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Analysis of Wake Effect in Clustered Wind Farm (IEEC 2016)

Sara Noor[1], Maryum Waris[2*] and Sajjad Haider Zaidi[3*]

[1] Department of Electronics and Power Engineering, National University of Sciences and Technology (PNEC), Islamabad, 44000, Pakistan [1] (saranoor@live.com)

[2] (maryumwaris@pnec.nust.edu.pk) * Corresponding author

[3] (zaidisy1@gmail.com) * Corresponding author

Abstract: This paper focuses on the phenomena of internal and external wake effects which arise in wind farms. Modeling and estimation of energy yield of a real wind farm (Jhimpir Pakistan) has been conducted using Wind Atlas Analysis and Application Program (WAsP). Present methodology implies evaluation of power output with appropriate micro sitting between turbines within a farm to maximize energy yield. Wind Resource of site has been analyzed to observe the wind potential. The results demonstrate that not only internal but also external wake contributes in reduction of power output of the farm. It has been found that proper planning of wind farms holds an immense importance and is highly effective to eliminate power losses that can arise due to wake effects. Reduction of wake can assist wind farm utilities to maximize their financial profits and can play a vital role in overcoming energy crises in the country.

Keywords: Wind turbines, wind farms, cluster wind farm, energy yield, wake effect, wake losses.

I. INTRODUCTION

Pakistan is facing problems related to energy crisis. The demand for energy has increased in tremendous proportions in the last few decades in Pakistan. In order to deal with this problem, apart from conventional power project wind farms are being installed and are gaining popularity in Pakistan. The Wind Atlas in Pakistan shows that there are many promising areas where we can install wind farms. New wind power projects have proven that wind energy is not only cost competitive but also offers additional benefits to the economy and the environment.

A study has been done to find wind corridor of Pakistan. It has been found that the potential region of wind in Pakistan is the coastal area of Sindh, Balochistan and desert of Punjab and Sindh. The coastal wind corridor of Pakistan is around 60km in width (Gharo and Kati Bender) and 180km in length. According to the AEDB [9], Jamphir (Gharo-Keti Bandar) wind corridor has a potential to generate up to 50,000MW of electricity whereas the total potential for electricity generation from wind in the country is 150,000MW. The region holds average wind speeds of around 7.3 meters per second (m/s). As there is good potential of wind in Jamphir area (i.e wind direction is stable, wind quality is better and there is no distortion of wind) many government and private wind farm developers have started installing wind farm in this region. Thus, it has been observed that there is a growth of wind farm in this locality.

The most important problem that is arising in these wind farms is the wake effect within and between large wind projects. Turbines are usually arranged in rows facing the wind direction. When the upwind turbine/farms extract wind power, it affects the flow of wind behind them. Thus, there will be a deficiency of wind speed behind the upwind turbines/farm which causes lower power production in downwind farms/turbines. No agency is present in Jhimpir to monitor the new installation of wind farms. Therefore, there should be a systematic approach regarding future installation of wind power projects.

In the first section of paper presented here wind potential is described. In the second section, wake effect of one turbine over the other is analyzed. In the third section, it is been demonstrated that how wake losses are minimized by increasing inter turbine distance. Subsequently, an investigation on wake interaction between clustered wind farms has been carried out in the fourth part. Afterwards in the fifth section, it is discussed that how important it is to take into account wake effects caused by neighboring wind farms. Later all of this research methodology is implemented on a real case of wind farm.

II. WIND POTENTIAL ASSESSMENT

Air consists of kinetic energy, when the air strikes the turbine it causes turbine blades to rotate and converts this kinetic energy into electrical energy. Actually the covering behind the blades contains the machinery that creates electricity. The power going into the wind turbine can be written in mathematical form as:

$$P = d \times D^2 \times V^3 \times C \quad (1)$$

Where,
d=Density of air
D=Turbine blade diameter
V=Velocity of wind
A= constant

But wind turbine cannot convert all the power present in wind into electricity. According to Betz, there is a theoretical limit for the conversion of kinetic energy of wind into electricity. Betz law states that wind turbine can convert only 59% of wind power into electricity i.e C_{pbetz} is 0.59. C_p is the ratio of the actual power produced by the turbine to the power in the wind. Normally C_p of good turbine is in between 40 percent to 50 percent. The mathematical representation of C_p is:

$$C_P = \frac{P}{\frac{1}{2}\rho U^3 \prod D^2} \quad (2)$$

III. SINGLE TURBINE PRODUCTION

In order to calculate the power produced by a single turbine we need to have power curve of that turbine as shown in Fig. 1, wind rose diagram as shown in Fig. 5 and the hub height of wind turbine. Next, we will calculate the mean power produced by the turbine with the help of Weibull function:

$$f_{weibull}(U) = \frac{K}{A}\left(\frac{U}{A}\right)^{k-1} e^{\left(\frac{U}{A}\right)} \quad (3)$$

Where,
k= shape parameter
A= scale parameter

The mean power produced can be estimated with the help of mathematical formula shown below:

$$P = \int_0^{\infty} \Pr(u) P(u) du \quad (4)$$

This integral is computed by numerical integration using trapezoidal rule. Also it is assumes that the direction of wind is unidirectional but practically this is not the case. Direction of wind is varying and it is essential to plot wind rose diagram (as shown in Fig. 4) that describes the flow of wind direction of a geographical location.

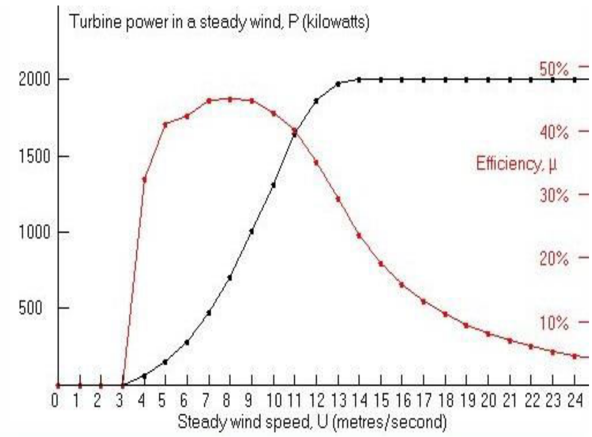

Fig.1 Power curve and thrust curve of a wind turbine

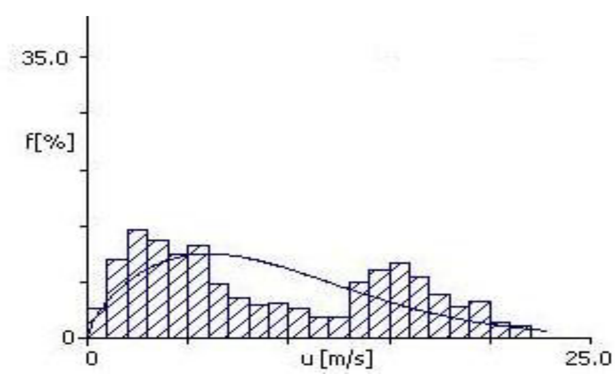

Fig.2 Weibull Distribution Function

Thus, we are using all sector wind speed distribution (i.e emergent distribution for wind speed). This distribution is the combined sum of the Weibull distributions from all the sectors of direction. This distribution not necessarily a Weibull distribution e.g. it may be bimodal if there are two sections that are dominant with varying speeds.

IV. WIND FARM PRODUCTION

In order to calculate the total power produced by a wind farm we cannot simply add the power produced by all turbines because of losses arises due to wake. Because of wake effect, when wind passes through the upstream wind turbines in the wind farm, there occurs a decline in speed of wind for wind turbines present behind upstream turbines and because of this speed deficit the downstream wind turbines will produce less power as compare to upstream wind turbines. To account for wake effects within the farm, WAsP (it's a software used for wind farm planning and modeling) has implemented N.O Jenson model [5] for estimating power produced by a wind farm. N.O Jenson model is based on momentum theory to anticipate the flow of wind. In this model it was assumed that wake behind the turbine expand in a linear way. Diagrammatical demonstration is shown in Fig. 3 below [5]. This model takes into account the velocity just behind the rotor, ambient wind velocity, wake decay constant and thrust efficient.

The expression given by Jenson to calculate the velocity deficit is:

$$\frac{V}{U} = 1 - \frac{2a}{(1 + 2kx/D)^2} \quad (5)$$

Where,
a is the initial deficit in velocity

$$a = \frac{1 - \sqrt{1 - C_t}}{2} \quad (6)$$

Where,
C_t is the thrust coefficient which is defined as the ratio of thrust force to dynamic force.

$$C_t = \frac{F}{\frac{1}{2}\rho U_o^2 \prod D^2} \quad (7)$$

Where,
T=Thrust force (thrust is an axial force it is created when air strikes the blades of turbines)

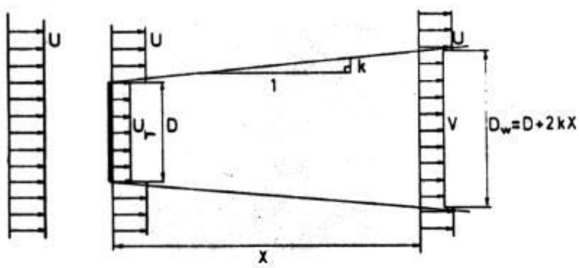

Fig.3 N.O Jenson Wake Model

Thrust coefficient is dependent on wind speed and helps in describing the flow in wake; the higher the C_t larger wake expansion. Thrust coefficient curves are provided by the manufacturing company and they are useful in calculating wind power production.
For multiple wake interaction the model was further modified by Katic. According to Katic, for multiple wake interaction we can assume that "kinetic energy deficit of a mixed wake be equal to the sum of the energy deficits for each wake"[5]. Thus with the help of Katic extended model we can calculate the effect of all interacting wake as

$$\delta U_n = \sqrt{\sum_{i=1}^{n-1} (\delta U)^2} \qquad (8)$$

Also we need other turbine characteristics such as turbine hub height, power curves, rotor diameter, curves of thrust coefficient and wind climatology to calculate power produced by a wind fam. Thus after calculating the wind speed deficit along with the consideration of site wind climatology and other characteristics we can estimate the power produced by following formula:

$$P = \int_0^\infty \Pr(u) P(u) du \qquad (9)$$

Here also emergent distribution for wind speed is calculated using Eq. (3).

V. CLUSTERED WIND FARM PRODUCTION

To calculate power production of a clustered wind farm, the same approach is applied that we have used in case of single wind farm. But here we take into account the wake effect that arises due to neighboring wind farms and cause wake losses.

VI. CASE STUDY

To implement this above mentioned proposed approach, cluster of wind farms in considered, located in Jhimpir, Thatta, Pakistan. The site coordinates are 25° 1'0"North, 68°1'0"East. This site is situated at a distance of 114 km from the city of Karachi. This Jhimpir area is completely uncultivated. According to AEBD, Jamphir lies in the wind corridor of Keti Bander, which can generate power up to 50,000MW. To analyze wind resource of our project site, wind data is captured from nearby meteorological station. After a detail wind resource assessment it is found out that mean wind speed is around 7.62 m/s^2. Other parameter such as mean power density, Weibull parameters are found to be 495 w/m^2, A=10.6m/s and k=4.02 respectively. Moreover, direction of wind speed is represented with the help of wind rose diagram shown in Fig. 4 below.

To find out the effect of wake, we have considered wind farm 'A' (name has been changed due to confidentiality of wind farm owner). Layout of wind farm 'A' and other existing wind farm is shown in Fig. 5. Wind turbines used in wind farm have a hub height of 85m, rotor diameter of 77m and are manufactured by GE Wind Energy. The capacity of this wind farm is around 50MW.The power curves and thrust curves of wind turbines are shown in Fig. 1.

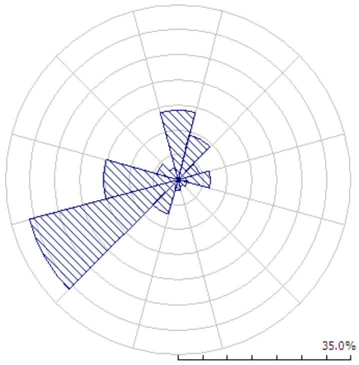

Fig. 4 Wind Rose Diagram of site location.

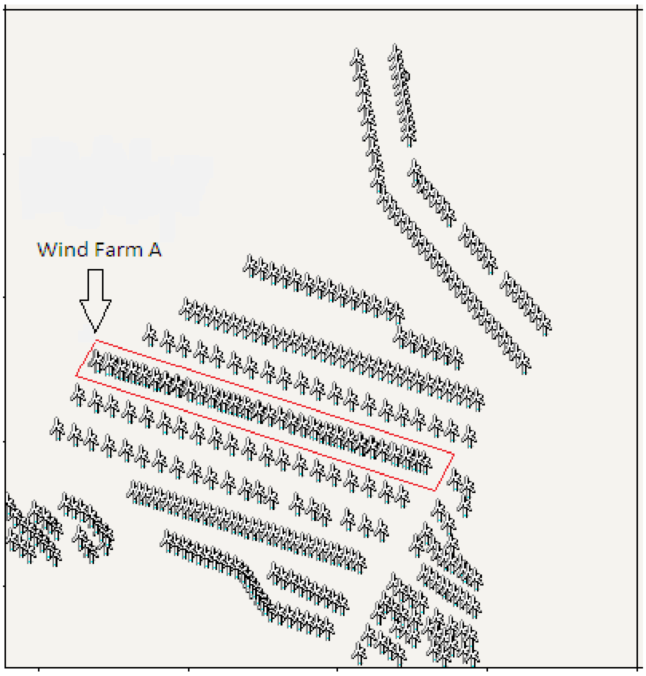

Fig. 5 Wind farm 'A' Layout of site designed in WAsP

A. Energy yield of a single Turbine

A single turbine is installed at the demarcated site location, and in the presence of estimated wind climatology of Jhimpir region energy yield of this turbine is estimated. While calculations wake effect of wind farms present in the vicinity are not considered.

Table 1 Single turbine energy calculations.

	Parameters	Values
(i)	Gross AEP (Gwh)	9.199
(i)	Net AEP (Gwh)	9.199
(iii)	Loss%	0.0

The above table shows the energy yield of a single turbine. It can be observed as no wake effect is considered, power losses are 0 percent.

B. Energy yield of a single wind farm

In this case, all the turbines are first installed and an estimation of energy yield of whole wind farm is done by including internal wake effects. In this scenario, three conditions are applied. Firstly, energy yield of wind farm is calculated by keeping 3.9 rotor diameter inter turbine spacing. Secondly, energy yield is calculated by keeping 3.5 rotor diameter distances between turbines. Lastly, energy yield is estimated by keeping 3 rotor diameter distance between turbines. After calculating the energy yield of wind farm 'A' in all these three condition, a comparison is made among them and it is analyzed in which situation energy yield of wind farm is maximum. It means, to maximize energy harvested from the wind, an optimum inter turbine distance should be found out first.

Table 2 Wind farm calculations w.r.t internal wakes.

		3.9D	3.5D	3D
(i)	Total Gross AEP (Gwh)	260.746	260.710	260.497
(ii)	Total Net AEP (Gwh)	252.250	250.504	247.302
(iii)	Wake losses (%)	3.26	3.9	5.07

In table 2 it can be observed that energy yield of wind farm is calculated by keeping 3.9 D, 3.5D, and 3.0D rotor diameter distance between turbines. Wake losses arising from internal wake effects are minimum when the spacing between turbines is 3.9D and are maximum when inter turbine spacing is 3D. Though at 3.5 D distance we observe an increase in Net AEP compared to Net AEP at 3D distance, but at 3.9D there is more increase in Net AEP as compare to 3.5D. Thus, it seems that wind farm will be more energy efficient when inter turbine spacing is 3.9 rotor diameter.

C. Energy Yield of Wind farm (In Cluster)

Next, energy yield of wind farm is estimated by keeping 3.9 rotor diameter inter turbine distance. Also the effects of internal as well as external wake (i.e. wake caused by wind farms present in the vicinity) are considered while calculating. It can be observed from Table 3 that by considering external wakes there is a reduction of around 32.512Gwh in energy yield, which corresponds to 13.02% increase in wake losses. Thus, energy output of a wind farm is not only affected by wake of internal turbines but also by wake of wind farms present in the neighborhood.

Table 3 Wind farm calculations w.r.t external wakes.

		External+ Internal wakes	Internal wakes
(i)	Total Gross AEP (Gwh)	263.861	260.746
(ii)	Total Net AEP(Gwh)	220.912	252.250
(iii)	Wake losses (%)	16.28	3.26

V CONCLUSION

This paper presents a research on effect of internal and external wakes. An analysis in this regard is done, which explores how wake interact and effect wind energy, which in turns effect the power production of wind farms/turbines. It also highlights the proper orientation of wind turbines in a wind farms to harvest maximum energy form wind. Also it has been observed that energy yield is not only affected by internal wakes but also by the wind farms present in the vicinity.

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