Assessment and analysis of wind energy generation and power control of wind turbine system

Évaluation et analyse de la production d'énergie éolienne et contrôle de puissances d'un système éolien

Khouloud Bedoud*[1, 2], Mahieddine Ali-Rachedi[3] & Rabah Lakel[1]

[1] Automatic Laboratory and Signals, Badji Mokhtar University, Po Box 12, 23000, Annaba, Algeria.
[2] Research Center in Industrial Technologies CRTI, ex CSC, Po Box 64, Cheraga, Algeria.
[3] Preparatory School in Sciences and Technics, 23000, Annaba, Algeria.

Soumis le : 22/12/2015 *Révisé le :18/02/2016* *Accepté le :08/03/2016*

ملخص

هذه الدراسة تخص تقييم إمكانات طاقة الرياح و إختيار توربينة الرياح حتى تثبت بالقرب من المطار الدولي رابح بيطاط بعنابة. وكذلك ,فعالية السيطرة على القوى لهذه التوربينة تم تطويرها. و لهدا، بيانات سرعة الرياح المقاسة من طرف محطة الأرصاد الجوية للمطار استخدمت. في البداية، خصائص التحليل الإحصائي للرياح واستقراء معلمات ويبل تم عرضها. من جهة أخرى ، أدى تحليل الطاقة المنتجة وعامل قدرة توربينات الرياح المقترحة الى اختيار توربينة إنركون E-82/2000 مع الخصائص: سرعة الرياح المحددة (13م/ثانية) ، سرعة الانطلاق(2.5م/ ثانية) وقوة محددة ب 2000 كيلوواط. وأخيرا، تم السيطرة على القوى من قبل آلية التكيف الغامض لمعلمات وحدالتحكم النسبي المتجزأ مع ماتلاب/سيميولينك، التي أجريت على توربينات الرياح 2 ميغاواط. نتائج الأداء والمتانة التي تم الحصول عليها تم عرضها وتحليلها.

الكلمات المفتاحية: *طاقة الرياح- سرعة الرياح- توزيع ويبل- عامل القدرة- الطاقة المنتجة*

Abstract

This study concerns the evaluation of wind power potential and the choice of a wind turbine to be installed near Rabah Bitat international airport of Annaba. Furthermore, the performances of power control of this turbine are developed. For this, the wind speed data measured by meteorological station of the airport are used. At the first time, a statistical analysis of wind characteristics and the extrapolation of weibull parameters are presented. Otherwise, the analysis of the power produced and the capacity factor led to the choice of the wind turbine Enercon E-82/2000 whose characteristics: Rated wind speed (13m / s), the cut-in wind speed (2.5m / s) and a rated power of 2000kW. Finally, the control of the active and reactive power, by adaptive fuzzy gain scheduling of proportional integral controller is simulated using software Matlab/Simulink, studies on a 2 MW DFIG wind generation system. Performance and robustness results obtained are presented and analyzed.

Keywords: *wind energy- wind speed- Weibull distribution-capacity factor-power output.*

Résumé

Cette étude concerne l’évaluation du potentiel de la puissance du vent et le choix d’une éolienne à installer à proximité de l’aéroport international Rabah Bitat de Annaba. En outre, les performances de la commande des puissances de cette turbine ont été développées. Pour cela, des données de la vitesse du vent mesurées par la station météorologique de l’aéroport sont utilisées. Dans un premier temps, une analyse statistique des caractéristiques du vent ainsi que l'extrapolation des paramètres de weibull sont présentées. Par ailleurs, l’analyse de la puissance produite et du facteur de capacité a mené au choix de l’éolienne Enercon E-82/2000 dont les caractéristiques : vitesse nominale du vent (13m/s), vitesse de démarrage (2.5m/s) et une puissance nominale de 2000kW. Finalement, la commande des puissances active et réactive par un mécanisme d’adaptation flou des paramètres du régulateur proportionnel intégral a été simulée sous Matlab/Simulink, réalisés sur une éolienne de 2 MW. Les résultats des performances et de robustesse obtenus sont présentés et analysés.

Mots clés : *energie éolienne-vitesse du vent-distribution de Weibull-facteur de capacité-puissance produite.*

---

[*] Corresponding author: *khouloud1981@yahoo.fr*

1. INTRODUCTION

Nowadays, renewable energies (RE) become a tremendous economic opportunity for countries looking for clean energy technologies. RE can contribute efficiently in the production of electricity. In the world, 80% of electricity is produced from exhaustible and polluting resources [1]. The major inconvenience of these sources is the massive clearing of polluting gas and enormous amount of gas that has greenhouse effect. According to a publication of the international agency of the energy, the world production of electricity should double during the next 25 years. Hence, to set a balance between the increasing demand in energy and notably in electrical energy on the one hand, and the strategies studied for the nature preservation and the care of the environment whose the objective is the reduction of the fossils use and to reduce carbon emission in the atmosphere [2] on the other hand. As a matter of fact, the world heads more and more toward the RE that use natural resources such as: sun, wind and biomass, for electricity production. Due to its important potential energy, the wind energy becomes the first source of RE after the hydraulics [3]. At present, the satisfaction of the energy needs in Algeria is basically founded on the hydrocarbons, notably the natural gas which is the main source of energy. In order to find reliable methods and bring durable solutions to the environmental challenges and to the problematic of the preservation of energy resources of fossil origin, the Algerian government aims to diversify the energy sources enhancing the inexhaustible resources as well as the decentralization of electricity production. This program will also constitute the vector of a national industry development of renewable energies [4]. Therefore, the installation of RE systems has been increased considerably in the world. Since the wind power potential for a site articulates on the wind speed, the period in which the wind is available, the air density, the turbine design and the tower height of the turbine [5]. However, the wind conversion systems cannot be installed randomly. They require the appropriate regions where wind can be more constant and has high speed. Generally, the high altitudes and the coastal sites are the appropriate places for the wind parks installation. Indeed, the estimation and the evaluation of wind power have also been carried out at many countries of the world, such as: Brazil, Saoudi Arabia, Italy, Hong Kong, North Aegean, Greece, Iran, Pakistan, GB and Algeria [6-18].

This work aims to estimate and determine correctly the wind energy potential as well as the prediction of the electric power produced at the studied site in Annaba, Algeria, according to the data wind speed history and propose a robust power control. The weibull distribution remains the most frequently used model in literature [19]. For the following advantages: very well fits of the wind distribution; flexible and scalable structure, varying according to the shape parameter of the distribution; easy determination of parameters; the number of parameters is few; and once the parameters for a certain height are determined, the wind data for various heights can be calculated using the predetermined parameters [20-23]. The main limitation of the weibull density function (WDF) is that it does not accurately represent the probabilities of observing zero or very low wind speeds [24].

The WDF has been used to determine the monthly and yearly power wind density. In addition, it will be used to estimate the weibull scale (c) and shape (k) parameters. It is worth recalling that the shape parameters indicate the wind frequency. Where, it will be large if there is a low variation of wind speed. On the other hand, the scale parameter represents relative cumulative wind speed frequency. When the means wind speed is higher, the scale parameter is larger [21]. A simulation model has been established to describe the characteristics of a particular wind turbine. Finally, for intensify wind power utilization as well as produced power quality of selected wind turbine, performances power control based on adaptive fuzzy gain scheduling of proportional integral controller AFG-PI are presented and analyzed using the MATLAB/Simulink environment.

2. WEIBULL PARAMETER DETERMINATION

There are several methods to calculate weibull parameters for the assessment of the wind energy potential [6, 20, 21, 25-27]. The Empirical method is a very effective method and it is frequently used to determine the Weibull parameters. Indeed, this method needs only the knowledge of the wind mean speed and the standard deviation σ [30]. The weibull shape and scale parameter can be determined as follows [19, 24]:

$$k = \left(\frac{\sigma}{v_m}\right)^{-1.086} \qquad (1)$$

3. ANALYSIS OF WIND POWER

Wind speed is a random variable, constantly changing its value throughout the times. In the aim to evaluate the potential of wind energy for Annaba city, it is very important to know about wind speed distribution. For this, we have using the weibull model to characterize by probability density function and cumulative function for wind data.

3.1. Weibull density function

The wind speed probability density function (PDF) can be calculated as [5, 6, 13, 23, 29]:

$$f(v) = \left(\frac{k}{c}\right).\left(\frac{v}{c}\right)^{k-1}.e^{\left[-\left(\frac{v}{c}\right)^{k}\right]} \qquad (3)$$

Where *f* (*v*) is the probability of observing wind speed *v* , *c(m/s)* is the weibull scale parameter and *k* is the dimensionless Weibull shape parameter which indicate the wind frequency.

The Weibull cumulative distribution function (CDF) is given by the equation below [5, 6, 13, 23, 29]:

$$F(v) = 1 - e^{\left[-\left(\frac{v}{c}\right)^{k}\right]} \qquad (4)$$

The wind speed and the variance are the indicator number one for the assessment of wind energy potential of wind power. The mean speed and the variance of data are given by the following equations:

$$v_m = \frac{1}{n}\sum_{i=1}^{n} v_i \qquad (5)$$

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2 \qquad (6)$$

Standard deviation can be written as:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_i - v_m)^2} \qquad (7)$$

Where n is the total number of wind speed records available, *i* is the measured three-hourly wind speed and σ is the standard deviation. On the other hand, the mean and the variance wind speed using weibull parameters can be calculated as [5, 28]:

$$v_m = c\,\gamma\left(1 + \frac{1}{k}\right) \qquad (8)$$

$$\sigma^2 = c^2\left|\gamma\left(1 + \frac{2}{k}\right) - \gamma^2\left(1 + \frac{1}{k}\right)\right| \qquad (9)$$

Where γ is a gamma function, calculated by:

$$\gamma(v) = \int_0^{\infty} e^{-u}u^{v-1}du \qquad (10)$$

3.2. Wind speed at hub heights

The wind speed as well as the weibull parameters varies proportionally according to the hub height. The weibull parameters and the wind speed (v_2) to the desired height (h_2) can be adjusted using following expression [28, 30, 31]:

$$c = \frac{v_m}{\gamma\left(1+\frac{1}{k}\right)} \qquad (2)$$

$$\frac{c_2}{c_1} = \left(\frac{h_2}{h_1}\right)^{n} \qquad (11)$$

The exponent n can be calculated by [31]:

$$n = \frac{0{,}37 - 0{,}088.ln(c_1)}{1 - 0{,}088.ln\left(\frac{h_2}{10}\right)} \qquad (12)$$

$$\frac{k_2}{k_1} = \frac{1 - 0{,}088.ln\left(\frac{h_1}{10}\right)}{1 - 0{,}088.ln\left(\frac{h_2}{10}\right)} \qquad (13)$$

The wind speed at the hub heights is expressed by [28, 30, 31]:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \qquad (14)$$

The exponent α which (the surface roughness) can be calculated by the following equation [31]:

$$\alpha = \frac{0{,}37 - 0{,}088.ln(v_1)}{1 - 0{,}088.ln\left(\frac{h_1}{10}\right)} \qquad (15)$$

Where: c_2, h_2 and v_2 are the scale parameter, the desired hub heights and the wind speed, respectively. Furthermore, c_1, k_1 and v_1 are the scale, shape parameters and the wind speed at the measurement height h_1, respectively.

3.3. Most probable wind speed and wind speed carrying maximum energy

The most probable wind speed (v_{mp}), and the wind speed carrying maximum energy (v_{maxE}) are the useful parameters, commonly used for the characterization of wind speed. They can be estimated from the following expressions for weibull distribution function [28, 30]:

$$v_{mp} = v_f = c.\left(\frac{k-1}{k}\right)^{1/k} \qquad (16)$$

$$v_{maxE} = v_e = c.\left(\frac{k+2}{k}\right)^{1/k} \qquad (17)$$

3.4. Wind power density estimation

The instantaneous wind power (P) and the theoretical power produced by the wind (P_{tur}) are given by [39]:

$$P = \frac{1}{2}.\rho.S.v_m^3 \qquad (18)$$

$$P_{tur} = C_p.\frac{\rho.S.v^3}{2} \qquad (19)$$

With ρ : airdensity (ρ =1,25 kg/m^3);

S : surface;

C_p: power coefficient of wind turbine.

In practice, the power recuperate by a wind turbine is only 59% (Betz limit) of kinetic wind energy can be transformed in energy mechanics [33, 34]. The power coefficient is a variable magnitude depends on each wind turbine, its evolution depends on the blade pitch angle (β) and the tip-speed ratio (λ) which is defined as [35]:

$$\lambda = \frac{\Omega_{tur} R}{v} \qquad (20)$$

The wind power density (WPD) shows the capacity of wind energy in a specific site. It is given by:

$$P_{dens} = \frac{P_{tur}}{S} = \frac{1}{2}.\rho.C_p.v^3 \qquad (21)$$

The WPD using weibull parameters can be calculated as [36]:

$$P_{dens} = \frac{P(v)}{S} = \frac{1}{2}.\rho.c^3\gamma\left(1+\frac{3}{k}\right) \qquad (22)$$

3.5. Wind energy estimation

The wind energy varies proportionally to the cube of the wind speed and that the wind speed distribution may be represented in the form of a time series [37]. The wind energy density (WED) extracted by a wind turbine is wind power density for a desired duration T (h). It can be estimated as [28]:

$$E_{dens} = \frac{1}{2}.\rho.c^3\gamma\left(1+\frac{3}{k}\right).T \qquad (23)$$

3.6. Wind turbine capacity factor

The wind turbine capacity factor (C_f) can be calculated by the following equation [31, 38]:

$$C_f = \frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k} \qquad (24)$$

The power produced (P_{out}) by wind turbine is the product of capacity factor by the total rated power (P_r) for certain time duration, given by:

$$P_{out} = C_f.P_r \qquad (25)$$

Where v_c, v_r and v_f are cut-in wind speed, rated wind speed and cut-off wind speed, respectively.

4. RESULTS AND ANALYSIS

In an objective to determine wind potential at the coastal city “Annaba”, deep analysis of wind characteristics is presented. The anemometric data for this study were collected during 15 years from January 2000 to December 2014 from meteorological station at Rabah-Bitat International airport with the latitude of 3.6° 50′ north and longitude of 7° 48′ east, situated in Annaba city at the northeastern region of Algeria in the north of Africa.

4.1. Statistical analysis

To find out different wind characteristics of the selected sites, the statistic analyze wind speed data prove to be necessary. Wind speed is measured over three-hours periods (08 observations per day) for 2014 and from January 2000 to December 2014 for fifteen years, is considered in this study. Wind data was converted to height of 12m. Fig.1 show the fifteen years monthly mean wind speed data, it can be observed that the mean wind speed is nearly 5.25m/s and 5m/s from 2000 to 2007 (Fig.1-a) and 2008 to 2014 (Fig.1-b), respectively. The maximum monthly mean wind speeds are 7.48m/s and 7.13m/s in February 2005 and July 2008 respectively, whereas the minimum is 3.9m/s in October 2001, October 2004, and is 4.1m/s in February 2008, January 2007 and Mars 2009. Yearly standard deviation and mean wind speed for fifteen years are represented in Fig. 2. This figure shows the evolution of the parameters mentioned above. However, it summarizes the interpretations of Fig.1. Furthermore, considerable changes are recorded on the variance as shown in figure.

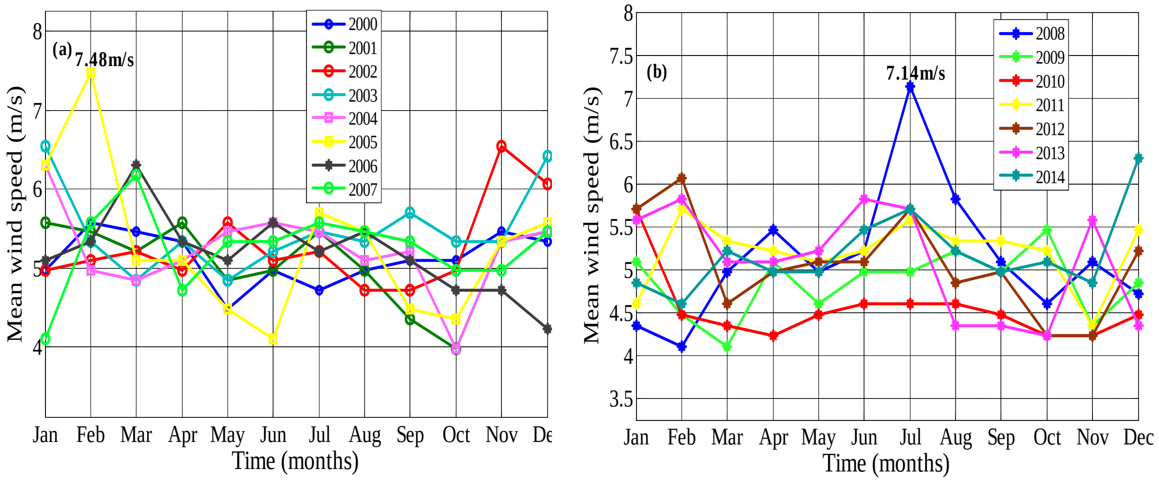


Figure 1. Monthly mean wind speed

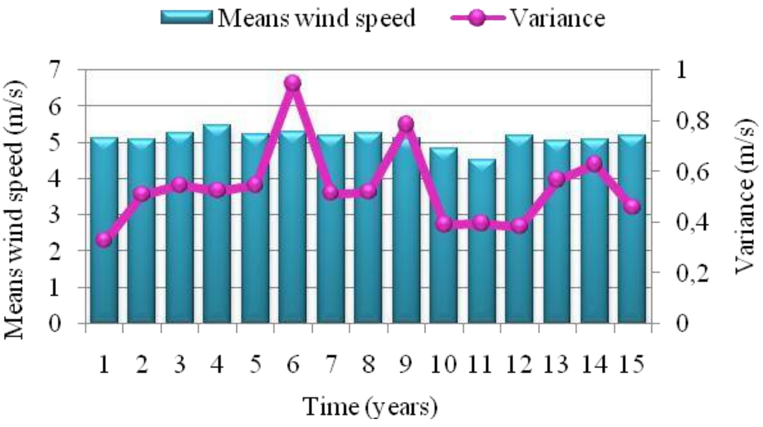


Figure. 2. Yearly mean wind speed and variance

As showing in figure 3, the maximum of most probable wind speed and wind speed carrying maximum energy among fifteen years are 5.66m/s in 2003, 5.9872m/s in 2005, respectively (Tab. 1).

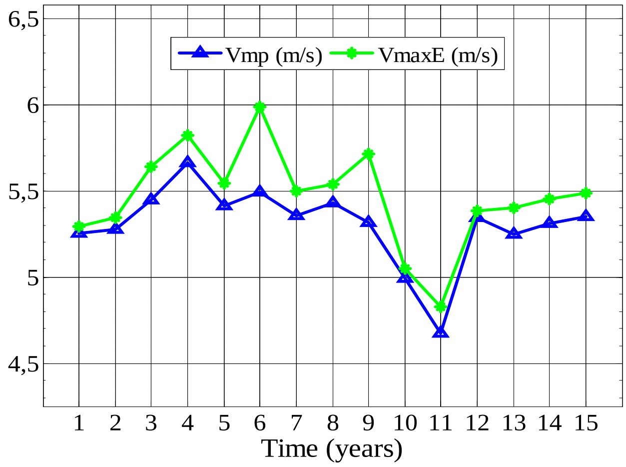


Figure 3. Most probable wind speed and wind speed carrying maximum energy during fifteen years (2000-2014)

4.2. Extrapolation of weibull parameters

Several methods have been use to determine the weibull shape and scale parameters. In this work, the scale and shape parameters are calculated using empirical method. Table 1 present the yearly values of: mean wind speed, standard deviation, most probable wind speed, wind speed carrying maximum energy, weibull parameters, power density and energy density among fifteen years. The Weibull scale parameter ranges from 5.0122m/s in 2009 to 5.7193m/s in 2003. In the other hand, the value of shape parameter is in the range from 5.7096 in 2005 to 19.7130, 15.1396 in 2000, 2001 respectively.

Table. 1 Yearly wind speed characteristics, weibull parameters, power density and energy density.

Period	**Characteristic**							
	v_m	σ	v_{mp}	v_{maxE}	c	κ	P_{dens}(W/m^2)	E$_{dens}$(KWh/m^2)
2000	5.1221	0.3269	5.2508	5.2906	5.2647	19.7130	83.3923	720.51
2001	5.0999	0.5082	5.2765	5.3440	5.3004	15.1396	83.7449	723.56
2002	5.2627	0.5450	5.4462	5.6372	5.5160	9.1193	91.8357	793.46
2003	5.4759	0.5245	5.6620	5.8201	5.7193	10.2271	102.8379	888.52
2004	5.2320	0.5449	5.4130	5.5455	5.4608	10.9253	89.8388	776.21
2005	5.2870	0.9440	5.4920	5.9872	5.6804	5.7096	99.6424	860.91
2006	5.1816	0.5129	5.3572	5.5001	5.4089	10.4640	90.1389	778.80
2007	5.2527	0.5178	5.4307	5.5376	5.4690	12.1849	90.8117	784.61
2008	5.1270	0.7837	5.3162	5.7155	5.4668	6.2459	88.6397	765.85
2009	4.8452	0.3906	4.9909	5.0513	5.0122	15.5658	71.0249	613.66
2010	4.5359	0.3938	4.6731	4.8267	4.7291	9.4212	57.9549	500.73
2011	5.2031	0.3827	5.3426	5.3842	5.3571	19.4360	87.8631	759.14
2012	5.0585	0.5653	5.2498	5.4013	5.3048	10.0569	82.0592	708.99
2013	5.0985	0.6268	5.3107	5.4520	5.3618	10.4736	84.8813	733.37
2014	5.1822	0.4578	5.3470	5.4883	5.3981	10.5103	86.6161	748.36

As seen in figure 4, the scale parameter changes according to the mean wind speed. When the mean wind speed is high, the scale parameter is large.

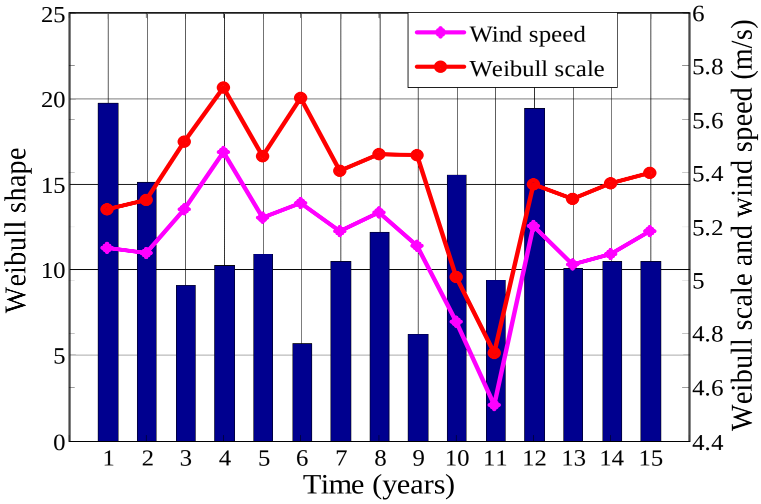


Figure 4 Yearly weibull parameters (c, k) and wind speed (2000÷2014)

Figure 5 Show the yearly wind power density and wind energy density (2000÷2014) in the studied site. It can be observed that the wind power density changes according to the mean wind speed. The wind power density during 2000 to 2014 is maximal at 2003 and 2005 with 102.8379 W/m^2 and 99.6424 W/m^2, respectively. However, the lowest value of wind power density is 57.9549 W/m^2 which occur in 2010. Otherwise, the wind energy densities are high from 2002 to 2008, its minimal value was registered in 2010 with 500.73 KWh/m^2.

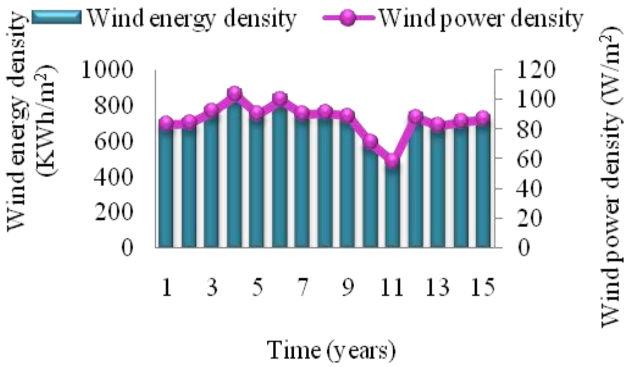


Figure. 5. Yearly wind power density and energy density (2000–2014)

4.3. *Analysis of wind data in 2014*

In this section, the wind data from January to December 2014 at 12m hub height has been analyzed. Figure 6 presents the daily mean wind speed data. The highest daily mean wind speeds are about 10.44m/s, 11.34m/s and 11m/s at which appear in January, November and December, respectively. In addition, the lowest daily mean wind speed is about 2.54m/s at which occur in January 2014. However, it is noted that the wind reaches low speed (Low wind speed period) between the 221 and 278 days as shown in figure. So, the monthly mean wind speed and variance are described in figure 7. The highest and lowest monthly wind speed values are 6.34m/s and 4.65m/s, which appear in January and December, respectively. The wind variance is the discrete degree of the wind data sequence relative to the mean value.

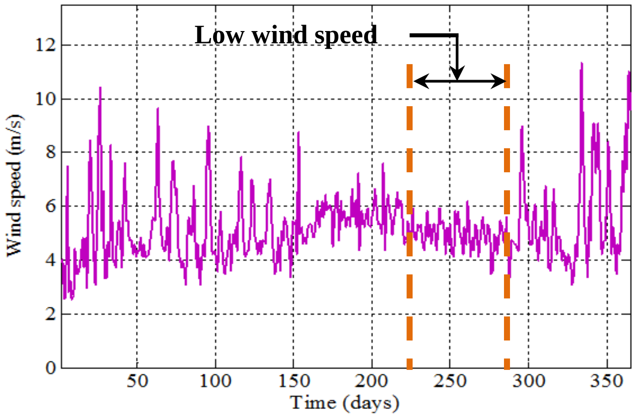


Figure 6. Daily mean wind speed data of the year 2014

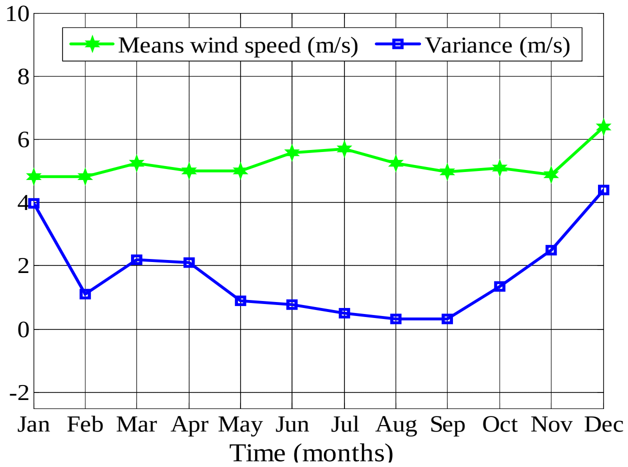


Figure 7. Monthly mean wind speed data of the year 2014

As demonstrated in figure 8, the maximum values of "Vmp", among twelve months are 6.1317m/s and 6.5899m/s in July and December, respectively. Besides, the highest value of wind speed carrying maximum energy "V_{maxE}" at the same period is 6.75m/s, 6.76m/s, 6.56m/s, 6.70m/s and 8.42m/s in January, Mars, April, November and December, respectively. Similarly, the lowest value of V_{mp} and V_{maxE} is 4.77m/s and 5.53m/s in January and September, respectively.

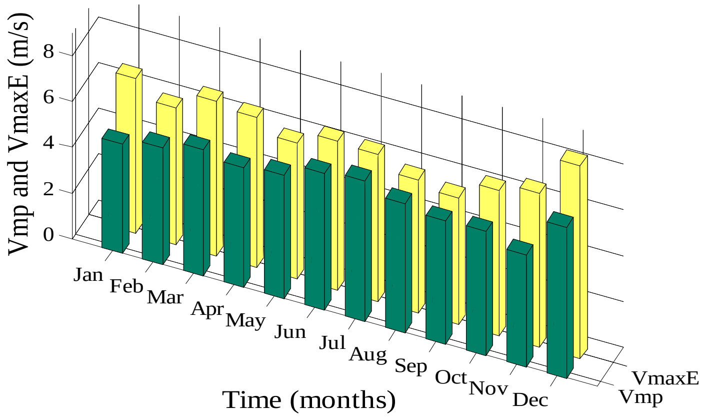


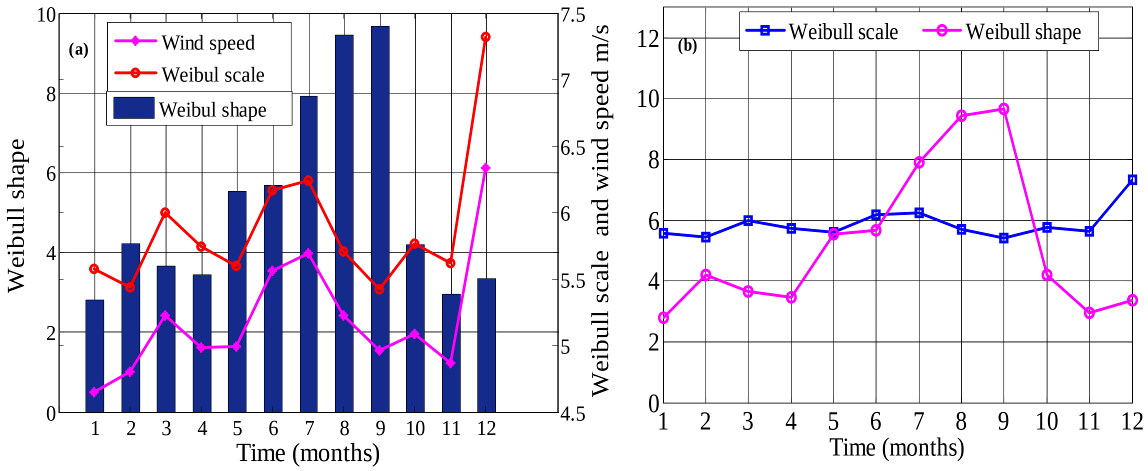
Figure 8. Monthly most probable wind speed and wind speed carrying maximum energy

The monthly variation of mean wind speed, standard deviation, most probable wind speed, wind speed carrying maximum energy, Weibull parameters, power density and energy density at 12m hub height among twelve months are summarized in table 2.

Table. 2 Monthly wind speed characteristics, Weibull parameters, power density and energy density.

Period	**Characteristic**							
	v_m	σ	v_{mp}	v_{maxE}	c	k	P_{dens}(W/m^2)	E_{dens}(KWh/m^2)
Jan	4.6460	3.9670	4.7687	6.7544	5.5776	2.8088	109.6379	78.94
Feb	4.8036	1.1129	5.1021	5.9679	5.4416	4.2100	89.8644	64.70
Mar	5.2264	2.1895	5.4951	6.7585	5.9975	3.6542	123.7930	89.13
Apr	4.9879	2.1103	5.2010	6.5550	5.7424	3.4528	110.3965	79.49
May	4.9913	0.8867	5.3983	5.9172	5.5963	5.5335	95.3459	68.65
Jun	5.5597	0.7663	5.9595	6.5042	6.1668	5.6714	127.4953	91.80
Jul	5.6955	0.4898	6.1317	6.4178	6.2375	7.9082	132.0704	95.09
Aug	5.2269	0.3378	5.6388	5.8229	5.7059	9.4529	101.7945	73.29
Sep	4.9620	0.3274	5.3623	5.5295	5.4231	9.6724	87.5314	63.02
Oct	5.0857	1.3525	5.4022	6.3290	5.7658	4.1884	107.1397	77.14
Nov	4.8661	2.4838	4.8922	6.6964	5.6240	2.9588	109.8399	79.09
Dec	6.3366	4.3893	6.5899	8.4190	7.3234	3.3543	230.5587	166.002
Yearly	5.1822	0.4578	5.3470	5.4883	5.3981	10.5103	86.6161	748.36

Concerning the monthly variation of Weibull scale and shape parameter among twelve months, as shown in the figures 9-a and 9-b. We remark that the change of the monthly Weibull scale is in function of monthly wind speed. Therefore, the scale parameter changes according to the mean wind speed. However, the value of Weibull scale parameter during 2014 year is in the range from 5.44m/s in February to 7.32m/s in December. While the Weibull shape parameter range from 2.81 to 9.67 in January and September, respectively. In addition, the highest value of the monthly Weibull shape parameter is about 5.53, 5.67, 7.91, 9.45, 9.67 and 4.19 at which occur in May, June, July, August, September and October, respectively. This can express the uniformity of the wind speed at this period. The high and very peaked values of the Weibull shape parameter explain that the wind speeds tend to be very close to a certain speed and the distribution is skewed towards higher wind speeds. Otherwise, the highest value of Weibull scale parameter imply that the distribution have more probability of higher mean wind speeds.



(a) (b)

Figure 9. Monthly weibull parameters (c, k) and wind speed

Figure 10, displays the evolution of monthly average wind power density and wind energy density for 2014 year. We can deduct that during twelve months, wind power density evolve according mean wind speed. The highest wind power density value is detected at December with 230.56W/m^2 who corresponds to the wind speed 6.34m/s. otherwise, the lowest power density value is detected at September with 87.53W/m^2. On the other hand, 166 KWh/m^2, 63 KWh/m^2 are the highest and the lowest wind energy density value calculated in December and September, respectively. The yearly wind power density and energy density are 86.62W/m^2 and 748.36 KWh/m^2 (Tab. 2).

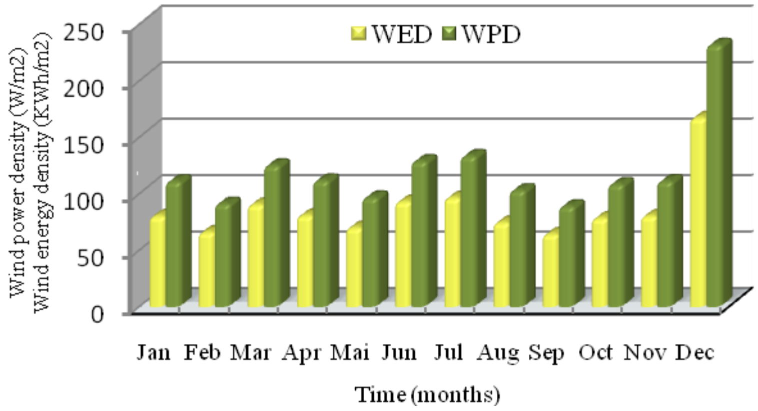


Figure 10. Monthly wind power density and energy density

The monthly weibull probability density distribution (PDF) of wind speed represented in figure 11, is estimated using equations (3). As seen, the maximum weibull probability values are in the range from 0.4÷0.7 in July, August and September, wile for the other months the maximum weibull probability values are smaller than 0.4. Additionally, the most frequent wind speed during the 12 months is in the range from 4.76m/s in January to 6.59m/s in December, which the maximum wind speed in December is located in the interval 6m/s÷7m/s. Indeed, the probability density for wind speed located in the interval 5m/s÷6m/s is the maximum.

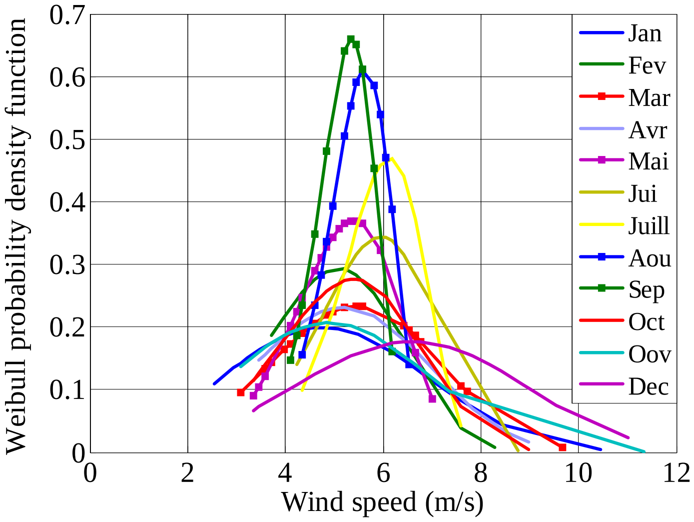


Figure 11. Monthly weibull probability density distribution of wind speed

4.4. Wind turbine power and energy produced

In this section, we look to find the adequate wind conversion system in function of wind characteristics which can operate at maximum efficiency at the studied site. The amount of powers produced over a period of time and the turbine's capacity factor permits to analyze and evaluate the performance of wind turbine. As seen in equation (30), the capacity factor depends on the weibull shape and scale parameters and the specifications of the wind turbine. Otherwise, in the interval ($v_c \div v_r$) the power produced by the wind turbine is proportional to the wind speed and it is constant in the interval ($v_r \div v_f$).

After the calculate wind speed for different hub heights, we noticed that the wind speed increases with the wind turbine hub height. Indeed, the lowest wind speeds value range between 4m/s and 5m/s at 60m and100m, respectively. While the highest wind speeds value range between 14m/s and 15m/s at 60m and 100m, respectively.

In the aim to choose the right and the better wind turbine for the studied site, the wind turbine performance assessment of nine selected wind turbines (Tab. 3) from different manufacturers [30] are presented and analyzed. The choice of these different turbines is justified by their interval of cut-in wind speeds (2.5m/s÷3m/s) and the interval of rated wind speeds (11.5÷15m/s). These wind turbines have a rated power in the range from 600kW (Bonus 600/44, De Wind 48 and Enercon E-40/600) to 2300kW (Bonus 2300/82.4). The capacity factor, wind power and annual energy output of nine wind turbine models for different hub heights are calculated and summarized in table.3. However, the capacity factor ranges from 0.23 to 0.56 for Bonus 600/44 and Enercon E-58/1000, respectively. The important capacity factor value of Enercon E-58/1000 can be explained by its low cut-in wind speed (2.5m/s) and rated wind speed (12m/s). In addition, Enercon E-82/2000 and De Wind 48 present also an important capacity factor value with 0.49 and 0.47, respectively. Enercon E-58/1000 capacity factor is superior to the Enercon E-82/2000 capacity factor with the same v_c and a less height (<9m), but the rated wind speed is 12m/s. On the other hand, with a hub height of 100m, Bonus 2300/82.4 has a small capacity factor (0.29). This is due to its important rated wind speed value (15 m/s) compared with the other wind turbine. For the wind turbines that have the same hub height (70m), De Wind 48 have the highest C_f with v_r, v_c are 11.5m/s, 3m/s, respectively. Although, the cut-in wind speeds of De Wind D6 model is 2.8m/s. The C_f of Bonus 600/44 model with the values of cut-in and rated wind speeds are 3m/s and 13m/s, respectively, is lower than that of Bonus 2300/82.4 model with the same v_r and v_c. In conclusion, rated wind speed is very important than cut-in wind speed and hub height. The maximum wind output powers are 979.2kW and 657.34kW by Enercon E-82/2000 and Bonus 2300/82.4 wind turbines, respectively. Moreover, the maximum annual energy produced is 8577.79MWh and 5758.3MWh. The lowest wind output power is 139.38kW by Bonus 600/44 wind turbine. 4905.6 and 4292.4 are the highest equivalent hour (production capability/year) by Enercon E-58/1000 and Enercon E-82/2000, respectively.

Table 3: Wind turbine models, capacity factor, wind power output and annual energy.

Turbine model	v_cm/s	v_rm/s	v_fm/s	p_r kW	Hub height m	C_f	E_c	P_{out}kW	E_pMWh
Bonus 2300/82.4	3	15	25	2300	100	0.29	2540.4	657.34	5758.3
Bonus 600/44	3	13	25	600	60	0.23	2014.8	139.38	1220.97
De Wind D8	3	13.5	25	2000	80	0.31	2715.6	615	5387.4
De Wind D6	2.8	12.5	25	1250	70	0.34	2978.4	427.38	3743.81
De Wind 48	3	11.5	22	600	70	0.47	4117.2	280.8	2459.81
Enercon E-82/2000	2.5	13	28	2000	98	0.49	4292.4	979.2	8577.79
Enercon E-58/1000	2.5	12	28	1000	89	0.56	4905.6	560.3	4908.23
Enercon E-40/600	2.5	12	28	600	65	0.36	3153.6	216.18	1893.74
Nordex N-70/1500	3	13	25	1500	70	0.29	2540.4	437.7	3834.25

After the study previously achieved on the choice of the adequate wind turbine, we opted for 2MW wind turbine, in which the characteristics are recapitulated in table. 4.

Table 4: 2MW DFIG Wind Turbine Parameters

Rated power	200 kW
Diameter (m)	82
Gearbox ratio	100
Friction coefficient : f	0.0024
Moment of inertia : J (Kg.m^2)	90
Stator voltage/Frequency (V/Hz)	690/50
R_s / R_r (Ω)	0.001/0.0013
L_m/L_{fs}/L_{fr} (H)	0.003/0.0007/0.0008
Number of pole pairs: p	2
M	1

5. CONTROL SYSTEM

In order to extend this study on the wind energy conversation systems (WECS), vector control strategy and adaptive fuzzy gain scheduling are proposed in the continuation of this work, to value system performances and robustness where WECS is based on doubly fed induction generator (DFIG). In practice, the machine parameters change inevitably during the time. So to overcome the disadvantages, PI controller with online adaptive mechanism based on a fuzzy logic is applied in this section.

5.1. Control strategy

The design of adaptive fuzzy-PI controller to control the active and reactive power is illustrated in figure 12.

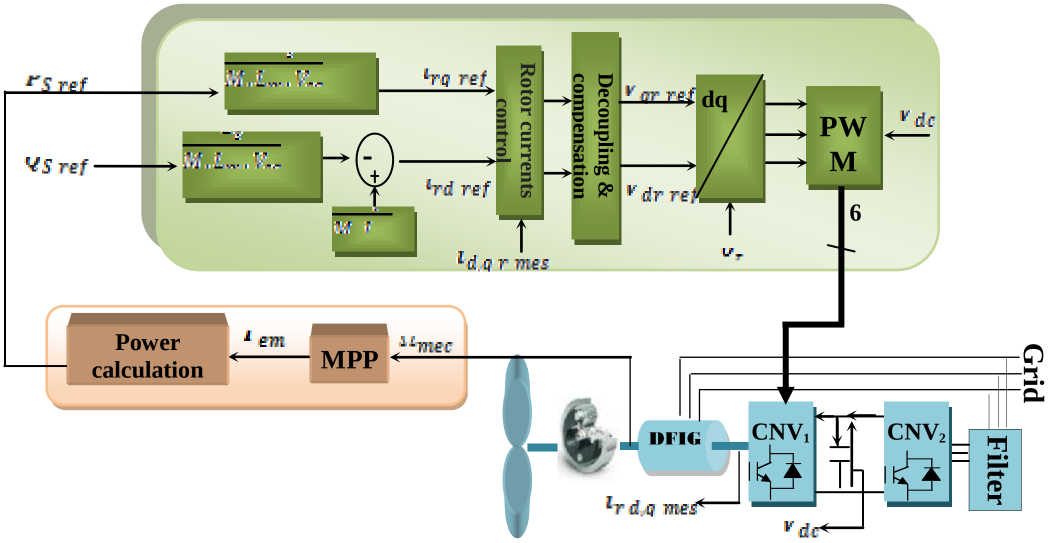


Figure 12. Block diagram control of active and reactive power

The electromagnetic torque reference determined by the maximum power point (MPP) control power is thus expressed by the following equation [39, 40]:

$$T_{em}^{*} = \frac{C_{popt}.\rho.\pi.R^{5}}{2.G^{3}.\lambda_{opt}^{3}}.\Omega_{mec}^{2} \qquad (31)$$

In the synchronous dq reference frame where the d-axis is aligned with the stator flux linkage vector φ_s, and then, ($\varphi_{sq} = 0,\ \varphi_{sd} = \varphi_s$) [41-43]. Active and reactive powers as well as electromagnetic torque (T_{em}) equations are expressed by (32) and (33), respectively:

$$\begin{cases} P_s = -\frac{V_s.M}{L_s}.i_{rq} \\ Q_s = \frac{V_s^2}{L_s\omega_s} - \frac{M.V_s}{L_s}.i_{rd} \\ P_r = g.\frac{V_s.M}{L_s}.i_{rq} \end{cases} \qquad (32)$$

$$T_{em} = -P.\frac{M}{L_s}\varphi_{sd}.i_{rq} \qquad (33)$$

So, after arrangement we demonstrate that the electromagnetic torque and the stator reactive power (Q_s) can be controlled by means of the DFIG current i_{rq} and i_{rd} respectively, as its showing in the following expressions:

$$i_{rd\_ref} = \frac{\varphi_{sd}}{M} - \frac{L_s}{M.V_s}.Q_{s\_ref} \qquad (34)$$

$$i_{rq\_ref} = -\frac{L_s}{M.P.\varphi_{sd}}.T_{em}^{*} \qquad (35)$$

5.1.1. Synthesis of Adaptive Fuzzy gain scheduling

The design of the controller is illustrated in figure 13, where the adaptive fuzzy gain scheduling of proportional integral controller AFG-PI inputs Ei_{r-dq} and dEi_{r-dq} are calculated as:

$$Ei_{r-dq} = i_{rdq\_ref} - i_{rdq\_mes} \qquad (36)$$

$$dEi_{r-dq}(k) = \frac{Ei_{r-dq}(k) - Ei_{r-dq}(k-1)}{T} \qquad (37)$$

Besides, the AFG-PI outputs are K'_{p_dq}, K'_{i_dq}, with *T* is the period of sampling. Otherwise, the normalization PI parameters (K_p, K_i) are given by:

$$K_p = (K_{pmax} - K_{pmin})K'_p + K_{pmin} \qquad (38)$$

$$K_i = (K_{imax} - K_{imin})K'_i + K_{imin} \qquad (39)$$

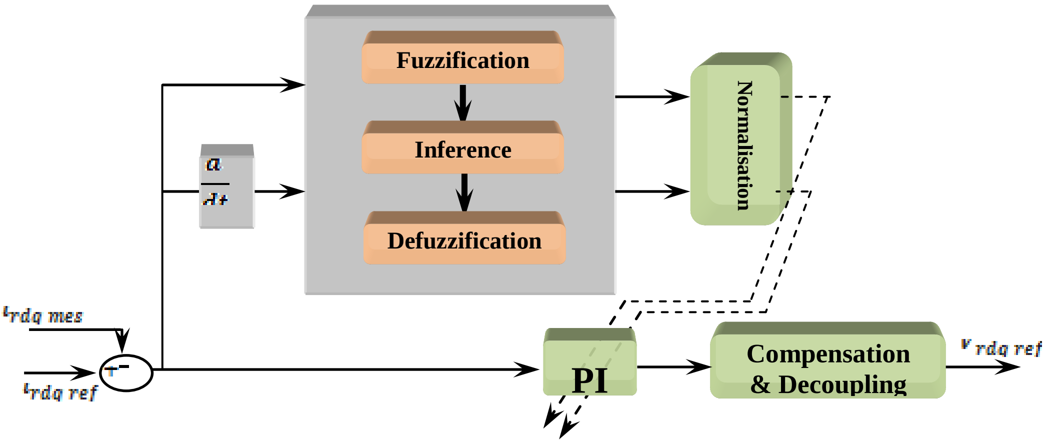


Figure13. Block diagram of the adaptive fuzzy gain scheduler

Figure 14 shows the fuzzy sets and corresponding trapezoidal membership function (MF) of the fuzzy variables. The fuzzy sets are defined as follows: Z=zero, P=Positive, SP=Small Positive, MP=Medium Positive, BP=Big Positive, BN=Big Negative. Fuzzy control rule database consists of series "IF-AND-THEN" fuzzy logic condition sentences.

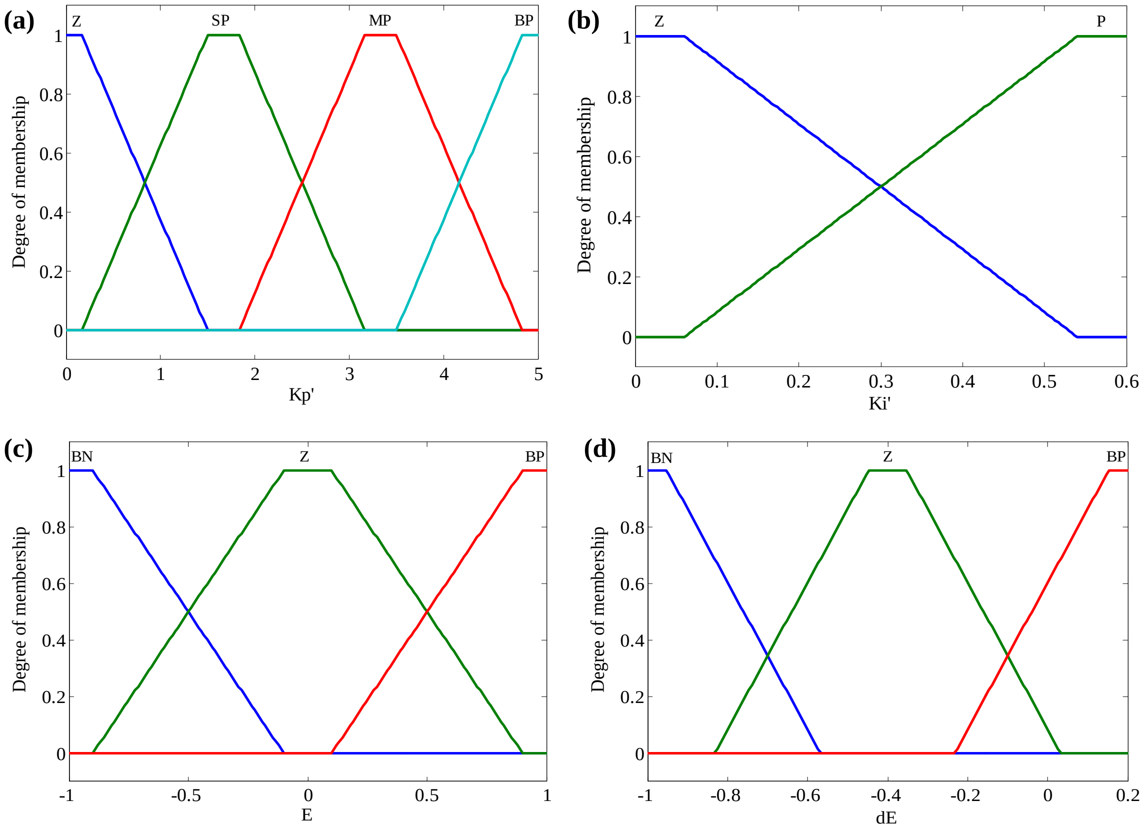
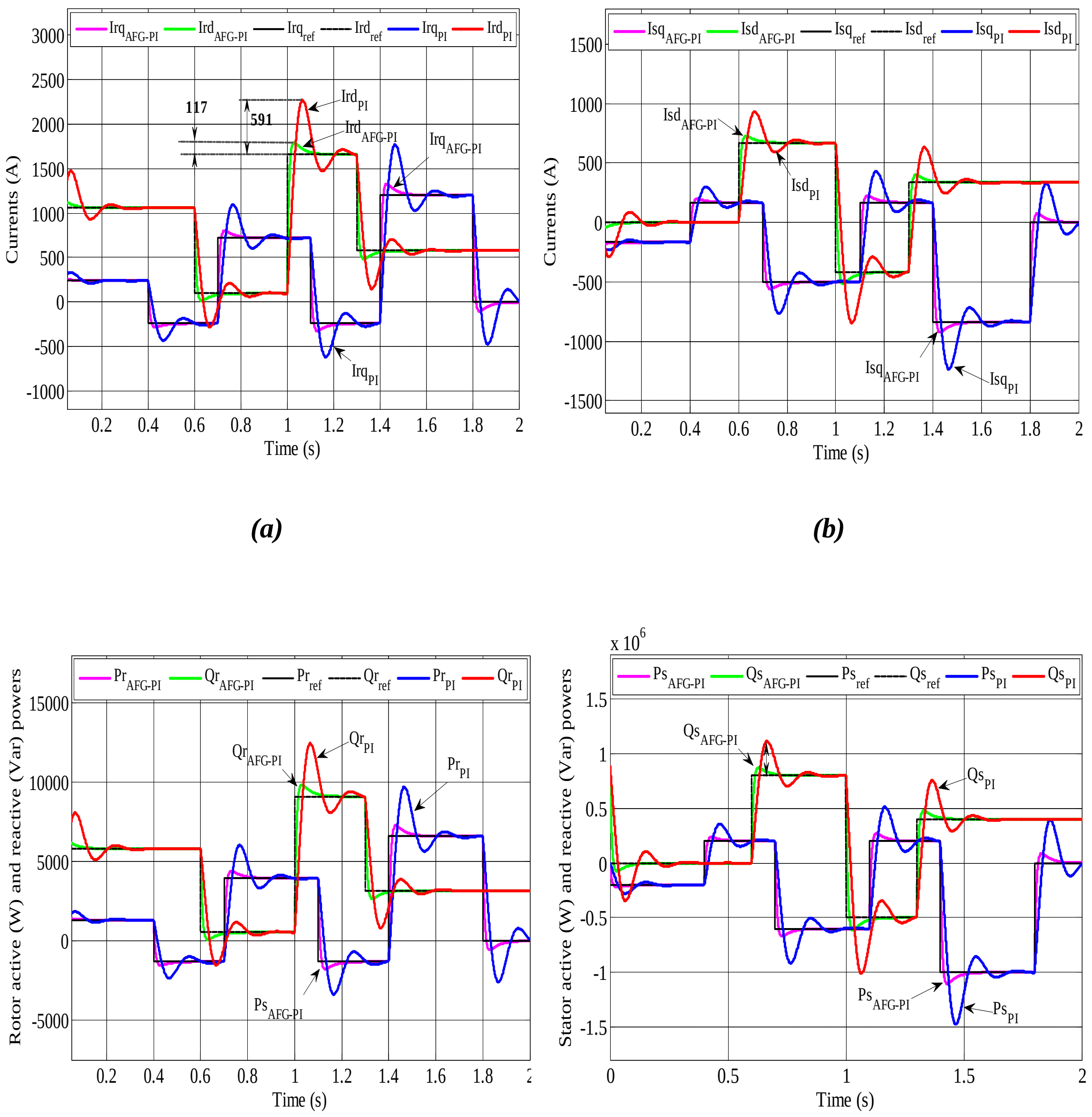


Figure14: Membership functions

5.2. *Results and analysis*

In this section, we want to develop the decoupling method between active and reactive powers and to improve the performances as well as the robustness of the proposed control system. However, the fact of the control of these powers separately permits to adjust the power factor of the installation and in consequence obtain better performance. Therefore, adaptive fuzzy gain scheduling of proportional integral controller was developed. To achieve, our works are validated through simulation studies on a 2MW DFIG wind generation system using software Matlab/Simulink. The value of the rotor resistance r_r, stator, rotor and mutual self inductances has been changed respectively as: (+45%) for r_r and (+25%) for all the self inductances. It has been demonstrated (Fig. 15) that although of parameters variation, the measured rotor and stator current components, active and reactive powers of the DFIG follows respectively their references. According to the analysis of results, we mainly notice that the maximum overshoot of currents and powers magnitudes are about 0,45% for PI controller and 0.1% for AFG-PI controller. Accordingly, the response time of AFG-PI controller is also very small (0.01s) compared to PI controller (0.03s). A good performance and robustness quality of AFGPI controller are shown in the simulation results.



(a) ***(b)***

(c) (d)

Figure15: (a, b) Currents d-q axis and (c, d) active and reactive powers.

6. CONCLUSION

This study articulate on the analysis of the wind data collected from January 2000 to December 2014 from meteorological station at Rabah-Bitat International airport situated in Annaba city at the northeastern region of Algeria. The weibull scale and shape parameters are calculated using empirical method. Otherwise, the analysis and the evaluation of wind power density, capacity factor and wind power generation through nine wind turbines are also carried out. The results of this paper can be concluded as follows:

- ✓ The monthly mean power density varies between 87.53W/m^2 and 230.56W/m^2 at 12m in 2014 while the annual mean power
- ✓ density for fifteen years (2000 to 2014) varies between 99.6424W/m^2 and 102.8379 W/m^2.
- ✓ The monthly mean wind energy density varies between 63 KWh/m^2 and 166 KWh/m^2 at 12m in 2014 while the annual mean wind energy density for fifteen years (2000 to 2014) varies between 51.138 KWh/m^2 and 888.52 KWh/m^2.
- ✓ For an investment in wind power to be cost effective, wind turbine models with a

capacity factor that exceeds or equals to 0.25 is advised [31, 44-46]. Indeed, based to the analysis of the estimated capacity factor. Enercon E-58/1000, Enercon E-82/2000 and De Wind 48 wind turbine models

- ✓ will be the best choice for the investigated site. This is due to its capacity factor of 0.56, 0.49 et 0.47, respectively, rated wind speed of 12m/s, 13m/s and 11.5m/s, respectively, and also to its low cut-in wind speed value range between 2.5m/s and 3m/s. Other wind turbine models have a capacity factor value range between 0.23 and 0.36, and a rated wind speed range from 12m/s to 15m/s, can also be chosen or wind turbine models with similar designed characteristics.
- ✓ Based on annual power produced, Enercon E-82/2000 wind turbine which 13m/s, 2.5m/s and 2000kW are rated wind speed, cut-in wind speed and rated power, respectively. Will be the best proposition for the wind power development for the studied site.
- ✓ The simulation results show that the proposed fuzzy adaptive control system provides better performance and good robustness because when the operating condition of system changes, the PI parameters are adjusted by the collection of “IF-THEN” fuzzy rules while remaining insensible to the variations of the parameters. Therefore, it can contribute to intensify wind energy utilization in the proposed site.

Finally, Annaba that is an inshore city, can be proposed as one of the favorable locations for wind turbines installation.

REFERENCES

[1] Multon B., 2003. Electric energy production by renewable sources, Techniques of the engineer, Treated electric Genius, D 4005, p. 11.

[2] Strupczewskim A., 2003. Accident risks in nuclear-power plants, *Applied Energy*, Vol. 75(1-2), pp. 79-86.

[3] Johnson L. P. a. K. E, 2011. Control of wind turbines. *IEEE Control system magazine*, pp. 44-61.

[4] www.neal-dz.net, 2015.

[5] Shahnawaz F.K., Kavita T., Soomro A.M., Dong L., Xiaozhong L., 2014. Evaluation of wind power production prospective and Weibull parameter estimation methods for Babaurband, Sindh Pakistan, *Energy Conversion and Management*, Vol. 78, pp. 956-967.

[6] de Andrade C. F., Hely F.M.N., Rocha P.A.C., da Silva M.E.V., 2014. An efficiency comparison of numerical methods for determining Weibull parameters for wind energy applications: A new approach applied to the northeast region of Brazil, *Energy Conversion and Management*, Vol. 86, pp. 801-808.

[7] Rehman S., 2004. Wind energy resources assessment for Yanbo, Saudi Arabia, *Energy Convers Manage*, Vol. 45, pp. 2019-2032.

[8]Giovanni G., Sauro S., 2014. Extrapolating wind speed time series vs.Weibull distribution to assess wind resource to the turbine hub height: A case study on coastal location in Southern Italy, *Renewable Energy*, Vol. 62, pp. 164-176.

[9] Lu L., Yang H., Burnett J., 2002. Investigation on wind power potential on Hong Kong islands-an analysis of wind power and wind turbine characteristics, *Renewable Energy*, Vol. 27, pp. 1-12.

[10] Vogiatzis N., Kotti K., Spanomitsios S., Stoukides M., 2004. Analysis of wind potential and characteristics in North Aegean, Greece, *Renew Energy*, Vol. 29, pp. 1193-1208.

[11] Mirhosseini M., Sharifi F., Sedaghat A., 2011. Assessing the wind energy potential locations in province of Semnan in Iran, *Journal Renewable and Sustainable Energy Reviews*, Vol. 15, pp. 449-59.

[12] Mostafaeipour A., 2010. Feasibility study of harnessing wind energy for turbine installation in province of Yazd in Iran. *Journal Renewable and Sustainable Energy Reviews*, Vol. 14, pp. 93-111.

[13] Pishgar-Komleh S.H., Keyhani A., Sefeedpari P., 2015. Wind speed and power density analysis based onWeibull and Rayleigh distributions, *Renewable and Sustainable Energy Reviews*, Vol. 42, pp. 313-322.

[14] Shoaib M., Siddiqui I., Firoz A., Rehman S., M.R.Tanveer and S.U. Jilani, 2015. Weibull Distribution Function for Wind Energy Estimation of Gharo (Sindh), *Journal of Basic & Applied Sciences*, Vol. 11, pp. 106-114.

[15] Mirza I.A, Khan N.A, Memon N., 2010. Development of benchmark wind speed for Gharo and Jhimpir, Pakistan, *Renewable Energy*, Vol. 35, pp. 576-82.

[16] Cannon D.J., Brayshaw D.J., Methven J., Coker P.J., Lenaghan D., 2015. Using reanalysis data to quantify extreme wind power generation statistics: A 33 year case study in Great Britain, *Renewable Energy*, Vol. 75, pp<; 767-778.

[17] Dahbi M., Benatiallah A., Sellam M., 2013. The Analysis of Wind Power Potential in Sahara Site of Algeria-an Estimation Using the ‘Weibull’ Density Function, *Energy Procedia*, Vol. 36, pp. 179-188.

[18] Boudia S.M., Benmansour A., Tabet Hellal M.A., 2014. Wind energy resource assessment at Tindouf region, extreme southwest of Algeria, *Applied Machanics and Materials*, 541-542, pp. 972-976.

[19] Celik A.N, Kolhe M., 2013. Generalized feed-forward based method for wind energy prediction, *Applied Energy*, Vol. 101, pp. 582–588.

[20] Akdağ S.A, Dinler A., 2009. A new method to estimate Weibull parameters for wind energy applications, *Energy Conversation Management*, Vol. 50, pp. 1761-1766.

[21] Chang T.P., 2011. Performance comparison of six numerical methods in estimating Weibull parameters for wind energy application, *Applied Energy*, Vol. 88, pp. 272-282.

[22] Dursun B., Alboyacı B., 2011. An evaluation of wind energy characteristics for four different locations in Balikesir. *Energy Sources, PartA: Recovery, Utilisation and Environmental Effects*, Vol. 33 (11), pp. 1086-1103.

[23] TalhaArslan. N, MuratBulut Y.,ArzuAltın Y., 2014. Comparative study of numerical methods for determining Weibull parameters for wind energy potential, *Renewable and Sustainable Energy Reviews*, Vol. 40, pp. 820-825.

[24] Persaud S., Flynn D., Fox B., 1999. Potential for wind generation on the Guyana coastlands, *Renewable Energy*, Vol. 18 (2), pp. 175-189.

[25] Costa R., Paulo A., Ricardo C.d.S., Carla F.d.A., Maria E.V.d.S., 2012. Comparison of seven numerical methods for determining Weibull parameters for wind energy generation in the northeast region of Brazil, *Applied Energy*, Vol. 89, pp. 395-400.

[26] Li X., 2011. Green energy-basic concepts and fundamentals, Springer; p. 79-134.

[27] Seguro J.V., Lambert T.W., 2000. Modern estimation of the parameters of the Weibull wind speed distribution for wind energy analysis, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 85, pp. 75-84.

[28] Keyhani A., Varnamkhasti G.M., Khanali M., Abbaszadeh R., 2010. An assessment of wind energy potential as a power generation source in the capital of Iran, Tehran, *Energy*, Vol. 35, pp. 188-201.

[29] Lima L.d.A., Filho C.R.B., 2012. Wind resource evaluation in Sao Joao do Cariri (SJC) Paraiba, Brazil, *Renewable and Sustainable Energy Reviews*, Vol. 16, pp. 474-480.

[30] Khahro S.F., Tabbassum K., Soomro A.M., Liao X., BuxAlvi M., LeiDong, Manzoor M.F., 2014. Techno-economical evaluation of wind energy potential and analysis of power generation from wind at Gharo, Sindh Pakistan, *Renewable and Sustainable Energy Reviews*, Vol. 35, pp. 460-474.

[31] Muyiwa S., Adaramola, Agelin-Chaab M., Samuel S.P., 2014. Assessment of wind power generation along the coast of Ghana, *Energy Conversion and Management*, Vol. 77, pp. 61-69

[32] Bedoud K., Ali-rachedi M., Lakel R., Bahi T., 2015. Adaptive fuzzy gain scheduling of PI controller for control of the wind energy conversion systems, *Energy Procedia*, Vol. 74, pp. 211-225.

[33] Laverdure N., 2009. The integration of the wind generators in the low or insular networks, Doctorate Theses, ENS of Cachan.

[34] Burton T., Sharpe D., Jenkins N., Bossanyi E., 2001. Wind Energy Handbook, Ed Wiley, 2001.

[35] Bedoud K., Ali-rachedi M., Lakel R., Bahi T., Grid A., 2015. Robust control of doubly fed induction generator for wind turbine under sub-synchronous operation mode, *Energy Procedia*, Vol. 74, pp. 886- 899.

[36] Ucar A., Balo F., 2009. Evaluation of wind energy potential and electricity generation at six locations in Turkey, *Applied Energy*, Vol. 86, pp. 1864-1872.

[37] Altunkaynak A., Erdik T., Dabanli I., Sen Z., 2012. Theoretical derivation of wind power probability distribution function and applications, *Applied Energy*, Vol. 92, pp. 809-814.

[38] Akpinar E.K., Akpinar S., 2005. An assessment on seasonal analysis of wind energy characteristics and wind turbine characteristics, *Energy Conversation Management*, Vol. 46, pp. 1848-1867.

[39] Fernandez L.M., Garcia C.A., Jurado F., 2008. Comparative study on the performance of control systems for doubly fed induction generator (DFIG) wind turbines operating with power regulation, *Energy,* Vol. 33, pp. 1438-1452.

[40] Boutoubat M., Mokrani L., Machmoum M., 2013. Control of a wind energy conversion system equipped by a DFIG for active power generation and power quality improvement, *Renewable Energy*, Vol. 50, pp. 378-386.

[41] Barambones O., de Durana J.M.G., Kremers E., 2013. Adaptive robust control to maximizing the power generation of a variable speed wind turbine, International Conference on Renewable Energy Research and Applications Madrid ICRERA'2013, IEEE, 20-23 October 2013, Spain.

[42] Gaillard A., 2010. Wind system based on the DFIG: contribution to the study of the quality of the electric energy and the continuity of service, Doctorat thesis, Henri Poincare University, Nancy-I, France.

[43] Ahmed M.K., Hasaneen K.M., Yousef A.M., 2013. Dynamic modeling and robust power control of DFIG driven by wind turbine at infinite grid, *Electrical Power and Energy Systems*, Vol. 44, pp. 375-382.

[44] Adaramola M.S., Oyewola O.M., 2011. Evaluating the performance of wind turbines in selected locations in Oyo state, Nigeria, *Renew Energy*, Vol. 36, pp. 3297-3304.

[45] Maatallah T., El-Alimi S., Dahmouni A.W., Nasrallah A.B., 2013. Wind power assessment and evaluation of electricity generation in the Gulf of Tunis, Tunisia, *Sustainable Cities and Society*, Vol. 6, pp. 1–10.

[46] Mathew S., 2006. Wind energy: fundamentals, resource analysis and economics. Heidelberg: Springer; 2006.