Arrangement of Wind Turbines in Wind Farms and Increasing of Efficiency for Power Generation in Wind Power Plant

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Abstract: - In this paper, optimum arrangement of wind turbines and the matter of their locations in wind farms including Khorasan Wind Power Plant in Iran will be studied, in this article, focus is made mostly on computerized simulation of power plant sites for optimized configuration of wind farm turbines by using wind specialized soft wares.

Key-Words: - Wind turbine, wind farm, wake flows

1 Introduction

Wind is a phenomenon which is generated by the internal movements of the earth or when the sun unequally shines on uneven surfaces of the earth, which causes changes in temperature and pressure. The gradient of wind pressure makes wind blowing directly from high-pressure center to low pressure center. But the earth rotation produces another power named Coriolis force, which effects on the wind blowing direction.

Wind is produced by the activity of pressure and Coriolis force together, also. Friction force affects on the speed and direction of wind.

2 Wind Farm

Wind farm contains a number of centralized wind turbines, which supply electrical energy through distribution network.

2.1 Arrangement of Wind Turbines in Wind Farms

Wind turbines, due to morphology (shape, form) of the area are installed with specified spaces in a suitable and symmetrical mode and compatible with nature view in a way to be placed in the direction of prevailing wind of the area to be able to produce maximum power [1]. Drawing wind roses by using specialized wind soft wares can recognize direction of prevailing wind.

In the case of existing limitation in the type of the ground, it is preferred to use turbine with high capacity, and their spaces shall be selected reasonable and in a calculated manner. In a wind farm, the turbines shall be scattered in a pattern so as to provide the best productivity and economical output. Reciprocal effect of turbine and winds depends at least on the two following items:

1. Aero-dynamic characteristics of the turbine.
2. Climatic condition of the selected area.

2.2 Efficiency of Wind Turbines

Different parameters affect on the efficiency of wind turbines. In order to show this effect clearly, severe effect of some parameters on the efficiency of wind turbines will be shown for a turbine with variable speeds of the rotor. Conclusion of output wind turbine is based on reduction of wind speed in the wake of each individual turbine.

As almost all towers of modern turbines have a circular cross-section, only the flow around a circular cylinder has to be considered. The internal friction of the flowing medium and the surface friction (boundary layer) of the encountered body cause an area of disturbed flow behind the body, the so-called flow wake area. The wake in the flow behind a circular cylinder consists of an extensive area of increased turbulence with a considerably decreased mean flow velocity. [2]

Passing liquid air with V_1 speed (equal to wind speed) through the turbine blades, rotates the rotor which some part of its kinetic energy will be absorbed by the turbine and finally the air flow with V_2 speed (which is less than inlet speed of V_1) goes out of the blades the less the outlet air speed (V_2) the higher will be the energy received by the turbine from the wind.

The air mass passes through the blades in a second is as follows:

$$m = \frac{P.A\ (V_1 + V_2)}{2}$$

Where:

P = air density

A = the area of air passing through the blades

V_1 = wind speed in front of the rotor

V_2 = wind speed at the back of the rotor

On the other hand the predicted annual energy production depends on the air mass passing through the blades which is calculated on the basis of Newton second low as per follows:

$$P = \frac{1}{2}\ m\ (V_1^2 - V_2^2)$$

$$P = \frac{\rho}{4}\ (V_1^2 - V_2^2)\ (V_1 + V_2)\ A$$

But the nominal power of wind (P_o) which is equal to $\frac{1}{2}\rho A V_1^3$, is not completely received by the turbine, therefore, ratio of the predicted annual energy production to nominal power will be as follows:

$$\frac{P}{P_o} = \frac{1}{2}\ (1 - (\frac{V_2}{V_1})^2)\ (1 + \frac{V_2}{V_1}) \qquad (1)$$

Thus ratio of P/P_o will be function based on the ratio of V_2/V_1, in a way that the smaller V_2/V_1, the ratio of P/P_o will come closer to the nominal value of one.

Studies showed that in theory, maximum value of V_2/V_1 would be equal to 1/3, therefore, the ratio of the P/P_o will be calculated as 0.59, i.e. in theory 59% of the wind energy will be produced by wind turbines, but this ratio for manufactured turbines are 0.2 to 0.4.

Predicted annual energy production in a wind turbine is proportionate to the third power of speed:

$$P = \frac{1}{2}\rho A V^3$$

The wake flows generated at the back of turbines has been made by the drop in the wind speed, which highly depends on the blades geometry, if adequate spacing is not observed in the wind farm for the wind turbines, the turbine function will be disturbed. One of the distinguished disturbances is producing vibration and effect of fatigue due to alternative loads on the turbine blades, while out coming wind of the turbine in contact with the next turbine does not have enough energy and could not generate enough productivity. Therefore, observance of proper space between wind turbines on a wind farm has a great effect on the turbine efficiency, and reduces the wake flows at the back of turbines Figure 1.

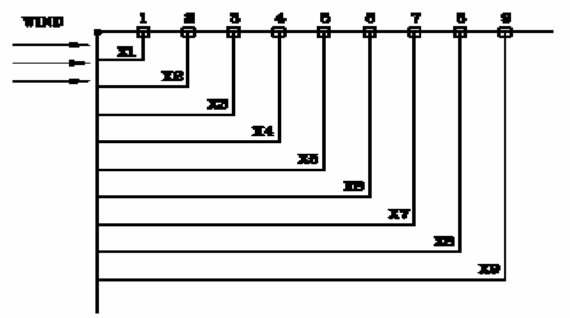

Figure 1

3 Calculations Related to Arrangement of Wind Turbines

Two methods for optimizing the space between wind turbines in a wind farms are as follows:

3.1 Linear Method

In this method, it is supposed that, a number of similar horizontal axis turbines, which are manufactured by similar factory, shall be arranged in a straight line with specified spaces and in direction of the wind.

The objective of optimization would be achievement of x_1, x_2, x_3, ……… and x_{n-1} spaces for maximum instantaneous power from wind farm. Figure 2 shows the turbines arrangement in comparison with each other.

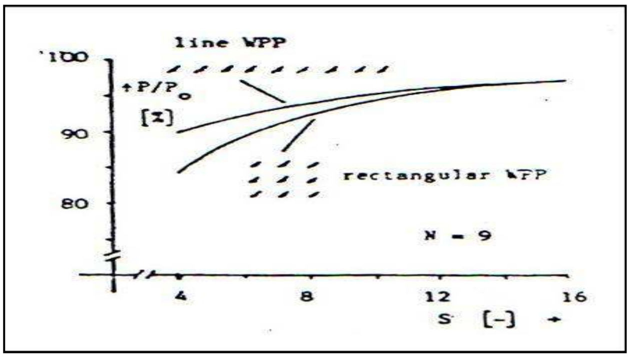

Figure 2

Wind speed = V_o

Distance up to i_{th} turbine = x_i

Length of settlement line of turbines: L = (WEPP)[1]

If, it is supposed that v_o, v_1, ……… v_{n-1} are the wind speeds which received by the turbines Nos. 0, 1, ………. N-1 and also, the power is a function of speed cube. Therefore:

Maximize $\sum_{i=o}^{n-1} \left(\frac{v_1}{v_o}\right)^3$

Therefore, in view of disturbances due to wake, it is assumed that x_f is minimum space between each of turbines.

So that:

$X_1 > x_f$

$X_i > x_{i-n} + x_f$ for: i = 2, 3, … n+1

$X_i < L$ for: i = 2, 3, … n–2

In order to use the above relation for optimizing of turbines space, the wind speed which is received by each turbine as well as x_f variable shall be mathematically related with space modifications and in question turbines particulars.

Two analytical methods for obtaining the optimized space are as follows:

One method was implemented by TEMPLIN, NEWMAN AND CARFOOD and the other named "wake model" was reviewed by LISSAMAN AND ABRAMOVICH.

3.3.1 Wake Model in Linear Method

Wake model was reviewed by LISSAMAN AND ABRAMOVICH.

Wake model provides the relationship between three important parameters including change in the rate of movement, value of wake growth and speed distribution in the wake. The main obtained equations are as follows:

$$\Delta V_m - \Delta V_{mo} \frac{-0.258m + [(0.258m)^2 + 0.536\ (1-m)(r_o/r_w)^2]^{1/2}}{0.268\ (1-m)} \quad (2)$$

in which:

ΔV_m = speed change in the flowing central line

ΔV_{mo} = speed change at the turbine axis

V_o = wind speed

$$m = \frac{V_o}{V_{mo}} \quad (3)$$

r_o = initial wake radius

r_w = radius of wake growth

ΔV = change of wind speed at the wake direction

$$\Delta V = \Delta V_m\, [1-(r/rw)^{1.5}]^2 \quad (4)$$

r = sectional radius of the wake

$$r_w = r_f + \alpha/0.36\ (x - x_f) \quad (5)$$

α = turbulence intensity

x = maximum space between two turbines

x_f = minimum space between two turbines

r_f = wake radius at minimum space between turbines

The optimized space in wake method will be obtained by solving 1 through 4 equations.

For example: The optimized space between two horizontal axis wind turbines, with power 160 kW, diameter 26 m in steady speed of 10 m/s has been calculated. Figure 5.1 shows the arrangement and the space between turbines.

Table 1: The Space between 160 kW Turbines

TURBINE NO.	1	2	3	4	5
DISTANCE FROM STARTING POINT (M)	127.44	251.77	371.42	470.17	577.77
DISTANCE UPTO PREVIOUS TURBINE (M)	127.44	124.33	119.56	98.75	107.60
TURBINE NO.	**6**	**7**	**8**	**9**	
DISTANCE FROM STARTING POINT (M)	682.43	786.75	899.27	1005.84	
DISTANCE UPTO PREVIOUS TURBINE (M)	109.66	104.32	112.52	106.57	

In this relation, x_9 = 1005.84, and the average turbines space would be 111.76 m which shall be proximately 3 or 4 times the diameter of each turbine. [3]

[1] Wind Energy Power Plant

3.2 Non Linear Method

In this method, optimized arrangement of turbines in a farm will be reviewed in x and y directions. Three considered conditions for the wind are as follows:

1. Stable flowing direction and wind intensity.
2. Variable flowing direction but stable wind intensity.
3. Variable both flowing direction and wind intensity.

In this method, wake decay model has been used and main equations are as follows:

$$V = V_o \left[1 - \frac{2\alpha}{1 + \alpha\ (x / r_1)^2}\right] \quad (6)$$

V = wind speed at the downstream
V_o = wind speed at the upstream
a = axial induction factor
α = height constant
x = space at the flow downstream
r_t = blade radius
r_1 = flow radius at the downstream
Turbine drive factor (C_T), i.e. a, r_1, will be related by the followings:

$$C_T = 4\alpha\ (1 - a)$$

$$r_1 = r_t \left(\frac{1 - a}{1 - 2a}\right)^{1/2} \quad (7)$$

$$\alpha = \frac{0.5}{L_i\ (Z / Z_o)} \quad (8)$$

Height constant will be calculated by the following relation:
Z = hub height
The obtained speed at the downstream for n turbines will be calculated by the following relation if, it is assumed that decay of Kinetic energy of a complex wake is equal with the total decaying energy.

$$\left(1 - \frac{V}{V_o}\right)^2 = \sum_{i = 1}^{n} \left(1 - \frac{V_i}{V_o}\right)^2 \quad (9)$$

V = average of wind speed
By using the relations of 6 through 9, for turbines with constant diameter 40 m, hub height 60 m, they could designate the arrangement of turbines as a wind farm in a random form.
A surface roughness of (Z_o) 0.3 m has been considered for an area of 2 by 2 km obtained results for different conditions of the wind is presented in Table 2.

Table 2: Minimum Space for Wind Turbines of Diameter 40

WIND CONDITION	NUMBER OF TURBINE	MINIMUM SPACE BETWEEN TURBINES (M)		
		LENGTH-WISE	WIDTH-WISE	TRANSVERSE
STABLE BOTH WIND DIRECTION AND INTENSITY	26	200	200	200
VARIABLE DIRECTION BUT STABLE INTENSITY	19	400	200	200
VARIABLE BOTH INTENSITY AND BLOWING DIRECTION	15	400	200	200

In the first method only one direction or a line of settlement will be studied and it is only for the case stable wind intensity and blowing direction, and the second method, is used mostly for wide areas and shows random arrangement of turbines. The results of the table show that the space of 5 to 10 times as much of rotor diameter, perpendicular and parallel to the wind blowing is considered.

4 Khorasan Wind Farm Power Plant

Khorasan wind power plant, with 28 MW total capacity is situated in Khorasan province, special topology of the area has virtually turned this into an air corridor between cold eastern zones and the desert land. Variable temperatures of the desert in different hours produced a pressure gradient of the air corridor at both sides. Therefore a wind with relatively high intensity is blowing in an area with about 50 km depth. On this basis, different arrangement for 43 wind turbines, VESTAS V47/660 kW was designated by using simulation software for wind project, and predicted annual energy production from all the power plants, for each arrangement was calculated.
It should be noted that, the following conditions were considered in all the calculations.
Average height of the site from sea level: 1450 m
Annual average temperature: 140°
In the analysis results related to each arrangement, the following were calculated:
Predicted annual energy production of the farm, efficiency of wind turbines assembly, energy content of the wind in each geographical segment, power table and curve of the power plant, Weibull distribution functions and speed windrose (for determination of prevailing wind).

After reviewing of the obtained results, the best arrangement for the power plant site as well as the best array was selected which in this mode Figure 3, electric power generation will be more in comparison with other arrangements.

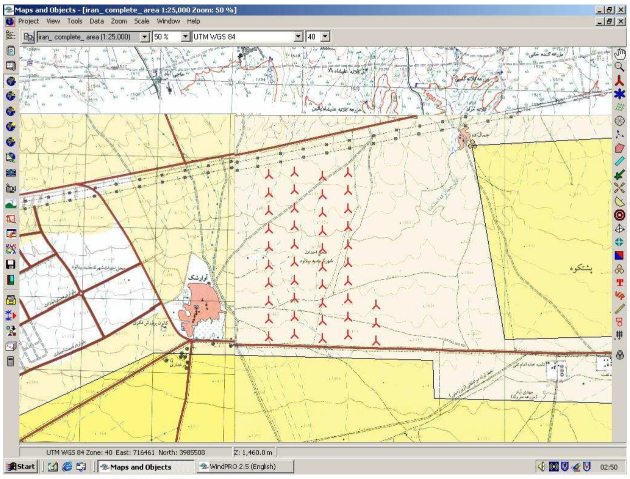

Figure 3

4.1 Efficiency of the Farm
This parameter, which is a function of arrangement and layout of each turbine, will be 95.5% in an optimized arrangement.

4.2 Annual Outgoing Energy
In this arrangement, gross and net annual outgoing energy will be higher in comparing with others; net annual outgoing energy will be 10% less than gross annual outgoing energy. The results are shown in the calculations.

5 Conclusion
Today, energy is one of the main economical bases in the world. In view of the existing limitations, a promotion of productivity is of the main activities to be performed. In wind farm power plants, observance optimized space between wind turbines on wind farms has a great effect on increasing efficiency on the power plants.

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