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Wake Effect on the Construction and Cost of Variable Speed Wind Farm

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ABSTRACT

This paper focuses on construction of wind farm, variable speed wind farm operation and weak effects on the power production from wind farm by using Jensen's weak model. This methodology can be done by using Matlab program.
The objective of every wind farm designer is producing as maximum, as possible of energy, with minimal cost of installation. The optimization is done by the minimum cost per unit of energy produced. In this study an algorithm has been developed to solve the rule of thumb a wind farm layout based on the wake model of Jensen. It has the capacity to estimate the optimal number of total power produced in wind farm, in comparison with predominant wind farm. Five different wind turbines types have been used.

KEY WORDS

Wind Turbine Module, Wind speed, Wake effect, Matlab program.

1. Introduction

If a wind turbine is working within the region of the wake of another turbine, or at a point within the wind farm which is affected by several of these wakes, then the turbine will produce less energy than those turbines that interact directly with the natural wind flow. Therefore the layout of wind farms is very important, since it has impact in the economic, safety and reliability evaluations of the system.

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2. Modification of Average Wind Speed to Hub Height

Usually weather stations measure wind speed at 10-m or 24.5-m above the ground. If these heights do not match the hub height of a wind turbine it is necessary to extrapolate the wind speeds to hub height of the turbine [1, 5]. This process can be done by the following equation:

$$u_h = u_{ho} * \left[\frac{h}{h_o} \right]^{\alpha} \tag{1}$$

Where: u_h is the wind speed at height of h-m above the ground, m/s, u_{ho} is the wind speed at height h_o-m, m/s, (h_o is used 24.5m), h is the height of turbine from ground, m and α is wind shear power law exponent. The wind shear power law exponent depends on the specific site. It is often equal to or near the value 1/7.

3. Wind turbine model

The power P_{wt} produced by the WT within the rotational speed interval [n_{min}; n_{max}] are proportional to the WTs blade radius R, air density ρ, wind speed u and a coefficient C_P .[1,3,10]

$$P_{wt} = C_p \left(\frac{1}{2} \rho A_w u^3 \right) = \frac{1}{2} \rho A_w u^3 C_p (\lambda, \beta) \tag{2}$$

Where; C_p is the coefficient of performance, P is the air density, is equal 1.225 kg/m^3 at sea level at temperature T=298K, A_w is the swept area of the turbine, m^2 and u is the wind speed, m/s.

Maximum value of C_p is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum C_p values in the range of 25-45%.[1]
The coefficient of performance is not constant, but varies with the wind speed, the rotational speed of the turbine, and turbine blade parameters such as angle of attack and pitch angle. Generally, it is said that power coefficient, C_p, is a function of tip speed ratio, λ, and blade pitch angle, β (deg). The tip speed ratio is defined as:[3,10]

$$\lambda = \frac{w_R r_m}{u} \tag{3}$$

Where: r_m is The maximum radius of the rotating turbine, m, w_R is The mechanical angular velocity of the turbine , rad/s.
The angular velocity w_R is determined from the rotational speed n (r/min) by the equation.

$$w_R = \frac{2\pi n}{60} \tag{4}$$

Where; n is the rotational speed, revolution per minute

Numerical approximations have been developed to calculate C_p for given values of β and λ. Here, the following approximation is used [2, 6,10]

$$C_p(\lambda,\beta)=0.73\left(\frac{151}{\lambda_i}-0.58*\beta-0.002*\beta^{2.14}-13.2\right)e^{\frac{-18.4}{\lambda_i}} \quad (5)$$

Where λ_i is described by the equation:

$$\lambda_i=\frac{1}{\frac{1}{\lambda+0.02*\beta}-\frac{0.03}{\beta^3+1}} \quad (6)$$

At rated wind speed, the rated electrical power output can be expressed as:

$$P_{eR}=C_{PR}\eta_{mR}\eta_{gR}\frac{\rho}{2}A_w u_R^3 \quad (7)$$

Where: C_{PR} is the coefficient of performance at the rated wind speed u_R, η_{mR} is the transmission efficiency at rated power, η_{gR} is the generator efficiency at rated power, ρ is the air density, and A_w is the turbine area. The efficiency for a gearbox or transmission efficiency is typically 90-95 percent and the efficiency for a generator is from around 90 percent to almost 100 percent [11,10].

The quantity $C_{PR}\eta_{mR}\eta_{gR}$ is the *rated overall efficiency* of the turbine. This quantity can be represented by a symbol of η_o:

$$\eta_o=C_{PR}\eta_{mR}\eta_{gR} \quad (8)$$

The electrical power output of a wind turbine is a function of the wind speed, the turbine angular velocity, and the efficiencies of each component in the drive train.

It is also a function of the type of turbine, the inertia of the system, and the gustiness of the wind. The *average power* $P_{e,ave}$ that would be expected from a given turbine at variation in wind speed.[10]

$$P_{e,ave}(t)=\begin{cases}0, & u<u_c\\ C_{PR}\eta_{mR}\eta_{gR}\frac{\rho}{2}A_w u_R^3 & u_c\le u<u_R\\ P_{eR}, & u_R\le u<u_F\\ 0, & u\ge u_F\end{cases} \quad (9)$$

Where; P_{eR} is rated Power of WTG, W, u_c is cut-in wind speed, m/s, u_R is rated wind speed, m/s and u_F is furling wind speed,m/s.

4. Turbine Placement

Turbines will typically be placed in rows perpendicular to the prevailing wind direction. We will define two turbine spacing, D_{cw} as the cross wind spacing within a row of turbines as from two to four rotor diameters, and D_{dw} as the downwind spacing between rows of turbines the range of from five to ten. These are calculated as constant times the number of rotor diameters D. Spacing the turbines further apart will produce more power, but at the expense of more land, more roads, and more electrical cables. [1]

4.1 Wind turbines type, number and placement modeling considerations

The main goal is to determine the optimal wind turbines type, number and placement to get maximal power output while minimizing the investment costs and considering different practical requirements and restrictions.

In this paper the comparative study will be done between two cases, the first case is predominant wind farm module and the second case is the thumb wind farm module as shown in Fig. 1 [3] .The downwind spacing D_{dw} is varying from 5 rotor diameters to 10.5 rotor diameters in rows and the cross wind D_{cw} is 3 rotor diameters Coolum apart for two cases.

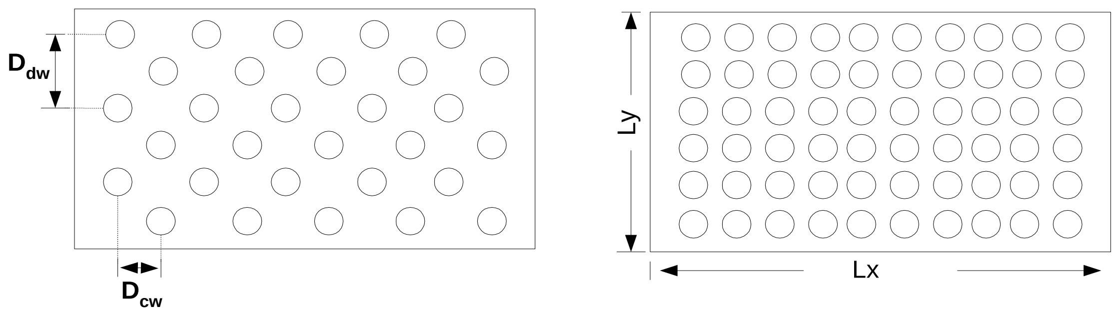

Fig. 1 Wind turbines sample placement for: (a) thumb wind farm module (b) for predominant wind farm module.

The number of wind turbines in a row N_{row}, and number of wind turbines in a column N_{col} can be determined for given area with length D_{row} and D_{col} taking into consideration the separation distances between turbines D_{dw} and D_{cw} as in ref. [1]:

$$N_{row} = D_{row}/D_{dw} + 1 \quad (10)$$

Analogically, the number of wind turbines in a column N_{col} can be determined as:

$$N_{col} = D_{col}/D_{cw} + 1 \quad (11)$$

The total number of turbines N, can be defined as multiplication of rows and columns turbines numbers N_{row} and N_{col}.

$$N = N_{row} N_{col} \quad (12)$$

4.2 Wake Effects and the Cost Model

To estimate the power produced from a wind turbine operating in the wake of one or more wind turbines, an analytical wake model developed by Jensen [3, 4,7 and 9] is chosen. It is based on global momentum conservation in the wake downstream of the wind turbine as shown in Fig. 2. The wake effect can be determined as Equation (13) [4, 7 and 8]

$$u_j = u_o\left(1 - u_{def}(j)\right) \quad (13)$$

Where; U_j is the wind set of turbines affecting position j with a wake and $u_{def}(j)$ is the wind affecting position j with a wake.

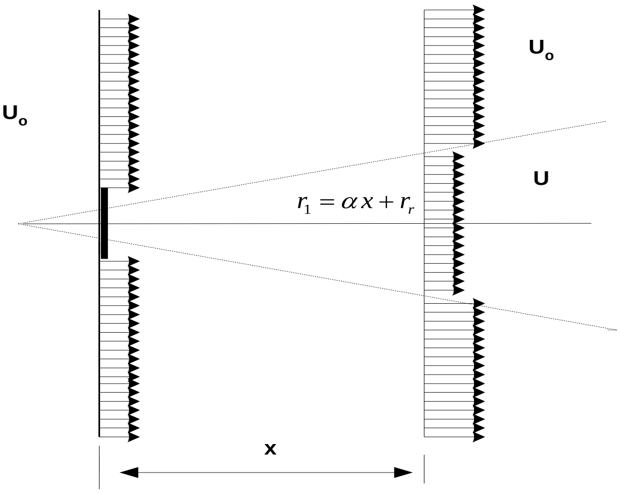

Fig. 2 Wake from a single wind turbine

To determine the cost of the wind farm, a cost model is selected. The model chosen was also used in previous studies [8]. The total cost per year for the entire wind farm can be expressed as: [6]

$$Cost = N\left[\frac{2}{3} + \frac{1}{3}e^{-0.00179*N^2}\right] \quad (14)$$

The objective function that will lead to optimization (minimum cost per unit of energy produced) is expressed as:

$$Objective\ \ function = \frac{Cost}{P_{e,ave}} \quad (15)$$

5. Results

In this study, the use of five types of wind turbines and the hourly wind speed for the selected site is the first data required for design of wind farm. The data has been obtained from the Egyptian Metrological Authority for Gable Elzait site at Gulf of Suez, Egypt [8]. Figure 3 shows the hourly wind speed over the year.

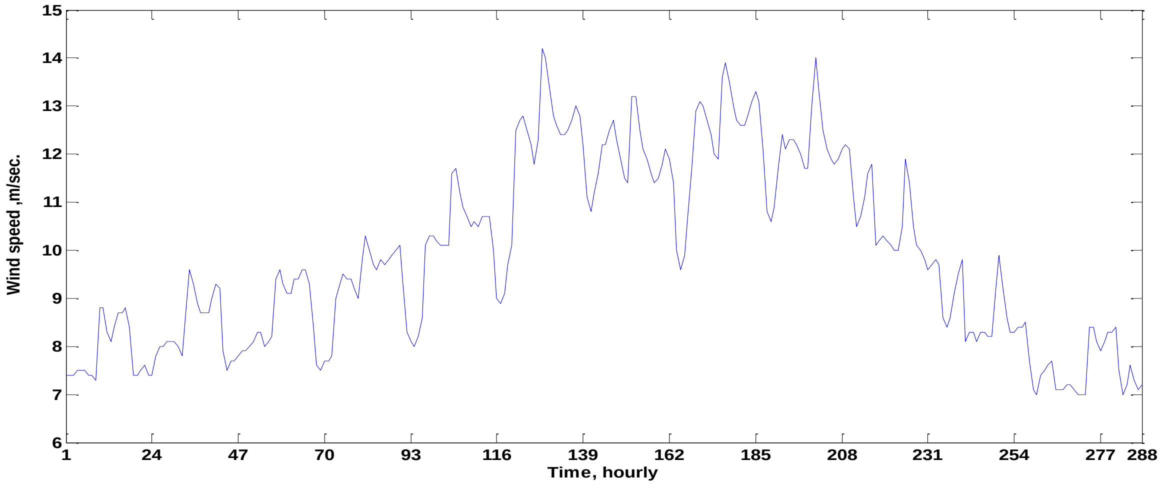

Fig. 3 : The hourly wind speed over the year.

MATLAB software has been used to design the program to find the most suitable setting for the turbines to the maximum power. To determine a situation of turbines ratios and optimum number of wind turbines the distance between each column has been taken to be 3 D and the distance between the rows has been changed from 5 D to 10.5 D. Table (1) shows the wind turbine characteristics.

TABLE-1: Characteristics of the selected WTG's

Charact. / Type	P_R MW	U_c m/s	U_R m/s	U_F m/s	H m	D m	Aw, m^2 $*10^3$	Operation interval rpm
GE 1.6	1.6	3.5	11	25	96	100	7.854	9.75-16.2
SWT 4	4	5	11	25	89.5	130	13.3	5-13
FD77	1.5	3	11.5	21	74	77	4.657	11.1-18.1
Repower	6.15	3.5	14	30	95	126	12.469	7.7-12.1
CT3000	3	3.5	11.7	25	90	103.94	8.48	8.34-15.73

The distributions of wind turbines in wind farm design have strong impact on the wind speed and also the power generated from wind farm. Effect of distance between turbine on yearly energy production for predominant wind farm and thump wind farm is shown in Fig.4. Figure 5 shows wind speed with wake effect on wind farm: (a) wind speed at row1 (b) wind speed at row2 (c) wind speed at row3: (d) wind speed at row4.

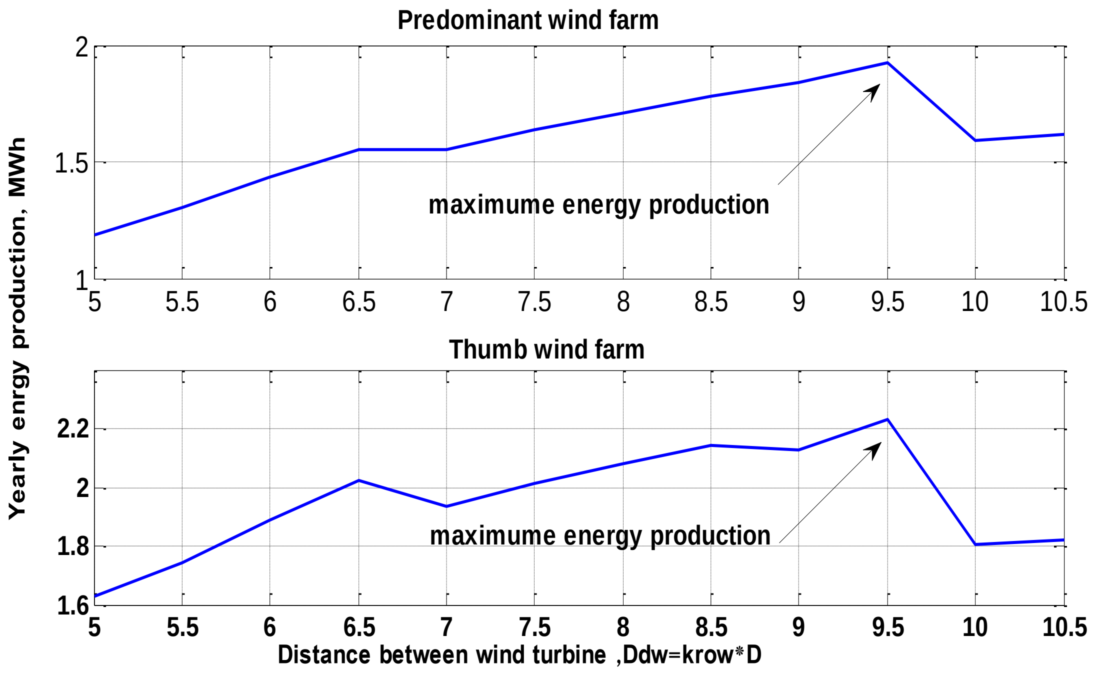

Fig. 4: Effect distance between turbines on yearly energy production for predominant wind farm and thump wind farm

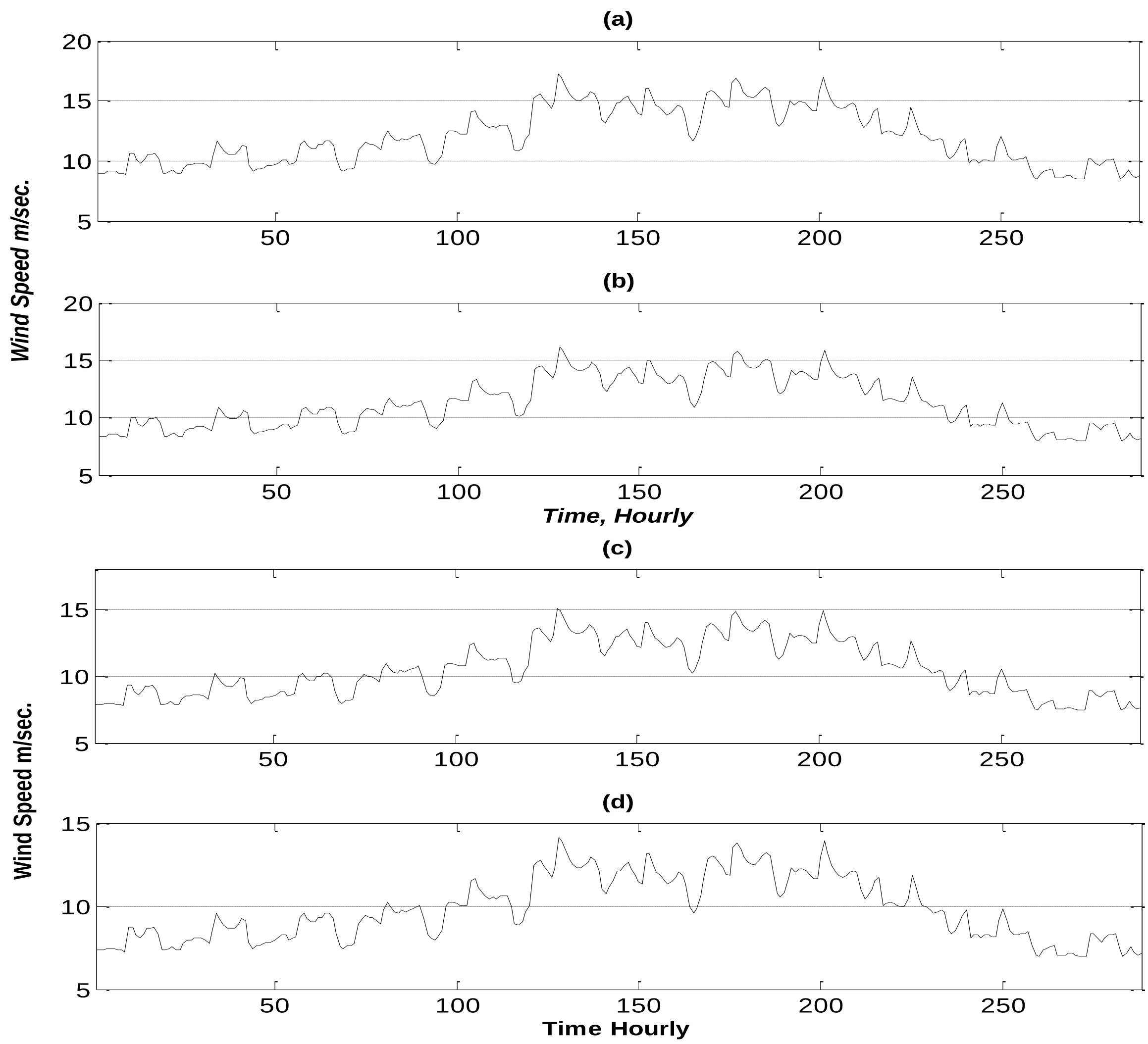

Fig.5: Wind speed with wake effect of wind farm: (a) wind speed at row1 (b) wind speed at row2 (c) wind speed at row3: (d) wind speed at row4

The energy produced by the turbines account with a change in wind speed and that is the most appropriate value for tip speed ratio λ_{opt} as well as the Power coefficient C_{pmax}. by the change in the angular velocity of the wind turbine generator with variable pitch angle β. Maximum power production for turbine with varying wind speed shows in Fig. 6. Figure 7, shows maximum power coefficient C_{pmax} . The Pitch angle control" will be set the angle of bleed at suitable value for the β with varying wind speeds as shown in Fig. 8. The tip speed ratio, TSR control" has been set to the most suitable value for the TSR λ_{opt}, as shown in Fig. 9.

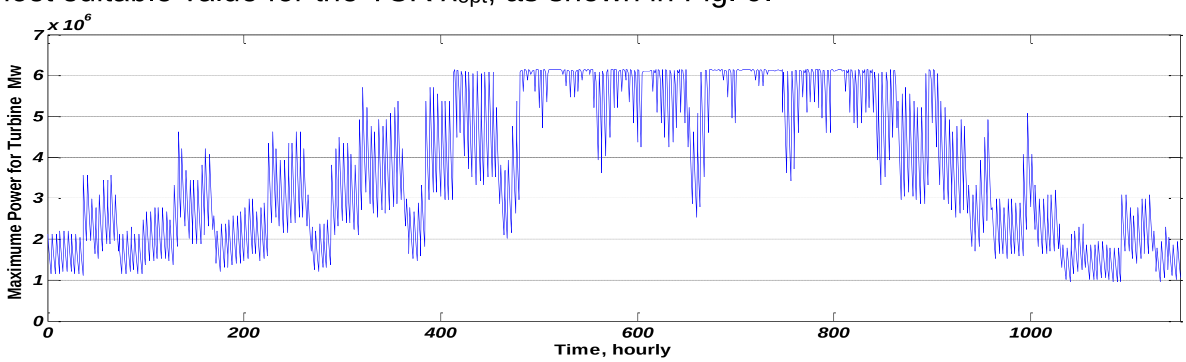

Fig. 6 Maximum power production for turbine with varying wind speed

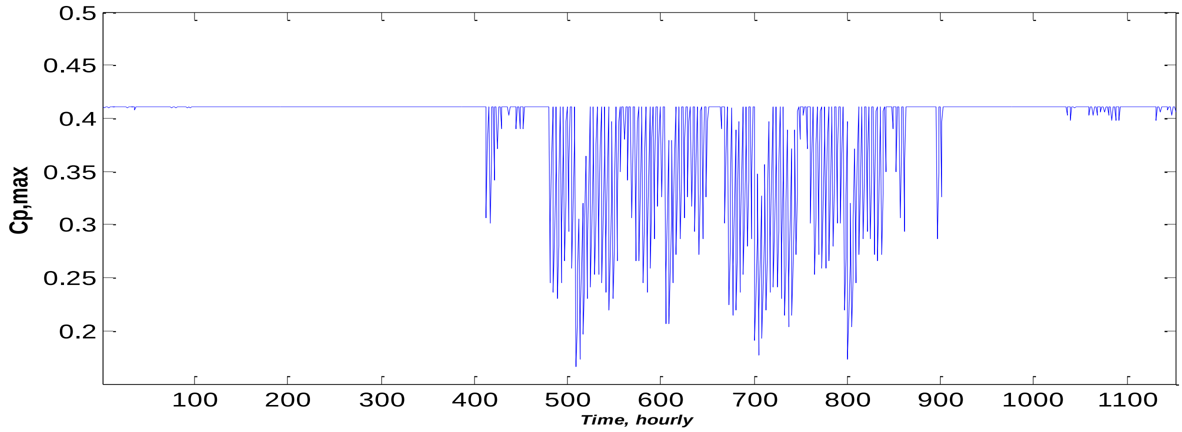

Fig. 7 maximum power coefficient C_{pmax}

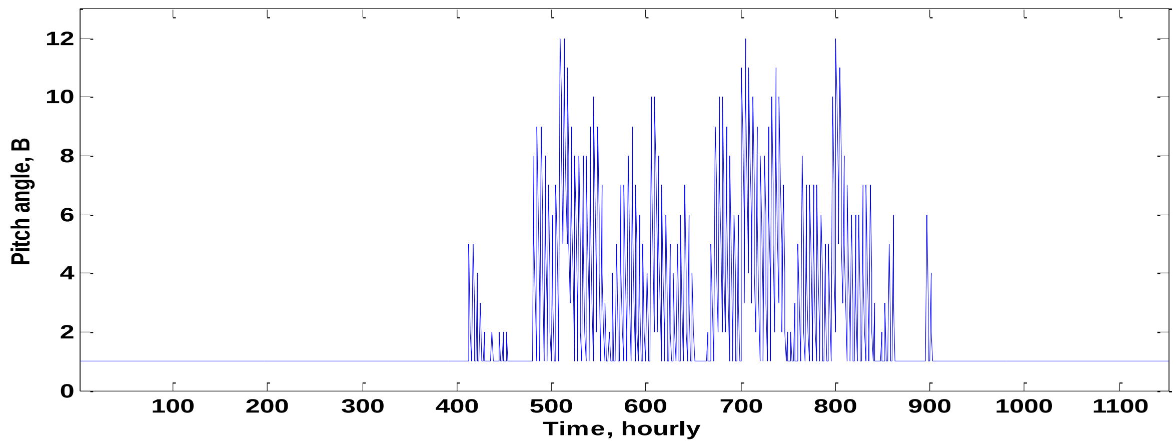

Fig. 8 pitch angle β with varying wind speed

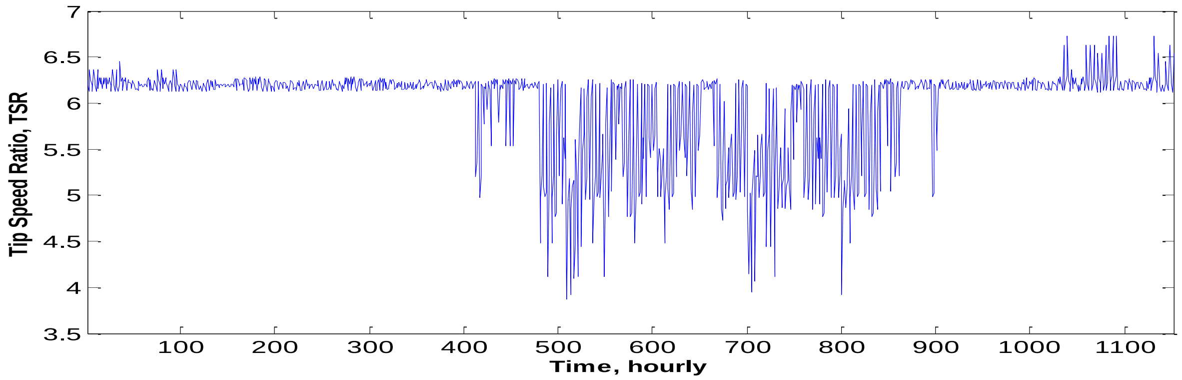

Fig. 9 Tip speed ratio, λ_{opt} with varying wind speed

In the case of the thumb wind farm module the Repower wind turbine produces yearly energy more than other turbines. This can be shown as in Table (2). From this table it can be seen that:-

1. The Repower wind turbine produces yearly energy more than the GE wind turbine with 46.71 % w. r. to the output of Repower wind turbine and less cost objective function.
2. The Repower wind turbine produces yearly energy more than the SWT wind turbine with 28.58 % w. r. to the output of Repower wind turbine and less cost objective function. But the cost for SWT is less than the cost of Repower wind turbine with 5% .

3. The Repower wind turbine produces yearly energy more than the FD wind turbine with 43.5 % w. r. to the output of Repower wind turbine and less cost objective function.
4. The Repower wind turbine produces yearly energy more than the CT wind turbine with 27.16 % w. r. to the output of Repower wind turbine and less cost objective function.

TABLE-2: Design parameters of the thumb wind farm using different selected wind turbines.

Type of Turbine	Distance between turbine m	N_{row}	N_{col}	N	Yearly Energy Production MWh	cost per unit of energy	Objective Function
GE 1.6-100	8.5D	5	21	105	$1.1951*10^6$	70	$5.86*10^{-5}$
SWT 4-130	9D	4	16	64	$1.6015*10^6$	42.6	$2.67*10^{-5}$
FD77-1500	8.5D	6	27	162	$1.2670*10^6$	108	$8.52*10^{-5}$
6M - repower	9.5D	4	17	68	$2.2425*10^6$	45.3	$2.02*10^{-5}$
C T 3000	8D	5	20	100	$1.6335*10^6$	66.6	$4.08*10^{-5}$

In the case of the predominated wind farm module the Repower wind turbine produces yearly energy more than other turbines. This can be shown as in Table (3).

TABLE-3: Design parameters of the predominant wind farm using different selected wind turbines.

Type of Turbine	Distance between turbine m	N_{row}	N_{col}	N	Yearly Energy Production MWh	cost per unit of energy	Objective Function
GE 1.6-100	8.5D	5	21	105	$1.0504*10^6$	70	$6.66*10^{-5}$
SWT 4-130	9D	4	16	64	$1.5058*10^6$	42.6	$2.85*10^{-5}$
FD77-1500	8.5D	6	27	162	$1.0545*10^6$	108	$10.21*10^{-5}$
6M - repower	9.5D	4	17	68	$1.9367*10^6$	45.3	$2.34*10^{-5}$
C T 3000	8D	5	20	100	$1.3932*10^6$	66.6	$4.79*10^{-5}$

From this table it can be seen that:-
The Repower wind turbine produces yearly energy more than the GE wind turbine with 45.76 % w. r. to the output of Repower wind turbine and less cost objective function.

1. The Repower wind turbine produces yearly energy more than the SWT wind turbine with 22.25 % w. r. to the output of Repower wind turbine and less cost

objective function. But the cost for SWT is less than the cost of Repower wind turbine with 5% .

2. The Repower wind turbine produces yearly energy more than the FD wind turbine with 45.55 % w. r. to the output of Repower wind turbine and less cost objective function.
3. The Repower wind turbine produces yearly energy more than the CT wind turbine with 28.06 % w. r. to the output of Repower wind turbine and less cost objective function.

6. CONCLUSION

From the study results described above it can be concluded that the power output in the case of the thumb is greater than that the power output in the case of predominant for each turbine under study as follows:
Use GE wind turbine increases energy production with the rate of 12.11%. Use SWT wind turbine increases energy, production with the rate of 5.98%. Use FD wind turbine increases energy production with the rate of 16.77%. Use Repower wind turbine increases energy production with the rate of 13.64%. Use CT wind turbine increases energy production with the rate of 14.71%. So, the thumbs wind farm module is appropriate in the design of the high productive capacity and low cost for the rest of the roads.

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