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## Model and Simulation of a Wind Turbine and its Associated Permanent Magnet Synchronous Generator

Fatima Zohra Naama<sup>a,b,c</sup>, Abdallah Zegaoui<sup>a</sup>, Yessad Benyessad<sup>a</sup>,  
Fatma Zohra Kessaissia<sup>a,b,c</sup>, Abdelkader Djahbar<sup>a</sup>, and Michel Aillerie<sup>b,c\*</sup>

<sup>a</sup>Department of Electrical Engineering, Faculty of technology, University of Chlef, Chlef, Algeria

<sup>b</sup>Laboratoire Matériaux Optiques, Photonique et Systèmes, LMOPS, EA 4423, Université de Lorraine, Metz, 57070, France

<sup>c</sup>Laboratoire Matériaux Optiques, Photonique et Systèmes, LMOPS, CentraleSupélec, Université Paris-Saclay, Metz, 57070, France

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### Abstract

In this paper, a modeling and simulation of the assemble of a wind turbine and a synchronous generator with permanent magnet operating are presented. In a first step, we present the result of simulation under Matlab / Simulink software of the wind turbine of the power coefficient  $C_p$  as a function of the orientation strategy of the blades. This strategy is important as it allows the wind turbine to operate autonomously according to the wind speed giving rise to variable maximum powers. In a second step, the permanent magnet synchronous generator (PMSG) is specifically modeled. In this approach, we recall the need to change the reference (abc) in order to simplify the equations and thus allow the realization of orders. Finally, the voltages of the idle operation of such a generator are simulated in real marks abc and that of Park dq, respectively. Thus the obtained results analyze, even optimize the behavior of the two main components allowing the conversion of the wind energy in electric energy, i.e. the wind turbine and the synchronous generator, of a medium power wind production chain.

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**Keywords:** Wind turbine; Blade orientation strategy;  $C_p$  power factor; Permanent magnet synchronous generator

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\* E-mail address: [michel.aillerie@univ-lorraine.fr](mailto:michel.aillerie@univ-lorraine.fr)

## 1. Introduction

Wind energy is more specifically the energy produced from the wind by means of a wind turbine to produce electric energy, or by means a windmill to produce mechanical energy. It is renewable and green as it does not produce atmospheric discharge or waste even the radioactive one. As the energy found in fossil fuels, renewable energies are derived from solar energy. Even the wind energy can be considered as it with about 1 to 2% of the energy emitted by the sun converted into wind energy. The kinetic energy contained in the wind is transformed in part into mechanical energy by the turbine, then into electrical energy by the generator.

An aero-generator, often called a wind turbine, is a device that converts a portion of the kinetic energy of the wind into electrical energy. In a first approach, the conversion and production processes seem simple. But in fact, even without the consideration of economical and distribution aspects [1], it presents a field of interaction of numerous scientific disciplines and know-how from meteorological and ecological aspects up to the technological ones relying among others electric, mechanic, fluidic, etc.

In this contribution, we present a modeling and simulation of the assemble of a wind turbine and a permanent magnet synchronous generator, PMSG. The study and the presentation are organized as follow. In a first step, we present the result of simulation under Matlab / Simulink software of the wind turbine of the power coefficient  $C_p$  as a function of the orientation strategy of the blades allowing the wind turbine to operate autonomously according to the wind speed giving rise to variable maximum powers. In a second part, the PMSG is specifically modeled. Finally, in a last part before conclusion, the voltages of the idle operation of such a generator are simulated in real marks abc and that of Park dq, respectively.

## 2. Model and simulation of the wind turbine

Three factors determine the energy of the windswept by the rotor: The air density  $\rho$ , the surface swept by the rotor  $S$ , and the wind speed  $v_{wind}$  [2]. They allow the determination of the wind power by

$$windpower = 1/2 * \rho * S * v_{wind}^3 \quad (1)$$

In practical application, the wind speeds behind and in front of the turbine,  $v_a$  and  $v_b$  respectively have to be considered. Thus, the maximum theoretical power developed by a wind sensor,  $P_{total}$  and the maximum power,  $P_{extract}$ , that can be extracted from the wind by the turbine are given by [4-8]:

$$p_{total} = 1/2 * \rho * R^2 * \pi * v_b^3 \quad (2)$$

$$p_{extract} = 1/2 * \rho * R^2 * \pi * \left( \frac{v_a + v_b}{2} \right) * (v_b^2 - v_a^2) \quad (3)$$

with  $R$  the radius of the blades.

$$\frac{v_a}{v_b} = \frac{1}{3} \quad (4)$$

$$\frac{p_{extract}}{p_{total}} = coefficient\ of\ power = C_p \quad (5)$$

Thus, the power coefficient as defined by the physical law, known as the Betz limit is equal to 16/27 the incident power of the wind passing through the wind turbine as

$$C_p = \frac{16}{27} = 59.3\% \quad (6)$$

Fig. 1 presents the simulated characteristic corresponding to the equation  $P_{\text{extract}}/P_{\text{total}}$  as a function of the wind speeds  $v_a$  and  $v_b$  in an ideal experimental case.

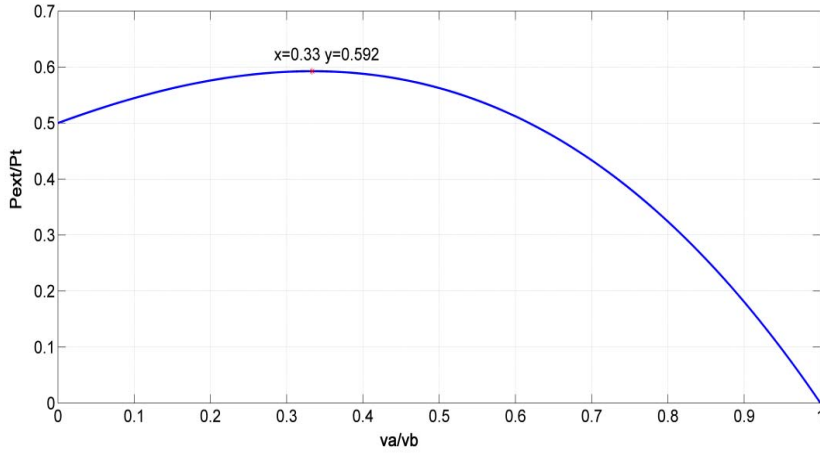


Fig. 1. The power coefficient  $C_p$  as a function of the wind speed ratios as ideal case

We can notice with results plotted in Fig. 1 that the power coefficient  $C_p$  presents a maximum value equal to  $16/27$  that verifies the law of Betz.

This theoretical Betz limit, fixes the maximum extractable power for a given wind speed. This limit is in fact never reached and each wind turbine is defined by its own power coefficient expressed as a function of the ratio between the speed of the tip of the blades of turbine and the speed of the wind. This ratio named  $\lambda$  is expressed according to [3] as:

$$\lambda = R * \frac{\Omega}{v} \quad (7)$$

where  $R$  is the length of the blade or radius of the turbine (meters),  $v$  is the wind speed (m/s), and  $\Omega$  is the mechanical rotation speed of the turbine (rad/s).

The mechanical power produced by the wind turbine is [14]

$$p_{\max} = 1/2 * \rho * C_p * S * v^3 \quad (8)$$

with the air density  $\rho = 1.224 \text{ kg/m}^3$  at  $15^\circ \text{C}$  and with  $S$ , the surface swept by the blades of the wind turbine

From the equation of  $P_{\max}$ , we can calculate the mechanical torque  $C_{\max}$  as [9, 10]:

$$C_{\max} = \frac{p_{\max}}{\Omega} \quad (9)$$

Finally, by the use of the above equation defining the normal or ideal working mode of the wind turbine in real case, we can define its model as a function of the ratio  $\lambda$ , i.e.  $C_p(\lambda)$  for different values of the angle of the blades,  $\beta$ .

The model simulate in this work is represented in the diagram of Fig. 2.

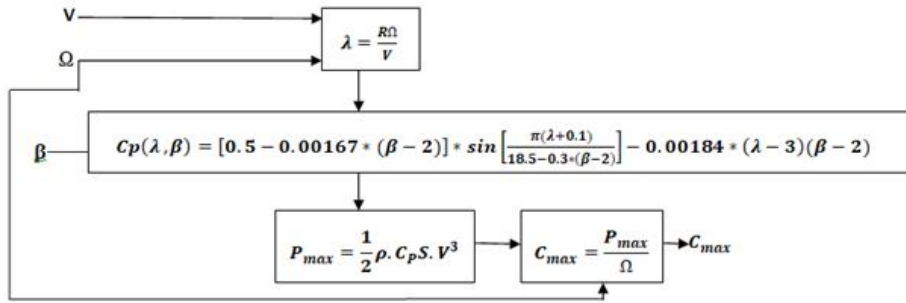
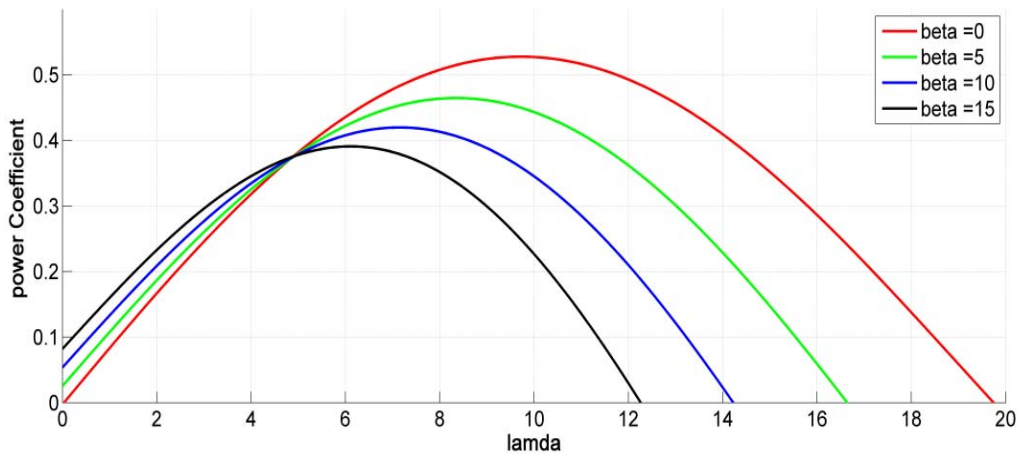


Fig. 2. Model of the wind turbine

Thus, it is possible to consider the model of the wind turbine when under real conditions, considering an ideal case where the turbine itself does not induce additional losses. Within these considerations, Fig. 3 presents the characteristic curves of the power coefficient  $C_p$  as a function of the ratio  $\lambda$ , i.e.  $C_p(\lambda)$  for different values of the angle of the blades,  $\beta$ .

Fig.3: Characteristic curves  $C_p(\lambda)_\beta$  ( $\beta$ , expressed in degree)

According to the parameters of the model in Fig. 2, we notice in Fig. 3 that the results of simulations point out that the turbine produces the maximum mechanical power with a maximum power coefficient  $C_p$  that corresponds, as well expected, to the case when the angle of the blades  $\beta$  is equal to 0. This extreme corresponds to  $\lambda = 9.6$  for a  $C_{p_{\max}} = 0.525$ . For the other working conditions, we notice that when the wedging angle  $\beta$  increases, the power coefficient  $C_p$  decreases yielding to a lower mechanical power delivered and available at the output of the turbine.

### 3. Model of the Permanent Magnet Synchronous Generator (PMSG)

In a renewable energy approach, synchronous generator is the second important part of a generator based on wind power after the wind turbine. The synchronous machine with permanent magnet considered in the current contribution is a commercially available generator, currently used the electricity generation in association with amid-power wind turbine [10]. It is constituted by three stator windings forming the three phases and magnets with the rotor distributed in 17 pairs of poles [10].

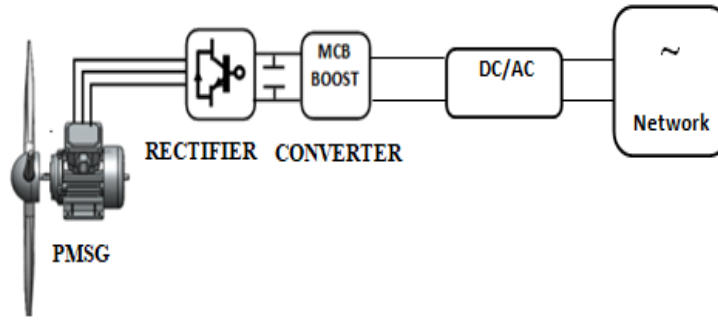


Fig.4: Operating mode of the wind turbine

The fluxes created by the permanent magnets are of sinusoidal shape along the gap. The expressions of the inductor-phase mutual flows are given by [10]:

$$\begin{cases} \phi_a = \phi_f \cos(p\theta) \\ \phi_b = \phi_f \cos(p\theta - \frac{2\pi}{3}) \\ \phi_c = \phi_f \cos(p\theta + \frac{2\pi}{3}) \end{cases} \quad (10)$$

$\phi_f$  is the peak value of the flux created by the permanent magnet through the stator windings. With  $[\phi_a, \phi_b, \phi_c]$ , the vectors of the stator flows and  $[R_s]$  the resistance of a stator winding phase.

The electrical characteristics as a function of the parameters of the PMSG in the plane (a,b,c) [10] can be written as:

$$\begin{cases} v_a = [R_s][i_a] + \frac{d\phi_a}{dt} \\ v_b = [R_s][i_b] + \frac{d\phi_b}{dt} \\ v_c = [R_s][i_c] + \frac{d\phi_c}{dt} \end{cases} \quad (11)$$

Modeling this machine also requires, like any other three-phase machines, to move from the three-phase (real) axis system to the two-phase axis system (and vice versa) named the Park model. Thus it is possible to represent the PMSG windings in the three-phase and in that of Park reference [11], as shown in Fig. 5.

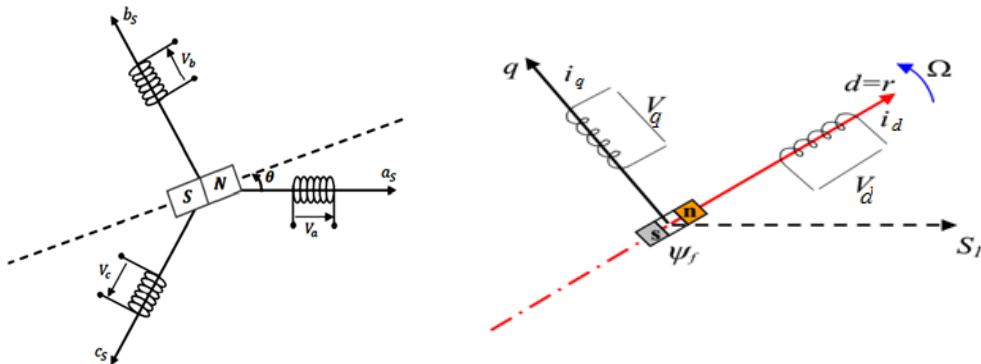


Fig.5: Representation of PMSG windings in the three-phase (a) and in Park(b) [11]

This representation of the PMSG in the reference of the Park model, used the transformation  $P(\theta)$ , described here for our model, which is a three-phase balanced system allowing to neglect the homo-polar component. The transformation of the expressions of the voltages, currents and flows yield to the following set of equation:

$$\begin{cases} [I_{dq}] = P(\theta)[I_{abc}] \\ [v_{dq}] = P(\theta)[V_{abc}] \\ [\phi_{dq}] = P(\theta)[\phi_{abc}] \end{cases} \quad (12)$$

with

$[I_{dq}]$  the components of the current in the park marker,  
 $[v_{dq}]$  the components of the stator voltage in the park marker,  
 $[\phi_{dq}]$  the components of the stator flow in the park marker,  
 $[I_{abc}]$  the stator phase currents,  
 $[V_{abc}]$  the stator phase voltages, and finally,  
 $[\phi_{abc}]$  the stator flow vectors of phases a,b,c.

The differential equation systems of the PMSG following the generalized Park referential are:  
 For the electric equations

$$\begin{cases} v_d = R_s I_d + \frac{d}{dt} \phi_d - \omega \phi_q \\ v_q = R_s I_q + \frac{d}{dt} \phi_q + \omega \phi_d \end{cases} \quad (13)$$

$R_s$  is the resistance of a stator winding phase

For the magnetic flux equations

$$\begin{cases} \phi_d = L_d I_d + \phi_f \\ \phi_q = L_q I_q \end{cases} \quad (14)$$

with

$L_d$  the stator inductance at the d,  
 $L_q$  the stator inductance at the q axis, and finally,  
 $\phi_f$  the effective value of flow creates by the permanent magnet through the stator windings.

The final equations of the synchronous machine in the Park landmark are obtained by replacing the magnetic flux equations in the electrical equations, given [11]

$$\begin{cases} v_d = R_s I_d + L_d \frac{d}{dt} I_d - \omega L_q I_q \\ v_q = R_s I_q + L_q \frac{d}{dt} I_q + \omega L_d I_d + \omega \phi_f \end{cases} \quad (15)$$

Finally, to complete the electromechanical model of the PMSG, we add the expression of the electromagnetic torque and the mechanical equation. The considered synchronous generator is at smooth pole, that is to say that  $L_q = L_d$ . This yields to the following Eqs 16 and 17 with Eq.16 defining the expression of the couple, and Eq.17 defining the expression of the mechanical behavior of the PMSG.

$$C_{em} = \frac{3}{2} P [(L_d - L_q) I_d I_q + I_q \phi_f] = \frac{3}{2} P I_q \phi_f \quad (16)$$

$$J \frac{d\Omega}{dt} - f_m \Omega = C_t - C_{em} \quad (17)$$

with

$C_{em}$  the electromechanical torque produced by the generator,

$J$  the total inertia that appears on the generator rotor,

$f_m$  the viscous friction coefficient of the machine, and finally

$C_t$  the turbine torque provided by the turbine.

#### 4. Model of the permanent magnet synchronous machine in generator mode

For the generator of the synchronous machine with permanent magnet, the directions of the currents  $I_d$  and  $I_q$  in the Park reference are reversed. Thus the model of the PMSG obtained can be written in the form [11, 12]

$$\begin{cases} v_d = -R_s I_d - L_d \frac{d}{dt} I_d + \omega L_q I_q \\ v_q = -R_s I_q - L_q \frac{d}{dt} I_q - \omega L_d I_d + \omega \Phi_f \end{cases} \quad (18)$$

In this mode, the stator currents of the PMSG are equal to zero, i.e.  $I_d = I_q = 0$ , then, we can write the following expressions for the voltages and the torque [13]:

$$\begin{cases} v_d = 0 \\ v_q = \omega \Phi_f \\ C_{em} = 0 \end{cases} \quad (19)$$

We have implemented the simulation model described above under Matlab / Simulink software environment. The block diagram is represented in Fig. 6 and the simulation results are plotted in Figs. 7 and 8.

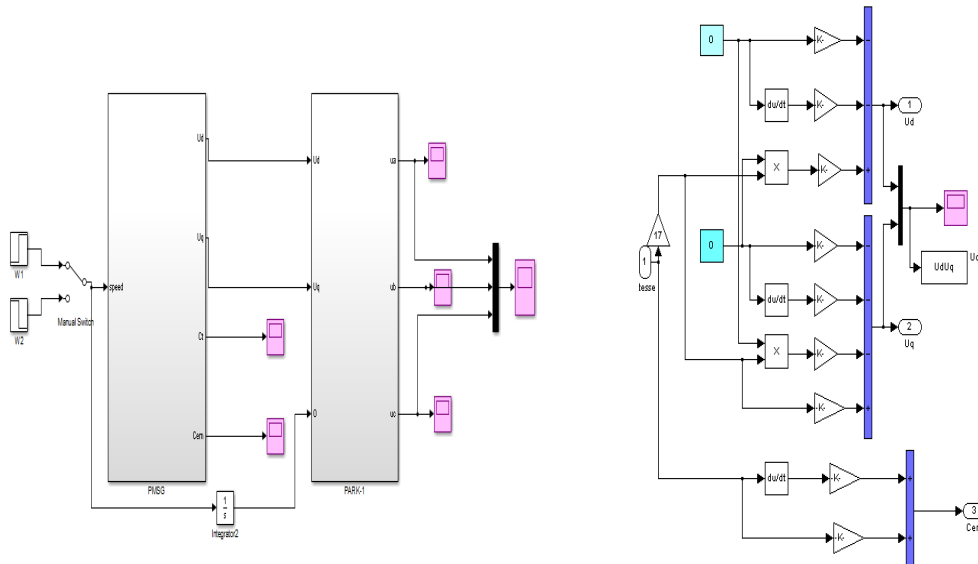


Fig. 6: Block diagram of the PMSG under Matlab / Simulink

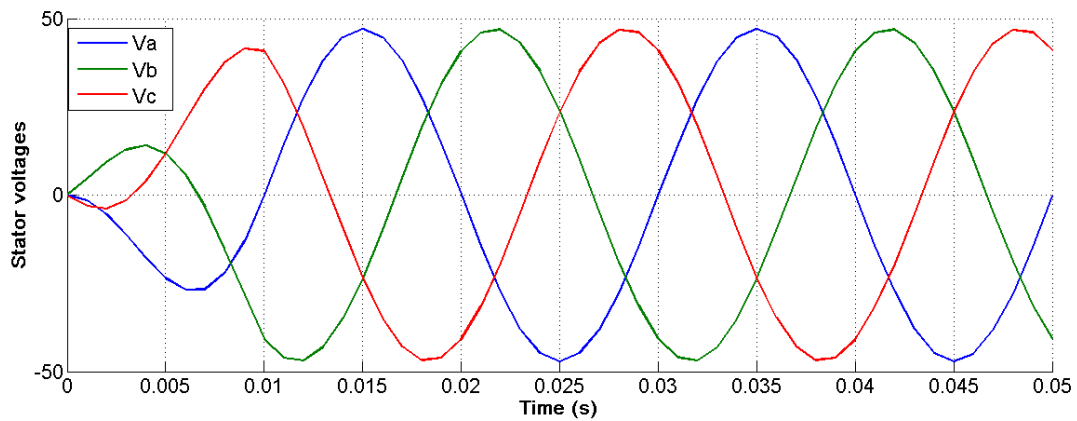


Fig. 7: Stator voltages of the vacuum PMSG

By driving the generator with the wind turbine torque equal to 3.0 Nm for a duration of 10ms, then, it can rotate freely. Fig.8 shows the voltages of the three phases.

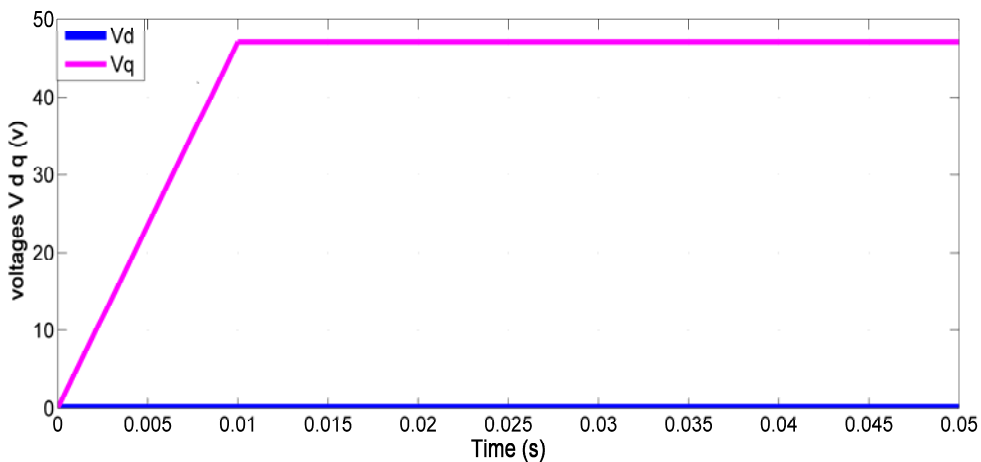


Fig.8: Components of stator voltages, direct  $V_d$  and quadratic  $V_q$ , in the Park marker

It can be seen in Fig. 7 that after the transient 10 ms the voltages become stable in a three-phase mode with a maximum voltage of about 50V at a frequency of 50 Hz. The harmonic distortion rate that we have calculated has been found lower than the IEEE standard and shows the relevance of the model and the simulation carried out.

## 5. Conclusion

In this article, we have described in details and presented models of the two essential parts of a wind energy conversion system. At first we have described the model of the wind turbine with the support of the influence of the wedging angle on the maximum power produced by evoking the power coefficient  $C_p$ . In a second step, we studied the model of a permanent magnet synchronous machine in generator mode and implement the model in Matlab /

Simulink. It is to be noted that this work is the upstream part of a larger renewable energy generation system, with only consideration in the above contribution of the wind-turbine associated with the permanent magnet synchronous generator, constituting the energy source for supplying a DC and even an HVDC bus. The complete system will integrate a rectifier and a boost converter allowing the production of electricity at defined voltages with higher efficiency than with AC voltage conversions. Finally, the simulation validated the models developed for the wind turbine and the permanent magnet synchronous generator.

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