Modeling of a Permanent Magnet Synchronous Generator in a Power Wind Generation System with an Electrochemical Energy Storage

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***Abstract*— With the development of power electronics, directly driven permanent magnet synchronous generators (PMSGs) have attracted increasing interest from wind turbine (WT) producers because of their benefits over other variable speed WTs. PMSGs have a big number of poles and competitive costs. In this article simplified model and real modeling of a small power wind conversion system are offered. The system consists on a horizontal axis WT, PMSG, diodes rectifier, and a low voltage lead-acid battery. The models implemented in the Matlab-Simulink software can reflect the real physical phenomena. A longer calculation time is required when adopting the detailed model compared to the simplified model. The results of the simulation demonstrate that the suggested simplified model has enough precision to analyze the dynamics of the WT system.**

***Index Terms*—modeling, wind turbine, PMSG, simplified model.**

I. INTRODUCTION

Global energy consumption has augmented dramatically these last years, because of the huge industrialization, which tends to increase more and more. The risks of fossil fuel depletion and their effects on weather change once again underline the importance of using renewable energy [1]. Among these, we meet the wind energy that has experienced strong growth and has become competitive through the developing of the wind turbine manufacturing, and the advances in semiconductor technology, as well as novel methodologies of turbine control at variable speeds. Nevertheless, several problems encountered, related on the one hand to the complication of wind energy conversion schemes; that is, the need for the gearbox between the turbine and the generator, and the instability of the wind speed on the other hand [2-4]. The use of well-designed wind structures, such as the high-pole PMSG, makes variable-speed wind turbine conversion systems more attractive than fixed-speed wind turbine systems because of the possibility of optimal power for diverse wind speeds, and reduced mechanical stress by eliminating the gear box, which enhances the reliability of the system, and reduced maintenance costs. [2,5]. Electrical systems in wind energy conversion can be subdivided into several main groups. Fixed speed systems use inductive generators connected directly to the network. Variable speed electrical systems use asynchronous machines, synchronous machines or unconventional machines. These are complicated and are all equipped with electronic converters. The chains of conversion of small power (some 100 W) and those of large power (more than 40 kW) are then very different. Either in isolated sites of small power or in systems connected to the network (also in small power), an intermediate DC bus is used before transforming the energy into alternating current. In the case of very small powers, the energy is directly consumed in direct current. The continuous bus has the advantage of more easily interconnecting various production systems (wind, photovoltaic, diesel, fuel cell, etc.) and electrochemical batteries that can be directly buffered on such buses. Such systems are called hybrid. The use of wind energy for the production of electrical energy is booming. The category of small wind turbines from 1 to 100 kW mainly owes its development generally in hybrid wind-photovoltaic or wind-diesel applications. Small power conversion chains are mainly for isolated sites. They are based on the use of a permanent magnet synchronous machine, which flows directly through a diode rectifier into a generally low voltage electrochemical accumulator (12 to 48 V). This configuration allows direct drive without speed multiplier and still connected directly to a diode rectifier. It has a reduced cost and fewer losses [6]. The ultimate goal is to contribute to the study of a hybrid wind and photovoltaic conversion chain with an electrochemical accumulator. In this paper, after a theoretical description of the characteristics of wind turbines, we propose a mathematical modeling of the wind energy system. The model is validated by numerical simulation via Matlab/Simulink software.

The rest of the document is intended as follows; the second part gives the description of the studied system; followed by characteristics of the wind turbine in the third part; simplified model and real modeling of the global wind conversion system are offered respectively in part 4 and 5; the sixth part analyzes and comments on the results of the simulation. Finally, in the seventh part, conclusions and perspectives are proposed.

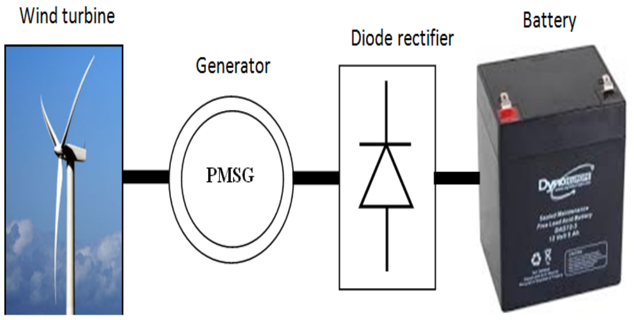

Fig. 1 Magnet wind turbine delivering directly through a diode bridge on the continuous bus

II. Studied Wind System

In this work, we are particularly interested in the wind energy conversion chain. Fig. 1 illustrates the system to be studied, consisting of a high-number of poles of PMSG, which flows directly through a three-phase diode bridge to the DC bus and the electrochemical accumulator. The direct flow of the synchronous machine on a DC voltage source through a simple diode bridge rectifier may surprise. A rectifier operating on a DC voltage source must be powered by an AC power source [7]. In fact, it is thanks to the high value of the armature inductance that the currents remain close to the sinusoidal forms and that the conversion efficiencies are correct. If the battery is overloaded (too much voltage), a contactor short-circuits the generator armature. The turbine is then stopped in rotation.

III. Characteristics of the Wind Turbine

The total kinetic power P_w of the wind through a disk of radius R is given by the following relation [4,8-9]:.

$$P_w = \frac{1}{2}\rho\pi R^2 V_w^3 \quad (1)$$

where ρ is the density of the air ($\rho = 1.225$ kg/m), V_w is the wind speed and R practically corresponds to the length of the blade.

A fraction of this power is captured by the wind turbine. It is characterized by a factor $C_P(\lambda,\beta)$, called coefficient of performance or power coefficient. This coefficient, which cannot exceed the value of 16/27 (Betz limit) due to aerodynamic and mechanical losses, depends on two parameters λ and β as expressed in [10-11] by (2) and (3).

$$C_P(\lambda,\beta) = c_1.(\frac{c_2}{\lambda_i} - c_3.\beta - c_4).e^{-\frac{c_5}{\lambda_i}} + c_6.\lambda \quad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{1+\beta^3} \quad (3)$$

The parameters of c1 to c6 are: c_1=0.5176, c_2=116, c_3=0.4, c_4=5, c_5=21, c_6=0.0068.

The p26-132-1-CE.docxarameter λ is the ratio between the linear speed of the blade tips on the wind speed, is known as tip speed ratio (TSR) and the second parameteris known as blade pitch angle. Fig. 2shows the evolution of C_p in function of λ for different β. It can be seen that when $\beta = 0°$ the optimal point corresponds to the couple of ($\lambda_{opt} = 8.1$ & $C_{p\max} = 0.48$).

The mechanical power $P_{turbine}$ harvested by the wind turbine can be expressed as:

$$P_{turbine} = C_p(\lambda)\cdot P_w \quad (4)$$

$$\lambda = \frac{\Omega_{turbine}\cdot R}{V_w} \quad (5)$$

where $\Omega_{turbine}$ is the angular rotation speed of the turbine.

The characteristic $C_p(\lambda)$ provided by the turbine manufacturer, being of parabolic shape, admits a maximum $C_{p\max}$ for λ_{opt} as illustrated in Fig. 2. For V_w given, corresponds a rotation speed which gives λ_{opt} and consequently, the power Max:

$$P_{turbine\max} = C_{p\max}\cdot\frac{1}{2}\rho\pi R^2 V_w^3 = k\cdot V_w^3 \quad (6)$$

where k is a constant.

Fig. 3 illustrates the theoretical characteristic of the turbine.

The wind turbine cannot operate either below a speed $V_{\min}$ called «threshold speed or cut-in speed», or beyond a speed $V_{\max}$ called "maximum speed or cut-out speed".The characteristic of the wind turbine shows us four distinct operating zones:

Zone I ($V_W < V_{\min}$): the turbine does not work;

Zone II ($V_{\min} < V_W < V_n$): the power supplied depends on the wind speed, where V_n is the wind speed with which the turbine reaches its nominal power;

Zone III ($V_n < V_W < V_{\max}$): the production is limited because the generator is always at its maximum power;

Zone IV ($V_{\max} < V_W$): the turbine is stopped to avoid the risks that a strong wind can bring.

The wind turbine considered in this study is composed of three blades like the one known as the Danish design. Knowing its characteristics, we have drawn a family of curves describing the mechanical power available on the rotor of the machine according to its speed of rotation for different wind speeds, as well as an operating characteristic which links the maximum mechanical powers corresponding to the various wind speeds, as illustrated in Fig. 4. The red curve shows the maximums. For this turbine, the maximum power coefficient is reached for $\lambda_{opt} = 8.1$; that is to say the peripheral speed at the end of the blade equals 8 times the wind speed.

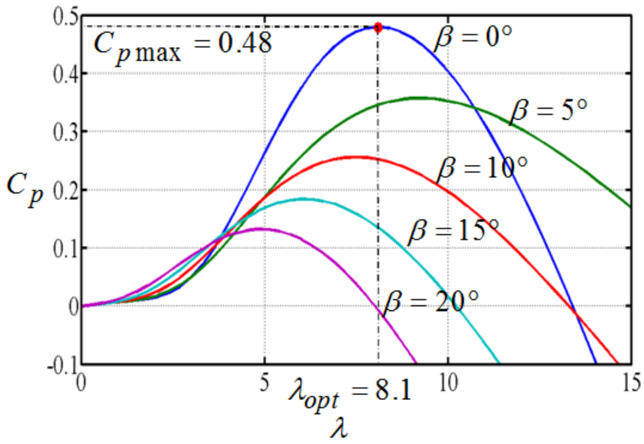

Fig. 2 Variation of C_p in function of λ for different β .

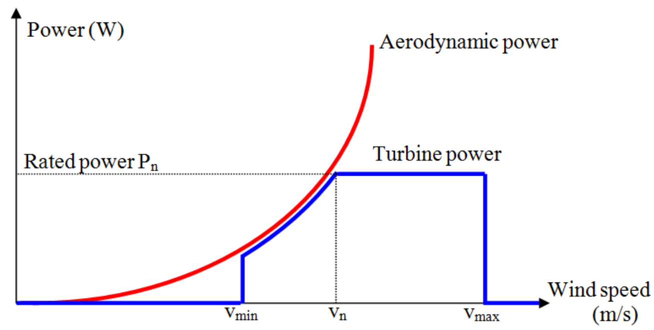

Fig. 3 Typical wind turbine power characteristic

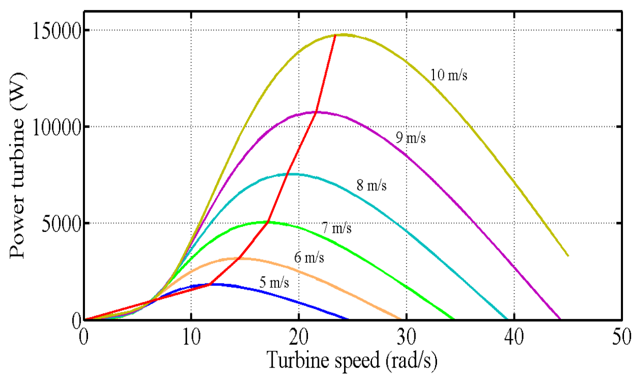

Fig. 4 Turbine power according to its rotation speed, parametrized in wind speed.The optimal operation is designated by the curve in red.

IV. Simplified Model of the Electric Conversion Chain

The simplified model of this wind energy chain is obtained by considering the battery of electrochemical accumulators as a perfectly constant voltage source. However, a static converter cannot connect two sources of the same nature. Therefore, the model used for the PMSG consists of a voltage source linked in series with a resistor and an inductance. The simplified electrical system is as in Fig. 5.

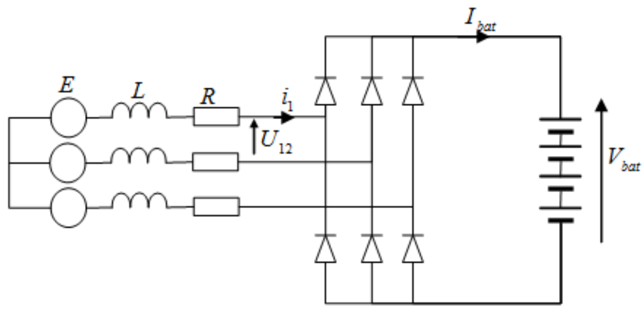

Fig. 5 Simplified model of the electrical conversion chain

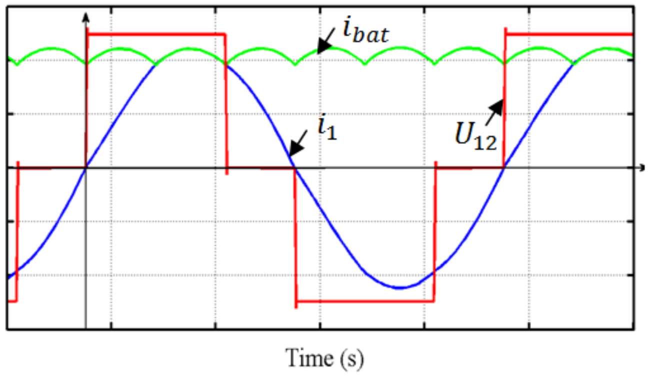

Fig. 6 Waveforms of some quantities using the simplified model: voltage U_{12} , current i_1 and the rectified current I_{bat} .

Fig. 6 shows the waveforms of the different quantities of this simplified study. The generator behaves like a current source, it delivers perfectly sinusoidal currents i_1. The current in the battery I_{bat} is formed of six portions of sinusoid per period. The phase-to-phase voltage U_{12} is rectangular in shape having three levels $+V_{bat}$, $-V_{bat}$ and zero. This last value means that a short-circuit between phases is applied due to the simultaneous conduction of the diodes due to the overlaps of the phases.

V. Real Modelling of the Electric Conversion Chain

In this part, we go from simplified study to real modeling that takes into account the actual waveforms of currents.

5.1. Model of transmission elements

The fundamental principle of dynamics is governed by the expression of electromagnetic torque T_{em}:

$$T_{em} - T_m = J \cdot \frac{d\Omega}{dt} + F\Omega \tag{7}$$

Where T_m is the mechanical torque applied on the generator shaft and F , J are respectively the coefficient of friction and the total moment of inertia of the system. This relationship makes it possible to determine the speed of rotation of the machine.

5.2. Model of PMSG

The coupling of magnet generators with power electronics becomes increasingly economically feasible, making them a serious contestant of asynchronous double-feed generators. Systems of this type have a failure rate that is considered low due to the elimination of certain sources of faults: suppression of the speed multiplier and the system of rings and brushes. The maintenance costs are then minimized which is very interesting in wind applications. The obligatory presence of the power electronics finally allows a simple regulation of the speed of rotation and thus an efficient energy optimization.
The model of the PMSG is based on the following equations:

$$v_d = -R_s.i_d - \omega.\phi_q - (L_{ls} + L_{md}).\frac{di_d}{dt} + L_{md}.\frac{di_{fd}}{dt} + L_{md}.\frac{di_{kd}}{dt} \quad (8)$$

$$v_q = -R_s.i_q + \omega.\phi_q - (L_{ls} + L_{mq}).\frac{diq}{dt} + L_{mq}.\frac{di_{kq}}{dt} \quad (9)$$

$$\varphi_d = -(L_{ls} + L_{md}).i_d + L_{md}.(i_{fd} + i_{kd}) \quad (10)$$

$$\varphi q = -(L_{ls} + L_{mq}).iq + L_{mq}.i_{kq} \quad (11)$$

where :

v_q , v_d : the quadrature and direct voltages;

i_q , i_d : the quadrature and direct currents;

i_{kd} , i_{kq} : currents in the windings kd, kq (reduced to the stator);

φ_d , φ_q : total stator fluxes in axes d, q;

R_s : the resistance of a stator phase;

L_{ls} : leakage inductance of a stator phase;

L_{md} , L_{mq} : mutual inductances along the axes d, q;

Equations of damping windings

$$0 = R_{kd}.i_{kd} - L_{md}.\frac{di_d}{dt} + L_{md}.\frac{di_{fd}}{dt} + (L_{lkd} + L_{md}).\frac{di_{kd}}{dt} \quad (12)$$

$$0 = R_{kq}.i_{kq} - L_{mq}.\frac{diq}{dt} + (L_{lkq} + L_{mq}).\frac{di_{kq}}{dt} \quad (13)$$

where:
R_{kd}, R_{kq} : resistances of windings kd and kq
L_{lkd} , L_{lkq} : inductances of windings kd and kq

The expression of the electromagnetic torque is given by:

$$T_{em} = \frac{3}{2}.p.(\varphi_d.i_q - \varphi_q.i_d) \quad (14)$$

where p is the number of pairs of poles

5.3. Static converter

The static converter used in this study is a diode bridge rectifier shown in Fig. 7. Its Simulink model is depicted in Fig. 8. It is governed by the following equations:

$$I_{bat} = \frac{3}{\pi}\sqrt{6}.I \quad (15)$$

$$U_{12} = \sqrt{\frac{2}{3}}.V_{bat} \quad (16)$$

I rms of the phase current
U_{12} rms of the phase to phase voltage

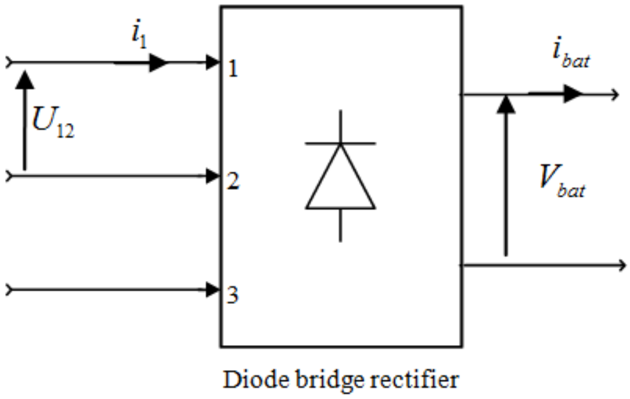

Fig. 7 Diode bridge rectifier

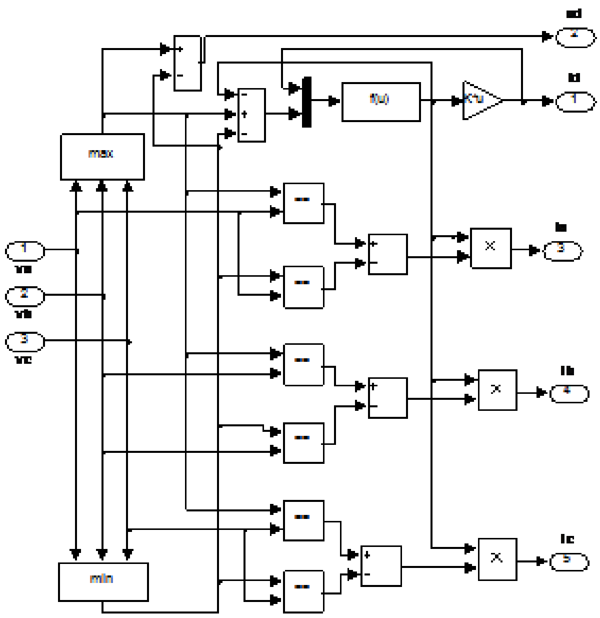

Fig. 8 Simulink model of the diode bridge

VI. Simulation Results and Interpretations

We have simulated the wind energy conversion system above for two different cases:

- The first case, for an operating point where the conduction is continuous. The waveforms of the phase current and the phase-to-phase voltage are shown in Fig. 9. At this point of operation, it can be seen that the current is quasi-sinusoidal because the amplitude of the electromotive forces of the generator is sufficient to allow continuous conduction.

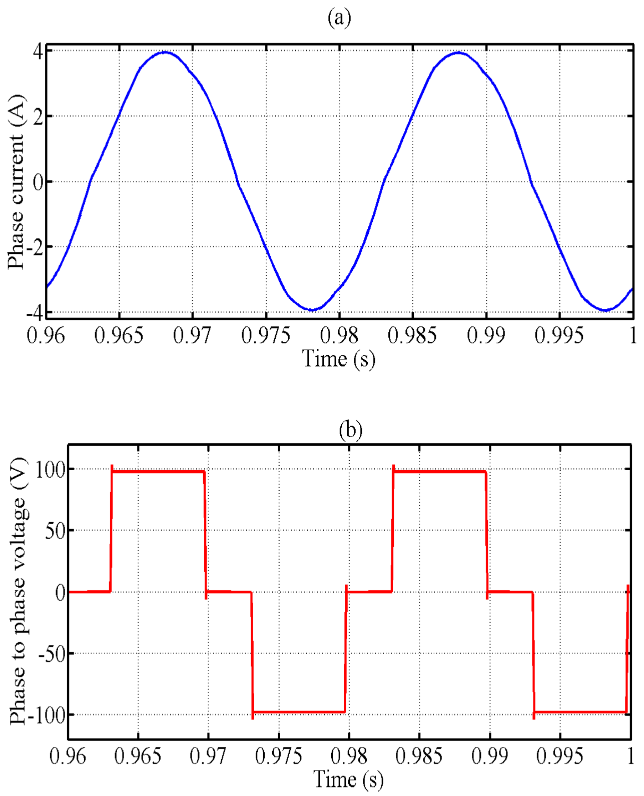

Fig. 9 Waveforms of the phase current (a) and the phase-to-phase voltage (b) in the case of continuous conduction.

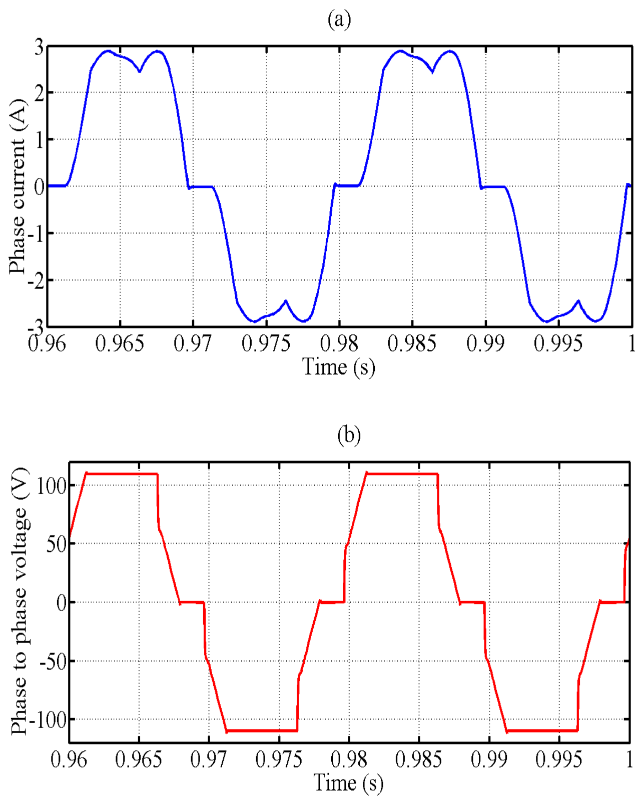

Fig. 10 Waveforms of the phase current (a) and the phase-to-phase voltage (b) in the case of discontinuous conduction.

- The second case, for an operating point where the electromotive force is not sufficient for continuous conduction. The waveforms of the same quantities are shown in Fig. 10. At this stage of operation, we can see that the current is non-sinusoidal and that the voltage is not really rectangular.

Finally, there is an approach in the simulation results between the simplified analysis and the actual modeling.

In perspective, this wind system of modest power can be used to feed loads continuously. However, it is equipped with a continuous bus. Then, we can connect it with the electricity network by means of an inverter as we can add other chains; for example a photovoltaic chain or a diesel generator.

VII. Conclusion

A simplified study and a real modeling of the permanent magnet WT generator were proposed in this article. Due to the fact that the field trials are not available, a comparison of simulation results using the Matlab-Simulink software with those provided by the simplified method was used. The results are close for both methods and the models are valid. So, the offered simplified model can be utilized efficiently to analyze the WT power system since its precision is enough and the time of simulation is reduced.

In the future, this conversion chain will be extended to connect other systems such as solar panels or diesel generators and even consider the possibility of transferring excess electricity to the grid.

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