Control of variable speed wind turbine with doubly-fed induction generator

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Abstract – The paper presents an overall control method for variable speed pitch controlled wind turbine with doubly-fed induction generator (DFIG). The attention is drawn to the control strategies and algorithms applied at each hierarchical control level of the wind turbine. The targets of the control system are: 1) to control the power drawn from the wind turbine in order to track the wind turbine maximum power operation point 2) to limit the power in case of high wind speeds and 3) to control the reactive power interchanged between the wind turbine generator and the grid. The present control method is designed for normal continuous operations. The strongest feature of the implemented control method is that it allows the turbine to operate with the optimum power efficiency over a wider range of wind speeds. The variable speed, variable pitch wind turbine with doubly-fed induction generator is implemented in the dynamic power system simulation tool DIgSILENT, which makes possible to investigate the dynamic performance of grid-connected wind turbines as a part of realistic electrical grid models. Simulation results are presented and analysed in different normal operating conditions.

Keywords: doubly-fed induction generator, variable speed wind turbine, power system, dynamic simulation, DIgSILENT

1 INTRODUCTION

During the last few years, variable speed wind turbines have become the most dominating type of yearly installed wind turbines (Hansen, A.D., 2004), (Hansen, L.H., et al., 2001). The increased interest in the variable speed wind turbines is due to their very attractive features, given by the presence of the power converter, with respect to both the wind turbine itself and to the more onerous grid requirements.

The variable speed wind turbines have a more complicated electrical system than the fixed speed wind turbines. They are typically equipped with an induction or synchronous generator and a power converter.

The presence of the power converter makes the variable speed operation itself possible. The variable speed wind turbines can therefore be designed to achieve maximum power coefficient over a wide range of wind speeds. The power converter controls the generator speed in such a way that the fast power fluctuations caused by wind variations are more or less absorbed by changing the generator speed and implicitly the wind turbine rotor speed. Seen from the wind turbine point of view, the most important advantages of the variable speed operation compared to the conventional fixed speed operation are:

- *reduced mechanical stress on the mechanical components such as shaft and gearbox* – the high inertia of the wind turbine is used as a flywheel during gusts, i.e. the power fluctuations are absorbed in the mechanical inertia of the wind turbine.
- *increased power capture* – due to the variable speed feature, it is possible to continuously adapt (accelerate or decelerate) the rotational speed of the wind turbine to the wind speed, in such a way that the power coefficient is kept at its maximum value.
- *reduced acoustical noise* – low speed operation is possible at low power conditions (lower wind speeds).

Additionally, the presence of power converters in wind turbines also provides high potential control capabilities for both large modern wind turbines and wind farms to fulfil the high technical demands imposed by the grid operators (Eltra, 2000), (Sørensen,P., et al.,2000), such as:

- *controllable active and reactive power (frequency and voltage control)*
- *quick response under transient and dynamic power system situations*
- *influence on network stability*
- *improved power quality (reduced flicker level, low order harmonics filtered out and limited in-rush and short circuit currents)*

All these attractive features make the variable speed wind turbine concept very popular despite the disadvantages, such as losses in power electronics and increased installation cost due to the power converter. Currently, there are three groups of variable speed wind turbine concepts on the market:

- *Variable speed concept with full scale frequency converter* – where the generator stator is interconnected to the grid through a full-scale power converter. The generator can be synchronous (wound rotor synchronous generator WRSG or permanent magnet synchronous generator PMSG) or induction generator (wound rotor induction generator WRIG).
- *Variable speed concept with partial scale frequency converter* – known as doubly-fed induction generator (DFIG) concept. The generator is a wound rotor induction generator (WRIG), where the stator is directly connected to the grid, while the rotor is controlled by a partial scale power converter. The rotor frequency and thus the rotor speed are controlled by the partial-scale frequency converter, whose size defines the range of the variable speed (typically +/- 30% around synchronous speed).
- *Variable speed concept with variable rotor resistance* - where the generator rotor's winding is connected in series with a controlled resistance, whose size defines the range of the variable speed (typically 0-10% above synchronous speed).

During the last few years, the concept with doubly-fed induction generator (DFIG) has distinguished itself as a very attractive option with a fast growing market demand (Hansen, A.D., 2004). The fundamental feature of the DFIG is that the power processed by the power converter is only a fraction of the total wind turbine power, and therefore its size, cost and losses are much smaller compared to a full-scale power converter used in the full variable speed concept.

This paper presents a new control method for variable speed pitch controlled wind turbines with DFIG, designed for normal continuous operations. The strongest feature of the implemented control method is that it allows the turbine to operate with the optimum power efficiency over a wider range of wind speeds. Moreover, due to the design of this control method, the transition between power optimization mode and power limitation mode is not dominated by large power fluctuations due to small changes in generator speed.

Since the electrical and mechanical dynamics in a wind turbine are of different time scales (i.e. the electrical dynamics are much faster than the mechanical), two hierarchical control levels, strongly connected to each other, can be distinguished in the overall control system:

- DFIG control level – with a fast dynamic response, contains the electrical control of the doubly-fed induction generator and has as goal to control the active and reactive power of the wind turbine independently.
- Wind turbine control level – with a slow dynamic response, contains the control of the wind turbine itself. It supervises the pitch control system of the wind turbine, as well as it provides active power reference signal to the electrical DFIG control level.

The variable speed pitch controlled wind turbine with doubly-fed induction generator and its control strategies are implemented in the power system simulation tool DIgSILENT (DIgSILENT GmbH, 2003), which makes possible to investigate the dynamic performance of grid-connected wind turbines as a part of realistic electrical grid models.

The paper is organised as follows. First, the characteristics of the variable speed wind turbine and of the doubly-fed induction generator are summarized. Then, the overall control system of the variable speed wind turbine with DFIG is described, with focus on the control strategies at the different control levels: DFIG control and wind turbine control. Promising simulation results are then presented and analysed in different normal operating conditions.

2 VARIABLE SPEED WIND TURBINE CHARACTERISTICS

A wind turbine is characterised by its power speed characteristics. For a horizontal axis wind turbine, the amount of mechanical power P_{mec} that a turbine produces in steady state is given by:

$$P_{mec} = \frac{1}{2} \rho \pi R^2 u^3 C_p(\theta, \lambda) \tag{1}$$

where ρ is the air density, R the turbine radius, u the wind speed and $C_p(\theta, \lambda)$ is the aerodynamic power coefficient, which for pitch controlled wind turbines depends on both the pitch angle θ and the tip speed ratio λ. The tip speed ratio λ is given by:

$$\lambda = \frac{\omega_{rot} R}{u} \tag{2}$$

where ω_{rot} denotes the turbine rotor speed.

The prime motivation for variable speed wind turbines at lower wind speeds is to adjust the rotor speed at changing wind speeds so that $C_p(\theta, \lambda)$ always is maintained at its maximum value. The power coefficient $C_p(\theta, \lambda)$ has a maximum for a particular tip-speed ratio λ_{opt} and pitch angle θ_{opt}. This means that for extracting maximum power from a particular wind speed, the control strategy has to change the turbine rotor speed in such a way that the optimum tip speed ratio λ_{opt} is always obtained. The maximum power a particular wind turbine can extract from the wind is a cubic function of the turbine optimum speed, as follows:

$$P_{mec}^{\max} = K_{opt} \left[\omega_{rot}^{opt}\right]^3 \tag{3}$$

where:

$$K_{opt} = \frac{1}{2} \rho \pi R^5 \frac{C_p^{\max}}{\lambda_{opt}^3} \tag{4}$$

K_{opt} depends on the turbine characteristics and the air density. Tracking the maximum power is the goal as long as the generated power is less then the rated power. At wind speeds higher than rated wind speed, the control strategy has to be changed so that the wind turbine no longer produces maximum power but only rated power. The blades are thus pitched to reduce the power coefficient $C_p(\theta, \lambda)$ and thereby to maintain the power at its rated value. Wind gusts are absorbed by rotor speed changes, the wind turbine's rotor behaving as energy storage.

3 DOUBLY-FED INDUCTION GENERATOR CHARACTERISTICS

The typical DFIG configuration, illustrated in Figure 1, consists of a wound rotor induction generator (WRIG) with the stator windings directly connected to the three-phase grid and with the rotor windings connected to a back-to-back partial scale power converter. The back-to-back converter is a bi-directional power converter. It consists of two independent controlled voltage source converters connected to a common dc-bus. These converters are illustrated in Figure 1, as rotor side converter and grid side converter. The behaviour of the generator is governed by these converters and their controllers both in normal and fault conditions. The converters control the rotor voltage in magnitude and phase angle and are therefore used for active and reactive power control.

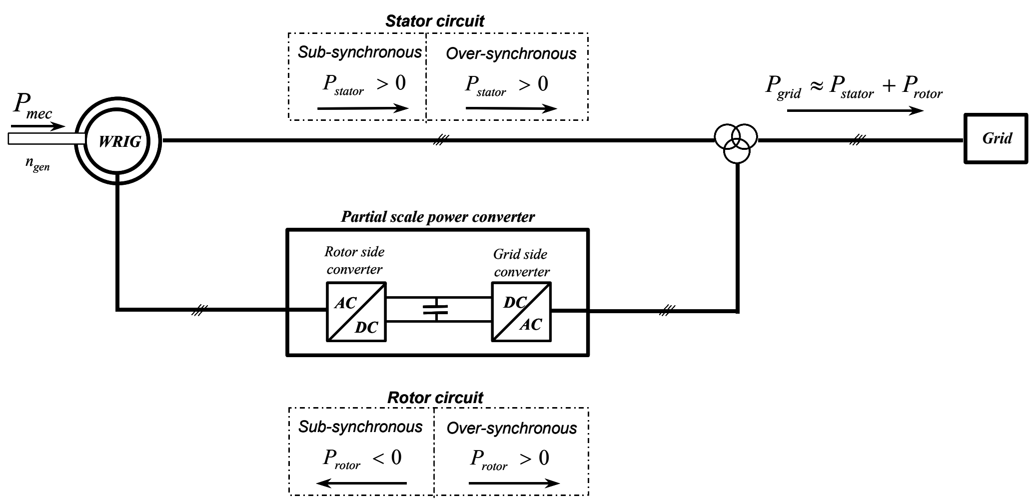

Figure 1: Principle diagram of the power flow in doubly-fed induction generator.

DFIG system allows variable speed operation over a large but restricted range. The smaller the operational speed range the less power has to be handled by the bi-directional power converter connected to the rotor. For example if the speed should be controllable between +/- 30%, the converter must have a rating of approximate 30% of the generator. Thus the size of the converter does not only relate to the total generator power but also to the selected speed range and hence the slip power (Heier, S., 1998), (Leonhard, W., 2001). Therefore, the cost of the power converter increases when the available dynamic speed range around synchronous speed increases.

Notice that, since the speed range is restricted, the slip-induced voltage is only a fraction of the grid voltage, depending on the turn-ratio between the stator and rotor. The dc bus voltage is thus relatively low. The operation at a lower dc bus voltage is possible because of the voltage reduction on the rotor side realised by the three winding transformer.

In order to cover a wide operating range from sub-synchronous to over-synchronous speed, i.e. the DFIG is able to work as a generator in both sub-synchronous (positive slip $s>0$) and over-synchronous (negative slip $s<0$) operating area, the power converter has to be able to operate with power flow in both directions. This is the reason why a back-to-back PWM (bi-directional) converter configuration is used. The slip is defined as:

$$s = \frac{n_{syn} - n_{gen}}{n_{syn}} \qquad (5)$$

where n_{syn} and n_{gen} are the synchronous speed and generator speed in rpm, respectively. For a doubly-fed induction machine, it is the sign of the electrical torque, independent of the slip, which indicates if the machine is working as motor or generator. Assuming that all the losses in the stator and rotor circuit can be neglected, the power through the power converter (through the rotor circuit), known as the slip power, can be expressed as the slip s multiplied with the stator power, P_{stator}. Furthermore, the delivered stator power can be expressed based on the grid power P_{grid}:

$$\begin{aligned} P_{rotor} &\approx -s\, P_{stator} \\ P_{stator} &\approx P_{grid} \,/\, (1-s) \end{aligned} \qquad (6)$$

Depending on the operating condition of the drive, the power is fed in or out of the rotor: it is flowing from the grid via the converter to the rotor ($P_{rotor} < 0$) in sub-synchronous mode or vice versa ($P_{rotor} > 0$) in over-synchronous mode, as it is indicated in Figure 1. In both cases (sub-synchronous and over-synchronous) the stator is feeding energy to the grid ($P_{stator} > 0$) (Leonhard, W., 2001).

The presence of the power converter allows DFIG a more versatile and flexible operation compared with a squirrel-cage induction machine. The power converter compensates for the difference between the mechanical and electrical frequency by injecting a rotor current with a variable frequency according to the shaft speed. Through slip rings, the power converter supplies thus the rotor windings with a voltage with variable magnitude and frequency. It improves the controllable capabilities of such generator, as for example:

- it provides DFIG the ability of reactive power control. DFIG is therefore capable of producing or absorbing reactive power to or from the grid, with the purpose of voltage control (i.e. in the case of weak grid, where the voltage may fluctuate).
- it can magnetize the DFIG through the rotor circuit, independently of the grid voltage.
- it decouples active and reactive power control by independent control of the rotor excitation current.

4 THE OVERALL CONTROL SYSTEM OF A VARIABLE SPEED WIND TURBINE WITH DFIG

The control system of a variable speed wind turbine with DFIG has as goals to control the reactive power interchanged between the generator and the grid and the active power drawn from the wind turbine in order to track the wind turbine optimum operation point or to limit the power in the case of high wind speeds.

Each wind turbine system contains subsystems (aerodynamical, mechanical, electrical) with different ranges of time constants, i.e. the electrical dynamics are typically much faster than the mechanical. This difference in time constants becomes even bigger in the case of a variable speed wind turbine, due to the presence of the power electronics. Such more complicated electrical system requires a more sophisticated control system too.

Figure 2 shows the overall control system of a variable speed DFIG wind turbine (Hansen, et.al., 2004). Two control levels with different bandwidths and strongly connected to each other, can be distinguished in the overall control system:

- Doubly-fed induction generator control (control of active and reactive power)
- Wind turbine control

The DFIG control, with a fast dynamic response, contains the electrical control of the power converters and of the doubly-fed induction generator. The DFIG control level has as goal to control the active and reactive power of the wind turbine independently. The wind turbine control, with slow dynamic response, supervises the pitch system of the wind turbine as well as the active power setpoint of the DFIG control level.

The DFIG control contains two controllers: one for the rotor side converter and one for the grid side converter. The wind turbine control contains two cross-coupled controllers: a speed controller and a power limitation controller.

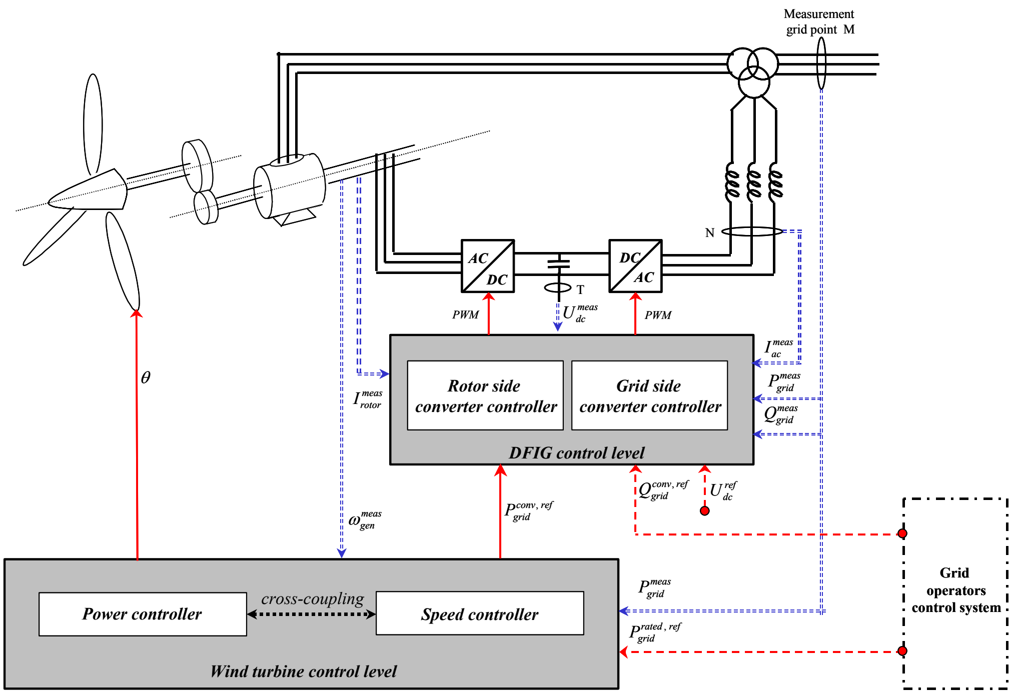

Figure 2: Overall control system of variable speed wind turbine with doubly-fed induction generator.

Notice that the overall control system requires information on different measured electrical signals: the active P_{grid}^{meas} and reactive Q_{grid}^{meas} power (measured in the measurement grid point M), the voltage U_{dc}^{meas} on the DC – busbar, the AC- converter current I_{ac}^{meas} (measured in point N), the generator speed ω_{gen}^{meas} and the rotor current I_{rotor}^{meas}.

The reference rated active power signal $P_{grid}^{rated,ref}$ is normally the nominal power of the wind turbine. In special situations, $P_{grid}^{rated,ref}$ can be extraordinarily imposed by the grid operators (based for example on a certain dispatch control) to a power value less than the nominal (rated) power of the wind turbine. The present paper considers the case when $P_{grid}^{rated,ref}$ is the nominal (rated) power of the wind turbine. Similarly to $P_{grid}^{rated,ref}$, the converter reference reactive power $Q_{grid}^{conv,ref}$ in the measurement grid point *M*, can be imposed in special situations by the grid operators control system. For example in the case of a weak grid or a voltage collapse, the DFIG can have as extra task to generate reactive power to the grid in the voltage regulation process. The reference DC- voltage U_{dc}^{ref} is a value strictly connected to the size of the converter, the stator-rotor voltage ratio and the modulation factor of the power converter.

The wind turbine control generates two control signals:

- The converter reference active power $P_{grid}^{conv,ref}$ - is the setpoint for the active power signal in the measurement grid point *M,* for the DFIG control level. It is generated based on the measured generator speed ω_{gen}^{meas} and the measured grid power P_{grid}^{meas} in the measurement grid point *M.* For example, when the wind speed is less than the rated wind speed, the wind turbine control level generates the converter reference active power $P_{grid}^{conv,ref}$ by adjusting the generator speed in such a way that the turbine captures the maximum power.
- The pitch angle θ - is delivered directly to the wind turbine blades. The pitch angle actuator system is implemented as a part of the power controller. It is generated based on the measured grid power P_{grid}^{meas} and the reference rated active power $P_{grid}^{rated,ref}$.

For example, as long as the power limit $P_{grid}^{rated,ref}$ is not reached (i.e. wind speeds less than the rated wind speed), the wind turbine control keeps the pitch angle to its optimal value and it generates the optimal active power reference $P_{grid}^{conv,ref}$ to the

DFIG control level. The DFIG control has then to adjust continuously the generator speed in order to keep the power reference provided by the wind turbine control level. In the case of wind speeds higher than rated wind speed, the wind turbine control level commands: 1) the pitch actuator system with a pitch angle that prevents the power generation from becoming too large and 2) the DFIG control level with power reference equal to the nominal power. The DFIG control level has then the goal to adjust the generator speed to its nominal value in a predefined dynamic speed range.

In the following sections, the two control levels with their individual controller are described.

5 DOUBLY-FED INDUCTION GENERATOR CONTROL

The doubly-fed induction generator (DFIG) control contains the fast electrical control of the doubly-fed induction generator. Control strategies and performance evaluation of doubly-fed induction generators have been widely discussed in the literature (Leonhard W., 2001), (Mohan N., et al., 1989), (Novotny D.W. et al., 1996), (Pena, R., et al., 1996). Briefly, the vector control techniques allow de-coupled control of active and reactive power. These techniques are based on the concept of d-q controlling in different reference frames, where the current and the voltage are discomposed into distinct components related to the active and reactive power. In this paper the stator flux oriented rotor current control with decoupled control of active power and reactive power is adopted (Novotny D.W. et al., 1996).

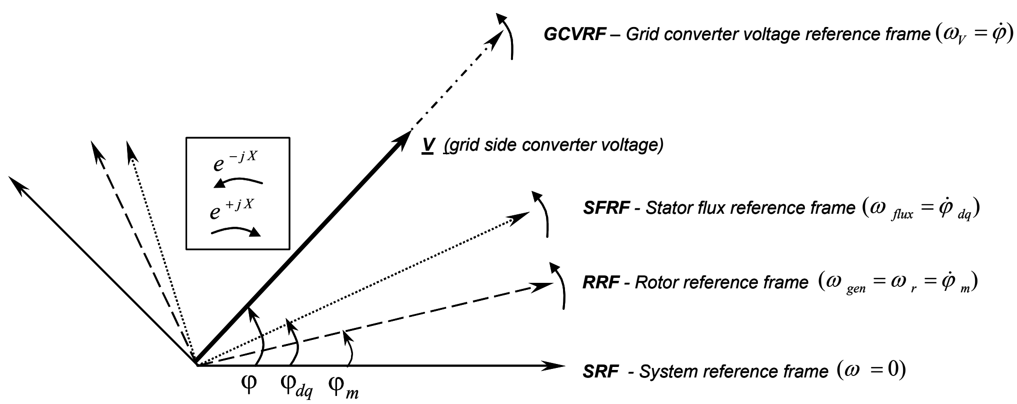

Figure 3: Reference frames used in doubly-fed induction generator control.

The doubly-fed induction generator DFIG and its control in DIgSILENT is using the following reference frames, illustrated in Figure 3:

- System reference frame *(SRF)*– is the reference frame fixed to the grid, and it is rotating with the grid reference voltage. Therefore its relative speed to the grid is considered zero.
- Rotor reference frame *(RRF)* - is the reference frame fixed to the rotor. The d-axis in the rotor reference frame is chosen collinear to the rotor phase winding. Consequently, the position of the rotor reference frame rotates with the actual position of the rotor φ_m.
- Stator flux reference frame *(SFRF)* – is the reference frame, which rotates synchronously with respect to the stator flux, namely its d-axis is chosen collinear to the stator flux vector. The position of stator flux reference frame is the instantaneous position φ_{dq} of the stator flux vector. This is calculated as $\tan(\varphi_{dq}) = \frac{\psi^{SRF}_{q,stator}}{\psi^{SRF}_{d,stator}}$ where $\psi^{SRF}_{d,stator}$ and $\psi^{SRF}_{q,stator}$ are its stationary components on *d*- and *q*- axis, respectively in the system reference frame *SRF*. Since the d-axis of this reference frame is chosen to be the instantaneous axis of the stator field, the phase angle φ_{dq} of the stator voltage is generally not a constant, although its frequency and magnitude are constants constrained by the power system. This reference frame is defined with respect to the stator flux and not to the stator voltage because the stator flux basically represents the integral of the stator voltage and is therefore much smoother.
- Grid converter voltage reference frame *(GCVRF)*– is the reference frame where d-axis is chosen collinear to the grid converter voltage $\underline{V}$. This reference frame is positioned by the voltage angle φ, which is measured with a PLL (phase-locked loop) block.

As illustrated in Figure 2, the DFIG control contains two decoupled control channels, corresponding to the two converters existing in the DFIG configuration:

1. *Rotor side converter*: is an integrated part of the DFIG model in DIgSILENT together with the d-q induction machine model (DIgSILENT GmbH, 2003). The DFIG model in DIgSILENT is expressed in the rotor reference frame *RRF* and it is a built-in model with predefined inputs and outputs. The controller of the rotor side converter is expressed in stator flux reference frame *SFRF*.
2. *Grid side converter* - is an independent component in DIgSILENT's library, which can be added to the machine model to form the DFIG with back-to-back converter. Its controller is expressed in system reference frame *SRF*.

5.1 Rotor side converter control

The aim of the rotor side converter is to control independently the active and reactive power in the measurement grid point M (see Figure 2). The active and reactive powers are not controlled directly, but by controlling the impressed rotor current. The control of the rotor side converter is illustrated in Figure 4. It 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, respectively. It contains two control loops in cascade: a slower (outer) power control loop and a fast (inner) rotor current control loop.

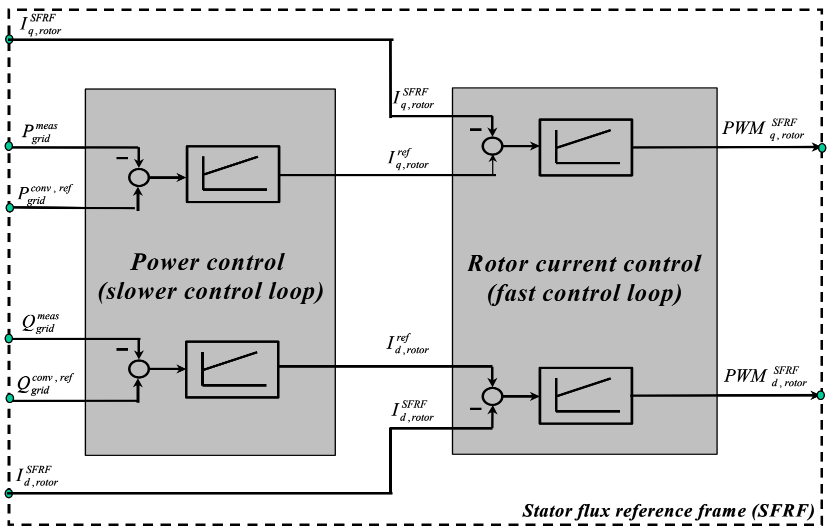

Figure 4: Rotor side converter control scheme using a cascade control structure.

The power control loop controls the active and reactive power, while the very fast current control loop regulates the machine's rotor currents to the reference values that are specified by the slower power controller.

Such cascade control structure is advantageous as the electrical and mechanical dynamics are in different time scales, i.e. the electrical dynamics are much faster than the mechanical dynamics. Since the electrical dynamics are the fastest, the rotor current control loop is the inner loop.

The active power control is achieved by controlling the *q*- component of the rotor current $I_{q,rotor}^{SFRF}$ orthogonal on the stator flux, while the reactive power Q control is achieved by controlling the *d*- component of the rotor current (the magnetising current) $I_{d,rotor}^{SFRF}$ collinear with the stator flux.

The power control loop generates the reference rotor current components $I_{q,rotor}^{ref}$ and $I_{d,rotor}^{ref}$, respectively, for the rotor current control loop. The rotor current control loop generates the reference rotor voltage components. As the pulse-width modulation factor *PWM* is the control variable of converter, the output of the rotor side converter's controller is expressed in terms of pulse-width modulation factor components $PWM_{d,rotor}^{SFRF}$ and $PWM_{q,rotor}^{SFRF}$, respectively.

Notice that the converter active and reactive power references $P_{grid}^{conv,ref}$ and $Q_{grid}^{conv,ref}$ for the measurement grid point *M*, respectively, used as inputs by the rotor side converter controller – see Figure 4, can be dynamically varied depending on each specific application.

The protection of the rotor side converter against over-currents is an integral part of the doubly-fed induction machine model in DIgSILENT and it is discussed in (Pöller, M., 2003).

5.2 Grid side converter control

The aim of the control of the grid side converter is to maintain the dc-link capacitor voltage in a set value regardless of the magnitude and the direction of the rotor power and to guarantee a converter operation with unity power factor (zero reactive power). This means that the grid side converter exchanges with the grid only active power, and therefore the transmission of reactive power from DFIG to the grid is done only through the stator. The dc-voltage and the reactive power are controlled indirectly by controlling the grid side converter current. The control of the grid side converter is shown in Figure 5. It contains two control loops in cascade: a slower (outer) dc-voltage control loop and a fast (inner) converter current control.

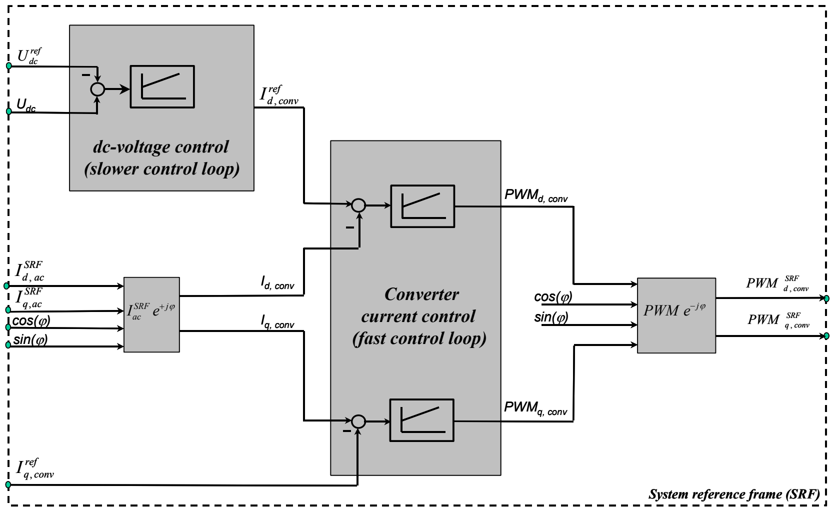

Figure 5: Grid side converter control scheme.

The DC- voltage control loop regulates the DC-link voltage to a predefined value U_{dc}^{ref}, while the very fast current control loop regulates the converter current to the reference value specified by the slower dc-voltage controller.

The outputs of the grid side converter controller define the magnitude and phase angle of the AC-voltage terminal of the converter. The converter current control operates in the grid converter voltage oriented reference frame *GCVRF*. The converter current is discomposed into a parallel and an orthogonal component on the grid side converter voltage. In such reference frame the d-axis is equivalent to the active component, while the q-axis is equivalent to the reactive component. The converter current component collinear with the converter voltage (direct phase) $I_{d,conv}$ is used to control the dc-voltage (active power), while the component orthogonal to the converter voltage (quadrature phase) $I_{q,conv}$ is used to control the reactive power.

The DC-link voltage is controlled in the outer slower control loop to its setpoint value U_{dc}^{ref} by the d-converter current component. It generates the reference of the direct phase component of the converter current $I_{d,conv}^{ref}$. The reference of the quadrature component of the converter current $I_{q,conv}^{ref}$ is constant, almost proportional to the reactive power. To operate the converter with unity power factor ($Q_{conv} = 0$) implies a zero q- current reference $I_{q,conv}^{ref} = 0$.

Notice that the converter current control loop generates the direct $PWM_{d,\,conv}$ and the orthogonal $PWM_{q,\,conv}$ component of the pulse-width modulation factor in the grid converter voltage oriented reference frame (*GCVRF)*. These components are then transformed into the system reference system *SRF*, as the grid converter requires controlling signals in *SRF*.

Notice in Figure 2 that the grid side converter is connected in series with inductors to the line in order to smooth the converter currents. These inductors may also be integrated into the transformer.

6 WIND TURBINE CONTROL

The wind turbine control, with a slower dynamic response than the DFIG control, controls the pitch angle of the wind turbine and the reference active power to the DFIG control level.

6.1 Control strategies

Different control strategies of variable speed, variable pitch wind turbine are widely presented in the literature (Novak P., et al., 1995), (Bossany E.A., 2000), (Bindner H., et al., 1997), (Hansen A. D., et al., 1999). In these strategies, the frequency converter controls directly the active power signal of the wind turbine.

The control method described in this paper is close to that described in (Wortmann B., et.al, 2000). In this control strategy, the frequency converter controls directly the generator speed. The strongest feature of the implemented control method is that it allows the turbine to operate with the optimum power efficiency over a wider range of wind speeds. Moreover, due to the design of this control method, the transition between power optimisation mode and power limitation mode is not dominated by large power fluctuations due to small changes in generator speed.

The present variable speed wind turbine control strategies are fundamentally based on the two static optimal curves, illustrated in Figure 6:

(a) Mechanical power of turbine versus wind speed
(b) Electrical power versus generator speed.

These characteristics are determined based on predefined aerodynamically data of the turbine. A parallel presentation of them, as shown in Figure 6 for a 2 MW wind turbine, provides a graphical illustration of the relation between the generated power, the wind speed and the generator speed for each operational stage of the wind turbine. Notice in Figure 6(b) that, as long as the speed can be varied, the maximum power extracted from the wind is a cubic function of the turbine optimum speed, as expressed in equation (4).

Each wind turbine has some physical operational restrictions, related to the acceptable noise emission, the mechanical loads and the size and the efficiency of the generator and of the frequency converter. It is therefore necessary to limit the stationary wind turbine rotational speed, to a range given by a minimum and a rated (nominal) value $\left[\omega_{rot}^{\min}, \omega_{rot}^{nom}\right]$. Notice that, the graph Figure 6 (b) also indicates the operational speed range $[n_{gen}^{\min}, n_{gen}^{dyn,\max}]$ for the generator speed. The generator speed can be expressed in [rad/s] or in [rpm] as follows:

$$\begin{aligned} \omega_{gen}(u) &= \eta_{gear}\,\omega_{rot}(u) && [rad/s] \\ n_{gen}(u) &= \frac{60}{2\pi}\omega_{gen}(u) = \frac{60}{2\pi}\eta_{gear}\,\omega_{rot}(u) && [rpm] \end{aligned} \qquad (7)$$

where η_{gear} is the gearbox ratio. The operational speed range $[n_{gen}^{\min}, n_{gen}^{dyn,\max}]$ covers the stationary generator speed range as well as the dynamical generator overspeed range, which is allowed by the doubly-fed induction generator DFIG's control.

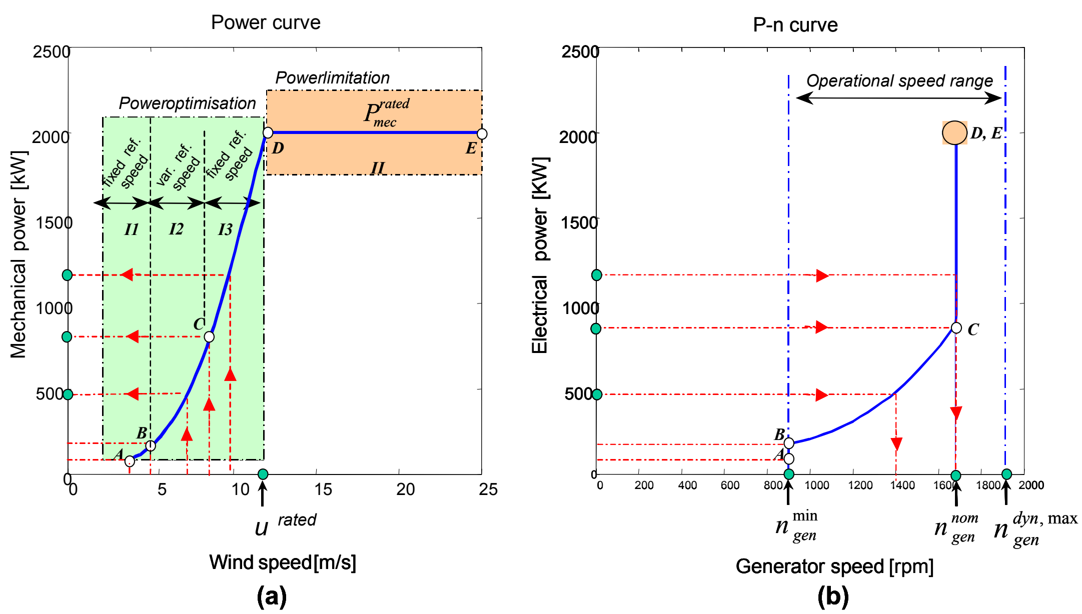

Figure 6: Two static curves used in the design of the control strategies for a doubly-fed induction generator: (a) mechanical power versus wind speed and (b) electrical power versus wind speed.

Two control strategies for the variable speed wind turbine are indicated in Figure 6:

I. ***Power optimisation strategy*** (below rated wind speed u^{rated})– where the energy capture is optimised. It is depicted by the range *A-B-C-D,* both in Figure 6(a) and in Figure 6(b).

II. ***Power limitation strategy*** (above rated wind speed u^{rated}) – where the goal of the controller is to track the nominal (rated) power reference $P_{grid}^{rated,ref}$ of the wind turbine. It is depicted by the range *D-E* both in Figure 6(a) and in Figure 6(b).

Figure 6 points out four different control modes for the control of the variable speed wind turbine:

Mode I1. *Partial load operation with fixed reference speed at the low limit* (power optimisation strategy zone *A-B*)

This mode corresponds to the situation when the wind speeds are so small that the rotational speed is less than the lower limit $\omega_{rot} \le \omega_{rot}^{\min}$ (the generator speed $n_{gen} \le n_{gen}^{\min}$). The turbine's reference speed is therefore set to the minimal value $\omega_{rot}^{ref} = \omega_{rot}^{\min}$ and the tip speed ratio *λ(u)* is calculated by $\lambda(u) = \omega_{rot}^{\min} R / u$. The rotor cannot be operated at the optimum tip speed. The optimum power is therefore achieved by keeping the optimal pitch and the turbine speed at the lower limit $\omega_{rot}^{\min}$.

Mode I2. *Partial load operation with variable reference speed* (power optimisation strategy zone *B-C*)

This mode corresponds to the situation when the rotational speed is higher than the lower limit and less than the nominal rotational speed $\omega_{rot}^{\min} < \omega_{rot} \le \omega_{rot}^{nom}$ (the generator speed $n_{gen}^{\min} < n_{gen} \le n_{gen}^{nom}$). The goal here is to maximise the energy capture by tracking the maximum power coefficient $C_p^{\max}$ curve. The maximum power coefficient value $C_p^{\max}$ corresponds to one pitch angle θ_{opt} and one tip speed ratio λ_{opt}. The pitch angle is therefore kept constant to the optimal value θ_{opt}, while the tip speed ratio is tuned to the optimal value λ_{opt} over different wind speeds by adapting the rotor speed ω_{rot} to its reference, expressed by:

$$\omega_{rot}^{ref}(u) = \frac{\lambda_{opt}\, u}{R} \qquad [rad/s] \qquad (8)$$

The maximal mechanical power is therefore achieved by tracking the reference rotational speed:

$$P_{mec}^{\max}(u) = \frac{1}{2}\,\rho\,\pi\,R^5\,\frac{C_p^{\max}}{\lambda_{opt}^3}\left[\omega_{rot}^{ref}(u)\right]^3 \qquad [W] \qquad (9)$$

Mode I3. *Partial load operation with fixed reference speed at the high limit* (power optimisation strategy zone *C-D*)

This mode corresponds to the situation when the turbine speed is restricted to the nominal value $\omega_{rot}^{ref} = \omega_{rot}^{nom}$ and when the generated power is less than the rated value ($P_{mec} < P_{mec}^{rated}$). For each determined tip speed ratio *λ(u)*, the optimal power coefficient value $C_p^{opt}(\lambda)$ and then the corresponding pitch angle θ is found in the look-up table $C_p(\theta,\lambda)$. The optimum power is therefore achieved by keeping the turbine speed at the lower limit ω_{rot}^{nom}:

$$P_{mec}^{opt}(u) = \frac{1}{2}\,\rho\,\pi\,R^5\,\frac{C_p^{opt}(u)}{\lambda^3(u)}\left[\omega_{rot}^{nom}\right]^3 \qquad [W] \qquad (10)$$

In this case, the highest efficiency is obtained by operating the turbine at nominal speed ω_{rot}^{nom}.

Mode II. *Full load operation* (power limitation strategy zone *D-E*)

This mode corresponds to the situation of wind speeds higher than the rated wind speed. The reference output power is the rated mechanical power $P_{mec}^{ref} = P_{mec}^{rated}$ while the reference rotor speed is the nominal rotor speed $\omega_{rot}^{ref} = \omega_{rot}^{nom}$. Thus, for each wind speed *u*, the power coefficient is calculated as:

$$C_p(\lambda) = \frac{2\,P_{mec}^{rated}\,\lambda^3(u)}{\rho\,\pi\,R^5\left[\omega_{rot}^{nom}\right]^3} \qquad (11)$$

Once the power coefficient value $C_p(\lambda)$ is calculated and the tip speed ratio $\lambda(u) = \omega_{rot}^{nom} R/u$ is known, the static pitch angle θ can then be determined by interpolation in the power coefficient table $C_p(\theta,\lambda)$.

An example of the pitch angle and rotor speed versus wind speed, determined based on the presented control strategies for a variable speed 2 MW wind turbine, is shown in Figure 7. Similar to Figure 6, Figure 7 also points out the wind turbine operation ranges (*A-B*, *B-C*, *C-D*, *D-E*). The pitch angle values in the power optimisation strategy are all found close to zero for the given wind turbine, while at higher wind speeds in order to limit the power, the pitch angle is increasing by a non-linear function. The static reference values of the rotor speed are, as expected, varying in zone *B-C* and otherwise kept constant. However, as the DFIG control design allows overspeed in the case of a wind gust, the rotor speed can vary dynamically in zone C-D-E. As illustrated in Figure 7, the ability to vary the rotor speed ω_{rot} is used in both strategies (power optimisation and power limitation), but it is mostly exploited below rated wind speed (in the power optimisation strategy). The ability to vary the pitch angle θ with wind speed is mostly used above rated wind speed to prevent over rated power production.

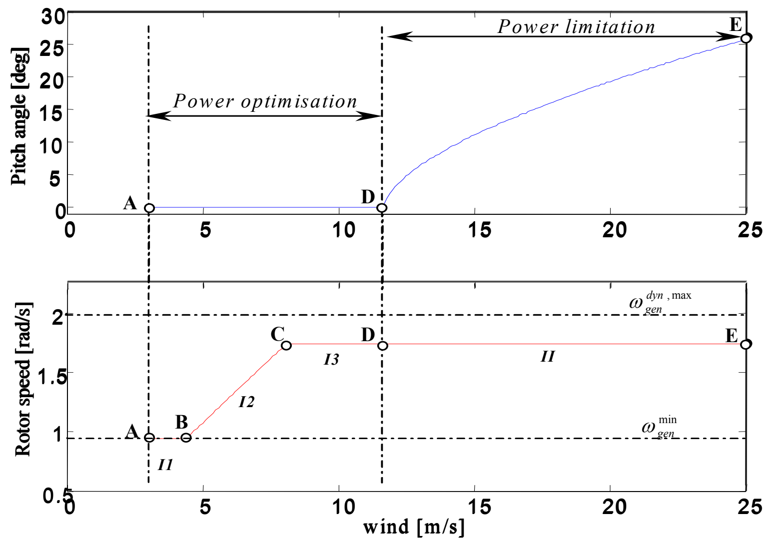

Figure 7: Generic static pitch angle and rotor speed versus wind speed - result of the control strategies.

6.2 Wind turbine controllers

As illustrated in Figure 2, the wind turbine control contains two controllers, which are cross-coupled to each other:

1. Speed controller
2. Power limitation controller

The design of these two controllers is based on the previously described control strategies.

6.2.1 Speed controller

The *speed controller* has as main tasks:

1. to achieve the optimum power by keeping the generator speed at the lower limit $\omega_{gen}^{\min}$ (***I1 control mode***) in power optimisation *A-B* zone with fixed low reference speed limit.

2. to keep the optimal tip speed ratio λ_{opt} over different wind speeds *u*, by adapting the steady state generator speed to its reference ω_{gen}^{ref} (***I2 control mode***) in power optimisation *B-C* zone with variable reference speed.

3. to control the generator speed to its nominal value, allowing however dynamic variations in the predefined speed range indicated in Figure 6(b). For wind speeds above rated wind speed u^{rated} (in power limitation), the speed control loop prevents the rotor/generator speed becoming too large.

Figure 8 shows the implemented speed control loop. It has as input the difference between the reference generator speed and the measured generator speed. The reference generator speed ω_{gen}^{ref} is obtained from the predefined static characteristic (see Figure 6(b)), and it corresponds to the generator speed at which the measured active power P_{grid}^{meas} on the grid is optimal. The error $\Delta\omega_{gen} = \omega_{gen}^{ref} - \omega_{gen}^{meas}$ is sent to a PI controller. The unbalance between turbine torque and generator torque will result in an accelerating torque until the desired speed is reached. The output of the speed controller is the reference power value on the grid $P_{grid}^{conv,ref}$ to the DFIG control.

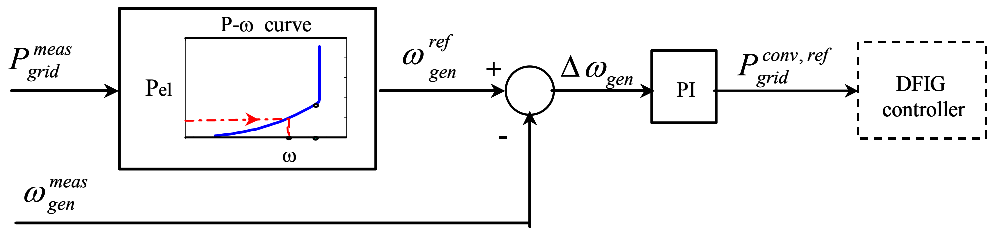

Figure 8: Speed controller of the wind turbine control.

Notice that the speed controller is active both in the power optimisation and power limitation operating modes. The parameters of the speed controller are changed depending on the wind turbine-operating mode (power optimisation or power limitation).

6.2.2 Power limitation controller with gain scheduling

The *power limitation controller* has as task to increase or decrease the pitch angle in the power limitation strategy, i.e. in order to limit the generated power at the rated power.

Figure 9 shows the power limitation control loop. The error signal $\Delta P = P_{grid}^{meas} - P_{grid}^{rated,ref}$ is sent to a PI-controller. The PI controller produces the reference pitch angle θ_{ref}. This reference is further compared to the actual pitch angle θ and then the error $\Delta\theta$ is corrected by the servomechanism. In order to get a realistic response in the pitch angle control system, the servomechanism model accounts for a servo time constant T_{servo} and the limitation of both the pitch angle and its gradient. The output of the power limitation controller is the pitch angle of the blades.

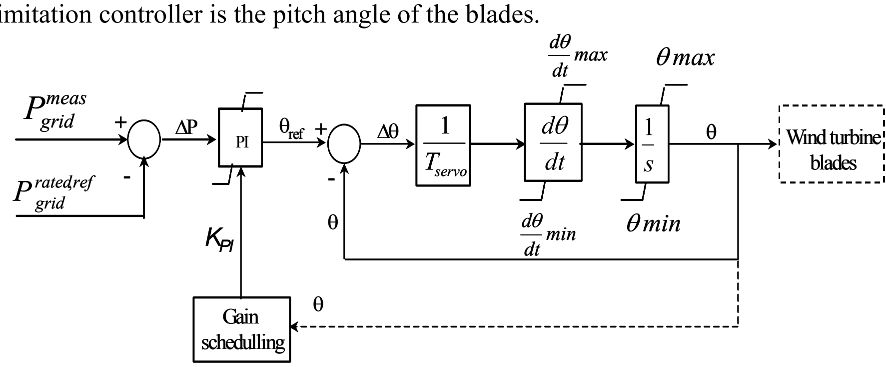

Figure 9: Power limitation controller of the wind turbine control, which controls the pitch.

A gain scheduling control of the pitch angle, as indicated in Figure 9, is implemented in order to compensate for the existing non-linear aerodynamic characteristics. Ideally, the control parameters would be chosen as a function of the wind speed, but this is not an appropriate procedure due to the fact that it is not possible to measure the wind speed precisely.

Assuming that the wind turbine system is well controlled, then the pitch angle and the active power can be used as gain-scheduling parameters instead of wind speed. Therefore, the implementation of the gain scheduling is performed based on knowledge of the pitch angle, which can be thus used to express the non-linear aerodynamic amplification in the system.

The non-linear variation of the pitch angle versus wind speed for high wind speeds, illustrated in Figure 7, implies the necessity of a non-linear control (gain scheduling). A linear control would result in instabilities at high wind speeds.

The total gain of the system in the power control loop K_{system}, can be expressed as a proportional gain K_{PI} in the PI controller times aerodynamic sensitivity of the system $\frac{dP}{d\theta}$:

$$K_{system} = K_{PI} \frac{dP}{d\theta} \tag{12}$$

The aerodynamic sensitivity $\frac{dP}{d\theta}$ of the system depends on the operating conditions (the setpoint power value, the wind speed or the pitch angle). Therefore, in order to maintain the total gain of the system K_{system} constant, the proportional gain of the PI controller K_{PI} is changed in such a way that it counteracts the variation of the aerodynamic sensitivity $\frac{dP}{d\theta}$. The gain of the controller K_{PI} must therefore incorporate information on the dependency of the variation of the power with the pitch angle.

The variation of the aerodynamic sensitivity with the pitch angle for a 2 MW wind turbine is illustrated in Figure 10(a). It increases numerically (absolute value) with the pitch angle and it can vary with a factor up to 10.

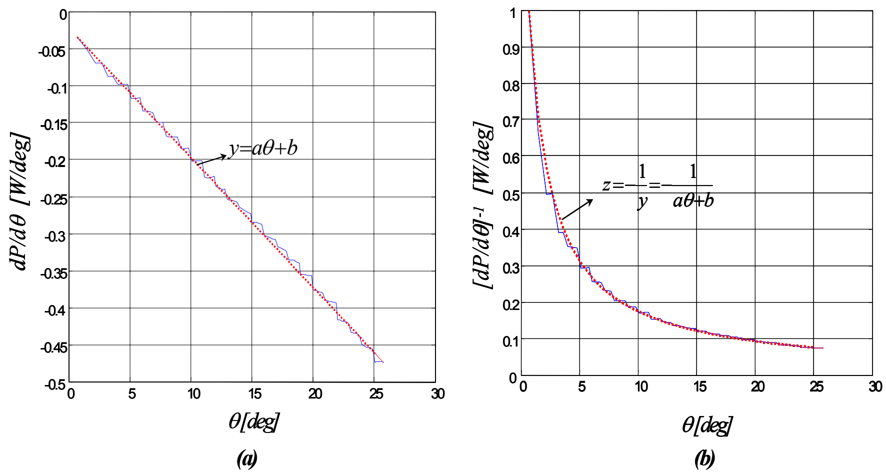

Figure 10: Sensitivity function and the inverse sensitivity function of the wind turbine. (a) sensitivity function $dP/d\theta$ versus pitch angle θ. (b) inverse sensitivity function $[dP/d\theta]^{-1}$ versus pitch angle θ.

Observe that the variation of the aerodynamic sensitivity is almost linear in the pitch angle θ and therefore a linear expression with the parameters *a* and *b* can be fitted:

$$\frac{dP}{d\theta} = a\theta + b \tag{13}$$

This linear description is used to determine the reciprocal of the aerodynamic sensitivity, defined as follows:

$$\left[\frac{dP}{d\theta}\right]^{-1} = -\frac{1}{a\theta + b} \tag{14}$$

where the negative sign compensates for the negative ramp of the aerodynamic sensitivity and thus assures that the sign of the total gain of the system does not change. Notice that the reciprocal sensitivity function $\left[\frac{dP}{d\theta}\right]^{-1}$, illustrated in Figure 10(b), is non-linear with the pitch angle. It is used in the definition of the controller gain K_{PI} to counteract the mentioned variation, as follows:

$$K_{PI} = K_{basis} \left[\frac{dP}{d\theta}\right]^{-1} \tag{15}$$

where K_{basis} is the constant proportional gain of the PI- controller, determined to be appropriate for one arbitrary wind speed.

Notice that the more sensitive the system is (larger pitch angles θ / higher wind speeds) the smaller the gain for the controller should be and vice versa. The introduction of the gain scheduling enables the PI- controller to perform an adequate control over the whole wind speed range.

Notice also that these two strategies do not need a wind speed measurement. Only the generator speed and active power are required. The speed controller is the main controller in the power optimisation strategy, while in the power limitation strategy both controllers are active and cross-coupled to each other. This interconnection can be exemplified as follows.

If the wind speed is less than the rated wind speed u^{rated}, the pitch angle is kept constant to the optimal value θ_{opt}, while the generator speed ω_{gen} is adjusted by the frequency converter control in such a way that the maximum power is obtained. If now a wind gust appears, the rotor speed ω_{rot} and thus also the generator speed ω_{gen} are increasing due to the increased aerodynamic torque, and the speed control loop reacts by increasing the power reference $P_{grid}^{conv,\ ref}$ (in Figure 8). If the wind speed increases further over the rated wind speed, then the power control loop reacts by increasing the pitch angle to prevent the power generation becoming too large. Meanwhile, the speed control loop controls the rotor speed to its nominal value, but allows rotor speed dynamic variations in a predefined speed range. The changes in the aerodynamic power are thus absorbed as changes in the rotational speed instead of as changes in torque and therefore the impact of the wind speed variations on the drive train loads is reduced.

7 SIMULATION RESULTS

Different scenarios are simulated to asses the performance both of DFIG controller and of the overall control of the variable speed /variable pitch wind turbine.

Power flow inside DFIG

Both Figure 11 and Figure 12 illustrate the results of a simulation, where a fictive non-turbulent wind speed with fixed mean value and a sinusoidal variation with a 3p frequency is used. A variable speed DFIG wind turbine with 2 MW rated power is considered. A step in the mean speed value from 7 m/s to 9 m/s is performed to force the system from sub-synchronous to over-synchronous operation. The purpose of this simulation is to illustrate:

- the power flow through the grid, stator and rotor when the DFIG changes between sub-synchronous and over-synchronous operations, due to a step in the wind speed.
- the filter effect of the mechanical 3p fluctuations in the electrical power.

Notice in Figure 11 that during sub-synchronous operation the power delivered to the grid is less than that delivered by the stator P_{stator}, as in the rotor circuit the power is flowing from the grid to the rotor via power converter ($P_{rotor}<0$). Meanwhile in over-synchronous operation, the power delivered to the grid is higher than that from the stator because of the power contribution from the rotor side. The rotor power flows from the rotor to the grid in over-synchronous operation ($P_{rotor}> 0$).

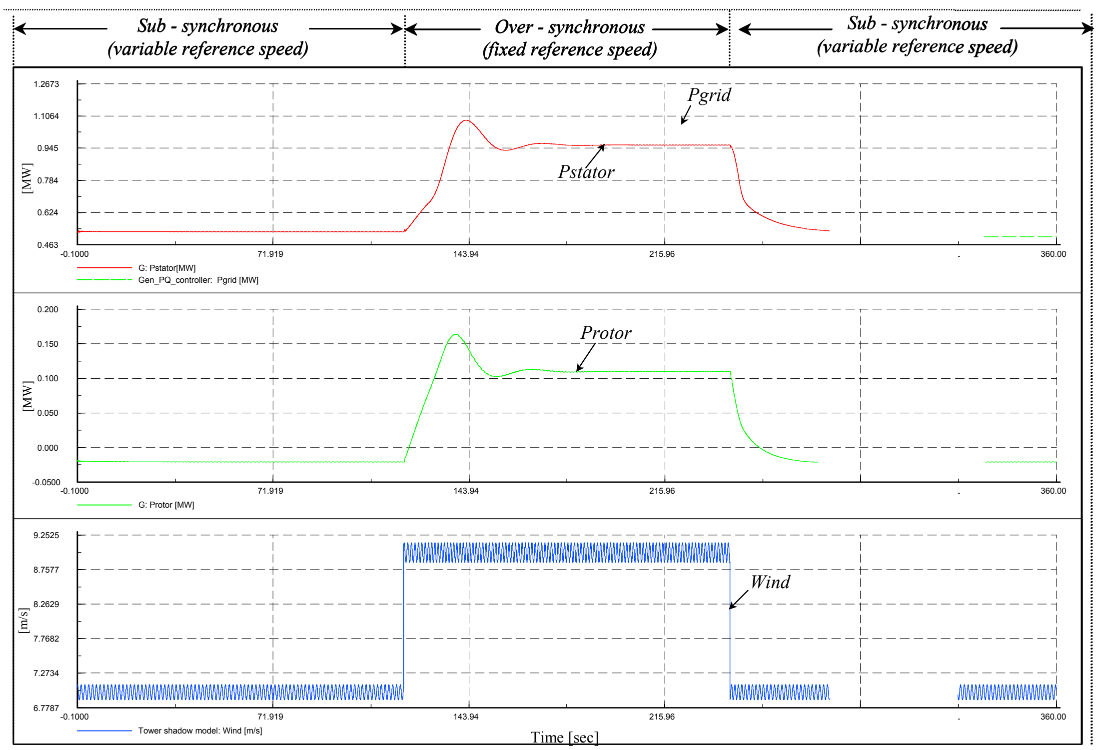

Figure 11: Simulated power through the grid, stator and rotor in sub-synchronous and over-synchronous operations.

The 3p fluctuations of the wind speed are present in the mechanical part of the system, i.e. in the aerodynamic torque, but not on the electrical part, i.e. in the electrical torque – see Figure 12. The 3p fluctuations in the wind are thus not visible in the electrical power. They are reduced effectively by the control of the DFIG. For this wind speed range (7 m/s to 9 m/s), the wind turbine operates in the power optimisation mode (zone B-C-D), where the speed controller seeks to maximise the power captured from the wind according to Figure 6(b). It thus adjusts the generator speed to its predefined reference (variable or fixed) to be able to capture as much energy from the wind as possible. The power limitation controller is not active here, as the rated power is not reached. The pitch angle is kept constant to its optimal value determined with the control mode ***I2*** and ***I3***.

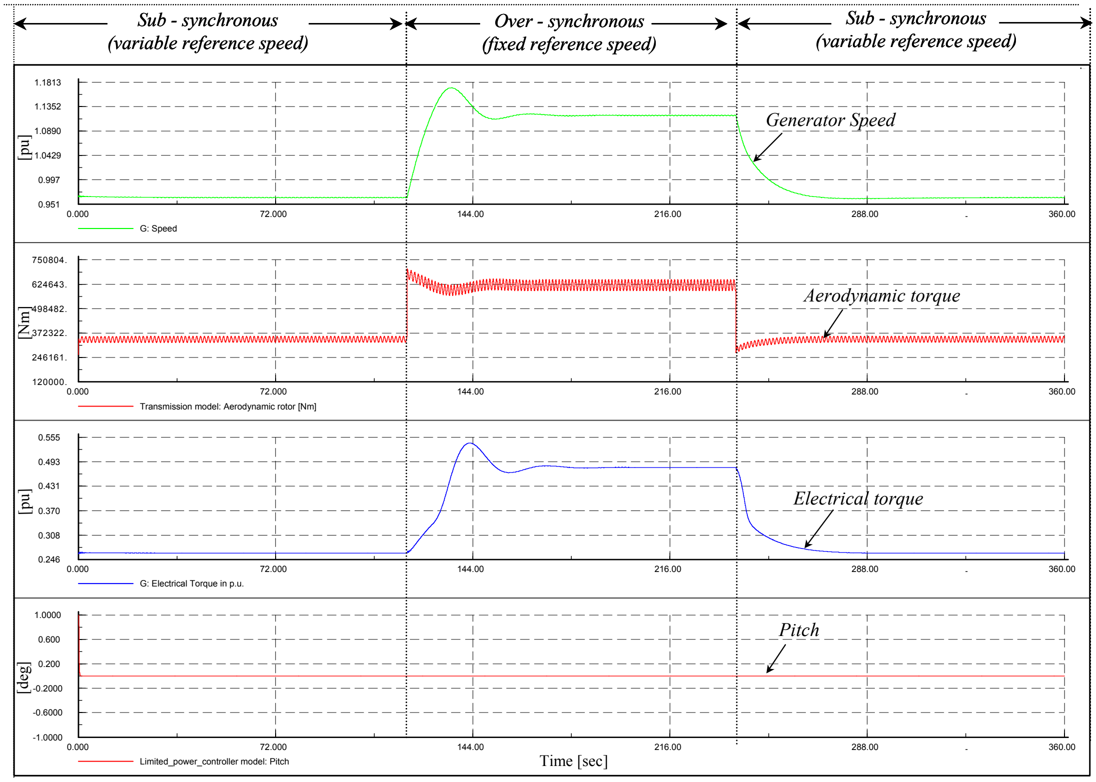

Figure 12: Simulated generator speed, aerodynamic torque, electrical torque and pitch angle.

<u>Overall control of the wind turbine</u>

Both Figure 13 and Figure 14 illustrate how the control algorithms are working at different operating conditions. Again a variable speed wind turbine with a rated power of 2 MW is used. The rated wind speed is 11.5 m/s and the rated generator speed ω_{gen}^{nom} is 1686 rpm. Typical quantities are shown: wind speed, generator speed and reference generator speed, the pitch angle and the generator power on the grid.

Figure 13 illustrates the simulation operation at 7 m/s mean value turbulent wind speed with turbulence intensity of 10%. This operation corresponds to the power optimisation with variable generator speed reference (zone B-C in Figure 6).

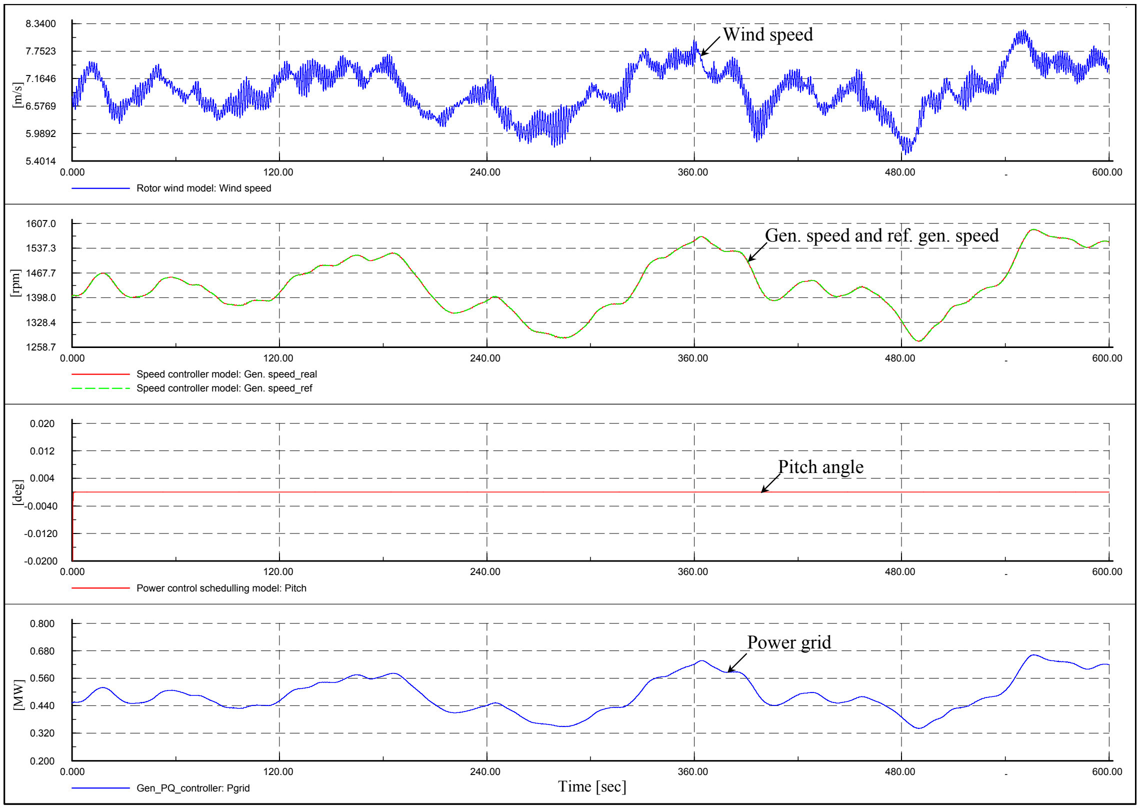

Figure 13: Simulation with turbulent wind speed, with mean 7m/s and turbulence intensity of 10%.

In power optimisation, the main turbine controller is the speed controller. As the rated power is not reached, the power limitation controller is not active. The speed controller has here to be strong and fast in order to seek to the maximum power. It has to assure that the generator speed follows very well the variable generator speed reference in order to be able to absorb the maximum energy from the wind. The speed reference is generated based on the static curve illustrated in graph (b) of Figure 6 and it corresponds to the generator speed for which the measured power is optimal. Notice that the generator speed follows very well its reference, whose trace is tracking the slow variation in the wind. As expected for this wind speed range (7 m/s mean value), the pitch angle is not active, being kept constant to its optimal value (i.e. zero for the considered wind turbine). Notice that the fast oscillations in the wind speed are completely filtered out from the electrical power.

Figure 14 shows the simulation results when a turbulent wind speed with a mean value of 18 m/s and a turbulence intensity of 10% is used. In order to illustrate the elasticity of the variable speed DFIG wind turbine, some gusts about 5 m/s up and down, respectively, are introduced in the wind speed at each 150s.

This simulation case corresponds to the power limitation strategy, where both the speed controller and the power limitation controller are active. The power limitation control loop is strong and fast, while the speed control loop is deliberately much slower, allowing dynamic variations of the generator speed in the speed range permitted by the size of the power converter.

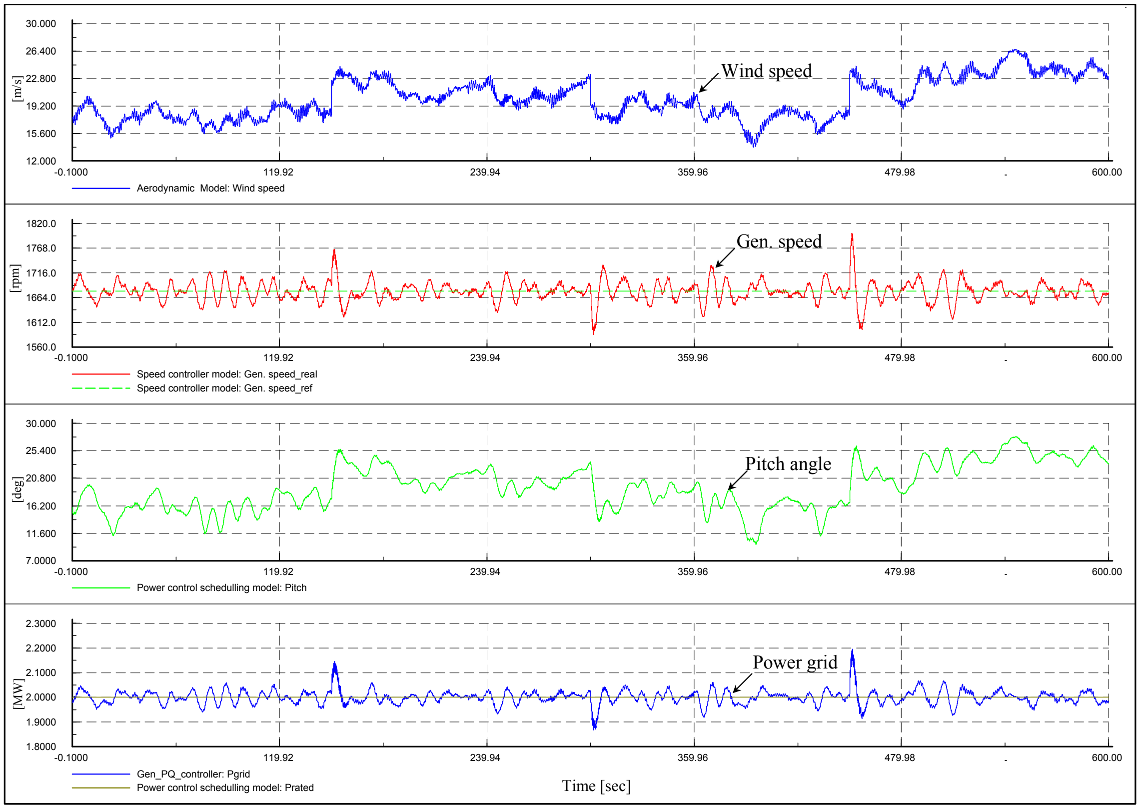

Figure 14: Simulation with turbulence wind speed, with mean speed 18 m/s, turbulence intensity 10% and gusts.

The power limitation controller changes the pitch angle to keep the rated power, while the speed controller prevents the generator speed from becoming too high. Contrary to the power optimisation, illustrated in the previous simulation, the speed controller allows here deviations of the generator speed from its reference (rated) value. For example, at the time instant t=150 s, the wind speed rapidly reaches 22 m/s. The generator speed increases quickly due to the increased aerodynamic torque. The electrical power increases too, until the pitch controller reacts modifying the pitch angle. The pitch controller is not fully capable of capturing this fast wind speed change. The pitch angle follows the slow variation in the wind speed, while fast gusts in the wind speed are absorbed as variation (peaks) in generator speed. The rotational speed of the turbine rotor is thus allowed to increase storing energy into the turbine's inertia.

8 CONCLUSIONS

The present paper describes an overall control method of the variable speed/variable pitch wind turbine with DFIG. Two hierarchical control levels, strongly connected to each other are depicted and presented: DFIG control level and wind turbine control level.

A vector control approach is adopted for the control of the DFIG, while the control of the wind turbine is a result of two cross-coupled controllers: a speed and a power limitation controller. The generator speed is directly controlled by the frequency converter, while the active power is regulated by the pitch angle.The strongest feature of the implemented control method is that it allows the turbine to operate with the optimum power efficiency over a wider range of wind speeds. Moreover, due to the design of this control method, the transition between power optimisation mode and power limitation mode is not dominated by large power fluctuations due to small changes in generator speed. A gain scheduling control of the pitch angle is also implemented in order to compensate for the non-linear aerodynamic characteristics.

The performed simulations show that the implemented control method is able to control efficiently the variable speed DFIG wind turbine at different normal operation conditions. At wind speeds lower than the rated wind speed, the speed controller seeks to maximise the power according to the maximum coefficient curve. As result, the variation of the generator speed follows the slow variation in the wind speed. At high wind speeds, 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 order to avoid mechanical stress in the gear-box and the shaft system. As a result, the pitch angle follows the slow variation in wind speed, while fast gusts are absorbed in variations of the generator speed.

The described control method is designed for normal continuous operations. One future research step is to investigate and enhance the controller's capabilities of DFIG to handle grid faults. Another interesting issue is to explore the present controller in the design of a whole wind farm controller with variable speed, variable pitch wind turbines with doubly-fed induction generators, where focus is drawn on the voltage and frequency regulation of the grid.

9 ACNOWLEDGEMENT

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