International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol.2, Issue.4, July-Aug. 2012 pp-2662-2667 ISSN: 2249-6645

Analysis of Modelling of Active Stall Controlled and Active Pitch controlled Variable Speed Wind Turbines

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Abstract: *Wind energy is a viable option to complement other types of pollution-free generation. In the early development of wind energy, the majority of wind turbines were operated at constant speed. Recently, the number of variable-speed wind turbines installed in wind farms has increased and more wind turbine manufacturers are making variable-speed wind turbines.*

A wind turbine model for control purposes needs to be based on linear mathematical models.The modeling of the wind turbine is based on certain aerodynamic phenomena (lift and drag) caused by the interaction of the rotor blade of the wind turbine and wind. The modeling of the wind turbine for control purposes involves the modeling of the relevant dynamics that affect the production of power and the stability of the wind turbine. This involves the rotor, the tower, the drive train, generator and the pitch actuator. The resulting non-linear model is then linearised at different working points. The linear model will be used for a rotor speed control algorithm.

This paper analysis the modelling of variable speed wind turbines with active pitch control and active stall control.

I. Introduction

Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow, or motion energy, when "harvested" by modern wind turbines, can be used to generate electricity. The terms "wind energy" or "wind power" describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks or a generator can convert this mechanical power into electricity.

To successfully convert the kinetic energy of wind into electrical energy, the wind turbine is equipped with a control system that ties the operation of all the subsystems of the wind turbine together. A wind turbine is always designed for specific rated conditions. By rated conditions here we mean rated wind speed, rated rotor speed and rated power. A wind turbine is designed to generate rated power which is the maximum power that the generater is designed to deliver(for example a wind 750i wind turbine is designed to generate a maximum of 750 KW). The speed of the rotor when the rated power is generated is known as rated rotor speed and the corresponding velocity of the wind is known as rated wind speed. But wind is stochastic (random or probabilistic but with some direction) in nature. Hence it is not always possible to obtain rated conditions for a wind turbine. Hence it is necessary to control the wind turbine in order to increase energy production and realize a long lifetime.

When the velocity of the wind is below the rated wind speed then it is known as below rated wind speed, and when the velocity is more than rated then it is known as above rated windspeed.All wind turbines are designed with some sort of power control. There are different ways to control aerodynamic forces on the turbine rotor and thus to limit the power in very high winds in order to avoid damage to the wind turbine.

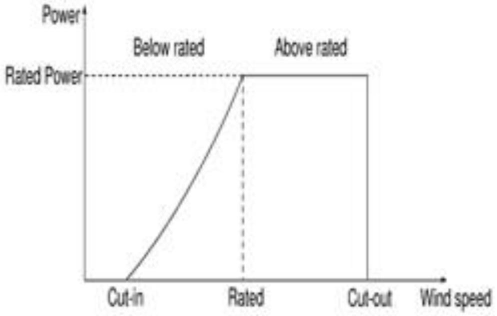


Figure 1 Power Generation as a function of Wind Speed

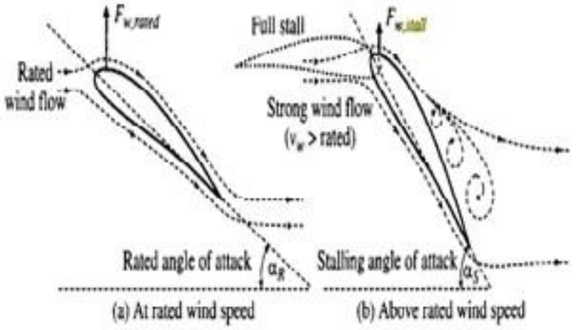
It is clear from figure 4 that there are two regimes of control, below rated and above rated and the two regimes have different control objectives. Two major systems are used to control wind turbine as follows:

1. For below rated(Generator Torque Control),This control system uses power electronic controller to maximize energy capture by adjusting rotor speed to follow wind speed variations.
   Control Law:
   $$Q = \frac{\Pr ated}{(\omega gen \bullet \eta gen)} \qquad 1.1$$
2. For above rated (Blade Pitch Control) vary rotor speed and pitch angle to regulate load and maintain power production at rated value . Blade Pitch Control changes the orientation of blades to change the aerodynamic forces.

It should be noted that wind is a stochastic input. Hence the overall wind speed measured can be defined as a sum of mean wind speed and turbulence. The rotor speed is always proportional to the mean wind speed. Hence for control purposes the rotor speed is taken as input and wind is considered as a disturbance (at above rated conditions).

II. Active stall control

Active stall control is the combination of stall and pitch control. It has the same regulated properties as in the pitch regulated turbines but has the stall properties of blade.The blades are designed same way as in stall control, but the entire blade can be turned to 90^0 to adjust it's pitch. Thus blade tip brakes are not required as in passive stall control .The idea is to pitch the blade gradually with negative pitch angle in order to increase the performance of blades over a wide range of wind speeds especially with low wind speed. It is found that only small changes of pitch angle are required to maintain the power output at rated, so pitch rates do not need to be as large as in active pitch control. Moreover, full aerodynamic braking requires pitch angles of only about -20^0 , so the travel of the pitch mechanism is very much reduced compared with positive pitch control. Active Stall control system compares the electric power output of the generator with its reference value which is defined in accordance with the incoming wind and sets the blade angle to minimize the error.



(a) At rated wind speed (b) Above rated wind speed

Figure 2 Active Stall Control at rated and aove rated speed

The stall phenomenon can be induced not only by higher wind speed but also by increasing the angle of attack. Thus active stall turbine has adjustable blades with a pitch control mechanism. When the wind speed exceeds the rated the blades are controlled to turn more into the wind, leading to reduction of capture power. The captured power thus be maintained at the rated by adjust the blade angle of attack.

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 machine at the beginning of a gust of wind. Another advantage is that the machine can be run almost exactly at rated power at all high wind speeds.

2.2 Active pitch control

Power limitation in high winds is typically achieved by using pitch angle control. This action, also called active-pitch control (or **pitch-to-feather**), corresponds to changing the pitch value such that the leading edge of the blade is moved into the wind (increase of E), thus inducing blade feathering effect. The range of blade pitch angles required for power control in this case is large, about 35° from the pitch reference. Therefore, for limiting power excursions, the pitching system has to act rapidly, with fast pitch change rates, i.e., 5°/s. Therefore, one could expect large gains within the power control loop.The power control structure employed is the same as for the active-stall control machines. Figure 3 shows the effect of pitch control on power flow in wind turbine generation.

1. Pitch Control At Standstill

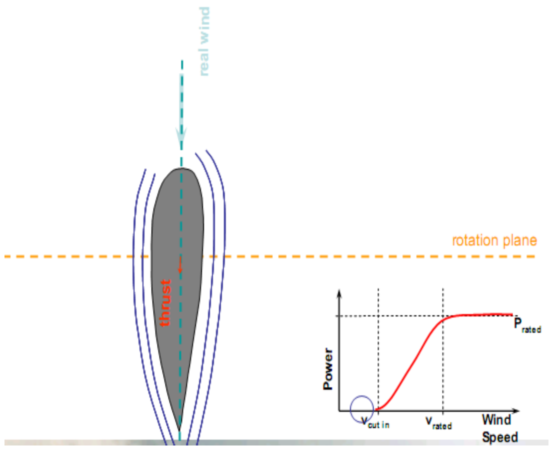


Figure 3 (a) Pitch Control At Standstill

2. Pitch Control At Start of operation

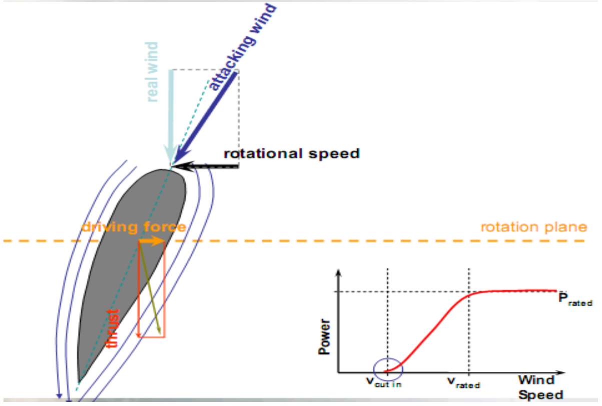
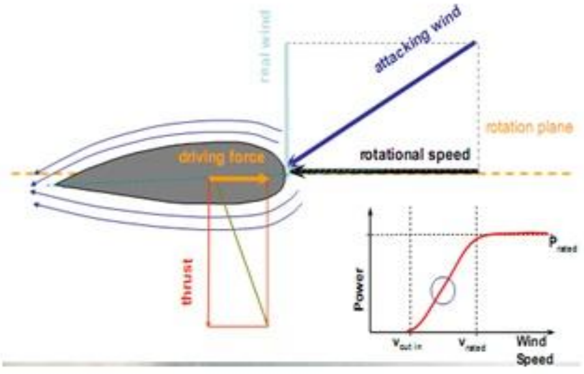


Figure 3 (b) Pitch Control At Start of operation

3. Pitch Control At Power Generation



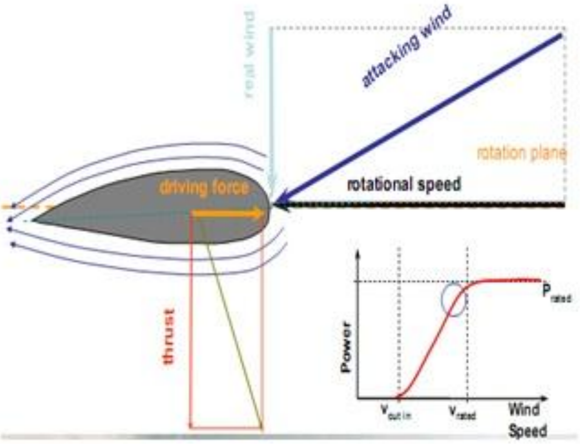


Figure 3(c) Pitch Control At Generation of power

4. Pitch Control At Power Limitation

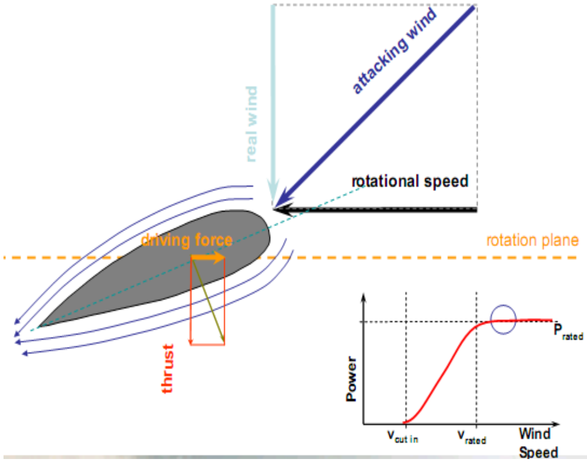


Figure 3(c) Pitch Control At Power Limitation

With pitch control, the power captured, Pcaptured, from the wind power Pwind can be controlled by a pitch actuator.The acceleration and deceleration is the result of the

3.1 Rotor Modelling of Variable Speed Turbine

The fundamental dynamics of this variable-speed wind turbine are captured with the following simple mathematical model

$$J_T \dot{\omega}_T = Q_A - Q_E \qquad 2.1$$

J_T =Moment of Inertia of Turbine Rotor
ω_T =Angular Shaft Spped
Q_A = Aerodymamic Torque
Q_E =Mechanical Torque nesseary to turn on the generator.
Arodynamic torque is represented by

$$Q_A = \frac{\rho}{2} A_{wt} R C_p(\lambda, \beta) v_w^{\ 2} \qquad 2.2$$

ρ = Air density (kg/m^3)
c_p = Performance coefficient
λ = Tip speed ratio vt/vw
β = Pitch angle (in degrees);
A_{wt} = Swept area(m^2)
R = Rotor Radius

The following well-known algebraic equation gives the relation between wind speed and mechanical power extracted from the wind (Heier, 1998; Patel, 2000):

$$P_{wt} = \frac{\rho}{2} A_{wt} C_p(\lambda, \beta) v w^3 \qquad 2.3$$

P_{wt} = Power extracted from the wind in watts

The following general equation to describe the rotor of variable-speed wind turbines

$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\beta^{c5} - C_6\right)\exp\left(\frac{-C_7}{\lambda_i}\right)$, where

$$\left[\left(\frac{1}{\lambda + C_8\beta}\right) - \left(\frac{C_9}{\beta^3 + 1}\right)\right]^{-1} \qquad 2.4$$

The structure of this equation originates from Heier (1998). However, the values of the constants c_1 to c_9 have been changed slightly in order to match the manufacturer data.

Table 1 includes both the original parameters and the parameters used here.

Power Co efficents	C_1	C_2	C_3	C_4	C_5
Heier	0.5	116	0.4	0	-
Variable Speed Wind Turbine	0.73	151	0.58	0.002	2.14
Power Co efficents	C_6	C_7	C_8	C_9	C_6
Heier	5	21	0.08	0.035	5
Variable Speed Wind Turbine	13.2	18.4	-.02	-0.003	13.2

Table 1 Approximation of power curves

High-frequency wind speed variations are very local and therefore even out over the rotor surface, particularly when wind turbines become larger. To approximate this effect, a low-pass filter is included in the rotor model.

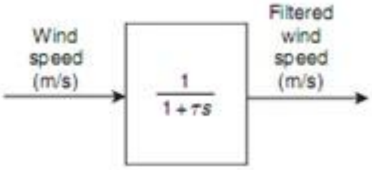


Figure 4: Low pass filter to even out high frequency wind speed

3.1 Unified Power control structure for active pitch and active stall control

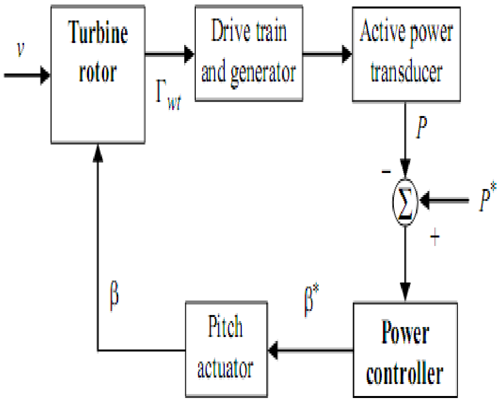


Figure 4 Power Control structure

Power limitation in high winds is typically achieved by using pitch angle control.This action, also called active-pitch control (or pitch-to-feather), corresponds to changing the pitch value such that the leading edge of the blade is moved into the wind (increase of E), thus inducing blade feathering effect. The range of blade pitch angles required for power control in this case is large, about 35° from the pitch reference. Therefore, for limiting power excursions, the pitching system has to act rapidly, with fast pitch change rates, i.e., 5°/s. Therefore, one could expect large gains within the power control loop. The power control structure employed is the same as for the active-stall control machines.

Active-stall control (also called negative-pitch control) reduces the aerodynamic power by diminishing the blade pitch angle, E , in order to increase the incidence angle. The blades are pitched towards stall, in the contrary direction to the pitch-control case, by turning the leading edge downwind. Only small changes of pitch angle are required to maintain the power output at its rated value, as the range of incidence angles required for power control is much smaller in this case than in the case of pitch control. Compared to the pitch-to-feather technique, the travel of the pitch mechanism is very much reduced; significantly greater thrust loads are encountered, but the thrust is much more constant, inducing smaller mechanical loads. The employed power control structure is briefed in Figure 4

3.2 Pitch Servo

In variable-pitch wind turbines, the blade angle is controlled by a pitch servo. The main control system produces a blade reference angle and the pitch servo is the actuator,which actually turns the turbine blades to the ordered angle.The pitch servo is subject to constructional limitations, such as angular limits min and max. That means that the blades can only be turned within certain physical limits. For active-stall-controlled wind turbines, the permissible range will be between -90° and 0°(or even a few degrees to the positive side), whereas for active pitch-controlled wind turbines the permissible range will lie between 0°and þ90° (or even a few degrees to the negative side). The control system may impose other, normally narrower, limits on the reference angle, though.Likewise, there are limitations on the pitch speed, dβ/dt. The pitch speed limit is likely to be higher for pitch-controlled wind turbines than for active-stall-controlled wind turbines, which have a higher angular sensitivity . The pitch speed limit may differ significantly for a positive $d\beta/dt_{pos}$, max) and negative ($d\beta/dt_{neg}$,max) turning of the blade. The pitch speed is normally less than 5°per second, although the pitch speed may exceed 10°per second during emergencies.

The dynamic behaviour of the pitch actuator operating in its linear region is described by the differential equation

$$\dot{\beta} = \left(\frac{1}{\tau}\beta - \frac{1}{\tau}\beta_d\right) 3.1$$

β_d = Desired Pitch Angle

β = actual Pitch angle.

in laplace domain as follows

$$\dot{\beta}(s) = H_{pt}(s) \bullet \dot{\beta}^*(s) \qquad 3.2$$

$$H_{pt}(s) = \frac{e^{-\left(T_d{}^{ptv} + T_d{}^{ptx}\right)s}}{\left(\dfrac{1}{\left(\omega_o{}^{pt}\right)^2 s^2 + \dfrac{2\beta_{pt}}{\omega_o{}^{pt}} s + 1}\right)} \dot{\beta}^*(s) \; 3.3$$

$T_d{}^{ptv}$ = The conditional delay time to overcome Coulomb friction

$T_d{}^{ptx}, \omega_o{}^{pt}, \beta_{pt}$ equivalent system parameters which represent the overall pitch actuation delay during normal operation: pitch delay time, pitch system eigen frequency, damping rate.

There are two modes of control while controlling the wind turbine.

- Below rated wind speed control
- Above rated wind speed control

3.2.1 Below rated wind speed control

Pitch and torque control are used at below rated conditions to generate as much power as possible. To ensure as much as possible energy yield, during partial load the electric torque set point is set such that the tip speed ratio, λ, is maintained at its optimal value, λopt.with the optima tip speed ratio, λopt.$\lambda_{opt} = \lambda \| C_p = C_{p,max}$ 3.2

The rotor speed is adjusted proportional to the wind speed by electric torque control, in such a way that the aerodynamic power extracted by the rotor (efficiency) is maximal.

Simulation Control structure for below rated Speed

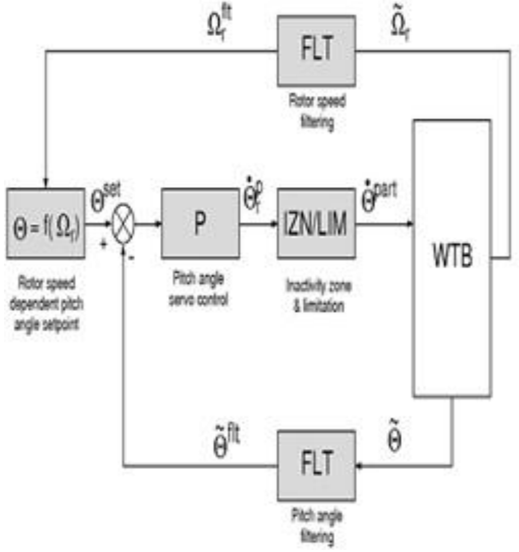


Figure 5 Below Rated Wind Sped Control

3.2.1 Above rated wind speed control

Design of an algorithm to control rotor speed above rated wind speed as follows pitching the rotor blades simultaneously in feathering direction. The 'constant power' control of the generator and the rotor inertia (fly wheel) will then establish good power quality. For this reason aerodynamic torque variations will result in rotor speed variations. The amount of rotor speed variation above its rated value, to maintain rated power, is restricted both by the maximum speed of the generator and perhaps by the tower eigen frequency to avoid tower resonance.

Simulation Control structure for above rated Speed

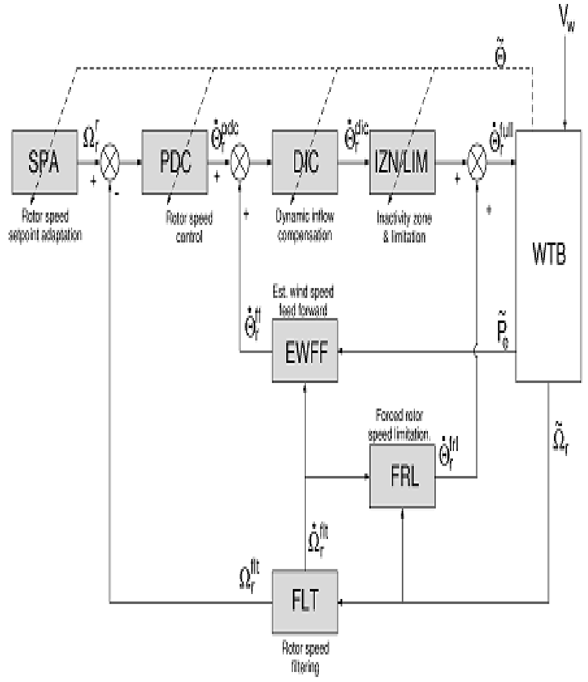
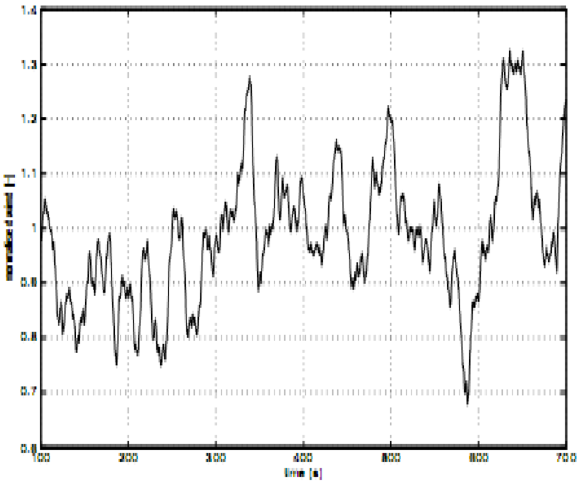
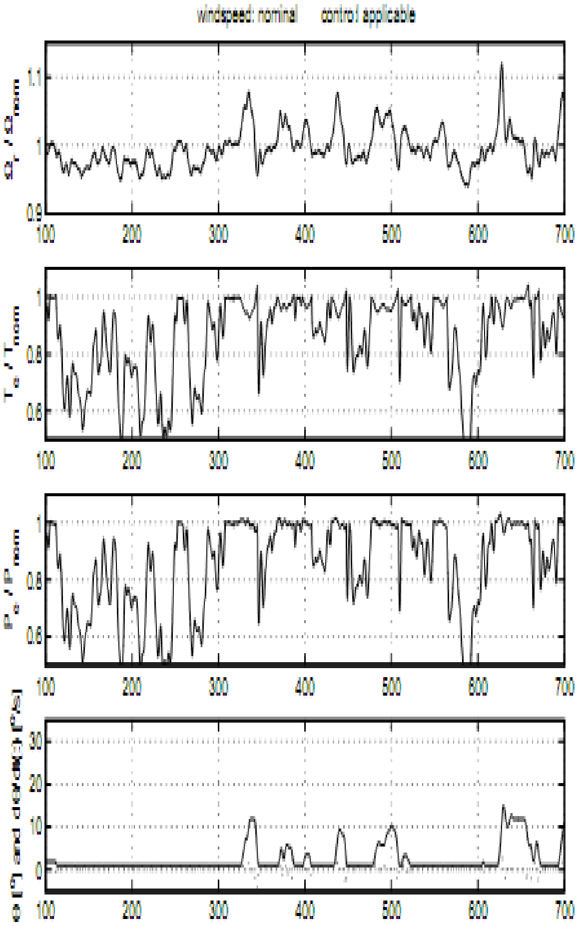


Figure 6 Above Rated Wind Sped Control

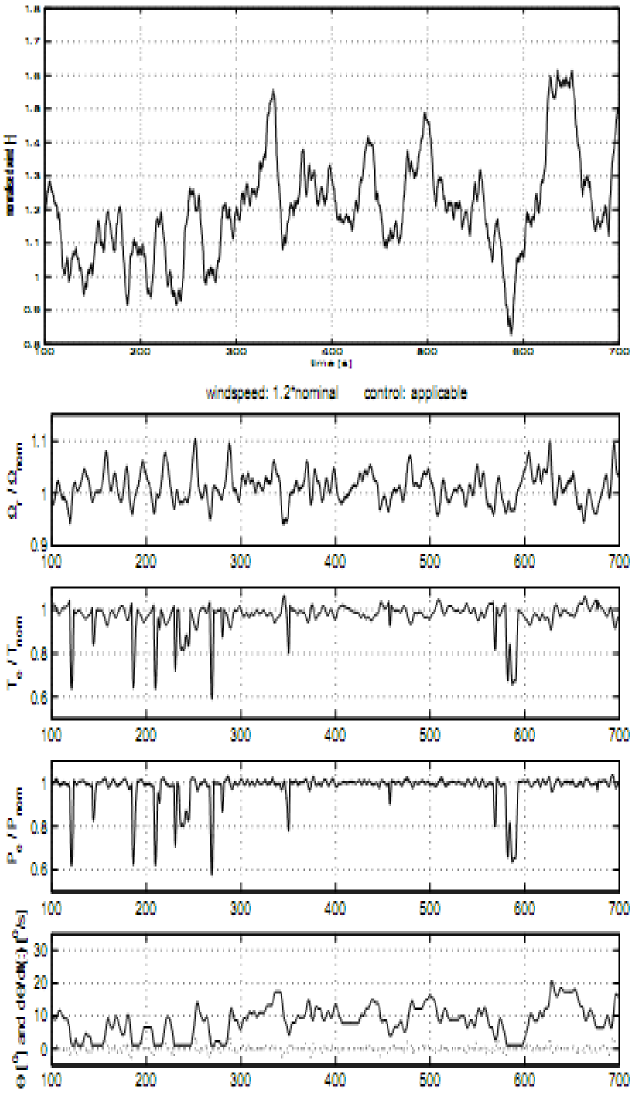
Simulation Results

4.1 Below rated wind speed control





4.1 Above rated wind speed control



IV. Conclusion

This paper deals the mathematical modelling of a unified power control of active stall and active pitch controlled variable speed turbine. Active stall control employs below rated operation to extract maximum power from wind .and at rated and above rated wind speed active pitch control method used to avoid damage of turbine.Basic controoler structure is simulated. Design of sposticated unified controller is on further study.Lots of reasearch needed to design such type of controller.Fuzzy logic conttroler can be employed .It is on further study.

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