Revue des Energies Renouvelables Vol. 12 N°2 (2009) 307 – 319
DOI: https://doi.org/10.54966/jreen.v12i2.141

Power maximization control of small wind system using permanent magnet synchronous generator

Soltane Belakehal*, Houcine Benalla and Amar Bentounsi

Laboratory of Electrotechnics of Constantine,
Faculty of Engineer Sciences, Mentouri-Constantine University
Ain El-Bey Road, 25000 Constantine, Algeria

(reçu le 10 Mars 2009 – accepté le 21 Juin 2009)

Abstract - *This article describes modeling and simulations to determine a method for the power performance evaluation of autonomous wind turbine system with this simple load scheme. The method applies to small systems equipped with a permanent magnet generator in the wind turbine a diode rectifier, boost converter and batteries. In this work, the aerodynamic characteristics of wind turbines and the power conversion system topology are explained. The maximum power tracking of the wind turbine generator system using the Matlab software is presented and its results show, at least in principle, that the maximum power tracking algorithm developed is suitable for wind turbine generation systems.*

Résumé - *Cet article décrit une méthode d'évaluation de la performance de la puissance d'une éolienne autonome avec son système de charge. La méthode s'applique à de petits systèmes équipés d'un générateur à aimant permanent couplé à une éolienne, suivi d'un redresseur et d'une batterie. Pour extraire la puissance maximale de cette chaîne de conversion, un algorithme est développé sous Matlab. Les résultats obtenus par simulation montrent que le rendement du système est très encourageant.*

Key words: Wind Turbine - Permanent Magnet Generator - MPPT - Diode Rectifier - DC/DC Converter.

1. INTRODUCTION

In recent years, the electrical power generation from renewable energy sources, such as wind, is increasingly attraction interest because of environmental problem and shortage of traditional energy source in the near future [1].

The wind power mainly depends on geographic and weather conditions and varies from time-to-time. Therefore it is necessary to construct a system that can generate maximum power for all operating conditions.

Recently, permanent magnet synchronous generator (PMSG) is used for wind power generating system because of its advantages such as better reliability, lower maintenance, and more efficient etc [1, 2].

The generator is actually dedicated to a vertical axis wind turbine. Using a diode rectifier simplifies the structure and reduces system cost (no position sensor and low-cost converter without control). An optimal energetic behavior is obtained if the excitation field of the synchronous generator can be tuned [2, 3].

Power electronics have an important role for controlling electrical characteristics of wind turbines. For the simulation wind turbine generator (SWTG) in battery charging

* bel_soltane@yahoo.fr , benalladz@yahoo.fr , amar_bentounsi@yahoo.fr

applications. DC-DC converters have been used for modifying the electrical load in order to maximize energy generation, on its various topologies: buck, boost and buck-boost, [4]. Input of the DC-DC converter is connected to bridge rectifier and a bulky capacitor (DC bus), and output is connected to the batteries, as illustrated in figure 1.

This scheme with a proper control algorithm to modify duty-cycle of DC-DC converter for maximum energy generation is known as Maximum Power Point Tracking (MPPT). The converter is used to change the apparent DC bus voltage seen by the generator. Thus by controlling the DC converter the terminal voltage of the PMSG is adjustable in order to maximize power production.

For maximum power transfer in all wind speeds, the converter must be able to reduce PMSG terminal voltage in low wind speeds, and increase in high wind speeds [5, 6]. Thus, the recommended converter for this type of application must have boost voltage characteristics.

This study presents the wind turbine converts the power in the wind to mechanical power in the rotor shaft; the mechanical power in the shaft is then converted to electricity using a permanent magnet synchronous generator (PMSG). The voltage generated by the permanent magnet machine is rectified using a three-phase passive rectifier, which converts the AC voltage generated by the PMSG to a DC voltage.

The main circuit composition of generators and boost chopper, etc. was replaced in the equivalent circuit in order to theoretically analyze this wind generator system. Characteristics such as generated output power and DC output voltage were expressed in functions of duty ratio of the boost chopper and the generator rotational speed.

The electric power generated from the generator has characteristics by the condition of the load with the peak point. Therefore, the optimum duty ratio for obtaining the maximum power was theoretically deduced by differentiating the equation of the generated output power by duty ratio of the boost chopper [7].

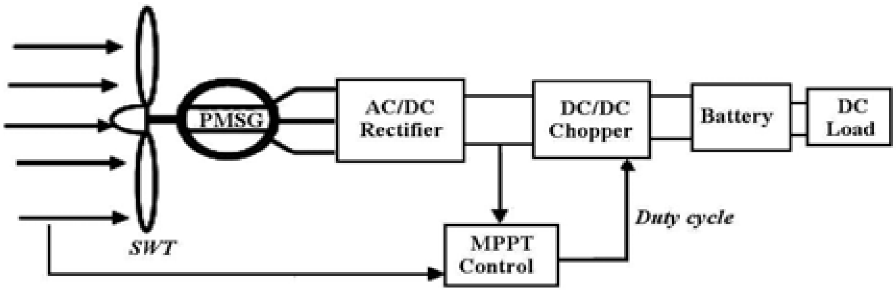

Fig. 1: Schematic diagram of control system of a permanent magnet generator directly driven by wind turbine

2. MODELING OF THE SYSTEM

2.1 Wind turbine model

The current as a function of wind speed V_v can be calculated from the equation of the wind turbine power [8]:

$$P_T = \frac{1}{2} C_p(\lambda) \times S \times \rho \times V_v^3 \tag{1}$$

where

ρ is the density of the air [kg/m^3] and S is the area [m^2] swept by the turbine.

For a VAWT, the turbine size can be included to calculate the power, i.e. $S = 2R \times H$.

C_p is the power coefficient defining the aerodynamic efficiency of the wind turbine rotor, and is a function of the tip speed ratio λ. The tip speed is defined as the ratio between the peripheral speed of the blades and the wind speed:

$$\lambda = \frac{\Omega \times R}{V_v} \tag{2}$$

where Ω is the rotational speed of the blades (the rotational speed of the low-speed shaft) and R is the blade length.

The typical performance curve for a Vertical axis wind turbine is given in figure 2.

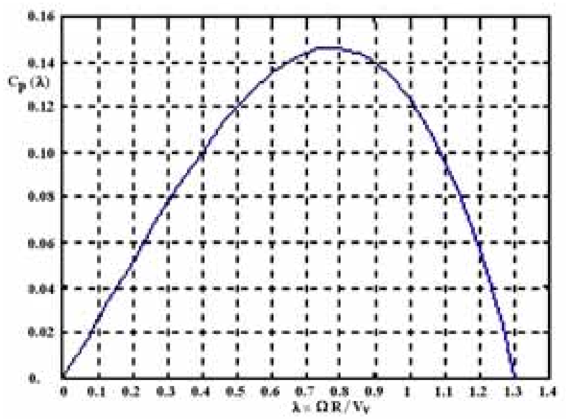

Fig. 2: Power coefficient versus tip speed

It presents a maximum for a well-determined tip speed, denoted by λ_{opt}, the power characteristics for different wind speeds are given in figure 2, for every wind speed they have a maximum. All these maxima determine a so-called '*Optimal Regimes Characteristic*' (ORC), as shown in figure 3. In order to maximize the power extracted from the wind, the tip speed ratio should be kept around its optimal.

The wind turbine torque on the shaft can be calculated from the power

$$T_T = \frac{P_T}{\Omega} = \frac{C_p(\lambda) \times \rho \times R^2 \times H \times V_v^2}{\lambda} \tag{3}$$

The shaft rotational speed optimal control solution using a set point from the wind speed information can be applied if the optimal value of the tip speed ratio, λ_{opt}, is known. The turbine operates on the ORC if $\lambda = \lambda_{opt}$, which supposes that the shaft rotational speed is closed-loop, controlled such that to reach its optimal value:

$$\Omega_{opt} = \frac{\lambda_{opt}}{R} V_v \tag{4}$$

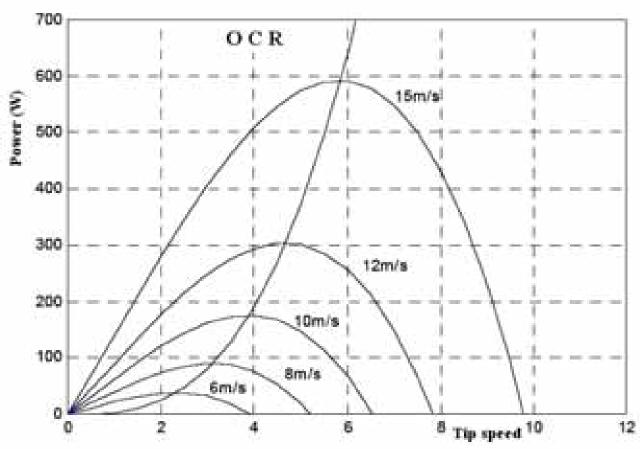

Fig. 3: The optimal regime characteristics

2.2 Permanent magnet synchronous generator model

Since the power for excitation source is not required for the permanent magnet synchronous generator, high efficiency is expected. And, since the electromotive force in proportion to rotational speed is generated, it is possible to take out the generated output in the easiness [9]. The equivalent circuit and a phasor diagram for one phase are represented (Fig. 4).

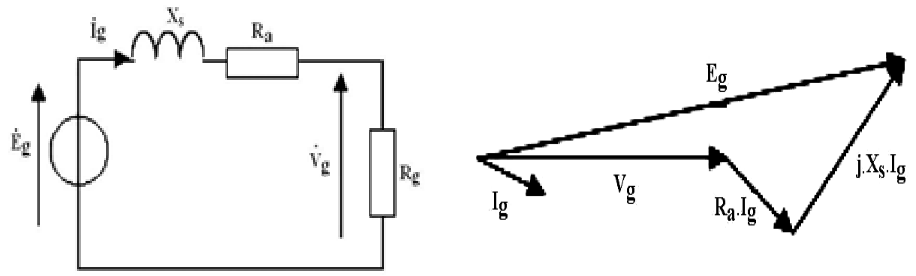

Fig. 4: Equivalent circuit per phase and the phasor diagram for a synchronous generator

When line current of the generator is defined as $\dot{I}_g$ the terminal voltage $\dot{V}_g$ of the generator is

$$\dot{V}_g = \dot{E}_g - jX_s \times \dot{I}_g - R_a \times \dot{I}_g \tag{5}$$

where R_a is the winding resistance per phase and X_s is the synchronous reactance per phase.

From equation (5) we deduce the line current

$$\dot{I}_g = \frac{\dot{E}_g}{\left(R_g + R_a\right) + j.X_s} \tag{6}$$

The amplitude of the line current is expressed as

$$\left|I_g\right| = \frac{\left|E_g\right|}{\sqrt{\left(R_a + R_g\right)^2 + X_s^2}} \tag{7}$$

The generated output power is

$$\begin{aligned} P &= 3\left|I_g\right|\left|V_g\right| \times \cos\varphi = 3\,R_g \times \left|I_g\right|^2 \\ P &= 3\,R_g \times \frac{E_g^2}{\left(R_g + R_a\right)^2 + X_s^2} \end{aligned} \tag{8}$$

2.3 Three-phase diode bridge rectifier

The diode rectifier is the most simple, cheap, and rugged topology used in power electronic applications. The drawback of this diode rectifier is its disability to work in bi-directional power flow. The generator is connected with rectifier circuits like (Fig. 5).

It is assumed that the AC power generated from the generator is converted into DC power through diode bridge rectifier circuits [5, 7, 10].

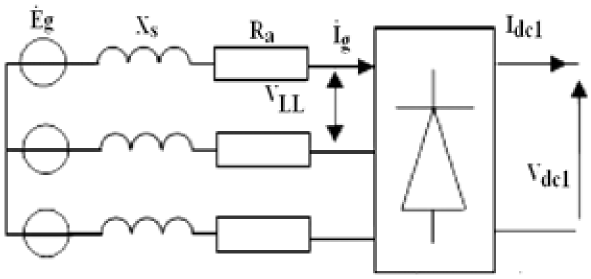

Fig. 5: Connection diode rectifier circuits to the generator

$$I_{dc1} \times V_{dc1} = 3\,V_g \times I_g \tag{9}$$

where, V_{dc1}, I_{dc1} are DC side voltage and DC side current, respectively. Three-phase diode rectifier circuits have the characteristics in which the phase of the largest line to line voltage is conducted.

The resistance value per one phase of rectifier circuits from the viewpoint of A.C. side is defined as R_g, and the maximum value of line-to-line voltage is defined as V_{LL}. The mean value of DC voltage is shown like the following:

$$V_{dc1} = \frac{3}{\pi}\int_{-\pi/6}^{\pi/6} V_{LL} = \frac{3\sqrt{2}}{\pi} V_{LL} \tag{10}$$

From this, the relationship between V_{dc1} and phase voltage V_g is shown as

$$V_{dc1} = \frac{3\sqrt{6}}{\pi} V_g \quad (11)$$

From equations (9) and (11), the relation between I_{dc1} and I_g is

$$I_{dc1} = \frac{\pi}{\sqrt{6}} I_g \quad (12)$$

The DC voltage V_{dc1} is

$$V_{dc1} = \frac{3\sqrt{6}}{\pi} R_g \times I_g \quad (13)$$

From (11) and (13), the following equation is obtained

$$R_g = (\pi^2 / 18) \; R_{dc1} \quad (14)$$

2.4 DC/DC Converters

The DC-to-DC converters are often used in regulated switch-mode dc power supplies and in dc motor drives applications. Frequently, the input to this converter is an unregulated dc voltage which can be obtained by rectifying an ac voltage source.

This unregulated voltage will fluctuate due to changes in the line. In order to control this unregulated dc voltage into a regulated DC output we need to use a DC-to-DC [5, 11].

In this model, the boost converter has been controlled to yield constant output DC voltage level, V_{dc2} by varying the duty ratio, D in response to variations in V_{dc1}.

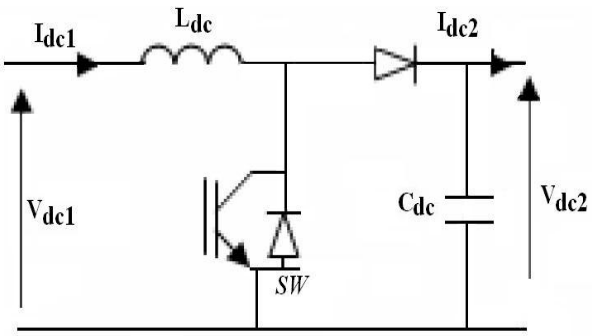

Fig. 6: Boost (DC-DC) converter

The relation between the input and output voltage and currents of the boost converter (Fig. 6) is expressed by the following equations

$$V_{dc2} = \frac{1}{(1-D)} V_{dc1} \quad (15)$$

$$I_{dc2} = (1-D) \, I_{dc1} \quad (16)$$

It is possible that boost chopper circuit and load resistance R_L are considered a kind of variable resistance changed by duty ratio from the viewpoint of the DC voltage source. This variable resistance R_{dc1} is defined as:

$$I_{dc1} = V_{dc1} / R_{dc1} \tag{17}$$

The output current I_{dc2} is expressed by output voltage V_{dc2} and load resistance R_L.

$$I_{dc2} = V_{dc2} / R_L \tag{18}$$

By dividing (15) by (16) we obtain

$$(V_{dc2} / I_{dc2}) = (V_{dc1} / I_{dc1}) / (1 - D)^2 \tag{19}$$

By dividing (17) by (18) we obtain

$$R_{dc1} = (1 - D)^2 \times R_L \tag{20}$$

From equation (19), it was confirmed that the boost chopper from the viewpoint of the DC voltage source could be expressed in the function of the duty ratio.

3. MPPT CONDITION

Two types of tracking algorithms (MPPT) exist, namely: methods based on the knowledge of the $C_p(\lambda)$ characteristic and methods that allow seeking the optimal operation without knowing the turbine characteristics.

Some control strategies are based on the power coefficient curve (C_p), eg. λ control method, which modifies angular speed of wind rotor for maintaining an optimum λ value and consequently a maximum power coefficient (C_p) for all wind speeds.

The wind turbine, when operating at maximum C_p, produces maximum mechanical power on shaft. To the small wind turbine used as reference on this work [12-14], the angular speed (Ω) for maximum mechanical power points do not coincide with angular speed for maximum electrical power points, so this strategy is not recommended.

The wind-turbine power is given by

$$P_T = \frac{1}{2} C_p(\lambda) \times S \times \rho \times V_v^3 \tag{21}$$

$$\lambda = \frac{\Omega \times R}{V_v} \Rightarrow V_v = \frac{\Omega \times R}{\lambda} \tag{22}$$

The maximum power is obtained if

$$C_p(\lambda) = C_p(\lambda_{opt}) = C_p^{max} \tag{23}$$

$$P_{opt}(\Omega) = \frac{C_p^{max} \times \rho \times R^4 \times H}{\lambda_{opt}^3} \times \Omega_{opt}^3 = K_{opt} \times \Omega_{opt}^3 \tag{24}$$

The optimal torque is obtained from the rotation speed value given by

$$T_{opt}(\Omega) = \frac{C_p^{max} \times \rho \times R^4 \times H}{\lambda_{opt}^3} \Omega_{opt}^2 \tag{25}$$

Thus, the following load torque has to be imposed to reach an optimal operation

$$T_{opt}(\Omega) = K_{opt}\, \Omega_{opt}^2 \tag{26}$$

In order to obtain maximum electrical power points, generator characteristics must be considered. To illustrate this fact, mechanical power produced by wind rotor (P_T) and electrical power produced by PMSG (P_g) versus Ω, for various wind speeds, can be determined by:

$$\begin{aligned} P_g &= 3R_g \times \left|I_g\right|^2 \\ &= \frac{\pi^2}{6}(1-D)R_L \frac{(K\Phi\Omega)^2}{\left\{\frac{\pi^2}{18}(1-D)^2 R_L + R_a^2 + X_s^2\right\}} \end{aligned} \tag{27}$$

The maximum power point is pursued. Based on (23), duty ratio D_m which the electric power becomes maximum value is deduced. The following equation is obtained,

$$\frac{dP_g}{dD} = 0 \tag{28}$$

It has the extreme value, when (23) becomes the zero, in the maximum power point is shown in (29), because D is within $0 \le D < 1$.

$$D_m = \frac{\pi\sqrt{R_L}}{\pi\sqrt{R_L} + 3\sqrt{2\sqrt{R_a^2 + X_s^2}}} \tag{29}$$

4. DC VOLTAGE IN MAXIMUM POWER POINT

By substituting D_m deduced in (29), the output voltage V_{dc1} of rectifier circuits and output voltage V_{dc2} of the boost chopper circuit are calculated by the following equation

$$V_{dc1} = \frac{3\sqrt{3}}{\pi} \frac{K\Phi\Omega\sqrt{R_a^2 + X_s^2}}{\sqrt{R_a^2 + X_s^2 + R_a\sqrt{R_a^2 + X_s^2}}} \tag{30}$$

$$V_{dc2} = \sqrt{\frac{3R_L}{2\sqrt{R_a^2 + X_a^2}}} \times \frac{K\Phi\Omega\sqrt{R_a^2 + X_a^2}}{\sqrt{R_a^2 + X_a^2 + R_a\sqrt{R_a^2 + X_a^2}}} \tag{31}$$

5. RESULTS AND DISCUSSION

Figure 7 has a set of characteristics of wind power as a function of the generator speed; the parameter is the wind speed. The blue one represents the optimum power, which corresponds to equation 1.

We note that the maximum power is if we are good at speed. Because the power curves maximum power is above the line of the optimum power for any operating point.

Figure 8 gives the optimal speed of the generator according to the speed of the wind.

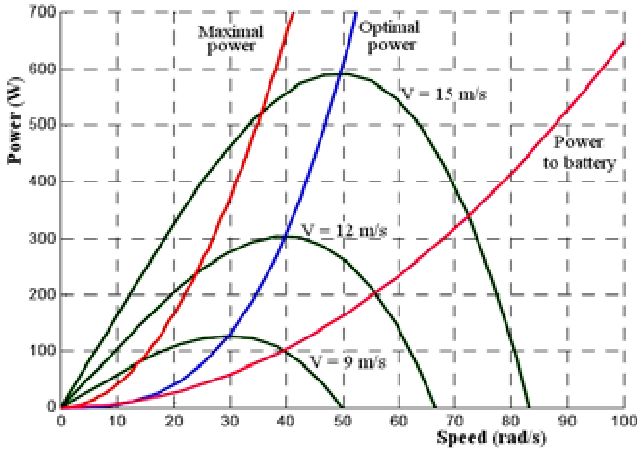

Fig. 7: Characteristics of mechanical power

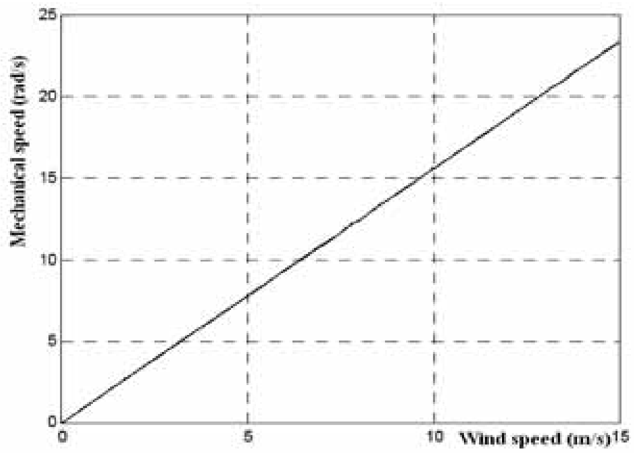

Fig. 8: Mechanical speed versus the wind speed

Figure 9 quantitatively confirms the theoretical development introduced in this paper; V_{dc2} and V_{dc1} evolves linearly with the speed of rotation.

The simulation result for the maximum power tracking algorithm will be show for wind speed profile. The signal represented in figure 10 shows a realistic wind profile, modeled as a non-stationary stochastic process [2] and used as the input to the simulation.

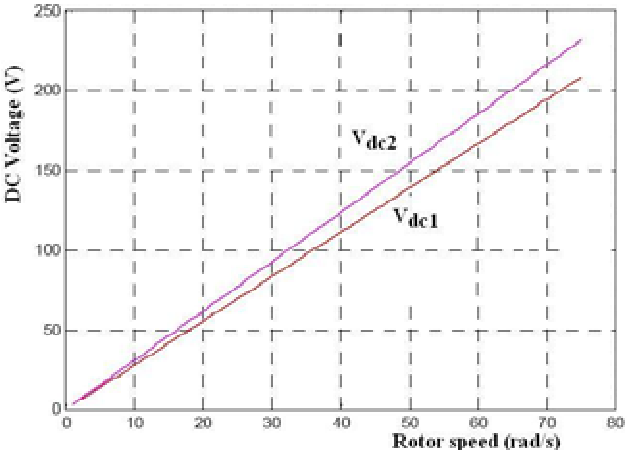

Fig. 9: Characteristics of DC output voltage

The wind profile covers a speed range between 5 – 15 m/s which represents the range between wind turbine starting speed and nominal speed.

This is the speed range that covers most of the wind turbine's operating time.

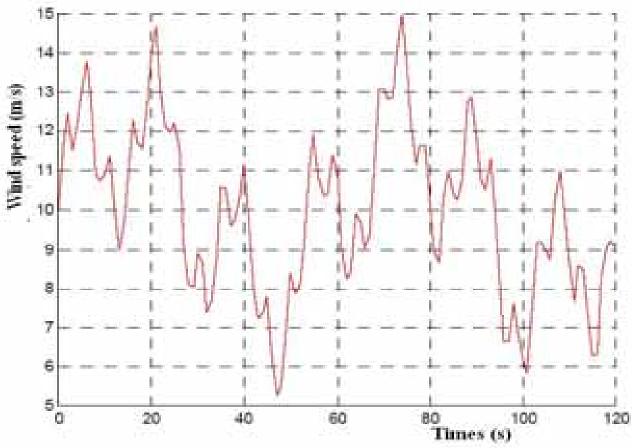

Fig. 10: Wind speed versus time

Figures 11 to 14 show the simulation results for the rotational speed Ω and compare respectively power and torque obtained from the turbine with the maximum value (Xmax) that could be achieved if the optimal conditions are permanently maintained and output voltage of the diode bridge rectifier is V_{dc1} and the output voltage of boost converter is V_{dc2} .

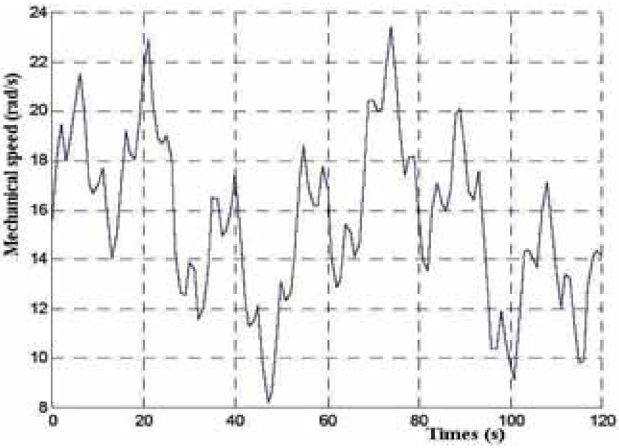

Fig. 11: Mechanical speed versus time

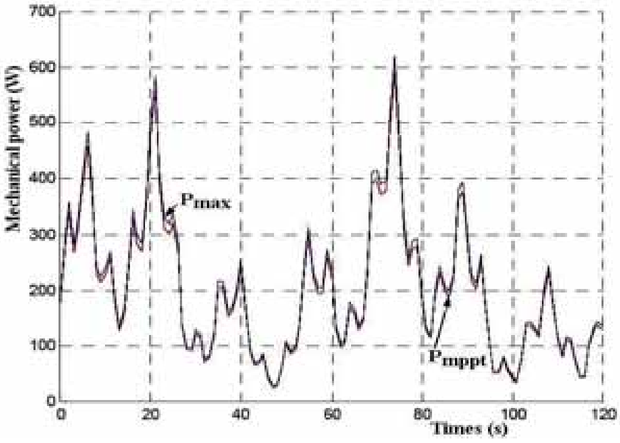

Fig. 12: MPPT and Maximum Mechanical power

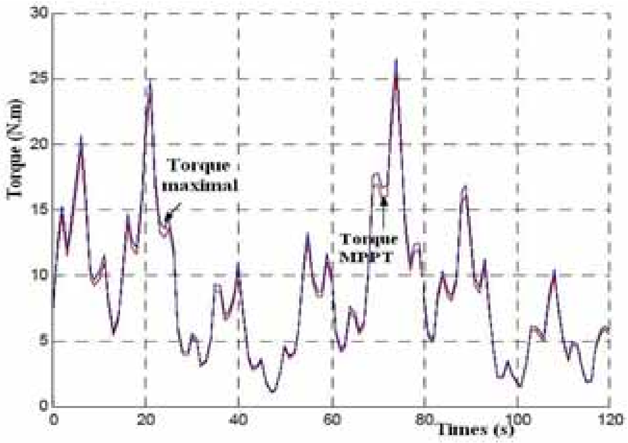

Fig. 13: MPPT and Maximum mechanical torque

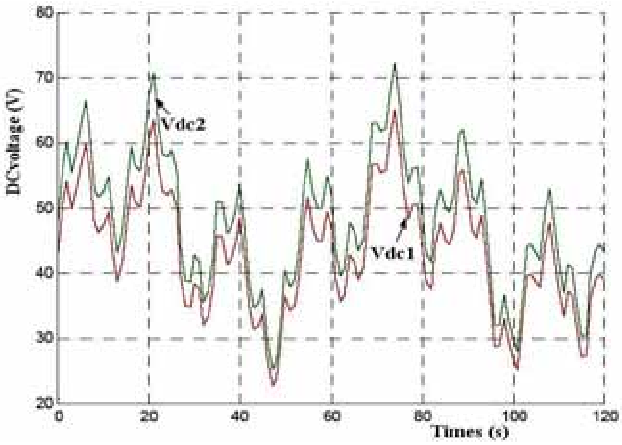

Fig. 14: Characteristics of DC output voltage

6. CONCLUSION

A simple system and control method for small scaled wind power generating system using permanent magnet synchronous generator has been proposed. The above analysis and simulation have shown that the step and search algorithm developed is suitable for wind turbine generation systems.

This algorithm is capable of extracting maximum power from the air stream at any wind speed without the knowledge of wind speed or rotor speed. In conclusion this control strategy and system design can be easily implemented and will be able to improve the efficiency of wind turbine systems.

Parameters of PMSM and turbine [2]

- PM synchronous generator power $P = 600\ \mathrm{W}$
- Number of pole pairs $p = 17$
- Magnet flux $\Phi = 0.15\ \mathrm{mWb}$
- Stator cyclic inductance $L_s = 2.7\ \mathrm{mH}$
- Stator resistance $R_s = 1.14\ \Omega$
- Coefficient de frottement $f = 0.06\ \mathrm{N.m.s/rad}$
- Wind-turbine area $S = 4\ \mathrm{m}^2$
- Wind-turbine optima power coefficients $\lambda_{opt} = 0.78$; $C_{opt} = 0.15$
- Voltage $V_{dc} = 12\ \mathrm{V}$
- Nominal capacity $C_{dc} = 38\ \mathrm{Ah}$

REFERENCES

[1] T. Tanaka, T. Toumiya and T. Suzuki, ‘A *study for adapted control interval of wind power system with resistance load controlled by hill-climbing method* ‘, National convention record 1EE.Japan 1998.

[2] A. Mirecki, 'Etude *Comparative de Chaînes de Conversion d'Energie Dédiées à une Eolienne de Petite* Puissance', Thèse de Doctorat, Université Paul Sabatier, Toulouse, Avril 2005.

[3] A. Abdelli, '*Optimisation Multicritère d'une Chaîne Eolienne Passive*', Thèse de Doctorat, Université Paul Sabatier; Toulouse, Octobre 2007.

[4] de Broe, A.M. Drouilhet, S. Gervorgian, '*A Peak Power Tracker for Small Wind Turbines in Battery Charging Applications*', IEEE Transactions on Energy Conversion, Vol. 14, N°4, 1999.

[5] N. Mohan, T. Undeland, and W. Robbins '*Power Electronics Converters, Application and Design* ', New York: John Wiley & Sons, 2003.

[6] J. Villar Alé, F. Daher Adegas and G. Cirlo da Silva Simioni, '*Maximum Power Point Tracker for Small Wind Turbines Including Harmonic Mitigation*', Wind Energy Conference & Exhibition European 2006.

[7] N. Yamamura, M. Ishida and T. Hori, 'A *Simple Wind Power Generating System with Permanent Magnet Type Synchronous Generator***',** IEEE Power Electronic and Drive Systems, PED'EDS'99, pp. 849 - 854, 1999.

[8] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, '*Wind Energy Handbook*', Ed. John Wiley, New, York 2001.

[9] O. Gergaud, B. Multon and H. Ben Ahmed, '*Modélisation d'une Chaîne de Conversion Eolienne de Petite Puissance*', Electrotechnique du Futur 2001 – Nancy 14-15 Novembre 2001.

[10] E. Muljadi, S. Drouilhet, F. Holz and V. Gevorgian, '*Analysis of Permanent Magnet Generator for Wind Power Battery Charging*', IEEE Industrial Applications, Conf. 1996, Vol. 1, pp. 541 - 548, 1996

[11] A.M. Eltamaly, '*Modeling of Wind Turbine Driving Permanent Magnet Generator with Maximum Power Point Tracking System*', J. King Saud Univ., Vol. 19, Eng. Sci. (2), pp. 223-237, Riyadh (1427H./2007).

[12] A. Mirecki, X. Roboam and F. Richardeau, '*Architecture Complexity and Energy Efficiency of Small Wind Turbines'*, IEEE Transactions on Industrial Electronics, Vol. 54, N°1, pp. 660 – 670, 2007.

[13] H.E.M. Lopez, 'Maximum *Power Tracking Control Scheme for Wind Generator Systems* ', Master of Science, Texas A&M University, December 2007.

[14] M.A. Rodríguez Otero, '*Power Quality Issues and Feasibility Study in a DC Residential Renewable Energy System*', Master Thesis, University of Puerto Rico, Mayaguez Campus, 2008.