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

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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 flu 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.

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 an 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, Saudi 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 $\sigma$ [30]. The weibull shape and scale parameter can be determined as follows [19, 24]:

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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]:

\[ f(v) = \left( \frac{k}{c} \right) \left( \frac{v}{c} \right)^{k-1} \exp \left( - \left( \frac{v}{c} \right)^k \right) \]  

Where \( f(v) \) is the probability of observing wind speed \( v \), \( c \) 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 \([5, 6, 13, 23, 29]\):

\[ F(v) = 1 - \exp \left( - \left( \frac{v}{c} \right)^k \right) \]  

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:

\[ v_m = \frac{1}{n} \sum_{i=1}^{n} v_i \]  
\[ \sigma^2 = \frac{1}{n} \sum_{i=1}^{n} (v_i - v_m)^2 \]  

Standard deviation can be written as:

\[ \sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (v_i - v_m)^2} \]  

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

\[ v_m = \frac{1}{k} \gamma \left( 1 + \frac{1}{k} \right) \]  
\[ \sigma^2 = \frac{1}{\gamma k^2} \gamma \left( 1 + \frac{1}{k} \right)^2 \]  

Where \( \gamma \) is a gamma function, calculated by:

\[ \gamma(v) = \int_0^\infty u^{v-1} e^{-u} du \]  

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 \( n_2 \) can be adjusted using following expression [28, 30, 31]:

\[ \frac{c_2}{c_1} = \left( \frac{n_2}{n_1} \right)^{\frac{k_1}{k_2}} \]  

The exponent \( n \) can be calculated by [31]:

\[ n = \frac{0.37 - 0.088 \ln(c_1)}{1 - 0.088 \ln(c_2)} \]  

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

\[ v_2 = \left( \frac{n_2}{n_1} \right)^{\alpha} \]  

Where \( v_2, n_2 \) 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 \( n_1 \), respectively.

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

The most probable wind speed (\( v_{\text{mp}} \)), and the wind speed carrying maximum energy (\( v_{\text{max}} \)) 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]:

\[ v_{\text{mp}} = v_f = c \sqrt[1-k]{\frac{1}{k}} \]  
\[ v_{\text{max}} = v_\theta = c \sqrt[k+2]{\frac{1}{k}} \]  

3.4. Wind power density estimation

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

\[ P = \frac{1}{2} \rho S v^3 \]  
\[ P_{\text{tur}} = C_P \frac{1}{2} \rho S v^3 \]  

With \( \rho \) : airdensity (\( \rho = 1.25 \text{ kg/m}^3 \));
S : surface; 
\( C_{w} \) : 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 (\( \beta \)) and the tip-speed ratio (\( \lambda \)) which is defined as [35]:

\[
\lambda = \frac{\omega_{t}}{\omega_{r}}
\]

(20)

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

\[
r_{\text{den}} = \frac{r_{\text{sur}}}{\pi} = \frac{1}{2} \cdot \rho \cdot C_{w} \cdot v^{3}
\]

(21)

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

\[
P_{\text{den}} = \frac{r_{\text{weibull}}}{\pi} = \frac{1}{2} \cdot \rho \cdot c^{3} \gamma \left( 1 + \frac{3}{\gamma} \right)
\]

(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]:

\[
E_{\text{den}} = \frac{r_{\text{sur}}}{\pi} \cdot c^{3} \gamma \left( 1 + \frac{3}{\gamma} \right) \cdot T
\]

(23)

3.6. Wind turbine capacity factor

The wind turbine capacity factor (\( C_{f} \)) can be calculated by the following equation [31, 38]:

\[
C_{f} = \frac{c^{3} \gamma \left( 1 + \frac{3}{\gamma} \right)}{\left( \frac{\rho \cdot \omega_{r}^{2} \cdot \gamma}{\pi} \right)^{k} \left( \frac{c^{3}}{\rho \cdot \omega_{r}^{2}} \right)^{k}} - e^{-\frac{\rho \cdot \omega_{r}^{2}}{2} \cdot \gamma}
\]

(24)

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

\[
r_{\text{out}} = C_{f} \cdot r_{r}
\]

(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 shown in Figure 3, the maximum of most probable wind speed and wind speed carrying maximum energy among fifteen years are 5.66 m/s in 2003, 5.9872 m/s in 2005, respectively (Tab. 1).
4.2. Extrapolation of weibull parameters

Several methods have been used to determine the weibull shape and scale parameters. In this work, the scale and shape parameters are calculated using empirical method. Table 1 presents 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 5.0122 m/s in 2009 to 5.7193 m/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.

<table>
<thead>
<tr>
<th>Period</th>
<th>Characteristic</th>
<th>$\sigma$</th>
<th>$\mu_{mp}$</th>
<th>$\mu_{avg}$</th>
<th>$\xi$</th>
<th>$\kappa$</th>
<th>$E_{den}$ (W/m$^2$)</th>
<th>$E_{dem}$ (KWh/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>$\mu_m$</td>
<td>5.1221</td>
<td>5.2508</td>
<td>5.2906</td>
<td>5.2647</td>
<td>19.7130</td>
<td>83.3923</td>
<td>720.51</td>
</tr>
<tr>
<td>2001</td>
<td>$\mu_m$</td>
<td>5.0999</td>
<td>5.2765</td>
<td>5.3440</td>
<td>5.3004</td>
<td>15.1396</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2002</td>
<td>$\mu_m$</td>
<td>5.2627</td>
<td>5.4462</td>
<td>5.6372</td>
<td>5.5160</td>
<td>9.1193</td>
<td>102.8379</td>
<td>888.52</td>
</tr>
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<td>2003</td>
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<td>5.5245</td>
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<td>5.7193</td>
<td>10.2271</td>
<td>102.8379</td>
<td>888.52</td>
</tr>
<tr>
<td>2004</td>
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<td>5.2320</td>
<td>5.4130</td>
<td>5.6372</td>
<td>5.7193</td>
<td>10.2271</td>
<td>83.3923</td>
<td>720.51</td>
</tr>
<tr>
<td>2005</td>
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<td>5.4200</td>
<td>5.5212</td>
<td>5.5160</td>
<td>10.2271</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2006</td>
<td>$\mu_m$</td>
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<td>5.4462</td>
<td>5.6372</td>
<td>5.5160</td>
<td>10.2271</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2007</td>
<td>$\mu_m$</td>
<td>5.2527</td>
<td>5.4462</td>
<td>5.6372</td>
<td>5.5160</td>
<td>10.2271</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2008</td>
<td>$\mu_m$</td>
<td>5.1270</td>
<td>5.4462</td>
<td>5.6372</td>
<td>5.5160</td>
<td>10.2271</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2009</td>
<td>$\mu_m$</td>
<td>4.8452</td>
<td>5.4462</td>
<td>5.6372</td>
<td>5.5160</td>
<td>10.2271</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2010</td>
<td>$\mu_m$</td>
<td>4.5359</td>
<td>4.7258</td>
<td>4.7258</td>
<td>4.7258</td>
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<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2011</td>
<td>$\mu_m$</td>
<td>5.2031</td>
<td>5.4372</td>
<td>5.6372</td>
<td>5.5160</td>
<td>10.2271</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
<tr>
<td>2012</td>
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<td>5.0585</td>
<td>5.4372</td>
<td>5.6372</td>
<td>5.5160</td>
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<td>723.56</td>
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<td>723.56</td>
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<tr>
<td>2014</td>
<td>$\mu_m$</td>
<td>5.1822</td>
<td>5.4372</td>
<td>5.6372</td>
<td>5.5160</td>
<td>10.2271</td>
<td>83.7449</td>
<td>723.56</td>
</tr>
</tbody>
</table>

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)](image)

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$^2$. 

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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 10.44 m/s, 11.34 m/s and 11 m/s at which appear in January, November and December, respectively. In addition, the lowest daily mean wind speed is about 2.54 m/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 6.34 m/s and 4.65 m/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.
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 “VmaxE” 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 Vmp and VmaxE 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](image)

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.

<table>
<thead>
<tr>
<th>Period</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V_m</td>
</tr>
<tr>
<td>Jan</td>
<td>4.6460</td>
</tr>
<tr>
<td>Feb</td>
<td>4.8036</td>
</tr>
<tr>
<td>Mar</td>
<td>5.2264</td>
</tr>
<tr>
<td>Apr</td>
<td>4.9879</td>
</tr>
<tr>
<td>May</td>
<td>4.9913</td>
</tr>
<tr>
<td>Jun</td>
<td>5.5970</td>
</tr>
<tr>
<td>Jul</td>
<td>5.6955</td>
</tr>
<tr>
<td>Aug</td>
<td>5.2269</td>
</tr>
<tr>
<td>Sep</td>
<td>4.9620</td>
</tr>
<tr>
<td>Oct</td>
<td>5.0857</td>
</tr>
<tr>
<td>Nov</td>
<td>4.8661</td>
</tr>
<tr>
<td>Yearly</td>
<td>5.1822</td>
</tr>
</tbody>
</table>

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.

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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).

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, while 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.
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 \((\nu_c, \nu_r)\) the power produced by the wind turbine is proportional to the wind speed and it is constant in the interval \((\nu_r, \nu_f)\).

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 and 100m, 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 \(\nu_c\) 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 with values of cut-in and rated wind speeds are 11.5m/s, 3m/s, respectively. Although, the cut-in wind speeds of De Wind D6 model is 2.8m/s. The \(\zeta_f\) 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 Enercon E-82/2000 with the same \(\nu_r\) and \(\nu_c\). 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.

<table>
<thead>
<tr>
<th>Turbine model</th>
<th>( \nu_1 ) m/s</th>
<th>( \nu_2 ) m/s</th>
<th>( \nu_3 ) m/s</th>
<th>( P_t ) kW</th>
<th>Hub height m</th>
<th>( C_f )</th>
<th>( C_e )</th>
<th>( E_{w} ) kW</th>
<th>( E_{p} ) MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonus 2300/82.4</td>
<td>3</td>
<td>15</td>
<td>25</td>
<td>2300</td>
<td>100</td>
<td>0.29</td>
<td>2540.4</td>
<td>657.34</td>
<td>5758.3</td>
</tr>
<tr>
<td>Bonus 600/44</td>
<td>3</td>
<td>13</td>
<td>25</td>
<td>600</td>
<td>80</td>
<td>0.23</td>
<td>2014.8</td>
<td>139.38</td>
<td>1220.97</td>
</tr>
<tr>
<td>De Wind D8</td>
<td>3</td>
<td>13.5</td>
<td>25</td>
<td>2000</td>
<td>80</td>
<td>0.31</td>
<td>2715.6</td>
<td>615</td>
<td>5387.4</td>
</tr>
<tr>
<td>De Wind D6</td>
<td>2.8</td>
<td>12.5</td>
<td>25</td>
<td>1250</td>
<td>70</td>
<td>0.34</td>
<td>2978.4</td>
<td>427.38</td>
<td>3743.81</td>
</tr>
<tr>
<td>De Wind 48</td>
<td>3</td>
<td>11.5</td>
<td>22</td>
<td>600</td>
<td>70</td>
<td>0.47</td>
<td>4117.2</td>
<td>280.8</td>
<td>2459.81</td>
</tr>
<tr>
<td>Enercon E-82/2000</td>
<td>2.5</td>
<td>13</td>
<td>28</td>
<td>2000</td>
<td>98</td>
<td>0.49</td>
<td>4292.4</td>
<td>979.2</td>
<td>8577.79</td>
</tr>
<tr>
<td>Enercon E-58/1000</td>
<td>2.5</td>
<td>12</td>
<td>28</td>
<td>1000</td>
<td>89</td>
<td>0.56</td>
<td>4905.6</td>
<td>560.3</td>
<td>4908.23</td>
</tr>
<tr>
<td>Enercon E-40/600</td>
<td>2.5</td>
<td>12</td>
<td>28</td>
<td>600</td>
<td>65</td>
<td>0.36</td>
<td>3153.6</td>
<td>216.18</td>
<td>1893.74</td>
</tr>
<tr>
<td>Nordex N-70/1500</td>
<td>3</td>
<td>13</td>
<td>25</td>
<td>1500</td>
<td>70</td>
<td>0.29</td>
<td>2540.4</td>
<td>437.7</td>
<td>3834.25</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>200 kW</td>
</tr>
<tr>
<td>Diameter (m)</td>
<td>82</td>
</tr>
<tr>
<td>Gearbox ratio</td>
<td>100</td>
</tr>
<tr>
<td>Friction coefficient : ( j )</td>
<td>0.0024</td>
</tr>
<tr>
<td>Moment of inertia : ( J ) (Kg.m²)</td>
<td>90</td>
</tr>
<tr>
<td>Stator voltage/Frequency (V/Hz)</td>
<td>690/50</td>
</tr>
<tr>
<td>( \pi ) / ( \pi ) ( T ) (s)</td>
<td>0.001/0.0013</td>
</tr>
<tr>
<td>( L_m / L_j ) ( S / L_j ) ( T ) (H)</td>
<td>0.003/0.0007/0.0008</td>
</tr>
<tr>
<td>Number of pole pairs: ( p )</td>
<td>2</td>
</tr>
<tr>
<td>( M )</td>
<td>1</td>
</tr>
</tbody>
</table>

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]: 

\[
T_{\text{em}}^* = \frac{c_{\text{popt}}}{2f_{\text{p}}} \frac{1}{\Omega_{\text{mec}}} \Omega_{\text{mec}}^2 \tag{31}
\]

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

\[
\begin{align*}
P_s &= -\frac{V_s M}{L_s^2} i_{rq} \\
Q_s &= \frac{V_s^2}{L_s} - \frac{M V_s}{L_s} i_{rd} \\
P_r &= g \frac{V_s M}{L_s^2} i_{rq} \\
T_{\text{em}} &= -P_r \frac{L_s}{L_s} \varphi_{sd} i_{rq}
\end{align*}
\tag{32}
\]

\[
\begin{align*}
T_{\text{em}} &= -P_r \frac{L_s}{L_s} \varphi_{sd} i_{rq} \\
\end{align*}
\tag{33}
\]

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

\[
\begin{align*}
i_{rd\_\text{ref}} &= \frac{\varphi_{sd}}{V_s} - \frac{L_s}{M} Q_s \tag{34} \\
i_{rq\_\text{ref}} &= -\frac{M}{V_s} T_{\text{em}} \tag{35}
\end{align*}
\]

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 \(e_{t_{r-d}}\) and \(a_{e_{t_{r-d}}}\) are calculated as:

\[
e_{t_{r-d}} = i_{rd\_\text{mes}} - i_{rd\_\text{ref}} \tag{36}
\]

\[
d_e k_{t_{r-d}} = \frac{a_{t_{r-d}} \cdot k_{t_{r-d}}}{{e_{t_{r-d}}} + a_{t_{r-d}} \cdot k_{t_{r-d}}} \tag{37}
\]

Besides, the AFG-PI outputs are \(K_{d} i_{rd\_\text{ref}}\) and \(K_{q} i_{rq\_\text{ref}}\), with \(T\) is the period of sampling. Otherwise, the normalization PI parameters \((K_{d}, K_{i})\) are given by:

\[
K_{d} = \left( K_{d_{\text{max}}} - K_{d_{\text{min}}} \right) K_{d} + K_{d_{\text{min}}} \tag{38}
\]

\[
K_{i} = \left( K_{i_{\text{max}}} - K_{i_{\text{min}}} \right) K_{i} + K_{i_{\text{min}}} \tag{39}
\]

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.
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 $r_p$, stator, rotor and mutual self inductances has been changed respectively as: (+45%) for $r_p$ 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.
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/m² and 230.56W/m² at 12m in 2014 while the annual mean power density for fifteen years (2000 to 2014) varies between 99.6424W/m² and 102.8379 W/m².
- The monthly mean wind energy density varies between 63 KWh/m² and 166 KWh/m² at 12m in 2014 while the annual mean wind energy density for fifteen years (2000 to 2014) varies between 51.138 KWh/m² and 888.52 KWh/m².
- For an investment in wind power to be cost effective, wind turbine models with a

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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 insensitive 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


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