International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 12, Number 11 (2019), pp. 2009-2016

Study the Impact of Wake on the Arrangement and Economic of WTGs Variable Speed

Abo-Hashima M. El-Sayed[1], E. G. Shehata[2], Ayman Yousef Nassef [3]

[1] *Professor of Electrical Power Engineering Faculty of Engineering Minia University Minia, Egypt. dr_mostafa555@yahoo.com*

[2] *Professor of Electrical Power Engineering Faculty of Engineering Minia University Minia, Egypt. emadgameil@mu.edu.eg*

[3]*Engineer in Middle Egypt Company for Electricity Distribution, Minia, Egypt. e.aymanelc@gmail.com*

ORCID ID: 0000-0003-4828-6012 (Ayman Yousef)

Abstract
Several factors are an impact on the design of the wind farm. Such as the maximum desired installed capacity from the wind farm, site constraints, and the total cost. While designing a wind farm, the main objective is to produce the maximum power from the wind farm while reducing the overall costs. The wake effects are one of the issues that affect power production from the wind farm. This paper focuses on the placement and operation of the variable speed wind farm, a comparative study between two methods, thumb and predominant proposed with the use Five different wind turbine types. The numerical methodology can do by using the Matlab program.

Keywords: Wind farm, Wind Turbine, Wake effect

I. INTRODUCTION

The recent times, many countries around the world are interested in wind energy. So, wind energy became one of the mainstream power sources in these countries [1]. Egypt has been interested in producing clean energy for the environment. In Egypt, at Kilo 118 in Jebel El-Zeit on the red sea, there is one of the most significant wind energy projects in Egypt and the world. The cost of the wind farm in Jebel El-Zait is about 591.307 million euros, adding to that the station contains the latest system of migratory birds at the cost of 2 million euros, through radar to stop the turbines when they pass and restart after traffic [2].

Wind turbine wakes have studied for many years, and various models have developed by researchers. These models can divide into two main categories, namely, analytical wake models and computational wake models. An analytical wake model characterizes the velocity in the wake by a set of analytical expressions whereas in computational wake models, fluid flow equations, whether simplified or not, must be solved to obtain the wake velocity field Analytical Wake Models are the simplest models. First introduced by Lanchester [3] and Betz [4], they are based on a control volume approach. Frandsen [5] developed a generalization of the Lanchester/Betz approximations and captured a family of previously developed wake models as well as advancing them to account for multiple interacting wakes. The model developed by Frandsen is limited in that that it handles only regular array geometries, i.e., the wind turbines should be in straight rows with equidistant spacing between turbines in each row and the equidistant spacing between rows. One of the most widely used wake models developed by Jensen [6, 7]. He treated the wake behind the wind turbine as a turbulent wake, which ignores the contribution of vortex shedding that is significant only in the near wake region. The wake model is, thus, derived by conserving momentum downstream of the wind turbine. The velocity in the wake given as a function of downstream distance from the turbine hub and it is assumed that the wake expands linearly downstream.

II. STUDYING CASE

In this paper, the wind farm understudying installed in Jebel El-Zait site at the Suez Gulf on the Red Sea and interconnected with the substation of Samalot city which located in middle Egypt. In this paper, the length of the overhead transmission line (OHTL) is about 285 km. Also, from the Egyptian Metrological Authority, the wind speed data in Jebel El-Zait is obtained. The first factor affecting the design of the wind farm is land availability, which determines how much space is available for the wind farm. In this study, a 3.591 km by 6.237 km rectangular region considered and shown in Fig.1.

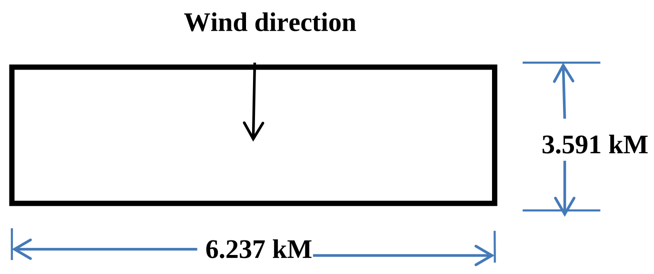

Fig. 1 Regions of the wind farm under study

III. WIND TURBINE MODEL

The wind speed measured 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 the hub height of the turbine [9]. This process calculates by the following equation:

$$u_h = u_{ho} * \left[\frac{h}{h_o} \right]^{\alpha} \quad \textbf{(1)}$$

Where:

u_h : The wind speed at the height of h-m above the ground, m/s.

w_{ho} : The wind speed at height ho-m, m/s, (ho, used to 24.5m)

h : The height from ground, m

α : Wind of shear power-law exponent

The wind of the shear power-law exponent depends on the specific site. It is often equal to or near the value 1/7.

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. The *average power* $P_{e,ave}$ that would be expected from a given turbine at variation in wind speed, is evaluated by the following equation:

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

Where;

P_{eR} : Rated Power of WTG, W

u_C : Cut-in wind speed m/s

u_R : Rated wind speed m/s.

u_F :Furling wind speed m/s.

The 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%. [9] The coefficient of performance varies with the wind speed, the rotational speed of the turbine, and turbine blade parameters such as the angle of attack and pitch angle. Generally, it said that the power coefficient, C_p, is a function of tip speed ratio, λ, and blade pitch angle, β (deg). The tip speed ratio defined as [10]and[11]

IV. DETERMINING OF SUITABLE TYPE, NUMBER, AND PLACEMENT OF WT

To determine the optimal wind turbine type, number, and placement to get maximum power, while minimizing the investment costs and considering different practical requirements and restrictions.

In this paper, the comparative study done between two cases, the first case is the predominant wind farm module, and the second case is the thumb wind farm module, as shown in Fig.2. [6]

The predominant wind farm module, the downwind spacing, D_{dw}, is 8–12 rotor diameters in rows apart and crosswind, D_{cw} , is 1.5–3 [11] or 2–4 rotor diameters Coolum apart, and the thumb wind farm module is the same predominant wind farm module. The downwind spacing D_{dw} is varying from 5 to 10.5 times of rotor diameter in rows, and the crosswind D_{cw} is three times of rotor diameter Coolum apart for the two cases.

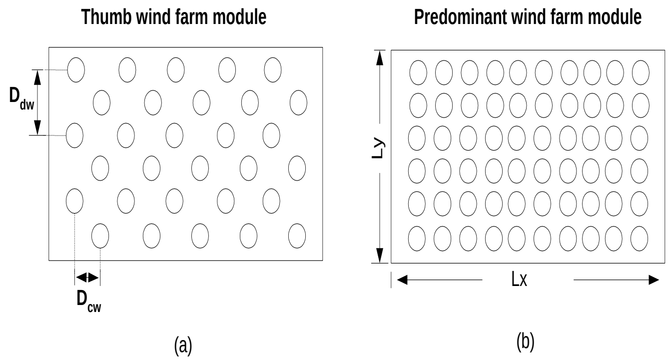

Fig. 2 Wind turbines sample placement for, (a) thumb wind farm module, (b) for the predominant wind farm module**.**

N_{row} , is a number of wind turbines in a row, can be determined for a given area with length, D_{row}, taking into consideration the separation distances between turbines, D_{dw}, as in ref. [9]:

$$N_{row} = \frac{D_{row}}{D_{dw}} + 1 \quad (3)$$

The existing recommendations about the turbines separation distance depending on the prevailing wind directions taken into account by introducing coefficients, k_{row}, and k_{col}, for wind turbines placement in rows and columns, respectively. Using, k_{now}, the D_{dw} , can be expressed by the turbine rotor diameter, D, as:

$$D_{dw} = k_{row} D \quad (4)$$

Also, it transformed to:

$$N_{row} = \frac{D_{row}}{k_{row} D} + 1 \quad (5)$$

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

$$N_{col} = \frac{D_{col}}{k_{col} D} + 1 \quad (6)$$

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

$$N = N_{row} N_{col} \quad \textbf{(7)}$$

V. 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 [6].

It is based on global momentum conservation in the wake downstream of the wind turbine, as shown in Fig. 3. [6]

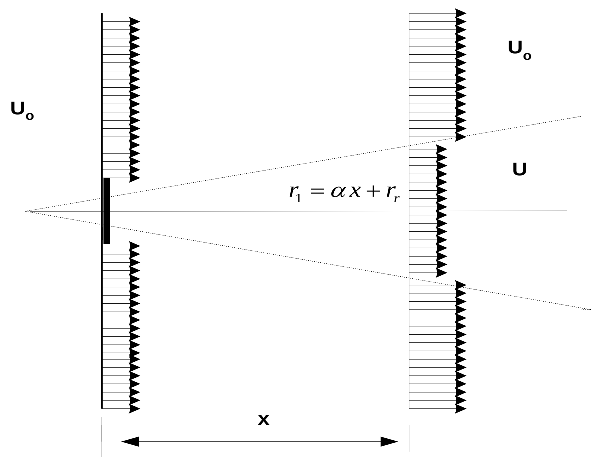

Figure 3 wakes from a single wind turbine

The wind blows from left to right at speed, U_o, and hits a turbine (represented as a black rectangle on the left) whose rotor radius is, r_r. At a distance, x, downwind, the wind speed is, u, and the wake radius (initially equal to, r_r,) becomes:

$$r_1 = \alpha\, x + r_r \quad (8)$$

The a-dimensional scalar α determines how quickly the wake expands with distance and defined as:

$$\alpha = \frac{0.5}{\ln\left(\frac{z}{z_o}\right)} \quad (9)$$

Where z is the hub height of the turbine generating the wake and Z_O is a constant called surface roughness, which depends on the terrain characteristics in this study, Z_O, is equal to 0.003 [11], and [12]. Evaluations of, Z_O, in deferent grounds, lead to the values listed in Table 1.

Table 1: Z_O, values in deferent grounds [11]

Z_O	Grounds	Class Roughness
10−4	**Water bodies**	
3 × 10−4	**Surface smooth sand**	**0**
10−3	**Smooth surface snow**	
5 × 10−4	**Smooth and bare soil**	
0.01	**Airport Runways and taxiways**	
0.03	**Agricultural land with very few buildings, trees,**	**1**
0.05	**An agricultural land open look**	
0.10	**Gated farmland look**	**2**
0.20	**A lot of trees and bushes**	
0.30	**Shafting windbreaks**	
0.5	**Suburbs**	**3**

Let i be the position of the turbine that generates the wake, j the position affected by it, u_0, the ambient wind speed, and u_j the wind speed at j. Then: [12] and [13]

$$u_j = u_o\left(1 - vd_{ij}\right) \quad (10)$$

Where, vd_{ij}, is the velocity deficit induced on position j by the wake generated by i., vd_{ij}, is computed as follows:

$$vd_{ij} = \frac{2a}{1 + a\left(\frac{x_{ij}}{r_d}\right)^2} \quad (11)$$

The term that appears in the numerator is called axial induction factor is computed by the following expression:

$$a = 0.5\left(1 - \sqrt{(1 - C_T)}\right) \quad (12)$$

Where:

C_T: Thrust coefficient of the wind turbine (is equal to 0.88).

The term r_d that appears in the denominator is called downstream rotor radius and is equal to:

$$r_d = r_r \sqrt{\frac{1-a}{1-2a}} \tag{13}$$

The term, x_{ij}, is the distance between positions i and j. [6]. Since many turbines installed on a wind farm, wakes can intersect and affect turbines downwind at the same time. In the Jensen model, the total velocity deficit, u_{def} (j), at a location j that is affected by more wakes obtained as follows:

$$u_{def}(j) = \sqrt{\sum_{i \in w(j)} vd_{ij}^2} \tag{14}$$

Where, u(j), is the set of turbines affecting position j with a wake, v_{def}(j), is then used in equation (2-35) in place of, vd_{ij}, to compute, u_j.

$$u_j = u_o\left(1 - u_{def}(j)\right) \tag{15}$$

The total cost per year for the entire wind farm expressed as [6]

$$Cost = N\left[\frac{2}{3} + \frac{1}{3}e^{-0.00179 * N^2}\right] \tag{16}$$

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

$$Objective\ function = \frac{Cost}{P_{e,ave}} \tag{17}$$

Where,

$P_{e,\,ave}$ Average power of wind turbine. Taken from ref. [8]

VI. RESULTS

In this study, the use of five types of wind turbines, and the first data required for the design of the wind farm is the hourly wind speed. The data obtained from the Egyptian Metrological Authority for Geble Elzait site at the Gulf of Suez, Egypt [14]. Figure 3 shows 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 an optimum number of wind turbines the distance between each column has been taken to be 3 D and the distance between the rows has changed from 5 D to 10.5 D. Table (2) shows the wind turbines characteristics [15, 16 and 17].

Table 2: Characteristics of the selected WTG's

Characteristics	Type of WTG				
	CT3000	Repower	FD77	SWT 4	GE 1.6
P_R, MW	3	6.15	1.5	4	1.6
U_c, m/s	3.5	3.5	3	5	3.5
U_R, m/s	11.7	14	11.5	11	11
U_F, m/s	25	30	21	25	25
H, m	90	95	74	89.5	96
D, m	103.94	126	77	130	100
Aw, m^2	$8.48*10^3$	$12.469*10^3$	$4.657*10^3$	$13.3*10^3$	$7.854*10^3$
Operation Interval, rpm	8.34-15.73	7.7-12.1	11.1-18.1	5-13	9.75-16.2
Voltage, V	690	660	690	690	690

VII. WIND FARM PERFORMANCES

The design of wind farms and the placement of turbines have done. To find the most suitable setting for the turbines, this gives the maximum of its output, considering that the distance between each column 3 D and change the distance between the rows from 5 D to 10.5 D to create a situation for turbines ratios and optimum number for a wind turbine.

Impact of the wake effect of wind speed resulting from the placement of wind turbines on a farm, in the same way, the use of the thumb wind farm module as well as in case of using predominant wind farm module, the Jensen weak model will estimate. The distributions of wind turbines in wind farm design have a substantial impact on the wind speed and also the power generated from the wind farm. The distributions of WT by using the thump method it is less effect on wind speed than the distributions of WT by using the predominant method, as shown in Fig. 4. Effect distance between turbine at yearly energy production for a predominant wind farm and thump wind farm, as shown in Fig. 5.

The cost and objective function has calculated. Figure 6 and Fig. 7 are shown the effect distance between the turbine at a cost per unit energy and objective function, respectively. Maximum power production for the turbine with varying wind speed shows in Fig.8

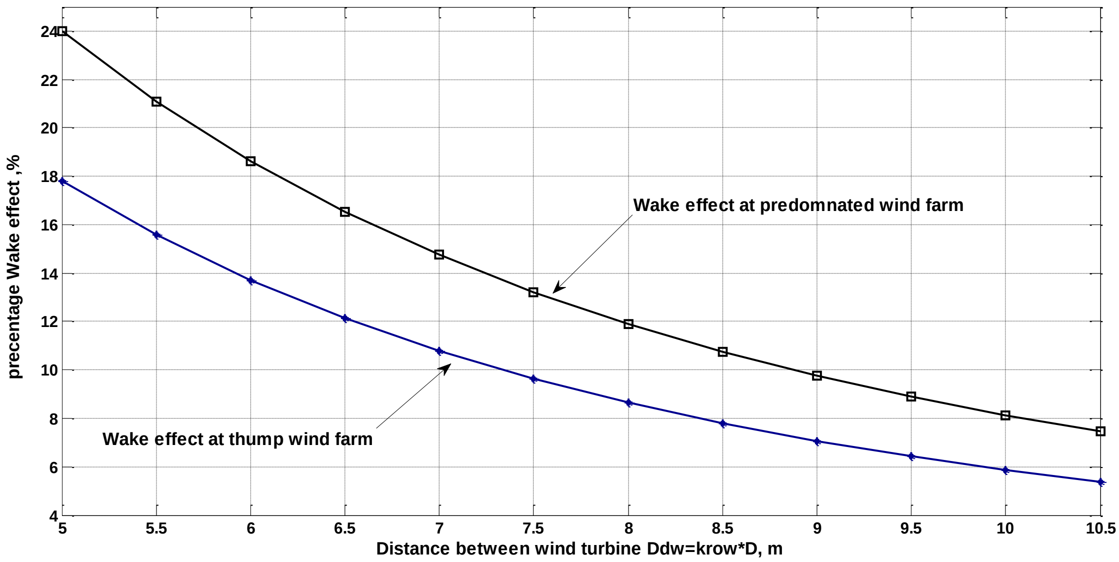

Fig. 4 Effect distance between turbine at wind wake effect for a predominant wind farm and thump wind farm.

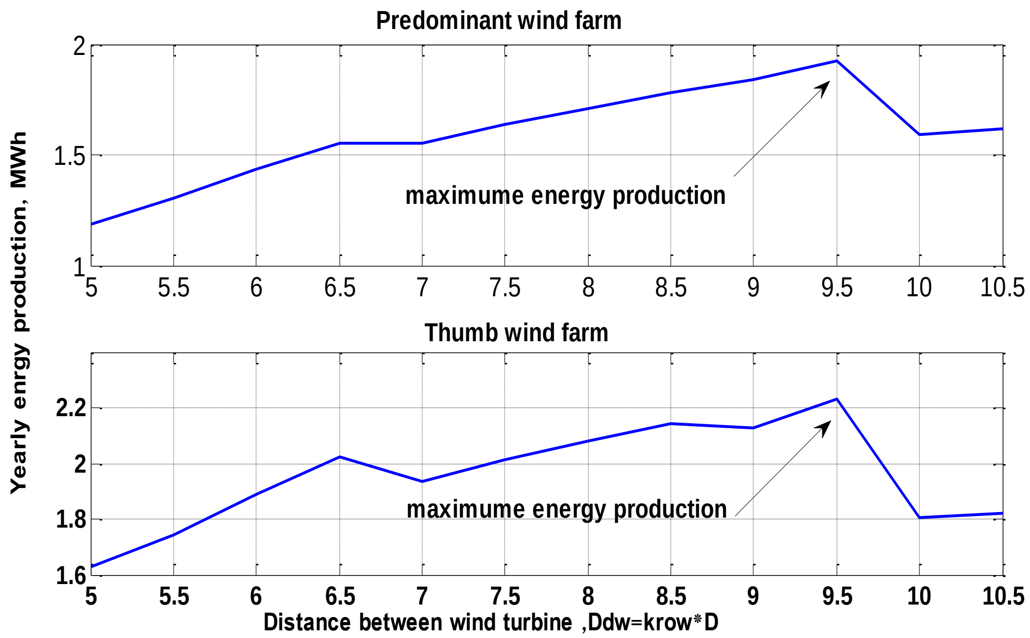

Fig. 5 Effect distance between turbine at yearly energy production for a predominant wind farm and thump wind farm.

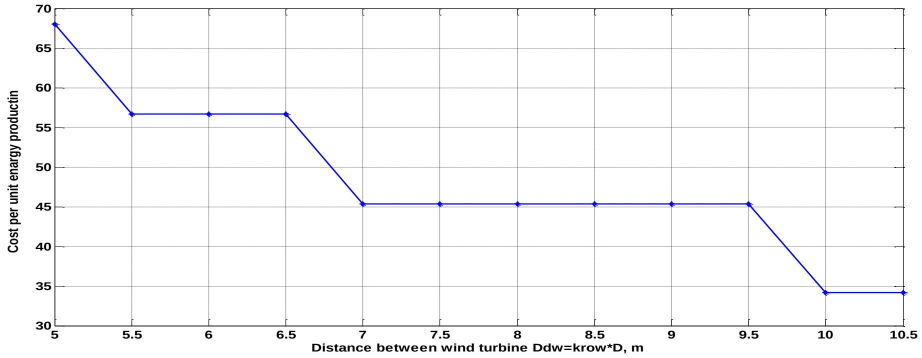

Fig. 6 Effect distance between turbine at a cost per unit energy

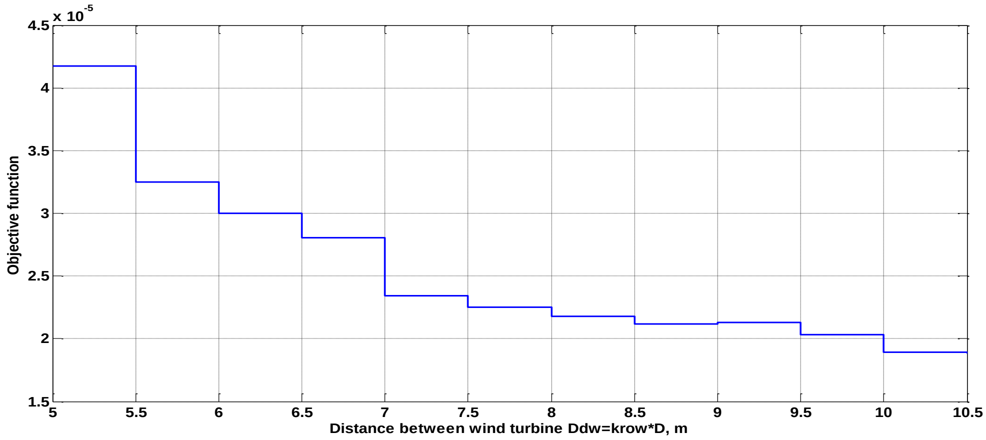

Fig. 7 Effect distance between turbine at the objective function

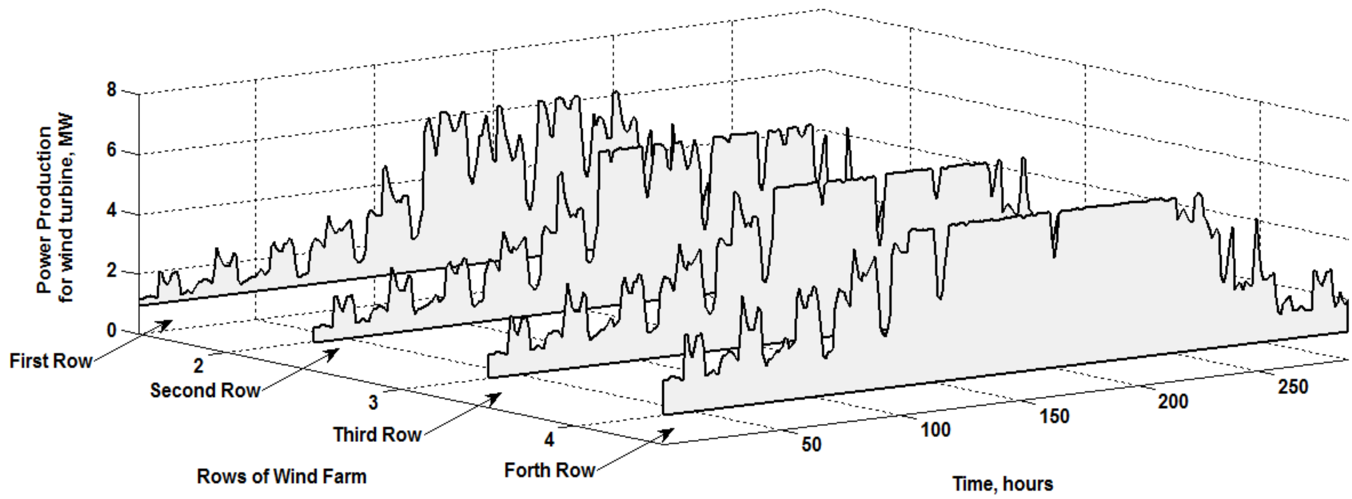

Fig. 8 Impact the distribution of WT on Power generated from WF by using the thump method**.**

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.

In the case of the thumb wind farm module, it will produce yearly energy when using Repower wind turbine more species of other turbines as follows:

Use Repower wind turbines have annual energy of producing more than a percentage of 46.71% of the use of GE wind turbines, and less cost objective function described in Table 3.

Use Repower wind turbines have yearly energy of producing more than a percentage of 28.58% of the use of SWT wind turbines and less cost objective function, but the cost for SWT will less than a rate of 5% of the use Repower wind turbine.

Use Repower wind turbines have yearly energy of producing more than a percentage of 43.50% of the use of FD wind turbines and less cost objective function.

Use Repower wind turbine have yearly energy of producing more than a percentage of 27.16% of the use of CT wind turbine and less cost objective function

In the case of the predominant wind farm module, it will produce yearly energy when using Repower wind turbine more species of other turbines as follows:

Use Repower wind turbines have annual energy of producing more than a percentage of 45.76% of the use of GE wind turbines, and less cost objective function described in Table 4.

Use Repower wind turbines have yearly energy of producing more than a percentage of 22.25% of the use of SWT wind turbines and less cost objective function, but the cost for SWT will less than a rate of 5% of the use Repower wind turbine.

Use Repower wind turbines have yearly energy of producing more than a percentage of 45.55% of the use of FD wind turbines and less cost objective function.

Use Repower wind turbines have yearly energy of producing more than a percentage of 28.06% of the use of CT wind turbines and less cost objective function.

Table 3: Design parameters of the thumb wind farm using differently selected wind turbines.

Type of Turbine	The distance between turbine m	Number of turbine per row	Number of turbine per Coolum	Total Number of turbine	Yearly Energy Production Mwh	Cost	Objective Function
GE 1.6-100	8.5D	5	21	105	$1.1951*10^6$	70	$5.8573*10^{-5}$
SWT 4-130	9D	4	16	64	$1.6015*10^6$	42.681	$2.6651*10^{-5}$
FD77-1500	8.5D	6	27	162	$1.2670*10^6$	108	$8.5242*10^{-5}$
6M Repower	9.5D	4	17	68	$2.2425*10^6$	45.339	$2.0218*10^{-5}$
C T 3000	8D	5	20	100	$1.6335*10^6$	66.667	$4.0811*10^{-5}$

Table 4: Design parameters of the predominant wind farm using differently selected wind turbines**.**

Type of Turbine	The distance between turbine m	Number of turbine per row	Number of turbine per Coolum	Total Number of turbine	Yearly Energy Production Mwh	Cost	Objective Function
GE 1.6-100	8.5D	5	21	105	$1.0504*10^6$	70	$6.6641*10^{-5}$
SWT 4-130	9D	4	16	64	$1.5058*10^6$	42.681	$2.8345*10^{-5}$
FD77-1500	8.5D	6	27	162	$1.0545*10^6$	108	$10.241*10^{-5}$
6M Repower	9.5D	4	17	68	$1.9367*10^6$	45.339	$2.3411*10^{-5}$
C T 3000	8D	5	20	100	$1.3932*10^6$	66.667	$4.7851*10^{-5}$

VIII. CONCLUSION

From the study results described above, it can conclude that the power output in the case of the thumb higher than that the power output in the case of predominant for each turbine understudy as follows:

Use GE wind turbine increases energy production with the rate of 12.11%. Use SWT wind turbine increases energy, production with a 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 a 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 production capacity and low cost for the rest of the roads.

REFERENCE

[1] S.M. Muyeen, Hany M. Hasanien, Ahmed Al-Durra" Transient stability enhancement of wind farms connected to a multi-machine power system by using an adaptive ANN-controlled SMES," Energy Conversion and Management 78 (2014) 412–420

[2] Egypt, Ministry of Electricity and Renewable Energy, New and Renewable Energy Authority.http://www.nrea.gov.eg/Technology/WindStations

[3] Lanchester FW, 1915. Contribution to the theory of propulsion and the screw propeller. Transactions of the Institution of Naval Architects; LVII: 98–116.

[4] Betz A, 1920. Der Maximum der theoretisch mölichen Ausnützung des Windes durch Windmotoren. Zeitschrift für das Gesamte Turbinenwesen ; 26: 307–309

[5] Frandsen S, Barthelmie R, Pryor S, Rathmann O, Larsen S, Hojstrup J, Thogersen M, 2006. "Analytical Modelling of Wind Speed Deficit in Large Offshore Wind Farms". , Wind Energy. Issue 9, 39-53

[6] Jensen, NO, 1983. A note on Wind Generator Interaction. Riso National Laboratory, Roskilde, Denmark

[7] Katic I, Hojstrup J, Jensen NO, 1986. A simple model for cluster efficiency. Proceedings of the European Wind Energy Conference and Exhibition. 407-410.

[8] DAVID C. YU ET AL., "BAYESIAN NETWORK MODEL FOR RELIABILITY ASSESSMENT OF POWER SYSTEMS" PROCEEDING ON IEEE TRANSACTIONS ON POWER SYSTEM, VOL. 14, NO. 2 MAY 1999, P. 426-432

[9] DR GARY L. JOHNSON," WIND ENERGY SYSTEMS" ELECTRONIC," HANDBOOK, EDITION OCTOBER 10, 2006.

[10] S.M. Muyeen, Junji Tamura, Toshiaki Murata, " Stability Augmentation of a Grid-connected Wind Farm," Book, © 2009 Springer-Verlag London Limited

[11] Brendan Fox, Leslie Bryans, Damian Flynn, Nick Jenkins, David Milborrow, Mark O'Malley, Richard Watson and Olimpo Anaya-Lara "Wind Power Integration Connection and System Operational Aspects" Book @ The Institution of Engineering and Technology Second Edition 2014

[12] J.G. Slootweg, S.W.H. De Haan (2003) General model for representing variable speed wind turbines in power system dynamics simulation. In: IEEE Trans. on Power Systems, Vol.18, Issue 1, pp.144 – 151

[13] Mosetti G, Poloni C, Diviacco B, 1994. Optimization of wind turbine positioning in large wind farms by means of a genetic algorithm. Journal of Wind Engineering and Industrial Aerodynamics, Issue 51, 105-116

[14] Hassan H. El-Tamaly, Ayman Yousef Nassef. "Tip speed ratio and Pitch angle control based on ANN for putting variable speed WTG on MPP," 2016 Eighteenth International Middle East Power Systems Conference (MEPCON), 2016

[15] www.Repower.com

[16] www.semens.com

[17] www.4coffshore.com

AUTHOR BIOGRAPHIES:

Abou-Hashema M. El-Sayed received his B.Sc., and M.Sc. in Electrical Engineering from Minia University, Minia, Egypt, in 1994 and 1998, respectively. He was a PhD student in the Institute of Electrical Power Systems and Protection, Faculty of Electrical Engineering, Dresden University of Technology, Dresden, Germany from 2000 to 2002. He received his PhD in Electrical Power from the Faculty of Engineering, Minia University, Egypt in 2002, according to a channel system program, which means a Scientific Co-operation between the Dresden University of Technology, Germany and Minia University, Egypt. Since 1994, he has been with the Department of Electrical Engineering, Faculty of Engineering, Minia University, as a Teaching Assistant, a Lecturer Assistant, an Assistant Professor, and Associate Professor. He was a Visiting Researcher at Kyushu University, Japan, from 2008 to 2009. He is the head of Mechatronics and Industrial Robotics Program, Faculty of Engineering, Minia University from 2011 till now. His research interests include Protection systems, renewable energy, and power systems.

Emad Gameil Shehata received the B.Sc., M.Sc., and PhD degrees in electrical engineering from the Electrical Engineering Department, Faculty of Engineering, Minia University, El Minia, Egypt, in 2002, 2006, and 2012, respectively. He is currently working as an associated professor with the Electrical Engineering Department, Faculty of Engineering, Minia University. His research interests include permanent magnet synchronous machines, doubly-fed induction generator, hybrid electric vehicles, renewable energy applications, and DC-DC converters for microgrids.

Ayman Yousef Naseef received the B.Sc., and M.Sc., degrees in electrical engineering from the Electrical Engineering Department, Faculty of Engineering, Minia University, El Minia city- Egypt, in 2002, and 2009 respectively. He is currently working as the Electrical Engineer in Middle Egypt Company for Electricity Distribution, El Minia city. His research interests include renewable energy, power quality in distribution systems, power system analysis, and transmission systems by HVAC and HVDC**.**