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Modelling and Control of Wind Turbine

Muhammad Nazir Abubakar

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ABSTRACT*: This work covers the modelling of wind turbines for power system studies. The operation of horizontal, variable speed wind turbines with pitch control was investigated. Complexities of various parts of a wind turbine model, such as aerodynamic conversion, drive train and generator representation were analyzed. The mathematical equations describing the dynamic behaviour of a wind energy system were successfully simulated in gPROMS. The wind turbine model was further tested upon step changes in the wind velocity as well as the blade pitch angle, confirming the need of power control. Using wind turbine model, a power control structure was generated, that takes into consideration the dynamical aspects of the wind turbine as well as constraints. An explicit parametric controller, a novel control method, was designed using MATLAB and the Parametric Optimization (POP) software. A simple explicit optimal control law was constructed that allows the on-line implementation via simple linear function evaluations. The controller was implemented using gO: MATLAB and the simulation results.*

KEYWORDS: modelling, control, wind, turbine

INTRODUCTION

Work Motivation

Wind energy is one of the fastest growing renewable energies in the world. The generation of wind power is clean and non-polluting; it does not produce any byproducts harmful to the environment. Nowadays, modeling is the basic tool for analysis, such as optimization, project, design and control. Wind energy conversion systems are very different in nature from conventional generators, and therefore dynamic studies must be addressed in order to integrate wind power into the power system. According to [Loony, 2003], in the case of power systems with classical sources of energy analysis, the modeling is relatively simple because the models of objects and controllers are well known and even standardized; the data are available. But in the case of wind turbine modeling, researchers meet problems related to the lack of data and lack of control-system structures due to strong competition between wind turbine manufacturers. This leads to the situation in which many researchers model the wind energy conversion systems in relatively simple form, almost neglecting the control systems which significantly influence the reliability of the analytical results.

Classical techniques such as proportional (P), integral (PI) and derivative (PID) controllers are typically used to regulate wind power. But by assuming the wind turbine operating in steady state conditions, most of the previous work regarding wind turbine control does not take into consideration the dynamical aspects of the wind and the turbine, which have strong non-linear characteristics [Balas et al, 2006]. Advances in wind turbine technology made necessary the design of more powerful control systems, to improve wind turbines behaviour and make them more profitable and reliable [Boukhezzar et al, 2005]. However, as stated in [Balas et al, 2006] "Controlling modern turbines to minimize the cost of wind energy is a complex task, and much research remains to be done to improve controllers". An interesting characteristic of wind energy systems is that wind speed determines the point of operation; it simply defines the available amount of energy that can be converted into electricity. The wind cannot be controlled; in other words the system is driven by noise, which makes wind turbine systems essentially different from most other systems. This explains the need for robust controller design [Bongers et al, 1992].

On the other hand, theoretically, the electrical output from a wind turbine should be smooth and non-fluctuating [Butterfield et al, 2001]. But electricity generated from wind farms can be highly variable on different time scales: from hour-to-hour, daily and seasonally. This represents a considerable challenge when incorporating wind power into a grid system, since in order to maintain grid stability energy supply and demand must remain in balance.

METHODOLOGY

Wind Turbine Modelling

Modeling is a basic tool for analysis, such as optimization, project, design and control. Wind energy conversion systems are very different in nature from conventional generators, and therefore dynamic studies must be addressed in order to integrate wind power into the power system. Models utilized for steady-state analysis are extremely simple, while the dynamic models for wind energy conversion systems are not easy to develop. Dynamic modeling is needed for various types of analysis related to system dynamics: stability, control system and optimization.

Referring to [Lubosny, 2003], in the case of power systems with classical sources of energy analysis, the modeling is relatively simple because the models and controllers of the processes are well known and even standardized; the data are available. But in the case of wind turbine modeling, researchers face problems related to the lack of data and lack of control system structures due to strong competition between wind turbine manufacturers. This leads to the situation in which many researchers model the wind energy conversion systems in relatively simple form, almost neglecting the control systems, which significantly influence the reliability of the analytical results.

Modern wind turbine generator systems are constructed mainly as systems with a horizontal axis of rotation, a wind wheel consisting of three blades, a high speed asynchronous generator (also known as induction generator) and a gear box. Asynchronous generators are used because of their advantages, such as simplicity of construction, possibilities of operating at various operational conditions, and low investment and operating costs. The wind turbine under study falls under this category and is also equipped with a blade pitch angle control system, which enables the power generated by the wind turbine to be controlled. A typical wind energy conversion system is displayed in Fig. 1.

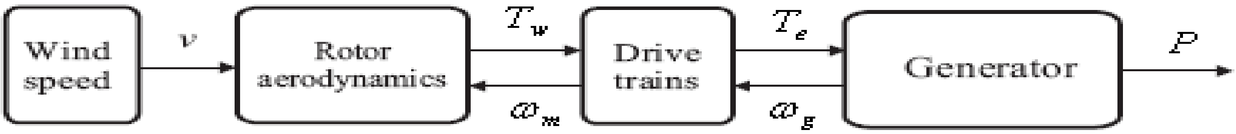

Figure 1. Wind turbine scheme [Boukhezzar et al, 2005]

The wind turbine model, consisting of the aerodynamic, drive train and electrical generator model is described next. These models are proposed by [Lubosny, 2003], [Martins et al, 2007] and [Lei et al, 2006].

Modelling of the Blades

As pointed out in Chapter 2, the wind turbine blades extract the kinetic energy in the wind and transform it into mechanical energy. The kinetic energy in air of an object of mass *m* moving with speed *v* is equal to

$$E=\frac{1}{2}.m.v^2 \quad \text{…………………………..} \ (2.1.1)$$

The power in the moving air (assuming constant speed velocity) is equal to

$$P_w = \frac{dE}{dt} = \frac{1}{2}.m.v^2 \quad \text{……………………………} \ (2.1.2)$$

where, *m* is the mass flow rate per second. When the air passes across an area A (e.g. the area swept by the rotor blades), the power in the air can be computed as

$$P_w = \frac{1}{2}.\rho.A.v^3 \ \dots\dots\dots\dots\dots\dots\dots \ (2.1.3)$$

where ρ is the air density. Air density can be expressed as a function of the turbine elevation above sea level H

$$\rho \ = \ \rho_0 - 1.194 \times 10^{-4}.H \ \text{……………………..} \ (2.1.4)$$

where 1.225 ρ_0 = kg/m^3 is the air density at sea level at temperature T=298K. The power extracted from the wind is given by

$$P_{BLADE} = C_P(\lambda,\beta).P_w \ = \ C_P(\lambda,\beta).\frac{1}{2}.\rho.A.v^3 \ \dots\dots\dots\dots\dots.. \ (2.1.5)$$

The power factor has a maximum theoretical value equal to Cp = 0.593.

The rotor power coefficient is usually given as a function of two parameters: the tip speed ratio λ and the blade pitch angle β (in degrees). The blade pitch angle is defined as the angle between the plane of rotation and the blade cross-section chord. And the tip speed ratio is defined as

$$\lambda = \frac{W_m.R}{v} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.1.6)$$

where ω $_m$is the angular velocity of the rotor and *R* the rotor radius (blade length).
The rotor torque T_w can be computed as

$$T_w = \frac{P_{BLADE}}{W_m} = \frac{\frac{1}{2}Cp(\lambda,\beta).\rho.A.v^3}{\omega_m} \dots\dots\dots\dots\dots\dots\dots\dots\dots.. (2.1.7)$$

The area covered by the blades is given by

$$\mathrm{A} = \pi.R^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (2.1.8)$$

Substituting Eq. 3.1.8 into Eq. 3.1.7 leads to

$$T_w = \frac{\frac{1}{2}.\pi.Cp(\lambda,\beta).\rho.R^2.v^3}{\omega_m} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (2.1.9)$$

Based on previous research, the power coefficient Cp can be defined as a function of the tip-speed ratio and the blade pitch angle as follows

$$\mathrm{Cp}\ (\lambda,\beta) = C_1.\left[\!\left[C_2.\frac{1}{\gamma} - C_3.\beta - C_4.\beta^x - C_5\right]\!\right] e^{-C6\frac{1}{\gamma}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.1.10)$$

with γ defined as

$$\frac{1}{2} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \dots\dots\dots\dots\dots\dots\dots\dots (2.1.11)$$

while the coefficients c1-c6 are proposed as equal to: C_1= 0.5, C_2= 116, C_3= 0.4, C_4= 0, C_5= 5, C_6= 21 (x is not used here because C_4= 0).

According to [Lubosny, 2003] an example of the power coefficient (*Cp*(λ,β)) characteristics computed taking into account equations 3.1.10 and 3.1.11 and the above parameters C_1-C_6 for a given rotor diameter, rotor speed and for various blade pitch angles β is presented in Figure 9.

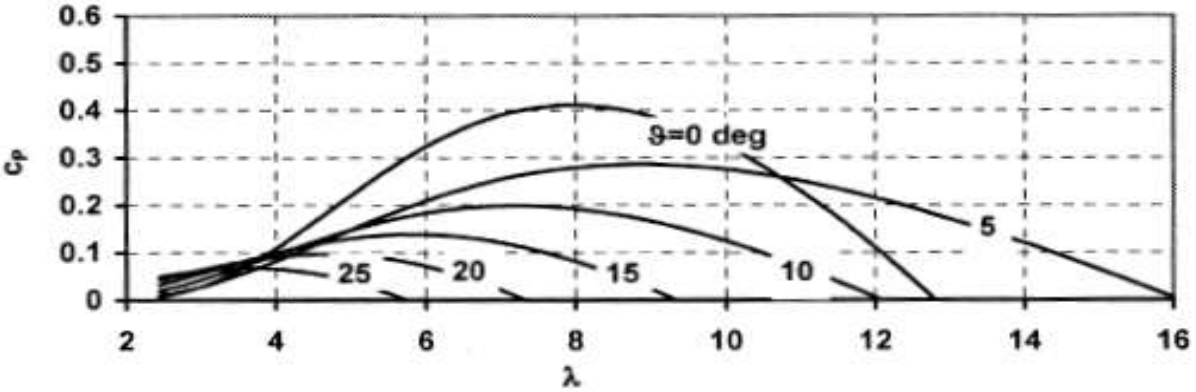

Figure 2. Analytical approximation of *Cp* (λ,β)characteristics (ω=2.09 rad/s, *R* =35m); blade pitch angle in degrees [Lubosny, 2003]

Modelling of the Drive Train

The drive train (mechanical parts) of a wind turbine system in general consists of a blade pitching mechanism, a hub with blades, a rotor shaft (relatively long in wind energy conversion systems with asynchronous generators) and a gearbox with generator. The drive train model presented in this paper includes the inertia of both the turbine and the generator. The moment of inertia of the wind wheel (hub with blades) is about 90% of the drive train total moment, while the generator rotor moment of inertia is equal to about 10%. At the same time, the generator represents the biggest torsional stiffness.

The acceptable and common way to model the drive train of a wind turbine in power system operation analysis is based on the assumption of two lumped/masses only: the generator (with gearbox) mass and the hub with blades (wind wheel) mass [Lubosny, 2003]. The structure of the model is presented in Figure 10.

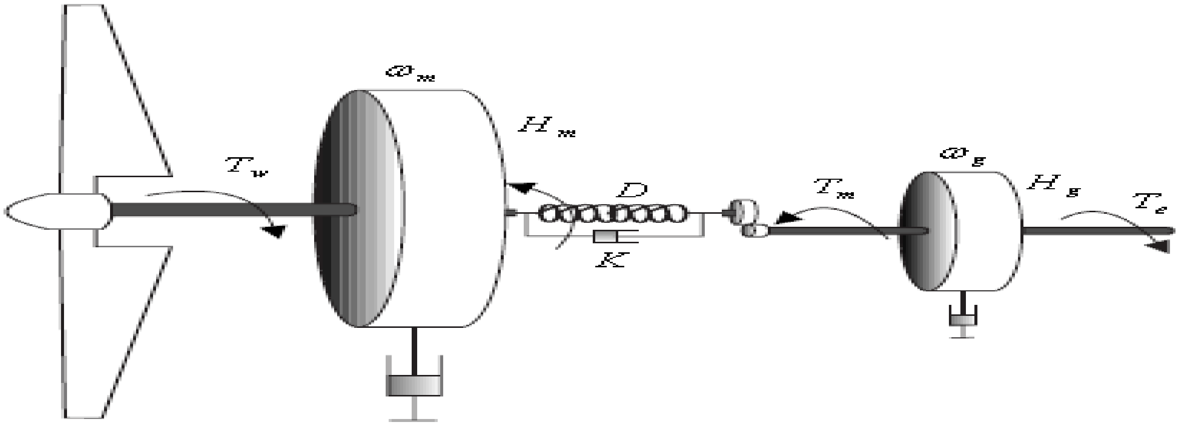

Figure 3. Drive train dynamics [Boukhezzar et al, 2005]

The equation of motion of the induction generator is given by

$$H_g.\frac{dw_g}{dt} = T_e + \frac{T_m}{n} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(2.2.1)$$

Additionally, since the wind turbine shaft and generator are coupled together via a gearbox, the wind turbine shaft system should not be considered stiff. To account for the interaction between the windmill and the rotor, an additional equation describing the motion of the windmill shaft is adopted

$$H_m.\frac{dw_m}{dt} = T_w - T_m \dots\dots\dots\dots\dots\dots\dots\dots.(2.2.2)$$

The mechanical torque T_m can be modeled with the following equation

$$T_m = K.\frac{\theta}{n} + D.\frac{w_g - w_m}{n} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..(2.2.3)$$

$$\frac{d\theta}{dt} = w_g - w_m \dots\dots\dots\dots\dots\dots\dots\dots (2.2.4)$$

where *n* is the gear ratio, θ is the angle between the turbine rotor and the generator rotor, w_m, w_g, $H_{m,}$ and H_g are the turbine and generator rotor speed and inertia constant, respectively, K and D are the drive train stiffness and damping constants, is the torque provided by the wind (from section 3.1) and T_e is the electromagnetic torque.

Modelling of the Asynchronous Generator

The mechanical power of the wind turbine is converted into electric power by an alternating current (AC) generator or a direct current (DC) generator. The AC generator can be either a synchronous machine or an induction (asynchronous) machine. The latter is most widely used in the wind power industry and was selected for this project. The electrical machine works on the principle of action and reaction of electromagnetic induction. The resulting electromechanical energy conversion is reversible. The same machine can be used as a motor for converting mechanical power into mechanical power or a as generator for converting mechanical power into electric power.

As pointed out by [Lubosny, 2003], it is assumed that the asynchronous generator, also called induction generator, has three-phase stator armature winding (AS, BS, CS) and a three-phase rotor winding (AR, BR, CR) as shown in Fig. 11. The stator is the outer stationary member and the rotor is the inner rotating member of the machine. The rotor is mounted on bearings fixed to the stator. In the electromagnetic structure of the induction generator, when the stator winding is supplied with three-phase current (waveforms of equal amplitude, displaced in time by one-third of a period), a rotating magnetic field is produced. The angular speed of the rotating magnetic field is called the synchronous speed, w_s. The relative speed between the rotating field and the rotor induces a current in the rotor. The resulting magnetic field interacts with the stator field to make the rotor rotate in the same direction. In this case, the machine acts as a motor since, in order for the rotor to rotate; energy is drawn from the electric power source. However, if an external mechanical torque (in this case the wind torque) is applied to the rotor to drive it beyond the synchronous speed, then electrical energy is pumped to the power grid, and the machine will act as a generator [Dorf, 2000].

An induction machine needs no electrical connection between the stator and the rotor. Its operation is entirely based on electromagnetic induction. The absence of rubbing electrical contacts and simplicity of its construction make the induction generator a very robust, reliable, and low-cost machine.

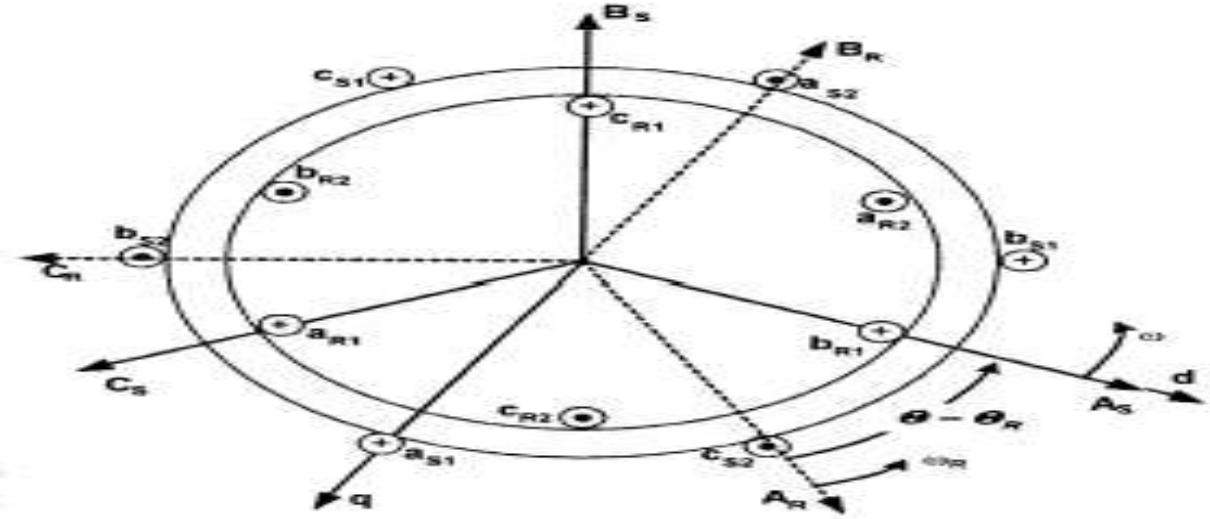

Figure 4. The windings in the asynchronous generator [Lubosny, 2003]

Model Assumptions

The mathematical model of an asynchronous generator for power system analysis is usually based on the following assumptions [Lubosny, 2003]:

- The stator currents are positive when flowing towards the network.
- The real and reactive powers are positive when fed into the grid.
- The stator and rotor windings are placed sinusoidally along the air-gap as far as the mutual effect with the rotor is concerned.
- The stator slots cause no appreciable variations of the rotor inductances with rotor position.
- The rotor slots cause no appreciable variations of the stator inductances with rotor position.
- Magnetic hysteresis and saturation effects are negligible.
- The stator and rotor windings are symmetrical.
- The capacitance of all the windings can be neglected.

More detailed modeling usually encounters difficulties in getting appropriate data. Additionally, for machine modeling, such a type of model is adequately precise.

0DQ Reference Frame

The set of equations of the asynchronous generator model is usually converted into a model related to an arbitrarily set reference frame: the machine is converted into the so-called *0dq* reference frame model. The *dq* axis representation of induction generator is used for simulation, taking flux linkage as basic variable [Jangamshetti et al, 2006]. It is based on fifth-order two axis representations. Mathematical transformations are used in the analysis and simulation of three-phase systems, mostly to decouple variables, to facilitate the solution of difficult equations with time-varying coefficients. Park's transformation [Slemon, 1989] decouples and rotates the stator variables into a *dq* reference frame. The positive d-axis of the *dq* frame is aligned with the magnetic axis of the field winding, that of the positive q-axis is ahead in the direction of rotation or lead the positive d-axis by π/2. *ds* and *qs* correspond to stator direct and quadrature axes; *dr* and *qr* correspond to rotor direct and quadrature axes.

Per Unit System

As stated in [Weedy et al, 1998], in electrical engineering the per unit (p. u) system is the expression of system quantities as fractions of a defined base unit quantity. These fractions are called per unit and the p. u. value of any quantity is defined as

$$\text{Value in p. u} = \frac{\text{actual value (in any unit)}}{\text{base or reference value in the same unit}}$$

Parameters of electrical generators are often specified in terms of per unit. Calculations are simplified because quantities expressed as per unit are the same regardless of the voltage level. Similar types of apparatus will have impedances, voltage drops and losses that are the same when expressed as a per-unit fraction of the equipment rating, even if the unit size varies widely. Although the use of p. u. values may at first sight seem a rather indirect method of expression there are several reasons for using a per-unit system:

- the use of the constant 3 is reduced in three-phase calculations.
- per unit quantities are the same on either side of a generator, independent of voltage level.
- by normalizing quantities to a common base, both hand and automatic calculations are simplified.

Referring to [Slootweg et al, 2001] it is difficult to calculate the per unit value of the power extracted from the wind, because aerodynamic and mechanical wind turbine characteristics such as rotor diameter and wind velocity come into play. Therefore the asynchronous generator equations are given in the-per unit system (p. u.), and the aerodynamic and drive train equations in the standard international units.

Asynchronous Generator Model

An appropriate model of the induction generator is the most complicated part of the total wind generation model. The model of such a system is well described in many books and papers [Karrari et al, 2005].

Two main induction generator models are used when performing power system dynamic studies [Martins et al, 2007]:

- A detailed model which includes electromagnetic transients both in the stator and the rotor circuits, containing four electromagnetic state variables. This model is also known as the fifth order model.
- A simplified model which neglects stator transients, containing two electromagnetic state variables. This model is sometimes referred in the literature as the third order model, accounting for the two electric state variables and the generator speed.

The following is a brief description of both models.

Model Including Stator Transients

To be able to simulate the induction generator and wind generation system, an equation relatingV_{ds}, V_{qs}, the stator direct and quadrature axis voltages, to I_{ds}, I_{qs}, the stator direct and quadrature axis currents, is required.

The complete model of an asynchronous generator, expressed in a *0dq* reference frame rotating at synchronous speed and taking positive currents going out from the machine, consists of the following equations:

- ❖ Magnetic fluxes

$$\varphi_{ds} = X_s . I_{ds} + X_m . I_{dr} \qquad (2.\ 3.\ 1)$$

$$\varphi_{qs} = X_s . I_{qs} + X_m . I_{qr} \qquad (2.\ 3.\ 2)$$

$$\varphi_{dr} = X_r . I_{dr} + X_m . I_{ds} \qquad (2.\ 3.\ 3)$$

$$\varphi_{qr} = X_r . I_{qr} + X_m . I_{qs} \qquad (2.\ 3.\ 4)$$

- ❖ Voltages

$$V_{ds} = -R_s . I_{ds} + w_s . \varphi_{qs} - \frac{d\varphi_{ds}}{dt} \qquad (2.3.5)$$

$$V_{qs} = -R_s . I_{qs} - W_s . \varphi_{ds} - \frac{d\varphi_{s}}{dt} \qquad (2.3.6)$$

$$0= -R_r.I_{dr} + S.W_s.\varphi_{qr} - \frac{d\varphi_{dr}}{dt} \qquad (2.3.7)$$

$$0= -R_r.I_{dr} - S.W_s.\varphi_{dr} - \frac{d\varphi_{qr}}{dt} \qquad (2.3.8)$$

where the sub indexes (s, r) stand for the stator and rotor quantities, respectively, and the sub indexes (d, q) stand for the components aligned with the d- and q- axis in a synchronous rotating reference frame. Variable ϕ represents the magnetic flux linkage, *V* the voltage and *I* the current. In the case of the traditional induction machine, the rotor voltage V_{dr} and V_{qr} is equal to zero, since the current is only fed into the stator. Variables w_s and w_g are the synchronous and generator rotor speed, respectively.

The slip of the rotor, s, is defined as follows

$$S= \frac{W_s-W_g}{W_s} \qquad (2.3.9)$$

The slip is positive in the motoring mode and negative in the generating mode.
The electric parameters of the machine R_s , X_s, X_m, R_r and X_r stand for the stator resistance and reactance, mutual reactance and rotor resistance and reactance, respectively. The electrical torque is given by

$$T_e = \varphi_{qr}.I_{dr} - \varphi_{dr}.I_{qr} \qquad (2.3.10)$$

The developed torque T_e is positive for motoring operation and negative for generation operation. Finally, the wind turbine active, reactive and apparent power output are given by the following equations

$$P_{active} = V_{ds}.I_{ds} + V_{qs}.I_{qs} \qquad (2.3.11)$$

$$Q_{reactive} = V_{qs}.I_{ds} - V_{ds}.I_{qs} \qquad (2.3.12)$$

$$P= V_{ds}.Ids + V_{qs}.I_{qs} + V_{qs}.I_{ds} - V_{ds}.I_{qs} \qquad (2.3.13)$$

Model Neglecting Stator Transients
For power system transient studies, the inclusion of the network transients and generator stator transients increases the order of the overall system model, thus limiting the size of the system that can be simulated. Furthermore, a small time step is required for numerical integration resulting in an increased computational time. For these reasons, it has become conventional to reduce the order of the generator and neglect the network transients for stability analysis [Ekanayake et al, 2003]. Different methods for reducing the generator equations are discussed in [Wasynezuk et al, 1985].

For this project, a standard method of reducing the order of the induction generator model was considered where the rate of change of stator flux linkage is neglected. This is common when performing stability simulations [Martins et al, 2007]. It is done by neglecting terms $\frac{d\varphi_{ds}}{dt}$ and $\frac{d\varphi_{qs}}{dt}$ in Equations 3.3.5-3.3.6, which is equivalent to assuming infinitely fast electromagnetic transients in the stator windings.

Rearranging equations 3.3.1-3.3.13 leads to the following simplified model

$$\varphi_{ds} = X_s.I_{ds} + X_m.I_{dr} \qquad (2.3.14)$$

$$\varphi_{qs} = X_s.I_{qs} + X_m.I_{qr} \qquad (2.3.15)$$

$$\varphi_{dr} = X_r.I_{dr} + X_m.I_{ds} \qquad (2.3.16)$$

$$\varphi_{qr} = X_r.I_{qr} + X_m.I_{qs} \qquad (2.3.17)$$

$$V_{ds} = -R_s.I_{ds} + W_s.\varphi_{qs} \qquad (2.3.18)$$

$$V_{qs} = -R_s.I_{qs} - W_s.\varphi_{ds} \qquad (2.3.19)$$

$$0 = -R_r.I_{dr} + S.W_s.\varphi_{qr} - \frac{d\varphi_{dr}}{dt} \qquad (2.3.20)$$

$$0 = -R_r.I_{qr} - S.W_s.\varphi_{dr} - \frac{d\varphi_{qr}}{dt} \qquad (2.3.21)$$

$$S = \frac{W_s - W_g}{W_s} \qquad (2.3.22)$$

$$T_e = \varphi_{qr}.I_{dr} - \varphi_{dr}.I_{qr} \qquad (2.3.23)$$

$$P_{active} = V_{ds}.I_{ds} + V_{qs}.I_{qs} \qquad (2.3.24)$$

$$P_{reactive} = V_{qs}.I_{ds} - V_{ds}.I_{qs} \qquad (2.3.25)$$

P= $V_{ds}.I_{ds} + V_{qs}.I_{qs} + V_{qs}.I_{ds} - V_{ds}.I_{qs}$ (2.3.26)

MODELLING AND SIMULATION IN gPROMS

MODELLING IN gPROMS

The mathematical equations above consist of a mixed set of ordinary differential and algebraic equations that express the wind turbine's physical laws of conservation of energy and momentum.

A state of the art software application, gPROMS, which enables the user to specify the order of polynomial and the number of points for discretisation of the spatial domain, was used here for dynamic simulation. The software gPROMS is an equation oriented modelling system used for building, validating and executing models. The wind turbine model described in sections 3.1, 3.2 and 3.3 was implemented in gPROMS. Details can be found in Appendix 3.
In table 1, the variables with a known value, the variables with an unknown value and the number of equations for the wind turbine are given.

Table1. Variables with a known value, variables with an unknown value and number of equations for wind turbine model

	WIND TURBINE MODEL
Known variables	β, v, V_{ds}, V_{qs}
Unknown variables	T_e , T_m , T_w , w_g , w_m , φ_{ds} , φ_{qs} , φ_{dr} , φ_{qr} , I_{ds} , I_{dr} , I_{qs} , I_{qr} , I_{ds} , s , θ, Cp, λ, γ, P
Number of equations	19

The table above shows that the number of unknown variables equals the number of equations for the wind turbine model. Therefore the number of degrees of freedom is equal to zero, and a simulation of the wind energy conversion system can be run.

SIMULATION RESULTS

The wind turbine parameters used for the simulation are given in Table 2.

Table 2. Wind turbine parameters PARAMETER	VALUE
Rotor radius, R	25
Air density, ρ	1.225
Aerodynamic coefficients, C_1-C_6	C_1=0.5, C_2=116, C_3=0.4, C_4=0, C_5=5, C_6=21
Gear ratio, n	65.27
Damping, D	1E6
Stiffness, K	6E7
Rotor inertia, H_m	1.6E6
Generator inertia, H_g	35.184
Stator resistance, R_s	0.0121
Stator reactance, X_s	0.0742
Mutual reactance, X_m	2.7626
Rotor resistance, R_r	0.0080
Rotor reactance, X_r	0.1761
Synchronous speed, W_s	1

[Lubosny, 2003], [Martins et al, 2007]

It is important to note that for simulation purposes, the initial conditions were taken as steady state (all time derivatives equal to zero).

BASE CASE

Wind turbines usually operate at a wind velocity between 5 m/s to 25m/s. Since the rated power is achieved at a wind velocity around 10 m/s, the wind velocity was set to 10 m/s for the base case. The transmission system and some portions of the distribution system are operated at voltages in the kilovolt (kV) range. Therefore V_{ds} and V_{qs} were assigned a value of 1000 V. The blade pitch angle β was set to zero in the base case, which translates in capturing all the available power from the wind. The simulation was run in gPROMS for 10 hours; results are shown in the following graphs.

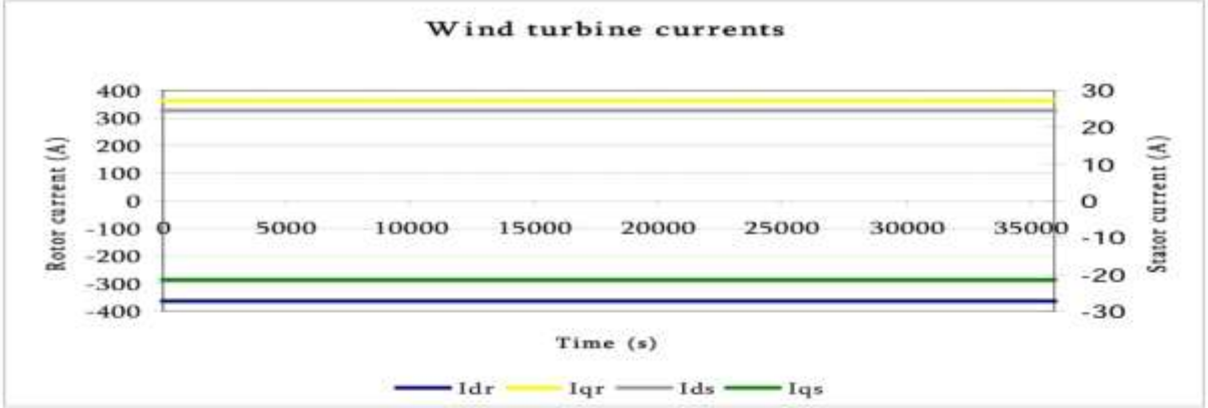

Figure 5. Wind turbine currents

The electromagnetic torque and the generator rotor slip are plotted in Fig. 6. As expected, they have negative values in the generating mode.

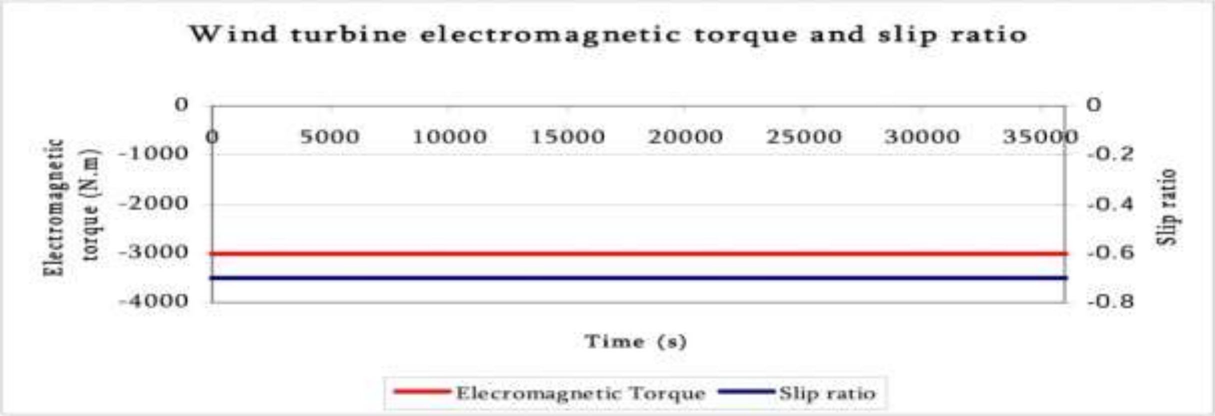

Figure 6. Wind turbine electromagnetic torque and slip ratio

The wind turbine output power is presented in the figure bellow.

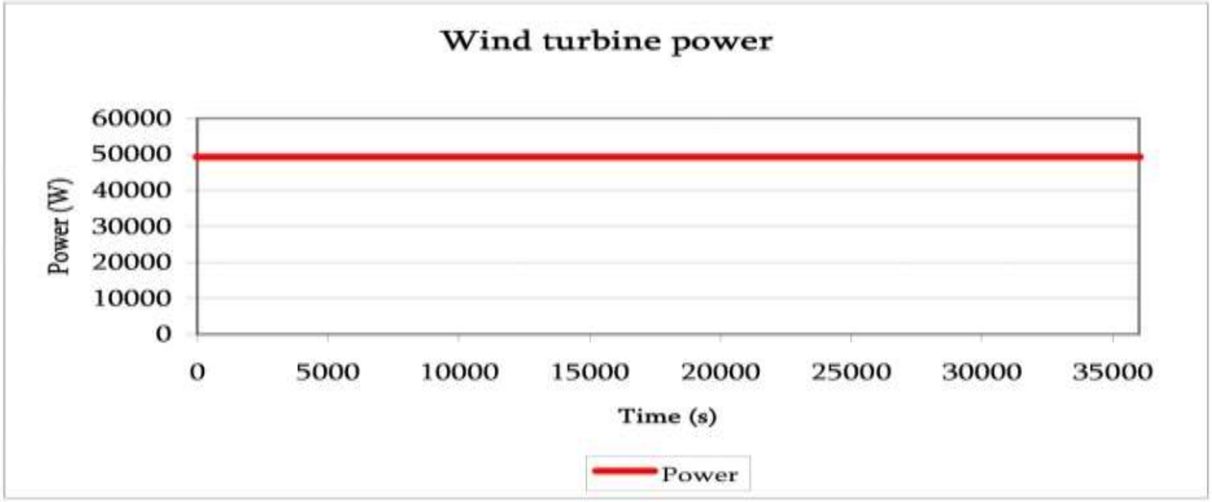

Figure 7. Wind turbine power

WIND VELOCITY STEP CHANGE

In order to observe how the wind velocity affects the wind turbine output power, a simulation was run modifying the wind speed. The initial wind speed was set to 8m/s for 10 hours, and then increased up to 10m/s for another 10 hours. Figure 15 shows that an increment in the wind speed results in a higher output power.

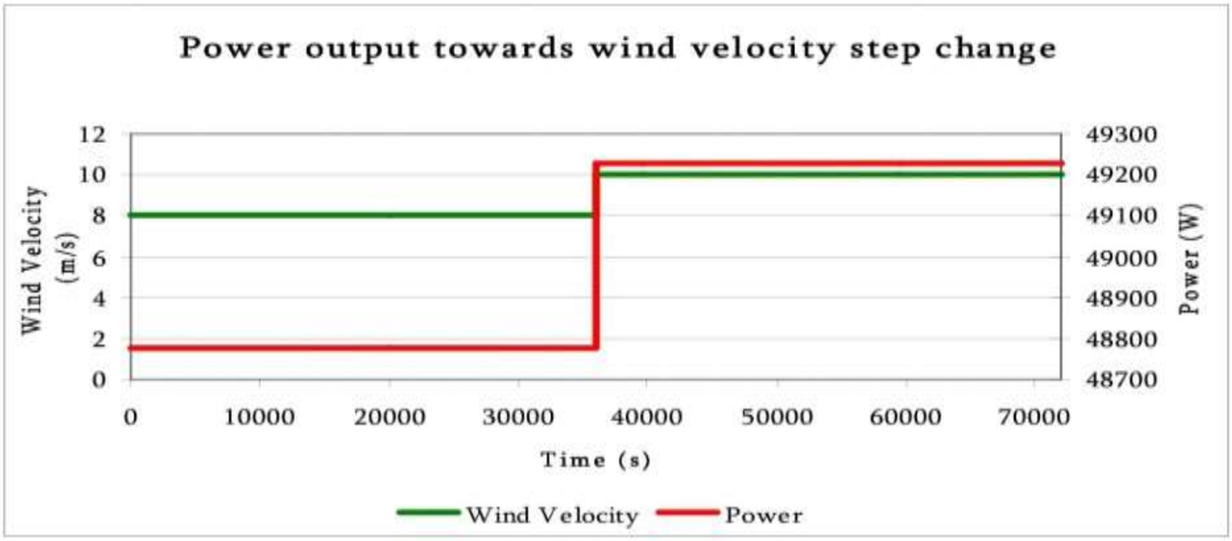

Figure 8. Power output towards wind velocity step change

BLADE PITCH ANGLE STEP CHANGE

The response of the wind turbine towards a blade pitch angle step change is shown in Figures 9 and 10. Figure 9 illustrates how an increment in the blade pitch angle β accurately translates in a reduction of the wind power coefficient.

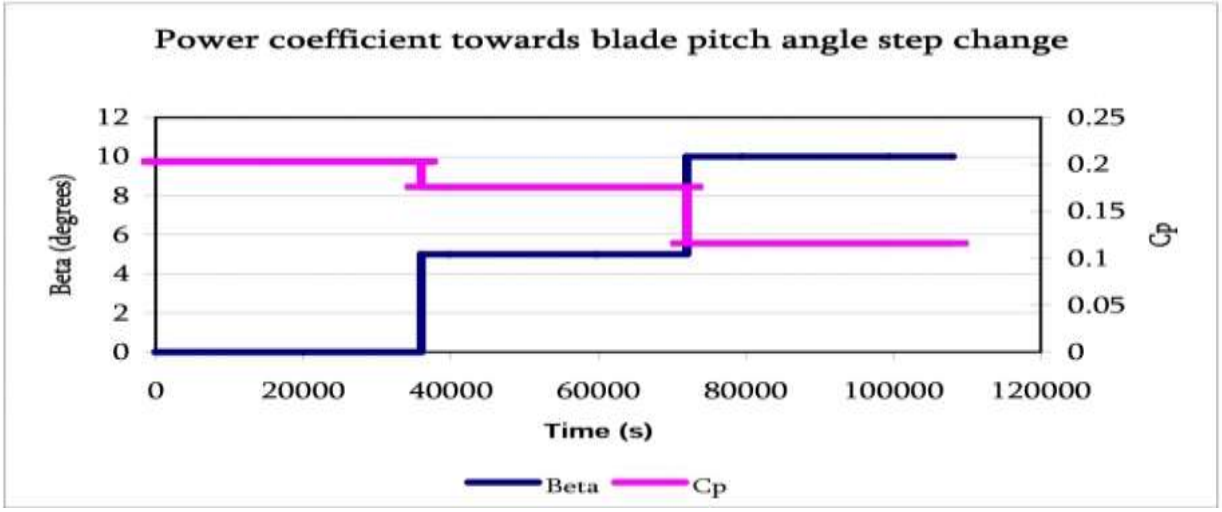

Figure 9. Power coefficient towards blade pitch angle step change

Figure 10 shows that the angle of the rotor blades can be adjusted in order to shed the unwanted power. When the wind speed becomes too high, a control structure could increase the blade pitch angle in order to reduce the aerodynamic power.

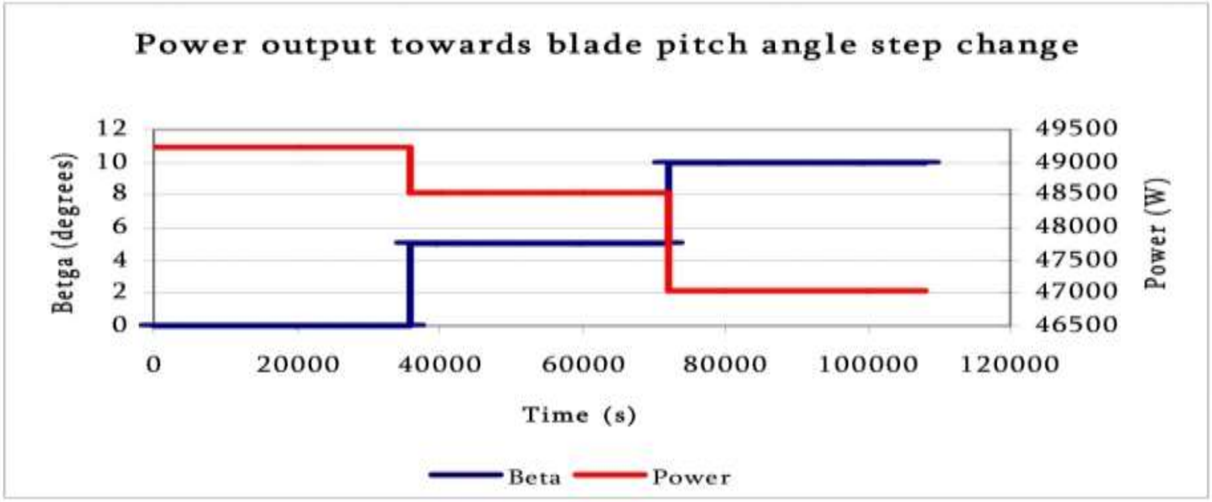

Figure 10. Power output towards blade pitch angle step change

CONTRIBUTIONS OF THIS THESIS

A wind energy conversion system consisting of the blades, mechanical parts and induction generator was modelled. Using the presented model, the output power for wind turbines was simulated in a simple way in gPROMS. To test the performance of the proposed model, wind turbine responses both to a step increase in wind speed and blade pitch angle were simulated. In both cases, the proposed model gave valuable insight into the performance of the variable speed wind turbine. As expected, the power generated increases with the wind speed, confirming the need of some sort of power control. On the other hand, an increment in the blade pitch angle proved to shed the aerodynamic power. As a normal dynamic simulation time step was adopted, this model was proven to be computationally efficient.

Based on the obtained rigorous wind turbine model, a blade pitch angle control strategy for output power levelling was developed. An explicit parametric controller was formulated using MATLAB and the Parametric Optimization (POP) software.

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