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Control of a variable speed and permanent magnet wind turbine: GARBI 150

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Abstract. This paper describes the revolutionary new wind turbine GARBI 150. The 150 kW permanent magnet synchronous generator and its full power converter with control in four quadrants make it interesting in medium scale wind power applications.
The generator allows direct connection to the electrical distribution grid.
The torque and pitch control have been designed to maximize energy capture and minimize fatigue loading of the turbine structure. These controllers are being validated with a first wind turbine prototype. A supervision system has also been implemented.

Key words

Permanent magnet generator, wind turbine, variable speed, control.

1. Introduction

Variable speed wind turbines with multipole permanent magnet synchronous generators (PSMG) and full-scale power converters are being used more frequently in wind turbine application. A multipole synchronous generator connected to a power converter can operate at low speeds, thus a gearbox can be omitted. However, this turbine has a gearbox with a relation of 8.5.
The GARBI 150 dynamical modelling scheme consists of a wind aerodynamic, mechanical and electrical system as well as a full power converter and wind turbine control [1].

The objective of this paper is to describe the implementation of a permanent magnet synchronous generator to a new medium power wind turbine of 150 kW. The design of this new wind generator tries to respond to the necessities of small industries beyond the electrical energy produced by wind farms. Following the basic technical characteristics of the wind turbine, we will now present control architecture and strategies used to maximize energy capture.

2. Electrical-Mechanical Design

The wind turbine has been designed as a three bladed, variable speed wind generator with a gearbox and synchronous generator.
The blade geometry has been designed to obtain the best aerodynamic performance and optimal structural design. The height of the hub is 35m and rotor diameter 28 m. The system has been equipped with multiple sensors for its control and supervision.
Power regulation is carried out by a hydraulic collective pitch system based on one hydraulic cylinder located in the shaft. Rotor and nacelle are up-wind oriented and are aligned towards wind direction by means of an active yaw system consisting of four electrical motors.
The power of the turbine is controlled according to a characteristic "design power curve" (see [2]) shown in Figure 1. The three most important values $V_{cut\text{-}in}$, V_{rated} and $V_{cut.out}$ are 2,5, 10.4 and 20 m/s, respectively.

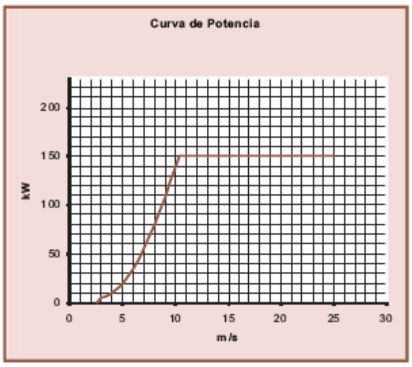

Fig. 1.·Wind turbine power curve

The electrical system is based on a synchronous gear driven generator and a converter for full power conversion: The converter system is used in order to adapt the voltage frequency in the rotor circle of the generator. This allows synchronization between the grid frequency and the rotational frequency of the generator. On the generator side the full power converter controls wind generator frequency (speed), torque and voltage. On the grid side the full power converter regulates the DC bus voltage of the intermediate circuit as well as providing the required active and reactive power to the grid combined with a power quality control for low harmonic distortion of the currents. The full power converter control has been specifically designed for this wind turbine by a leading commercial brand.

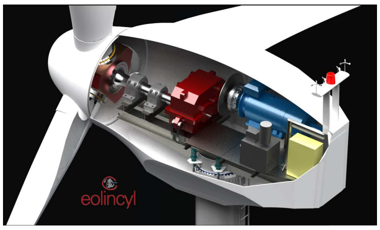

Fig. 2.· GARBI-150. Wind Turbine Scheme

3. System Modelling

The output power of the turbine is given by the following equation:

$$P_m = C_p(\lambda,\beta)\frac{\rho A}{2}v^3 \qquad (1)$$

where ρ is the air density, A is the turbine swept area, v is the wind speed and the power coefficient C_p.

The power coefficient is a non linear function depending on the tip speed ratio λ and β blade pitch angle. $C_p = C_p(\lambda,\beta)$.

λ is defined as

$$\lambda = \frac{\omega R}{v} \qquad (2)$$

where ω is the rotation speed of the rotor, R is the rotor radius and v the wind speed.

C_p value is calculated using a generic equation proposed in [3] given by

$$C_p(\lambda,\beta) = 0.258\left(\frac{100}{\lambda_i} - 0.4\beta - 2.164\right)\exp\left(\frac{-15.21}{\lambda_i}\right) + 0.00571\lambda$$

where

$$\lambda_i = \left[\frac{1}{(\lambda + 0.08\beta)} - \frac{0.035}{(\beta^3 + 1)}\right]^{-1} \qquad (3)$$

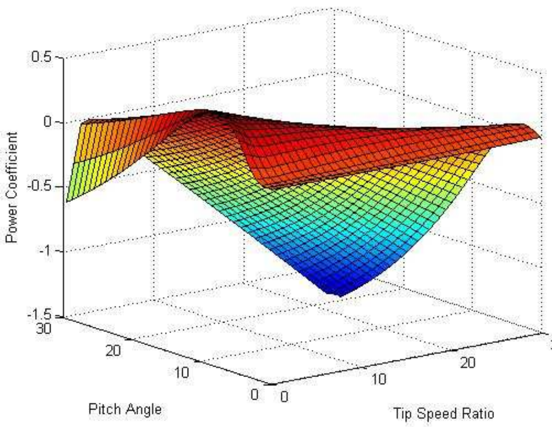

Fig. 3. Power coefficient curve

The power coefficient function is displayed in Fig 3.

Any change in the rotor speed or the wind speed induces a change in the tip speed ratio leading to power coefficient Cp. Figure 4 shows C_p performance versus tip speed ratio for different values of β.

The maximum power coefficient is $C_{p\text{-}max}$=0.49 and is obtained for β=0 and an optimum tip speed ratio λ_{opt}=7.96 that corresponds to the maximum energy captured from the wind.

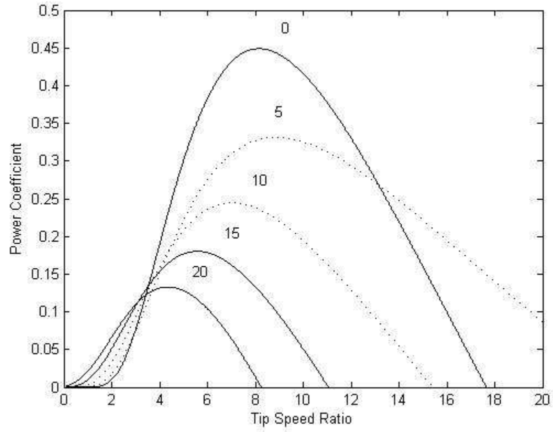

Fig. 4.·Power coefficient Cp

The mechanical model of the turbine is calculated taking into consideration the following equation:

$$J\frac{d\omega_m}{dt} = T_m - T_{em} - k\omega \qquad (4)$$

where

J is the rotational inertia of the rotor, gearbox, shaft and generator.

T_{em} is the generator electromagnetic torque

k is the shaft friction coefficient.

4. Control Strategies

The variable speed control system of the GARBI turbine implemented corresponds to an indirect control of speed [4]. This pitch system control has the objective to limit the speed of the generator instead of limiting its power. It has two controllers:

-**Torque Control** generates the active power reference signal in order for the torque power control loop to maximize energy capture. This reference signal is determined by the predefined characteristic P-W look-up table, depicted in Figure 5. This characteristic is based on aerodynamic data of the wind turbine's rotor and it corresponds to the maximum aerodynamic efficiency.

At lower wind speed, the pitch angle is set to a null value by speed control. In this case the torque control operates changing the value of the generator torque according to generator speed as is shown in Figure 5.

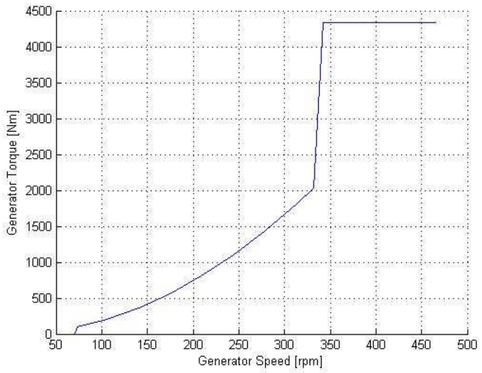

Fig. 5. Generator torque versus speed curve

- **Speed Control** the primary objective is to keep power output of the turbine and associated loads on the turbine structure within design limits. The pitch control is required to adjust the pitch angle of the rotor blades to maintain the peak rotor below the rated speed.

Speed control loop is based on PID cascade control systems with two PI controllers.

The error between the measured generator speed and the reference generator speed is sent to the master control. The output of this PI-controller is used as a reference pitch signal to the pitch system. This signal is then compared to the actual pitch angle and the error is corrected by the hydraulic pitch actuator. Due to the fact that the aerodynamic torque sensitivity does not change linearly with pitch angle a gain scheduling control has been implemented in order to compensate this variation. Figure 6 explicitly illustrates the PID cascade control.

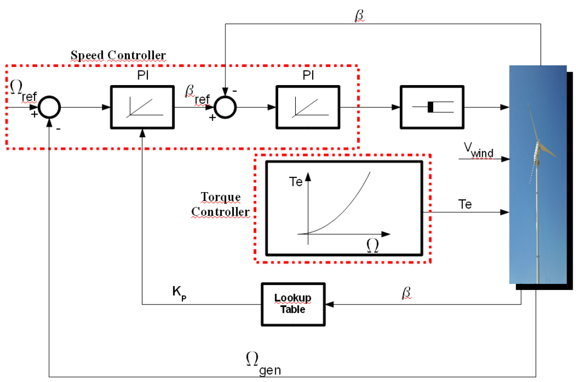

Fig. 6. Block diagram of the GARBI-150 control system

In this approach both control loops run together, while one of them is running the other control loop is into saturation depending on rated wind speed. There are useful methods [5] to avoid interferences when both controllers are operating around the rated point.

5. Simulation Results

The wind turbine control systems were simulated using a MATLAB/SIMULINK tool to evaluate the system's performance. In Figure 7 the power coefficient, pitch angle and speed generator are shown for increases in wind of 0.5 m/s.

These results show real wind turbine behaviour in the power control regions of wind turbine shown in Fig 1.

For low wind speeds below 7.6 m/s the turbine operates at a maximum power coefficient. The rotational speed of the rotor is variable due to power reference signal of the torque control.

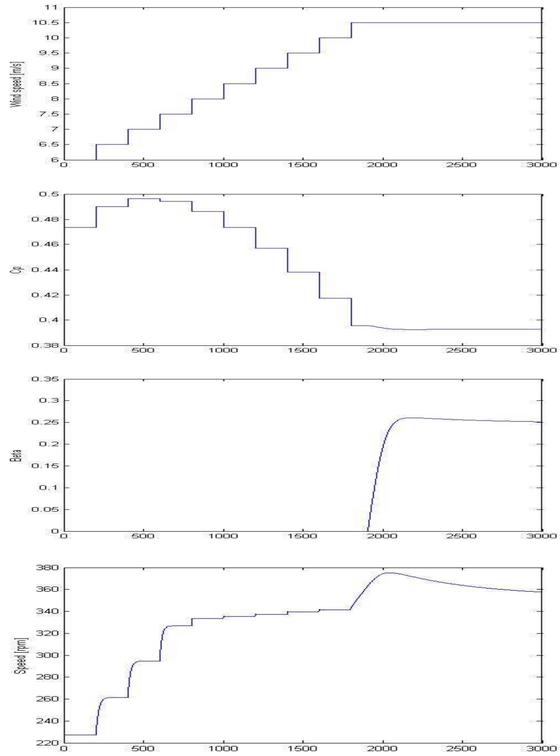

Fig. 7. Torque and speed control upon wind increase

For wind speeds of 7.6 m/s to 10.4 m/s the turbine operates with a constant speed of 350 rpm and the tip speed ratio goes down according to wind speed. The cp decreases slightly; therefore the mechanical power of the rotor deviates from optimal power curve of the rotor. At this point the power reference signal is at its maximum. In both cases, the speed controller is passive, keeping the pitch angle constant to the optimal value (zero).

At 10 m/s rated power is reached and rotor speed is controlled by pitch adjustment.

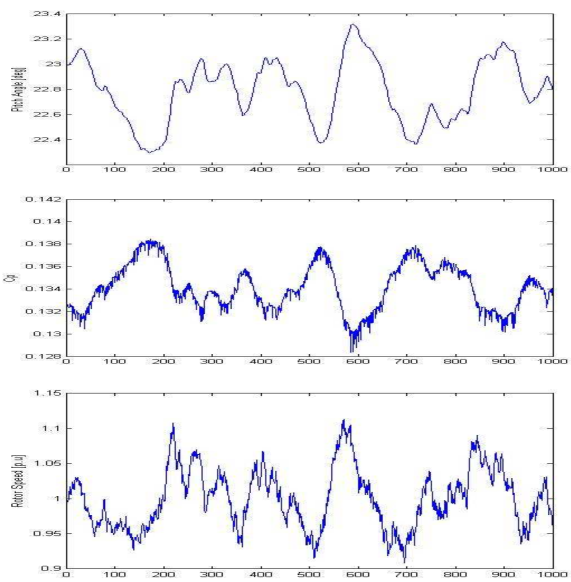

Fig. 8. Cp, pitch angle and rotor speed using control speed control strategy

Figure 8 shows simulation results under stochastic wind conditions with a mean of 15 m/s and a turbulence intensity of 10%.
The pitch angle and speed signal reflect the stochastic character of the wind.
Above rated wind speed the speed control controls the generator speed and indirectly the power output to their rated values.

6. Conclusion

The present paper has shown the GARBI 150 a new medium power wind turbine designed by Electria Wind (Figure 9).
The enter design of this new variable speed wind turbine with a multipole permanent magnet synchronous generator represents an efficient and low maintenance solution, which can be beneficial for medium power applications.
Simulations show the behaviour of torque and speed control within a range of normal operations. Experimental results are being analysed at this moment.
PID algorithms are a good starting point for the pitch control in variable speed turbines. Advanced controller design methods can offer better results in the future.

Fig. 9.View of the experimental GARBI-150

Acknowledgments

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