Energy Estimation on Large-Scale Time of Stand-Alone Wind Turbine

Habib Cherif

University of Tunis, DGE-ESSTT
University of Tunis El Manar, LSE-ENIT
Tunis, Tunisia
cherif.habib@ieee.org

Jamel Belhadj

University of Tunis, DGE-ESSTT
University of Tunis El Manar, LSE-ENIT
Tunis, Tunisia
Jamel.Belhadj@esstt.rnu.tn

Abstract -- In this paper, accurate energy production estimation of stand-alone wind turbine in southern Tunisia has been studied. Energy estimation by Weibull distribution and meteorological data is applied. The design of the wind turbine system architecture according to all the characteristics of the studied site was presented. Monthly average wind energy production is estimated with the integration of converters losses. Loss models of boost and rectifier converters are investigated. The obtained results show that the integration of converters losses and using the statistical distributions leads to a better energy estimation taking into account all the characteristics of the southern Tunisia site.

Index Terms--Turbine, Wind energy estimation, Weibull distribution, Converters losses.

I. INTRODUCTION

TODAY there are many wind farms that produce electricity, but decrease in the cost of wind energy can be achieved by reducing the relative investment cost, introducing reliability design methods, and exploiting the best available wind sites [1]-[3]. In order to obtain reliable and economical electricity from wind turbine, it is important to estimate the wind energy potential.

In this context, we focus on a large-scale time evaluation for energy estimation of stand-alone wind turbine in southern Tunisia (Djerba). We design the wind turbine architecture according to all the characteristics of the site [4]. The evaluation for energy production estimation is developed with Weibull distribution model and all converters losses integration [5], [6]. The extraction of the electrical energy from the wind turbine is based on a Maximum Power Point Tracking (MPPT) algorithm. Wind energy output estimation can be used for supply many applications as water pumping, desalination lighting and communications in rural or urban areas [7]-[9].

II. WIND ENERGY CONVERSION SYSTEM

The studied system is composed of 10kW wind turbine interconnected to a DC bus through (AC/DC) converter and (DC/DC) converter. The three-phase output of the Permanent Magnet Synchronous Generator (PMSG) are rectified with a diode bridge rectifier and controlled by a (DC/DC) boost converter. Fig. 1 shows the scheme of the stand-alone wind turbine architecture with a 600 DC bus voltage [10].

The studied system is located in Djerba Island (South Tunisia). The latter region is situated in Northern hemisphere at $33^{\circ}9'$ North latitude and $10^{\circ}8'$ East longitude. The monthly average metrological data are summarized in Table 1.

TABLE I
MEASURED METEOROLOGICAL DATA

Month	Air Temperature (°C)	Wind speed (m/s)
January	12.9	7.9
February	13.4	8
March	15.7	8.3
April	18.0	8.4
May	21.6	8.4
June	25.1	8.4
July	27.6	7.8
August	28.6	7.6
September	26.9	7.9
October	23.3	7.6
November	18.5	7.8
December	14.3	8.4
Annual Average	20.5	8

Fig. 1. Stand-alone wind turbine architecture without battery storage.

III. WIND ENERGY OUTPUT ESTIMATION MODEL

A. Wind Turbine Power

The wind turbine power is given by

$$P_w = 0.5 \cdot \rho \cdot S \cdot V^3 \quad (1)$$

where V is the average wind speed (m/s), ρ is the air

This work was supported by the Tunisian Ministry of High Education and Research under Grant LSE-ENIT – LR 11ES15.

density (kg/m^3) and S is the swept area (m^2).

The wind turbine power per surface is given by

$$P_{w/S} = 0.5 \cdot \rho \cdot V^3 \quad (2)$$

Using the monthly average wind speed, we show in Fig. 2, the wind power per surface.

The electrical output power of the wind turbine is given by

$$P_e = 0.5 \cdot \rho \cdot S \cdot V^3 \cdot C_P \cdot \eta \quad (3)$$

where C_P is the power coefficient, η is the generator efficiency (%).

The wind speed in Djerba Island is weak, so for a case study we choose a 10 kW rated power wind turbine, characterized by a starting speed of 3.4 m/s and a rated speed of 13 m/s. The wind turbine characteristics are given in Table 2. Fig. 3 shows the open loop electric wind power curve and Fig. 4 shows the electrical output power produced versus months at hub height. It appears clearly that the electrical output power production is about 2.44 kW and a maximal production of 2.8 kW with wind speed of 8.4 m/s.

Fig. 2. Theoretical wind power per surface.

TABLE II
WIND TURBINE CHARACTERISTICS

Rotor diameter (D)	7 m
Swept area (S)	38.48 m^2
Hub height (z_{hub})	18.3 m
Power coefficient ($C_{p,max}$)	0.25
Generator efficiency (η)	80 %

Fig. 3. Power curve of the wind turbine (Bergey BWC Exe).

Fig. 4. Theoretical Produced electrical power by the selected wind turbine.

B. Weibull Distribution

Different wind speed distribution models, including the Weibull, the Rayleigh, the Rice and the Lognormal were applied to characterize the wind speed probability distribution at a particular location [11]. The produced energy by the selected wind turbine is calculated according to the wind speed distribution. However, the most commonly model used is the Weibull distribution [9]. For estimating the two parameters of the Weibull distribution, we use the least squares method (linear regression model).

The probability density function is given by

$$f(v) = \frac{k}{c} \left(\frac{v}{c} \right)^{k-1} \exp \left\{ - \left(\frac{v}{c} \right)^k \right\} \quad (4)$$

where v is the wind speed, k is the shape factor and c is the scale parameter.

Equation (5) relates the two parameters of the Weibull distribution and the average wind speed.

$$\bar{v} = c \cdot \Gamma \left(\frac{1}{k} + 1 \right) \quad (5)$$

where Γ is the gamma function.

The observed occurrence frequencies f_i are given in Fig. 5 and the cumulated frequencies F_i of Weibull distribution are given by

$$F_i = F_{i-1} + f_i \quad (6)$$

The cumulative distribution function is defined as

$$F(v) = 1 - \exp \left[- \left(\frac{v}{c} \right)^k \right] \quad (7)$$

The cumulative distribution function can be given as follows

$$\ln[-\ln(1-F_i)] = k[\ln(v_i) - \ln(c)] \quad (8)$$

with the following substitution:

$$\begin{cases} X_i = \ln(v_i) \\ Y_i = \ln[-\ln(1-F_i)] \end{cases} \quad (9)$$

The goal is to find the straight line equation:

$$Y_i = A + BX_i \quad (10)$$

with

$$B=k \text{ and } A=-k \ln(c)=-B \ln(c)$$

which gives

$$A = \frac{\sum Y_i \sum X_i^2 - \sum X_i \sum X_i Y_i}{D} \quad (11)$$

$$B = \frac{n \sum X_i Y_i - \sum X_i \sum Y_i}{D} \quad (12)$$

$$D = n \sum X_i^2 - (\sum X_i)^2 \quad (13)$$

with n is the interval number of wind speed.

The scale and shape parameters of the Weibull distribution relating to southern Tunisia are

$$\begin{cases} k = B \\ c = \exp\left(-\frac{A}{B}\right) \end{cases} \quad (14)$$

So, the estimated parameters of the Weibull distribution according to our data are $k=2.20$ and $c=8.70$.

The cumulative frequencies of wind speed are given in Fig. 6 and Fig. 7 shows the applied simple linear regression model. Fig. 8 shows the probability density curve of the Weibull distribution superimposed with the observed occurrence frequencies of the studied site. To characterize the wind energy availability of the selected site, we present in Fig. 9, using the Weibull distribution and Fig. 2, the annual wind energy output per surface from the selected wind turbine. The estimated monthly average electricity of wind turbine according to the wind speed distribution is given in Fig. 10. We note here that the estimated electrical energy is important for all months of the year. It's shown that the estimated electrical wind turbine energy by Weibull distribution model is given with accuracy. Furthermore, Fig. 11 shows the day to day electrical wind energy production for January of the selected site. We note here that the daily electrical energy production value varies between 0.2 kWh and 95 kWh and this result allows us to quantify the produced wind energy rate to southern Tunisia.

Fig. 7. Simple linear regression.

Fig. 8. Weibull distribution and observed probability.

Fig. 5. Wind frequency

Fig. 6. Cumulative frequencies.

Fig. 9. Estimated wind energy per surface of the studied site.

Fig. 10. Monthly average estimated energy from the wind turbine.

Fig. 11. Daily electrical wind energy production_January.

IV. CONVERTERS LOSSES MODELS

For estimated electricity at the DC bus, it is necessary to introduce the converters losses [12], [13]. We adopted a small wind turbine coupled to a PMSG, the variable voltage of the generator is first converted to DC using a diode bridge rectifier and a boost converter is used to match the variable DC voltage with the DC bus and to track maximum power available from the wind turbine energy. The electric wind power supplied to the load without battery storage is imposed by the wind source. Fig. 12 shows the scheme of the wind turbine architecture.

A. Bridge Diode Rectifier Losses

The average conduction power loss diode is defined as

$$P_{rec_cond} = 6(V_{d0} + r_d \cdot I_{dc}) \cdot I_{dc} \quad (15)$$

where I_{dc} is the average rectifier current and V_{dc} is the average rectifier voltage, are given as

$$I_{dc} = \frac{\pi}{\sqrt{6}} \cdot I \quad (16)$$

$$V_{dc} = \frac{3\sqrt{6}}{\pi} \cdot V \quad (17)$$

where V and I are the RMS values of the PMSG output voltage and current, respectively.

Using the typical diode voltage/current graph, the diode voltage drops is approximated by

$$U_d = V_{d0} + r_d \cdot I_{dc} \quad (18)$$

where V_{d0} is the threshold voltage and r_d is the dynamic resistance of diode. The diode conduction losses data are given in Table 3.

B. Boost Converter Losses

a) *Switching losses*: Switching loss includes IGBT (T) turn-on loss and turn off loss [14]-[16]. The total IGBT turn-on loss can be defined as

$$W_{on} = \frac{U_T^{ref} \cdot (I_{on} + I_{rr}) \cdot (t_{r_i} + t_{rr})}{2} \quad (19)$$

where I_{on} is the turn-on current, I_{rr} is the peak reverse recovery current of the diode (free-wheeling diode), t_{r_i} is the current increase time, t_{rr} is the reverse recovery time of the diode, U_T^{ref} is the IGBT voltage reference.

The total IGBT turn-off loss can be calculated by

$$W_{off} = \frac{U_T^{ref} \cdot I_{off} \cdot t_{f_i}}{2} \quad (20)$$

where I_{off} is the turn-off current and t_{f_i} is the turn-off time. t_{r_i} , t_{rr} and t_{f_i} parameters are depend on the properties of the IGBT giving by manufacturer's data sheet.

Fig. 12. Wind turbine architecture with diode bridge rectifier and (DC/DC) boost converter.

TABLE III
DIODE CONDUCTION LOSSES DATA

Parameters	Values
V_{d0}	0.8 V
r_d	20 m Ω
I_{dc}	23.68 A
V_{dc}	421.81 V
I	18.48 A
V	180.31 V
P_{rec_cond}	181 W

The average total IGBT switching losses (on+off) are given by

$$P_{IGBT_sw} = (W_{on} + W_{off}) \cdot f_s \quad (21)$$

where f_s is the switching frequency. The IGBT switching loss data is summarized in Table 4.

b) *Conduction losses:* Using the typical IGBT voltage-current graph, the IGBT voltage drops is given by

$$V_{CE} = U_{CE(sat)} + R_d \cdot I_c \quad (22)$$

where $U_{CE(sat)}$ is the threshold voltage and R_d is the dynamic resistance of the IGBT.

Using the typical diode voltage/current graph, the diode voltage drops is approximated by

$$V_F = U_{d0} + R_{d0} \cdot I_0 \quad (23)$$

where U_{d0} is the threshold voltage and R_{d0} is the dynamic resistance of diode. $U_{CE(sat)}$, R_d , U_{d0} and R_{d0} can be determined by static characteristics of the IGBT and diode available from manufacturer's data sheets.

The average conduction power loss of the IGBT and diode can be expressed respectively as

$$P_{IGBT_cond} = V_{CE} \cdot I_c \cdot d \quad (24)$$

$$P_{diode_cond} = V_F \cdot I_0 \cdot (1-d) \quad (25)$$

where d is the duty cycle. The IGBT and diode conduction losses calculation are given in Table 5.

The estimated total power loss of the converters (AC/DC and DC/DC) of the proposed wind turbine is 227 W. We present in Fig. 13, the estimated electrical energy in the fixed DC bus with and without converters losses. In the DC-bus, the estimated energy is decreased by nearly 10 % compared to estimated energy without converters losses. It's shown that the loss models of the boost converter and the rectifier are interesting for accurate energy estimation of the proposed wind turbine. The Weibull distribution showed an excellent fit for energy estimation.

TABLE IV
IGBT SWITCHING LOSSES (ON+OFF) DATA

Parameters	Values
U_T^{ref}	421.81 V
I_{on}	16.6 A
t_{r_i}	$1.14 \cdot 10^{-7}$ s
t_{rr}	$120 \cdot 10^{-9}$ s
I_{off}	16.6 A
t_{f_i}	$1.63 \cdot 10^{-7}$ s
f_s	10 kHz
W_{on}	$11 \cdot 10^{-4}$ J
W_{off}	$5.71 \cdot 10^{-4}$ J
P_{IGBT_sw}	17 W

TABLE V
IGBT AND DIODE CONDUCTION LOSSES DATA

Parameters	Values
$U_{CE(sat)}$	2.3 V
R_d	17.5 m Ω
U_{d0}	1.1 V
R_{d0}	15 m Ω
I_o	16.6 A
I_c	16.6 A
P_{IGBT_cond}	13 W
P_{diode_cond}	15.7 W

Fig. 13. Monthly average estimated energy in the DC-bus with and without converters losses.

V. CONCLUSION

In this paper the authors have used the Weibull distribution model to estimate on large-scale time the wind energy production in southern Tunisia. Geographic and climatic conditions about southern Tunisia were used. An accurate monthly wind energy estimation taking into account all the characteristics of the location was presented. The evaluation for wind energy production estimation has been investigated with integration of converters losses. The

obtained results show that the integration of converters losses and using Weibull distribution leads to a better energy estimation of the stand-alone wind turbine. It has been shown that the converters losses models and the Weibull distribution are interesting for accurate wind energy estimation. The wind power prediction is very important for load dispatch and to know how much power can be extracted to supplement the power demand. A techno-economic study can be presented in this paper. The wind turbine can be used in conjunction with other electrical power sources as photovoltaic station. In southern Tunisia, wind turbine energy can increase the electricity demand as hotels while respecting the HEQ standards.

VI. REFERENCES

- [1] E. Koutroulis and K. Kalaitzakis, "Design of a maximum power tracking system for wind-energy-conversion applications," *IEEE Trans Industrial Electronics*, vol. 53, pp. 486–494, April 2006.
- [2] A. Mirecki, X. Roboam and F. Richardeau, "Comparative study of maximum power strategy in wind turbines," *IEEE International Symposium on Industrial Electronics*, vol. 2, pp. 895–900, 2004.
- [3] C. Boccaletti, P. Di Felice and E. Santini, "Designing wind plants for extreme ambient conditions," *IEEE International Conference on Electrical Machines (ICEM)*, pp. 1–6, Sep 2010.
- [4] B.S. Borowy and Z.M. Salameh, "Dynamic response of a stand-alone wind energy conversion system with battery energy storage to a wind gust," *IEEE Trans Energy Conversion*, vol. 12, pp. 73–78, Mars 1997.
- [5] I.Y.F. Lun and J.C. Lam, "A study of Weibull parameters using long-term wind observations," *Renewable Energy*, vol. 20, pp. 145–153, June 2000.
- [6] T.P. Chang, "Performance comparison of six numerical methods in estimating Weibull parameters for wind energy application," *Applied Energy*, vol. 88, pp. 272–282, January 2011.
- [7] M. Forstmeier, F. Mannerheim, F. D'Amato, M. Shah, Y. Liu, M. Baldea and A. Stella, "Feasibility study on wind-powered desalination," *Desalination*, vol. 203, pp. 463–470, February 2007.
- [8] S. Mathew and K. P. Pandey, "Modelling the integrated output of wind-driven roto-dynamic pumps," *Renewable Energy*, vol. 28, pp. 1143–1155, June 2003.
- [9] M.S. Miranda and D. Infield, "A wind powered seawater reverse osmosis system without batteries," *Desalination*, vol. 153, pp. 9–16, February 2003.
- [10] H. Cherif and J. Belhadj, "Large-scale time evaluation for energy estimation of stand-alone hybrid photovoltaic-wind system feeding a reverse osmosis desalination unit," *Energy*, vol. 36, pp. 6058–6067, October 2011.
- [11] A.N. Celik, "Energy output estimation for small-scale wind power generators using Weibull-representative wind data," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 91, pp. 693–707, April 2003.
- [12] A. Mirecki, X. Roboam and F. Richardeau, "Architecture complexity and energy efficiency of small wind turbines," *IEEE Trans Industrial Electronics*, vol. 54, pp. 660–670, February 2007.
- [13] H. Cherif and J. Belhadj, "Methodology for accurate energy production estimation of photovoltaic power generation station," *IEEE International Mediterranean Electrotechnical Conference*, pp. 561–566, March 2012.
- [14] M. Dali, J. Belhadj and X. Roboam, "Control and energy management of a wind-photovoltaic hybrid system," *12th European Conference on Power Electronics and Applications – EPE 2007*, 2–5 September 2007, Aalborg, Denmark.
- [15] G. Graditi, D. Colonnese, and N. Femia, "Efficiency and reliability comparison of DC-DC converters for single phase grid connected photovoltaic inverters," *IEEE International Symposium on Power Electronics Electrical Drives Automation and Motion*, pp. 140–147, Aout 2010.
- [16] A. Stabile, A.J.M. Cardoso, C. Boccaletti, "Efficiency Analysis of Power Converters for Urban Wind Turbine Applications," *IEEE International Conference on Sustainable Energy Technologies (ICSET)*, pp. 1–6, Dec 2010.