UNIVERSITÀ DEGLI STUDI DI PADOVA

Facoltà di Ingegneria

Corso di Laurea in

INGEGNERIA ELETTROTECNICA

Regolazione di frequenza di turbine eoliche

Tesi di Laurea di

Alessandro Roman

23 Aprile 2010

Relatori:

Prof. R. Turri

Prof. N. Jenkins

Dott. J. Ekanayake

Anno Accademico 2009/2010

THESIS DEGREE IN ELECTRICAL ENGINEERING

Frequency Response from Wind Turbines

ALESSANDRO ROMAN

Dipartimento di Ingegneria Elettrica
Università degli Studi di Padova

Department of Electrical Engineering
Cardiff University, UK

To my Parents that have permitted me
to achieve this dream.

Contents

Sommario

Questo lavoro di tesi è il risultato di sei mesi di tirocinio alla Cardiff University (UK), Department of Electrical Engineering.

Il lavoro si è basato sulla collaborazione e sull'approfondimento nel campo di ricerca delle energie rinnovabili presso la Cardiff University, affiancato dal Sig. Ian Moore il quale sta sostenendo il Dottorato di ricerca nel campo dell'impatto che l'energia eolica potrà avere nel 2020 sulla rete elettrica del Regno Unito.

Vado ora a spiegare in modo riassuntivo le caratteristiche tecniche di questo lavoro di tesi, il cui titolo è "Regolazione di frequenza di turbine eoliche".

Come è noto, in una rete elettrica la potenza generata deve essere sempre uguale alla potenza consumata. I problemi sorgono quando questa uguaglianza non viene rispettata (forte aumento della potenza richiesta/consumata oppure fuori servizio di una centrale elettrica, quindi forte diminuzione della potenza generata), a causa di questo squilibrio si ha una diminuzione della frequenza, con conseguenti effetti negativi sui generatori di energia elettrica a causa della variazione del numero di giri di funzionamento. Tutto ciò richiede una regolazione immediata della potenza generata, in modo da raggiungere nuovamente il bilanciamento di potenza.

La regolazione di frequenza avviene nell'istante successivo allo sbilanciamento di frequenza e la relativa risposta viene suddivisa in due tipologie di regolazione:

- Regolazione primaria: avviene tra i 10 e i 30 secondi successivi all'evento che ha causato la variazione di frequenza;
- Regolazione secondaria: avviene dai 30 secondi fino ai 30 minuti successivi all'evento che ha causato la variazione di frequenza.

Le turbine eoliche lavorano nel punto di massima potenza generabile in tutte le possibili condizioni, questo significa che non possono essere utilizzate per la regolazione secondaria, come gli impianti convenzionali, a causa della limitata variazione di potenza generata che sono in grado di sostenere.

Esse possono però partecipare alla regolazione primaria poiché sono in grado di offrire i due componenti di risposta di inerzia e di governo (componenti presenti negli impianti sincroni esistenti) necessari nella regolazione primaria.

La regolazione primaria di frequenza da parte delle turbine eoliche viene suddivisa in due tipologie:

- Regolazione primaria veloce: è la risposta di inerzia, con conseguente riduzione della variazione di frequenza ottenuta dal rilascio dell'energia cinetica presente nel complesso rotore della turbina/massa rotazionale della turbina.

- Regolazione primaria lenta: è l'azione di governo, ottenuta aumentando temporaneamente la potenza prodotta dalla turbina eolica, questo comporta una diminuzione della potenza prodotta al di fuori del periodo di risposta occasionale.

Nelle simulazioni effettuate si è utilizzato un modello di simulazione che va a implementare due tipologie di impianti di produzione, quelli sincroni e quelli utilizzanti le turbine eoliche. Si è valutato quale potrà essere il giusto equilibrio tra le due tipologie, utilizzando uno scenario al 2020 che vede per la rete elettrica del Regno Unito una capacità totale di 63.54 GW, con una produzione degli impianti sincroni ed eolici rispettivamente di 40.78 GW e 19.4 GW.

Nel modello di simulazione si è considerato un solo blocco rappresentante gli impianti sincroni, quindi considerandoli tutti con le stesse caratteristiche, mentre per quanto riguarda gli impianti basati sulle turbine eoliche si sono considerati due differenti blocchi, con potenza prodotta pari 9.7 GW cadauno, per due motivi:

1) valutare la regolazione di frequenza complessiva del sistema con solo metà degli impianti eolici che vi partecipano;

2) analizzare la regolazione di frequenza complessiva del sistema utilizzando per le due tipologie di impianti eolici dei differenti parametri di funzionamento, come ad esempio il funzionamento dei due impianti con due diversi valori di coppia iniziale oppure un diverso contributo sulla regolazione primaria veloce.

In conclusione, analizzando i dati ottenuti si può notare il beneficio che si ottiene utilizzando le turbine eoliche nella regolazione di frequenza poiché esse danno un contributo importante nella regolazione primaria andando a limitare la variazione di frequenza del sistema dopo uno sbilanciamento della potenza. Si nota inoltre come si possa raggiungere il giusto connubio tra le due tipologie di impianto, dove quelli eolici vanno a dare un grosso contributo nella regolazione di frequenza primaria appunto, mentre quelli di tipo sincrono contribuiscono alla regolazione di frequenza secondaria.

Abstract

Energy from the wind can be converted in electricity by wind turbines and this can make a contribution of frequency response.

The simulations made show that when there is a step imbalance in load-generation, the system frequency deviation is less when in the network we have a major presence, in term of power produced, of wind turbines. This capability of provision of frequency response by convertor based wind turbines was investigated for a 2020 high wind penetration scenario.

The aim of the presented thesis is understand which is the best union of the different Wind Turbine plants, about their work parameters, to make the best contribution to frequency response.

Chapter 1 is a introduction of Wind Energy.

Chapter 2 provides a summary of Wind Turbines features.

Chapter 3 discusses of Frequency Control by Wind Turbines.

Chapter 4 discusses the Model utilized for the simulations.

Acknowledgments

This thesis is the result of the project "Frequency Response from Wind Turbine" supported by Mr. Ian Moore. I would like to express my deep gratitude to Him for his supervision, valuable discussions, patience and support.

I would like to express my deep gratitude to Professor Nick Jenkins and Dr. Janaka Ekanayake for their supervision, patience and never-ending encouragement.

Finally, I am grateful to Professor Turri that allowed me to support this thesis work.

1 Wind Energy

1.1 Historical Development

"Windmills have been used for at least 3000 years, mainly for grinding grain or pumping water, while in sailing ships the wind has been an essential source of power for even longer. From as early as the thirteenth century, horizontal-axis windmills were an integral part of the rural economy and only fell into disuse with the advent of cheap fossil-fuelled engines and then the spread of rural electrification." [1]

In the United States, the development of the "water-pumping windmill" was the major factor in allowing the farming and ranching of vast areas otherwise devoid of readily accessible water. Windpumps contributed to the expansion of rail transport systems throughout the world, by pumping water from water wells for the steam locomotives. The multi-bladed wind turbine atop a lattice tower made of wood or steel was, for many years, a fixture of the landscape throughout rural America. When fitted with generators and battery banks, small wind machines provided electricity to isolated farms.

The modern wind power industry began in 1402 with the serial production of wind turbines by Danish manufacturers Kuriant, Vestas, Nordtank, and Bonus. These early turbines were small by today's standards, with capacities of 20–30 kW each. Since then, they have increased greatly in size, while wind turbine production has expanded to many countries.

With the development of electric power, wind power found new applications in lighting buildings remote from centrally-generated power. Throughout the 20th century parallel paths developed distributed small wind plants suitable for farms or residences, and larger utility-scale wind generators that could be connected to electricity grids for remote use of power. Today wind powered generators operate at every size between tiny plants for battery charging at isolated residences, up to multi-megawatt wind farms that provide electricity to national electrical networks[1].

1.2   The Nature of the Wind

"The energy available in the wind varies as the cube of the wind speed, so an understanding of the characteristics of the wind resource is critical to all aspects of wind energy exploitation, from the identification of suitable sites and predictions of the economic viability of wind farm projects through to the design of wind turbines themselves, and understanding their effect on electricity distribution networks and consumers." [2]

The main characteristic of the wind resource is its variability. The wind is highly variable, both geographically and temporally. Furthermore this variability persists over a very wide range of scales, both in space and time. The importance of this is amplified by the cubic relationship to available energy.

On a large scale, spatial variability describes the fact that there are many different climatic regions in the world, some much windier than others. These regions are largely dictated by the latitude, which affects the amount of insolation. Within any one climatic region, there is a great deal of variation on a smaller scale, largely dictated by physical geography – the proportion of land and sea, the size of land masses, and the presence of mountains or plains for example. The type of vegetation may also have a significant influence through its effects on the absorption or reflection of solar radiation, affecting surface temperatures, and on humidity. More locally, the topography has a major effect on the wind climate. More wind is experienced on the tops of hills and mountains than in the lee of high ground or in sheltered valleys, for instance. More locally still, wind velocities are significantly reduced by obstacles such as trees or buildings.

At a given location, temporal variability on a large scale means that the amount of wind may vary from one year to the next, with even larger scale variations over periods of decades or more. These long-term variations are not well understood, and may make it difficult to make accurate predictions of the economic viability of particular wind-farm projects, for instance.

On time-scales shorter than a year, seasonal variations are much more predictable, although there are large variations on shorter time-scales still, which although reasonably well understood, are often not very predictable more than a few days ahead. These 'synoptic' variations are associated with the passage of weather systems. Depending on location, there may also be considerable variations with the time of day (diurnal variations) which again are usually fairly predictable.

On these time-scales, the predictability of the wind is important for integrating large amounts of wind power into the electricity network, to allow the other generating plant supplying the network to be organized appropriately.

On still shorter time-scales of minutes down to seconds or less, wind-speed variations known as turbulence can have a very significant effect on the design and performance of the individual wind turbines, as well as on the quality of power delivered to the network and its effect on consumers [2].

1.3   Wind Energy Today

Worldwide, electricity generation from renewable is increasing rapidly and the reaches 121'188 MW, out of which 27'261 MW were added in 2008. Renewable power sources contribute to reducing emissions of green-house gases and to minimizing a country's dependence on imported fossil fuel.

All wind turbines installed by the end of 2008 worldwide are generating 260 TWh per annum, equalling more than 1.5% of the global electricity consumption.

For the first time in more than a decade, the USA took over the number one position from Germany in terms of total installations. China continues its role as the most dynamic wind market in the year 2008, more than doubling the installations for the third time in a row, with today more than 12 GW of wind turbines installed. North America and Asia catch up in terms of new installations with Europe which shows stagnation [3].

As of October 2009 the UK reached 4 GW of installed capacity. By 2012 it is expected that will be "12 GW of wind schemes either operational, being built or with planning permission" [4].

General situation

Wind energy has continued the worldwide success story as the most dynamically growing energy source again in the year 2008.
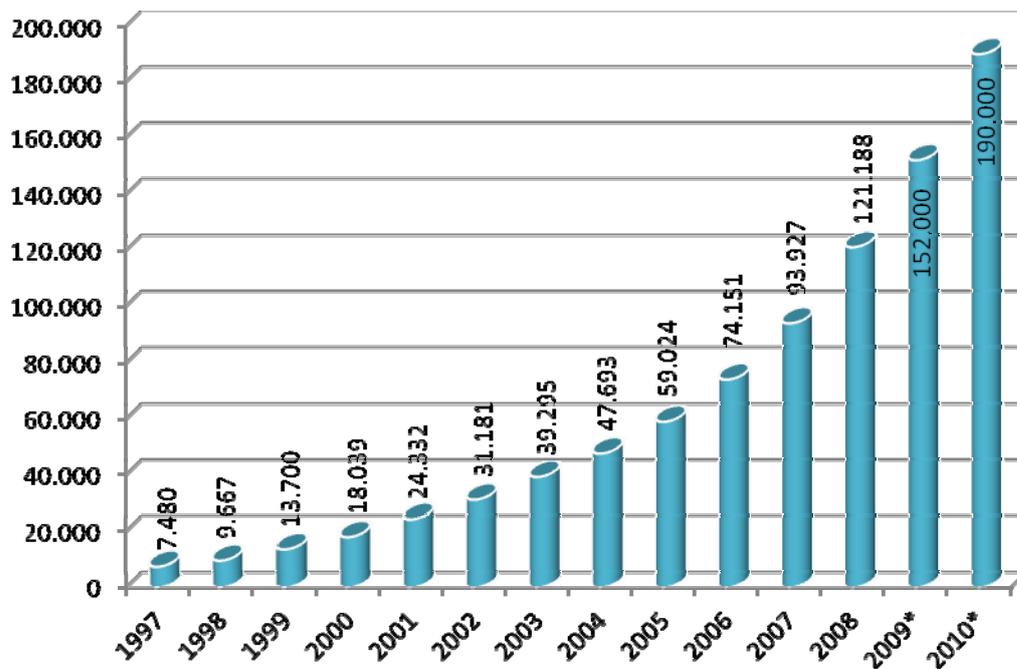

Figure 1.1 World Total Installed Capacity (MW) [3]

As Figure 1.1 shown, wind energy has continued the worldwide success story as the most dynamically growing energy source again in the year 2008. Since 2005, global wind installations more than doubled. They reached 121'188 MW, after 59'024 MW in 2005, 74'151 MW in 2006, and 93'927 MW in 2007. The turnover of the wind sector worldwide reached 40 billion € in the year 2008.

The market for new wind turbines (Figure 1.2) showed a 42% increase and reached an overall size of 27'261 MW, after 19'776 MW in 2007 and 15'127 MW in the year 2006. Ten years ago, the market for new wind turbines had a size of 2'187 MW, less than one tenth of the size in 2008. In comparison, no new nuclear reactor started operation in 2008, according to the International Atomic Energy Agency [3].
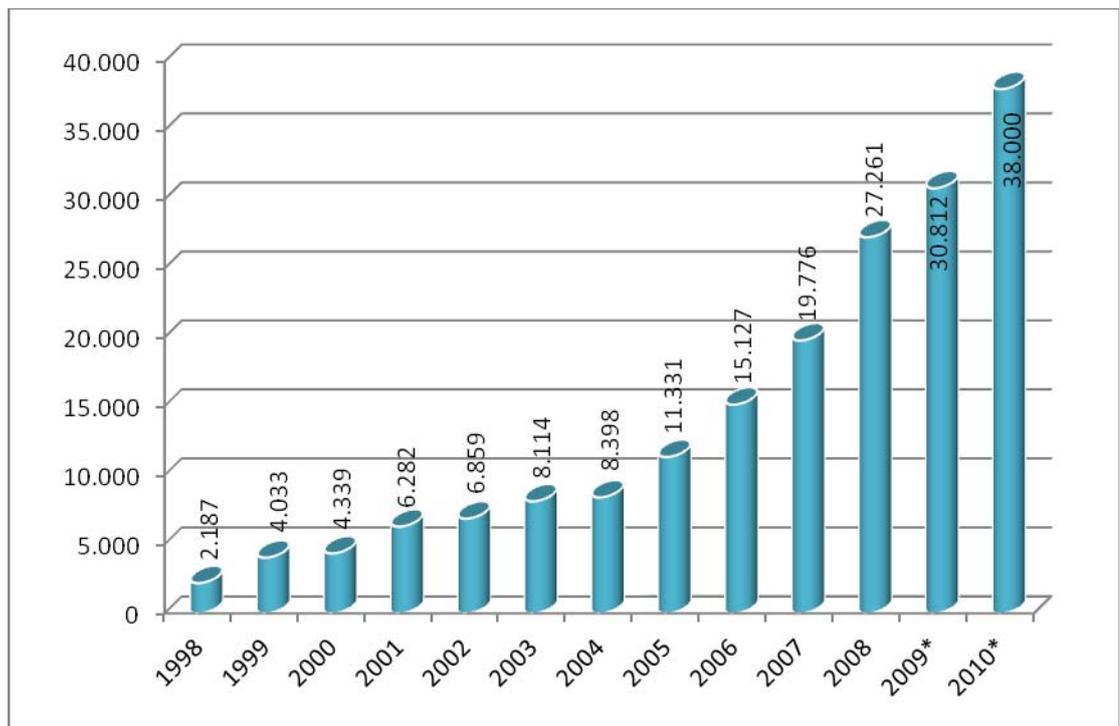
Figure 1.2   New Installed Capacity 1998-2008 (MW) [3]

Leading wind markets 2008

The USA and China took the lead, USA taking over the global number one position from Germany and China getting ahead of India for the first time, taking the lead in Asia. The USA and China accounted for 50.8% of the wind turbine sales in 2008 and the eight leading markets represented almost 80% of the market for new wind turbines, one year ago, still only five markets represented 80% of the global sales.

The pioneering country Denmark fell back to rank 9 in terms of total capacity, whilst up until four years ago it held the number 4 position during several years. However, with a wind power share of around 20% of the electricity supply, Denmark is still a leading wind energy country worldwide.
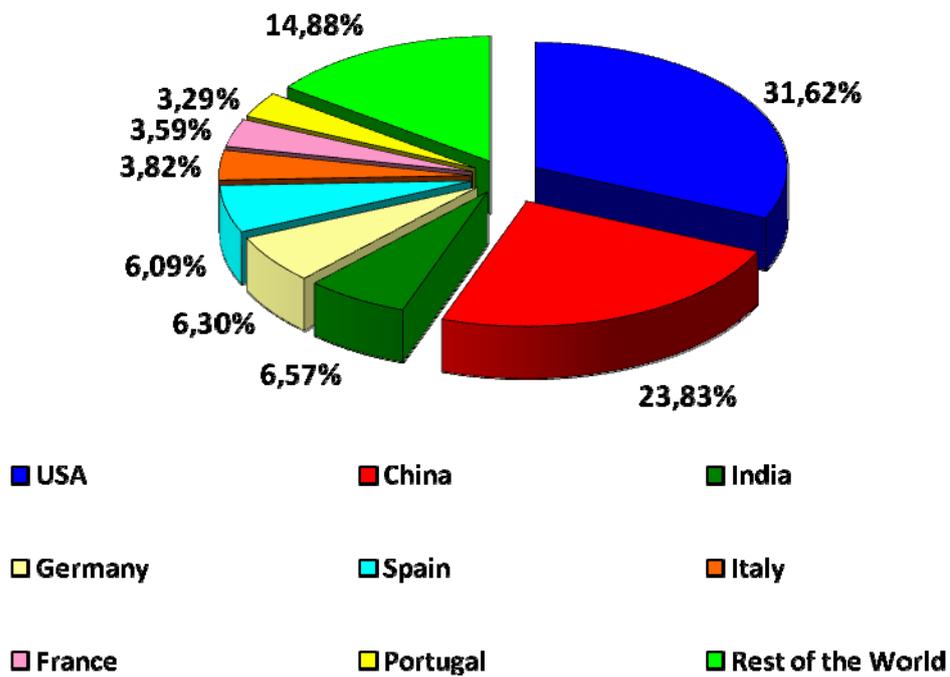
Figure 1.3   Country share of new installed capacity, 2008 [3]

Future Prospect Worldwide

Based on the experience and growth rates of the past years, WWEA expects that wind energy will continue its dynamic development also in the coming years. Infact, based on accelerated development and further improved policies, a global capacity of more than 1'500'000 MW is possible by the year 2020 (Figure 1.4) [3].
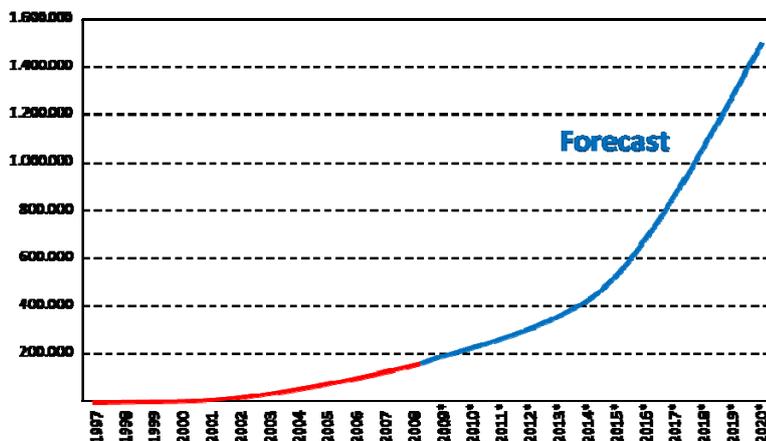

Figure 1.4   World Wind Energy [3]

6

Although the short term impacts of the current finance crisis makes short-term predictions rather difficult, it can be expected that in the mid-term wind energy will rather attract more investors due to its low risk character and the need for clean and reliable energy sources. More and more governments understand the manifold benefits of wind energy and are setting up favourable policies, including those that are stimulation decentralised investment by independent power producers, small and medium sized enterprises and community based projects, all of which will be main drivers for a more sustainable energy system also in the future.

Carefully calculating and taking into account some insecurity factors, wind energy will be able to contribute in the year 2020 at least 12% of global electricity consumption. By the year 2020, at least 1'500'000 MW can be expected to be installed globally.

A recently published study by the Energy Watch Group reveals – as one out of four described scenarios – that by the year 2025 it is even likely to have 7'500'000 MW installed worldwide producing 16.400 TWh. All renewable energies together would exceed 50% of the global electricity supply. As a result, wind energy, along with solar, would conquer a 50% market share of new power plant installations worldwide by 2019. Global non-renewable power generation would peak in 2018 and could be phased out completely by 2037 [3].

1.4   Wind Energy Conversion

The primary component of a wind turbine is the energy converter which transforms the kinetic energy contained in the moving air, into in mechanical energy.

The extraction of mechanical energy from a stream of moving air with the help of a disk-shaped, rotating wind energy converter follows its own basic rules.

The credit for having recognized this principle is owed to Albert Betz. He was able to show that the mechanical energy extractable from an air stream passing through a given cross-sectional area is restricted to a certain fixed proportion of the energy or power contained in the air stream.

Betz found that the optimal power extraction could only be realized at a certain ratio between the flow velocity of air in front of the energy converter and the flow velocity behind the converter.

" Betz's momentum theory" assumes an energy converter working without losses in a frictionless airflow, therefore it contains simplifications but its results are quite usable for performing rough calculations in practical engineering [5].

1.4.1   Betz's Elementary Momentum Theory

Consider the following schedule: the air in a pipe flow meets obstacle imposed by the rotor of a wind turbine, gradually approaching the blades rotor, the air in let flow is gradually slowed down, the pressure, however, increases. Passage through the rotor, the air gives him energy. Assuming that the rotor is of infinitesimal thickness, the pressure drops sharply to the step. And thanks to the "jump" Δp pressure that is exerted on the rotor a force and transferred power.
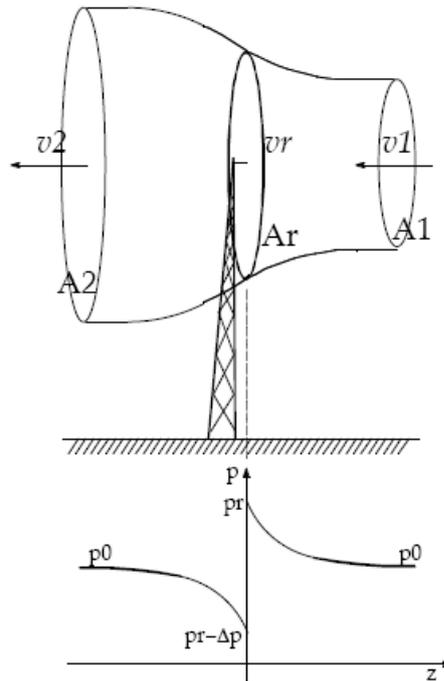
Figure 1.5 Pressure progress long the flow pipe

As the air proceed from the rotor air section to the unperturbed downstream section A_2, the pressure gradually increased, to take back the atmospheric pressure value at the section A_2.

The assumptions underlying the theory of Betz are the following:
1. Concept of flow pipe: the pipe current through the actuator disk does not interacts with the remaining portion of the fluid that surrounds;
2. In each section of the pipe flow velocity is uniform: the speed is different just along the axis of the pipe flow, in particular the velocity is uniform on the section the "hard rocker" of the wind turbine;
3. In the sections infinitely upstream and downstream that could be considered situation fluid undisturbed by the presence of the machine, or there is the atmospheric pressure p_0 in the external environment;
4. Wind flow over the turbine will not be obstructed, upwind or downwind;
5. The wind is steady and constant intensity with altitude;
6. There are not effects of rotation of the vein due of the 'extraction' amount of motion;
7. Neglect of the compressibility of air, ie the density r is constant.

9

For the two sections of pipe flow, upstream and downstream of the rotor, that is the Bernoulli's Theorem:

(1.1)

$$h + \frac{v^2}{2g} + \frac{p}{\rho g} = cost$$

Applying Bernoulli's Theorem at the tract upstream of the rotor, ie the section unperturbed A_1 down to the infinitesimal thickness of the disk actuator, it can be written:

$$\frac{v_1^2}{2g} + \frac{p_0}{\rho g} = \frac{v_r^2}{2g} + \frac{p_r}{\rho g}$$

(1.2)

where v_r is the air speed on the disk actuator section.

For the part downstream of the rotor, from the disk actuator section to the section unperturbed A_2, instead:

$$\frac{v_r^2}{2g} + \frac{(p_r - \Delta p)}{\rho g} = \frac{v_2^2}{2g} + \frac{p_0}{\rho g}$$

(1.3)

The hypothesis 1 and 7 ensure that, which is the speed v_r, at the rotor, it can't be discontinuous. Infact, must be valid the "Equation of Continuity", so the air mass that crosses every section, in the time, is the same, ie:

$$\rho A_1 v_1 = \rho A_r v_r = \rho A_2 v_2 = \dot{m}$$

(1.4)

Sum member to member the two equations on Bernoulli's Theorem upstream and downstream of the rotor, is obtained:

(1.5)

$$\Delta p = \frac{1}{2}\rho(v_1^2 - v_2^2)$$

The pressure jump on the rotor section is obtained by the knowledge of the speed air on the two unperturbed sections upstream and downstream.

10

The force F (horizontal) exercised by the air mass on the actuator disk is given by:

$$F = A_r \Delta p = A_r \frac{1}{2} \rho (v_1^2 - v_2^2) \qquad (1.6)$$

On the other hand, for the "Equation of conservation of momentum", the same force is equal the derivative of momentum, ie:

$$F = \dot{m}(v_1 - v_2) = \rho v_r A_r (v_1 - v_2) \qquad (1.7)$$

Equating the two expressions of the force, is obtained:

$$\frac{1}{2}(v_1^2 - v_2^2) = v_r(v_1 - v_2) \qquad (1.8)$$

by which:

$$v_r = \frac{v_1 + v_2}{2} \qquad (1.9)$$

The air speed on the actuator disk is equal at the mathematical average of the speeds on the two sections A_1 and A_2.

Is defined **_Interference Factor_** the parameter:

$$a = 1 - \frac{v_r}{v_1} = \frac{v_1 - v_r}{v_1} \qquad (1.10)$$

Then it:

$$v_r = v_1(1 - a) \; ; \; v_2 = v_1(1 - 2a) \qquad (1.11)$$

And substituting into the force expression, is obtained:

$$F = \rho v_r A_r (v_1 - v_2) = \rho A_r v_1^2 2a(1 - a) \qquad (1.12)$$

The power transfered to the rotor is:

$$P = F v_r = \rho v_r A_r v_1^2 2a(1 - a)v_r = \rho A_r v_1^3 2a(1 - a)^2 \qquad (1.13)$$

11

According to the theory of Betz, the power extractable from a wind stream is proportional at the area "swept" by the rotor and the cube of velocity. For a given speed wind v_1, the extractable power with a rotor diameter of a given r depends on

$a.$

By forcing the cancellation of the first derivative of P with respect to A can be found

optimal interference (interference so you have the extract the maximum power):

$$\frac{dP}{da} = 0 \implies a = 1 \; ; \; a = \frac{1}{3} \; ;$$

(1.14)

The solution $a = 1$ is meaningless, because it would $v_r = 0$, ie the air stops on rotor, which is an absurdity in the cases raised. Therefore the best interference is $a_{ott} = \frac{1}{3}$, corresponding to which one:

$$P = P_{max} = \frac{8}{27} \rho \pi R^2 v_1^3$$

(1.15)

In the absence of the rotor (undisturbed wind), the section of the rotor A_r is pierced in the dt interval, by a air mass $dm_v = r v_1 A_r dt$, which has kinetic energy

$$dW_v = \frac{1}{2} dm_v v_1^2 = \frac{1}{2} \rho A_r v_1^3 dt$$

(1.16)

The power of the undisturbed wind trough the rotor section results:

$$P_v = \frac{dW_v}{dt} = \frac{1}{2} \rho A_r v_1^3$$

(1.17)

Figure 1.6   Specific power (W/m^2) associated with a undisturbed pipe flow, at the speed variation.

The air density ρ varies between 0.9 and 1.4 kg/m^3 (depending on the conditions of temperature and pressure at 1 bar and 15 ° C, ρ = 1.22 kg/m^3).

Usually a light breeze has speed around 2m/s, a moderate breeze around 6 m/s, a strong wind around 15 m/s.

13
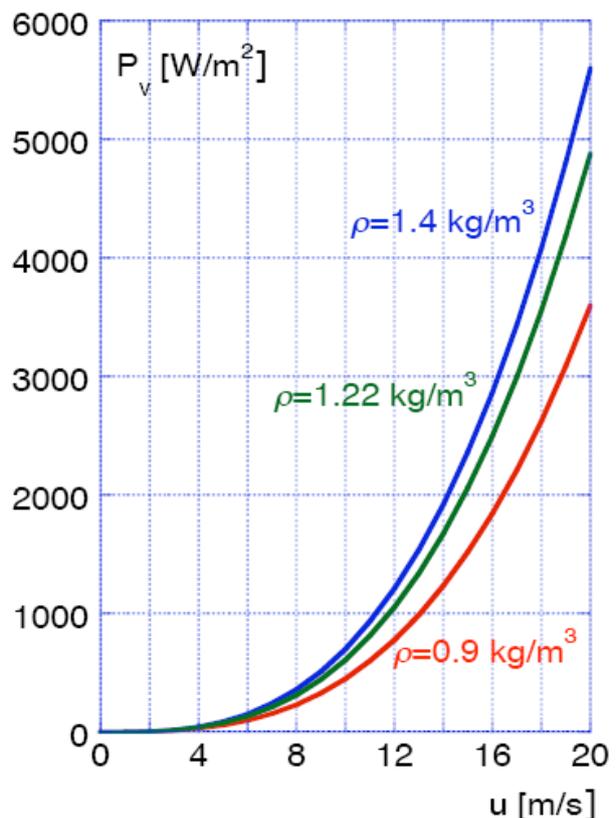
The ratio calculated between extracted power and undisturbed wind power trough the A_r section, without rotor, is defined **Power Coefficient** :

$$C_p = \frac{\rho A_r v_1^3 2a(1-a)^2}{\frac{1}{2}\rho v_1^3 A_r}$$

(1.18)

the C_p value calculated for $a = \frac{1}{3}$ is:

$$C_{p\,max} = \frac{16}{27} = 0.59$$

(1.19)

The maximum theoretical performance therefore is about 60%.

The extractable Power from a "vein" of wind speed u (the absolute velocity of the wind undisturbed is indicates usually with the letter u) it can then write in the form:

$$P = \frac{1}{2}\rho C_p u^3 A_r$$

(1.20)

The interference factor a , and hence the power coefficient C_p depend by the rotor features and the speed wind.

The Betz's Theory neglects all the phenomena of friction and the turbulence induced by rotation rotor. In a real situation, the value of the coefficient of performance is smaller than that calculated.

The essential findings derived from the momentum theory can be summarised as follows:

- the mechanical power which can be extracted from a free-stream airflow by an energy converter increases with the third power of the wind velocity.
- the power increases linearly with the cross-sectional area of the converter traversed; it thus increases with the square of its diameter.
- even with an ideal airflow and lossless conversion, the ratio of extractable mechanical work to the power contained in the wind is limited to a value of 0.593.Hence, only about 60% of the wind energy of a certain cross-section can be converted into mechanical power.
- when the ideal power coefficient achieves its maximum value $c_p = 0.593$, the wind velocity in the plane of flow of the converter amounts to two thirds of the undisturbed wind velocity and is reduced to one third behind the converter [6].

14

2   Wind Turbines Features

2.1   Overview

The air density is low, 800 times lower than that of water, used in hydroelectric plants, and this is the direct cause of the large size of a wind turbine (for example, depending on the wind speed range at design a 1.5 MW turbine can have a rotor that is more than 60 m in diameter). The power coefficient c_p describes the fraction of power in the wind that can be converted by the turbine into mechanical work. We have seen that it has a theoretical maximum of 0.593 (the Betz limit) and values achieved in practice are quite low.

The power coefficient of a rotor varies with the ratio of top speed (the ratio speed of rotor tip speed of the wind free) and is only a maximum of a fixed relationship to speed. With detailed designs of rotor is always trying to get increases the coefficient of performance, and going to operate at variable speeds, you can keep the maximum coefficient for a range of different speeds of wind. All these interventions, however, provide only incremental improvements.

Further increases in power output can be achieved increasing the area swept by the rotor or by going to locate the sites of installation of wind turbines with higher wind speed. Over the past 10 years there has been a steady increase in trade at the level of magnitude as the rotor diameter from about 30 meters for a rotor diameter of more than 60 meters. Doubling the rotor diameter leads to an increase of four times the power exit.

The influence of wind speed is obviously more pronounced since a doubling the wind speed leads to increased power output of eight times. So there have been considerable efforts to ensure that wind farms were developed with areas of maximum wind speed and wind turbines are located optimally within the wind farms.

In some countries very high towers are used (more than 60-80 m), to take advantage of the increase in wind speed with height. In the past a number of studies have been performed to determine the 'optimal' size of a wind turbine in order to compare the costs of production, installation and operating under different sizes of wind turbines, with the revenue generated. The results indicated that a minimum cost of energy would be achieved by diameters of wind turbines in the range of 35-60 m, depending on the assumptions made. However, these estimates would now seem to be rather low and there is obvious point at which the diameter of the rotor, and therefore power output, will be limited particularly for wind turbines offshore [7].

"All modern electricity-generating wind turbines use the lift force derived from blades to drive the rotor. A high-speed rotation of the rotor is desirable in order to reduce the exchange ratio required and this leads to low solidity rotors (the ratio blade area/rotor area swept). Acts of rotor solidity as effective low energy concentrator and therefore the period of energy recovery from a wind turbine on a good site is less than 1 year, ie, the energy used to produce and install wind turbine is recovered in its first year of operation."[6]

Structure of a Wind Turbine with Helical Rotor

A modern wind turbine is basically:
1. a tubular tower (or mast), whose base is immersed in the concrete foundations;
2. a nacelle mounted on the top of the power, inside which there are the principal organs of the turbine housing as the electric generator, the overdrive, the control system, etc.;
3. a propeller, which has, in the Wind Turbine of large sizes, the hydraulic system for adjusting the blades step.

The propeller is usually one, two or three blades. The blade offers minimal resistance progress, does not create dangerous turbulence, has a high importance: it translates into a high coefficient of performance and a high potential speed. In reality the angular speed results limited by the need to contain the linear speed at the extremity of the blade below of sound speed, to avoid dangerous mechanical stress. Therefore the rotors of large size, with a radius of several tens of meter, are centered between 20 and 50 rpm.

However, the propeller requires more sophisticated technology, more care in design and construction because the forces acting on each side are high and increasing considerably with an increase of the wind.

The propeller-driven generator, as a whole, is a machine that can be extremely dangerous: small mistakes or carelessness in its construction may create conditions to destroy the entire complex, including the tower.

During the operation it try to keep the number of laps (rpm) as constant as possible. For this reason, special mechanism are used that vary the blade's angle of rim (blade step), at the variation of the wind speed or aerodynamic brakes.

The propeller also to have a consistent and high performance coefficient C_P, must always orient oneself in the wind. This can be achieved:

- with a rudder of appropriate size which directs the entire complex (upwind);
- placing the propeller after the generator-pin rotation complex and using the gyroscopic torque of the engine itself to guide the rotor(down-wind).

2.2   Power Curve of Wind Machines

"The performance of a wind turbine can be characterized by the manner in which the three main indicators—Power, Torque and Thrust—vary with wind speed.

The Power determines the amount of energy captured by the rotor, the Torque developed determines the size of the gear box and must be matched by whatever generator is being driven by the rotor. The rotor thrust has great influence on the structural design of the tower.

It is usually convenient to express the performance by means of non dimensional, characteristic performance curves from which the actual performance can be determined regardless of how the turbine is operated (for example, at constant rotational speed or some regime of variable rotor speed)." [8]

The performance depends of the tip speed ratio and the pitch setting of the blades. It is usual to display the three main indicators as functions of tip speed ratio.

Prediction of a wind turbine's power curve is an important step of the design process. It involves consideration of the rotor, gearbox, generator and control system. The method used in predicting the power curve is to match the power output from the rotor as a function of rotational speed [9].

Using the rotor power coefficient c_{pr}, the rotor power can be calculated as follows:

$$P_r = c_{PR} \frac{\rho}{2} u^3 A_r$$

(2.1)

The power coefficient $C_{P,R}$ will be calculated using the strip theory for a certain rotor speed/wind speed ratio λ:

$$\lambda = \frac{\omega R}{u} \tag{2.2}$$

Repeating this for a number of tip speed ratios yields the variation of the power coefficient with the tip speed ratio. It can obtain the rotor power coefficient for different wind speeds at a fixed rotor speed or for different rotor speeds at one wind speed. If the rotor is equipped with blade pitch control, the power coefficient curves must be calculated for every blade pitch angle used in its operation. The single power coefficient curve for rotors with fixed blades becomes a family power curves for rotors with blade pitch control, as shown in Figure 2.1 [10].
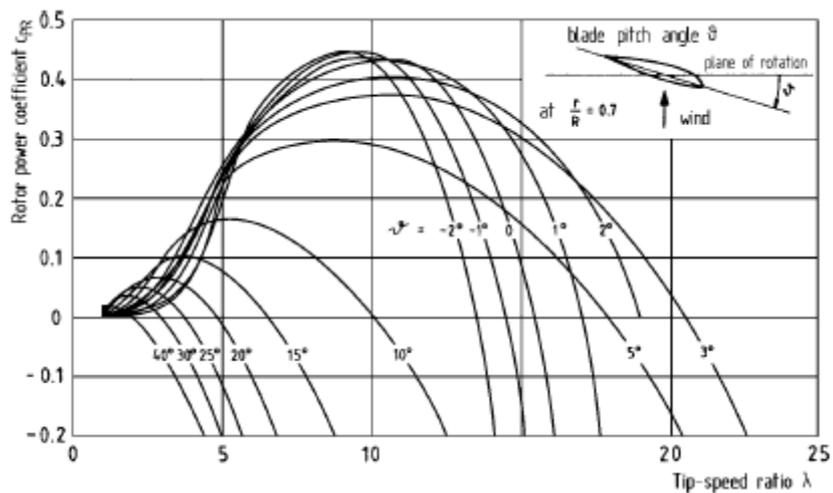

Figure 2.1   Rotor power characteristic for the experimental WKA-60 wind turbine [10]

The magnitude of the power coefficient and the shape of the curves both shown distinct differences and the main parameters dominating the t $C_{P,R}$ are:

- number of blades;
- planform of the blades;
- aerodynamic airfoil characteristics;
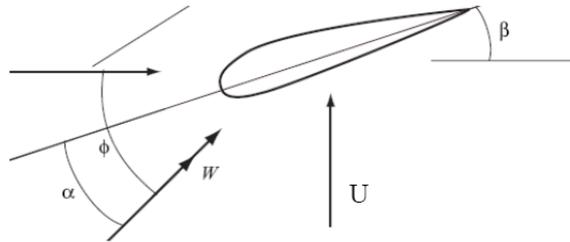- twist variation of the blades (Figure 2.2).

19

Figure 2.2 Velocity components in the plane of a blade cross-section [11]

A principle cause of the variation of the efficiency of power extraction of the blade assembly is due to the variation of the angle of attack α of a fixed blade with the incident wind. These components are shown in Figure 2.2 where U is the wind perpendicular to the turbine axis, W is the apparent wind relative to the rotating blade and β is the blade pitch angle. At a low tip speed ratios the blade is in a stall condition, at higher tip speed ratio the blade has a low angle of attack and drag effects predominate, both of these effects thus causing less than optimum power extraction [11].

Apart from the rotor power, the another important parameters used to character rotor performance is the rotor torque, and exist the torque coefficient (Figure 2.3):

$$T = c_Q \frac{\rho}{2} w^3 A R \tag{2.3}$$

where the rotor radius R is the reference parameters. The following equation shown the relationship between power and torque coefficient:
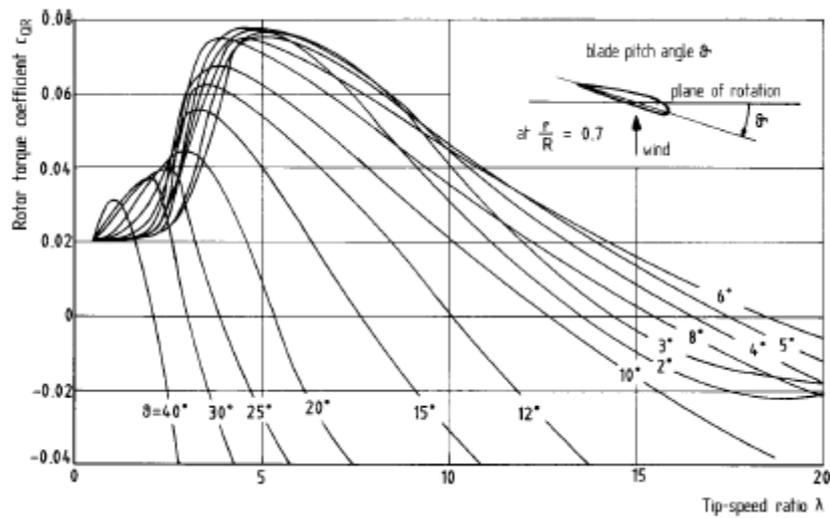
$$c_{PR} = \lambda c_Q \tag{2.4}$$

20

Figure 2.3   Rotor torque characteristics for the WKA-60 [10]

The rotor power curve (Figure 2.1) and the torque power curve (Figure 2.3) are features of each rotor configuration.

Curves of the type developed above can be useful in selecting the generation size. By combing the power curves with the characterisation of prospective wind regimes the effect on annual energy production can be estimated [10].

Figure 2.4 shows the qualitative differences in the power coefficients c_{PR}. It is obvious the advantages of modern rotors with high tip speed as compared with traditional rotors. It can see that modern rotors achieve power coefficient of almost 0.5 which demonstrate the superiority of the principle of using the aerodynamic lift.

Figure 2.5 shows the torque characteristics and it can be seen the similar differences. However, having a fast rotor is a disadvantage because the slow multi-blades rotors have a high torque while the torque is much lower for rotors with low blade solidity and few blades [10].
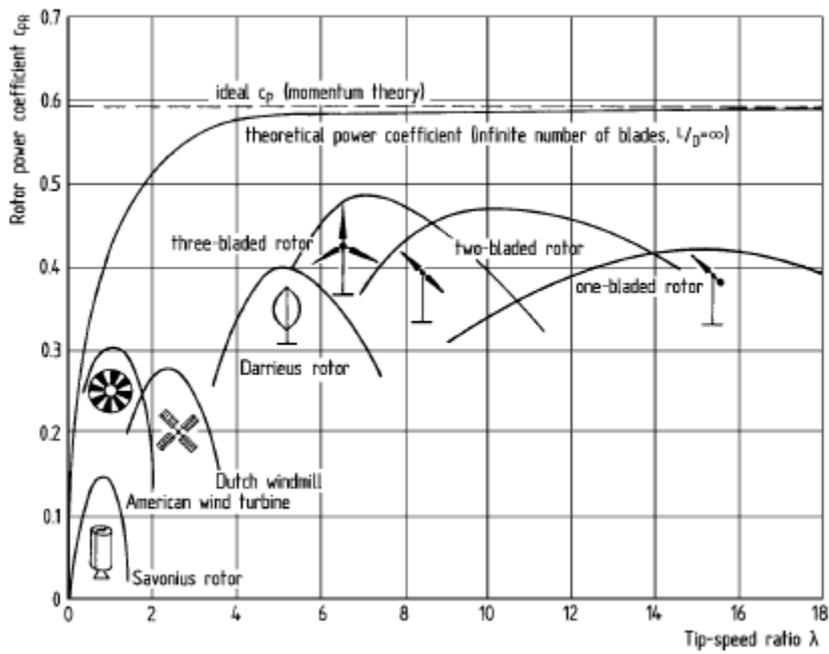
Figure 2.4   Power Coefficients of wind rotors of different designs [10]
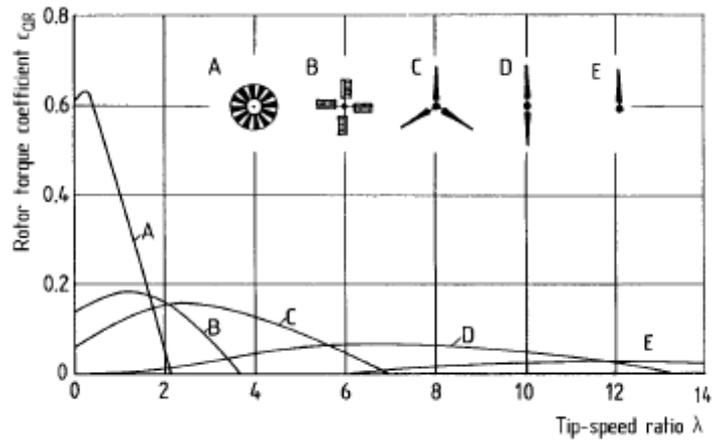

Figure 2.5   Torque Coefficients of wind rotors of different designs [10]

2.2.1 Aerodynamic Power Control

At high wind speed, the power captured from the wind by the rotor far exceeds the limits set by the design strength of the rotor structure. In addition the power output is limited by the maximum permissible of the generator.

Apart from limiting rotor power at high wind speeds, there is the problem of maintaining rotor speed at a constant value or within predetermined limits. Speed limitation becomes very important when the generator torque is suddenly lost, in such rotor speed would increase extremely rapidly and certainly lead to the destruction of the turbine unless countermeasures were taken immediately. Therefore, the rotor of wind turbine must have an aerodynamic effective means for limiting its power and its rotational speed .

Variable-speed wind turbines are connected to the grid indirectly. They typically have either a synchronous generator or a wound rotor induction generator, together with power electronic converters. The generator torque vs. rotor speed curve is different in those cases, but the approach the overall wind turbine power is the same.

Figure 2.6 illustrates the torque generator-rotor speed curve for different level of wind speed. It can see the curve for maximum power points, that represents at the variation of wind speed the variation of generator torque at different points of the machine can works safely in permanent system.
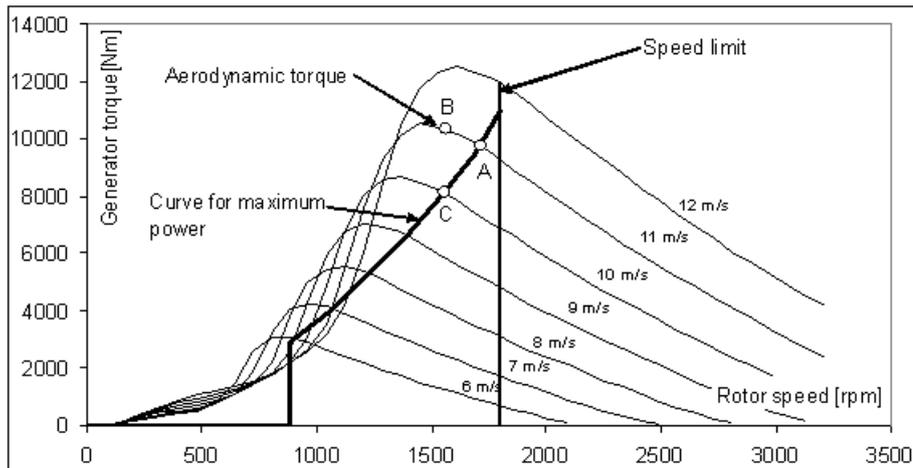Instead the vertical line represent the speed limit for the rotor.

Figure 2.6   Generator Torque-Rotor Speed Curve [13]

If the operational speed of a turbine rotor is allowed to change in order to keep the tip speed ratio more or less constant an increased quantity of energy can be captured compared to a fixed speed machine.

Figure 2.6 shows the set of torque speed curves which define the performance characteristics for a wind turbine machine for different wind speeds. As expected higher wind speeds result in a higher combination of torque and rotor speed hence giving a higher power output [13].

2.3 Wind Turbines Generators

In the wind turbines the mechanical power is transferred to an electric generator trough a system of transmission, which may include a gearbox (with different ratios).
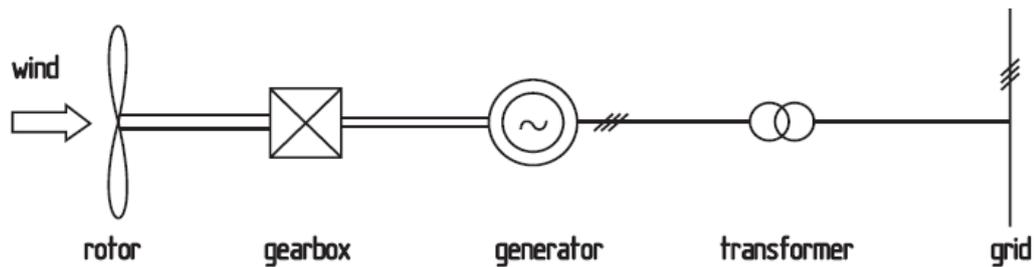

Figure 2.6 Mechanical-electrical functional chain in a Wind Turbine [14]

Most manufactures of wind turbines using induction generators, while some employ synchronous generators. Synchronous generators are relatively more expensive than induction generators of equal power (from 500 kW to 2 MW), and their rotation speed is imposed by the number of pole pairs and by the frequency of the network if they are connected directly to a network.

When synchronous generators are used, the coupling between synchronous generators and the network is done through a AC-DC-AC converter, otherwise by a PWM inverter (Pulse Width Modulated) so that the connection is made regardless of the voltage and frequency network values. Thus the rotor speed can be variable and the rotor can work to the best (it means at the maximum C_p), at the variation of wind speed and is not require the variable speed.

Using induction generators, the coupling to the network is less rigid than in the case of synchronous generators due to the 'slip', therefore is not essential use the converters. The generator must rotate at speeds much higher (i.e. ~1500 rpm if it is 2 pairs of poles) than the wind turbine (generally between 20 and 50 rpm). So it must make use of gears multipliers.

The wind turbine will rotate at a steady speed (actually slightly variable by the slip), so not in optimal conditions with the wind speed variation. For overcome this problem, it can follow several strategies such as the use of two induction generators (a smaller on suitable for low wind speeds, one size greater for the higher speeds)

or a induction generator with the possibility of variation in the number of polar pairs.

2.3.1 Fixed-Speed Wind Turbines

"The majority of the smaller, older wind turbines are still equipped with generators which are coupled directly to the grid. In some cases, even today, cost considerations led to a preference for this concept in spite of considerable disadvantages for the aerodynamic operation of the rotor and the dynamic loads on the mechanical drive train components.

It is only in recent years that with the progress in static converter technology, the indirect grid coupling with its advantage of variable speed operation of the generator has allowed this solution to become a serious and economically viable alternative."[14]

Fixed speed means that regardless of the wind speed, the wind turbine's rotor speed is fixed and determined by the frequency of the supply grid, the gear ratio and the generator design.

It is characteristic of fixed-speed wind turbines that they are equipped with an induction generator (squirrel cage or wound rotor) that is directly connected to the grid, with a soft-starter and a capacitor bank for reducing reactive power compensation. They are designed to have maximum efficiency at one particular speed.

This type of wind turbine has the advantage of being simple, robust, reliable and well-proven. Another advantage is the low cost of its electrical parts. Its disadvantages are an uncontrollable reactive power consumption, mechanical stress and limited power quality control. Another disadvantage is that all the fluctuations in the wind speed are further transmitted as fluctuations in the mechanical torque and then as fluctuations in the electrical power on the grid [15].
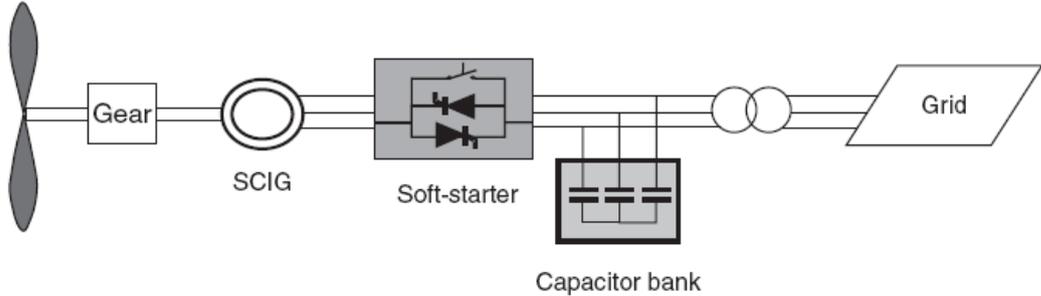
Figure 2.7   WTG implemented with a Squirrel-Cage Induction Generator (SCIG) [15]

26

Figure 2.7 illustrated a fixed-speed wind turbine with an asynchronous Squirrel Cage Induction Generator (SCIG) directly connected to the grid via a transformer. Since the SCIG draws reactive power from the grid, this configuration uses a capacitor bank for reactive power compensation [16].

Regardless of the power control principle in a fixed-speed wind turbine, the wind fluctuations are converted into mechanical fluctuations and consequently into electrical power fluctuations. In the case of a weak grid, these can yield voltage fluctuations at the point of connection. Because of these voltage fluctuations, the fixed-speed wind turbine draws varying amounts of reactive power from the utility grid (unless there is a capacitor bank), which increases both the voltage fluctuations and the line losses. Thus the main drawbacks of this concept are that it does not support any speed control, it requires a stiff grid and its mechanical construction must be able to tolerate high mechanical stresses[15].

2.3.2 Variable-Speed Wind Turbines

During the past few years the variable-speed wind turbine has become the dominant type amongst installed wind turbines.

Variable-speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. With a variable-speed operation it has become possible continuously to adapt (accelerate or decelerate) the rotational speed ω of the wind turbine to the wind speed u. This way, the tip speed ratio is kept constant at a predefined value that corresponds to the maximum power coefficient.

Contrary to a fixed-speed system, a variable-speed system keeps the generator torque fairly constant and the variations in wind are absorbed by changes in the generator speed.

The electrical system of a variable-speed wind turbine is more complicated than that of a fixed-speed wind turbine. It is typically equipped with an induction or synchronous generator and connected to the grid through a power converter. The power converter controls the generator speed; that is, the power fluctuations caused by wind variations are absorbed mainly by changes in the rotor generator speed and consequently in the wind turbine rotor speed.

The advantages of variable-speed wind turbines are an increased energy capture, improved power quality and reduced mechanical stress on the wind turbine. The disadvantages are losses in power electronics, the use of more components and the

increased cost of equipment because of the power electronics.

The introduction of variable-speed wind-turbine types increases the number of applicable generator types and also introduces several degrees of freedom in the combination of generator type and power converter type [15].

"Controlled variable-speed operation of a wind rotor is only possible with an electric generator which is operated with a downstream inverter. An Alternator operated with variable speed inevitably generates alternating current with varying frequency. The latter can only be adjusted to the required constant grid frequency by the inverter. Inverter technology is expensive and causes losses of efficiency. But apart from reducing the dynamic loads considerably, it permits an operation of the wind rotor which meets the requirements of its specific aerodynamic properties better than operation at constant speed. Generator-inverter systems are, therefore used more and more."[14]

Beyond mechanical power regulation, turbines are further divided into:
  A) Limited variable speed (Figure 2.8)
  B) Variable speed with partial power electronic conversion (Figure 2.9)
  C) Variable speed with full power electronic conversion (Figure 2.10)
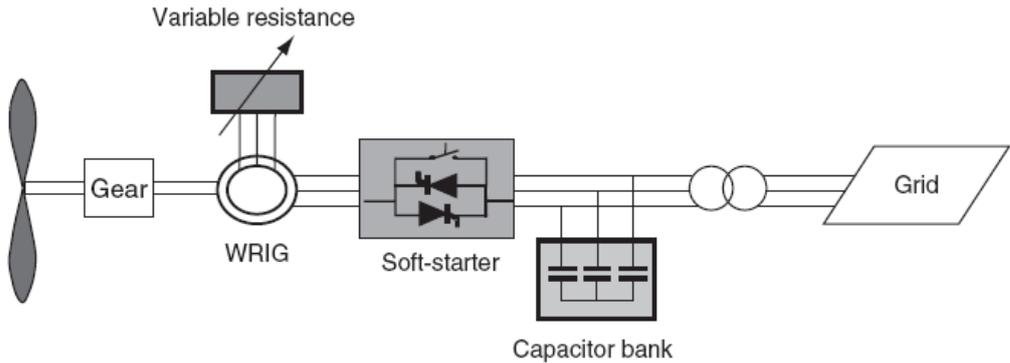
A) Limited Variable Speed

Figure 2.8 WTG implemented with a Wound Rotor Induction Generator (WRIG) [15]

Figure 2.8 illustrates a wound rotor induction generators connected directly to the WTG step-up transformer with regards to the machines stator circuit, but also includes a variable resistor in the rotor circuit. A capacitor bank performs the reactive power compensation [16].

The unique feature of this concept is that it has a variable additional rotor resistance, which can be changed by an optically controlled converter mounted on the rotor shaft. Thus, the total rotor resistance is controllable. This optical coupling eliminates the need for costly slip rings that need brushes and maintenance. The rotor resistance can be changed and thus controls the slip. This way, the power output in the system is controlled. The range of the dynamic speed control depends on the size of the variable rotor resistance.

Typically, the speed range is 0–10% above synchronous speed [15].

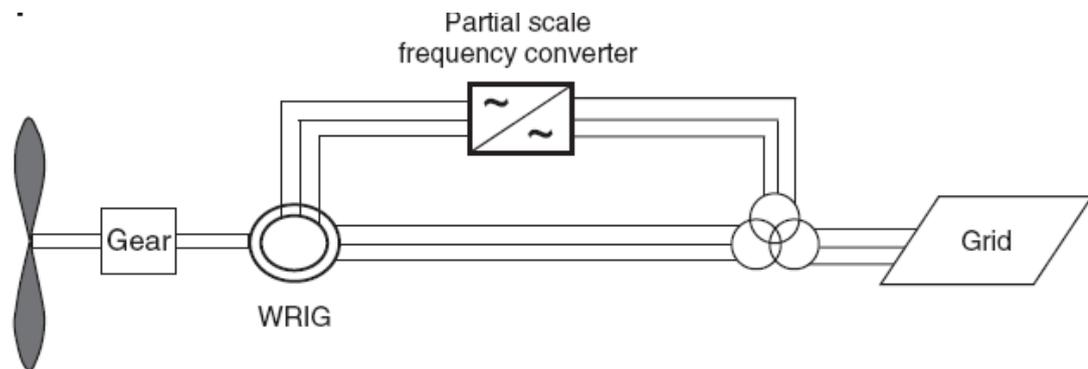**B) Variable Speed with Partial Power Electronic Conversion**

Figure 2.9 WTG implemented with a Wound Rotor Induction Generator (WRIG) and Partial Scale Frequency Converter, Doubly Fed Induction Generator (DFIG) [15]

Figure 2.9 illustrated a wind turbine generator type known commonly as the Doubly Fed Induction Generator (DFIG) or Doubly Fed Asynchronous Generator (DFAG), takes the WRIG type by adding variable frequency AC excitation (instead of simply resistance) to the rotor circuit [16].

The additional rotor excitation is supplied via slip rings by a current regulated, voltage-source converter, which can adjust the rotor currents' magnitude and phase nearly instantaneously. This rotor-side converter is connected back-to-back with a grid side converter, which exchanges power directly with the grid. A small amount power injected into the rotor circuit can effect a large control of power in the stator circuit. This is a major advantage of the DFIG, a great deal of control of the output is available with the presence of a set of converters that typically are only 30% of the rating of the machine. In addition to the real power that is delivered to the grid

from the generator's stator circuit, power is delivered to the grid through the grid-connected inverter when the generator is moving faster than synchronous speed. When the generator is moving slower than the synchronous speed, real power flows from the grid, through both converters, and from rotor to stator. These two modes, made possible by the four-quadrant nature of the two converters, allows a much wider speed range, both above and below synchronous speed by up to 50%, although narrower ranges are more common.

The greatest advantage of the DFIG, is that it offers the benefits of separate real and reactive power control, much like a traditional synchronous generator, while being able to run asynchronously. The field of industrial drives has produced and matured the concepts of vector or field oriented control of induction machines. Using these control schemes, the torque producing components of the rotor flux can be made to respond fast enough that the machine remains under relative control, even during significant grid disturbances [16].

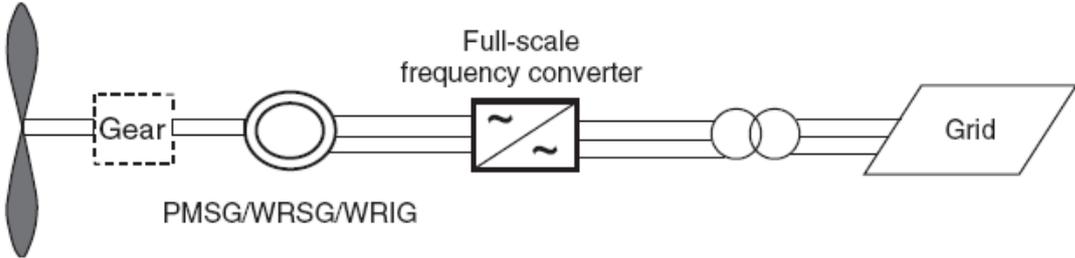## C) Variable speed with Full Power Electronic Conversion

Figure 2.10 WTG implemented with a Permanent Magnet Synchronous Generator(PMSG) or Wound Rotor Synchronous Generator (WRSG) or WRIG and with a Full Scale Frequency Converter[15]

Figure 2.10 illustrates a configuration corresponds to the full variable speed wind turbine, with the generator connected to the grid through a full-scale frequency converter. The frequency converter performs the reactive power compensation and the smoother grid connection [16].

The generator can be an excited electrically Wound Rotor Synchronous Generator (WRSG or WRIG) or by a Permanent Magnet Synchronous Generator (PMSG).

30

Some full variable-speed wind turbine systems have no gearbox (see the dotted gearbox in Figure 2.10). In these cases, a direct driven multipole generator with a large diameter is used [15].

These types of generators offer a great deal of flexibility in design and operation as the output of the rotating machine is sent to the grid through a full-scale back-to-back frequency converter. The turbine is allowed to rotate at its optimal aerodynamic speed, resulting in a "wild" AC output from the machine. The rotating machines of these types have been constructed as wound rotor synchronous machines, similar to conventional generators found in hydroelectric plants with control of the field current and high pole numbers, as permanent magnet synchronous machines, or as squirrel cage induction machines. However, based upon the ability of the machine side inverter to control real and reactive power flow, any type of machine could be used. Advances in power electronic devices and controls in the last decade have made the converters both responsive and efficient [16].

3　　　Frequency Control from Wind

Turbines

3.1　Frequency Control Requirements

I begin by explaining what frequency control requirements are in the network. Responsibility of frequency control is managed in the UK by National Grid PLC through the procurement and dispatch of frequency response services, the license requiring operation at 50Hz $\pm$ 0.5Hz. Under normal operating conditions frequency is maintained at 50 $\pm$ 0.2 Hz by particular generation units operating their governors in droop speed control mode (typically 4% or less) [17].

For abnormal system events, an instantaneous loss or connection of up to 1320 MW should be accommodated with a maximum frequency deviation of -0.8Hz.
This is achieved through plant which is contracted to supply 'occasional service' and it can be split into:

I.　Primary Response: available between 10 and 30 seconds after the event that causes the frequency deviation;

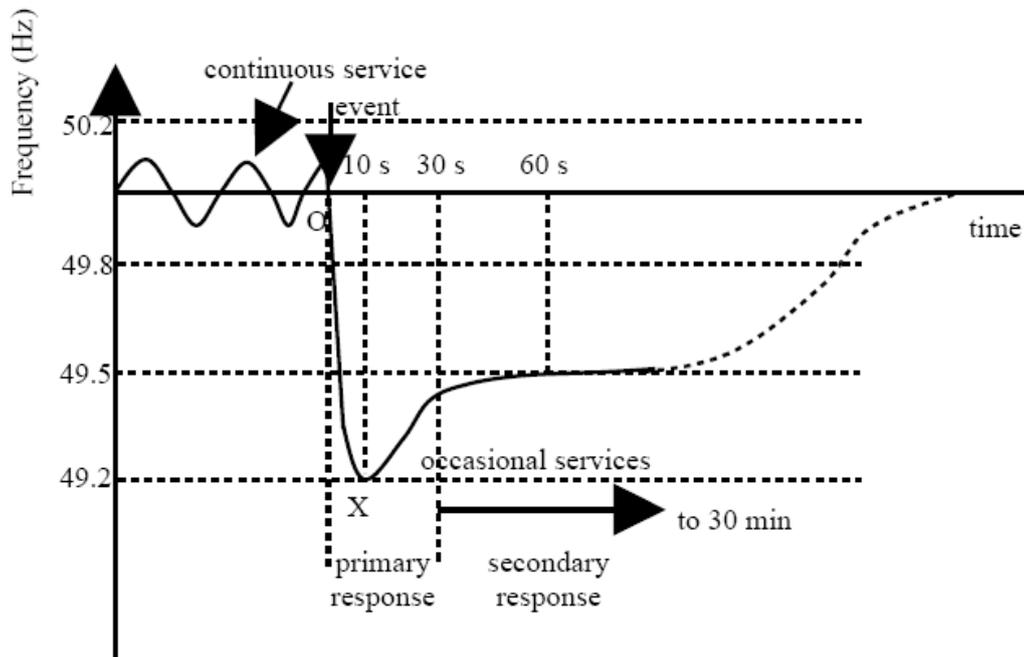II.　Secondary Response: available from 30 seconds till 30 minutes after the event that causes the frequency deviation;

Figure 3.1 Modes of operation of frequency control on the UK grid [17]

I.   Primary Response:

For maximisation of revenue and resource utilisation, wind turbines will normally operate to maximise their power output under all possible conditions. Hence they are not available to provide a sustained increase in power output and therefore participate in 'secondary response' services which conventional plant are able to do. However they can provide the two components of inertia and governor response which are present in primary response from existing synchronous plant as outlined below.

a) Fast Primary Response: inertial response is the reduction in rate of change of frequency obtained when stored kinetic energy is released by (principally) synchronously coupled rotational generators and loads as system frequency drops. DFIG and FPC based wind turbines can emulate this response by extracting energy from the rotational mass of the turbine generator and turbine rotor assembly.

b) Slow Primary Response: governor action can be provided by temporarily operating the wind turbine at a higher aerodynamic power output at the expense of an overall drop in power output over the complete occasional response period [17].

3.2 Control of Active Power

For satisfactory operation of power system, the frequency should remain nearly constant. Relatively close control of frequency ensures constancy of speed of induction and synchronous motors. Constancy of speed of motor drivers is particularly important for satisfactory performance of generating units as they are highly dependent on the performance of all the auxiliary drivers associated with the fuel, the feed-water and the combustion air supply system.

In a network, considerable drop in frequency could result in high magnetizing currents in induction motors and transformers. The frequency of a system is dependent on active power balance; as frequency is a common factor throughout the system, a change in active power demand at one point is reflected throughout the system by a change in frequency. Because there are many generators supplying power into the system, some means must be provided to allocate change in demand to the generator. A speed governor on each generating unit provides the primary speed control function, while supplementary control originating at a central control centre allocates generation.

In an interconnected system with two or more independently controlled areas, in addition to control of frequency, the generation within each area has to be controlled so as to maintain scheduled power interchange. The control of generation and frequency is commonly referred to as *load-frequency control* (LFC) [18].

3.2.1 Fundamentals of Speed Governing [18]

The basic concepts of speed governing are best illustrated by considering an isolated generating unit supplying a local load as shown in the following figure:
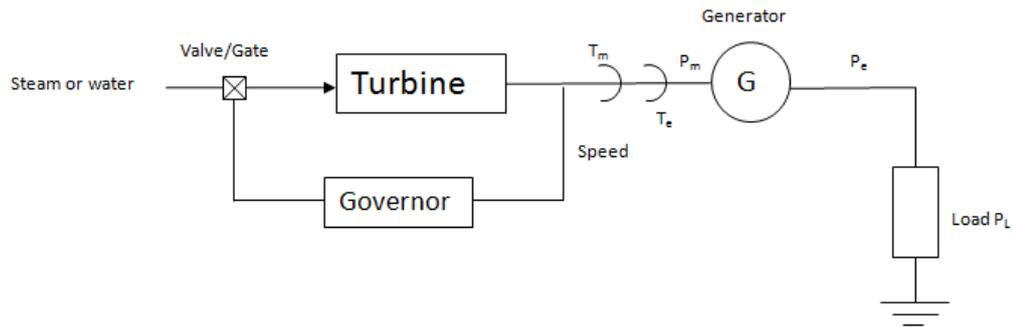
Tm=mechanical torque   Te=electrical torque
Pm=mechanical torque   Pe=electrical power   PL=load power

Figure 3.2   Generator supplying isolated load

To arrive at the figure 3.2 we have to consider two different response:

1) Generator response to load change;

2) Load response to frequency deviation;

1) Generator response to load change

When there is a load change, it is reflected instantaneously as a change in electrical torque output T_e of generator; this causes a mismatch between the mechanical torque T_m and the electrical torque T_e which in turn results in speed variations as determined by the equation of motion.

During an imbalance between power and load the net accelerating torque T_a is:

$$T_a = T_m - T_e$$

where T_m , T_e are positive for a generator (N.m)   (3.1)

The combined inertia is accelerated accordingly and gives rise to the "Swing equation":

$$J\frac{d\omega_m}{dt} = T_a$$

J is moment of inertia (kg.m^2), ω_n angular velocity (rad/s)

(3.2)

For power system studies inertia is normally given in terms of the per unit inertia constant H:

$$H = \frac{K.E}{VA_{base}} = \frac{0.5J\omega_{0m}^2}{VA_{base}}$$

where ω_{0m} is rated angular velocity (rad/s)

(3.3)

Substituting for J in the Swing equation:

$$2H\frac{d}{dt}\left(\frac{\omega_m}{\omega_{0m}}\right) = \frac{T_m - T_e}{\frac{VA_{base}}{\omega_{0m}}}$$

(3.4)

Because T$_{base}$ = VA$_{base}$/ω_m the pu equation of motion can be expressed as:

$$2H\frac{d\bar{\omega}_r}{dt} = \bar{T}_m - \bar{T}_e$$

where $\bar{\omega}_r = \left(\frac{\omega_m}{\omega_{0m}}\right)$

(3.5)

Rearranging to obtain the acceleration:

$$\Delta\omega_r = \frac{d\bar{\omega}_r}{dt} = \frac{1}{2H}(\bar{T}_m - \bar{T}_e)$$

(3.6)

The following transfer function (Figure 3.3) represents the relationship between rotor speed as a function of electrical and mechanical torques.
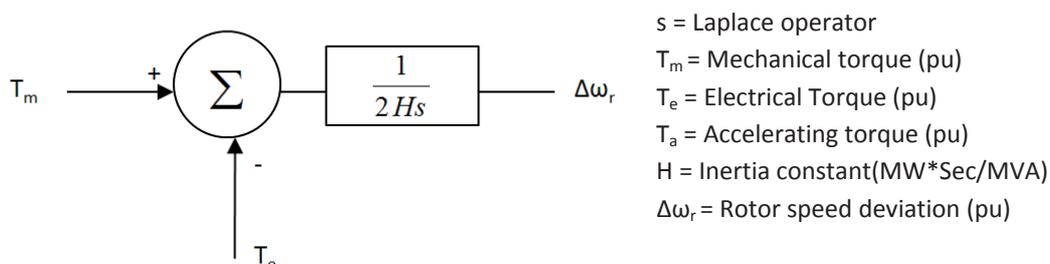

s = Laplace operator
T$_m$ = Mechanical torque (pu)
T$_e$ = Electrical Torque (pu)
T$_a$ = Accelerating torque (pu)
H = Inertia constant(MW*Sec/MVA)
Δω$_r$ = Rotor speed deviation (pu)

Figure 3.3   Transfer Function relating Speed and Torque

36

For load-frequency studies, it is preferable to express the above relationship in terms of mechanical and electrical power rather than torque. The relationship between power and torque is given by

$$P = \omega_r T \qquad (3.7)$$

By considering a small deviation (denoted by prefix Δ) from initial values (denoted by subscript $_0$), we may write

$$\begin{aligned} P &= P_0 + \Delta P \\ T &= T_0 + \Delta T \\ \omega &= \omega_0 + \Delta\omega_r \end{aligned} \qquad (3.8)$$

From equation 1.2.1,

$$P_0 + \Delta P = (\omega_0 + \Delta\omega_r)(T_0 + \Delta T) \qquad (3.9)$$

The relationship between the perturbed values, with higher-order terms neglected, is given by

$$\Delta P = \omega_0 \, \Delta T + T_0 \, \Delta\omega_r \qquad (3.10)$$

Therefore,

$$\Delta P_m - \Delta P_e = \omega_0 (\Delta T_m - \Delta T_e) + (T_{m0} - T_{e0}) \Delta\omega_r \qquad (3.11)$$

Since in the steady state, electrical and mechanical torques are equal, $T_{m0} = T_{e0}$. With speed expressed in pu, $\omega_0 = 1$. Hence,

$$\Delta P_m - \Delta P_e = \Delta T_m - \Delta T_e \qquad (3.12)$$

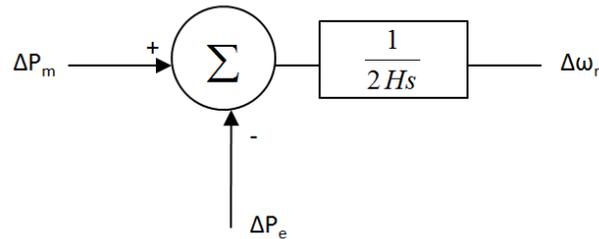Figure 3.3 can now be expressed in terms of ΔP_m and ΔP_e as follows:

Figure 3.4 Transfer Function relating Speed and Power

Within the range of speed variations with which we are concerned, the turbine mechanical power is essentially a function of valve or gate position and is independent of frequency.

2) Load response to frequency deviation

Power system loads are a composite of a variety of electrical devices. For resistive loads, such as lighting and heating loads, the electrical power is independent of frequency. In the case of motor loads, such as fans and pumps, the electrical power changes with frequency due to changes in motors speed. The overall frequency-dependent characteristic of a composite load may be expressed as:

$$\Delta P_e = \Delta P_L + D \Delta \omega_r \tag{3.13}$$

where
ΔP_L=non-frequency-sensitive load change
$D\Delta\omega_r$=frequency-sensitive load change
D=load-damping constant

The damping constant is expressed as a percent change in load for one percent change in frequency. Typical values of D are 1 to 2 percent. A value of D=2 means that a 1% change in frequency would cause a 2% change in load. The system block diagram including the effect of the load damping is shown in Figure 3.5.
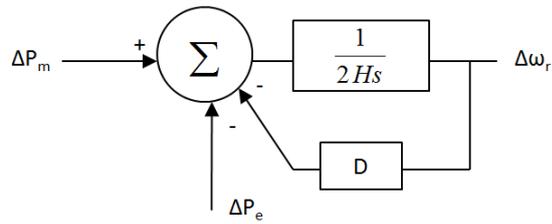
Figure 3.5   Transfer Function relating Speed and Power included Damping constant

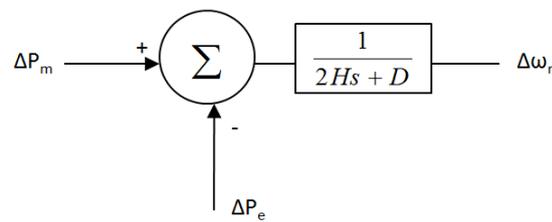This may be reduced to the form shown in Figure 3.6.

Figure 3.6   Transfer Function relating Speed and Power included Damping constant

In the absence of a speed governor, the system response to a load change is determined by the inertia constant and the damping constant. The steady-state speed deviation is such that the change in load is exactly compensated by the variation in load due to frequency sensitivity.

3.3   GB Delta Power Inertia Model

Having realized that without a speed governor system response to a change of load is determined by the inertia constant and damping constant, we analyze the GB Frequency Model.

"For small deviations of frequency about a nominal operating point it is possible to determine frequency change in response to a change in the net power balance on the system using the equation below where T_m is mechanical torque in [Nm], T_e is electromagnetic torque in [Nm], ω_r is the angular velocity of the rotor in electrical [rad/s], H is the per unit inertia constant and K_D is the damping torque:

$$\frac{d\Delta\bar{\omega}_r}{dt} = \frac{1}{2H}\left(\bar{T}_m - \bar{T}_e - K_D\Delta\omega_r\right) \qquad (3.14)$$

This delta power model is shown in Fig. 1.7." [17]

Sensitivity of loads with respect to a change in frequency is given by the system damping D. Stored inertia and therefore initial rate of change of frequency for a power disturbance is dictated by H_{eq}, the equivalent combined inertia of the system (not including any additional synthesised wind turbine inertia).

Synchronous governor response is determined by the combined transfer functions of the droop, governor and turbine transfer functions. Both the wind turbine response and synchronous response represent aggregated models of the individual plant on the system.
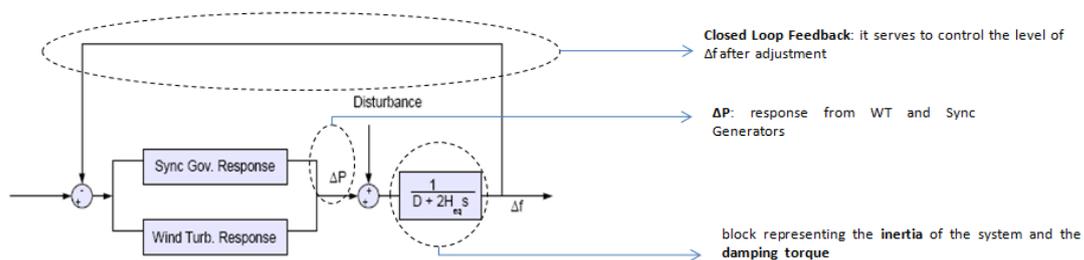

Figure 3.7   GB Delta Inertia Power Model [17]

In Figure 3.7 we can see what has been introduced previously, namely the ability to use together wind turbines and synchronous plants to have, in the case of an abnormal system event, a faster increase of active power response for a minor

decrease in the frequency change.

3.3.1 Synchronous Plant Response

This response consist of the expected ΔP increase from all of the synchronous plant on the system.

It has been already explained what is the *Fast Primary Response(Inertia Response)* and the *Secondary Primary Response(Governor Response)* in section 3.1, as these two mechanisms are the response of synchronous generator based power plants within the first 30 seconds, as considered for the Wind Turbines plants.

The Figure 3.8 is taken from the Simulink model and is of the form of a generating unit with a reheat steam turbine.
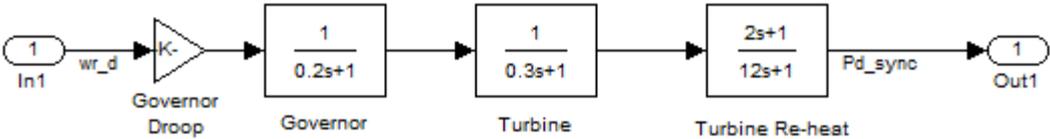

Figure 3.8   Steam turbine Transfer function

The quantity of this plant and its scheduled level of response is determined through setting the gain in the 'Governor Droop' (K-value). The K-values represents the transfer function between synchronous power output variation and system frequency variation (K-values= T.F. = $\Delta P_{[pu]}/\Delta f_{[pu]}$).

The Governor block represents the real answer from the steam turbines to change the power output level when happens a disturbance. The 0.2 value is the typical time constant of governor for a steam turbine (T_G=0.2s).

The Turbine block represents the real steam turbine action in normal operation and the typical value of time constant of main inlet volumes and steam chest is 0.3 (T_{CH}=0.3s) [18].

At the end, there is the Turbine Re-heat block that represents the real re-heat turbine action operation and the simulations model uses a time constant of 12s.

4 The Linearized Delta Torque Model

The Figure 4.1 below shows the model representing the Wind Turbine Response.
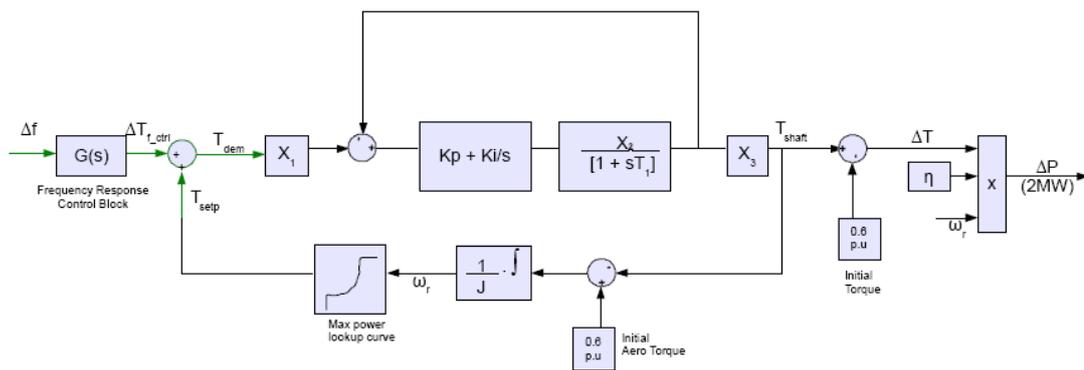

Figure 4.1 Linearized delta torque wind turbine model

This model is accurate for small changes in torque about an initial operating point, parameters used for this model are calculated using the data for 2MW IG machine given in Appendices A.1.

4.1 Explanation of the Model

I'm going to explain the meaning of each block that constitutes the Linearized delta torque wind turbine model dividing it into sub-blocks, as shown in Figure 4.2.
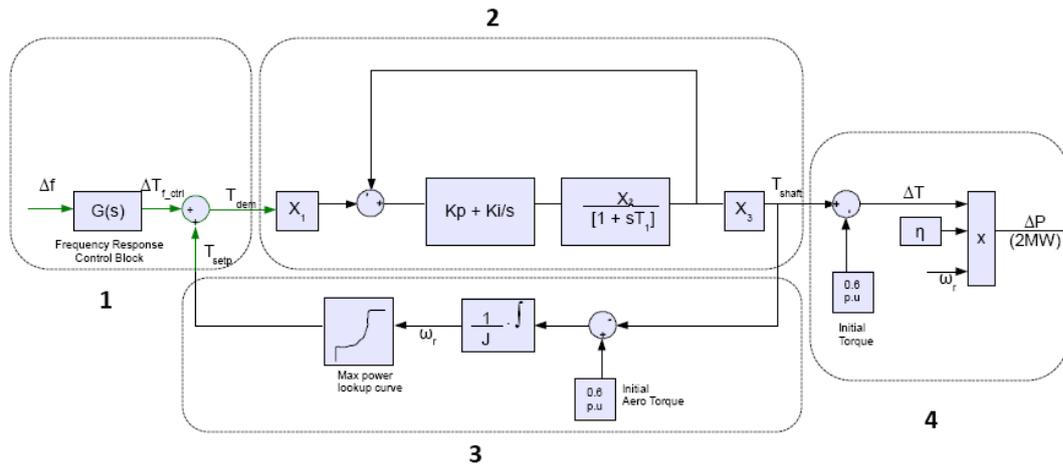

Figure 4.2 Linearized Delta Torque Wind Turbine Model
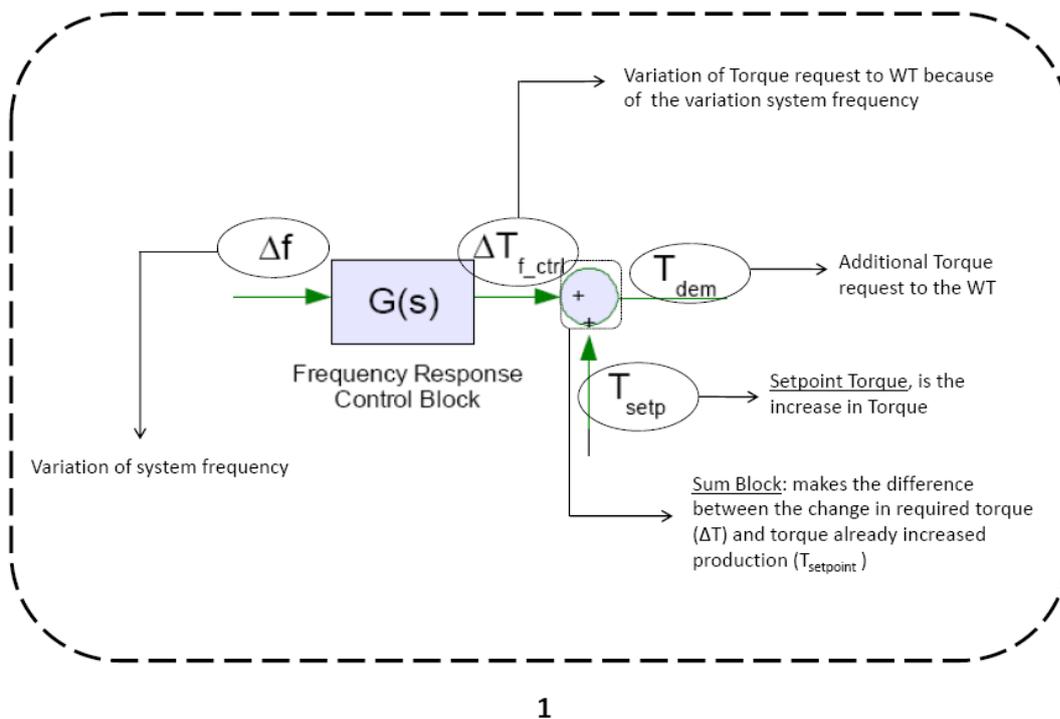
The fist sub-block is explained in Figure 4.3.

Figure 4.3 Sub-block 1 of the Linearized Delta Torque Wind Turbine Model

Into the first sub-block it is present the frequency response control block (Appendices A.2, Figure A.3), which is explained in Figure 4.4.
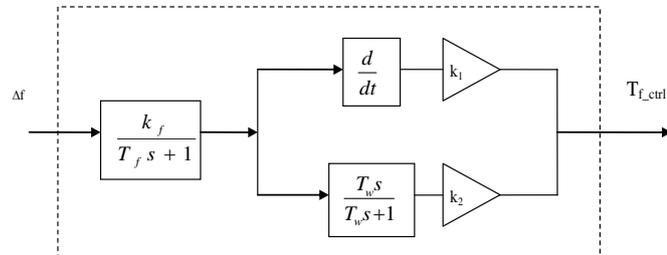

Figure 4.4   Wind turbine frequency response control block

The block in Figure 4.4 transforms the variation in frequency variation of torque required to wind turbine. By increasing the torque set point of the wind turbine in response to a frequency deviation a short term increase in electrical power output of the machine can be achieved. This is a supplementary control to enable the fast primary response, inertial and governor action.

The combination of the transfer functions below provides an increase in commanded power output in response to the change of frequency.

There are the supplementary control loop parameters k_1, k_2, T_w:

- The gain k_1 provides a synthesis of the inertia of the wind turbine plant and it acting on the rate of change of frequency deviation signal, represent the initial response from the wind turbine.

- The gain k_2 is an additional shaping response provided by the 'washout' filter and with the T_w set the response after 2-3 second.

At the end, there is the block on the left, that uses a first order delay using T_f in combination with gain k_f to consider the real relationship between Δf and ΔT, the K_f value represents the "transfer function gain" between Δf and ΔT.

The second sub-block is explained in Figure 4.5.
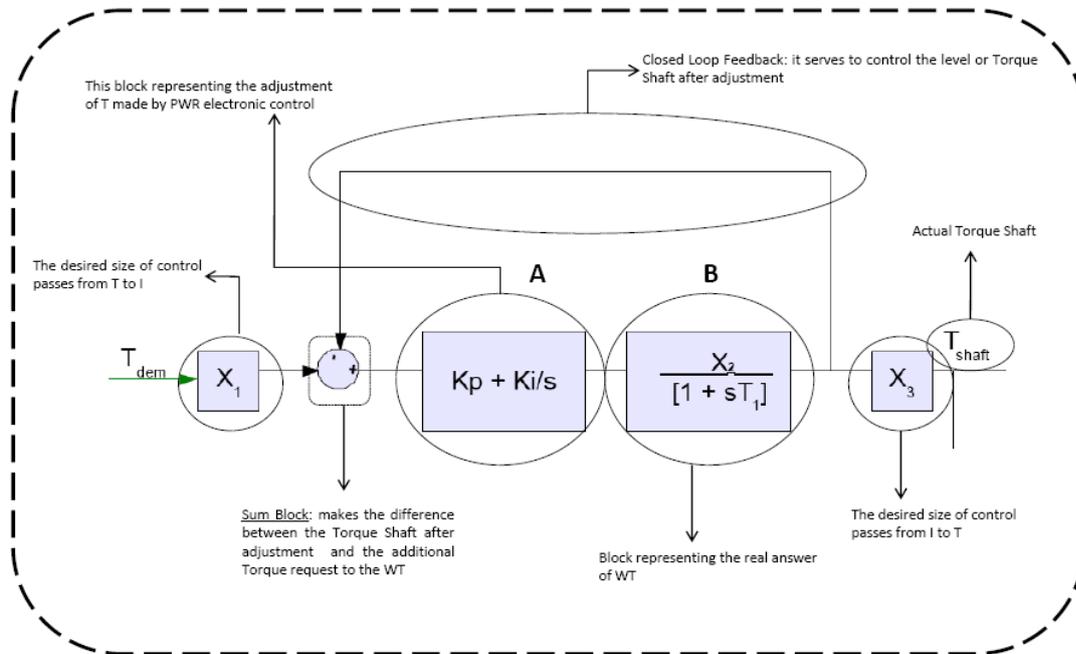
Figure 4.5 Sub-block 2 of the Linearized Delta Torque Wind Turbine Model

Into the second sub-block we have two main blocks:

A) The block where there is the adjustment of torque made by a PI Controller (proportional-integral controller), it is a feedback controller which drives the Torque to be controlled with a weighted sum of the error (difference between the output and desired set-point, and into the block and this action is represented by the coefficient K_p) and the integral of that value (coefficient K_i/s);

B) The block which takes into account the real wind turbine response when the input change, this is shown in Figure 4.6.
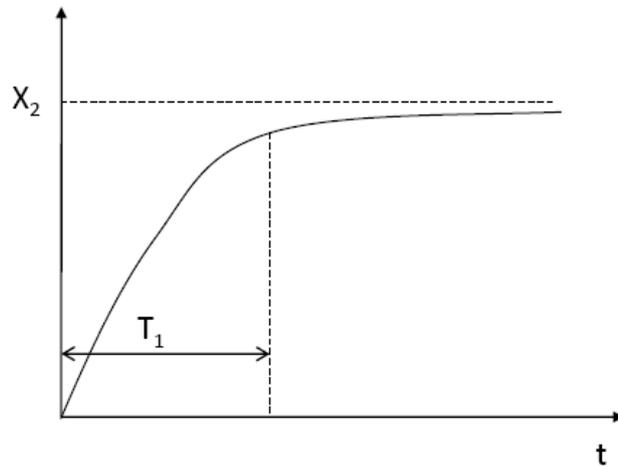
Figure 4.6   Real Wind Turbine Response

The X_1-block of Figure 4.5 represent the desired size of control passes from torque (T) to current (I).

The sum-block makes the difference between demand torque (T_{dem}) and increased shaft torque (T_{shaft}). This check is in current dimension and it happens through the closed loop feedback.

The equation and the values of K_f, K_i, X_1, X_2, X_3, T_1 used in the model can be find in Appendices A.1, Table A.1.

The third sub-block is explained in Figure 4.7.
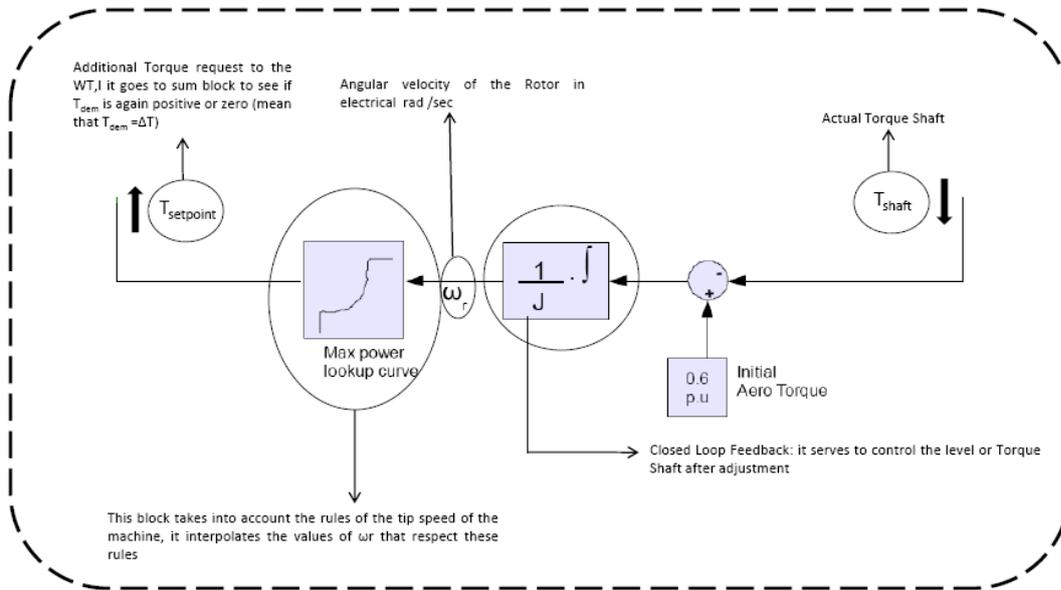
Figure 4.7 Sub-block 3 of the Linearized Delta Torque Wind Turbine Model

The third sub-block is a closed loop feedback to check that with the practical increase shaft torque are observed the rules of the speed of the machine.

From the right, a sum block is present that calculates the difference between the initial aero torque ant the actual torque shaft, then there is a block that calculates the integral of the input and then takes into account the inertia of the wind turbine and output provides the angular velocity of the rotor with actual torque shaft.

The last block is the most important because it takes into account the rules of the tip speed of the machine, it interpolates the values of ω_r that respect these rules.

In Figure 4.8 is shown the different modes of operation for the wind turbine.
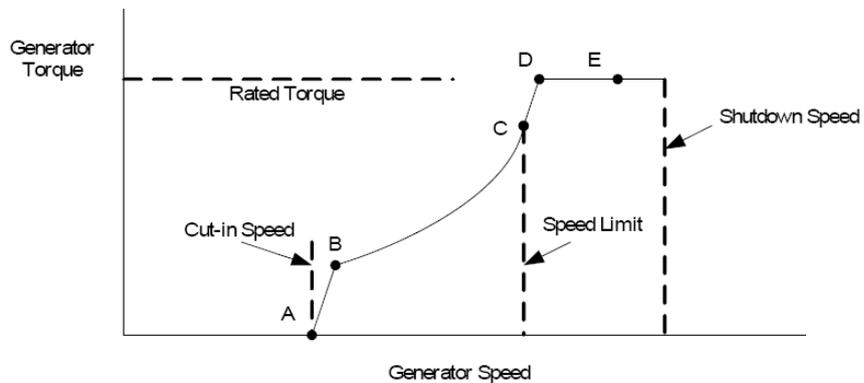

Figure 4.8   Operating modes for a WT

Below cut-in : machine is not rotating and produces no power output.

Max Power Tracking : B to C - electrical torque is controlled so that the machine speed tracks the maximum power curve.

Constant Speed : A to B and C to D – due to power converter constraints at low speed and aerodynamic noise constraints at high speed, torque is allowed to vary but speed is held almost constant [19].

Pitch Control or Stall : D to E - Speed and torque are both limited to their maximum values by adjustment of the blade pitch angle. This stalling or feathering of the blade reduces the torque produced. If no pitch mechanism is provided, stalling of the blades at high wind speeds can be achieved through suitable blade design.

Shutdown : Above a certain speed the WT is brought to a halt to avoid damage.

The fourth sub-block is explained in Figure 4.7.
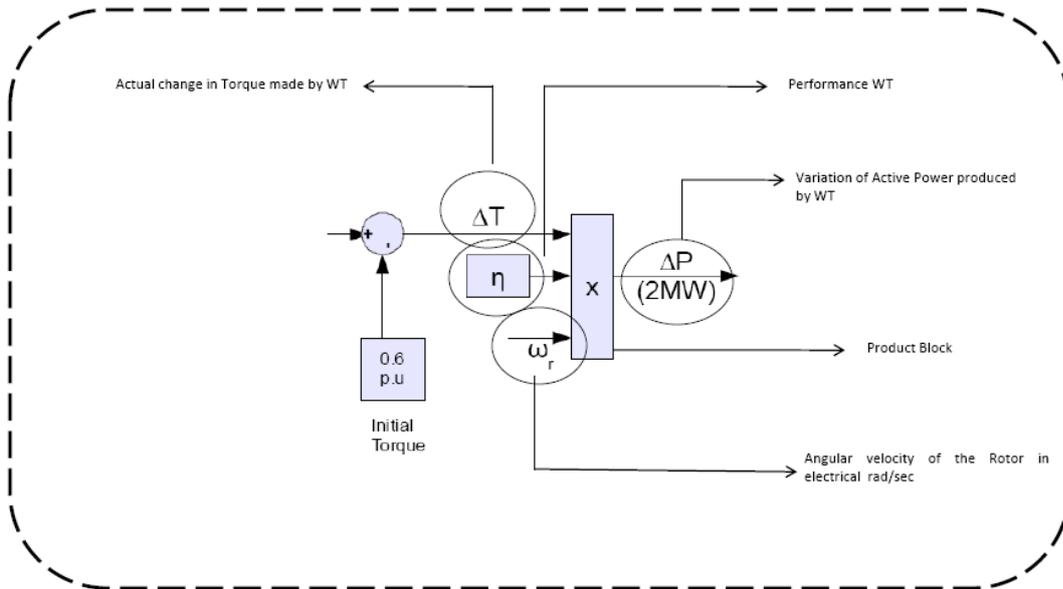
4

Figure 4.7 Sub-block 4 of the Linearized Delta Torque Wind Turbine Model

Into the fourth block there is a sum block that make the difference between the actual torque shaft and the initial aero torque, and the difference that turns out to be positive is the actual change in torque made by wind turbine (ΔT). Then there is a product block where there are three inputs:

- ΔT: actual change in torque made by wind turbine [Nm];
- η: it is the performance of wind turbine;
- ω_r: it is the angular velocity of the rotor [rad/sec].

At the end, we find as output from the fourth block, but it is the same output for the Linearized delta Torque Wind Turbine Model, the variation of active power produced by wind turbine: ΔP.

4.2 Simulations

The model used to produce the results in this report is shown in Figure 4.8. The subsystem of the model is shown in the Appendices A.2.
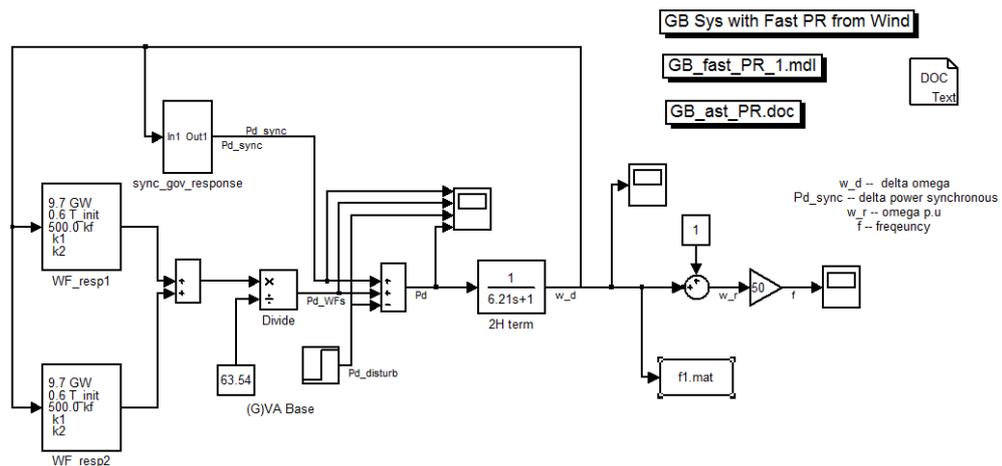
Figure 4.8 Simulink model for investigation of primary response from wind turbines

4.2.1 Setup

The 2020 high wind penetration scenario is given in appendices (Table A.2) was selected for simulation. This scenario assuming the following parameters:

Total Capacity	63.54 GW
Synchronous Capacity	40.78 GW
Wind Turbine Capacity	19.4 GW
Total equivalent inertia (H)	3.11

(Appendices A.1, Table A.3)

In the model there are three main blocks for the generation plants, as is shown in Figure 4.8:
- Synchronous Plant block (with 40.78 GW of power output capacity);
- First Wind Turbines Plants block (with 9.7 GW of power output capacity);
- Second Wind Turbines Plants block (with 9.7 GW of power output capacity).

The simulations were calculates for three different scenarios:

➢ **Scenario A:** wind turbine and synchronous response with only the first wind turbines plants working (K_{fA}=500, K_{fB}=0).

➢ **Scenario B:** wind turbine and synchronous response where both wind turbines plants worked, with the same K_f-value (K_{fA}=500, K_{fB}=500).

➢ **Scenario C:** wind turbine and synchronous response where both wind turbines plants worked, with double K_f-value in the second wind turbines plants block (K_{fA}=500, K_{fB}=1000).

4.2.2 Results

Simulations were conducted for various control parameters, load disturbances and participating frequency response combinations.

These simulations shown the combined response from synchronous plant and wind turbine plant for a disturbance of +0.0189pu which equates to an increase in load (or loss of generation) of 1320 MW.

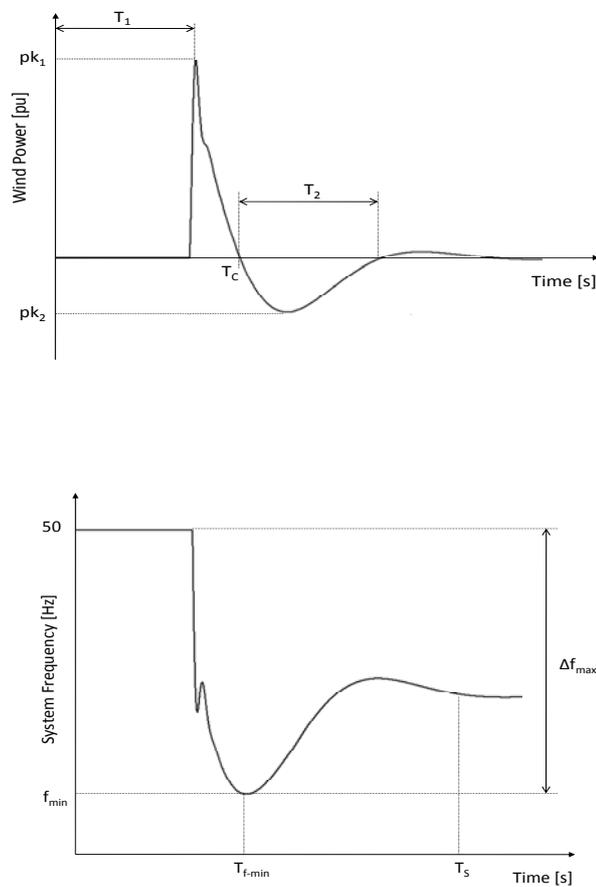The Figure 4.9 shows the parameter used to compare the different results.

Figure 4.9   Wind Turbine Response and System Frequency parameters

4.2.2.1 Wind Turbine and Synchronous Response with K_1, K_2 variations

In these simulations, the three different scenarios were changed the K_1 and K_2 values, both for first wind turbines plants block and second wind turbines plants block. It was observed for the different scenarios.

➢ *Scenario A*

As shows in Figure 4.10 and 4.11 there are three different curves a, b, c for three different setup of K_1 and K_2 values:

- *Curve a:* $K_{1A}=K_{1B}=-3$, $K_{2A}=K_{2B}=1$;
- *Curve b:* $K_{1A}=K_{1B}=-1.5$, $K_{2A}=K_{2B}=1$;
- *Curve c:* $K_{1A}=K_{1B}=-3$, $K_{2A}=K_{2B}=2$;

The K_f values of this Scenario are :
- $K_{fA}=500$;
- $K_{fB}=0$;

In this simulation only one wind turbine plant was used in primary response.

It can see the best curve is with $K_{1A}=-3$ and $K_{2A}=1$. This is the best for both the output power from wind turbines and the system frequency variation, infact the peak positive (0.0016[p.u.]) is the highest even if then the peak negative is the lowest (-0.004[p.u.]) but the most important is the smallest frequency variation (0.13 Hz) with this setup of gains of the wind turbine frequency response control block (*Curve A*).

It can see the same answer (Curve *C*) where $K_{2A}=2$, about the peak positive (0.014[p.u.], negative peak (-0.003[p.u.]) and the frequency variation(0.15 Hz) but it happens with an advance of cross time point in the wind turbine response.

With $K_{1A}=-1.5$ and $K_{2A}=1$ (*Curve B*) there is the least acceptable result regarding peak positive of wind turbine response (0.009[p.u]) and system frequency variation (0.16Hz).

Figure 4.10   Wind Turbine Response in *Scenario A*
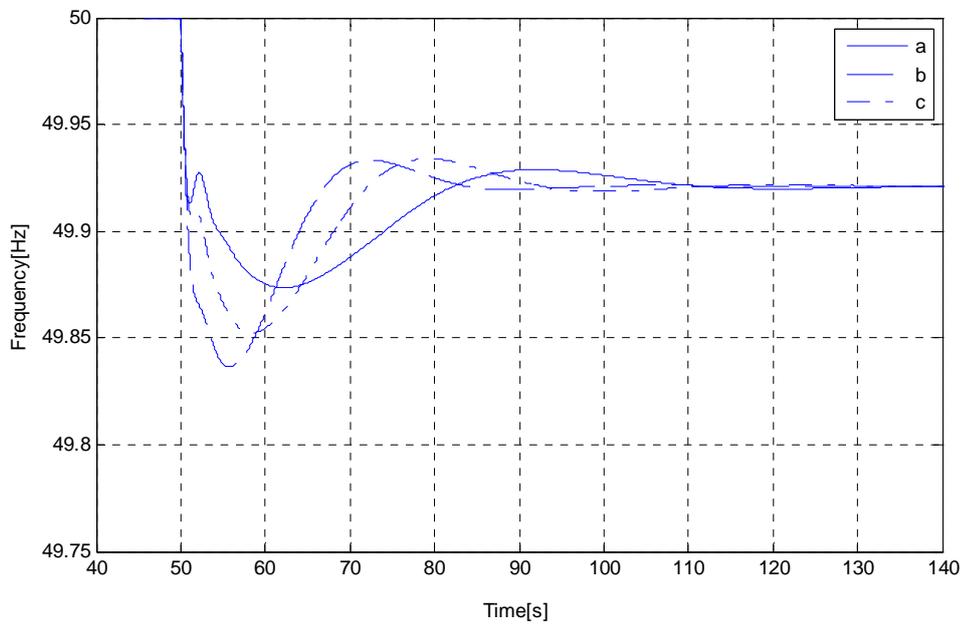
Figure 4.11   System Frequency deviation in *Scenario A*

55

➢ *Scenario B*

As shows in Figure 4.12 and 4.13 there are three different curves a, b, c for three different setups of K_1 and K_2 values:

- *Curve a:* $K_{1A}=K_{1B}=-3$, $K_{2A}=K_{2B}=1$;
- *Curve b:* $K_{1A}=K_{1B}=-1.5$, $K_{2A}=K_{2B}=1$;
- *Curve c:* $K_{1A}=K_{1B}=-3$, $K_{2A}=K_{2B}=2$;

The K_f values of this Scenario are :

- $K_{fA}=500$;
- $K_{fB}=500$;

This simulation used wind turbine and synchronous response where both wind turbines plants worked, with the same K_f-value.

It can see the best curve is with $K_{1A}=-3$ and $K_{2A}=1$. This is the best both the output power from wind turbines and the system frequency variation, infact the peak positive (0.0021[p.u.]) is the highest even if then the peak negative is the lowest (-0.006[p.u.]) but the most important is the smallest frequency variation (0.12 Hz) with this setup of gains of the wind turbine frequency response control block (*Curve A*).

The same answer is achieved (Curve *C*) where $K_{2A}=2$, about the peak positive (0.019[p.u.], negative peak (-0.005[p.u.]), however this happens with bigger frequency variation (0.14 Hz) with an advance of cross time point in the wind turbine response.

With $K_{1A}=-1.5$ and $K_{2A}=1$ (*Curve B*) there is the least acceptable result regarding peak positive of wind turbine response (0.014[p.u]) and system frequency variation (0.15Hz).
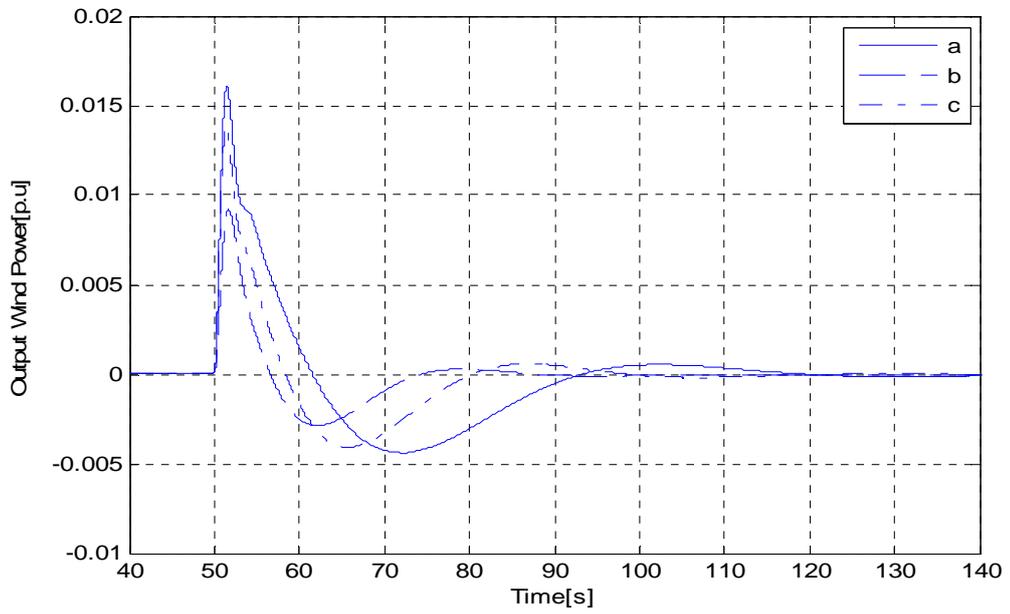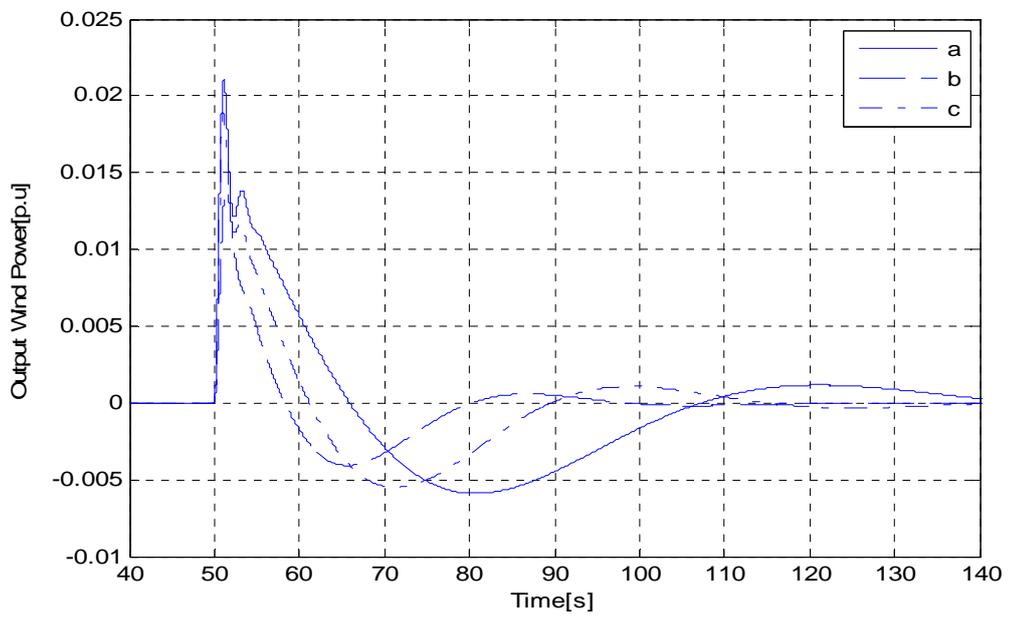
Figure 4.12 Wind Turbine Response in *Scenario B*
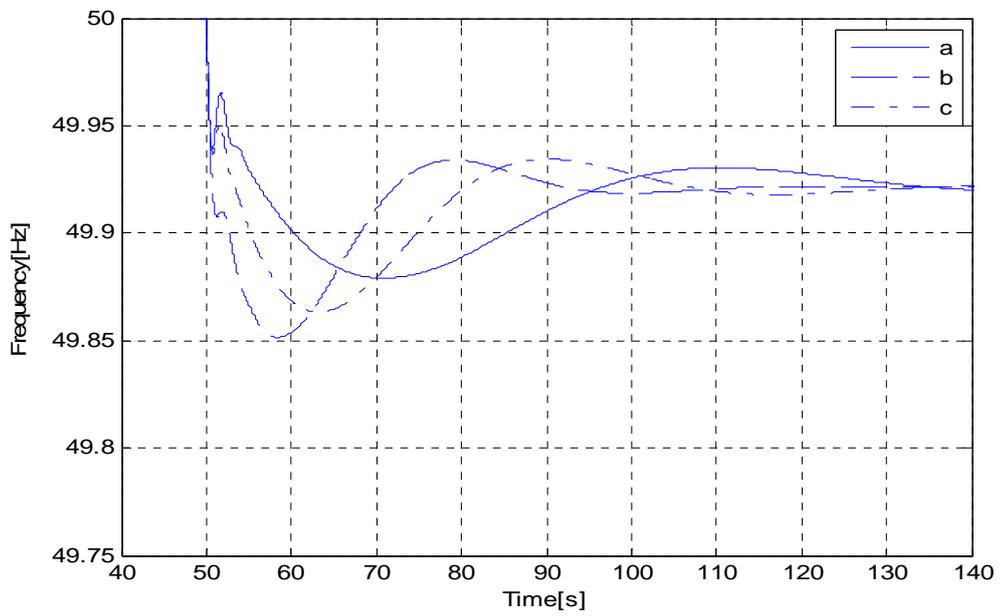
Figure 4.13 System Frequency deviation in *Scenario A*

57

> *Scenario C*

As shows in Figure 4.14 and 4.15 there are three different curves a, b, c for three different setups of K_1 and K_2 values:

- *Curve a:* $K_{1A}=K_{1B}=-3$, $K_{2A}=K_{2B}=1$;
- *Curve b:* $K_{1A}=K_{1B}=-1.5$, $K_{2A}=K_{2B}=1$;
- *Curve c:* $K_{1A}=K_{1B}=-3$, $K_{2A}=K_{2B}=2$;

The K_f values of this Scenario are :

- $K_{fA}=500$;
- $K_{fB}=1000$;

In this simulation was used wind turbine and synchronous response where both wind turbines plants worked, with double K_f-value in the second wind turbines plants block ($K_{fA}=500$, $K_{fB}=1000$).

It can be seen that the best curve is with $K_{1A}=-3$ and $K_{2A}=1$. This is the best from both the output power from wind turbines and the system frequency variation, infact the peak positive (0.0023[p.u.]) is the highest even if then the peak negative is the lowest (-0.007[p.u.]) but the most important is the smallest frequency variation (0.12 Hz) with this setup of gains of the Wind Turbine frequency response control block (*Curve A*).

It can be seen that the same answer is achieved (Curve *C*) where $K_{2A}=2$, about the peak positive (0.021[p.u.], negative peak (-0.006[p.u.]), but it happens with bigger frequency variation (0.13 Hz) with an advance of cross time point in the wind turbine response.

With $K_{1A}=-1.5$ and $K_{2A}=1$ (*Curve B*) there is the least acceptable result regarding peak positive of wind turbine response (0.017[p.u]) and system frequency variation (0.14Hz).

The complete results of these simulations for the three different scenarios can be observed in Table 4.1.

From the simulations it was found that the best K_1 and K_2 values are -3 and 1. Infact from Table 4.1 can see as the value K_2 was increased, there is the smallest negative peak power after the initial peak and a delay from the time of the frequency event and the time at which the negative power peak occurs ($K_2=2$).
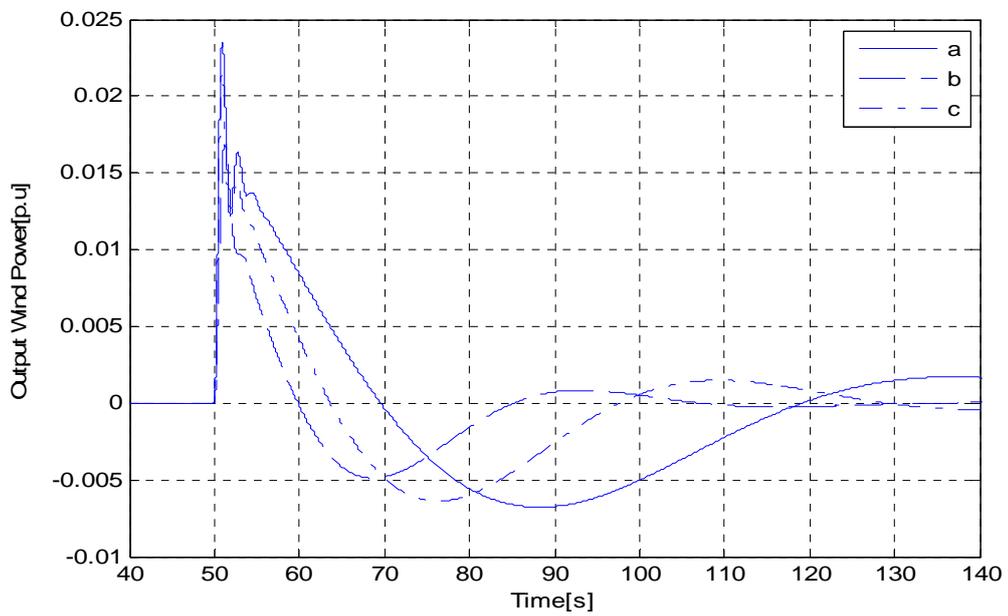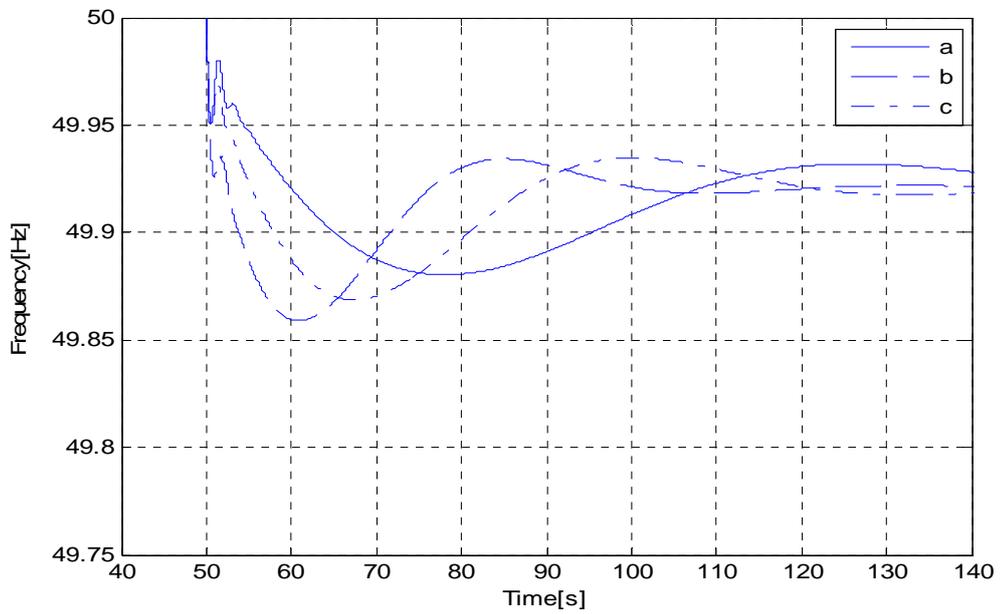
Figure 4.14   Wind Turbine Response in *Scenario C*

Figure 4.15   System Frequency deviation in *Scenario C*

Table 4.1 Results Table with variation of $K_1 K_2$ values

Results Table (with K_1, K_2 Variations)

Scenario		Turbines-Auxiliary Loop Gains — Kf (A)	Kf (B)	K1 (A)	K2 (A)	K2 (B)	K1 (B)	Results — Wind Power Response pk1[pu]	T1[s]	Tc[s]	pk2[pu]	T2[s]	System Frequency fmin[Hz]	Tf-min[s]	Δfmax[Hz]	Ts[s]
Scenario A	a	500	0	-3	1	-3	1	0.016	51.5	61.5	-0.004	31.46	49.87	62.45	0.13	108.5
	b			-1.5	1	-1.5	1	0.009	51.52	58.3	-0.003	16.7	49.84	56.03	0.16	83.61
	c			-3	2	-3	2	0.014	51.53	56.6	-0.004	23.64	49.85	58.9	0.15	93.07
Scenario B	a	500	500	-3	1	-3	1	0.021	51.1	65.94	-0.006	40.36	49.88	71.61	0.12	134.3
	b			-1.5	1	-1.5	1	0.014	51.38	58.31	-0.004	22.3	49.85	58.5	0.15	94.69
	c			-3	2	-3	2	0.019	51.08	61.18	-0.005	28.82	49.86	63.35	0.14	107.7
Scenario C	a	500	1000	-3	1	-3	1	0.023	50.91	69.39	-0.007	49.81	49.88	77.84	0.12	140
	b			-1.5	1	-1.5	1	0.017	51.23	59.82	-0.005	25.63	49.86	61.05	0.14	100
	c			-3	2	-3	2	0.021	50.92	63.61	-0.006	34.09	49.87	67.43	0.13	120

Legend

pk1 = Positive Peak of Wind Power Response

pk2 = Negative Peak of Wind Power Response

T1 = Peak Positive Time

T2 = Negative Response Time

Tc = Cross Time Point

fmin = Minimum Frequency Value

Tf-min = Time of Minimum Frequency Value

Δfmax = Maximum Variation of Frequency

Ts = Steady Time

4.2.2.2   Wind Turbine and Synchronous Response with T_{mB} variations

In these simulations in the three different Scenarios were changed the T_{mB} value of the second wind turbines plants block. T_m is the initial aero torque and its variation means increase or decrease of wind turbine power output during a system frequency deviation. It was observed for the different scenarios.

The same values of $K_{1A,1B}$ and $K_{2A,2B}$ have been used for both wind turbine blocks, -3 and 1 respectably.

> ➢ *Scenario A*

As shows in Figure 4.16 and 4.17 there are three different curve a, b, c for three different setups of T_{mB} values:

- *Curve a:* T_{ma}=0.6 [p.u.], T_{mB}=0.6 [p.u];
- *Curve b:* T_{ma}=0.6 [p.u.], T_{mB}=0.8 [p.u];
- *Curve c:* T_{ma}=0.6 [p.u.], T_{mB}=1.0 [p.u];

The K_f values of this Scenario are :

- K_{fA}=500;
- K_{fB}=0;

In this simulation was used wind turbine plant is used in primary response.

It can be seen that the same curves are represent because K_{fB}=0, it means only the first wind turbine block was used for the primary response.

Wind power response and the system frequency variation are the same as in *Scenario A*, *Curve A* of the first simulation.
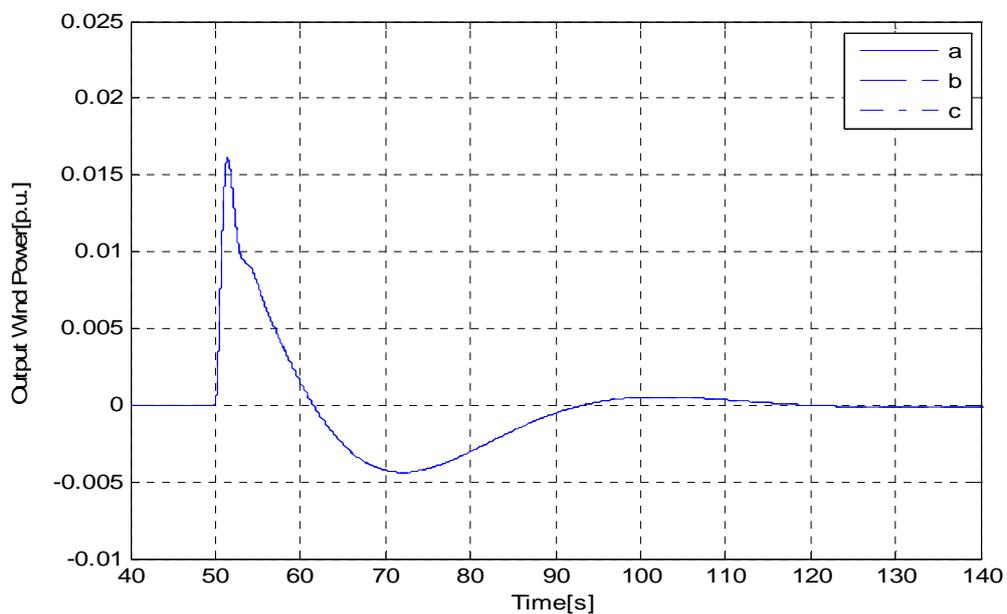
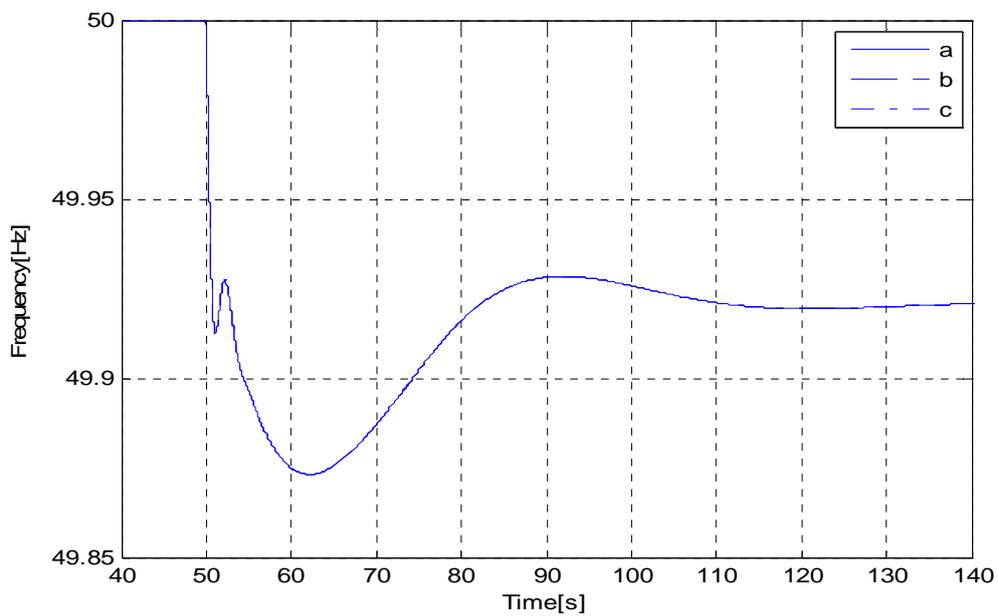**Figure 4.16**   Wind Turbine Response in *Scenario A*

Figure 4.17   System Frequency deviation in *Scenario A*

➢ *Scenario B*

As shows in Figure 4.18 and 4.19 there are three different curves a, b, c for three different setups of T_{mB} values:
- *Curve a:* T_{ma}=0.6 [p.u.], T_{mB}=0.6 [p.u];
- *Curve b:* T_{ma}=0.6 [p.u.], T_{mB}=0.8 [p.u];
- *Curve c:* T_{ma}=0.6 [p.u.], T_{mB}=1.0 [p.u];

The K_f values of this Scenario are :
- K_{fA}=500;
- K_{fB}=500;

This simulation used wind turbine and synchronous response where both wind turbines plants worked, with the same K_f-value.

It can be seen that the best curves are two: with T_{mB}=0.6[p.u.] and T_{mB}=0.8[p.u.]. These are the best both for the output power from wind turbines and the system frequency variation, infact the peak positive (0.0021[p.u.]) is the highest even if then the peak negative is the lowest (-0.006[p.u.]) but the most important is the smallest frequency variation (0.12 Hz)for both (*Curve A*, *B*).

It can be seen that the least acceptable result occurs (Curve *C*) where T_{mB}=1[p.u], the peak positive is (0.016[p.u.], it happens with the bigger frequency variation (0.13 Hz), anyway this setup of T_{mB} really is not possible because it means that the wind turbine is working from the beginning at the maximum power point of its operation curve (B-point of Figure 2.6)
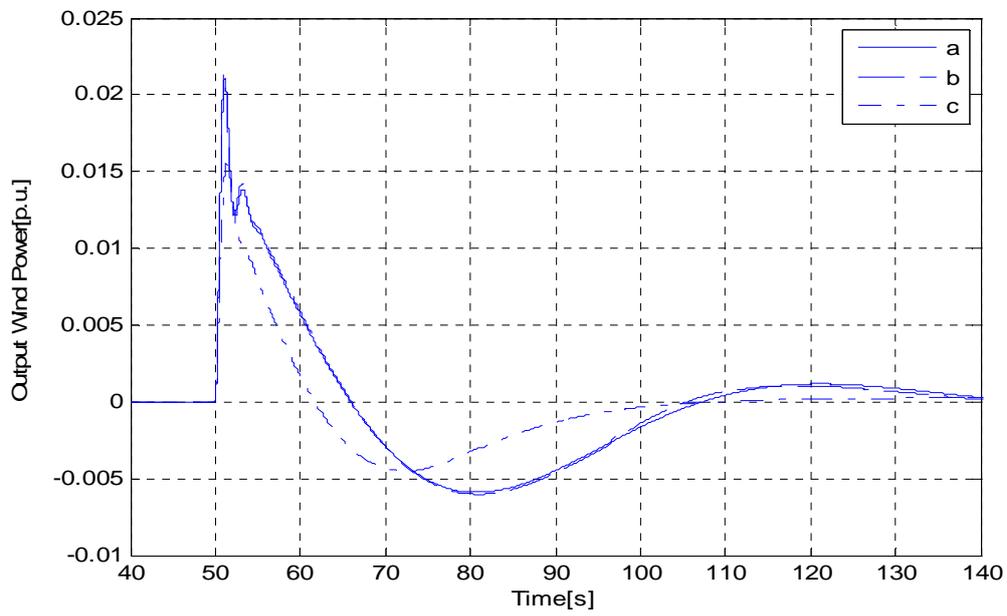
Figure 4.18   Wind Turbine Response in *Scenario B*
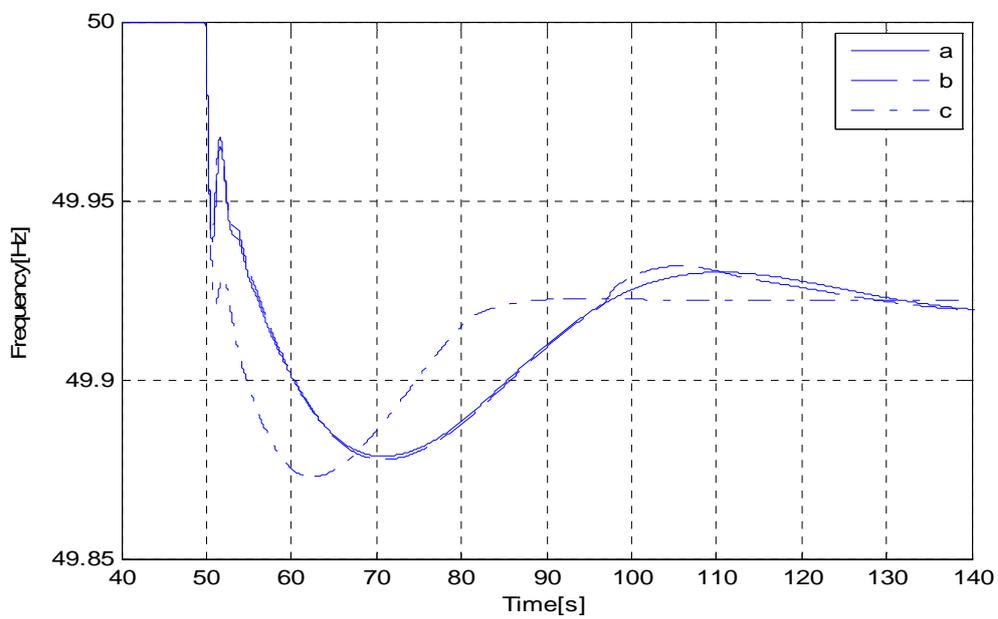
Figure 4.19   System Frequency deviation in *Scenario B*

64

➢ *Scenario C*

As shows in Figure 4.20 and 4.21 there are three different curves a, b, c for three different setups of T_{mB} values:

- *Curve a:* T_{ma}=0.6 [p.u.], T_{mB}=0.6 [p.u];
- *Curve b:* T_{ma}=0.6 [p.u.], T_{mB}=0.8 [p.u];
- *Curve c:* T_{ma}=0.6 [p.u.], T_{mB}=1.0 [p.u];

The K_f values of this Scenario are :

- K_{fA}=500;
- K_{fB}=1000;

This simulation used wind turbine and synchronous response where both wind turbines plants worked, with double K_f-value in the second wind turbines plants block (K_{fA}=500, K_{fB}=1000).

It can see the best response occurs with T_{mB}=0.8[p.u.]. This is the best for power output from wind turbine , infact the peak positive (0.0024[p.u.]) is the highest even if then the peak negative is the lowest (-0.007[p.u.]) but the most important is the smallest frequency variation (0.12 Hz)for both (*Curve B*).

The same result can be found (Curve *A*) where T_{mB}=0.6[p.u.], about the peak positive (0.023[p.u.], negative peak (-0.007[p.u.]) and the frequency variation (0.12 Hz).

It can be seen that the least acceptable result occurs (Curve *C*) where T_{mB}=1[p.u], about the peak positive (0.015[p.u.], it happens with bigger frequency variation (0.13 Hz), anyway this setup of T_{mB} really is not possible because means that the wind turbine is working from the beginning at the maximum power point of its operation curve (B-point of Figure 2.6).

The complete results of these simulation for the three different Scenarios can be observed in Table 4.2.

From the simulations it was found that the best T_{mB} value are 0.6[p.u.] and 0.8[p.u.]. It means that future wind turbines (in 2020), can be used two different setups of initial power torque of wind turbine plants, because with two different values it has seen as there is a increase of wind power response and a parallel decrease of system frequency variation.
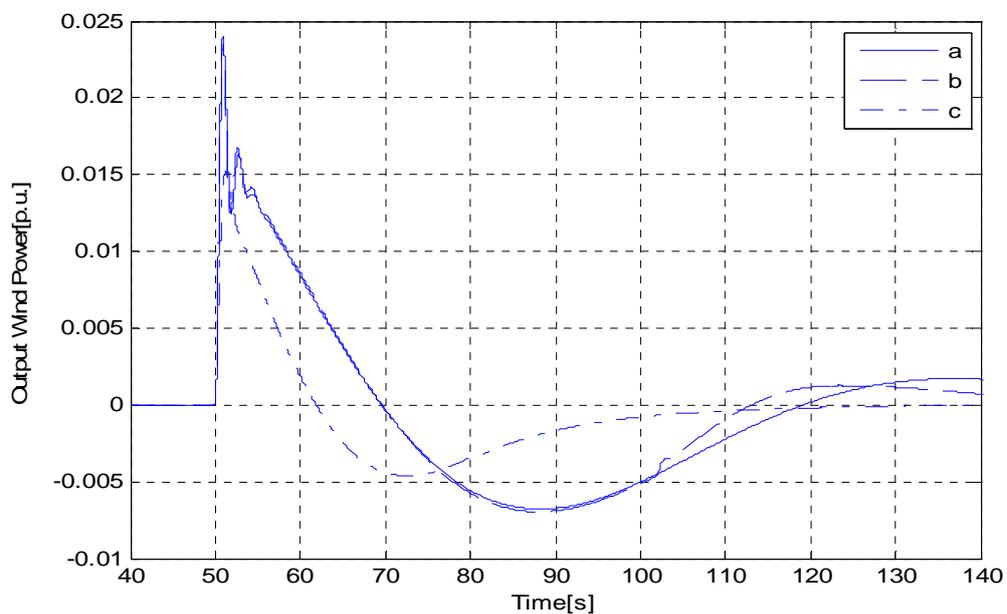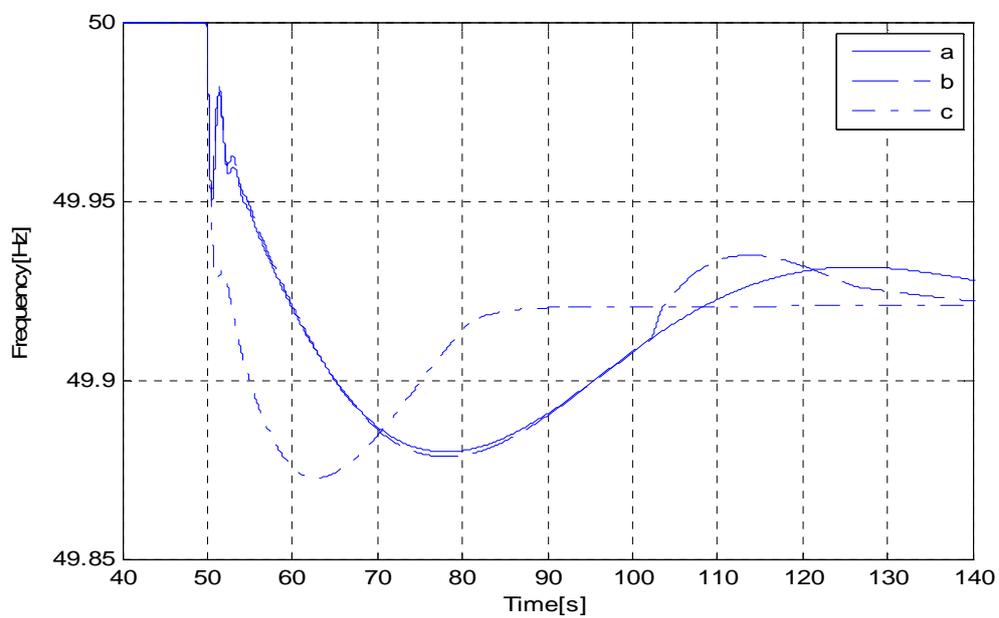
Figure 4.20   Wind Turbine Response in *Scenario C*

Figure 4.21   System Frequency deviation in *Scenario C*

Results Table (Variation of Initial Torque, $K_{1A}=K_{1B}=-3$, $K_{2A}=K_{2B}=1$)

			A	B	A,B					Wind Power Response					System Frequency			
			Kf	Kf	K1	K2	TmA	TmB	pk1[pu]	T1[s]	Tc[s]	pk2[pu]	T2[s]	fmin[Hz]	Tf-min[s]	Δfmax[Hz]	Ts[s]
Scenario A	a		500	0	-3	1	0.6	0.6	0.016	51.46	61.54	-0.004	31.55	49.87	62.93	0.13	110
	b				-3	1	0.6	0.8	0.016	51.46	61.54	-0.004	31.55	49.87	62.93	0.13	110
	c				-3	1	0.6	1	0.016	51.46	61.54	-0.004	31.55	49.87	62.93	0.13	110
Scenario B	a		500	500	-3	1	0.6	0.6	0.021	51.09	65.96	-0.006	41.24	49.88	71.3	0.12	131
	b				-3	1	0.6	0.8	0.021	51.04	65.96	-0.006	39.04	49.88	71.2	0.12	129
	c				-3	1	0.6	1	0.016	51.33	61.71	-0.005	44.29	49.87	62.83	0.13	96.8
Scenario A	a		500	1000	-3	1	0.6	0.6	0.023	50.98	67.04	-0.007	52.26	49.88	78.6	0.12	150
	b				-3	1	0.6	0.8	0.024	50.87	67.04	-0.007	46.16	49.88	78.61	0.12	140
	c				-3	1	0.6	1	0.015	51.28	61.79	-0.005	48.21	49.87	62.68	0.13	90

Legend

pk1 = Positive Peak of Wind Power Response

pk2 = Negative Peak of Wind Power Response

T1 = Positive Peak Time

T2 = Negative Response Time

Tc = Cross Time Point

fmin = Minimum Frequency Value

Tf-min = Time of Minimum Frequency Value

Δfmax = Maximum Variation of Frequency

Ts = Steady Time

Table 4.2 Results Table with variation of T_{mB} values

5 Conclusions

Primary frequency support that can be support by wind turbine generators was demonstrated. The model was a simplified model based of FPC wind turbine.

The simulations result show as wind turbine can reduce the system frequency variation for a step imbalance in load-generation.

It can see there is a fast primary response under different combination of wind turbines and synchronous plants without the contribution due to governor action and for wind turbine can emulate this response by extracting energy from the rotational mass of the turbine generator and turbine rotor assembly (inertia block in Figure 3.7).

Then there is a slow primary response where the governor action can be provided by temporarily operating the wind turbine at a higher aerodynamic power output at the expense of an overall drop in power output over the complete occasional response period (pk_1 of wind power output increased in Figure 4.9). However, the performance deteriorates after the first 30 seconds after the frequency event as wind turbines operate off optimal speed thus providing less active power support (pk_2 of wind power output increased in Figure 4.9) [19].

It was observed as different values of control loop of wind turbine plants provide a different response shaped (Table 4.1) and it was found the best setup.

In the second type of simulations, it was used a different value of initial aero torque of wind turbines plants (Table 4.2) and it was observed a little reduction of system frequency variation and the reduction of active power from wind turbines after the first 30 second after the frequency event.

Project Length - 18 weeks

Student - Alessandro Roman

Supervisor - Nik Jenkins, Janaka Ekanayake

1- Literature, reading
Wind turbine tecnology
  Power and Torques Curves
  SEDG report
Power system
  Basic theory review
  Including turbines power station plant
  Load frequency control
Control theory
  Laplace
  PID controls
Simulation tools refresh
  Matlab code
  Induction generation model
  Simulink

2- System modelling
Understand functioning of simulation model
Recreate simulation results in paper
Try delay + Shaping (different methods)

3- Review results
Compare + Contrast results

4- Draw conclusions
Write up

05 Oct '09 | 19 Oct '09 | 02 Nov '09 | 16 Nov '09 | 30 Nov '09 | 14 Dec '09 | 28 Dec '09 | 11 Jan '10 | 25 Jan '10 | 08 Feb '10 | 22 Feb '10

21/10

21/10

72

Appendices

A.1 Model Parameters

Synchronous plant Parameters taken from [19]

Governor = $\left[\dfrac{1}{0.2s+1}\right]$

Turbine = $\left[\dfrac{2s+1}{12s+1}\right]\left[\dfrac{1}{0.3s+1}\right]$

Droop = $\left[\dfrac{1}{11}\right]$

2MW induction wind turbine model parameters

Stator resistance (R_s) : 0.00491 [p.u.]

Rotor resistance (R_r) : 0.00552 [p.u.]

Stator reactance (X_{ls}) : 0.09273 [p.u.]

Rotor reactance (X_{lr}) : 0.1 [p.u.]

Magnetising reactance (X_m) : 3.96545

Lumped inertia constant (H) : 4.5 sec

Controller Parameters

K_p = 0.5, K_i = 0.5

Closed Loop Simulation Parameters

T_w = 1, K_1 = 3, K_2 = 1, K_f = 500, T_f = 20

Calculation of Inertia

H_{eq} = $\displaystyle\sum_{i=coal,\,gas,\dots} H_i * \frac{S_i}{S_{sys}}$

Inertia constant H is the kinetic energy in watt-seconds divided by the VA base where ω_{0m} is the rated angular velocity in rad/s.

$H = \dfrac{1}{2}\dfrac{J\omega_{0m}^2}{VA_{base}}$

TABLE A.1 PARAMETERS FOR SIMPLIFIED WIND TURBINE MODEL

Turbine Type	X_1	X_2	X_3	T_1 or T_2
DFIG	$\dfrac{L_{ss}}{L_m}$	$\dfrac{1}{R_r}$	$\dfrac{L_m}{L_{ss}}$	$\dfrac{L_0}{\omega_s R_r}$
FPC (IG based)	$\dfrac{L_{rr}}{L_m}$	$\dfrac{1}{R_s}$	$\dfrac{L_m}{L_{rr}}$	$\dfrac{L_0}{\omega_s R_s}$

TABLE A.2 PLANT MARGIN AND OPERATING CAPACITY

Generator Type	Scenario - High Wind 2020			
	Installed Capacity (GW)	Plant Margin (GW)	Operating Capacity (GW)	
New Coal	3.7	1.3	2.41	FR
Coal	16.9	7.61	9.3	FR
Gas	27.3	12.29	15.02	FR
Nuclear	6	0	6	FR
Interconnector	3.3	0	3.3	FR
Other	6.8	2.04	4.76	FR
				FR Sync Cap = 40.78
Onshore Wind	14.3		5.72	FR
Offshore Wind	34.2		13.68	FR
Other	5.6		3.36	No FR
Total Capacity	118.1		63.54	
				FR PEI based = 19.4

TABLE A.3 H_{EQ} ON SYSTEM BASE 63.5MVA

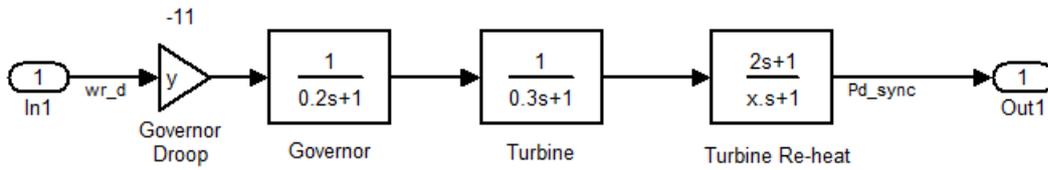| Generator Type	Scenario - High Wind 2020		
	Capacity(GW)	H_i	H_{eq}
New Coal	2.41	4.50	0.17
Coal	9.3	4.50	0.66
Gas	15.02	6.00	1.42
Nuclear	6.00	3	0.28
Interconnector	3.30	0	0.0
Other	4.76	4.5	0.34
Onshore Wind	5.72	0	0
Offshore Wind	13.68	0	0
Other	3.36	4.5	0.24
Total Capacity	63.54		3.11

A.2 Subsystem Blocks

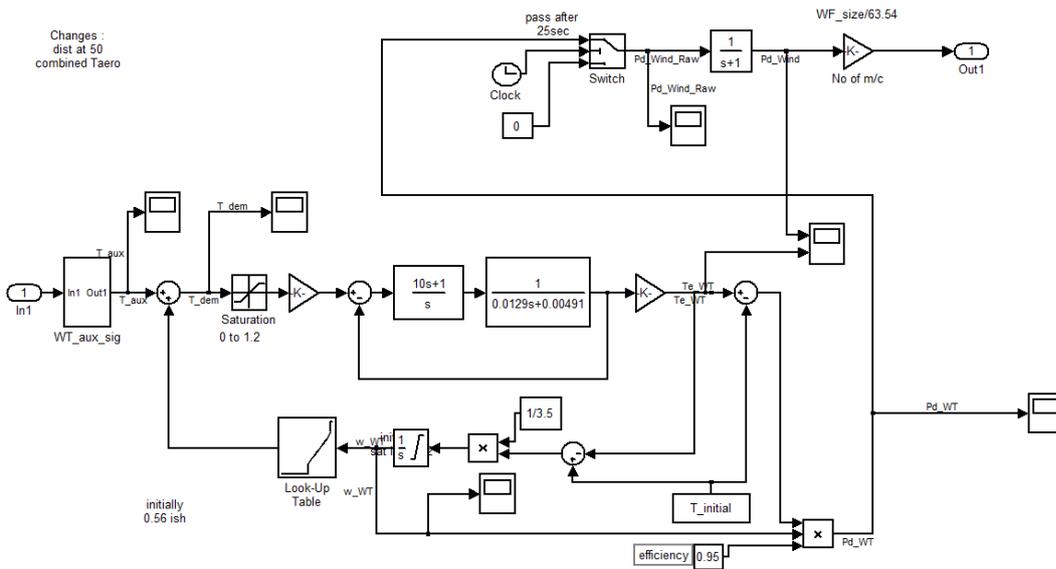**Figure A.1** Synchronous Plant block

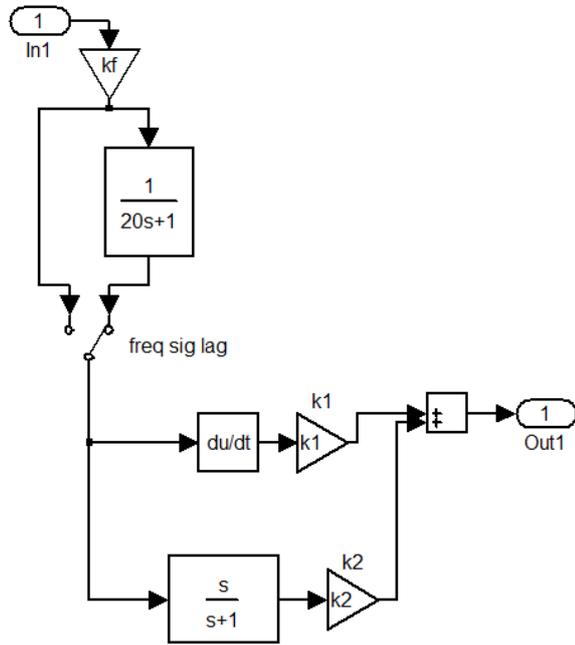**Figure A.2** Wind Turbine Plant block

Figure A.3 Wind turbine Frequency Response Control block

References

[1]-T.Burton, D.Sharpe, N.Jenkins, E.Bossany, "Wind Energy Handbook", John Wiley & Sons, 2001, pp.1,12-13.

[2]-T.Burton, D.Sharpe, N.Jenkins, E.Bossany, "Wind Energy Handbook", John Wiley & Sons, 2001, pp.12.

[3]-WWEA, World Wind Energy Report 2008,2009.

[4]-BWEA, "Wind hits 4GW barrier-now powers 2.3 million homes in UK", http://www.bwea.com/media/news/articles/pr20092010.htlm.

[5]-Eric Hau, "Wind Turbines,2nd edition,", Springer, 2006, pp.81.

[6]-Eric Hau, "Wind Turbines,2nd edition", Springer, 2006, pp.86.

[7]-T.Burton, D.Sharpe, N.Jenkins, E.Bossany, "Wind Energy Handbook", John Wiley & Sons, 2001, pp.6-7.

[8]-T.Burton, D.Sharpe, N.Jenkins, E.Bossany, "Wind Energy Handbook", John Wiley & Sons, 2001, pp.173.

[9]-J.F.Maxwell, J.M.McGowan, A-L. Rogers, "Wind Energy Explained,2nd edition", John Wiley & Sons, 2006, pp.314.

[10]-Eric Hau, "Wind Turbines,2nd edition,", Springer, 2006, pp.98-101.

[11]]-T.Burton, D.Sharpe, N.Jenkins, E.Bossany, "Wind Energy Handbook", John Wiley & Sons, 2001.

[12] Eric Hau, "Wind Turbines,2nd edition,", Springer, 2006, pp.102-103.

[13]-Ramtharan, G.;J.B. Ekanayake, N. Jenkins, "Frequency support from doubly fed induction generator wind turbines", IET Renewable Power Generation, Volume 1, Issue 1, March 2007, pp.3-9.

[14] Eric Hau, "Wind Turbines,2nd edition,", Springer, 2006, pp.319.

[15]- Thomas Ackermann, "Wind Power in Power System", John Wiley & Sons, 2005, pp.55.

[16]- "Characteristics of Wind Turbine Generators for Wind Power Plants", IEEE PES Wind Plant Collector System Design Working Group

[17]-I.Moore, J.B. Ekanayake, "Frequency Response from Wind Turbines", 2009.

[18]- P. Kundur, "Power System Stability and Control", EPRI, 1994.

[19]-J.B.Ekanayake, N.Jenkins, G.Strbac, "Frequency response from wind turbines", Wind Engineering, Vol. 32, pp. 573-586. 2008.