Doubly Fed Induction Generator Systems For Variable Speed Wind Turbine

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Abstract. This paper presents results of a study concerning the dynamic behaviour of a wind energy system powered by a doubly fed induction generator with the rotor connected to the electric network through an AC-AC converter.
A tendency to put up more and more wind turbines can be observed all over the world. Also, there is awareness in taking into account the requirements of a clean environment, due to the need to preserve our habitat.
Renewable energy sources not contributing to the enhanced greenhouse effect, especially wind power, are becoming an important component of the total generation. Hence, research concerning the dynamic behaviour of wind energy systems is important to achieve a better knowledge.

Key words

Wind energy, Wind turbine, doubly fed induction generator, AC-AC converter.

1. Introduction

Wind energy continues to move forward in Europe, following Directive 2001/77/CE. States and customers are interested in providing the needed energy, taking into account the requirements of a clean environment. Renewable energy sources not contributing to the enhanced greenhouse effect, particularly wind power, are becoming an important component of the total mix generation.
Wind Energy Conversion Systems, WECS, research has focused in wind power autonomous systems and grid-connected systems.
An autonomous system directly supplies electricity to customers and it is especially appealing in areas with poor accessibility conditions for transmission lines, but autonomous system wind power generation should be complemented with other sources of power, because wind is an unpredictable energy source. Hence, it does not ensure continuous power supply. While, a grid-connected system have the advantage of ensuring continuous power supply, because when wind energy is insufficient the electrical grid satisfy the demand.
A comparison between the variable speed wind turbine and the constant speed wind turbine [1] shows that variable speed reduce mechanical stresses: gusts of wind can be absorbed, dynamically compensate for torque and power pulsations caused by back pressure of the tower. This backpressure causes noticeable torque pulsations at a rate equal to the turbine rotor speed times the number of rotor blades. The used of a doubly fed induction generator in WECS with the rotor connected to the electric grid through an AC-AC converter offers the following advantages:

- only the electric power injected by the rotor needs to be handled by the convert [1], implying a less cost AC-AC converter;
- improved system efficiency and power factor control can be implemented at lower cost, the converter has to provide only excitation energy [2].

Hence, taking advantage of power electronic advances in recent years, WECS equipped with doubly fed induction generator systems for variable speed wind turbine are one of the most efficient configurations for wind energy conversion.
Portugal is expected until 2010 to have 3750 MW of wind power due to government resolution 63/2003. (Table I) shows data for the wind power capacity installed and in the construction phase in Portugal, Madeira and Azores at December 2004 [3].
Hydro power in Portugal accounts for about 20.25% in an average year. While, wind energy accounts for about 1.7% of the total energy consumed in Portugal. This total figure is still too far from the established goal of 39% of the total energy produced in accordance with the Directive 2001/77/CE.

Table I. - Wind power, December 2004.

WECS	Portugal	Madeira	Azores	Total
Cons.(MW)	746.0	0.0	1.8	747.8
Inst. (MW)	505.5	9.6	5.3	520.4

Portugal WECS's are grid-connected systems and the last year statistic shows that doubly fed induction generator systems are the option preferred for the WECS recently installed and in construction phase.
This paper presents results of a study concerning the dynamic behaviour of a wind energy system powered by a doubly fed induction generator. Which is the actual preferred configuration for WECS in Portugal, due to the advantages.

We choose for the case study a WECS illustrated in Fig. 1, composed by a grid-connected system with a variable speed doubly fed induction generator.

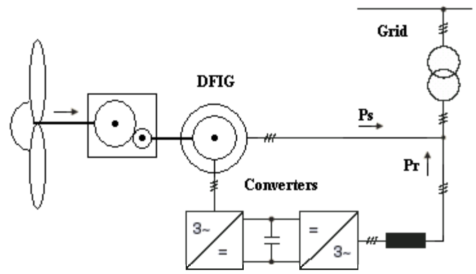

Fig. 1. Doubly fed induction generator WECS.

The system is equipped with controllers namely: pitch controller, speed controller and voltage controller.

2. Formulation

The turbine model is based on the following: the mechanical power of the turbine is given by

$$P_m = \frac{1}{8}\rho\,\pi\,D^2 v^3 c_p(\beta,\lambda_i) \tag{1}$$

where ρ is the air density, D is the diameter of the area covered by the movement of the blades, v is the wind speed, c_p is the power coefficient [4], we consider it given by

$$c_p(\beta,\lambda_i) = 0.73\left(\frac{151}{\lambda_i} - 0.002\,\beta - 13.2\right) e^{\frac{-18.4}{\lambda_i}}$$

where
$$\lambda_i = \frac{1}{\dfrac{1}{(\lambda + 0.08\,\beta)} - \dfrac{0.035}{(\beta^3+1)}}$$

and
$$\lambda = \frac{1}{2}\frac{D\,\omega_r}{v} \tag{2}$$

λ is the tip speed ratio, β is the pitch angle of rotor blades in degrees, ω_m is the mechanical angular speed. The power coefficient function in (2), is shown in (Fig.2) parameterised in function of the pitch angle.

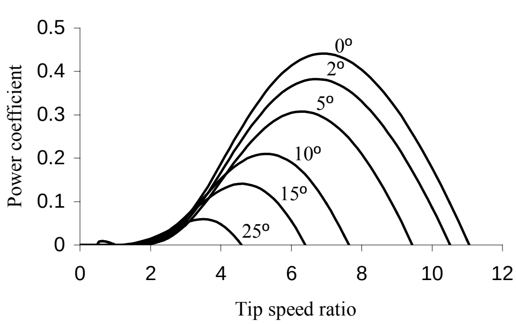

Fig. 2. Power coefficient.

At lower wind speed, the pitch angle is set to a null value, because, the maximum power coefficient is obtained for this angle. Hence, the maximum power coefficient is computed by the following nonlinear mathematical programming

$$c_p(0,\lambda_i)_{\max} = \max \quad 110.23\left(\frac{1}{\lambda} - 0.11976\right) e^{-18.4\ (1/\lambda - 0.003)}$$
$$\text{s.t}$$
$$\lambda \geq 0$$

giving $c_p(0,\lambda_i)_{\max} = 0.4412$ for $\lambda_{opt} = 6.9$ (3)

Pitch angle control operates only when the value for wind speed is greater than the nominal wind speed.
Half of the world's leading wind turbine manufacturers use the doubly fed induction generator systems. This is due to the fact that the power electronic converter only has to handle a fraction (20% – 30%) of the total power, i.e., the slip power. This means that if the speed is in the range ±30% around the synchronous speed, the converter has a rating of 30% of the rated turbine power, reducing the losses in the power electronic converter, compared to a system where the converter has to handle the total power. In addition, the cost of the converter becomes lower [1]. The doubly fed induction generator has been used in wind turbines for a long time. In the past, the AC-AC converter connected to the rotor consisted of a rectifier and inverter based on thyristor bridges [5]. Nowadays, AC-AC converters are equipped with bi-directional IGBT's [2], connecting the rotor of the variable speed doubly fed induction generator to the electrical grid.
The equation of rotor motion is given by

$$d\omega_r/dt = 2\,P_a/(J\omega_r) \tag{4}$$

where J is the moment of inertia due to the rotating mass and P_a is the rotor accelerate mechanical power. The angular velocity of the rotor is considered in the region $0.7\,\omega \leq \omega_r \leq 1.3\,\omega$ for the case study presented in this paper. The doubly fed induction generator equations, using the motor convention, are the following

$$\begin{aligned} d\lambda_{ds}/dt &= u_{ds} - R_s\,i_{ds} + \omega\lambda_{qs} \\ d\lambda_{qs}/dt &= u_{qs} - R_s\,i_{qs} - \omega\lambda_{ds} \\ d\lambda_{dr}/dt &= u_{dr} - R_r\,i_{dr} + s\omega\lambda_{qr} \\ d\lambda_{qr}/dt &= u_{qr} - R_r\,i_{qr} - s\omega\lambda_{dr} \end{aligned} \tag{5}$$

The stator electric values are indicated by the subscript s and the rotor electric values are indicated by the subscript r. u is a voltage, R is a resistance, i is a current, λ is a flux linkage. ω is the stator electrical frequency and s is the rotor slip. The flux linkages are given by

$$\begin{aligned} \lambda_{ds} &= L_s\,i_{ds} + M\,i_{dr} \\ \lambda_{qs} &= L_s\,i_{qs} + M\,i_{qr} \\ \lambda_{dr} &= L_r\,i_{dr} + M\,i_{ds} \\ \lambda_{qr} &= L_r\,i_{qr} + M\,i_{qs} \end{aligned} \tag{6}$$

L_s, L_r and M are respectively the stator and the rotor leakage inductance and the mutual inductance between the stator and the rotor. The stator and rotor active power [6] are given by

$$P_s = 3/2\,(u_{ds}i_{ds} + u_{qs}i_{qs})$$
$$P_r = 3/2\,(u_{dr}i_{dr} + u_{qr}i_{qr}) \tag{7}$$

The rotor accelerate mechanical power is given by

$$P_a = P_s - P_m - P_r \tag{8}$$

we neglected the mechanical losses, due to the small value normally achieved by this losses.

3. Case study

The main objective of the simulations is to evaluate the behaviour of the doubly fed induction generator system due to gusts of wind. We consider the wind speed change as shown in Fig. 3.

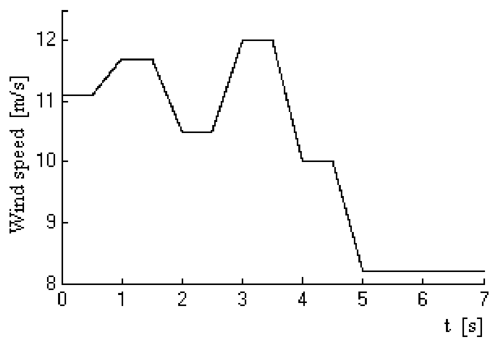

Fig. 3. Wind speed.

The mechanical power due to the wind speed change is shown in Fig. 4.

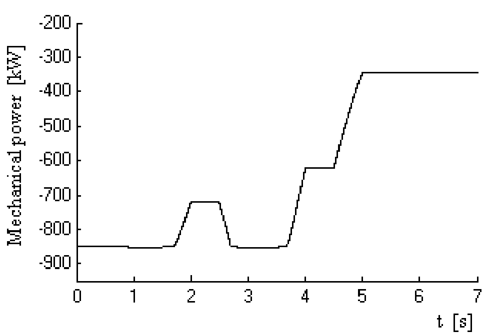

Fig. 4. Mechanical power.

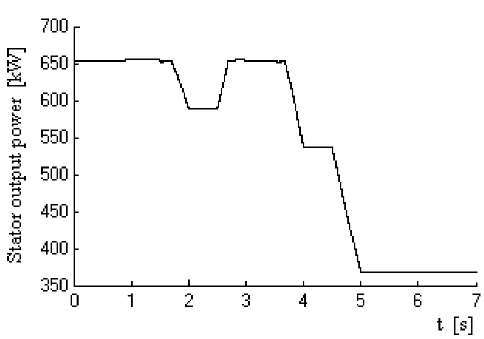

Fig. 5. Stator power.

Fig. 5 and Fig. 6 show respectively the behaviour of the stator power and of the rotor power.

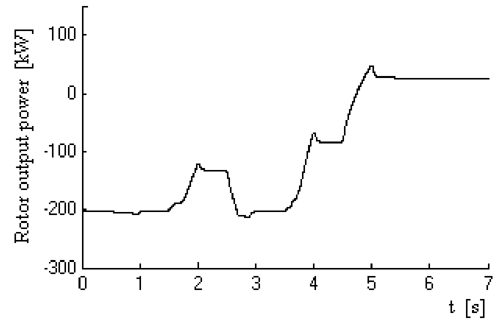

Fig. 6. Rotor power.

Fig. 7 shows the output power injected in electrical grid given by the difference of the stator power with the rotor power, due to the power convention followed.

Fig. 7. Output power.

Fig. 8 shows the corresponding pitch angle increase in order to limit the excursion of the mechanical power.

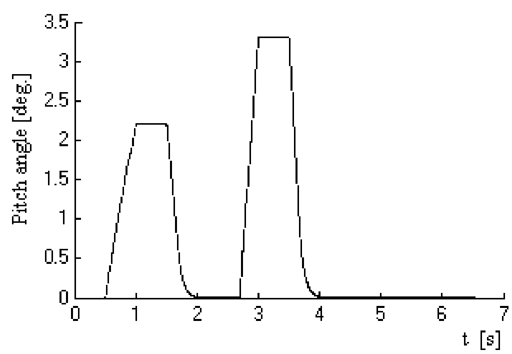

Fig. 8. Pitch angle.

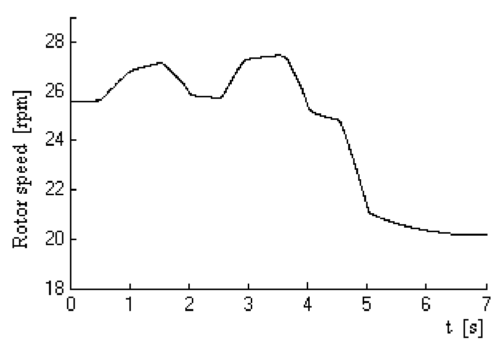

Fig. 9. Turbine rotor speed.

Fig. 9 and Fig. 10 show the turbine rotor speed and the rotor slip.

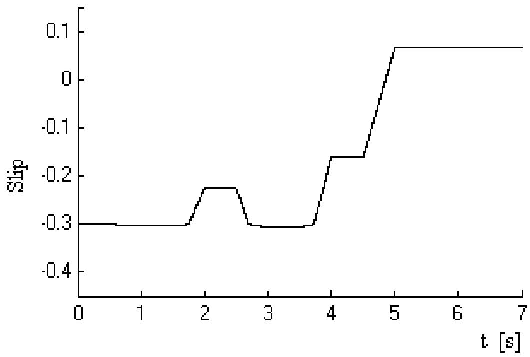

Fig. 10. Rotor slip.

The nominal power of the wind turbine is 850 kW and the nominal wind speed for the turbine is 11.4 m/s. The increase in the wind speed, Fig. 3, implies that the mechanical power has tendency to be greater than the nominal power for the turbine, but owing to the pitch angle control, Fig. 9, augmentation the mechanical power excursion is controlled in due time, Fig. 4. Afterwards, with the decrease in the wind speed, the mechanical power is reduced and the pitch angle returns to a null pitch angle.

4. Conclusions

Wind energy continues to move forward in Europe and deregulation provides an opportunity for investments in WECS. Hence, it is expected that wind power will be a significant component of the total generation mix in the near future.

Due to the advances in power electronics it is advantaged to use the doubly fed induction generator system with variable speed connected to the electrical grid through an AC-AC converter, improving the efficiency of the power conversion.

Without control, mechanical power can exceed nominal mechanical power in a wind turbine, due to wind speed increase above the nominal wind speed for the turbine. Hence, the WECS operation is unsustainable, getting out of running is one option to be faced.

For a horizontal axis wind turbine, pitch angle control is one method to control the peak of the mechanical power, returning to normal power condition without stopping the WECS. Our case studies show that the control of the pitch angle is able to limit the mechanical power excursion, but the response takes time to capture normal operation condition, depending on the inertia of the rotor.

Where the rotor speed is greater than the electrical synchronous speed of the stator, the slip is negative and the rotor delivers electric energy to the electric grid, due to the super-synchronous generating mode. This mode is a very efficient generating mode. In contrary, if the slip is positive, the rotor receives electric energy from the grid, but the stator keeps on delivering electric energy to the grid, this is, sub-synchronous generating mode.

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