

WORKING LIMITS OF A DOUBLY-FED INDUCTION WIND TURBINE

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ABSTRACT: The purpose of this paper is to show the working limits of a Variable Speed Wind Turbine. The system is based on a Doubly-Fed Induction Generator and a Fixed-Pitch Wind Turbine. The machine rotor is connected to the network through an AC/AC Converter in order to allow energy recovery. Thermal, mechanical and electric limits are investigated. The study of the machine is based on a steady state model, which provides an easy way to understand the physical behaviour related to the normal operation of the system.

Keywords: Variable-Speed Operation – 1, Models (Mathematical) – 2, Power Electronics – 3

1. INTRODUCTION

Nowadays, the Wind Energy Conversion Systems (WECS's) manufacturers are developing systems that can work at different speeds, Variable Speed Wind Turbines. So, the energy capture can be optimised and the mechanical stress can be reduced. There are several configurations [1][2] to achieve this behaviour, and the Doubly Feed Induction Generator (DFIG) have clear advantages over other configurations, e.g. the reduced size of the required electronic equipment (see Figure 1).

In this paper, a study of the capabilities of the DFIG scheme against a Fixed Speed Turbine is presented in order to see the possibilities of this configuration. The idea is well known (Kramer, Scherbius...) but the introduction of new technologies [3], e.g. GTO, help to develop these systems.

In this paper, the DFIG steady state behaviour is shown, in order to explore its limits.

2. MODEL

The elements of these systems are:

- Wind Turbine: in order to make the comparisons easier, a fixed pitch one has been chosen.
- DFIG: it is an induction machine with wound rotor and slip rings.

- AC/AC Converter: the energy transference between the rotor (low and variable frequency) and the network (fixed frequency) is possible by means of this device.

- Step-Down Transformer: it is used to increase the operation margin of the AC/AC Converter.

The model of these elements is depicted in the following sections.

2.1 Wind Turbine Model

The wind turbine is a fixed pitch one, and the expression for the power extracted from the wind is:

$$P_U = \frac{1}{2} \rho A U^3 c_p$$

where:

- ρ is the air density
- A is the swept area
- U is the wind speed
- c_p is the power coefficient

The power coefficient c_p is function of the tip speed ratio (λ):

$$\lambda = \frac{\Omega_r R}{U}$$

where:

Ω_r : is the turbine rotor speed.

R is the rotor radius

In the literature [4] several expressions for the function $c_p(\lambda)$ can be found. However, in this paper, a polynomial

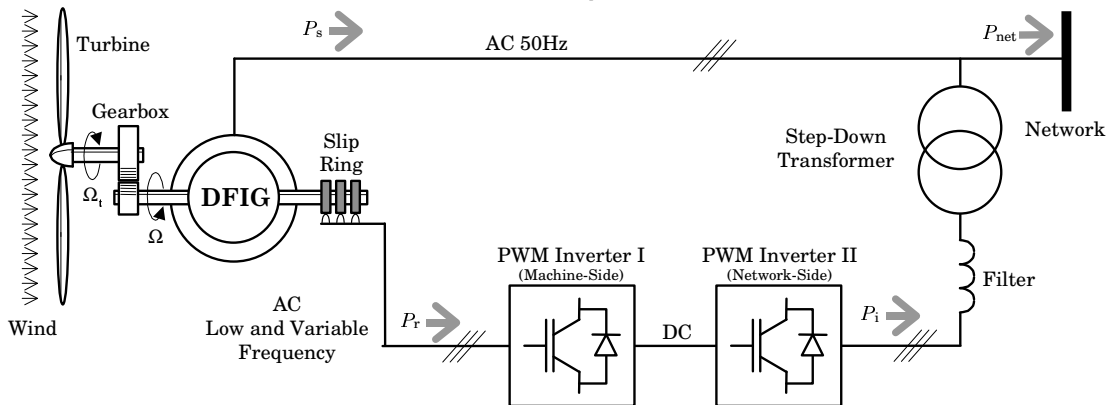


Figure 1: Variable Speed Fixed-Pitch Wind Turbine

approximation [5] is used (see Figure 2), so:

$$c_p = \sum_{k=1}^N a_k \lambda^k$$

where a_k are the polynomial coefficients.

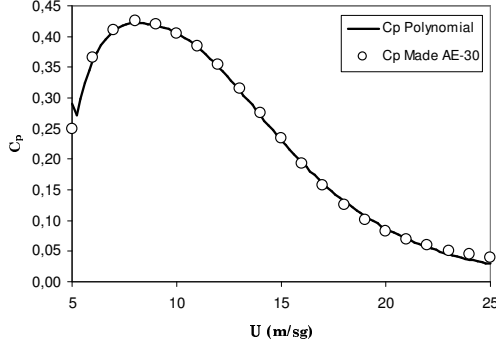


Figure 2: Approximation of $C_p(\lambda)$

2.2 DFIG Model

In this section a model for the DFIG is presented. The model is obtained from a d-q decomposition [6][7] and the equivalent scheme can be seen in Figure 3, where

- R_s, X_1, R_r, X_2 are the parameters of the machine
- $\bar{V}_s, \bar{V}_r, \bar{I}_s$ and \bar{I}_r are the voltages and currents in stator and rotor.
- s is the slip

The slip s is given by:

$$s = \frac{\omega_s - P\Omega}{\omega_s}$$

where:

- ω_s is the synchronous speed
- Ω is the DFIG rotor speed
- P is the number of pole pairs

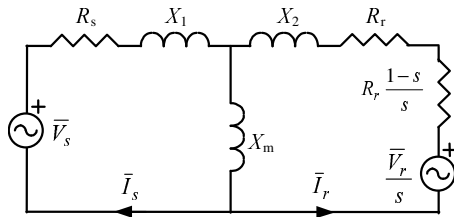


Figure 3: DFIG equivalent circuit.

The electromechanical equation used in steady state is:

$$\frac{P_m}{1-s} - P_e = 0$$

where P_m is the mechanical power from the turbine and P_e is the air-gap power:

$$P_e = \frac{1}{s} \left(\text{real} \{ \bar{V}_r \bar{I}_r^* \} - R_r |\bar{I}_r|^2 \right)$$

An amount of power is delivered (or injected) through the slip rings, the electric rotor power (P_r):

$$P_r = -\text{real} \{ \bar{V}_r \bar{I}_r^* \}$$

2.3 AC-AC Converter

In this system, it is necessary to allow energy flow between rotor and network. This is achieved by means of

an AC-AC Autonomous Converter [8], formed by two PWM Converters (machine-side and network-side).

In this paper, the high-frequency components of voltage and current are neglected due to the presence of rotor and the filter reactances, and the high commutation frequency used by PWM converters.

Machine-side converter connects the rotor and the DC-side, and then its modulation values are given by:

$$m_I = \frac{\sqrt{2} |\bar{V}_r|}{E} \quad \delta_I = \angle \bar{V}_r$$

where:

- E is the DC voltage, it is fixed at constant value
- m_I is the modulation index
- δ_I is the modulation angle.

The modulation parameters of network-side converter are used to control the delivered active (P_i) and reactive (Q_i) power, so:

$$m_{II} = \frac{\sqrt{2} k_i |\bar{V}_s|}{E} \sqrt{\frac{X_f P_i}{k_t^2 |\bar{V}_s|^2} \left(1 + \frac{X_f Q_i}{k_t^2 |\bar{V}_s|^2} \right)}$$

$$\tan(\delta_{II}) = \frac{X_f P_i}{k_t^2 |\bar{V}_s|^2} \left(1 + \frac{X_f Q_i}{k_t^2 |\bar{V}_s|^2} \right)^{-1}$$

where:

- m_{II} is the modulation index
- δ_{II} is the modulation angle.
- X_f is the filtering reactance and transformer reactance.
- k_i is the transformer ratio
- P_i is the active power delivered to the network
- Q_i is the reactive power delivered to the network

When the losses in the converter are neglected, the value of P_i is equal to P_r , so:

$$P_{net} = P_i + P_s = P_r + P_s$$

where P_s is the stator electric power.

The Q_i value can be fixed at zero to minimize the necessary converter size. However, another criterion for its value can be followed (e.g. $Q_{net} = 0$)

Rotor side frequency, and so slip, is determined by the machine-side Converter, by the relation:

$$P\Omega = \omega_s + \omega_I$$

where ω_I is the frequency of rotor and machine-side converter currents.

Network-side converter currents must have the network or synchronous frequency (e.g. 50Hz).

2.4 Limits

In order to obtain the working limits some constraints must be taken into account:

DFIG: the current values must be under their nominal value, ($|\bar{I}_r| < 1 pu, |\bar{I}_s| < 1 pu$)

TURBINE: The power of the turbine (P_m) must be under its limit, and tip speed ratio between its minimum and maximum values.

AC/AC CONVERTER: Modulation index (m_i, m_{II}) cannot be greater than 1.

3. RESULTS

Once the models and constraints have been established, the simulation of steady state conditions is made. For this purpose, two control strategies have been simulated:

- *Constant Power*: power extracted from wind is maintained constant against wind variations.
- *Maximum Power*: the system operates to obtain the maximum energy from the wind.

In both cases, the reactive power of network-side converter is zero, and the voltage in the DC-side is maintained at a constant value.

The next figures show the evolution of the power injected into the network (P_{net}), slip (s) and rotor electrical power (P_r) at different mechanical powers (P_m) and wind speeds (U).

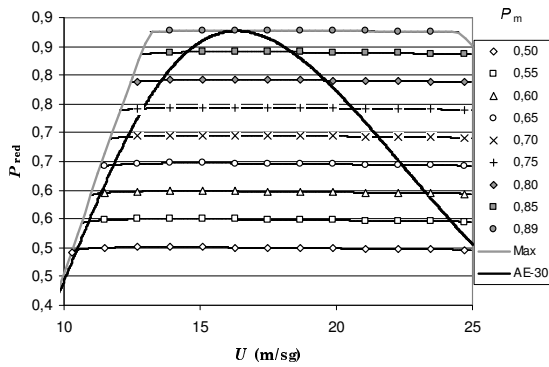


Figure 4: Power injected in the network (P_{net}).

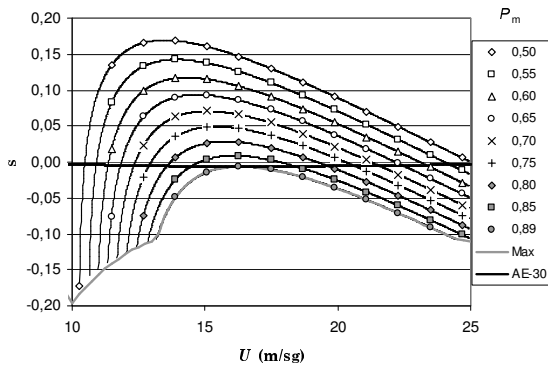


Figure 5: Slip (s) evolution.

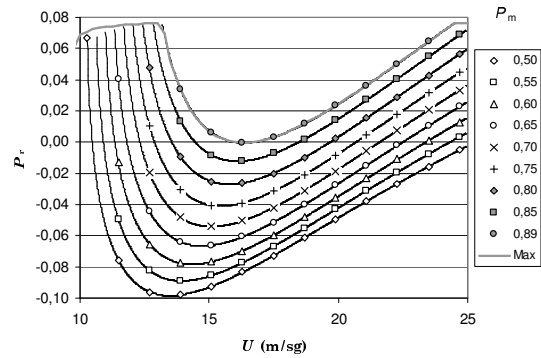


Figure 6: Rotor Electrical Power (P_r).

As can be seen in Figure 4, in the constant power strategy, constant values of P_{net} can be achieved for a wide range of wind speeds (U). In other way, with the maximum power strategy, high values of power are injected into the network over the entire simulated wind speed range. The slip evolution in Figure 5 shows that variations until the 20%.

Values of P_r shown in Figure 6 are related to the size of AC/AC converter (until 10% of DFIG nominal power). So, the size requirements for the converters in this kind of systems are low.

Next figures show the rotor voltage evolution during both constant power and maximum power strategies. These figures can help us to choose appropriate values for DC-side voltage and step-down transformer ratio.

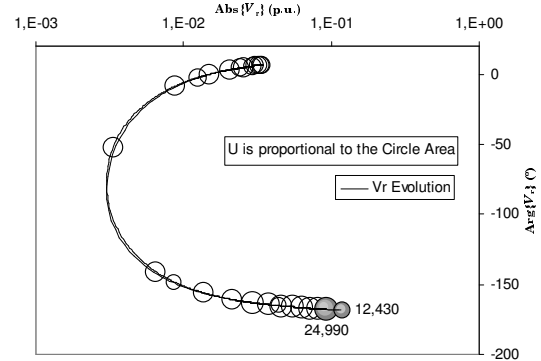


Figure 7: V_r and U evolution with $P_m = 0,8$ pu.

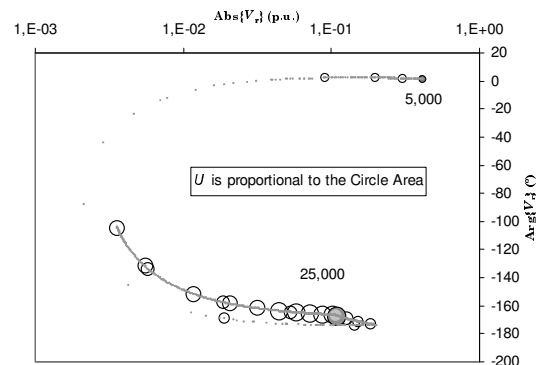


Figure 8: V_r and U evolution with maximum P_m

4. CONCLUSIONS

A set of steady state simulations is presented in this paper in order to evaluate the behaviour of a variable-speed wind energy converter. As can be seen, the main advantage of this system is the reduced size of the AC/AC converter and behaviour improvement with respect to fixed systems. The model used here can be used as a tool for dimensioning the elements involved in the conversion (converters, transformer...).

The presented system is very simple and can be improved by means of a variable pitch wind turbine, which a solution used by some WECS manufacturers.

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