Model, design, analysis and state-of-the-art control from *the blowing wind* to *the sinusoidal voltages and currents*

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1 Introduction

The interest in windmill electrical distributed generation installation based on renewable energies has been growing for the last decade due to the environmental benefits and the energy independence from the fossil combustion. It is undeniable the remarkable increment achieved in Spain and all Europe recently as regards the windmill electrical energy. This propagation is willing to continue, and the figure of 150GW-installed power is the target for 2020 in all Europe.

Naturally, in parallel with this spectacular growth in wind electrical energy, it is achieved an evolution of the used technology. From the first Wind Turbines (WT) of constant speed, based on squirrel cage induction generators and low power (around 100kW), it has evolved to variable speed turbines used nowadays, which are based on Double Fed Asynchronous Generators or Permanent Magnet Synchronous Generators, whose rated power can achieve up to 5MW per unit (Fig. 1).

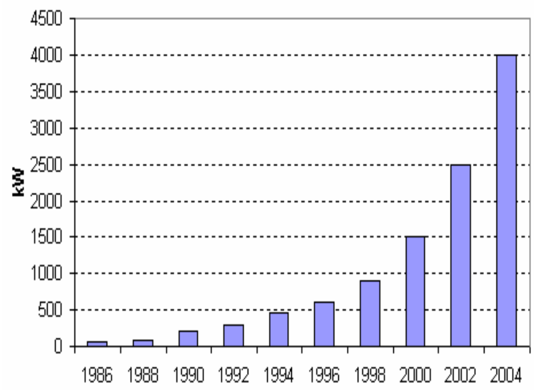

Fig. 1. Evolution of total power accumulated per Generator.

With this energy production novel scenario, arises the need to develop state of the art criteria, knowledge and background to responsibly face the novel challenges such as equipment costs reduction, reliability and power quality improvements.

In order to face these continuous improvements and challenges, this paper proposes a model description of the whole system, addressing not only a deep block diagram analysis but also all *hot topics* in the design and control of the entire system.

Fig. 2 shows the whole scheme, which is modelled and analysed in this research, for further state of the art control improvements.

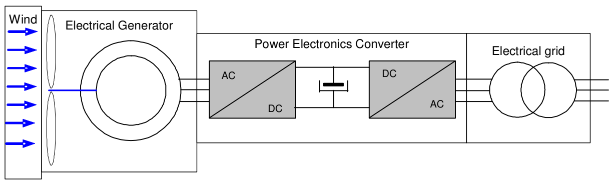

Fig. 2. Electrical Wind turbine scheme.

2 Wind modeling

The *blowing wind* is transformed in mechanical torque in the WT blades which will make the Generator to turn to finally generate electrical energy. In this section it is presented a first approach to model such torque created by the wind. Several expressions have been proposed in order to calculate the torque from physical parameters of wind speed; being one of the most recent expressions the following one [1]:

$$Q_a = \tfrac{1}{2}\rho\pi r^2 \frac{|\vec{v}|^3}{\omega_r} c_P(\beta,\lambda) \qquad (1)$$

being: Q_a the torque, ρ the air density, r the rotor radius, $|\vec{v}|$ the module of effective wind speed (celerity), ω_r the rotor angular speed, β the pitch position, $\lambda = |\vec{v}|^{-1}\omega_r r$ the tip speed ratio and $c_P(\beta,\lambda)$ the power coefficient.

It is assumed that the average in uniform time periods of wind celerity $|\vec{v}|$, follows a Weibull distribution. The data set used in this work consists of wind velocity measures at different highs; data consists on average wind velocity (module) in 5 minutes' interval, taken 20 times per second. Assuming the high of the tower as 32 m, parameters founded of Weibull distribution of wind speed data are $k = 2.278$ (shape parameter) and $c = 0.015$ (scale parameter); those values have been obtained by applying maximum likelihood method [2]. From data set, average daily values of wind celerity are obtained; for a 20-days period, a 6-degree polynomial is used for fitting wind celerity as a function of time, with a correlation coefficient $R^2 = 0.817$ and finally equation (2) is obtained. Fig. 3 illustrates these data values and the fitted function.

$$|\vec{v}|(t) = -0.00003t^6 + 0.0017t^5 - 0.0365t^4 + \\ + 0.3811t^3 - 2.0146t^2 + 4.5001t + 3.5419 \qquad (2)$$

Once this function is obtained, expression (1) can be applied to obtain the torque as a function of time. Fig. 4 shows three simulated functions corresponding and the values are listed on Table 1.

This methodology can be applied for different time periods, depending on data information, and also can be used with wind values forecasting.

Table 1. Torque values Simulation parameters

Air density	$\rho = 1.297\,\mathrm{kg/m^3}$
Power coefficient	$c_P = 0.4$
Rotor radius,	$r = 15\,\mathrm{m}$
Rotor angular speed	(a) $\omega_r = 1.5\,\mathrm{s^{-1}}$ (b) $\omega_r = 2.5\,\mathrm{s^{-1}}$ (c) $\omega_r = 3.5\,\mathrm{s^{-1}}$

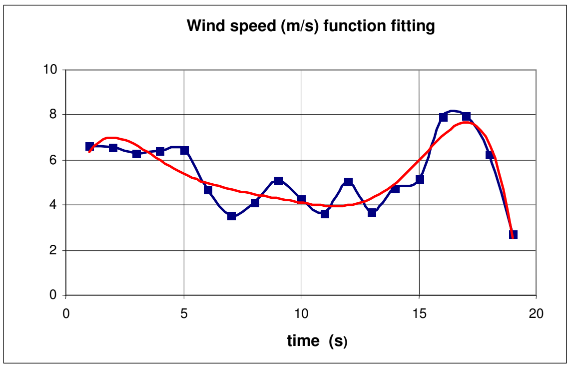

Fig. 3. Wind celerity time samples (blue) and fitted function (red).

To sum up, it must be mentioned that the time torque function produced by the *blowing wind* can be obtained from wind celerity function and tower and air parameters, from a function fitted using wind data information.

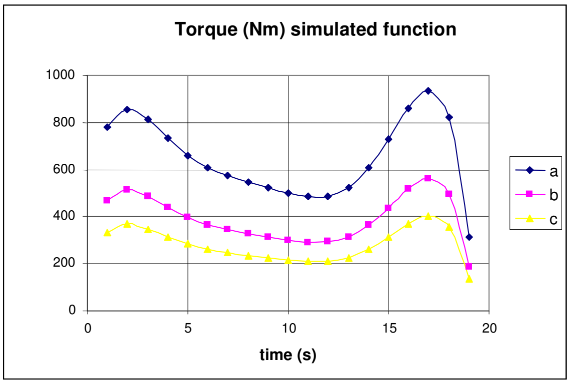

Fig. 4. Torque for three different rotor speeds.

3 Electrical Generator

A. Electrical Generator Types

There are mainly two different options as regards the Electrical Generator: the Double Fed Asynchronous Generator (DFAG) and the Permanent Magnet Synchronous Generator (PMSG) as Fig. 5 and Fig. 6 illustrates.

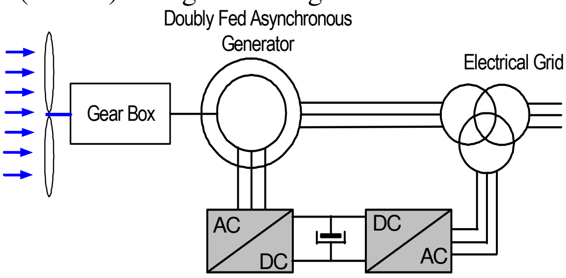

Fig. 5. Doubly Fed Asynchronous Generator scheme

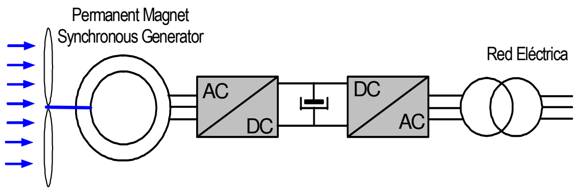

Fig. 6. Permanent Magnet Synchronous Generator scheme

As the name indicates, the DFAG has two power (three phase) connections, feeding not only the stator, which is directly connected to the mains, but also the rotor, which is the one controlled by means of a proper fully controlled PWM inverter and rectifier with the so called back to back connection. The most important advantage of this option is the fact that the rotor part handles just one third of the total electrical power of the EG and hence the Power Electronics Converters are dimensioned for such reduced power factor.

Alternatively, PMSG are gaining market because of its higher power density, higher efficiency and better dynamic performance. As it's name indicates Permanent Magnet (PM) machines are characterised by the use of magnetic material to establish the flux, which replaces the electromagnetic field excitation in electric machines having several advantages. The most obvious advantage for using permanent magnets to replace electromagnetic excitation is the absence of excitation losses which increases the efficiency of the motor. Additionally, the placement of the magnets in the rotor concentrate the conduction losses in the stator where they are easily dissipated. This allows for smaller rotor diameters and smaller total motor sizes, resulting in higher power density and lower rotor inertia. It is a fact also that PM machines are already introduced in applications where the savings in energy offset the higher initial cost such as WT [3,4].

B. Electrical Generator Control

Many EG control methods exist, but among them Field Orientated Control (FOC) and Direct Torque Control (DTC) deserve special attention since both techniques can be considered as high performance vector controllers based on the flux and torque decoupling. Both methods are considered vector methods, which imply that all electrical machine variables, such as currents, voltages and magnetic fluxes, are expressed mathematically as space vectors, and therefore characterised by an angle position and a magnitude. These Vector Control methods act controlling these space vectors during both transient and steady-state conditions, providing an accurate control of all variables each sampling period (which usually is around 100µs). In both methods, the aim is to decouple the EG like in DC motors. Therefore, there are mainly two control and independent loops, one for the torque and the other for the magnetic flux.

being currently highly developed and it can be considered as a mature and state of the art technique, being available on the market of variable speed drives from several manufacturers.

Fig. 7 illustrates a FOC scheme, where the mentioned two control loops are the d and q currents components which control through a conventional PI the EG flux and torque respectively. These two current PIs give the so-called voltage reference value which is synthesised by means of a Voltage Modulator, being the most popular and used the Space Vector Modulator.

The overall performance is directly proportional to the PIs bandwidth, being a typical step response value a few *ms*.

There is also and outer and much slower control loop for the EG speed, whose bandwidth and step response time will depend on the mechanical inertia of the whole system including the WT blades.

The FOC inconveniences are the high computational level required and the mandatory use of a Voltage Modulator. On the other hand the advantages are an accurate control of the EG and the constant switching frequency.

In the mid 1980s, when there was a trend toward standardization of the control system based on the FOC principle, a new technique called Direct Torque Control (DTC) appeared. It was introduced by Isao Takahashi and Toshihiko Noguchi [6]. M. Depenbrock introduced a similar idea under the name Direct-Self Control (DSC) [7]. This method has emerged over the last two decades to become one possible alternative to FOC.

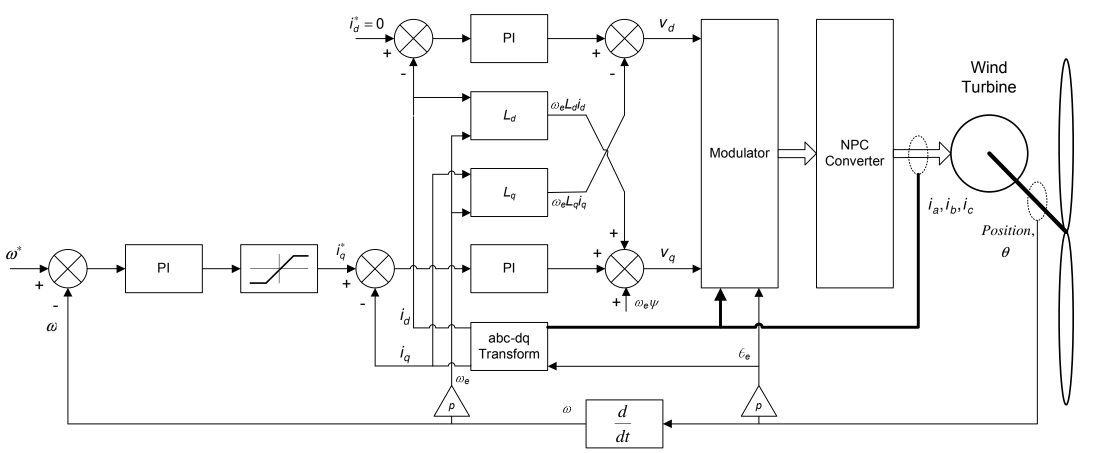

Fig. 7. Field Oriented Control scheme.

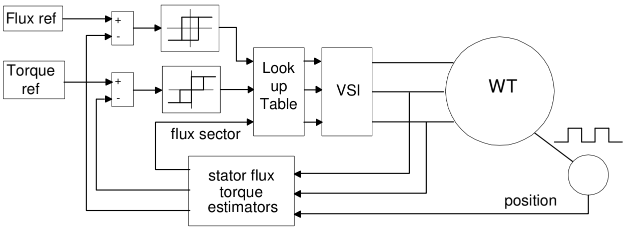

Fig. 8. Direct Torque Control scheme.

The basic motivation for their work was to obtain a faster torque response. This was achieved by directly controlling the stator flux vector by means of the stator voltage without employing current control loops and voltage modulators, as Fig. 8 shows, resulting in its major advantage together with the simplicity of the method. In DTC the step time response for torque is reduced ten times when compared to FOC. However, DTC disadvantages are the ripple which exists in the torque and flux variables. This undesirable ripple is of higher value when the selected state of the inverter remains unchanged for several sampling periods, which accordingly implies that the switching frequency of the inverter is not constant. The first commercial drive based on the DTC principle was developed by the AC drives division of the company Asea Brown Bovery (ABB), and it was commercially launched in 1995 [8,9]. Since then DTC has gained a large acknowledgement from industry and academia [10].

C. Sensorless control

The accurate control of these machines requires rotor position information to realize the coordinate transformation of the vector control and to obtain speed and position feedback control signals. Optical encoders or magnetic resolvers are normally fitted to the machine shaft in order to directly measure these variables. This has the disadvantages of adding to the total cost and size of the drive as well as reducing its reliability. For these reasons, significant research efforts have been conducted in order to achieve Sensorless (without encoders or resolvers) Vector Control. These techniques can be broadly divided into model based techniques, where the back-emf of the machine is used for rotor magnet flux detection and injection techniques where a probe signal, usually high-frequency (*hf*) AC voltage or voltage pulses, are used to detect the rotor saliency position.

Model based techniques e.g. [11-13], successfully achieve sensorless control at medium and high rotor speed but fail at low excitation frequencies due to the reduction and eventual disappearance of the back-emf induced by the rotor magnets at low rotor speed. Injection methods, on the other hand, detect the angular dependent saliency of the machine and rotor position estimation is fundamentally speed independent [14-17]. Several variations of the method have been proposed. In [14,15] a *hf* rotating voltage vector is applied in the stationary frame and the rotor position information is obtained by demodulating the resulting *hf* currents. In [16,17] a pulsating voltage is applied in a synchronous frame in order to track the orientation of the minimum inductance; only the orientation error is extracted from the measured *hf* currents and the rotor position information is obtained with a tracking observer.

4 Power Electronics Converter

A. *AC-DC-AC* topologies

The use of Power Electronics Converters, to make the rotational speed of the blades independent of the utility frequency, is traditionally solved with standard Voltage Source Inverters (VSI). However, other options are addressed in this research, which are Matrix Converters and three level VSI. The former has the potential for improved power density and reliability in addition to regenerative power flow. Moreover, sinusoidal input currents and the lack of significant energy storage are interesting advantages [18].

The latter are especially indicated since the rated power of wind generators is expected to grow up further in the near future [19] and high-power converter topologies will play an important roll in this field. Multilevel converters are especially interesting for power values above 2-3 MW. Among the various multilevel topologies, the most widely used nowadays is the three-level neutral-point-clamped (NPC) converter [20].

B. Power Electronic Converter Control

One side of the Power Converter is connected to the grid, and it is supposed to inject the Power to the mains at a constant frequency of 50Hz, while the other side is connected to the EG which provides a variable frequency and voltage.

The control of part of the converter connected to the mains can be considered as a dual problem with vector control of an EG [21].

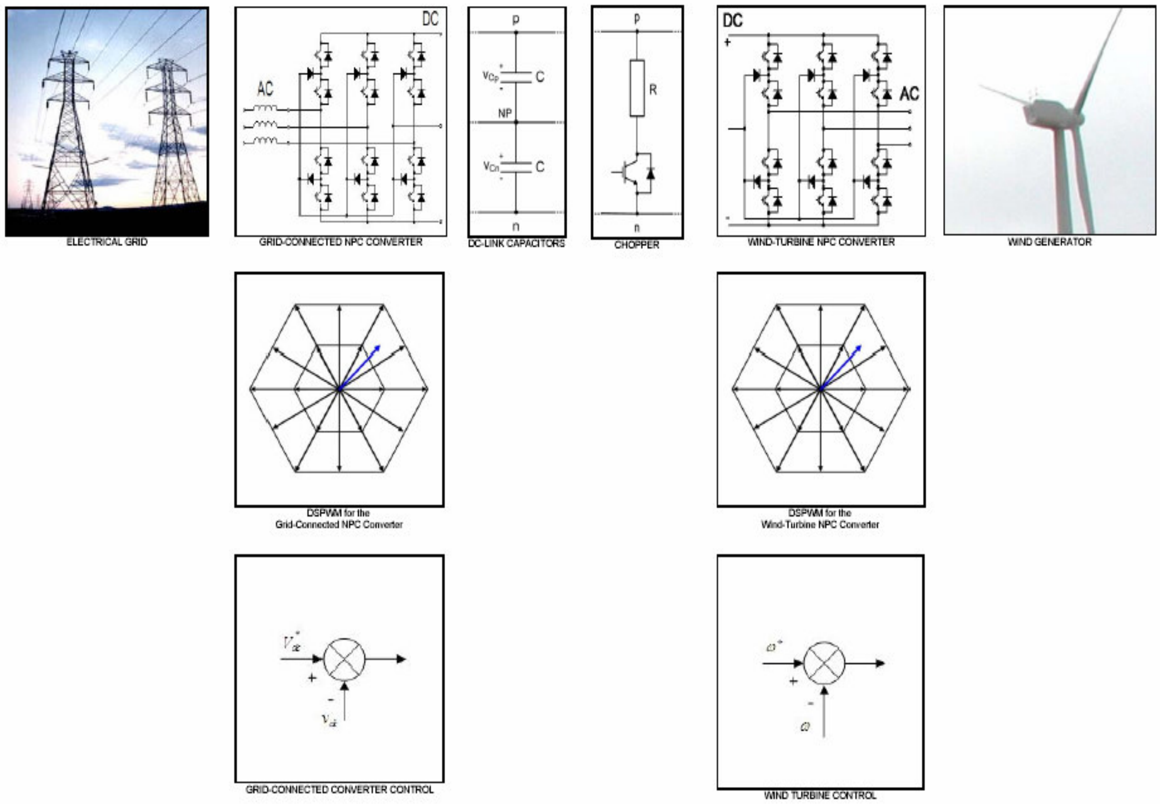

Fig. 9. Modular Matlab-Simulink program of the wind generation system.

The FOC equivalent for the mains side is called Voltage Oriented Control and the DTC one is called Direct Power Control. Following this analogy, the decoupled control of the mains power converter is achieved controlling the variables of active power instead of torque and reactive power instead of magnetic field.

C. Electrical Grid

The fact that WT supplies the electrical grid might end up in a power quality reduction [22,23]. The first issue to consider is the not constant behaviour of the injected power, mainly due to the fact that it depends on the wind which is not constant either. The other problem occurs when there is a mains cut, since the WT itself can not supply its power to the grid and its rotational parts might accelerate which might end up in a disconnection. In order to smooth the instant power value delivered to the grid and to improve its quality, energy storage elements such as inductors must be considered, which must already be considered when Power Converters are used.

5 Results

Some Matlab-Simulink simulations of the wind-generation system were performed. The program was made in a modular way, so that each module can be substituted by another one provided the input and output variables are the same as shown in Fig 9.

A particular multi-pole PMSG has been specially designed for this project. The generator has an external rotor to where the mill blades will be directly assembled in the final system. At the prototype level, the generator is just propelled by means of a motor drive system.

A FOC is applied to the generator-connected converter.

The data used in the simulations are defined regarding the experimental set up of the laboratory, which are; V_{grid}= 380 V (rms line-to-line), f_g=50 Hz, L_g= 6 mH, C=4.4 mF, V_{dc}=750 V, and switching frequency of f_s=5 kHz for the two converters.

The nominal specifications of the PMSG are: 10 pair of poles, nominal power 13.5 kW, voltage 380 V, currents 20.5 A, torque 1,200 Nm and rotational speed 120 rpm. An acceleration process of the wind turbine is shown in Fig. 10. The speed reference is 10 rd/s and the torque 1000 Nm. In this process, the rotational speed reaches the reference value in about one second. Observe how the amplitudes of the currents are adjusted to control the WT.

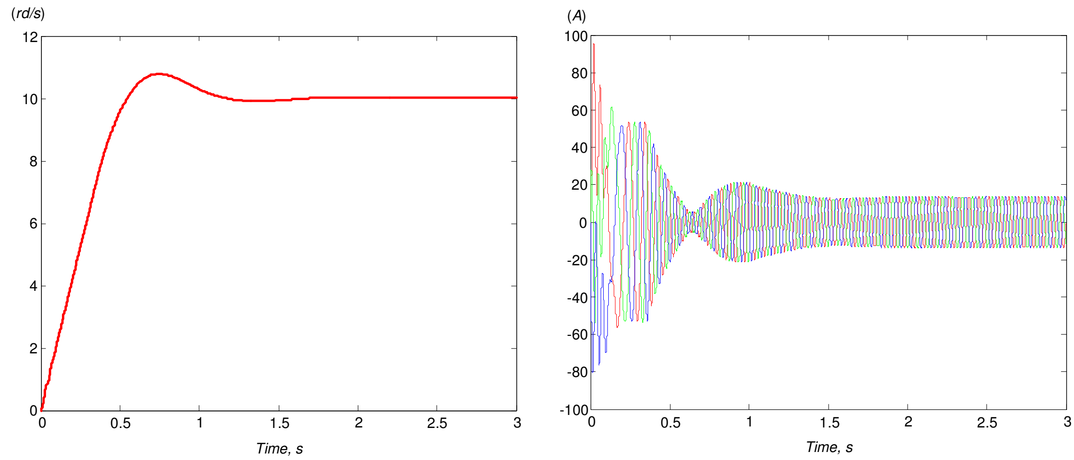

Fig. 10: Acceleration of the wind turbine: (a) angular speed and (b) generator currents.

During the initial acceleration, the transformed current references provided to the inner control loop are saturated to the rated values of the converter.

6 Conclusions

This paper is meant to answer wind energy sector enterprises' questions in order to face the future with warranties. A multi disciplinary research team is working in order to provide knowledge from the air Physics to Power Converters Design and Control and Electrical Machines. The model presented in this paper is also meant to help in the real prototypes' design and building processes as well as performance evaluation.

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