Fatima Zohra NAAMA[1,2], Abdallah ZEGAOUI[1], Abdelkader DJAHBAR[1], Michel AILLERIE[2]

[1] Université Hassiba Benbouali de Chlef, Laboratoire Génie Electrique et Energies Renouvelables, LGEER, 02180, Algérie
[2] Université de Lorraine, CentraleSupélec, LMOPS, F-57000 Metz, France

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Simulation and modeling of a small permanent magnet synchronous generator wind turbine directly from its datasheet

***Abstract**. A model of Small Wind Turbines (SWT) based on the general functional equations under Matlab/Simulink and validate by the modeling of a real generator for residential usage is presented. The considered SWT is based on a variable rotational speed system coupled to a PMSG The method presents a huge original interest thanks to its simplicity by considering at first the response to the wind velocity in agreement to the SWT datasheet, without the necessity of a MPPT technique. Simulations are carried out with discussions showing the effectiveness of the approach.*

Streszczenie**. Zaprezentowano model małej turbiny wiatrowej bazujący na równaniach funkcji. Model obliczono w Matlab/Simulink i zweryfikowano w postaci wykonanej turbiny do celów domowych.. Dzięki swej prostocie model potrafi odwzorować różne warunki pracy, przede wszystkim zmienną prędkość wiatru. **Symulacja i modelowanie małego generatora synchronicznego z magnesami trwałymi w zastosowaniu do turbiny wiatrowej.

Keywords: Wind Energy Conversion System, Small Wind Turbine, Permanent Magnet Synchronous Generator, Matlab modeling

Słowa kluczowe: turbina wiatrowa, generator synchroniczny, modelowanie i symulacja.

Introduction

Power energy wind system, or wind energy conversion system (WECS) aims to convert the wind's kinetic of the wind into mechanical energy and then, as it is concerned here, into electrical energy through a generator. Electrical energy providing from wind, then produced by WECS, are considered as the main renewable energy resource that will take place until now and in the future in the global energy. Thus, wind energy is playing and will play a critical role in the establishment of an environmentally sustainable low carbon economy. European wind power industry has formulated generation targets of 180 GW, and 300 GW in 2020 and 2030, respectively [1,2].

Within these general considerations and to achieve these goals, wind turbine are developed at various scales with generators delivering up to several megawatt in the case of turbines that are part of large wind power plants at some MW production levels, down to small ones, delivering some kW and dedicated to residential or for stand-alone electricity production. Indeed, as example, the wind turbine presented in our work belongs to this second category of small wind turbines (SWT) delivering power in the range of 5KW.

The SWTs for residential or stand-alone usages are simple systems usually having fixed pitch allowing reduction of the complexity of the system and then inducing a simplification of the maintenance and its driving monitoring, then a reduction of the initial investment and of the global operating cost during the all SWT life. Moreover, as in many commercial models of SWTs, the shaft supporting the blades is connected with a synchronous generator with permanent magnet, (PMSG), which is characterized by a high torque/size ratio, a low inertia and low inductances, then a high efficiency. Indeed, the efficiency of PMSGs is higher than other generators as synchronous generators in the moderate-size range. These characteristics offer to wind generators high performances and efficiency associated to the possibility of direct control of the functioning point with the wind velocity.

The variable speed operation of SWTs is a key factor to assume a maximum wind power extraction. For this purpose, manufacturers integrate the monitoring or tracking of the power or the torque to achieve the best extraction and then conversion of the wind energy in electrical energy [3]. These control strategies assumed by the integration in the SWT of a maximum power point tracking (MPPT) system allow the optimization of the required motion speed of the rotor of the PMSG as function of the wind velocity [4].

In the current contribution, the model of a commercial wind turbine developed under Matlab/Simulink assumes that the input operation of the wind turbine, i.e. its rotational speed is straightforwardly associated with the variable wind velocity thanks to the SWT datasheet given by the manufacturer.. Nevertheless, the datasheet of commercial WECS never gives technical information concerning the tracker, having for straightforward consequence, the non-possibility to model it. On the other hand, the response of the SWT to the wind velocity is generally given by the manufacturer in the datasheet, indicating the behavior of some of its functional parameters as a function of the wind speed and in particular with the speed range in which the wind turbine operates.

On the strength of this observation, we present in the current contribution a modeling of a SWT by only considering the manufacturer's data, which makes it possible to propose a simple and universal solution for the modeling of these kinds of wind generators. Thus, the associated algorithm calculating the SWT speed as function of the wind velocity from which we can deduce the optimal operation of the wind turbine in all its operating range (wind velocity, rotation speed) allows replacing the complex modeling of the tracker of the maximum power point.

In the current contribution, this model is developed under Matlab/Simulink from the basic equations of wind turbine coupled with a synchronous generators with permanent magnet, thereby forming a wind generator. In order to make this model general, we have independently considered the SWT of its usage, namely in autonomous or stand-alone usage or connected to the distribution grid, with or without storage solution.

Thus, the first part of this contribution will recall the basic equations which were then integrated into the model developed under Matlab / Simulink modules as presented in the following paragraphs. The application to a commercial wind turbine (Anelion SW 3.5 GT) and the associated results obtained on the functional parameters as a function of the wind speed are then presented and discussed.

Power energy wind generator and associated generation system topologies

The main limitation of SWT-PMSG generator is its inability to control the output voltage under varying loads and wind velocities at a fixed level requested by the consumer in case of stand-alone system or by the grid in case of grid connected turbine. To regulate the output voltage, a dynamic reactive power support appears to be a solution.

Additionally, energy storage devices, as electrochemical batteries, fuel cells, super-capacitors and/or electrolyzers, are required and generally associated to the turbine to meet the power demand in the condition of low wind velocity. In the current contribution, we focus on the modeling of the SWT-PMSG system considered with its rectifier as a part of the whole generator system. For that, the modeling procedure will consider an output power supply constituted by a simple resistive load. This choice allows the treatment of the specific generation part independently of the choices done in the regulation and electrical [5] interfaces for the adaptation of the output voltage and output electrical power to a stand-alone or grid-connected system [6]. The block diagram of the whole wind generator with its various configurations of energy outputs is presented in Fig. 1 with parts in bold corresponding to the current development

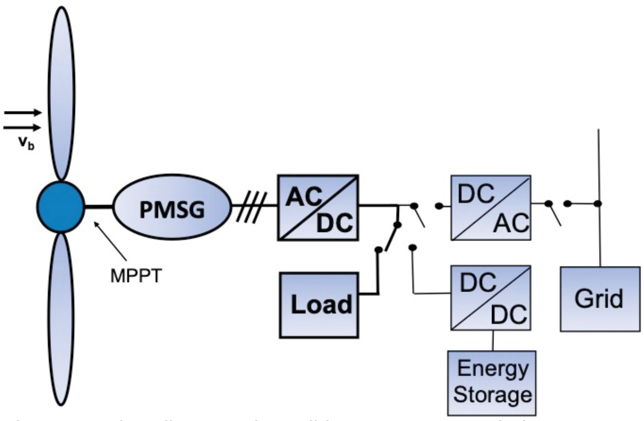

Fig.1. Overview diagram of possible power energy wind generator topologies.

Wind power basics

The input parameter of the overall wind generator is the wind velocity (m/s) in the front of the turbine, v_b. The power available from the wind, P_{wind} is proportional to the cubic wind velocity and to the area swept by the blades of a wind turbine [7, 8]:

$$P_{wind} = \frac{1}{2}\pi R^2 \rho v_b^3 \quad (1)$$

with R the turbine rotor radius (m) and ρ the air density (Kg/m^3), The mechanical power extracted by the wind turbine from the wind is expressed as:

$$P_{extract} = \frac{1}{2}\pi R^2 \rho \left(\frac{v_a + v_b}{2}\right)\left(v_b^2 - v_a^2\right) \quad (2)$$

with v_a the wind velocity (m/s) behind the turbine. Based on the Betz's theory C_p is the power coefficient defined as the ratio between the extracted power on the power available from the wind flowing into the turbine blades at specific wind velocity, i.e.

$$C_p = \frac{P_{extract}}{P_{wind}} \quad (3)$$

The maximum value of C_p, first calculated by Betz from fundamentals laws of fluid mechanics, currently known as the Betz limit is equal to $16/27 \approx 59.3$. In fact, C_p in the wind velocity range available for the turbine is not constant and strongly depends on turbine rotor blade pitch angle, noted b and on the tip-speed ratio, noted λ defined as the ratio between the speed of the tips of the turbine blades by the wind velocity, i.e. [9]:

$$\lambda = \frac{R\omega_m}{v_b} \quad (4)$$

ω_m being the rotor mechanical speed (rad/sec).

As above mentioned in introduction, small wind turbines are simple systems usually having fixed pitch. This is the case of the wind turbine used as reference in the current study. This wind turbine (Anelion SW 3.5 GT) possesses a nominal power equal to 3.5 kW. At a wind velocity of 3 m/s, the wind turbine starts its work until a stopped wind velocity of 17 m/s, thanks to an active electronic braking system and redundant passive electrical / mechanical safety system.

The rotor diameter of the wind turbine is 3.5m corresponding to an active surface of the rotor amounts to 9.62 m^2. The wind turbine is fitted with 3 rotor blades. The maximum speed of the rotor is 465 U/min. Its maximum delivered power is 5kW and the maximum value of Cp is equal to 0.37.

The values of the parameters and characteristics of the PMSG-SWT considered in the simulation are those given by the manufacturer (Anelion) in the datasheet. All functional parameters are given in Table 1.

Table 1. SWT-PMSG simulation model parameters

Parameter	value
Rated Power	5 KW
Moment of inertia	1kg m^2
d-Axis inductance	0.029 mH
q-Axis inductance	0.029 mH
Damping constant	0.024 kg m^2/s
Rated speed	100 rpm - 465 rpm
Number of poles pairs	10
PM flux linkage	0.40 Wb
Starting Wind velocity	3 m/s
Cut-Off Wind velocity	17 m/s

The relationship between C_p and the wind velocity is given from the wind turbine datasheet provided by the manufacturer. This relationship is illustrated in Figure 2.

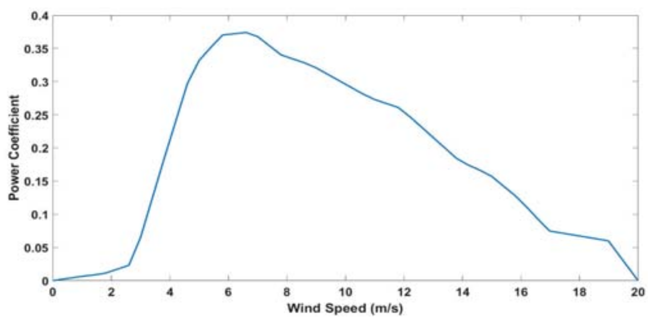

Fig.2. Power Coefficient of the SWT as a function of Wind velocity. (extracted from the SWT datasheet)

The turbine Control Strategy

The rotation control strategy, mentioned in introduction, allowing the variable speed and pitch regulation function requires the definition of a global control strategy taking into account the variations in rotational speed, torque or power desired as a function of variations of the wind velocity [10].

We report in Figure 3 the rotational speed response of the reference SWT with the wind velocity as modeled using Matlab from data providing from the SWT datasheet.

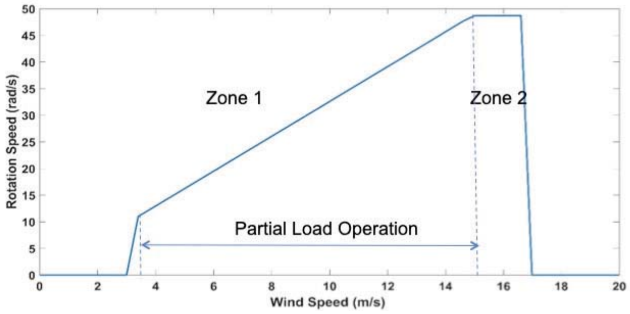

Fig.3. Turbine Rotation Speed as a function of Wind velocity

The variable speed operation of a wind turbine requires the definition of a global control strategy for the generator taking into account the variations in rotational speed, torque or power desired as a function of variations in the wind. In the classic control strategy developed for variable speed wind generation systems, the variation of the rotational speed of the wind-turbine as a function of the variation of the wind speed has a natural form as modeled here for the wind turbine considered in Fig. 3. Beyond the starting wind speed, we have considered a first operating zone in which the wind generator works at partial load. Optimization of the energy efficiency is ensured by an evolution of the rotation speed as a function of the wind speed so as to remain in the operating point of maximum aerodynamic efficiency. As indicated above, this consideration avoids taking into account the operation of the maximum power point tracker in the simulation because this optimization is considered according to the manufacturers' data in the datasheet. In this zone, the electromagnetic torque is the only degree of freedom considered for the control. Zone 2 presented in Fig. 3 for wind speeds greater than 15m / s up to the cut-off speed 17m / s corresponds to operation at full load. Here, the electromagnetic torque is maintained at its nominal value and the mechanical power is limited by an active electronic braking system associated with a redundant passive electrical / mechanical safety system allowing regulation at nominal speed and therefore at nominal power. Beyond the cut-off speed, this braking system blocks the operation of the wind turbine.

The Permanent Magnet Synchronous Generator (PMSG)

In SWTs, the mechanical input elements of the turbine, i.e. the blades and the rotor are directly coupled via a single shaft, without a mechanical interface or adaptation given by a gearbox to the electrical generator, i.e. to the PMSG. Thus the wind velocity straightforwardly induces the rotor mechanical rotational speed ω_m and then a rotor electrical rotational speed, ω_e defined by:

(5) $$\omega_e = p\omega_m$$

with *p*, the number of pairs of pole.

In a PMSG, the rotor is composed by a permanent magnet, PM not supplied by an external source to produce the necessary magnetic field and only stator voltages V_{sd} and V_{sq} have to be considered in the dq-frame. The stator fluxes φ_{sx} (with $x = d$ and q, respectively) are given by:

(6) $$\varphi_{sd} = L_d I_{sd} + \varphi_m$$

(7) $$\varphi_{sq} = L_q I_{sq} + \varphi_m$$

where I_x and L_x are the stator currents and inductances and φ_m the flux linkage.

Considering the stator-winding resistance, R_s the stator voltages along the two axes *d* and *q* of the park representation are given by [11,12]:

(8) $$V_{sd} = R_s I_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_e \varphi_{sq}$$

(9) $$V_{sq} = R_s I_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_e \varphi_{sd}$$

where, From Equations 6-9:

(10) $$V_{sd} = R_s I_{sd} + L_d \frac{di_{sd}}{dt} - \omega_e L_q I_{sq}$$

(11) $$V_{sq} = R_s I_{sq} + L_q \frac{di_{sq}}{dt} + \omega_e L_d I_{sd} + \omega_e \varphi_m$$

The block diagrams representative of static components of the PMSG in the Park's representation as well as the relations between currents and voltages in both real and park's representations are illustrated in Figs. 4.

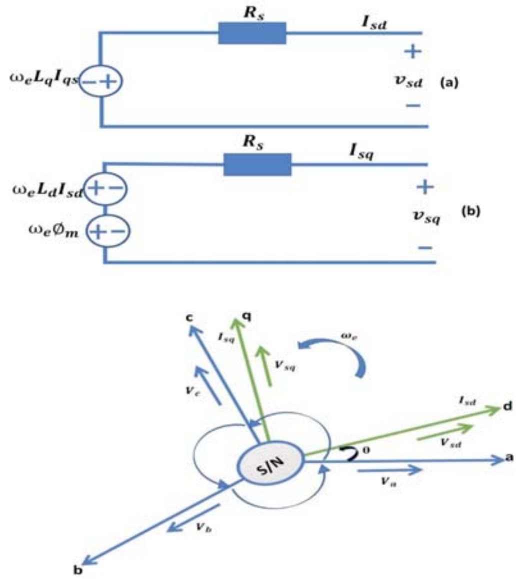

Fig.4. PMSG model (a) (direct)- axis, (b) (quadrature)-axis, and In (a,b,c) axis and (d,q) axis

When the generator (PMSG) supplies an electrical charge (R_{ch}, L_{ch}), voltages and currents resulting from the application of this load are given by the voltages expressions written as follows [13]:

(12) $$V_{sd} = -R_s I_{sd} - L_d \frac{di_{sd}}{dt} + \omega_e L_q I_{sq}$$

(13) $$V_{sq} = -R_s I_{sq} - L_q \frac{di_{sq}}{dt} - \omega_e L_d I_{sd} + \omega_e \varphi_m$$

On the other hand, the application of voltages V_{sd} and V_{sq} on the load gives [14]:

(14) $$V_{sd} = R_{ch} I_{sd} + L_{ch} \frac{di_{sd}}{dt} - \omega_e L_{ch} I_{sq}$$

(15) $$V_{sq} = R_{ch} I_{sq} + L_{ch} \frac{di_{sq}}{dt} + \omega_e L_{ch} I_{sd}$$

By replacing the expressions of V_{sd} and V_{sq} in Eqs.12 and 13 in Eqs.14 and 15, we obtain the following system:

(16) $$\frac{di_{sd}}{dt} = \frac{1}{L_d + L_{ch}}\left[-\left(R_s + R_{ch}\right)I_{sd} + \omega_e\left(L_q + L_{ch}\right)I_{sq}\right]$$

(17) $$\frac{di_{sq}}{dt} = \frac{1}{L_d + L_{ch}}\left[-\left(R_s + R_{ch}\right)I_{sq} - \omega_e\left(L_d + L_{ch}\right)I_{sd}\right] + \omega_e\varphi_m$$

The electromagnetic torque can be written as:

(18) $$T_e = \frac{3}{2}p\left[\varphi_m I_{sq} + \left(L_d - L_q\right)\right]I_{sd}I_{sq}$$

Finally, the PMSG considered here is a generator with smooth poles given $L_d = L_q$, and then T_e can be simplified as:

(19) $$T_e = \frac{3}{2}p\varphi_m I_{sq}$$

The wind System Connected with the PMSG

The Matlab/Simulink model of the PMSG-SWT system associated with its rectifier is shown in Fig< 5. The first bloc is associated to the wind turbine and converts the wind velocity in the rotor mechanical speed following a defined wind profile covering the whole available functioning speed range of the SWT. The three following main blocs, associated with a parallel one are related to the PMSG itself for the modeling of the voltages and currents in the dq frame, then in the tri-phase normal representation. Finally, the last parts of the model is related to the rectifier or AC/DC converter considered here connected to a resistive load equal to 50 Ω.

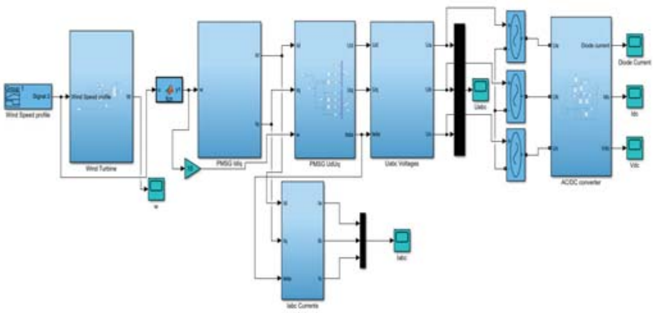

Fig.5. Wind chain Simulation Model

Amplitudes of both voltage and current follow the evolution of the turbine rotation speed in the operating range starting at 3 m/s and shutting down at 17 m/s. The shape of the voltage, as shown in the insert of Fig. 6, possesses a pure sinusoidal shape.

The AC/DC Conversion (Diode Bridge Rectifier)

The simple topology for wind energy conversion systems is based on a conversion element with a three phase rectifier. This topology of converter is commonly used for high power applications as they have highest possible transformer utilization factor for a three-phase system. Then, the rectified voltage at the output of the rectifier is expressed by [14]:

(20) $$V_{dc} = \frac{3\sqrt{3}}{\pi}V_{ac}$$

Within the input turbine rotation speed as a function of wind velocity as presented in Fig. 2, the simulation results, as obtained by the model using Matlab / Simulink, of the voltage at the output of the PMSG and the output current are plotted in Figs. 6 and 7. The current reported in Fig. 7 is evaluated on one phase at the output of the PMSG at the converter input. The inserts in Figs. 6 and 7 are time zooms of the plotted signals:

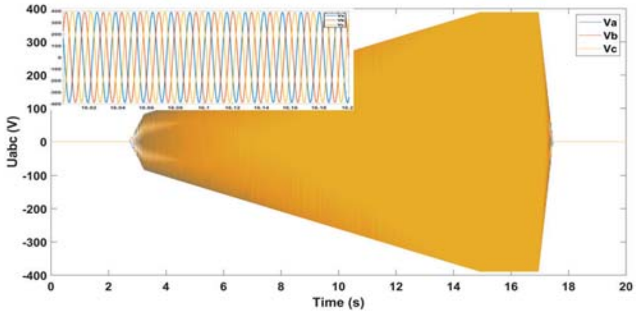

Fig.6. Stator Voltage of the PMSG

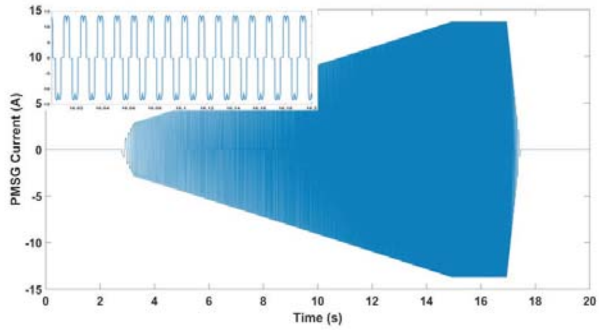

Fig.7. PMSG Stator Current

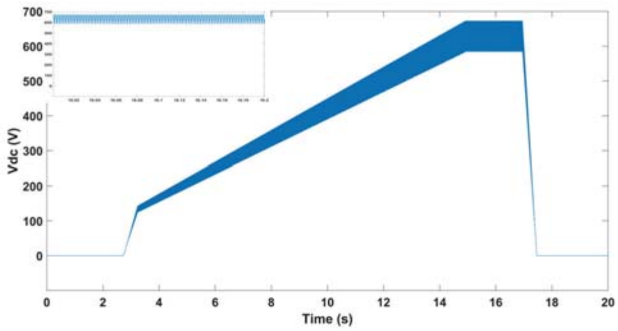

Fig.8. Rectified Voltage of the AC/DC Converter

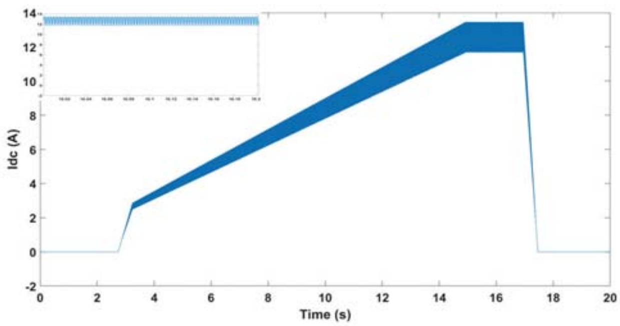

Fig.9. Current of the AC/DC Converter

From Figs. 8 and 9, it can be observed that the voltage and the current at the output of the converter track the input turbine rotation speed as a function of the wind velocity. The residual harmonics in the voltage and the current at the output of the converter achieves a maximum of 10% of the total voltage and current amplitude, respectively.

This results proves the possibility to model a SWT by optimizing the response of the turbine with the associated data provided by the manufacturer without the need to introduce complex tracking system for the management of the maximum power point knowing that this one is directly considered upstream when the turbine rotation speed is plotted as a function of the wind velocity. This model of the Wind-PMSG-AC/DC chain can be now used as the electrical power source in more complex systems as presented in Fig. 1

In order to use this model of wind turbines as a stand-alone model that can cover the electricity needs of a specific load, or connected to the grid directly after passing through an inverter, it will then be necessary to consider a constant output voltage value which can be ensured by a battery via a system composed by a charger and a boost converter or a buck-boost system. In operating mode not constrained by an output voltage level imposed or fixed by a DC source, the AC output voltage is controlled in terms of amplitude and frequency directly by considering the response of the rotational speed as a function of the wind velocity. Nevertheless, in normal operation mode in an autonomous system, a power dc grid can be envisage with the level of the output voltage guaranteed constant thanks to an energy backup system of battery type associated with a charge and discharge control system. But, in the case of autonomous source ac or in the case of PSW generator to be connected to the distribution ac grid, the power of the PMSG wind turbine is then supplied to the AC/DC converter then to a DC/AC inverters whose output will be at an AC output voltage having a specified and constant amplitude that can also be provided by a constant level voltage source, which in addition, depending on the available power generated by the SWT, will supplement the necessary power requested by the load.

Conclusion

In this article we have developed a model for small wind turbine, SWT, and applied it to a commercial model connected to a PMSG. The main originality of this work is the universality and the simple approach being rendered possible thanks to the consideration in the modeling process of the functional data provided in the datasheet of the SWT by the manufacturer. The only input parameter is thus the wind turbine rotation speed vs the wind velocity. Within this approach the complex usual modeling process was not necessary to implement, especially the maximum power point tracking procedure. The second originality is the direct consideration, part by part of the equations governing the operation of the wind turbine, then of the PMSG then finally of the AC / DC converter. This development can, now, be integrated in a complete power energy wind generator adapted to the intended application, namely, stand-alone or connected to the distribution grid, with or without energy storage systems.

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Authors

Fatima Zohra Naama, Abdallah Zegaoui, Abdelkader Djahbar, University Hassiba Benbouali of Chlef, Faculty of Technology, Electrical Engineering and Renewable Energy laboratory (LGEER), 02180, Chlef, Algeria,
E-mail: fat9110@yahoo.fr, abd.zegaoui@gmail.com, a_djahbar@yahoo.fr ,
Fatima Zohra Naama, Michel Aillerie, Laboratoire Matériaux Optiques, Photonique et Systèmes (LMOPS), UR 4423, Université de Lorraine and CentraleSupelec, France, E-mail: fat9110@yahoo.fr, michel.aillerie@univ-lorraine.fr.

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