CONTROL STRATEGIES FOR LARGE WIND TURBINE APPLICATIONS

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Abstract: ***This paper gives an overview of the state of the art control strategies for large wind turbines using induction generators. An active stall constant speed wind turbine controller with its actuator system for variable pitch angle and a control strategy for a pitch controlled variable speed wind turbine are described. The simulation results of a 2 MW constant speed wind turbine using cage rotor induction generator (CRIG) with both passive stall control and an active stall control strategy are modeled, digitally simulated and compared. To evaluate the performance for an active stall constant speed wind turbine using CRIG versus a pitch controlled variable speed wind turbine using Doubly fed induction generator (DFIG), a set of simulations are performed for wind gusts at an average wind speed higher than the rated value.***

Key words: *rotor efficiency, stall and pitch control, wind turbines.*

1. Introduction

The wind energy industry has developed rapidly through the last 20 years. The development has been concentrated in main for grid connected wind turbines (wind farms) and their control strategies. Conventional stall wind turbines are equipped with cage rotor induction generators [1-2], in which the speed is almost constant, while the variable speed and variable pitch wind turbines use doubly-fed induction generators or synchronous generators in connection with a power converter (partial rate or full rate) [1-4]. The variable speed wind turbine has a more complicated electrical system than the fixed-speed wind turbine [3], but it is able to achieve maximum power coefficient over a wide range of wind speeds and about 5-10 % gain in the energy capture can be obtained.

The aim of a wind turbine controller is to ensure that the wind turbine is able to produce energy at the lowest possible cost (minimum price per kWh) [1-4]. The cost of wind-generated electricity has declined about 90 % over the last 20 years.

Today, large new wind farms at excellent wind sites generate electricity at a cost of 0.04 to 0.06 US dollars / kWh [5]. That places the cost of power from the most efficient wind farms in a range that is competitive with that of electricity from new conventional power plants.

The goal of this paper is to give an overview over the state of art in wind turbines control strategies and to evaluate their performance.

2. Control strategies for wind turbines

Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are therefore generally designed so that they yield maximum output power at wind speeds around (12-15) meters per second [4, 10-12]. In case of stronger winds it is necessary to waste a part of the excess energy of the wind in order to avoid damaging the wind turbine. All wind turbines are therefore designed with some sort of power control [2-4 and 6]. There are two different ways of doing this safely on modern wind turbines [4]: pitch control and active stall control, as will be described as follows.

A. Pitch Controlled Wind Turbines

On a pitch controlled wind turbine the electronic controller checks the output power of the turbine several times per second. When the output power becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind [12]. Conversely, the blades are turned back into the wind whenever the wind drops again. The rotor blades thus have to be able to turn around their longitudinal axis (to pitch). During normal operation the blades will pitch a fraction of a degree at a time - and the rotor will be turning at the same time. Designing a pitch controlled wind turbine requires some clever engineering to make sure that the rotor blades pitch exactly the amount required. The pitch mechanism is usually operated using hydraulics or electric stepper motors [1, 2 and 4]. As with pitch control it is largely an economic question whether it is worthwhile to pay for the added complexity of the machine, when the blade pitch mechanism is added.

B. Stall Controlled Wind Turbines

Stall controlled (passive stall controlled) wind turbines have the rotor blades bolted onto the hub at a fixed angle. The geometry of the rotor blade profile however has been aerodynamically designed to ensure that the moment when the wind speed becomes too high [2, 6]; it creates turbulence on the side of the rotor blade which is not facing the wind. This stall prevents the lifting force of the rotor blade from acting on the rotor. As the actual wind speed in the area increases, the angle of attack of the rotor blade will increase, until at some point it starts to stall. If you look closely at a rotor blade for a stall controlled wind turbine you will notice that the blade is twisted slightly as you move along its longitudinal axis. This is partly done in order to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value [12]. The basic advantage of stall control is that one avoids moving parts in the rotor itself, and a complex control system. A normal passive stall controlled wind turbine will usually have a drop in the electrical power output for higher wind speeds, as the rotor blades go into deeper stall. On the other hand, stall control represents a very complex aerodynamic design problem, and related design challenges in the structural dynamics of the whole wind turbine, e.g. to avoid stall-induced vibrations.

C. Active Stall Controlled Wind Turbines

An increasing number of larger wind turbines (1 MW and more) are developed with an active stall power control mechanism. Technically the active stall turbines resemble pitch controlled turbines, since they have pitch able blades. In order to get a reasonably large torque (turning force) at low wind speeds, the wind turbines will usually be programmed to pitch their blades much like a pitch controlled wind turbine at low wind speeds [4]. (Often they use only a few fixed steps depending upon the wind speed). When the turbine reaches its rated power, however, it will notice an important difference from the pitch controlled wind turbines: If the generator is about to be overloaded, the turbine will pitch its blades in the opposite direction from what a pitch controlled wind turbine does. In other words, it will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall, thus wasting the excess energy in the wind. One of the advantages of active stall is that one can control the power output more accurately than with passive stall, so as to avoid overshooting the rated power of the turbine at the beginning of a gust of wind [4, 6]. Another advantage is that the wind generator can be run almost exactly at rated power at all high wind speeds.

D. Rotor Efficiency under Stall and Pitch Controlled Wind Turbines

The output power of wind turbines varies with wind speed, but is not proportional to it, as the energy that the wind contains increases with the cube of the wind speed. At low wind speeds (1-3 m/s), wind turbines are shut down, as they would be able to generate little or no power (Fig. 1). Wind turbines only start up at wind speeds between 2.5 and 5 m/s, known as the “cut-in” wind speed. “Nominal” or “rated” wind speed, at which nominal output power is reached, is normally between 12 and 15 m/s. The precise value depends on the ratio of generator capacity to rotor surface area, and is a design variable. Finally, any wind turbine has a “cut-out wind speed”: this is the wind speed at which the turbine is shut down to avoid structural overload. Its value is around 25 m/s for IEC Wind class I and II turbines [4]. For IEC Wind Class III turbines, which generate maximum output power at lower wind speeds, the cut-out value is in the range of 17-20 m/s. Wind turbines are shut down if the 10-minute average of the wind speed is above this design value. Below nominal wind speed, the aim is to maximize rotor efficiency (Fig. 1). The rotor efficiency depends on the ratio of the rotor blade tip speed and wind speed, known as the “tip speed ratio” (λ), described by:

$$\lambda = \omega_{rot} \cdot R / u_{eq} \quad \text{..............(1)}$$

Where R represents the radius of wind turbine rotor blades, u_{eq}-equivalent wind speed and ω_{rot} denotes the turbine rotor speed.

The tip speed ratio of a fixed speed wind turbine cannot be controlled, as the rotor speed (and thus the blade tip speed) is fixed. Nevertheless, the tip speed ratio varies with wind speed, and thus reaches the optimum value at one wind speed only in case of fixed speed designs (or at two speeds if the wind turbine can operate at two different, but constant, rotor speeds), [4, 6, 7]. With a variable speed wind turbine, the tip speed ratio varies, and depends both on wind speed and rotor speed. For maximum rotor efficiency, the tip speed ratio must be maintained at the value that corresponds to optimum rotor efficiency (usually 6-9) at all times. This is achieved by controlling the rotor speed accordingly. The higher aerodynamic efficiency that is thus achieved explains why a variable speed turbine generates more energy for the same wind speed regime.

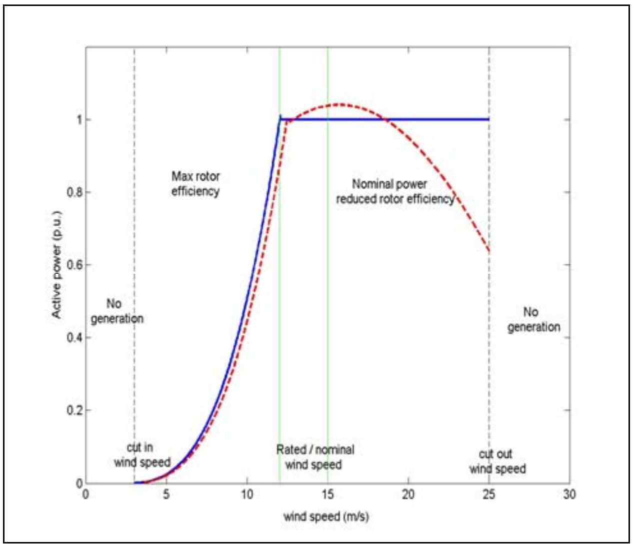

Fig. 1. Typical power curves and operation areas of a stall (dashed line) and pitch controlled (solid line) wind turbines [7].

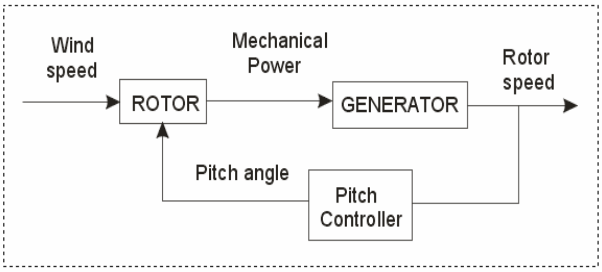

Fig. 2. Rotor speed control principle for wind speeds above nominal.

At wind speeds below nominal, the aim is to extract energy from the wind as efficiently as possible; however, this ceases to apply above nominal wind speed, as this would overload the generator and/or the converter system. Above nominal wind speed, therefore, the mechanical power extracted from the wind must remain constant. To achieve this, the aerodynamic rotor efficiency must be reduced when the wind speed increases, as can also be seen in Fig. 1. In a stall controlled wind turbine, the blades are designed such that the rotor efficiency "collapses" at high wind speeds. Due to the blade design, this behavior is intrinsic, and no active control systems are required to achieve the aerodynamic efficiency reduction. In a pitch controlled wind turbine, the blades are gradually turned out of the wind, so the wind impact angle changes and the aerodynamic efficiency is reduced. In this case active stall control is applied, by means of hydraulics or an electric drive system. The input variable for the pitch controller is the rotor speed, as it is depicted in Fig. 2. The higher the rotor speed, the more the blades are turned out of the wind. The blades are turned back into the wind when the rotor speed falls. In general, fixed speed turbines use stall control for technical reasons, while variable speed turbines are usually equipped with pitch control [7, 9].

A relatively recent innovation is the active-stall concept. This is similar to normal stall power limitation, except that the whole blade can be rotated backwards (in the opposite direction as is the case with pitch control) by a few (3-5) degrees at the nominal speed range in order to give better rotor control. The application of this concept is more or less restricted to fixed speed turbines.

Typical active-stall representatives are the Danish manufacturers Bonus (1 MW and over) and NEG Micon (now Vestas) (1.5, 2 MW and over) [4-5, 10-11].

The difference from active pitch control is not only that the range of blade angle variation is less, but also that the direction of the variation is opposite.

All what follows refers basically to two 2 MW wind generator systems using induction generators with the data in appendix.

3. Active stall constant speed wind turbine using cage rotor induction generators

A common control concept for new megawatt-size wind turbines/wind farms without power electronic converters is the active stall regulation. An active stall wind turbine is a stall controlled turbine with variable pitch angle. At high wind speeds, the pitch angle is adjusted to obtain the desired rated power level. When connecting the wind generator to the grid, the pitch angle is also adjusted in order to obtain a smooth connection. The use of active stall control also facilitates the emergency stopping of the turbine.

The control strategy called active stall constant speed involves the combined interaction between wind model, pitch control and the aerodynamics of the wind turbine [4], as can be seen in Fig. 3.

The blade angle control block models the active stall control of the wind turbine, based on the measured power and the set point, where rotational speed is the controlled variable [4, 10 & 11].

The most used electrical generator of an active stall constant speed turbine is a cage rotor induction generator connected to the grid through a soft starter, as can be seen in Fig. 3.

A clear difference between stall and active stall controlled wind turbines is a pitch actuator system for variable pitch angles, which allows the stall effect to be controlled, as can be seen in Fig. 4.

The model of the pitch control system [4], is based on the measured generator power (P_m) and the aerodynamic power of wind turbine as a function of measured wind speed (v_{wind}) at different pitch angles. The measured power is compared with its reference (P_{ref}) and the error signal (P_{err}) multiplied by pitch angle of power control ($f_1(v_{av})$) is sent to the PI-controller producing the pitch angle demand (θ_{dp}), which together with maximum pitch angle-upper limit (θ_{max}) are sent to the pitch limitation non-linear block producing the reference value of the pitch angle (θ_{ref}).

The reference value is in the range between the optimised pitch (θ_{dp}) and the maximal pitch angle ($\theta_{max}=90^0$). The maximum value is defined as a function of average wind speed ($f_2(v_{av})$). The reference value is, further, compared to the actual pitch angle (θ_{pitch}) and the error signal (θ_{e2}) is corrected by the pitch hydraulics.

This control strategy takes its origin in the power coefficient curves $C_p(\theta, u)$ [4], typical for a 2 MW constant speed wind turbine, as it is shown in Fig. 5. C_p represents the rotor efficiency of the wind turbine and depends on the pitch angle θ and on the tip speed ratio λ. For a constant speed wind turbine, the power coefficient C_p decreases when the wind speed u_{eq} increases (λ small), as can also be seen in Fig. 5.

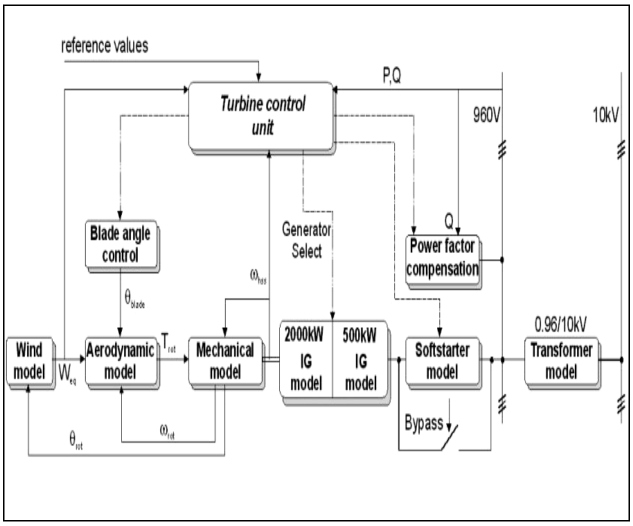

Fig. 3. Block diagram of an active stall controlled wind turbine with constant speed using a cage-rotor induction generator.

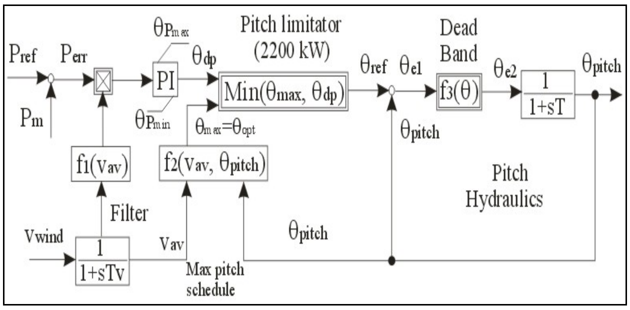

Fig. 4. The block diagram of blade pitch angle control system.

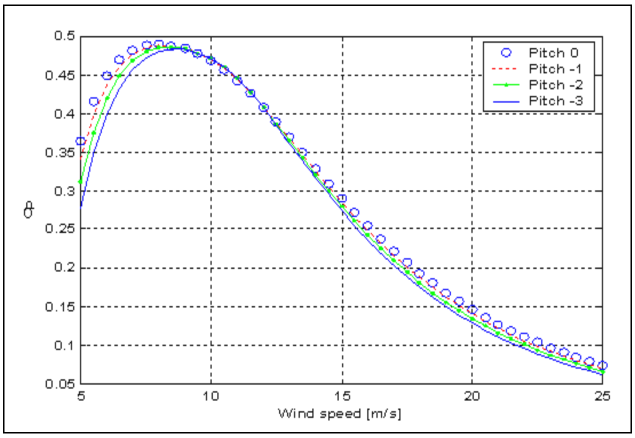

Fig. 5. Power coefficient (Cp) of a 2MW constant speed wind turbine versus wind speed for different pitch angles, used in the blade pitch angle control system.

The aerodynamic power is calculated according to:

$$P_{aero} = \frac{1}{2}\,\rho\,\pi\,R^2\,u_{eq}^{\;3}\,C_p(\lambda,\theta_{pitch})\;....(2)$$

In order to achieve maximum power yield for each wind speed the maximal C_p and the corresponding θ has to be found. In fact, the control strategy is characterised by two terms: the optimal region and the power limiting region. In the optimal region (between start-up wind speed and nominal wind speed), the output power is designed to fulfil the criterion of maximal C_p, which corresponds to the optimal energy capture, by keeping the tip speed ration (λ) constant. In the power limiting region (between nominal wind speed and cut-out wind speed), the output power is kept constant, while the wind turbine will pitch the blades a few degrees every time when the wind changes in order to keep the rotor blades at the optimum angle. When the wind turbine reaches its rated power, and the generator is about to be overloaded, the turbine will pitch its blades in the opposite direction. In this way, it will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall, thus wasting the excess energy in the wind.

4. Control design for a variable speed wind turbine using doubly-fed induction generators

Figure 6 presents the control system of a variable-speed wind turbine with DFIG. The control system contains two control levels: the DFIG control level, with a fast dynamic response, and the wind turbine control level, with a slow dynamic response.

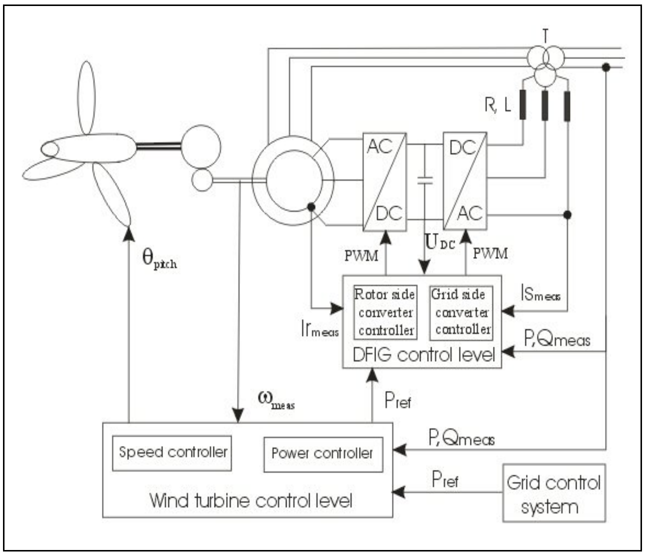

Fig. 6. The block diagram of the control system of a variable-speed wind turbine with DFIG fed by a back-to-back VSI.

A doubly-fed induction generator (DFIG) is a standard wound-rotor induction machine with the stator windings directly connected to the grid and with the rotor windings connected to a back-to-back partial scale frequency converter. The frequency converter consists of two independent converters connected to a common dc-bus. The behaviour of the generator is governed by these converters and their controllers. The DFIG control level contains two controllers: the rotor side converter controller, which controls independently the active and reactive power on the grid and the grid side converter controller, which controls the DC link voltage and maintains unity power factor. The rotor side converter controller contains an independent cascade control branches, one for active power control and the other for reactive power control, controlled indirectly by controlling the impressed rotor currents [3, 4, 6]. The DFIG model is expressed in the rotor reference frame and the rotor side converter controller is expressed in the stator flux reference frame. The control of rotor side converter is based on the stator flux oriented rotor current control approach, where the rotor current is split into a parallel and orthogonal component to the stator flux. It contains two control loops in cascade: a slower (outer) power control loop and a fast (inner) rotor current control loop [4]. The parameters of the PI controllers in the rotor side converter, for the 2 MW machine investigated are: K_P=0.1 and T_I=0.1 (for the power

controller) and K_P=1 and T_I=0.01 (for the current controller).
The control of the grid side converter also contains two control loops in cascade, a slower (outer) dc-voltage control loop, which regulates the dc link voltage to a predefined value, and a fast (inner) converter current control, which regulates the converter current to the reference value specified by the slower dc-voltage controller [3].
Similarly to the rotor side converter, the grid side converter is current regulated. The dc-voltage and the reactive power are controlled indirectly by controlling the grid side converter current. The parameters of DC-link voltage controller are K_P=0.35 and T_I=0.02, while the parameters of converter current controller are K_P=4.8 and T_I=0.08.
The wind turbine control provides reference signals both to the pitch system of the blades and to the DFIG control level. It contains two controllers: speed controller, which controls the generator speed at high wind speeds and maximum power tracking controller, which generates the active power reference signal for the active power control loop. This reference signal is determined from the electrical power versus generator speed characteristic (Fig. 7), taken from a look-up table. This characteristic is based on aerodynamic data of the wind turbine's rotor and its points correspond to the maximum aerodynamic efficiency. Up to 8.5 m/s with a tip speed ratio of around 8.7 (optimum), the rotor speed is proportional to the wind speed (lower part of the curve up to 800 kW/1500 rpm-Fig. 7). From 8.5 m/s to 12 m/s (rated) the rotor speed is controlled until the rated power of 2 MW at 1580 rpm is reaches. If the turbine accelerates to above 1580 rpm, due to the wind speed above rated value, the generator power is kept constant at the rated value (2 MW) by the power limitation controller, while the speed controller it takes no action (there is no longer any control of the generator speed). Both the speed controller and the maximum power-tracking controller are active in the power limitation strategy, while only maximum power tracking controller is active in the optimisation power strategy.
Figure 8 shows the speed controller, the maximum power tracking one and the rotor side and grid side converter controllers. All these controllers, except maximum power tracking controller, contains PI-controllers with anti-windup. Both the speed controller and the maximum power tracking have as input the filtered measured generator speed. The generator speed is measured and then a low-pass filter is used. The pitch angle controller is also developed, as a part of the power controller in order to compensate the non-linear aerodynamic characteristics. The error between the filtered measured generator speed and the rated value is sent to the PI speed controller. The output of this controller is used as reference pitch signal θ_{ref} to the pitch system.

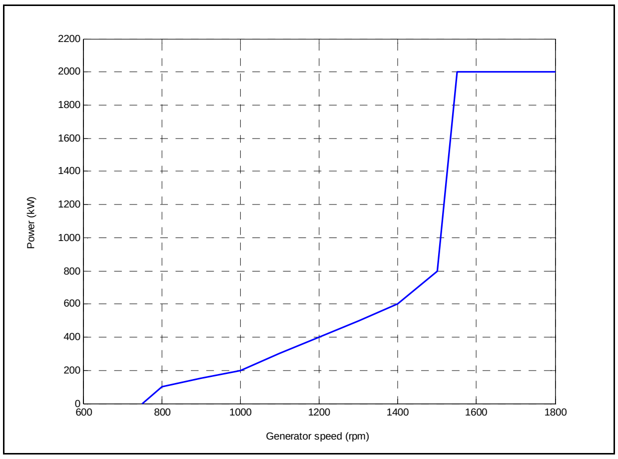

Fig. 7. Electrical power versus generator speed characteristic used in the maximum power tracking controller.

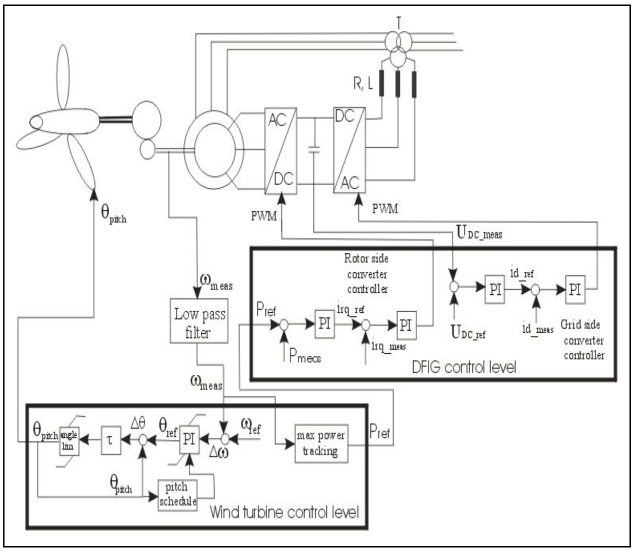

Fig. 8. An overview of the variable-speed wind turbine control strategy.

The reference is compared to the actual pitch angle θ and then the error Δθ is corrected by the servomechanism, as can also be seen in Fig. 8. Assuming that the dynamic behaviour of the speed controller can be approximated with a second order system behaviour, the parameter design of the PI speed controller can be based on the transient response analysis. The parameters of the PI speed controller are: K_P=850 and T_I=2.2, where the integral time it was directly determined based on design parameters (damping ratio and natural frequency) while the proportional gain has a proportional variation with the aerodynamic sensitivity dP/dθ.

5. Simulation results

To evaluate the performance of both wind turbine control systems presented before and implemented in MATLAB-Simulink and DIgSILENT software packages, a set of simulations are performed. More details about wind turbine models and software's implementation are described in [3] and [4].

A. Comparison between passive stall and active stall constant speed wind turbine

Figure 9 shows a comparison between active stall and passive stall of a 2 MW constant speed wind turbine at a mean wind speed (18 m/s) higher than rated wind speed (12 m/s). One of the advantages of the active stall control, point out in Fig. 9, is that it can control the power output more accurately than with passive stall, so as to avoid overshooting the rated power of the induction generator of the beginning of a gust of wind. Another advantage is that the machine can be run almost exactly at the rated power at all high wind speeds. In a stall controlled wind turbine the pitch angle is fixed and the output power cannot be held constant, while the maximum output power of an active stall turbine can be controlled to a constant value (nominal rated value). In Fig. 9 the pitch angle control is only used during active stall control strategy.

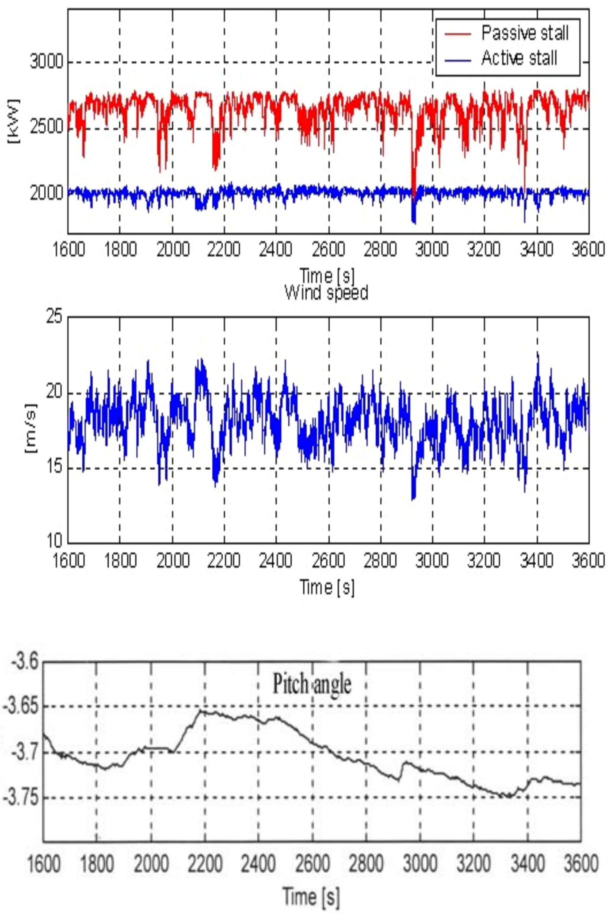

Fig. 9. Comparison between simulated active power with active stall control and passive stall control at an average wind speed u_{eq}=18 (m/s) and at turbulence intensity of ti=0.12.

B. Active stall constant speed versus pitch control variable speed wind turbines in heavy transients

Both Fig. 10 and Fig. 11 show how a 2 MW wind turbine, with variable speed (Fig. 10) and constant speed (Fig. 11), works during different operation conditions, such as sudden changes in wind speed (wind gusts) with a turbulence intensity of 12 %, at high wind speed.
Figure 10 presents the simulation results of 2MW variable speed wind turbine that works at a mean wind speed higher than rated one (16 m/s>12 m/s) corresponding to the power limitation strategy, in which both the speed controller and the power limitation controller are active.
The power limitation controller sets the blade angle to keep the rated power, while the speed controller permits a dynamic variation of the generator speed, in a predefined speed range (in the speed range allowed by the size of the power converter), in order to avoid mechanical stress in the gearbox and the rotor shaft.
To illustrate the elasticity of the variable speed DFIG wind turbine and to test the power controller performance, some wind gusts of 6 m/s up and down, are introduced in wind speed at each 150 seconds (at 150 s, 300 s and 450 s).
For instance, at t=150 s the mean wind speed suddenly reaches from 16 m/s to 22 m/s. In the same time the generator speed and the electrical power increases too. The power limitation control loop is strong and fast and the generator speed follows very well the generator speed reference in order to be able to absorb the maximum energy from the wind.
The pitch controller also reacts modifying the pitch angle, while the wind gusts are absorbed as variation in the generator speed, as can also be seen in Fig. 10. The rotational speed of the wind turbine rotor is thus allowed to increase storing energy into the wind turbine's inertia.
The control strategy of active stall constant speed wind turbine contains three modes of operation: acceleration control (speed control), power control (power limiting region) and direct pitch control (blade angle control).

The acceleration and pitch control modes are used during start-up, shut down and emergency conditions, while the power control mode is only used during normal operations.

In Fig. 11 the 2 MW induction generator was connected to the grid through a soft-starter (in order to reduce the transient current), at t=73 seconds and then the soft-starter was by-passed at t=77 seconds.

In the same time the power factor compensation unit started to work using capacitor switching, as a function of average value of measured reactive power [4, 8, 10].

The mean wind speed was 12 m/s. At t=100 seconds the mean wind speed was modified to 18 (m/s) and at t=170 seconds mean wind speed was modified again at 11 (m/s) to simulate sudden changes in wind speed and to test the system performance and implemented control strategy. The active and reactive powers have been able to follow these changes in all situations. It is concluded that the wind turbine absorbed the transients very fast and the control strategy offers a good stability of the system during transition of dynamic changes.

DISCUSSION AND CONCLUSION

The state of the art of wind turbines seen from electrical point of view includes old and new potential concepts of generators and power electronics based on technical aspects and market trends.

Several generic types of generator are possible candidates in wind turbines. The squirrel cage induction generator has been frequently applied commercially. The most dominating type, especially in the last five years, is the induction generator with wound rotor, while the third is the current excited synchronous generator.

A large number of alternative wind turbine designs exist but the state of the art wind turbine may be summarized as a 3-bladed upwind turbine using active stall control with constant speed using cage rotor asynchronous generator or pitch control combined with variable speed using DFIG.

Active stall constant speed combines the advantages of passive stall, namely simplicity due to the absence of a pitch mechanism, with the advantages of pitch control, namely controllability.

Simulation results of a 2 MW active stall constant speed wind turbine had shown a good stability of the system during normal operation and also during transition of dynamic changes in wind speed.

The overall control of the variable speed pitch controlled wind turbine with DFIG has as goal to track the optimum operation point, to limit the power in the case of high wind speeds and to control the reactive power interchanged between the wind turbine generator and the grid.

The control strategy contains two control levels: DFIG control level (control of active and reactive power using vector control approach) and wind turbine control level (speed controller and power limitation controller).

The variable speed wind turbine has a more complicated electrical system than the fixed-speed wind turbine, but it is able to achieve maximum power coefficient over a wide range of wind speeds and about 5-10 % gain in the energy capture can be obtained.

The simulation results showed that the implemented control strategy for a 2 MW variable speed pitch controlled wind turbine is able to control efficiently the DFIG parameters during normal operation and during sudden changes in wind speed.

An important difference between an active stall controlled wind turbine and a pitch controlled wind turbine, when they reach rated power, is that the active stall wind turbine pitch the blades in the opposite direction (negative direction) from what a pitch controlled wind turbine does.

Both wind turbine control strategies implemented are an important step towards the long term objective of developing tools for study and improvement of the dynamic interaction between wind turbines and power systems.

APPENDIX

1. ***Generator data***:

A. three phase cage rotor induction machine: nominal power 2 MW, 4 poles, V_S=960 V, f=50 Hz, I_S (full load current)-1320 A, T_L(full load torque)-13050 Nm, cosφ=0.92, n=1480 rpm, Moment of inertia-90 kgm^2, R_s=5 mΩ, R_r=8.9 mΩ, X_s=128 mΩ, X_M=5 Ω, R_{Fe}-135 Ω, X_r=94 mΩ,;

B. Three phase wound rotor induction machine: nominal power-2 MW, number of poles-4, moment of inertia-65 kgm^2, R_s=1.164 mΩ, R_r=1.3 mΩ, X_s=22 mΩ, X_M=0.95 Ω, X_r=23.7 mΩ, V_s=400 V, V_R=690 V, f=50 Hz.

2. ***Wind turbine data***:

Rated power-2 MW, number of blades-3, rotor diameter-80 m, hub height-60 m, turbine rotor speed (rated)-17 rpm, cut-in wind speed-4 m/s, cut-out wind speed-25 m/s, gear ratio-1:88.8, rotor shaft inertia-440 000 kgm^2.

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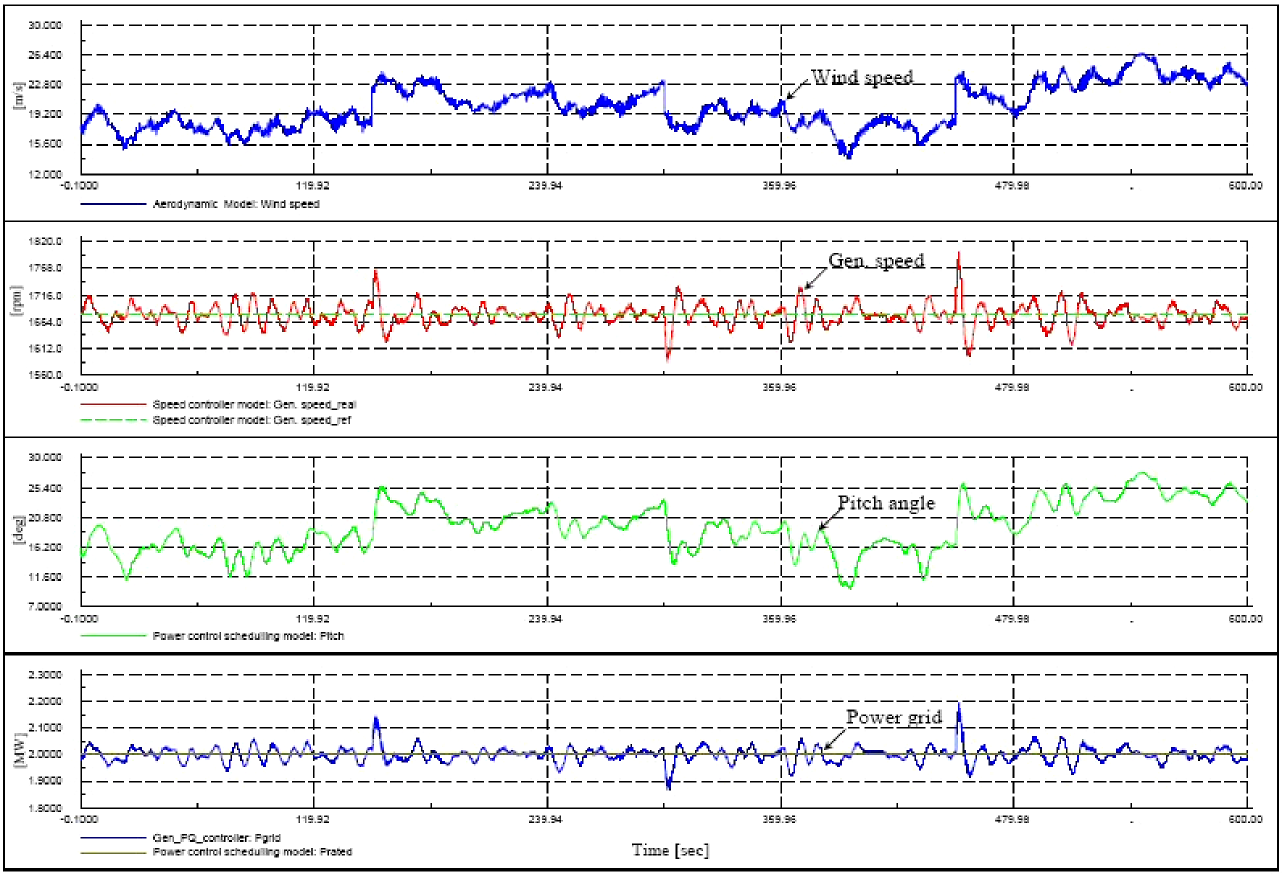

Fig. 10. Simulation results for a 2MW pitch controlled variable-speed wind turbine using DFIG with power control strategy implemented.

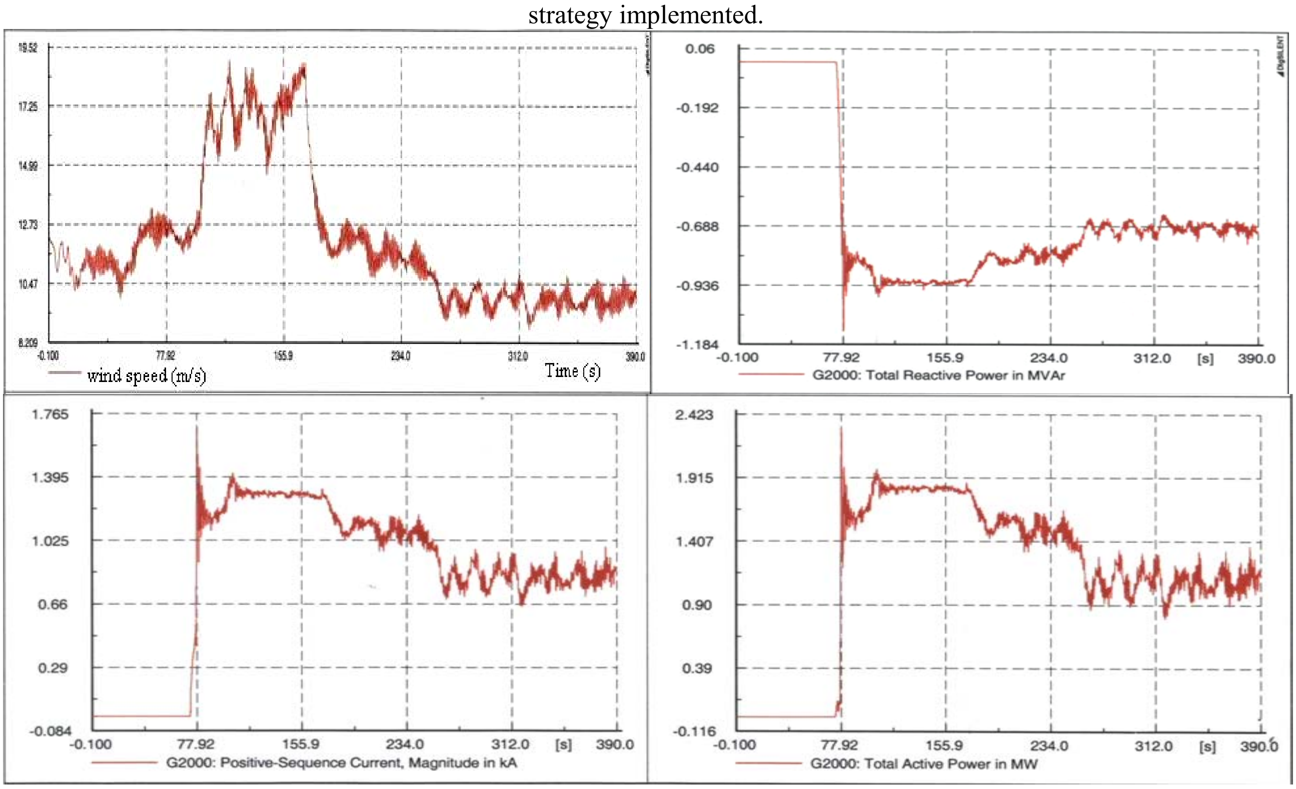

Fig. 11. Simulation results for a 2MW active stall constant-speed wind turbine using CRIG connected to the grid through a soft-starter.