If the wake effect on the turbulence level is neglected [3], then the power spectra for all wind turbines would be the same ($S_{ii}(f) = S(f)$) and regarding (18) and (13), the total power spectra becomes $S_\Sigma(f) = NS(f)$ (N is the number of wind turbines in the wind farm) and the variance of total power is N times that of individual wind turbine. Thus, the fluctuation level (the ratio of standard deviation to mean value (2)) is decreased by $1/\sqrt{N}$, compared to that of individual wind turbine. Nevertheless, since according to (7) the turbulence level is increased for downstream wind turbines, so the factor of decrement in fluctuation level of total power is less than$1/\sqrt{N}$, which is considered in this paper.

Some previous studies state that deviations in the range of 10 minutes do not appear in the total wind farm power [4]. They considered the wind speed profile as a moving wave that it has just a time delay for wind turbines along the wind direction. Also they did not consider the wake effect. Some papers don't consider the coherence between wind turbine profiles and assume the same turbulence wave (unit coherence) for all units, which causes larger deviation in the total wind farm power [15]. Moreover, the wake effect is not separated for the wind speed mean value and turbulence.

IV. Results

In this section at first the power characteristics of individual wind turbines are obtained and then the total power of wind farm is analyzed.

A. *Wind Turbine Power*

For a typical wind speed (Fig.3), the mean value and turbulence intensity are given in table I. Also the mean value and standard deviation of the output power for one wind turbine are calculated according to (10), as given in table I. Also the output power, obtained by simulation in MATLAB software is shown in Fig.4. The mean value and standard deviation of this profile is also presented in table I for comparing with the results of proposed method given by (12).

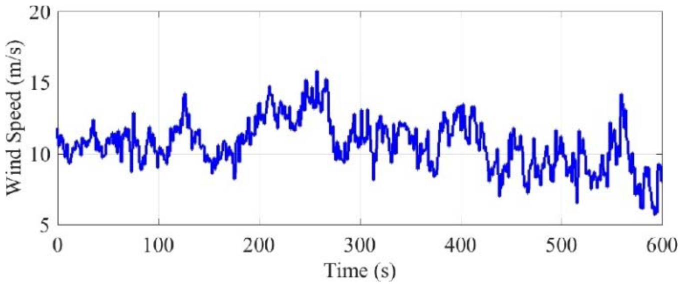

Fig.3. Typical wind speed profile.

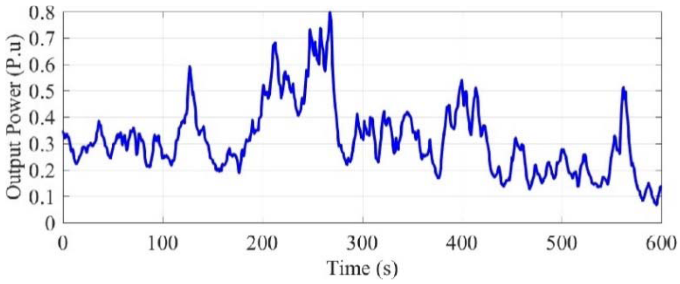

Fig.4. Output power of a wind turbine.

Table I. Mean and standard deviation for wind speed and power of individual wind turbine

	Mean	**standard deviation (σ)**	**Turbulence intensity (I %)**
Wind Speed	10.6 (m/s) (0.66p.u*)	1.7 (0.1p.u)	16
Power (proposed method)	0.313p.u**	0.14	44.7
Power (simulation)	0.315p.u**	0.13	41.2

*1 p.u is equivalent to 16m/s, **1 p.u is equivalent to 2MW.

As table I indicates, simulation results confirm (12), i.e. the wind speed and output power have normal distribution and the standard deviations obtained by the two approaches are very close. Since for the other wind turbines, the wind profiles are not available, the mean value and standard deviation ((5), (7)) are used to obtain their power fluctuation level from (12).

B. Wind Farm Power

The Horns Rev 1 offshore wind farm with 80 turbines (in 8*10 array) is considered as a typical wind farm to determining the battery capacity [14]. To calculate characteristics of the wind farm total power, first the wind speed characteristics at the location of all wind turbines should be obtained. It is assumed that the wind speed at the location of the first row of wind turbines has the profile shown in Fig.3. Then according to (5), (6) and (7), considering the wake effect, wind speed characteristics for the other wind turbines are calculated. The results are presented in table II. For simplicity, the wake effect due to lateral wind turbines is neglected and just the effect of upstream wind turbine is considered. Each column in table II corresponds to the 8 turbines of a row along the wind direction.

Then according to (12), the power characteristic for other wind turbines are shown in table III.

In addition the results for without wake effect condition is shown in table IV. In this condition the mean and turbulence level for all wind turbines are same.

The variance of total power is calculated using (18) and the farm total mean power is the sum of individual wind turbines' mean value. The characteristics of total power is shown in table V.As it can be seen, if the wake effect is neglected, so the fluctuation level is the same for all wind turbines and the fluctuation level of the total power is decreased from 45% for individual wind turbine to 5%, because of uncorrelated components in the range of turbulence. However, the wake effect causes increase in the turbulence level at down wind turbines, so fluctuation level in the total power is decreased to 6.6%. In overall, the results shows that the output power of wind farm has fluctuations in range of less than 10 minutes. The effect of this fluctuation on the required battery capacity is shown in next subsection. In addition the results for average condition, neglecting the turbulence, is shown for comparison.

V. CONCLUSIONS

In this paper the effect of three factors; wake, turbulence and power smoothing on the power fluctuation in a wind farm are analyzed, simultaneously. At first the wake effects on the mean value and the turbulence level of wind speed are analyzed. Then the total power of wind farm with considering the wake effect and the spatial smoothing is obtained. The wind speed and power profile is defined according to the mean value and standard deviation characteristics. It is shown that despite the spatial smoothing in wind farm; that causes decrease in fluctuation level of the total power, there are still some deviations in total power. The power fluctuation level is affected by wake and turbulence intensity.

REFERENCES

[1] C. Luo and B. T. Ooi, "Frequency deviation of thermal power plants due to wind farms," IEEE Trans. Energy Convers., vol. 21, no. 3, pp. 708–716, Sep. 2006.

[2] J. F. Manwell, and at.al, "Wind Energy Explained", 2nd edition, Willey Press, 2009.

[3] H. G. Beyer, J. Luther, R. Steinberger, "Power Fluctuations in Spatially Dispersed Wind Turbine Systems", Solar Energy, Vol. 50, No. 4, pp. 297-305, 1993.

[4] P. Li, H. Banakar, P. Keung, H. Golestani, B. Ooi, " Macromodel of Spatial Smoothing in Wind Farms", IEEE Transaction on Energy Conversion, Vol. 22, No. 1, 2007.

Table II. Wind speed characteristics at different location in wind farm

	T1-T8	T9-T16	T17-T24	T25-T32	T33-T40	T41-T48	T49-T56	T57-T64	T65-T72	T73-T80
Mean Speed (m/s)	10.6	9	8.8	8.7	8.68	8.66	8.65	8.65	8.64	8.64
Standard Deviation	1.7	1.93	1.89	1.87	1.87	1.86	1.86	1.86	1.86	1.86
Turbulence Intensity (I %)	16	21.4	21.5	21.5	21.5	21.5	21.5	21.5	21.5	21.5

Table III. Power characteristics at different location in wind farm with wake effect

	T1-T8	T9-T16	T17-T24	T25-T32	T33-T40	T41-T48	T49-T56	T57-T64	T65-T72	T73-T80
Mean power (p.u*)	0.313	0.204	0.189	0.184	0.182	0.181	0.180	0.180	0.179	0.179
Standard Deviation	0.14	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Fluctuation level (%)	45	61	61	61	61	61	61	61	61	61

*1 p.u is equivalent to 2MW.

Table IV. Power characteristics at different location in wind farm without wake effect

	T1-T8	T9-T16	T17-T24	T25-T32	T33-T40	T41-T48	T49-T56	T57-T64	T65-T72	T73-T80
Mean power (p.u*)	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313	0.313
Standard Deviation	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Fluctuation level (%)	45	45	45	45	45	45	45	45	45	45

Table V. Characteristics of wind farm power for 10 min

	Without wake effect		**With wake effect**	
	Instantaneous	Average	Instantaneous	Average
Mean Power (p.u*)	25	25	15.80	15.8
Standard Deviation	1.25	0	1.05	0
Fluctuation level (%)	5	0	6.6	0

*1 p.u is equivalent to 2MW.

[5] I. Katic, J. Hojstrup, N. O. Jensen, "A Simple Model for Cluster Efficiency", European Wind Energy Association Conference and Exhibition, Rome, 1986.

[6] E. L. Petersen, N. G. Mortensen, L. Landberg, J. Hojstrup, H. P. Frank, "Wind Power Metrology", RISO-I-1206(EN), Riso National Laboratory, Roskilde, Denmark, 1997.

[7] S. Roy, "Impact of Short Duration Wind Variations on Output of a Pitch Angle Controlled Turbine," IEEE Transactions on Sustainable Energy, Vol. 3, No. 3, JULY 2012.

[8] L. J. Vermeer, J. N. Sorensen, A. Crespo, "Wind Turbine Wake Aerodynamic", Progress in Aerospace Science 39, pp. 467-510, 2003.

[9] A. Duckworth and R. J. Barthelmie, "Investigation and validation of wind turbine wake models," Wind Eng., vol. 32, no. 5, pp. 459–475, 2008.

[10] A. Crespo, J. Hernandez, "Turbulence characteristics in wind turbine wakes", Journal of Wind Engineering and Industrial Aerodynamics vol. 61, pp. 71-85, 1996.

[11] S. Frandsen, M. L. Thogersen, "Integrated fatigue loading for wind turbines in wind farms by combining ambient turbulence and wakes", Wind Eng, vol. 23 (6), pp. 327-339, 1999.

[12] J. S. Bendat, A. G. Piersol, "Random Data; Analysis and Measurement Procedures," 4th edition, Wiley Press, New Jersey, 2010.

[13] J. Hojstrup, "Spectral coherence in wind turbine wakes," Journal of Wind Engineering And Industrial Aerodynamics 80, pp. 137-146, 1999.

[14] LORC tests and demonstrates technology for harvesting renewable energy offshore [online]. Available: http://www.lorc.dk/offshore-wind-farms-map/horns-rev-1.

[15] A. M. Howlader, T. Senjyu, A. Y. Saber, "An Integrated Power Smoothing Control for a Grid-Interactive Wind Farm Considering Wake Effects ", IEEE Systems Journal, Vol. 9, No. 3, 2015.