Power Control of a PMSG based Wind Turbine System Above Rated Wind Speed

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Abstract **-Variable speed wind turbines have a capability to deliver more power than the fixed speed ones, but this power may exceed the required power that will be delivered to the grid. This paper is focused on limiting the power in a variable-speed wind turbine when wind speeds exceed rated speed. The system is equipped with a PMSG (Permanent Magnet Synchronous Generator) connected to the grid through a switch mode rectifier, a braking chopper and a PWM inverter. Two systems are used to control the power excess. One mechanical which is used to limit the aerodynamic power by using the blade pitch angle controller and the other one is electrical which is used to regulate the power on the dc bus voltage by means of a braking chopper. The interaction between the two systems is also discussed. Using MATLAB/SIMULINK® simulation results were obtained for both ramping wind speeds and real wind conditions.**

Keywords – Wind Turbine Systems, Wind Power excess limiting, pitch angle control, Braking Chopper, Switch Mode Rectifier

1. Introduction

The last few years have seen the development of renewable energy system based mainly on wind and solar power. The main advantage of electricity generation from renewable sources is the absence of harmful emission and the infinite availability of the prime mover that is converted to electricity [1]. Wind energy technology has developed extremely rapidly and many commercial wind turbines in the market have capacity of 2 MW or more. Variable Speed Wind Turbines (VSWTs) are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. Their rotation speed is continuously adapted (accelerated or decelerated) to wind speed. The tip speed ratio λ is kept constant at a predefined value that corresponds to the maximum power coefficient. VSWTs are typically equipped with induction or synchronous generators and connected to the grid through power converters. When wind speed exceeds turbine rated speed, excess aerodynamic power should be limited in order to keep the shaft torque within its design limits. The electrical resulting power should also be controlled to maintain the dc link voltage at a maximum value. There are two ways to control the excess power output from wind turbines. The primary braking system is mechanical and limits the aerodynamics forces (powers) on the turbine rotor above rated wind speed by changing the pitch angle of the blades. The secondary braking system is electrical and where either the generator output power or the dc bus powers are limited. In this paper the under-study VSWT system is first described. Then the strategy of the power excess control is developed and finally simulation results are presented.

2. Variable Speed Wind Turbine System

The structure and control of the VSWT system is shown in Fig.1. It is composed of a PMSG, a switch mode rectifier, a braking chopper, an inverter, and a pitch angle controller. The generator side converter is controlled in order to extract the maximum amount of power available in the wind. The grid side converter is controlled in order to transfer all the power available in the dc link into the grid up to a certain maximum amount. The power limitation is realized by the pitch angle controller and the braking chopper before the power reaches the grid side converter.

2.1. Wind turbine

The output power of the wind turbine P_t is given by**:**

$$P_t = \frac{1}{2} C_p(\lambda) A \upsilon^3 \tag{1}$$

A is the blades swept area, v the wind speed, C_p is the power coefficient and λ tip speed ratio:

$$\lambda = \frac{u}{\upsilon_1} = \frac{r\omega_R}{\upsilon_1} \quad (2)$$

The mechanical power versus the generator rotor speed for different wind speeds is shown in Fig.2 [2].

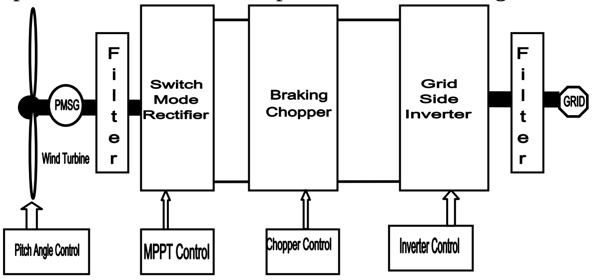

Figure 1.VSWT System Structure and Control

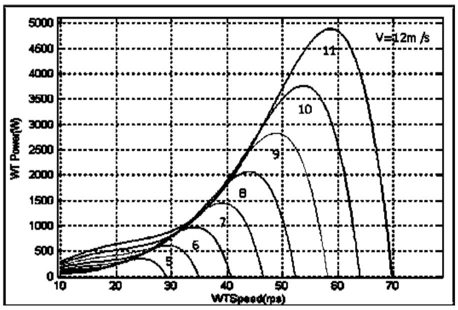

Figure 2. Wind Turbine Power versus speed [2]

2.2. Switch Mode Rectifier

It consists of a three-phase diode bridge rectifier and a dc to dc converter as shown in Fig.3. The duty cycle of the IGBT switch is controlled at any wind speed in order to extract maximum power from the wind turbine. The Maximum Power Point Tracking (MPPT) algorithm can be achieved through measurement of wind speed as developed in [3] or by detecting only the dc link voltage as given in [2].

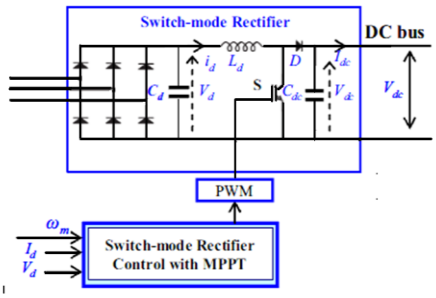

Figure 3. Switch-mode rectifier structure [3]

2.3. Permanent Magnet Synchronous Generator

Without the brushes and the slip rings, and because of the permanent magnets, the PMSG has a smaller physical size, a low moment of inertia which means a higher reliability and power density per volume ratio. Also the electrical losses in the rotor are eliminated. However, the disadvantages are high costs for permanent magnet materials and a fixed excitation, which cannot be changed according to the operational point [4]. The model used in this study was developed in the d-q synchronous rotating reference frame as given in [2].

2.4. Grid Side Converter

It is connected to the grid through an isolation transformer and a filter. It ensures the dc-voltage regulation and a unitary-power factor. The PI regulators design is given in [2]. The GSC is controlled to cope with the IEEE 1547 [5] and IEC 61400-21 [6] standards which request that the WT systems contribute to preserve the grid power quality in terms of voltage amplitude, frequency and phase. Particularly, the current injected into the grid should not have a total harmonic distortion (THD) higher than 5%. The recommended limits for each harmonic are given in [5]. In the European standard [6], the WT systems are treated as polluting loads. Depending on the grid, it is required that the current THD is lower than 6-8 % [7].

3. Power Excess Control

3.1. Aerodynamics Power Limiting methods

The amount of energy that is extracted from wind and converted into mechanical energy is depending on the radial force acting on the blade. The formation of the force depends on particular profile design and dimension and is shown in Fig.4. The C_p (λ, β) characteristic gives us a power coefficient that depends on the tip speed ratio λ and the pitch angle β. For blade profiles two forces are generally used to describe the characteristics, lift force component F_{LIFT} and a drag component F_{DRAG} which resulting as F_{TOTAL}. The F_{LIFT} component and a F_{DRAG} together are transformed into a pair of axial F_{THRUST} force and rotor's directions F_{TORQUE} components, where only the F_{TORQUE} produces the driving torque around the rotor shaft. By varying the pitch angle β the size and the direction of F_{TOTAL} components can be changed. The axial forces F_{THRUST} have no driving effect but put stress on rotor blades and furthermore lead to a thrust on the nacelle and on tower [8]. There are three methods to limit the aerodynamic conversion at high wind speed: Pitch control which turn the blades out of the wind and stall control, where the blades lose their aerodynamic efficiency at high wind speeds.

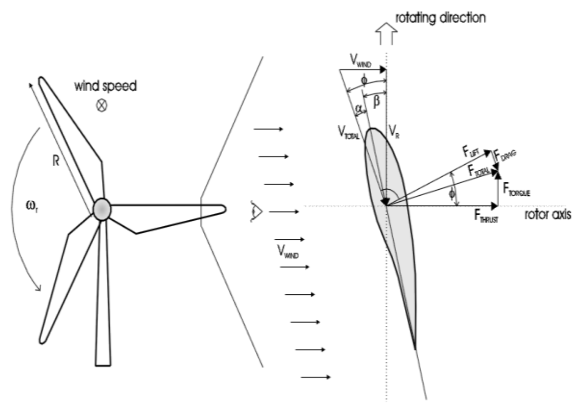

Figure 4. Aerodynamic forces at a rotor blade [8]

3.1.1. Passive stall Control

Passive stall controlled wind turbines have the rotor firmly attached to the hub at a fixed angle. Accordingly, using the passive stall method the pitch angle β is always constant, no mechanism to turn the blades around their axes is necessary. The blades are aerodynamically designed to stall at higher wind speeds, and the incoming power is limited close to the rated. This concept is used for around 60% of the constant speed wind turbine in the world. Advantages of the stall control system are that moving parts in the rotor blades are avoided and a complex control system is not necessary. On the other hand, stall control involves a very complex aerodynamic design. A drawback is that wind turbines usually have a drop in the electrical power output for higher wind speeds, as the rotor blades go into deeper stall. For fixed-speed operation, an advantage is the lower power pulsation compared to pitch control [8].

3.1.2. Pitch Angle Control

A mechanism to physically turn the blades around their longitudinal axes is used. At low wind speed a control system will use this feature to maximize energy extracted from the wind. During the higher wind speed the torque or power can easily be limited to its rated value by adjusting the pitch angle β. In addition the axial aerodynamics forces are reduced. This method is almost always used with variable speed turbines in order to make operation at high wind speed possible and safety. The turbine's electronic controller checks the power output constantly. When the power output becomes too high the blade pitch mechanism is asked to immediately turn the blades slightly out of the wind. When the wind speed is less strong the blades are turned back, into the most effective position [8].

3.1.3. Active Stall Control

The active stall regulation offers both, the advantages of pitch-controlled blades and the stall effect. Due to the pitch-controlled blades, one of the advantages of active stall is that one can control the power output more accurately than with passive stall, so that the average power is always at the rated value at wind speed above rated. As with pitch control it is largely an economic question whether it is worth to pay for the added complexity of the machine, when the blade pitch mechanism is added. Besides providing power control, the blade pitch system is also used to accelerate the blades from idling to operational speed and bringing the rotor back to a safe idling situation in case of a grid loss or any other functional error. The rotor blades are able to be pitched like the pitch controlled wind turbines. The difference is that when the machine reaches its rated power, the blades will pitch in the opposite direction, increasing their angle to the wind and going into a deeper stall. The active stall control system is often installed in the large fixed speed turbines (1 MW and more) [8].

3.2. Mechanical Braking Control

The blades pitch angle control is primarily used to limit the aerodynamic power above rated wind speed in order to keep the turbine shaft torque within its design limits. The inertia of the blades turned by the drive is large and the pitch actuator has thus limited capabilities. The torque generated by the wind turbine is controlled. Rotor speed, torque or power error can be taken to regulate the pitch angle. In this paper the power error is used. In Fig.5 the error ΔP between the limitation power and the measured power at the output of the PMSG is sent to a PI controller to generate the reference value of the pitch angle β_{ref}. This reference value is sent to pitch actuator which can be electrical or hydraulic in order to turn the blades of the wind turbine along their longitudinal axis. The complete system model of the pitch angle controller is shown in Fig.6.

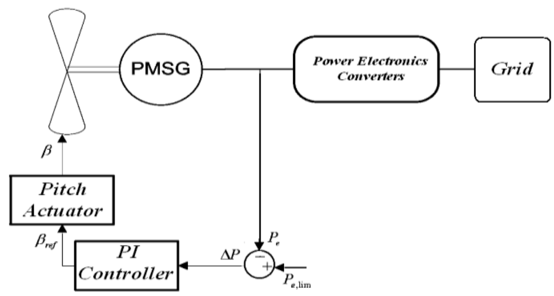

Figure 5. Block diagram of pitch control system

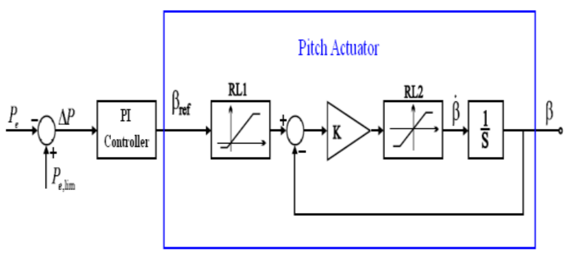

Figure 6. Pitch controller system model

RL1 is the pitch angle limitation, *RL2* is the pitching speed limitation and *K* is the “softness” coefficient when the limit is approaching. This actuator is modeled in closed loop with saturation of the pitch angle and a pitch rate limitation. This configuration with an integrator gives similar result as a first order transfer function but with limitation of the pitch rate. Also while the β_{ref} is on the lower limit, the integrator is prevented from growing indefinitely or winding up [8]. Simulation results of the step responses for two different ramping speeds and two different K coefficients are shown in Fig.7.

3.3. Braking Chopper Control

The braking chopper is composed of an IGBT switch a diode, a damp resistor and a PI controller for the duty cycle.
The potential excess of power will be dissipated in the damp resistor and the dc link voltage will be maintained constant. This linear control increases the duty cycle as a function of the over voltage amount.

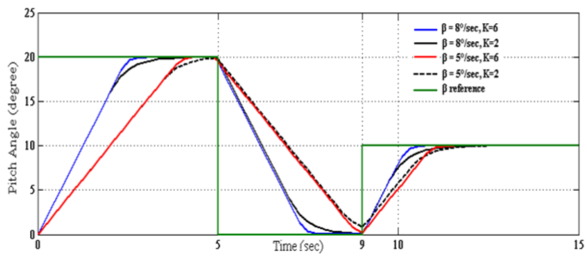

Figure 7. Responses of pitch angle demand

If the dc link voltage exceeds the maximum limit a short circuit through the resistor R will occur as shown in Fig.8. The power balance principle gives:

$$P_i = P_C + P_{BC} + P_O \tag{3}$$

Then

$$P_i - P_O = P_{BC} + P_C \tag{4}$$

$$P_{BC} = \frac{(k\upsilon_{dc})^2}{R} \tag{5}$$

$$P_C = \frac{d}{dt}(\frac{1}{2}C\upsilon_{dc}^{\ 2}) \tag{6}$$

Where P_{BC} is the power dissipated by the braking chopper, P_C the power dissipated by the capacitor and *k* the duty cycle of the switch SW.

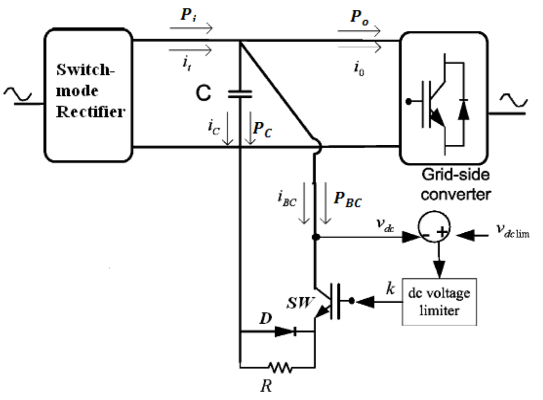

Figure 8.DC bus model highlighted [9]

In small signal variation:

$$\upsilon_{dc} = V_{dc} + \Delta V_{dc} \tag{7}$$

$$k = K + \Delta k \tag{8}$$

K and V_{dc} are the working point values while ΔV_{dc} and Δk are the small signal variations. Eqn.4 becomes:

$$(P_i + \Delta P_i) - (P_O + \Delta P_O) = \frac{(K+\Delta K)^2 (V_{dc} + \Delta V_{dc})^2}{R} + \frac{d}{dt}[\frac{1}{2}C(V_{dc} + \Delta V_{dc})^2] \tag{9}$$

Assuming that at steady state the capacitor power is neglected ($P_C = 0$), the relation between the duty cycle k and its effect on the dc voltage in Laplace domain is given by:

$$G(s) = \frac{V_{dc}(s)}{K(s)} = \frac{\frac{V_{dc}}{K}}{1 + (\frac{RC}{2K^2})s} \tag{10}$$

‘S’ is the Laplace operator. The braking chopper control loop is shown in Fig.9. The error between the dc voltage V_{dc} and the limit dc voltage V_{dclim} is sent to a PI controller to produce the duty cycle *k*. When $V_{dc} \leq V_{dclim}$ the braking chopper is off and no power is absorbed by the damp resistor, otherwise when $V_{dc} \geq V_{dclim}$ the braking chopper in on and the damp resistor dissipates the power in excess keeping $V_{dc} = V_{dclim}$. Simulation results given in Fig.10 show the principle work of the braking chopper with V_{dclim} = 750V in addition to the power delivered by the braking chopper.

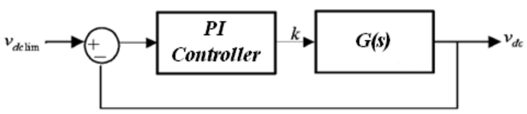

Figure 9. Braking chopper control loop

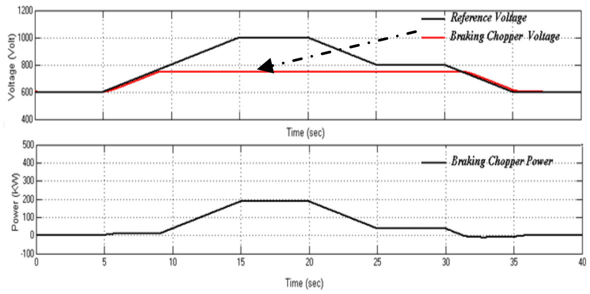

Figure 10. Braking Chopper voltage and power

4. Simulation and Comments

Simulation results using MATLAB/SIMULINK are shown in the case of a ramping wind speed and in the case of real wind conditions. The blade pitch angle used is limited between $\beta = 0°$ and $\beta = 75°$ while the pitch angle rate is considered for two values ±*5 degrees/s* and ±*8 degrees/s*. In all the figures the plots are given as: (a) the wind speed, (b) the rotor speed, (c) the pitch angle, (d) the generator power, (e) the braking chopper power, (f) the grid power, and (g) the dc voltage.

4.1. Ramp Wind Condition

In order to evaluate the interaction of the two braking systems, the system has been simulated with different ramp wind conditions.
The blades pitch angle control system limits the generator power in above rated wind speed and the braking chopper control system regulates the dc voltage to V_{dclim} = 750V.

4.1.1. Pitch Angle rate of ±5 degrees/s

First a wind variation of 0.5 m/s per second with a maximum of 20 m/s is considered. This is shown in Fig.11. The pitch angle controller is able to follow the increase of the wind speed and controls the generator power (Fig.11 (d)). The braking chopper limits the dc voltage to V_{dclim} = 750V (Fig.11 (g)). The results for a wind variation of 1 m/s per second are given in Fig.12. The pitch angle controller is not able to control the generator output power which means that the pitch angle control is slower than the variation of the wind speed (Fig.12 (d)), while the braking chopper control is able to manage the dc voltage and dissipates the excess power before it reaches to the grid side converter (Fig.12 (f)).

4.1.2. Pitch angle rate of ±8 degrees/s

The system has been simulated for two different ramp wind speed at *pitch angle rate of ±8 degrees/s*. For wind variation of 1 m/s per second and a maximum wind speed of 20 m/s, the results obtained are shown in Fig.13. The pitch angle controller is able to control the generator power (Fig.13 (d)), and the braking chopper controls the dc voltage (Fig.13 (f)). For wind variation of 4 m/s per second the results are given in Fig.14. The pitch angle is slow and not able to control the generator power, while the braking chopper manage the dc power and dissipate the power in excess before it goes to the grid-side converter.

4.1.3. General Comments

From the results obtained in the case of ramp wind conditions we can notice the following:
- The dc voltage increases from 700V to 750V when the grid power reaches the demanded power.
- As the variation of the wind increases the pitch angle controller is not able to follow this increasing and the generator produces power more than the limitation power.
- The braking chopper power at ±*8 degrees/s* is lower than when ±*5 degrees/s*.
-The quality of the grid power when ±*8 degrees/s* is better than when ±*5 degrees/s*.

4.2. Real Wind Conditions

For wind turbulence intensity of 10%, simulation results are given as follows:
In Fig.15 for pitching rate of ±*5 degrees/s*, the pitch controller is inefficient and the braking chopper guarantees the control of the dc bus voltage.
In Fig.16 for pitching rate of ±*8 degrees/s*, the pitch control is able to regulate the generator power while the braking chopper regulates the dc link voltage.

5. Conclusion

Two control systems used to limit the power of a VSWT system above rated wind speed were defined. The pitch angle controller limits the aerodynamic power when the wind velocity is above the rated value, while the braking chopper limits the dc bus power. The pitch angle controller is characterized by the pitching rate and the pitch angle interval while the braking chopper has a limitation dc voltage value. Two values of the pitching rate (±*5 degrees/s and* ±*8 degrees/s)* and a limitation dc voltage value of 750V were used in the simulation. Results with different ramp wind conditions and real wind conditions were obtained. The pitch angle controller sometimes results in a slow limitation of the generator power, while the braking chopper guarantees the control of the dc voltage. Under real wind conditions the two control systems regulates the generator power and the dc voltage without any problem.

6. References

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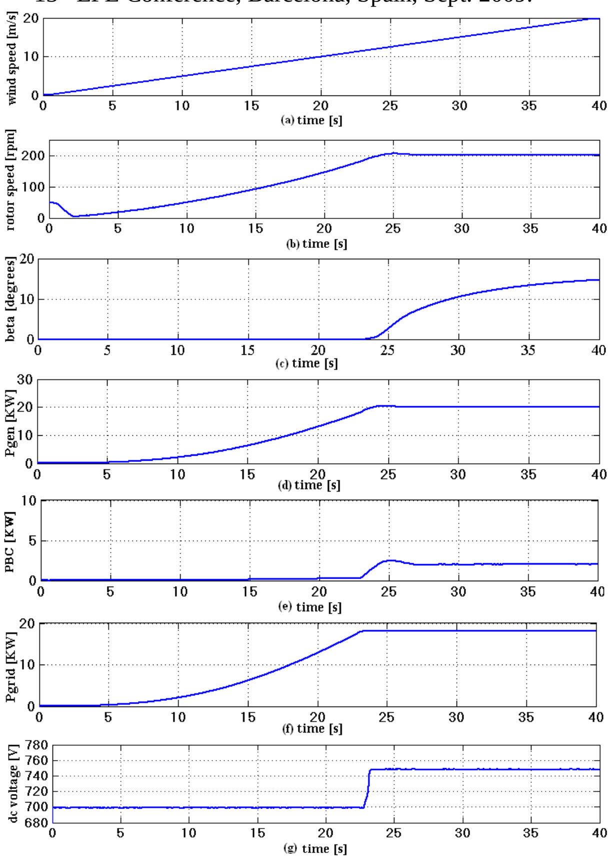

Figure 11. Wind speed rate 0.5 m/s^2 & $\dot{\beta}$ = ±5 deg/s

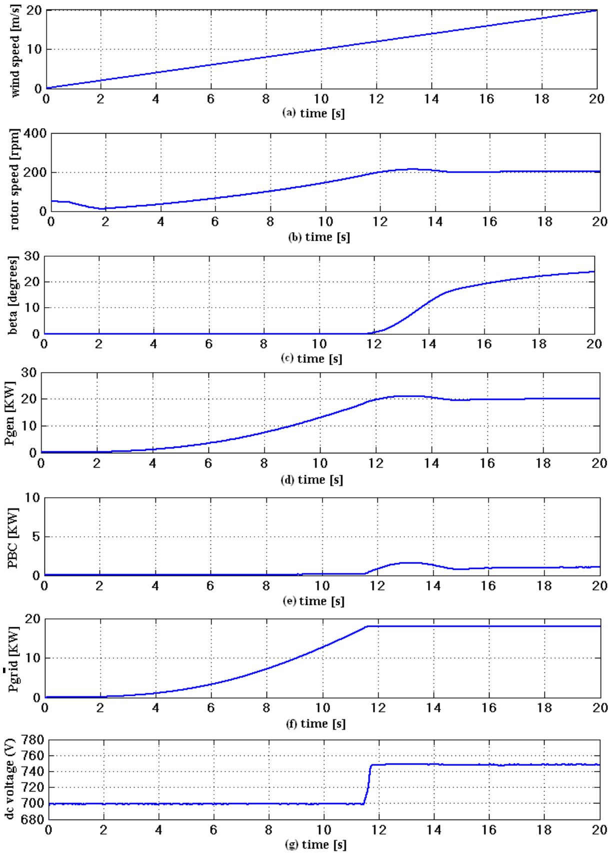

Figure 13. Wind speed rate of 1 m/s^2 & $\dot{\beta}$ = ±8 deg/s

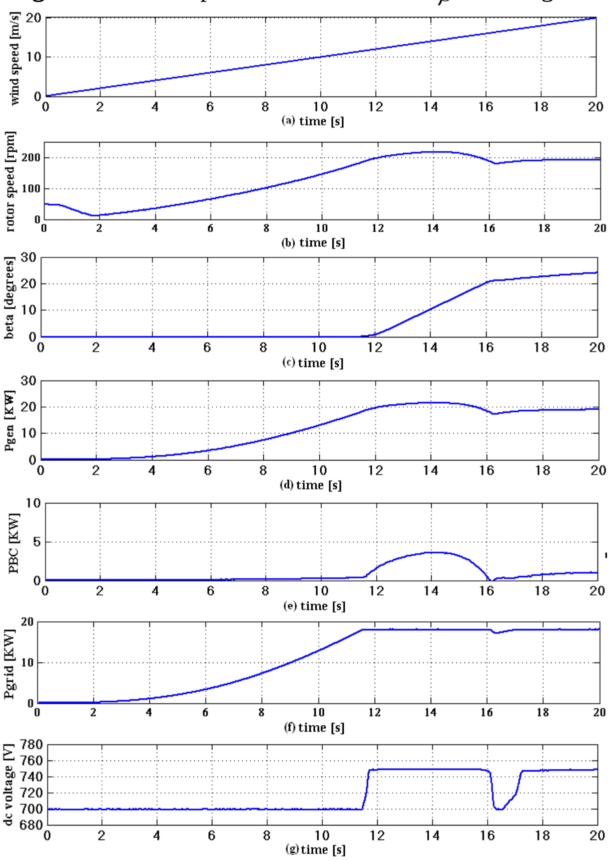

Figure 12. Wind speed rate of 1 m/s^2 & $\dot{\beta}$ = ±5 deg/s

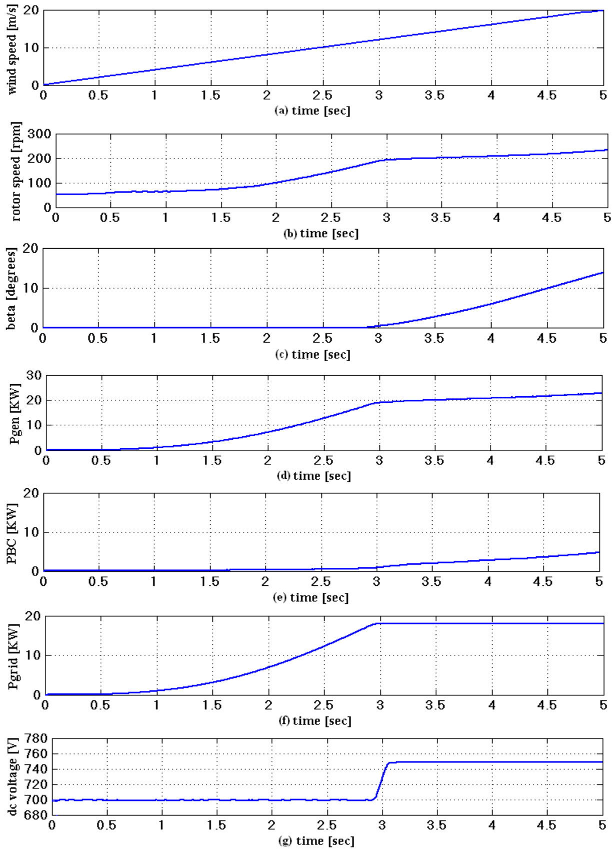

Figure 14. Wind speed rate of 4 m/s^2 & $\dot{\beta}$ = ±8 deg/s

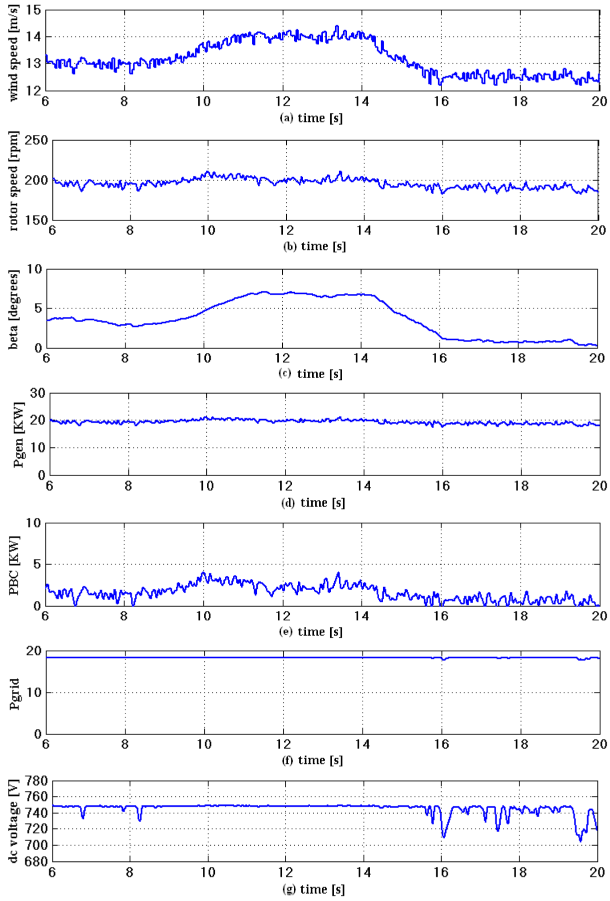

Figure 15. WindTurbulence of 10% & $\dot{\beta}$ = ±5 deg/s

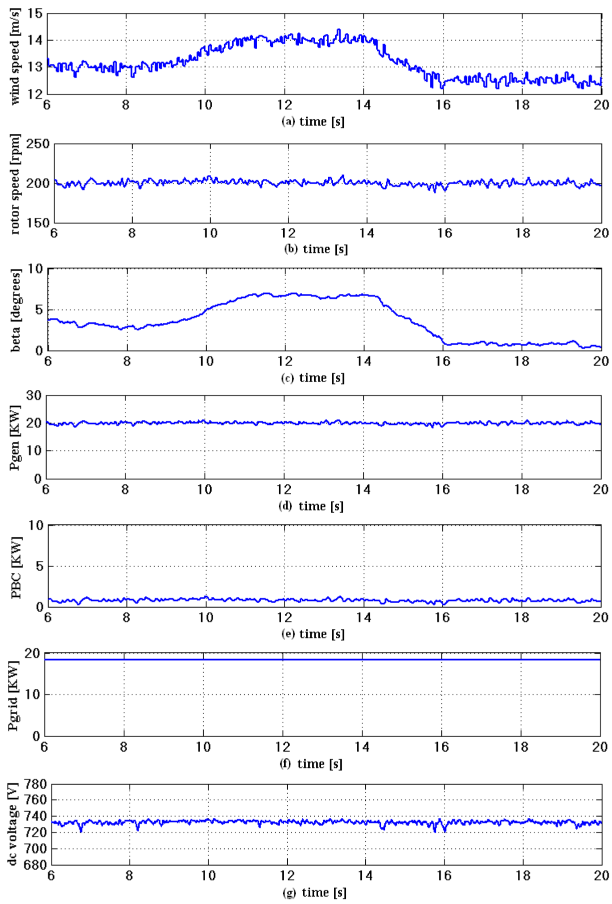

Figure 16. Wind Turbulence of 10% & $\dot{\beta}$ = ±8 deg/s