

**FREQUENCY CONTROL IN AN ISOLATED
POWER SYSTEM WITH HIGH PENETRATION OF
WIND POWER**

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**by
Ali HASSAN**

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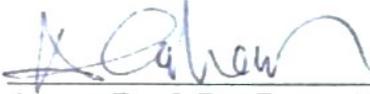
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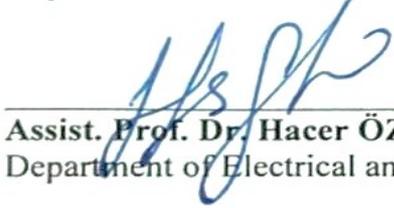
Assist. Prof. Dr. Ferhat BİNGÖL

Department of Energy Systems Engineering, İzmir Institute of Technology



Assoc. Prof. Dr. Barış ATAKAN

Department of Electrical and Electronics Engineering, İzmir Institute of Technology



Assist. Prof. Dr. Hacer ÖZTURA

Department of Electrical and Electronics Engineering, Yaşar University

13 March 2019



Assist. Prof. Dr. Ferhat BİNGÖL

Supervisor, Department of Energy
Systems Engineering,
İzmir Institute of Technology



Researcher Dr. Müfit ALTIN

Co-Supervisor, Department of
Wind Energy,
Technical University of Denmark



Prof. Dr. Güliden Gökçen AKKURT

Head of the Department of Energy
Engineering

Prof. Dr. Aysun SOFUOĞLU

Dean of the Graduate School of
Engineering and Sciences

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ABSTRACT

FREQUENCY CONTROL IN AN ISOLATED POWER SYSTEM WITH HIGH PENETRATION OF WIND POWER

As the percentage of wind energy in global energy portfolio rises, the wind turbine control is becoming increasingly important for the integration of wind turbines in power systems. The early control objective of wind turbine control was only to maximize the power output but now the wind turbines are required to provide frequency control as well. To emulate the inertia response (IR) of the conventional synchronous machines the wind turbines can be provided with an inertia emulation controller. The modelling work presented in this thesis aims at equipping the modern Type D wind turbine with inertia response and primary frequency control capabilities. Two controllers — inertial and droop, are implemented and their frequency control capabilities are compared in an isolated power system consisting of a conventional steam turbine generator and a wind farm. A model of one Type D wind turbine is simulated and aggregated for the whole wind farm. The ability of wind turbines to provide inertial response (IR) and primary frequency control (PFC) after a frequency deviation shows a better performance than the case when there is no contribution to frequency control through wind turbines.

ÖZET

YÜKSEK RÜZGAR ENERJİSİ PENETRASYONU OLAN İZOLE GÜÇ SİSTEMİNDE FREKANS KONTROLÜ

Rüzgar enerjisinin global enerjideki oran artıkça, rüzgar türbinlerini güç sistemlerine entegrasyonu ile birlikte rüzgar türbinlerinin kontrolü daha önemli hale gelmektedir. Daha önceki amaç türbinde sadece güç üretimini maksimum elde etmeye dayalı iken artık frekans kontrolü de gerekli olmaktadır. Geleneksel senkron makinelerin ataleti, atalet kontrolcü ile rüzgar türbinlerinde de sağlanabilir. Bu tezin amacı rüzgar türbinlerinde atalet emülasyonu ve birincil frekans kontrol (PFC) sağlayan değişken hız rüzgar türbinleri (VSWT) atalet kontrolcü ve droop kontrolcü tasarlamaktadır. İzole edilmiş geleneksel bir buhar türbini jeneratörü ve 4 adet aynı Type D rüzgar türbininden oluşan bir güç sistemi Simulink ile simule edilmiştir. Modellerden bir tanesi simule edilmiştir ve diğerlerini temsil etmek üzere tüm rüzgar çiftliğinin gerçek hız değerleri ile test edilmiştir. Sonuçlar, yükteki ani bir yüksek durumda, rüzgar türbinlerinin frekans kontrolüne hiçbir katkısı olmayan duruma göre, atalet ve droop kontrolcülerin frekanstaki düşüşü iyeleştirmeye daha iyi performans olduğunu göstermektedir

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LIST OF ABBREVIATIONS

AGC	Automatic Generation Control
DER	Distributed Energy Resources
ENTSO-E	European Network of Transmission System Operator for Electricity
FC	Frequency Control
FSWT	Fixed Speed Wind Turbine
GHG	Green House Gases
HAWT	Horizontal Axis Wind Turbine
IR	Inertia Response
LOLP	Loss of load probability
PCC	Point of Common Coupling
PFC	Primary Frequency Control
PMSG	Permanent Magnet Synchronous Generator
TSR	Tip Speed Ratio
ROCOF	Rate of Change of Frequency
VAWT	Vertical Axis Wind Turbine
VSWT	Variable Speed Wind Turbine
WT	Wind Turbine
WTG	Wind Turbine Generator
WPP	Wind Power Pl

CHAPTER 1

INTRODUCTION

1.1. Overview

The increase in global electricity demand, depleting fossil fuels and concerns about the environmental pollution have made the use of renewable energy sources a necessity. Last decade has seen a considerable increase in the use of wind, solar, biogas and fuel cells for electricity generation.

Most utilized renewable energy resources around the globe are wind and solar (Leung et al., 2012). Though emission free, they exhibit an intermittent behavior — Solar PV panels are an active source of electricity during the day time while powerless at nights, likewise the wind has a start-stop nature throughout the day. Wind Turbines (WTs) also require a minimum wind speed (V_{cut-in}) called the ‘cut-in speed’ to start producing power. This poses major challenges for the integration of renewable electricity resources in the power system.

A power system is a network of generation, transmission and distribution of electric power. The most important attributes of the power system are its ‘reliability’, ‘stability’ and ‘power quality’ (Saadat, 2010). Reliability refers to an uninterrupted power supply to the consumers, stability is the tendency of the power system to develop restoring forces equal to or more than the disturbing forces to maintain the equilibrium, while ‘power quality’ means that the consumers should get the electrical power at rated frequency (50 Hz in Europe/Turkey, 60 Hz in US/Canada) and voltage (220-240V AC). Any deviation of these parameters, i.e. frequency and voltage, would mean inefficient operation of the electrical machines and appliances which can lead to their failure. To maintain a stable frequency, a balance between generation and consumption needs to be maintained at all the times.

To ensure a stable frequency, the power system must monitor the grid frequency constantly. The conventional power system (i.e. system consisting of steam, nuclear, thermal and hydro generation) is equipped with the ancillary services which maintain the

balance between generation and consumption which is essential for a constant and stable frequency. Such a power system consists of large number of synchronous generators provided with governor control responsible for increasing or decreasing the amount of the fuel in response to the fall or rise in the system frequency. Moreover, all the synchronous generators are working in parallel to each other and have an inherent inertia response (IR) which plays a crucial role in stabilizing the deviating frequency.

The wind energy constitutes the highest percentage of renewable generation capacity in the world (GWEC, 2018). The wind is the driving force for the wind turbines and unlike the case of conventional generation, the wind is not under our control. Therefore, a surge or a drop of wind speed directly translates into surge or a drop in generated power. Modern Variable Speed Wind Turbines (VSWT) are isolated from the power grid through power electronic converters and practically have zero Inertia Response (Yingcheng and Nengling, 2011). Because of this, any such power system which contains huge amount of wind generation will face an issue of frequency stability. Furthermore, the remote electricity consumers (residential, commercial or industrial) are provided with electricity by the means of isolated grid (also called islanded grid or microgrid) which makes use of the local generation through wind or solar. These grids can be coupled with battery storage, steam turbine generators or diesel generators (Ackermann, 2012). In such isolated grids the wind energy's contribution is normally high, which poses the frequency stability issues.

Some countries have already deployed huge number of onshore and offshore wind farms for electricity production. For example, in Denmark and Germany, the penetration of wind power has reached 48% and 19% of the total generation respectively (GWEC, 2018). Other countries are also following the suite as Paris agreement urges to cut down on carbon emissions and restrict the global temperature rise to under 2°C (Rogelj et al., 2016). With more wind farms replacing the conventional generation, the need for wind turbines to actively participate in providing frequency stabilization is increasing.

Wind farms are normally erected in the places where there is more wind throughout the year. Wind speed at a certain amount of time determines the electrical power output of the wind turbine. The wind speed is measured in meters per second (*m/s*), other units include miles per hours (*mph*), Knots (*Kn*) and Kilometers per hour (*Km/h*). Like electrical loads, wind speed can also be forecasted utilizing various methods. The methods for forecasting wind speeds have improved over the years. The forecast is

normally used to determine how much load percentage needs to be met by the conventional generation. However, there is always a chance of error between the forecasted and actual wind speed and hence the wind electrical power.

With the projected rise of wind generation, the potential concern for the Transmission System Operators (TSO) is the capability of wind turbines/wind farms to provide the frequency control in the event of frequency deviation. Moreover, with the increasing electrification of the remote villages the concept of isolated grids or microgrids is becoming ubiquitous which demands an active frequency control from the wind turbines (Morren et al., 2006).

In the following sections, few important concepts and definitions are presented.

1.2. Penetration Level of Wind Power

The penetration level is defined as the percentage of demand covered by wind energy in a region or a power system (Bevrani, 2012).

$$\text{Wind energy penetration} = \frac{\text{Total annual wind energy(TWh)}}{\text{Gross annual demand (TWh)}}$$

Figure 1 shows the penetration of wind energy in various countries. Denmark leads with 48%.

Low penetration of wind power in large power system does not affect the frequency control because a power system has enough synchronous generators and hence enough inertia response to stabilize the frequency variations. The exact percentage for wind power penetration to cause frequency stabilizing problems varies from one system to another. However, most of the studies have shown that for a penetration level greater than 10% the turbines need to actively participate in the frequency control (Rogelj et.al, 2016).

Any event that upsets the balance between the supply and demand is termed as disturbance or contingency in electrical power engineering terms. The disturbance can be in the form of a loss in transmission line, loss or failure of an equipment in the power system or a sudden increase or decrease in the electrical load (Ackermann, 2012).

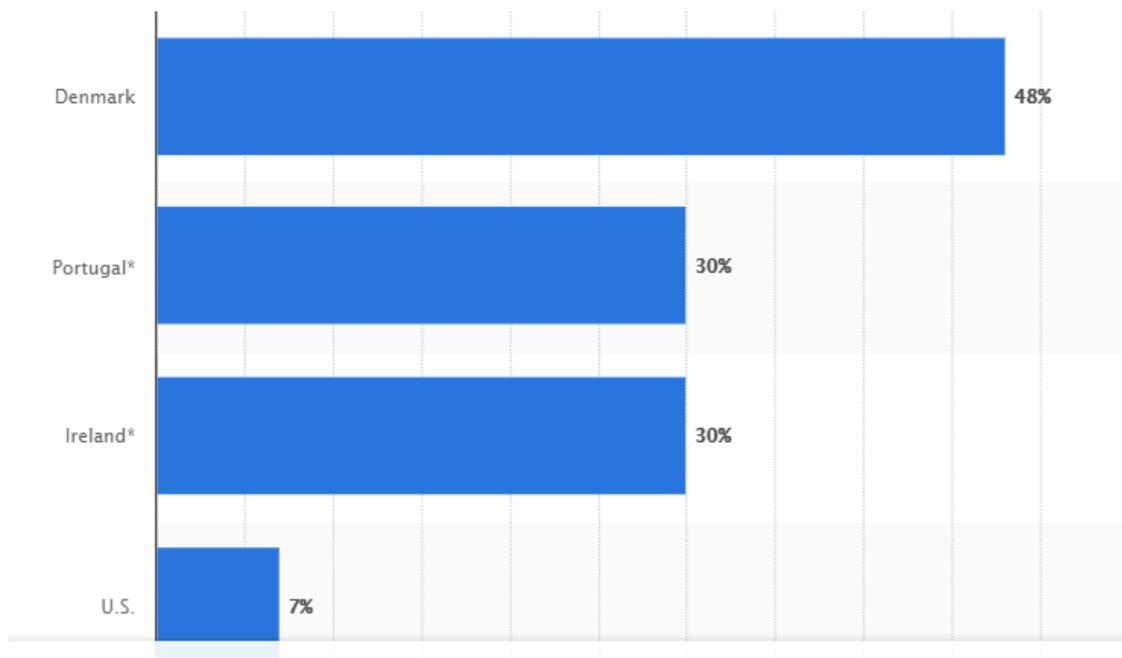


Figure 1. Penetration of wind power in different countries 2017-18
(Source: www.statista.com)

1.3. Conventional Synchronous Power System

A regional power system that operates at a synchronized frequency is termed as synchronous power system (Hansen et al., 2016). In Europe and Turkey all the grids are synchronized at 50Hz while in USA/Canada grids operate at 60 Hz. The frequency in a power system directly corresponds to the rotating speed of synchronous generators. The frequency in various regions can vary owing to the local oscillations in the synchronous generators. The generators in a power system work in tandem as shown in Figure 2. This is also called tandem configuration which means that they share same load through the chain (Ackermann, 2012). However, the load division in power plants is dependent on their speed droop characteristics (Kundur, 2009).

A concept of frequency stabilization is depicted in Figure 3. The balance between supply and demand is key to maintain a stable frequency at 50 Hz.

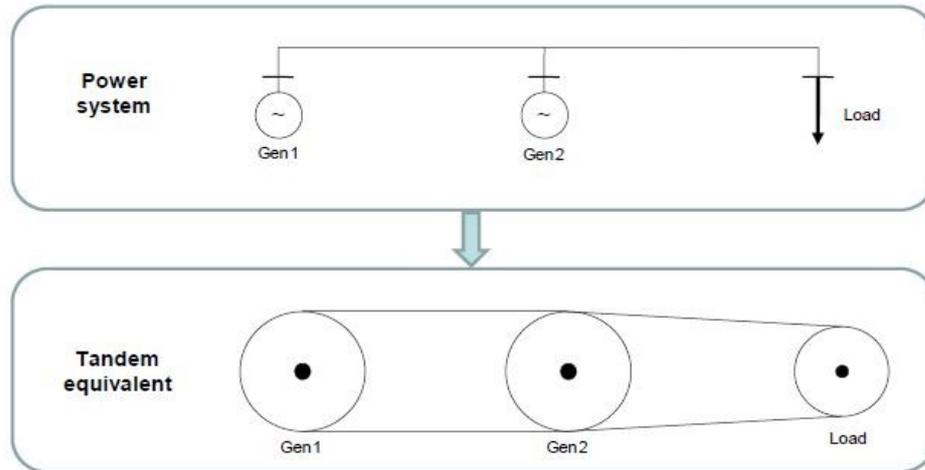


Figure 2. Mechanical equivalent of a synchronous power system
(Source: Soder, 2002)

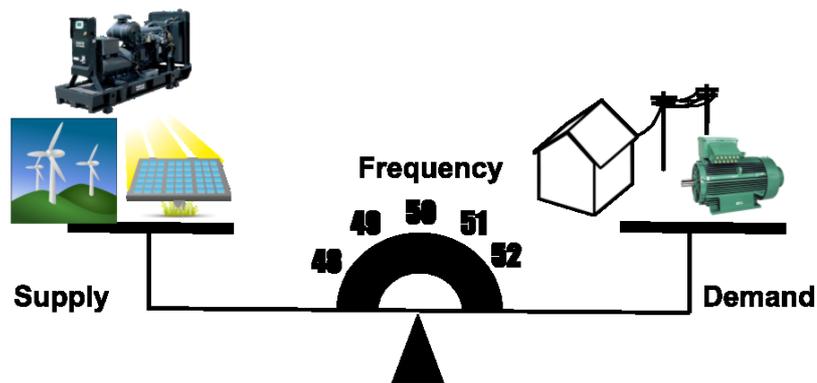


Figure 3. The concept of stabilizing frequency in power system

Conventional generators have two kind of responses to the disturbances named as inertia response and frequency control.

1.4. Inertia Response (IR) of Synchronous Generators

Inertia is defined as the resistance posed by a physical object to the change of its state of motion, including its speed and the direction of motion.

Power system's inertia can be defined as the resistance of the power system to the frequency deviation. The inertia response is a natural response to a sudden decrease or increase in the frequency of the system that causes the speed of a turbine and generator

to drop or rise respectively. It uses the stored kinetic energy (KE) in the rotating parts of the turbine and generator. This KE is extracted to rehabilitate the balance between the demand and supply gap and the generator stabilizes at a new synchronous speed. This acceleration in the speed i.e. the KE extraction depends on the inertia constant of the system ' H ' (Attya et.al, 2018). In power systems the rotating objects are the synchronous generators and the most common factor that tries to change this speed of rotation is the increase or decrease in the electrical load. For a synchronous generator driven by a prime-mover, the motion of rotor is represented by the following equation, also known as swing equation.

$$J \frac{d^2 \theta_m}{dt^2} = T_m - T_e \quad (1.1)$$

Where

- J is the total moment of inertia of the rotor mass in kgm^2
- T_m is the mechanical torque supplied by the prime mover in N-m
- T_e is the electrical torque output of the alternator in N-m
- θ_m is the angular position of the rotor w.r.t stationary axis

If mechanical torque ' T_m ' and electrical torque ' T_e ' remain equal, the rotor angle ' δ ' which corresponds to grid's frequency ' f ' remains at a constant value. A mismatch in the load and generation cause the rotor angle δ to change and the frequency changes.

As mentioned before, the conventional power system has high inertia while modern power system with high wind penetration has low inertia. This is because the modern wind turbine generators are connected to the grid through power electronics and the frequency of grid does not have a direct connection with wind turbine generator's or rotor's rotating speed.

1.5. Frequency Control

The three main ancillary services in a conventional power system include frequency control, voltage control and black start provision. Out of these three, frequency

control is the one that is provided by maintaining power balance between generation and the consumption. The other two are not in the scope of this thesis.

Electrical grid codes which are defined as the set of rules governing a power system for a stable and reliable electricity generation, state different tolerance limits for the deviation in frequency. These grid codes vary from one power system to the other. In most countries the frequency is maintained within $\pm 1\%$ of the nominal value. In Turkey, the grid codes suggest that frequency needs to be maintained within $\pm 0.2\%$ of 50 Hz under normal circumstances (Teiaş, 2008). In Nordic system the 50 Hz frequency needs to be maintained within operational limits of ± 0.1 Hz from the nominal frequency value (Kundur, 2009).

Frequency deviations from the nominal value due to faults or contingencies lead to generation of various alerts and warnings. A large negative deviation in the frequency value is a threat to the power system's security which might lead to partial load shedding or a black out. Load shedding means that some part of the load is cut-off from the system to restore the frequency while a black out is the total outage of the regional power system. Both cases are against the reliability requirements of the power system.

The main role of the frequency control is to maintain a constant frequency, divide the load equally among the generators and control the tie line power exchanges (Soder, 2002). Large power systems are usually interconnected where several synchronous generators are operating in parallel. In the case of load increase, the generators must keep up with the power demand to restore the power system frequency.

The names of the ancillary services for frequency control vary from one region to another and from one power system to another. For example, in European Network of Transmission System Operator for Electricity (ENTSO-E) the primary response is termed as 'Frequency Containment Reserve', secondary response as 'Frequency Restoration Reserve' and tertiary response as 'Replacement Reserve'.

1.5.1. Primary Frequency Control (PFC)

The primary frequency control is also known as governor control or droop control. It is provided within 30 seconds of the frequency drop. The concept can be understood

by Figure 4 in which a load power ' P_L ' is being met by a generator rotated by the turbine. Whenever the load ' P_L ' is increased the electrical power ' P_e ' exceeds the mechanical power ' P_m '. The mismatch causes the speed of the rotating generator to drop which in turn results in changing the rotor angle $\Delta \delta$ and the frequency falls from the nominal value. The error signal is then amplified and transformed by the governor to P_v which in turn opens the valve to increase the flow of steam or water to increase the turbine speed and mechanical power P_m (Ackermann, 2012).

The task of PFC is to bring the value of frequency back to short term acceptable values. Therefore, during PFC the frequency is stabilized temporary to a lower level of frequency than the initial one.

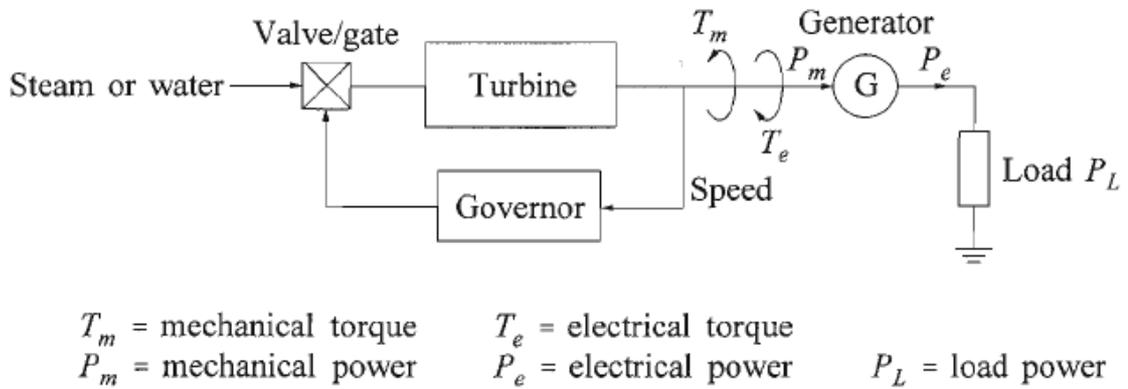


Figure 4. Schematic diagram of primary frequency control
(Source: Power System stability and Control, Kundur)

1.5.2. Secondary Frequency Control (SFC)

Secondary frequency control is slower than PFC. The duration of SFC is between 30 seconds up to 30 minutes or more after the occurrence of a disturbance (Kundur, 2009).

When the speed governor increases the mechanical power to cope with the deviating frequency the generator or the system is not operating according to its power set point and there is an offset. To remove this offset, Integrator loop with gain K_i is added that integrates the error signal of the deviation from the power set point and removes the offset. The power setpoint of generators is changed in order to produce more power to

correct the offset (Saadat, 2010).

1.5.3. Tertiary Frequency Control (TFC)

To restore the power generating capacity of the normally operating power plants some reserve units are activated. These units are usually the slow starting power plants. Tertiary frequency control is essential in the case of large contingencies that go on for long time. In case the secondary frequency control units are exhausted TFC makes sure that the secondary control units have ample capacity to cope with any further contingency. The time range of tertiary frequency control ranges up to several hours.

Figure 5 shows a typical frequency regulation scenario in the case of a contingency in which the frequency dips below the governor frequency band and reaches the frequency nadir. During the first few seconds (0s-5s), the Inertia Response comes into the action and tries to slow down the Rate of Change of Frequency (ROCOF). Following IR, the primary frequency control (PFC) or droop control tends to improve frequency nadir which is then helped by SFC and TFC to bring frequency back to the nominal value i.e. 50 Hz.

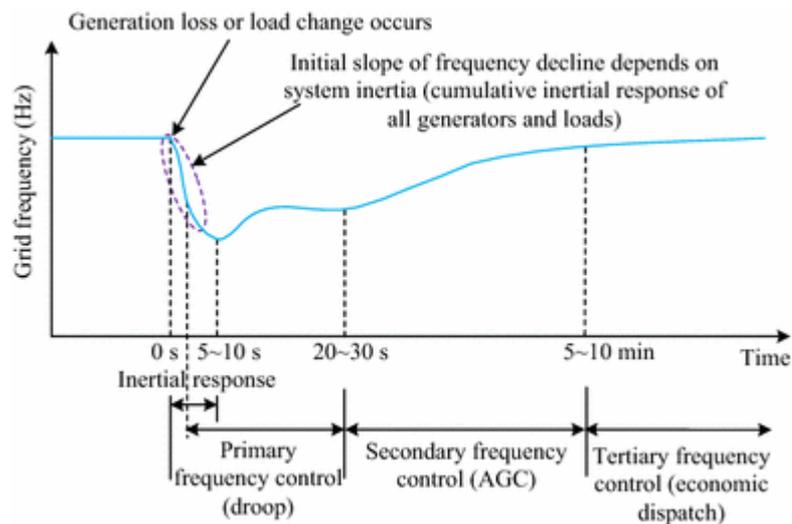


Figure 5. Frequency control in conventional power system.

1.6. Isolated Power System

An isolated power system is defined as a power system that supplies power to remote loads far away from the main grid. Such loads are normally located in remote areas away from urban centers. The generation comes mostly from wind, solar and other distributed energy resources (DERs) in addition to conventional generators such as diesel generator. The renewable energy sources such as wind, solar or bio mass cannot be relied upon solely because their generation comes from the sources that are non-dispatchable. Therefore, renewable sources are used in combination with conventional sources.

The isolated system can operate in complete isolation from the grid. The past two decades have seen substantial increase in isolated power systems everywhere specially across the developing world. For the electrification of loads which are away from the urban centers e.g. remote villages and far-off valleys the extension of transmission lines from the main grid is normally an expensive choice. For this reason, local generation from the renewable plants in combination with diesel/steam turbine generators is preferred. Figure 6 shows a typical AC based renewable power system containing a wind turbine, PV array, a generator, battery bank and load.

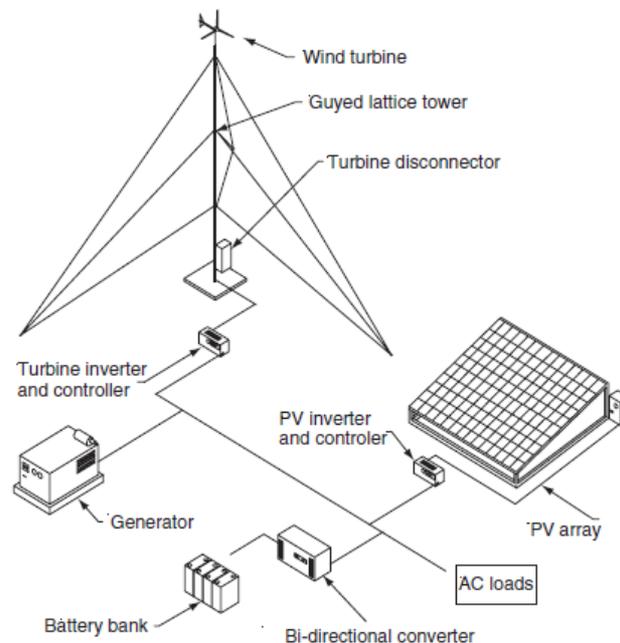


Figure 6. Isolated power system
Source: (Ackermann, 2012)

1.7. Literature Survey

With the increasing penetration of wind turbines in the power system, the randomness and fluctuation of wind causes the frequency deviations in the power system (Yingcheng and Nengling, 2011). Among all the renewable energy resources the wind power is set to play a leading role in the future electricity generation. Generally, the wind farms are equipped with protective relays that disconnect the wind farm from the power system in the case of large frequency disturbance. However, in the case of high wind power penetration a massive wind farm disconnection may lead to power system oscillations and instability (Causebrook et al., 2007).

Secondly, most of the modern wind farms make use of variable speed wind turbines (VSWT) that are connected to the grid through back to back power electronic convertors. This disconnects the grid frequency from the wind turbine generator's rotor and the overall inertia of the power system is decreased (Yingcheng and Nengling, 2011). Consequently, greater frequency deviations are observed in the case of disturbances (e.g. sudden generation loss or load changes). This effect is more evident in the case of isolated power systems with high wind power penetration (Lalor et al., 2004). The increase in rate of change of frequency (ROCOF) burdens the conventional units more and there have been cases where the wind energy from wind farms had to be curtailed to avoid system's instability.

Third, in the case of increasing wind power penetration, conventional generation plants are provided as reserves to maintain the frequency stability. This not only increases the cost but also puts an extra stress on the conventional units used as reserves in the case of frequency deviation. As more and more wind generation replace the conventional generation, the number of units available as reserves are declining and there are less units available to provide grid frequency stabilization and share the reserve burden. This issue becomes serious in the cases of isolated power system in which power regulation capabilities are poor (Yingcheng and Nengling, 2011).

To manage the huge penetration of wind power the wind farms need to be more grid friendly. This means that the wind turbines need to provide the ancillary services which were provided by the conventional plants. Therefore, there is a need for wind turbines to regulate active and reactive power and provide frequency and voltage control on the grid.

Grid codes across power systems of various countries are becoming stricter as the wind penetration across the country increases. They urge the wind farms to participate in frequency control and active power regulation. In Great Britain (GB), the grid codes urge the wind farms to provide primary, secondary and higher frequency responses like the conventional generators. So, in case of a frequency deviation (say 0.5 Hz) the output from the wind turbine generator should increase by an amount equal to primary response within 0s – 10s and it should be able to sustain this increase for 20s more (The grid code, 2006). Denmark, which is the leader in terms of wind energy installed capacity has introduced the grid codes which require to control the output power of wind turbine generators using automatic frequency regulation controllers. The Hydro-Quebec, Canada grid code states that the wind farms with a capacity greater than 10 MW must be able to provide the primary frequency control in case of frequency deviation $>0.5\text{Hz}$ in time duration of $<10\text{s}$ (Ackermann, 2012). The Transmission System Operator (TSO) may demand a contribution from the wind farms to the primary frequency control when the frequency drops from 50 Hz to 47 Hz or generation curtailment in case of rise in frequency from 50Hz to 53Hz (Elkraft report, 2004). Likewise, German grid codes require their wind farms to reduce the energy yield when frequency increases. The grid codes state that the wind farm must be able to change their output by +2% of the rated power output evenly for 30s and be able to maintain this output for 15 minutes (On, 2006).

In the classical generating plants, there are large rotating synchronous machines that are coupled to each other. In case of frequency deviations in the system e.g. due to sudden load increase frequency drops, this coupling allows the generators to generate a temporary increase in power to stabilize the frequency. Even though there is inherent inertia in the rotor blades of the wind turbines, this cannot be used to provide the frequency control (Yingcheng and Nengling, 2011). More wind turbines with wind generators equipped with frequency regulation functions are expected to be integrated in power systems (Ziping et al., 2018)

The normal operation of wind turbine is termed as Maximum Power Point Power Tracking (MPPT). In this mode the wind turbine, depending on the wind speed, follows the maximum power coefficient (C_p) according to the given power curve. To provide upregulating frequency response (i.e. the case in which frequency drops) the ‘deloading’ concept is used. The operation of wind turbine in which it is operated at lower than the maximum capability to keep some reserve capacity to provide frequency control is termed

as deloading (TransEnergie, 2003). The deloading of wind turbine can be achieved by two methods. One is through the pitch control and other one is to run the turbine at increasing speed (Alsharafi, 2018). However, it must be made sure that the speed does not exceed the upper limit of rotor speed (Janssens, 2007). A control scheme related to speed control for frequency regulation is proposed in (Aziz, 2018). This is usually done by employing the pitch control during power optimization and power limitation mode of the power curve. The drawback of this type of wind turbine operation is that the turbine always works below its maximum efficiency. This effect when combined in huge number of turbines and wind farms translates in to economic loss for wind farm owners.

Another aspect of frequency stability is the increase in frequency also known as frequency rise which occurs because of more generation than the demand, can be stabilized by cutting down the wind power generation when the frequency rises from a certain level (Attya, 2018). However, this aspect is out of the scope of the thesis.

1.8. Research Problem

The modern Wind Turbine Generators (WTG) is interfaced to the electrical grid through power electronics which screens any deviation in the frequency of the grid due to the fast response of the power electronics. Even though, the inherent inertia of the WTG is sometimes than the conventional generators (depending on the rating of wind turbine), it cannot be used to provide the frequency control (Aziz, 2018). The contribution of this thesis lies first in the fact that a relatively small isolated power system consisting of a conventional steam turbine generator and a wind farm, is modelled. Such an isolated system's frequency stabilization is more demanding than a large power system. Secondly, two controllers are implemented for a wind turbine that can provide the Inertia Response like the synchronous generators and provide frequency control (PFC) after a disturbance in the grid.

Key research objectives of the thesis are:

- Modelling a type D wind turbine in Simulink based on the standard parameters and ratings.
- Implementing two controllers — inertial controller and droop controller — on the top of normal wind turbine operation, that will help the wind

turbines to provide support to the frequency deviation.

Inertial controller helps the wind turbines to emulate the inertia response (IR) of conventional generator, while the droop controller helps it to provide the primary frequency control.

1.9. Thesis Outline

The thesis is divided in to 5 chapters. Chapter 1 gives the introduction, definitions, literature review and research problem. Chapter 2 presents the short-term and long-term issues related to integration of wind power in the power systems. Chapter 3 discusses wind turbine types and its components. Chapter 4 describes the methodology and the results of the simulation followed by Chapter 5 which gives the conclusion and future work recommendations.

CHAPTER 2

EFFECTS OF WIND ENERGY ON POWER SYSTEMS

The effects of the wind power on the power systems depend on the size, flexibility and complexity of power system and varies from one system to another. It also depends on the penetration level of the wind energy in the system. This chapter deals with the challenges of integrating wind energy in power systems.

Broadly speaking the effects of wind power on power system can be categorized as

- i) Short term effects
- ii) Long term effects

Figure 7 shows a summary of the short-term and long-term effects of wind energy on the power systems.

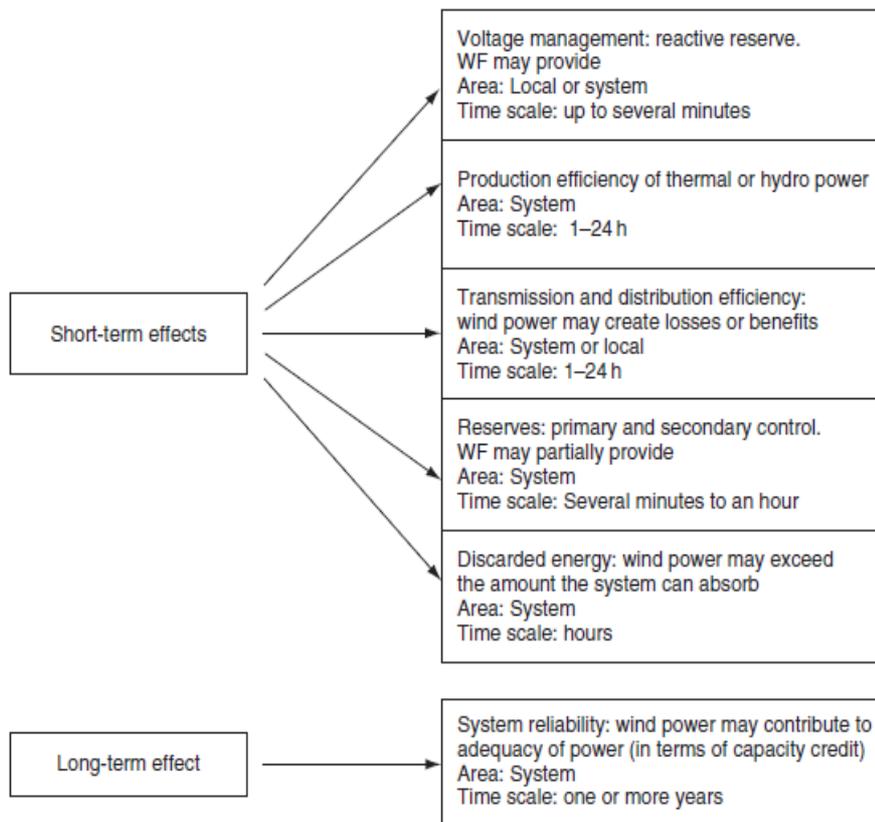


Figure 7. Short-term and long-term effects of wind energy on power system
Source: (Ackermann, 2012)

2.1 Short-Term Effects

As discussed in chapter 1, the short-term effects of the wind power on power system are related to balancing the power variations. Wind power is variable and fluctuates all the time. It still can be predicted from few hours up to 40 hours ahead using numerical weather models and other techniques. However, the prediction comes along with its errors. The predicted fluctuations in the output of wind farms must be met with the power output from the conventional generation stations. The part of the prediction that is erroneous must be tackled by the reserve conventional units. Therefore, for modern power system the system operator must deal with a fluctuating demand along with the fluctuating supply from wind power plants.

The conventional power plants used as reserves are allocated for the frequency control operation. They are dimensioned according to the largest unit outage. For example, if the largest unit in the system is 20 MW then the reserves must be at least 20 MW or more than that. The hourly and intra-hour wind variations affect the reserve requirement used for frequency control. The prediction of wind power is important because in case of a power system with high wind energy penetration, the system operator deals with the load fluctuations as well as the unpredicted wind variations. Accurate forecasts reduce errors which results in reduced costs for allocating reserves.

On a time-scale of 15 minutes to 1 hour the load variations are better predicted than the wind prediction. The estimates of the reserve requirement have shown to be increased with the increasing wind power penetration. For a wind penetration level of 10 % the estimated reserve requirement ranges from 2-8%.

The net load seen by the system is the load minus the wind power production. If the load variations are uncorrelated with the wind power variations the net load variations are simple addition of wind and net load variations (Ackermann, 2012)

Mathematically:

$$(\sigma_{\text{total}})^2 = (\sigma_{\text{wind}})^2 + (\sigma_{\text{net load}})^2$$

where

σ_{total} = load standard deviation

σ_{wind} = Wind standard deviation

$\sigma_{\text{net load}}$ = Net load standard deviation

Other short-term effects of wind generation on power system include the effects on transmission and distribution losses and the CO₂ emissions.

2.1.1. Effects on Transmission and Distribution Loss

High amount of wind energy farms dispersed over a large geographical region increases the transmission of energy from remote areas and hence result in increased transmission losses. Also, the Unit Commitment (Hansen, 2016) of the conventional plants (Hydro and thermal) becomes perplexed by the introduction of highly variable wind energy as they are operated below or above their optimal level in the presence of fluctuating wind energy.

In cases, where the wind power production exceeds the load demand, energy production needs to be curtailed. This means economical loss for wind farm owners.

2.1.2. Effects On CO₂ Emissions

Prime purpose of introducing wind turbines is to curtail CO₂ emissions. The operation of wind turbine is totally CO₂ free, however during its construction the CO₂ emission value is estimated to be 10 g CO₂ kWh⁻¹ (Ackermann, 2012). The amount of CO₂ emissions reduced by the wind energy depends on the type and the size of the fuel that is displaced. In most of the cases wind energy displaces the power plants with high marginal fuel costs which generally are the old coal fired plants resulting in CO₂ abatement of 800-900g CO₂ kWh⁻¹. Sometimes, in case of excess production, wind energy displaces the zero CO₂ emission options such as hydro and biomass as well.

2.2. Long-Term Effects

The reason why system operators are sometimes reluctant to rely on the intermittent wind energy is because of the reliability issues in the power system. The

reliability of the power system is measured in terms of its Loss of Load Probability (LOLP) index which includes the probability and the consequence of the event causing black out of whole system. The acceptable reliability of a power system is one large black out in 10-50 years (Ackermann, 2012).

To assess the long-term effects of wind energy on the power systems we need to have data of wind energy over several years. The amount of energy that can be supplied by the wind farms during the peak load durations determines the conventional generation that can be replaced by the wind generation. It also varies from region to region and across various power systems. The case where generation from wind power plants coincides with the load demand results into a positive integration of these sources in the power system. For example, Solar output corresponds to the Air-conditioning requirements (Sharper the sunlight, hotter it is) while the wind output corresponds to the heating requirements (cold winds blowing causes temperature to drop).

In short because of the positive effects and despite the challenges wind power penetration is bound to increase in the power system in coming decade.

2.3. Other Challenges

The positive correlation of the wind energy with the load demand makes the accommodation of the wind power easy but the problem arises when the demand and supply move in opposite direction. For example, if strong wind blows overnight when demand is less, the conventional thermal generation needs to be curtailed to accommodate the surplus wind power resulting in inefficient operation of the conventional units. Likewise, in case of slow or no wind during a hot humid day when load demand is on its peak, the demand must be met by the conventional units which hints at the need of reserve requirements almost equal to the amount of wind energy installed. Both the cases present a major challenge for wind energy integration.

Increasing wind energy will displace huge portions of conventional generation and will have to actively participate in the frequency control. For that there is a need of energy storage that would capture the excess energy from wind, solar and other Distributed Energy Resources (DERs) for later use. Transmission side energy storage options include pumped hydro storage, flywheels and compressed air storage while on the distribution side there are regular flow batteries and Superconducting Magnetic

Energy Storage (SMES).

In conclusion, because of the positive effects and despite the challenges, wind power penetration is bound to increase in the power system in coming decade.

CHAPTER 3

WIND TURBINE TYPES AND COMPONENTS

Before modelling a wind turbine, various types and its working are presented in this chapter.

3.1. Wind Energy Scenario In The World

The global installed wind capacity is around 539,531 MW. The top countries contributing are China, USA, Germany, India, Spain, UK, France and Brazil (GWEC, 2018). Figure 8 shows the wind energy scenario across the world.

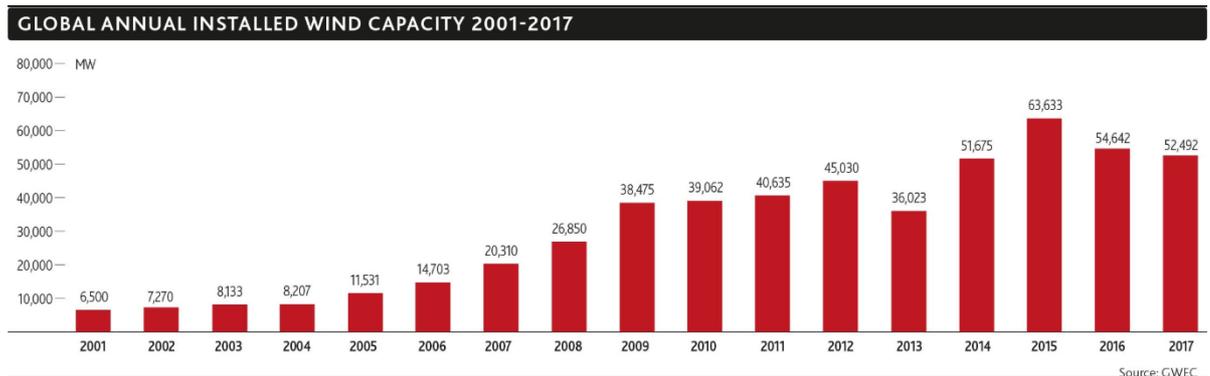


Figure 8. Wind energy scenario in the world

(Source: GWEC, 2018)

3.2. Wind Energy Scenario In Turkey

In Turkey the electricity production through wind power plants stands at 6872MW. The country also has a rich offshore wind power potential and the wind penetration is expected to increase over the coming years. Figure 10 shows the increasing trend of wind energy in Turkey according to Turkish Wind Energy Association's report

(TWEA, 2018).

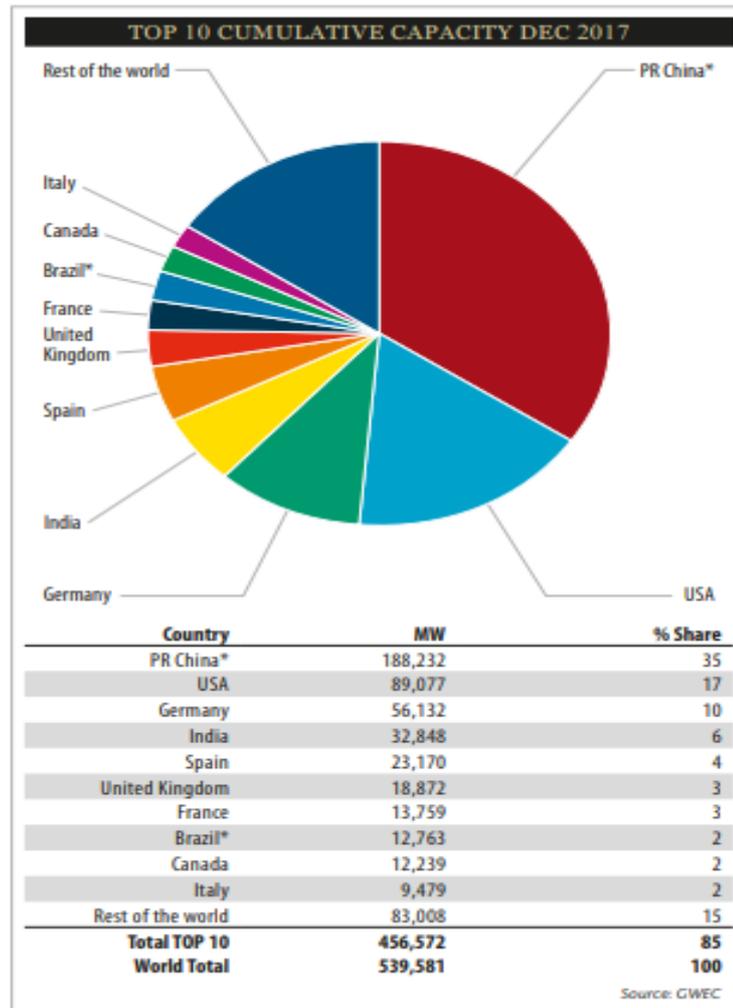


Figure 9. Top 10 countries in terms of wind energy capacity (Source: GWEC, 2018)

The current Turkish electrical grid codes do not require wind farms to provide the ancillary services but the goal of 20,000 MW generation by 2023 means that wind penetration in country's generation mix will be more than 10% and like Denmark, Ireland and other Nordic countries, Turkish grid codes are projected to be revised (TWEA, 2018).

3.3. Wind Turbine

Wind turbine is a power generating machine which is driven by the kinetic energy

of the wind. It is one of the leading renewable energy sources contributing to clean power in the world.



Figure 10. Year by year increase in wind energy in Turkey
(Source: TWEA report 2018)

3.4. Wind Turbine Types

Since their inception, various types of wind turbine concepts have been introduced. The two main types of wind turbines are Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbines (VAWT). HAWT are the dominant types and used all around the globe due to many different reasons including efficiency and ease of installation.

Wind turbines can be classified based on various attributes as explained below.

3.4.1. Classification Based On Speed Control

In terms of speed control, there are two types of wind turbines.

- i. Fixed Speed Wind Turbines (FSWT)
- ii. Variable Speed Wind Turbines (VSWT)

3.4.1.1. Fixed Speed Wind Turbines (FSWT)

These type of wind turbines rotate at fixed speed under all wind conditions. The efficiency is lower than the variable speed wind turbines because the rotating speed cannot be varied according to the changing wind speed. Therefore, these types of wind turbines are installed in the locations where a certain wind speed is dominant throughout the year. The advantage of the constant speed wind turbine is that its construction is relatively simple, and their cost is cheaper than the variable speed wind turbines. However, the construction requirements are more robust. Since the rotor speed cannot be varied, fluctuations in wind speed are directly converted to drive train torque fluctuations which can cause higher structural loads.

3.4.1.2. Variable Speed Wind Turbines (VSWT)

VSWT can change their speed of rotation with the help of pitch control. This allows the turbines to adapt to various wind speeds. The turbine follows different power coefficient (C_p) curves for different wind speeds. In VSWT the mechanical stress is less as the rotors act as a fly wheel (storing energy as a buffer) reducing the variations in drive train torque. Figure 11 shows the power coefficient of a typical VSWT where at different wind speeds the turbine follows a different curve. The tip of each curve corresponds to the maximum power output of the wind turbine at a certain wind speed value. Black line passes through all the maximum power outputs (Muljadi et al., 2013).

3.4.2. Classification Based On Pitch Control

In terms of pitch control, following are the various types of wind turbines.

- i. Stall regulated
- ii. Pitch regulated

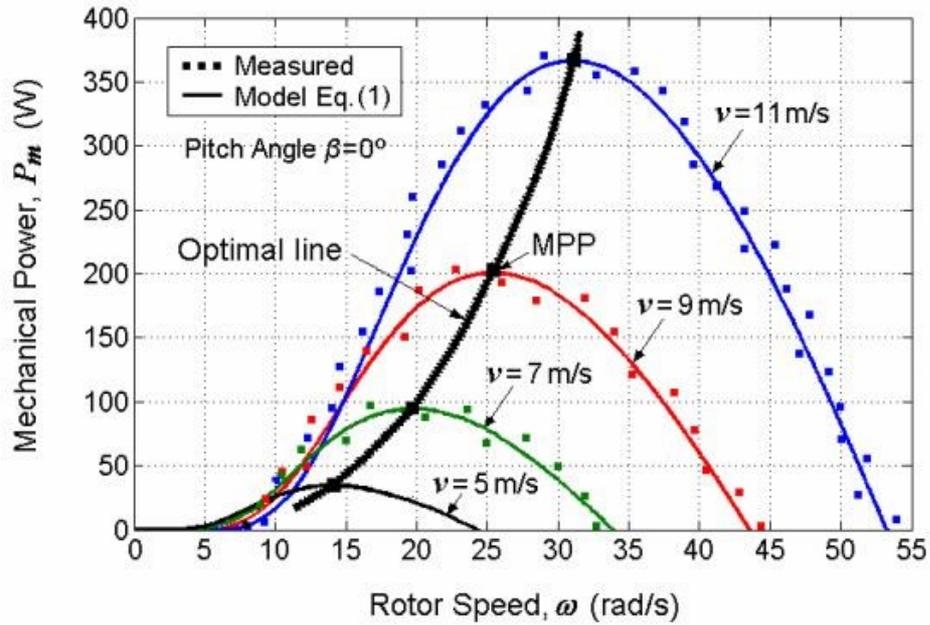


Figure 11. C_p curve for VSWT

3.4.2.1 Stall Regulated Wind Turbine

Stall regulation is achieved by shaping the wind turbine blades in such a manner that they stall at high wind speeds hence decreasing the torque and bringing the turbine to stop. They are simple and inexpensive and lack pitch control mechanism.

3.4.2.2. Pitch Regulated Wind Turbines

The pitch regulated wind turbines have a pitch mechanism usually in the form of servo motor that changes the blade's angles of the turbine around its axis hence changing the angle of attack between the incoming wind and the leading edge of the blades.

3.4.3. Iec Standard Types

International Electrotechnical Commission (IEC) has defined various type standards of HAWTs¹ (Ackermann, 2012). These are,

¹ Type A,B,C and D are also termed as Type I, II, III and IV

- 1) Type A wind turbine
- 2) Type B wind turbine
- 3) Type C wind turbine
- 4) Type D wind turbine

Table 1. Types of wind turbine based on pitch and stall control

Wind turbine concept	Rotational speed	Pitch angle
Passive stall control	Fixed	Fixed
Active stall control	Fixed	Variable
Pitch control	Variable	Variable

Table shows a summary of the classification.

Table 2. Types of Wind Turbines

Speed control		Power control		
		Stall	Pitch	Active Stall
Fixed speed	Type A	Type A0	Type A1	Type A2
Variable speed	Type B	Type B0	Type B1	Type B2
	Type C	Type C0	Type C1	Type C2
	Type D	Type D0	Type D1	Type D2

3.4.3.1. Type A

Type A wind turbine is a fixed speed wind turbine which is directly coupled to the generator and any fluctuations in mechanical rotations are directly converted to the fluctuations in electrical output. The turbine is designed to rotate at a fixed speed and often accompanied with a capacitor bank to provide for the reactive power. Type A wind turbines uses Squirrel Cage Induction Generator (SCIG) for electricity production.

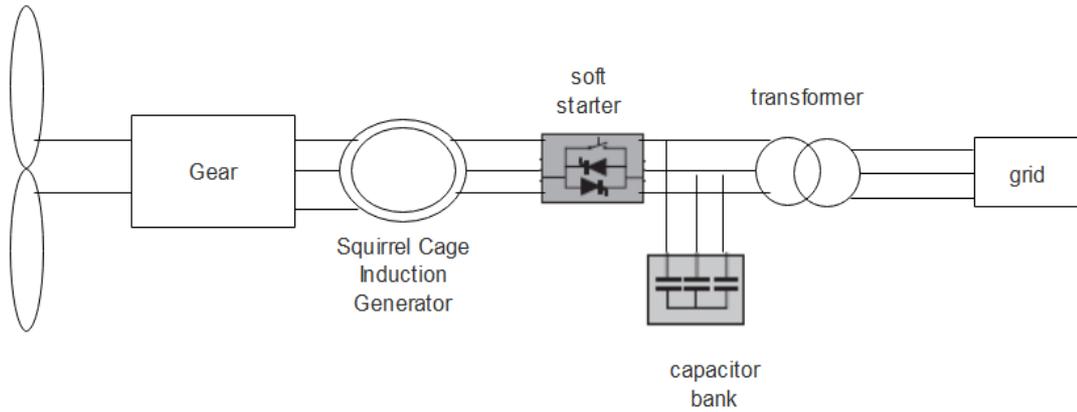


Figure 12. Type A wind turbine

Type A wind turbines are further classified into A0, A1 and A2 types based on stall, pitch and active stall control.

3.4.3.2. Type B

This type of wind turbine is known as a limited variable speed wind turbine. It has a Wound Rotor Induction Generator (WRIG) for electricity generation. The generator has a variable resistance which helps in controlling the rotational speed.

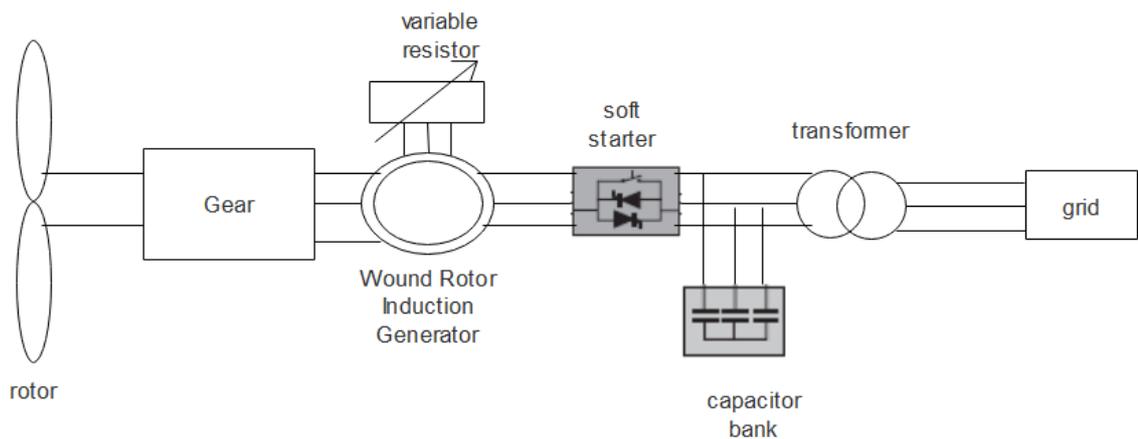


Figure 13. Type B wind turbine

3.4.3.3. Type C

Type C wind turbine is equipped with Wound Rotor Induction Generator (WRIG) along with partial scale frequency converter. This type of wind turbine provides a better control of the wind turbine's dynamic speed. Depending on the partial scale frequency converter, the type C turbine can provide a speed range from 40% to 30% of the synchronous speed.

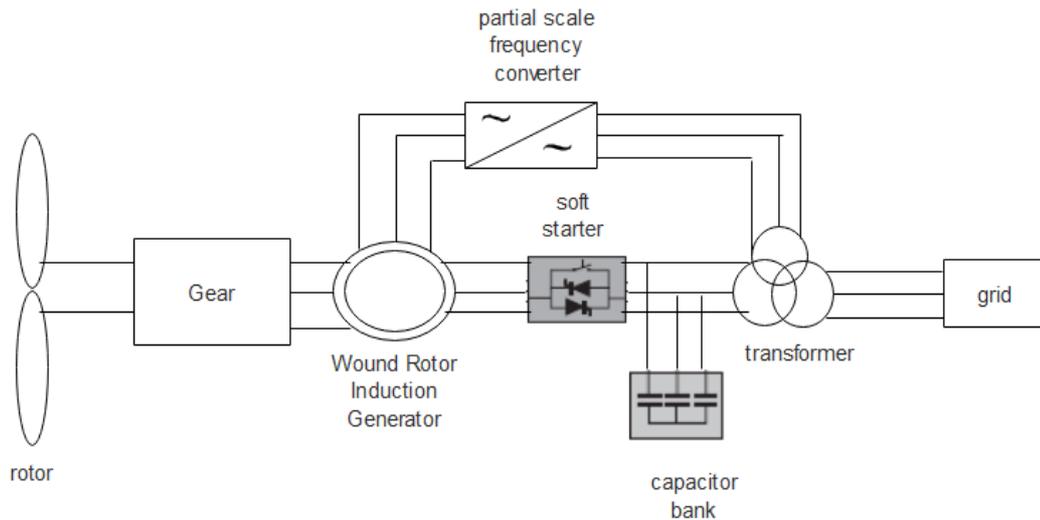


Figure 14. Type C wind turbine

3.4.3.4. Type D

Type D wind turbine is a full Variable Speed Wind Turbine in which the generator is connected to the grid through full scale frequency convertor. The generator commonly used is the Permanent Magnet Synchronous Generator (PMSG) or a Doubly Fed Induction Generator (DFIG). The type 4 wind turbine allows to extract maximum power from the wind turbine by optimizing the turbine rotor's speed at low wind speeds and minimizing the stresses on the wind turbine's drive train during wind gusts (Gagnon, 2018). The power electronic interface provides the necessary reactive power support as well as a smoother connection to the grid.

The full scale frequency converter in Type D wind turbine converts the electricity generated at different voltage and frequency levels to a standard grid voltage and

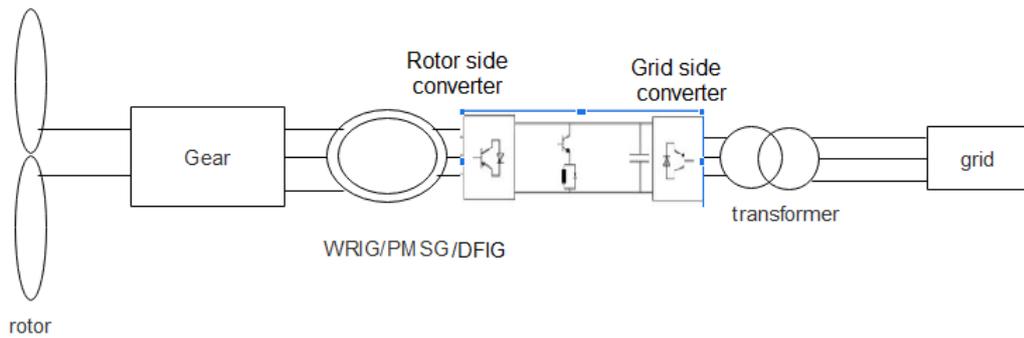


Figure 15. Type D wind turbine

frequency. It contains a power electronics circuitry consisting of rectifiers, inverters and other power electronic components. It consists of a rotor side converter and a grid side converter. The rotor side converter controls the torque and reactive power of the wind turbine generator while the grid side converter is responsible for changing the level of voltage and frequency of output power. For this thesis, type D wind turbine has been used. The values of the power coefficient C_p and the power curve has been taken from a 2 MW reference wind turbine used in wind energy department of Denmark Technical University. The reason this wind turbine has been used is because it is the latest type of VSWT which is being used in majority of the wind farms. This type of wind turbine is equipped with full scale frequency converter that fully controls the power output from the wind turbine.

3.5. Working Principle Of Wind Turbine

In this section the physics behind the wind turbine's operation is presented. Like all other generation processes, wind turbine converts the kinetic energy of wind to the rotation of the turbine blades. This torque is converted to the rotational motion of the generator which in turn converts it to electrical energy. The main difference lies in the primary source of power which in the case of wind turbine is natural resource, i.e. wind.

A standard 3-blade HAWT consists of various components that contribute in converting the kinetic energy in the wind in to electrical energy. Figure 16 shows the basic wind turbine components. The aerodynamic rotors capture the energy in the flowing wind and are connected to the generator through a shaft and a gear box which rotates and produces the electrical power. The modern wind turbines are equipped with power

electronics circuitry at the output. The generator output is further connected to the transformer to step up the voltage so that the wind power plants can be connected to different voltage levels of the grid (transmission, sub-transmission or distribution) (Hansen, 2016)

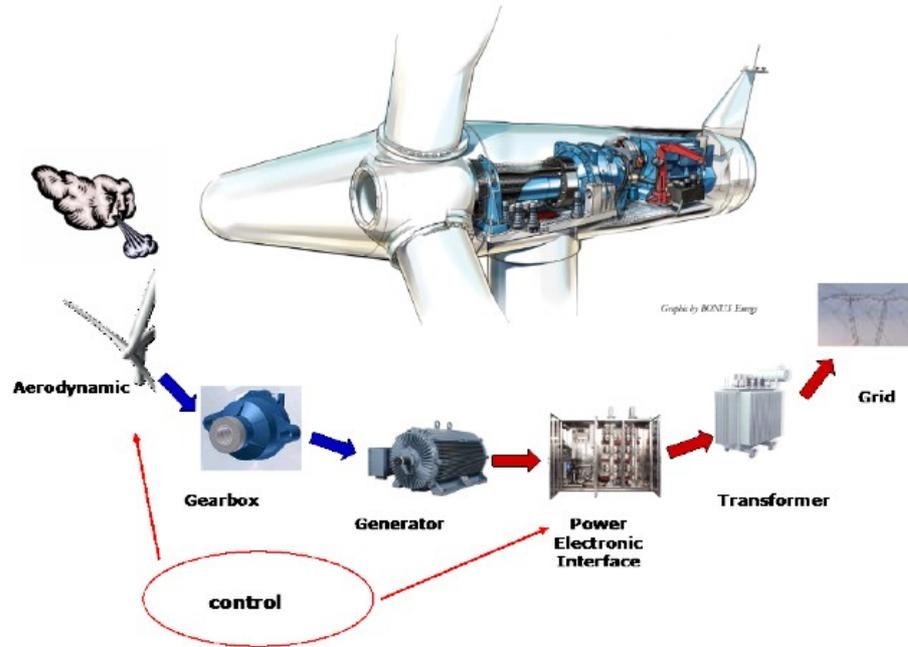


Figure 16. Wind turbine components
Source: (Hansen, 2016)

3.5.1. Rotor Aerodynamics

Wind turbine rotor consists of three blades which are connected at the base to the hub. The power generated from the wind turbines is expressed as

$$P = \frac{1}{2} \rho \pi R^2 U^3 C_p(\lambda, \theta) \quad (3.1)$$

where

' ρ ' is the density of the air, taken as 1.225 Kg/m^3

' R ' is the radius in meters of the turbine rotor

' U ' is the wind speed in m/s

' C_p ' is the power coefficient

' λ ' is the tip speed ratio

' θ ' is the pitch angle

3.5.2. Power Coefficient (C_p)

Power coefficient is a curve of wind turbine that shows the percentage of the power that it can extract from the wind. The mechanical power P_{mech} , can be shown in terms of the total power in the wind P_{wind} by

$$P_{mech} = C_p \cdot P_{wind}$$

The theoretical upper limit of C_p is 16/27 or 0.59 according to Betz limit formula which means that a wind turbine can extract a maximum of 59 percent of the power from the incoming wind (Van Kuik, 2007). C_p depends is the function of Tip Speed Ratio (TSR) and the pitch angle β

$$C_p = f_{c_p}(\lambda, \beta)$$

The formula used for calculating ' C_p ' is

$$C_p = \frac{1}{2}(\lambda_i - 0.022\beta^2 - 56)e^{-0.17\lambda_i} \quad (3.2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3.3)$$

Where

λ is the Tip Speed Ratio (TSR) and β is the pitch angle.

TSR(λ) is defined as a ratio of the speed of turbine blade tips (w_{rotor}) to the incoming wind speed (U)

$$\lambda = \frac{w_{rotor}R}{U} \quad (3.4)$$

Figure 17 shows a typical performance coefficient C_p curve of a wind turbine.

3.5.2. Power Curve

Power curve shows the relationship between the wind speed and the power output of the wind turbine.

Figure 19 shows aerodynamic power and the power curve of a standard wind turbine. The dotted curve is the maximum aerodynamic power that can be extracted by the turbine

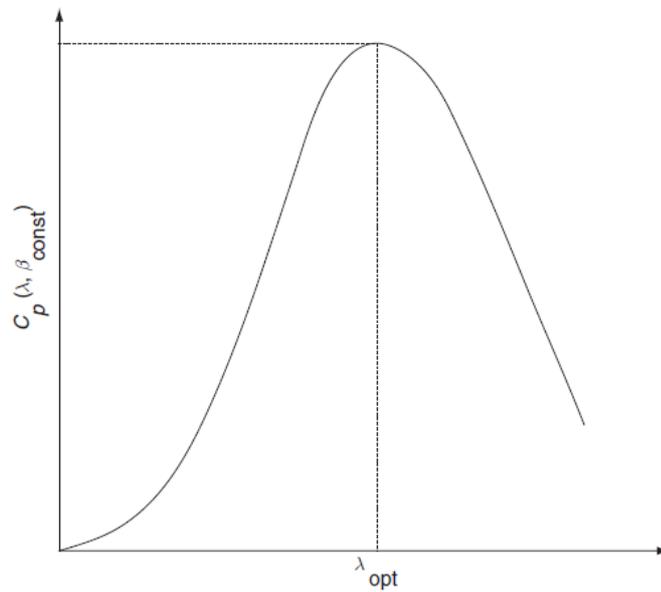


Figure 17. C_p vs tip speed ratio curve

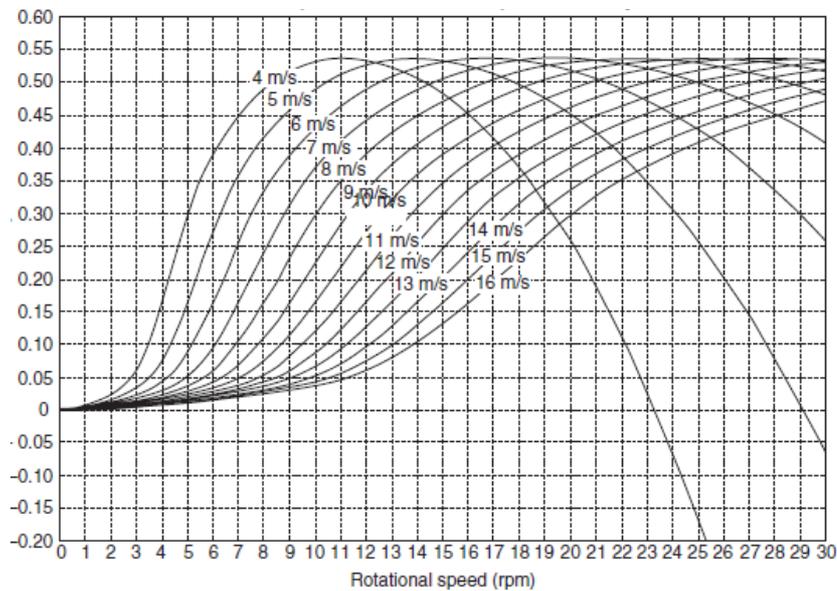


Figure 18. C_p curve of a 2 MW reference wind turbine at various wind speeds

rotors according to (2.1), while the solid black line represents the actual or practical power extracted by the wind turbine as the result of wind turbine limitations and control.

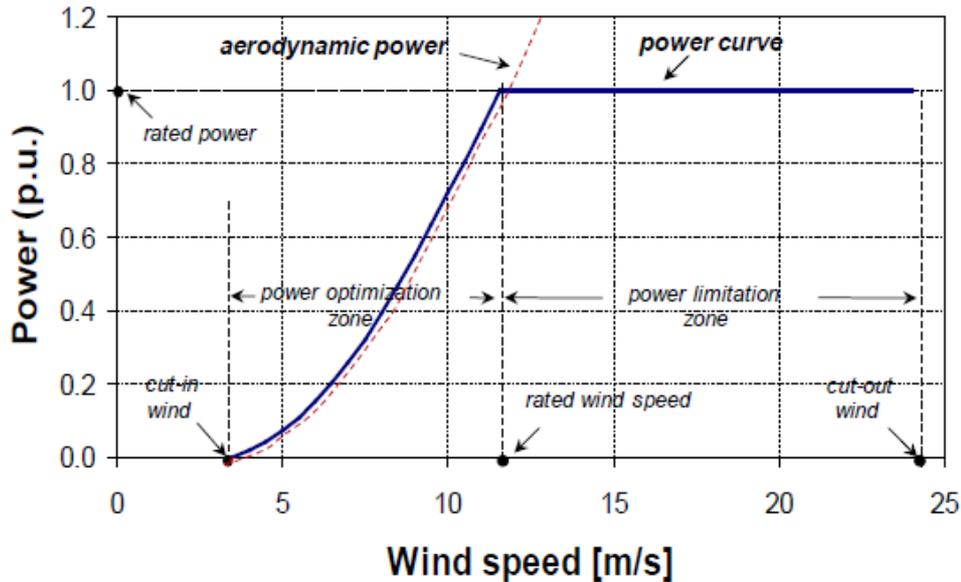


Figure 19. Power curve of a wind turbine
Source: (Hansen, 2016)

The power curve consists of two zones

- i. power optimization zone
- ii. power limitation zone.

3.5.2.1. Power Optimization Zone

The portion of power curve between the V_{cut-in} (cut-in wind speed) and V_{rated} (rated wind speed) is called power optimization zone. The wind turbine produces the maximum power according to the wind speed in this region.

- V_{cut-in} is the minimum wind speed which is needed for the wind turbine to start rotating and producing electrical power
- V_{rated} is the rated wind speed is the wind speed at which the wind turbine reaches its maximum power limit and caps any further increase in the power output.
- $V_{cut-out}$ is the last value of wind speed after which the turbine needs to be stopped to avoid the run-off condition which may cause permanent mechanical damages.

3.5.2.2. Power Limitation Zone

This is the area of power curve between the rated wind speed and cut-out wind speed. During this portion of the curve the power output is limited to the maximum rating of the turbine.

3.5.3. Generator

The generator is the mechanical device that converts the rotational motion of the rotors to the electrical energy output. As explained previously, the generators used in a wind turbine can be synchronous, asynchronous or induction generators.

For type D wind turbine Permanent Magnet Synchronous Generator (PMSG) is normally used.

The electrical angular speed is given by

$$\omega_{e0} = 2\pi f_0 \quad [\text{rad/s}] \quad (3.5)$$

Where,

' f_0 ' is the frequency of the grid (50Hz)

The synchronous rotation speed of generator is given by

$$\omega_{gen0} = \frac{\omega_{e0}}{N_{pp}} = \frac{2\pi f_0}{N_{pp}} \quad (3.6)$$

where

' N_{pp} ' is the number of pole-pairs in the generator.

To convert in the rotation speed in rpm

$$n_{gen0} = 60 \frac{f_0}{N_{pp}} \quad (3.7)$$

3.5.4. Gearbox

Gearbox is the mechanical device that converts the slow rotation of the rotor into

high rotation of the generator. The gear box ratio is given by

$$N_{gear} = \frac{\omega_{gen}}{\omega_{rotor}} \quad (3.8)$$

This ratio varies as the number of pole pairs in the generator vary.

3.5.5. Power Electronics Interface

Presence of power electronics convertors depends on the type of wind turbine. The old fixed speed wind turbine consists of cheap power electronic interface while the VSWT wind turbine has a complex power electronics interface that practically isolates the turbine and the generator from the grid. The Type D wind turbine has a full-scale frequency converter (consisting of a rotor side converter and a grid side converter). This power electronic interface provides better grid control capabilities and enable wind turbines to vary the output according to grid needs.

CHAPTER 4

METHODOLOGY

4.1. Methodological Framework

The type D wind turbine has been chosen in this thesis because of its variable speed characteristics and its wide deployment in modern wind farms. The flow chart of the methodology is given in Figure 20.

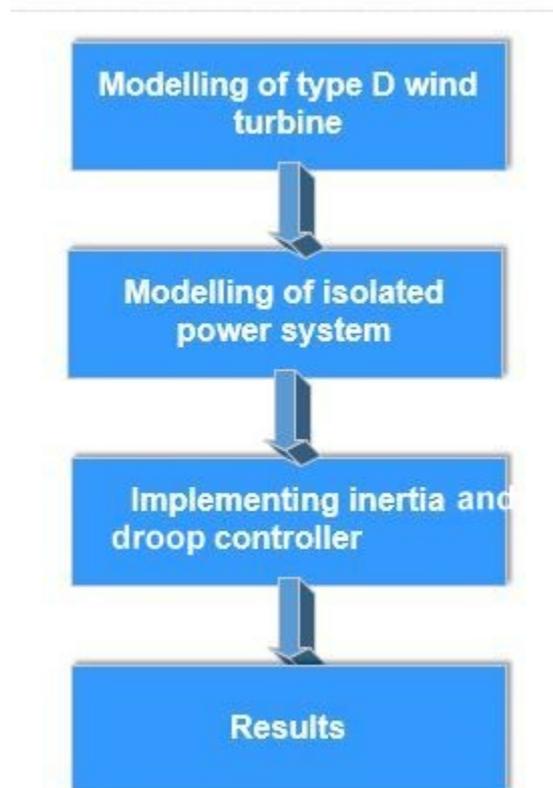


Figure 20. Flow chart

As a first step, the modelling of wind turbine is done followed by the modelling of various components of a steam turbine generator. An inertial controller and a droop controller are implemented on the top of this wind turbine and the results are obtained.

Why do simulations and modelling?

Modelling complex systems and machines is a common practice in engineering. Computer simulation allows to test various properties in design and construction phase as well as the application phase. The simulation of wind turbines allows to save a lot of effort in design and development phase. Thus, a computer simulation is a cost-effective way to design and test the system without exposing the prototype to real full-scale tests. However, the modelling details vary as per the requirement of the investigation.

4.2. MATLAB and SIMULINK

SIMULINK software is used for modelling and simulation. Simulink is a block diagram-based software for simulating, modelling and analyzing multi domain dynamical systems which comes with MATLAB.

MATLAB is a vector-based programming software that can be used for variety of engineering fields. Both are the product of MathWorks².

4.3. Per Unit (P.U.) System Of Calculations

Most of the power system simulation software use per unit system of calculations which is definition of new set of basic measuring units of a physical system. This means that instead of measuring the instantaneous power output from a wind turbine in kW or MW it can be measured as the percentage of the rated power of the wind turbine (Ackermann, 2012). Likewise, all voltages at the same voltage level of the wind turbine are measured as the percentage of the nominal voltage of the wind turbine.

For calculating p.u value, a base unit of a quantity is chosen. For example, for the case of p.u power, the maximum power rating of wind turbine (2MW in thesis) is chosen as the base (P_{base}) value. The actual value of the power at any instant is divided by the

² www.mathworks.com

base power at to obtain the p.u power.

$$P(p.u) = \frac{P_{actual}}{P_{base}}$$

The per unit values have no units because they are the ratio of similar quantities. The advantage of per unit system of calculations is that the system measurements can be scaled to any size.

4.4. Wind Turbine Control

As described in chapter 2, wind turbine consists of various components. There is a constant requirement of controlling various mechanical movements within the turbine to achieve an optimized performance.

Following is a brief description of why there is need of control in a wind turbine

4.4.1. Optimized Power Production

Wind turbine blade movement needs to be controlled to follow the power curve when the wind speed is less than the rated value and to limit the power output once the wind speed exceeds the rated value for safety. Therefore, there is a need of a control mechanism that could alter the blade angles accordingly.

4.4.2. Mechanical Load Reduction

The control also facilitates the drive train oscillations reduction and yaw angle control, details of which are out of scope of this thesis.

4.4.3. Compliance With Grid Requirement

For wind farms to provide the electrical power according to the grid codes the control of power output is needed.

Following are few of the control actions needed by the wind turbine in response to the grid requirements.

- frequency control
- reactive power control (Voltage)
- fault ride through (FRT)

4.4.4. Disturbance Mitigation

The control mechanism in wind turbine also tends to mitigate the disturbances caused by the turbine. The two main disturbances are the noise generated by turbines rotation and the shadow flickering.

4.5. Modelling of Type D Wind Turbine In Simulink

The power curve used for the wind turbine simulation is shown in Figure 21. Various specifications of the turbine are given in Table 1. This is a generic model of a wind turbine and do not emulate the complete real behavior of the turbine.

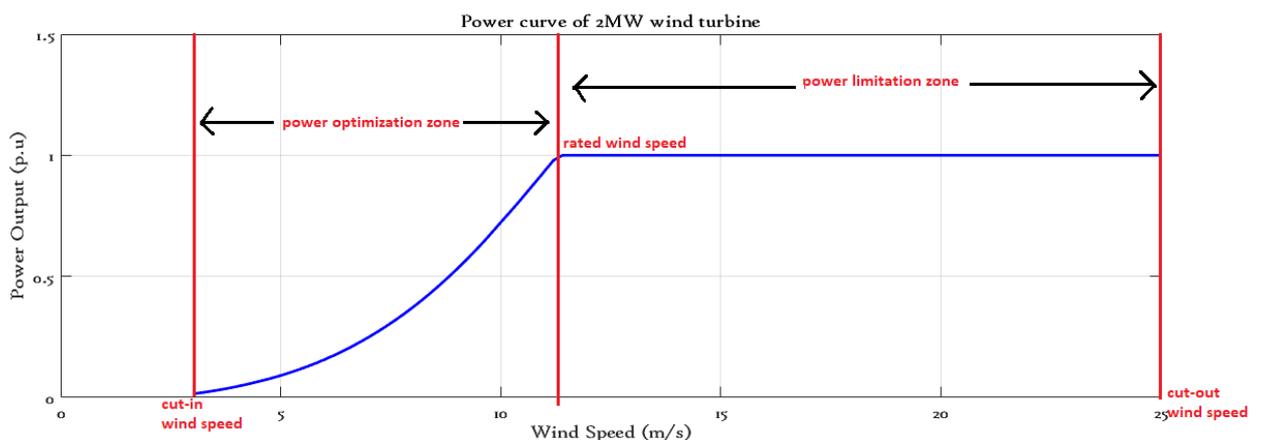


Figure 21. Power curve of a type D 2MW wind turbine

Table 3. Type D Wind Turbine specifications

Wind turbine power rating (MW)	2
Cut-in wind speed (m/s)	3
Rated wind speed (m/s)	11.6
Cut-out wind speed (m/s)	25
Height	100 m

Figure 22, shows the various blocks numbered (i) to (v)

- I. Aerodynamic model
- II. Pitch control block model
- III. Mechanical model
- IV. Maximum Power Point Tracking block

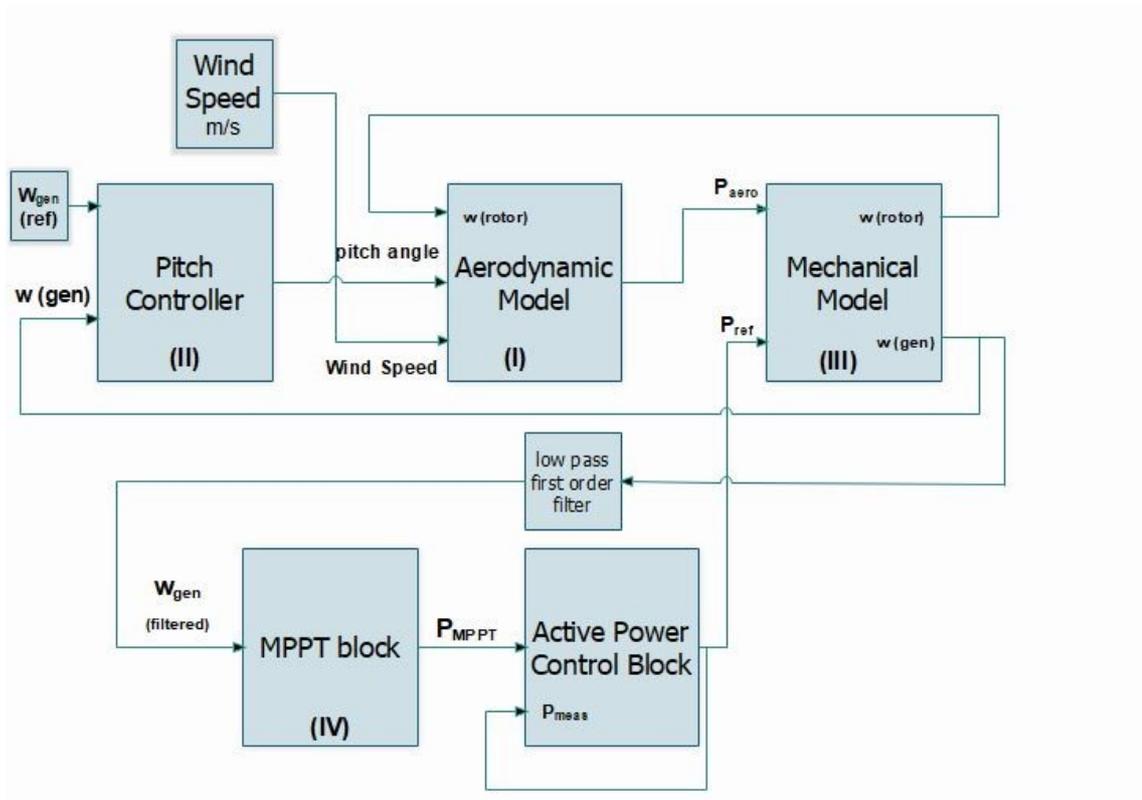


Figure 22. Block diagram of a type D wind turbine model

Various parameter values and the MATLAB code used while modelling the individual wind turbine blocks are given in Appendix A. The parameters used are standard for this wind turbine type.

4.5.1. Aerodynamic Model

The aerodynamic power is given by the equation (3.1) which is restated here.

$$P = \frac{1}{2} \rho \pi R^2 U^3 C_p(\lambda, \theta)$$

where

' ρ ' (Kg/m³) is the density of air taken as 1.225 kg/m³, ' R '(m) is the radius of the rotor blade, ' U ' (m/s) is the air velocity, ' $P(W)$ ' is the Aerodynamic Power, ' C_p ' power coefficient which depends on the tip speed ratio λ and the pitch of the rotor blades ' θ '.

The values of C_p specified for various values of λ and β were already given for our reference wind turbine. The C_p - λ - β table is used as a 2-D lookup table in the model in Simulink in Figure 23. MATLAB performs the interpolation of the values during while testing the model.

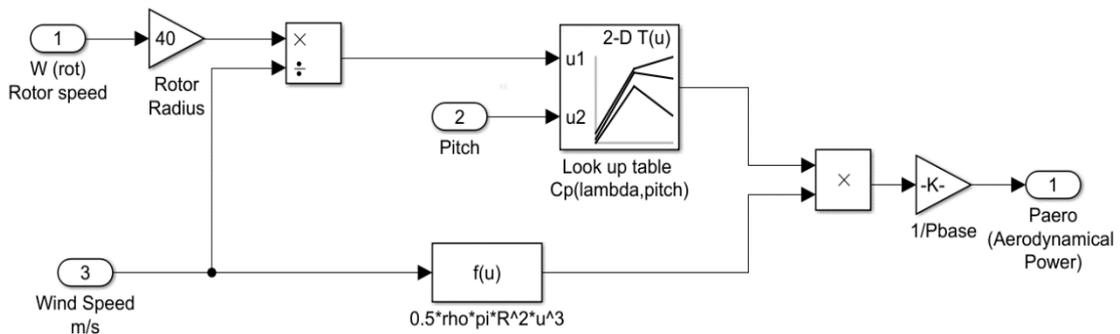


Figure 23. Aerodynamical Simulink model

4.5.2. Pitch Controller

In variable speed wind turbines, pitch controller changes the pitch angle of the turbine blades against the wind to change the power output from the turbine. The PI control system generates a reference blade angle and the pitch servo motor serves as an actuator which turns the blades to a certain angle. Figure 24 shows the pitch controller consisting of a Proportional Integral (PI) controller and an actuator. The error between

the generator's actual speed and its manual speed is fed as an input to the PI controller which generates the reference value which is further compared to the actual pitch angle. The actuator sets the new pitch angle according to the wind turbine's generator speed.

The pitch servo is subjected to certain constructional limitations such as angle limitations, β_{\min} and β_{\max} . It means that the blades can be turned within certain angle limits. For the reference type D wind turbine these values are 0 and 30 degrees respectively. Likewise, there is also a pitch speed limitation, $\frac{d\beta}{dt}$ i.e. the rate of change of angle of the turbine's blade.

The pitch controller remains passive in the power optimization zone. The optimal value of the pitch is zero for this period. It is activated only when the wind turbine is operating in its power limiting zone under high wind speeds when there is a need to limit the rotors angular velocity and hence limit the production. The values of the gains used are given in Appendix A.

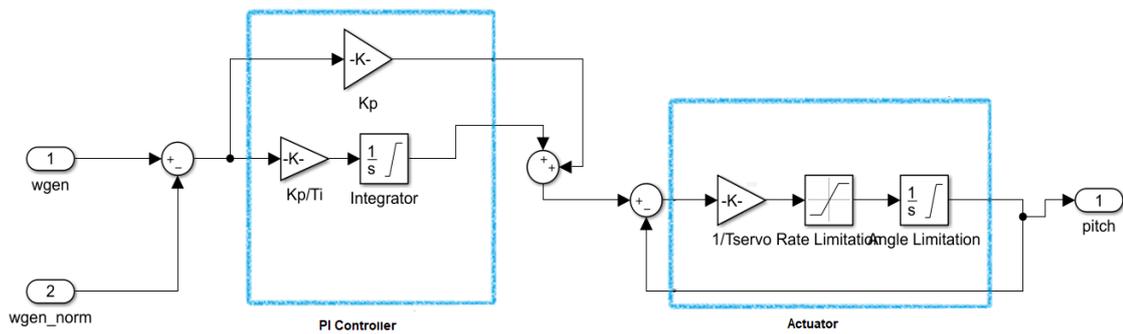


Figure 24. Pitch control Simulink model

4.5.3. Mechanical Model

The drive train is taken into consideration in mechanical model which is connected on one side with the turbine's rotor blades (low speed LS) and with the generator on the other side (high speed HS). The low speed turbine rotations are converted into high speed generator rotations through a gearbox.

The drive train as shown in Figure 4, is modelled as a two mass system. A rotor which is connected to generator through a shaft. The high-speed shaft (i.e. generator side)

is assumed to be stiff whereas the low speed shaft (i.e. rotor side) is assumed as flexible with a stiffness ' k ' and damping coefficient ' c '.

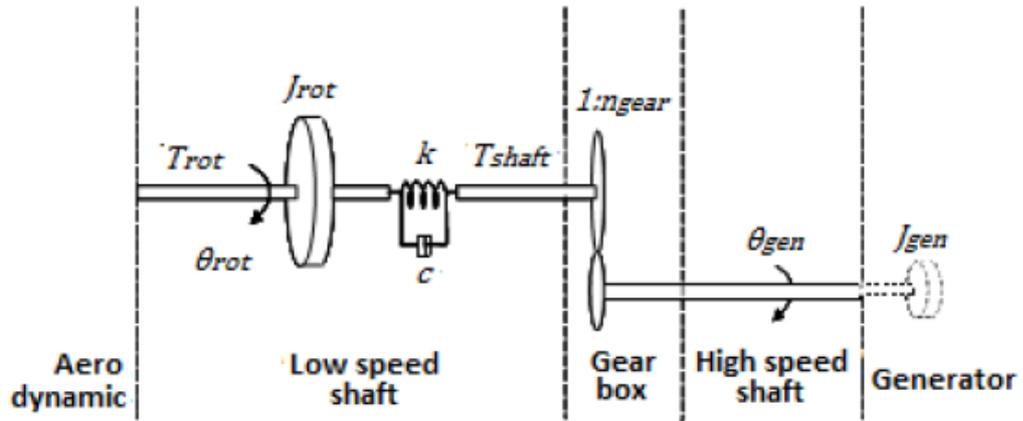


Figure 25. Two-mass mechanical model

The dynamical behavior of the drive train model is governed by the following mathematical equations.

$$T_{rot} - T_{shaft} = J_{rot}\ddot{\theta}$$

$$T_{shaft} - T_{gen} = J_{gen}\ddot{\theta}_{gen}$$

$$T_{shaft} = k\Delta\theta + c\Delta\omega$$

$$T_{shaft} = k\left(\theta_{rot} - \frac{\theta_{rot}}{n_{gear}}\right) + c\left(\dot{\theta}_{rot} - \frac{\dot{\theta}_{rot}}{n_{gear}}\right)$$

Where

- J_{rot} is the rotor inertia
- T_{rot} is aerodynamic torque
- θ_{rot} is a rotor angle
- J_{gen} is generator inertia
- T_{gen} is generator torque
- θ_{gen} is generator angle
- T_{shaft} is mechanical torque of flexible shaft
- $\Delta\theta$ is the angular difference

- $\Delta\omega$ is the speed difference between two ends of a shaft
- k is the stiffness
- c is the damping coefficient.

Now,

H is used as the inertia time constant and is given by,

$$H = \frac{JW_{base}^2}{2P_{base}}$$

Unlike many p.u values that are without any unit, inertia time constant is measured in seconds (s).

The above equations can be transformed by taking laplace into

$$W_{rot\ p.u} = \frac{1}{2sH_{rot\ p.u}} (T_{rot\ p.u} - T_{shaft\ p.u}) \quad (4.1)$$

$$W_{gen\ p.u} = \frac{1}{2sH_{gen\ p.u}} (T_{shaft\ p.u} - T_{gen\ p.u}) \quad (4.2)$$

$$T_{shaft\ p.u} = k\Delta\theta_{pu} + c\Delta w_{pu} \quad (4.3)$$

Equations (4.1) – (4.3) are used to implement the two-mass model behavior shown in Figure 26 where

$P_{(aero)}$ is aerodynamic power

H_{rot} is the wind turbine's rotor inertia

$w_{(rot)}$ is the rotor speed

$P_{(meas)}$ is the measured power

H_{gen} is the constant inertia of the generator

w_{gen} is the generator speed

k is the shaft stiffness

c is the damping constant.

Calculation of various parameters of mechanical block.

The base value chosen is 2 MW which is the maximum power of the wind turbine.

$$P_{base} = 2MW$$

Considering a 50 Hz electrical system, the electrical base speed in rad/s becomes,

$$w_{base.el} = 50 * 2 * 3.14 = 314.16 \text{ rad/s}$$

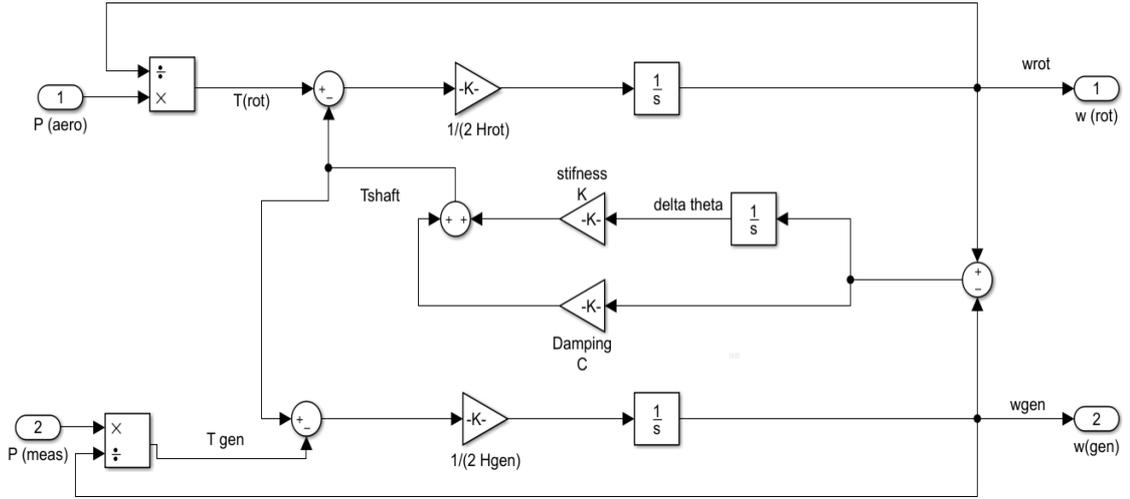


Figure 26. Mechanical block Simulink model

LS and HS are the acronyms for Low speed and HS side of the shaft i.e rotor and generator respectively.

$$\theta_{base} = 1 \text{ rad (traditional choice)}$$

$$RPM = 3000 \text{ (generator's)}$$

Calculations of the High Speed (HS) side:

$$\omega_{base,HS} = \frac{\omega_{base,el}}{n_{pp}} = \frac{314.16}{2} \text{ rad/s} = 157.1 \text{ rad/s}$$

$$\theta_{base,HS} = \frac{\theta_{base,el.}}{n_{pp}} = \frac{1}{2} \text{ rad} = 0.5 \text{ rad}$$

$$RPM_{nom,HS} = \frac{RPM_{nom,el}}{n_{pp}} = \frac{3000}{2} = 1500$$

Calculations for Low Speed (LS) side:

$$\omega_{base,LS} = \frac{\omega_{base,el}}{n_{pp}n_{gear}} = \frac{314.16}{2 * 93.75} = 1.676 \text{ rad/s}$$

$$\theta_{base,LS} = \frac{\theta_{base,el.}}{n_{pp}n_{gear}} = \frac{1.0}{2 * 93.75} \text{ rad} = 0.00533 \text{ rad}$$

$$RPM_{nom,LS} = \frac{RPM_{nom,el}}{n_{pp}n_{gear}} = \frac{3000}{2 * 93.75} = 16$$

Using the angular speed base values the inertia time constants can be calculated as,

$$H_{gen} = \frac{J_{gen}(\omega_{base,HS})^2}{2P_{base}} = 0.75s$$

$$H_{turb} = \frac{J_{turb}(w_{base,LS})^2}{2P_{base}} = 4.5s$$

4.5.4. Maximum Power Point Tracking (MPPT) Block

Each wind turbine has a MPPT table that shows the relation between power output of turbine (P_{ref}) and generator speed (w_{gen}). The MPPT block takes filtered generator speed as input and gives the optimized power P_{ref} as an output.

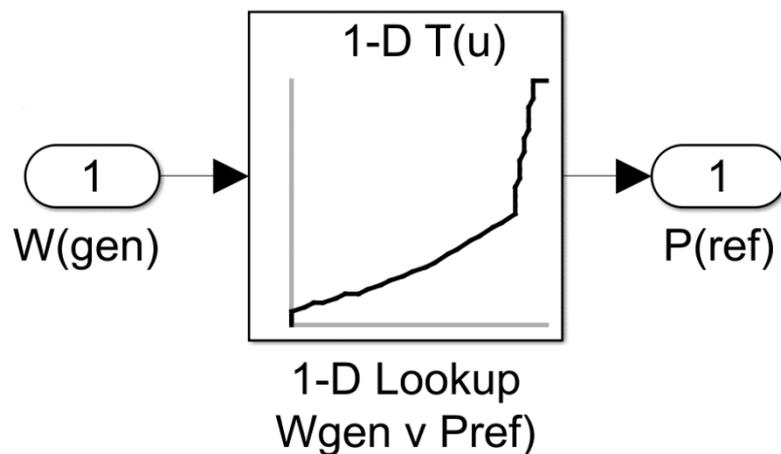


Figure 27. MPPT Lookup table

4.6. Wind Turbine Model Performance

The input to the model wind turbine is the wind speed which is fed to the aerodynamic block. The performance of the model is evaluated for deterministic wind speed and turbulent wind speeds

4.6.1. Performance Under Pre-Defined Wind Speeds

The modelled wind turbine was tested first for a pre-defined increasing wind speed input ranging from 4m/s up to 21m/s. which covers all the three portions of the power curve discussed in section 2.4.

Figure 28 shows the pitch value (degrees), generator's rotational speed (p.u) and the power output (p.u) against the wind speed which is increasing deterministically from 4 m/s to 12 m/s. This bracket of wind speed corresponds to the power optimization zone of the power curve. The pitch value remains at 0 degrees to keep the angle of the turbine's wings in optimal position and extract maximum power.

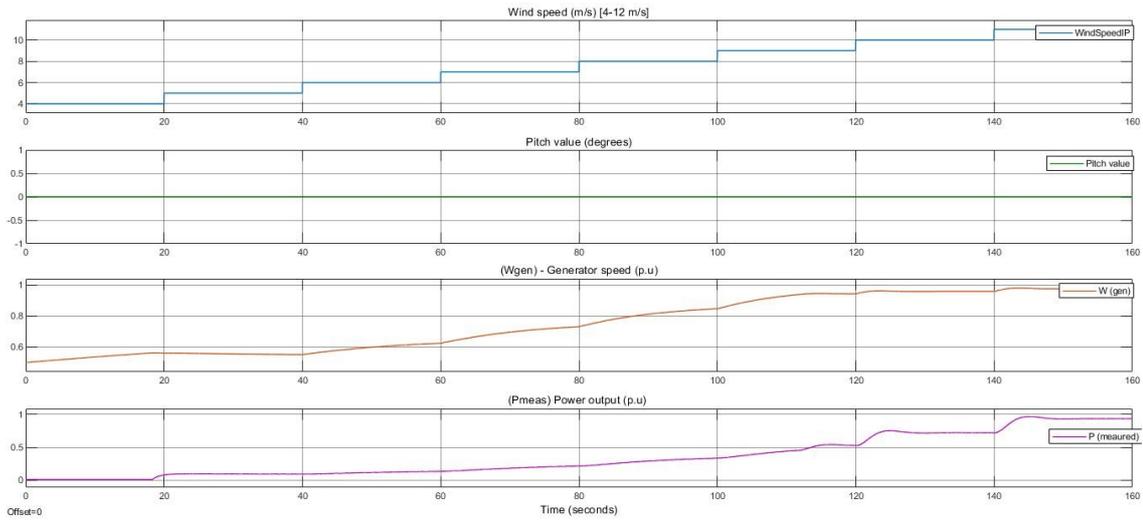


Figure 28. Simulation of wind turbine model under predefined wind speeds (5-13m/s)

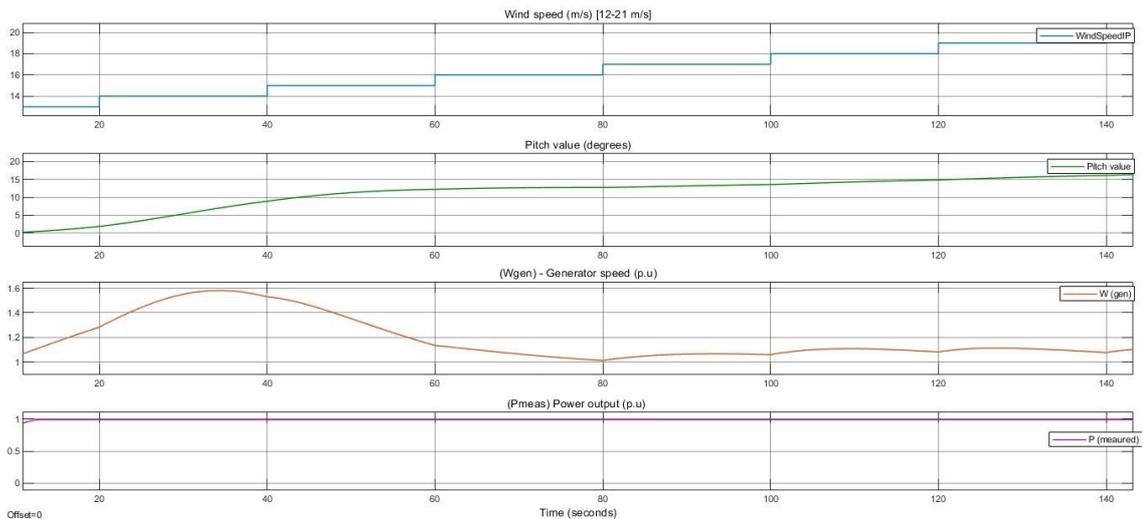


Figure 29. Simulation of wind turbine model under predefined increasing wind speeds(12-21m/s)

Figure 29 shows the turbines output against deterministically increasing wind

speed 12m/s to 21 m/s which corresponds to power limitation zone of the power curve. The pitch angle values for this range are increasing hence adjusting the turbine blade angles to the incoming wind speeds which caps the output for the wind turbine to 1 p.u.

4.6.2. Performance Under Turbulent Wind Speeds

The wind turbine model was tested for a turbulent wind speed data which varies around the rated wind speed of 11 m/s . So, the wind turbine covers both the power optimization as well as power limitation zone. The wind speed, pitch value, generator speed and power measurement are shown in

Figure 30. The wind speed data is based on the real wind data from a 100m met mast located in Izmir Institute of Technology.

For the wind speeds greater than the rated, output is held at 1 p.u by pitch controller.

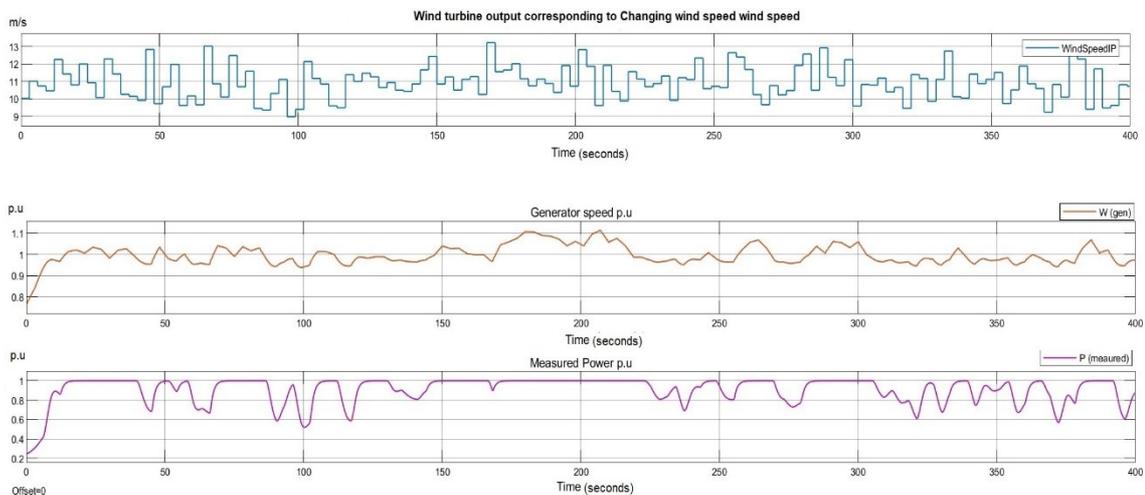


Figure 30. Simulation of wind turbine model under turbulent wind speeds

4.7. Isolated Power System Modelling

As discussed in chapter 2, the role of wind power plants or wind turbines in frequency regulation becomes substantial when the penetration of wind generation

exceeds 10% in a power system. In this thesis an isolated simple power system is considered for simulation purposes consisting of electrical load, steam turbine generator and a small wind farm comprising four identical type D wind turbines. This configuration is selected for wind turbines to have a substantial percentage in the generation. A one-line diagram of the isolated power system is shown in Figure 32.

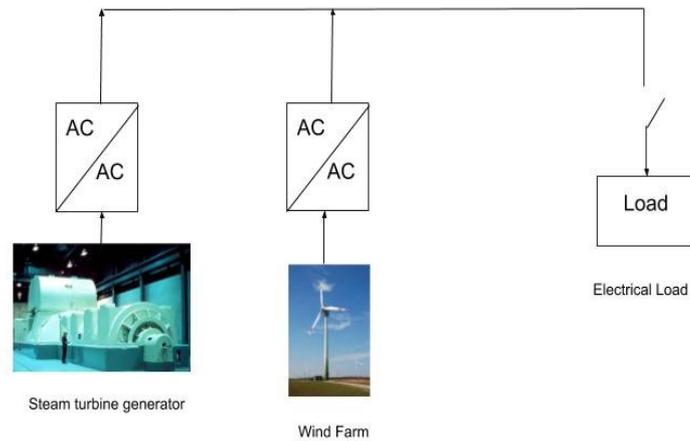


Figure 31. Isolated power system containing steam turbine generator, wind farm and electrical load.

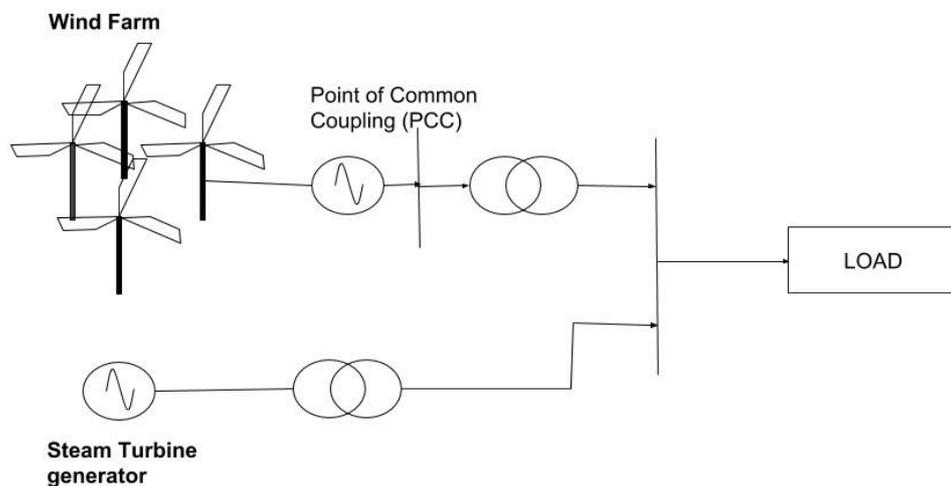


Figure 32. One-line diagram of isolated power system

Table 4. Isolated power system parameters

Wind generations	$4 \times 2 = 8\text{MW}$
Steam turbine Generation	50 MW
Load	50 MW

A technically-effective isolated power system provides a firm electric power, using wind power to its maximum potential to reduce the fuel costs. The extra cost incurred on the wind turbines and other system control options is recovered in terms of fuel costs over time.

4.7.1. Steam Turbine Generator Modelling

The various components of modelling the steam turbine generator are its governor, turbine, prime over and load. The first step in analyzing these components is their mathematical modelling (Saadat, 2010).

4.7.1.1. Generator Model

The swing equation for a synchronous generator can be restated as

$$\frac{2H}{w_s} \frac{d^2\delta}{dt^2} = \Delta P_m - \Delta P_e \quad (4.4)$$

Where,

$$H = \frac{\text{kinetic energy in MJ at rated speed}}{\text{machine rating in MVA}} = \frac{Jw_s^2}{S_B}$$

' P_m ' (pu) and ' P_e ' (pu) are the per unit mechanical and per unit electrical power respectively.

' w_s ' is the synchronous speed of the generator (constant)

' δ ' is the electrical power angle

In terms of a small deviation of speed,

$$\frac{d\Delta \frac{w}{w_s}}{dt} = \frac{1}{2H} (\Delta P_m - \Delta P_e)$$

with speed expressed in per unit

$$\frac{d\Delta w}{dt} = \frac{1}{2H} (\Delta P_m - \Delta P_e)$$

taking Laplace transform on both sides

$$\Delta w_r = \frac{1}{2Hs} [\Delta P_m(s) - \Delta P_e(s)] \quad (4.5)$$

Let

$$M = 2H$$

The block diagram representation of above equation is as under

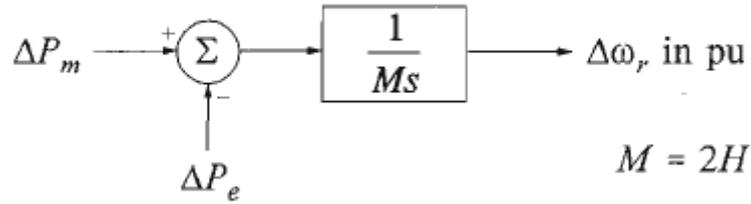


Figure 33. Generator model

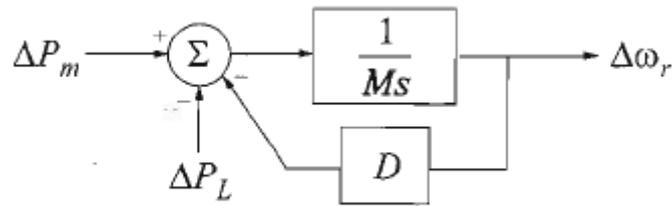
4.7.1.2. Load Model

The electrical load in a power system can consist of variety of electrical devices. The resistive load such as heating, and lighting is insensitive to the changes in frequency, while the inductive load such as motors are sensitive to the changes in frequency.

There are loads that are composite which means that they consist of both a frequency sensitive and insensitive portion and mathematically can be depicted as.

$$\Delta P_e = \Delta P_L + D\Delta w \quad (4.6)$$

Where, ΔP_L is the frequency insensitive and $D\Delta w$ is the frequency sensitive load. 'D' is defined as the percentage change of load divided by percentage change in frequency. For example, if a load undergoes a change of 2 percent results in 1 percent change in frequency the value of D is 2. Figure 34 shows the result after including load model in the generator block diagram.



which can further be reduced to

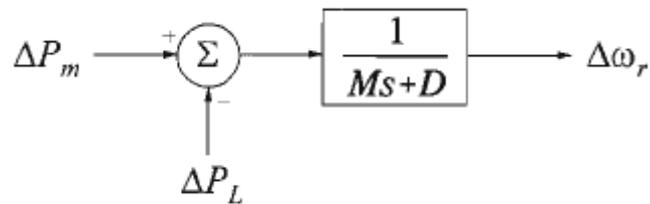


Figure 34. Generator and load block combined

4.7.1.3. Prime-Mover Model

The prime mover is basically the mechanical power responsible for rotating the generators. In the case of steam turbine generator this mechanical power comes from steam turbine. They relate the mechanical power output P_e to the valve position. While the modelling of various types of prime-movers is different, a simple form of prime mover can be modelled by a simple time constant ' τ_T ', whose transfer function is given by

$$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_v(s)} = \frac{1}{1 + \tau_T s} \quad (4.7)$$

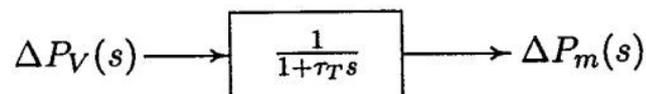


Figure 35. Prime-mover model

4.7.1.4. Governor Model

When an electrical load is increased the excessive power is supplied by the rotating part of the governor through the stored kinetic energy. This causes the turbine

speed to slow down and hence the system frequency drops which is then sensed by the governor which gives a signal to the valve to open and increase the water or steam flow depending on the turbine type (Ackermann, 2012). Earlier types of governors were called the Watt governors and consisted of the fly-balls. The modern governors use the electronic controllers to provide the frequency stabilization.

There are two type of governor models

- i. Isochronous governor model
- ii. Speed droop governor model

4.7.1.5. Isochronous Governor Model

Isochronous governor model keeps the frequency constant always in response to the changing load. The block diagram and the frequency response are shown.

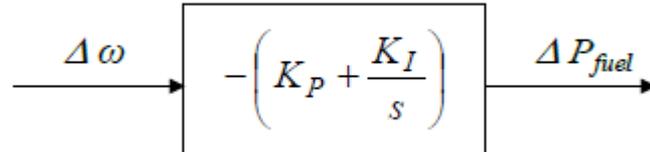


Figure 36. Isochronous governor model

K_p and K_i are the proportional and Integral controller gains. The input $\Delta \omega$ is change in the frequency and the error signal is amplified and integrated to generate the delta P fuel that in turn brings the frequency back to normal.

4.7.1.6. Speed Droop Governor Model

The speed droop governor has a characteristic negative slope. Which means that with the increase in load and drop of frequency the output power of the unit is increased. The slope of the curve is represented by R and is called speed regulation. The speed droop

governor acts as comparator where its output ΔP_g is the difference between the reference power ΔP_{ref} and $\frac{1}{R} \Delta \omega$.

$$\Delta P_g = \Delta P_{ref} - \frac{1}{R} \Delta \omega$$

Taking Laplace and re arranging yields

$$\Delta P_g(s) = \Delta P_{ref} - \frac{1}{R} \Delta \Omega(s)$$

Figure 37 shows the frequency responses of generator units equipped with isochronous and speed droop governor.

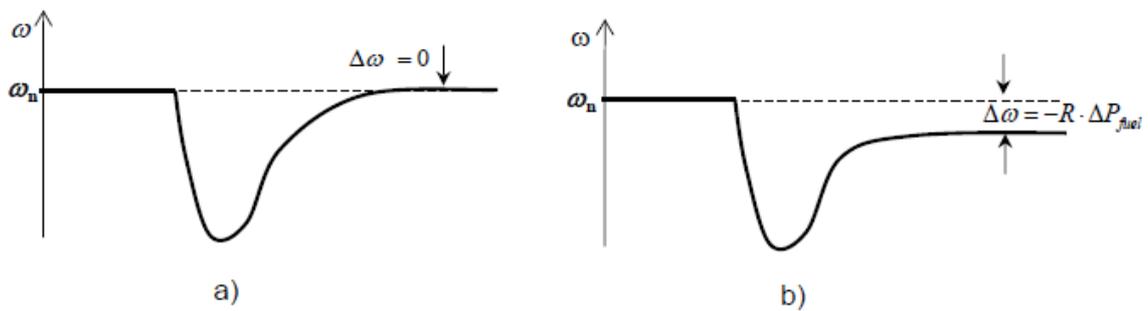


Figure 37.a) frequency response of an Isochronous governor
b) frequency response of a speed droop governor

The various components of the steam turbine generator are combined in Figure 38. Isochronous governor is used in the modelling.

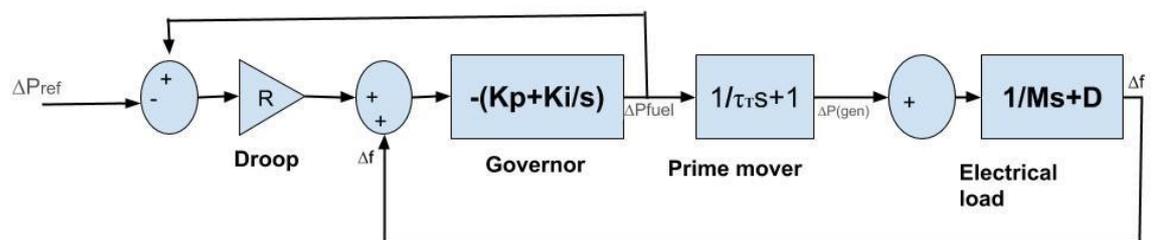


Figure 38. Steam turbine generator model

Other than the steam turbine generator a wind farm consisting of four identical turbines is the source of power generation in the isolated power system considered in this thesis. The wind turbines are located such that there is no wake disturbance from one wind turbine to another and the outputs of one turbine is multiplied by 4.

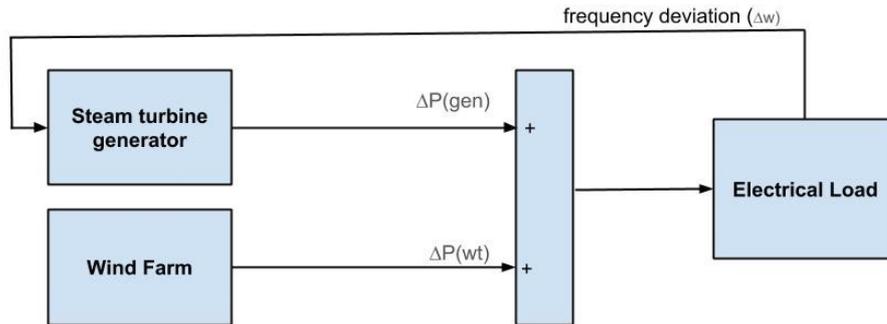


Figure 39. Block diagram of isolated power system

In the Figure 39 the electrical load is being fed by the generator and wind farm. The wind turbines in the wind farm are not participating in the frequency control and therefore the frequency deviation (Δw) is only being fed back to the steam turbine generator. A disturbance in the form of a sudden load increase will decrease the frequency and the steam turbine generator provides the frequency control response.

Figure 40 shows the Simulink block diagram of this setup. The disturbance in the form of a sudden load increase is introduced in the form of a unit step of 0.2 pu at 10 seconds. 0.2 pu corresponds to 10 MW for a 50 MW load. This leads to the drop in the value of frequency because the system sees it as a disbalance between the generation and the load.

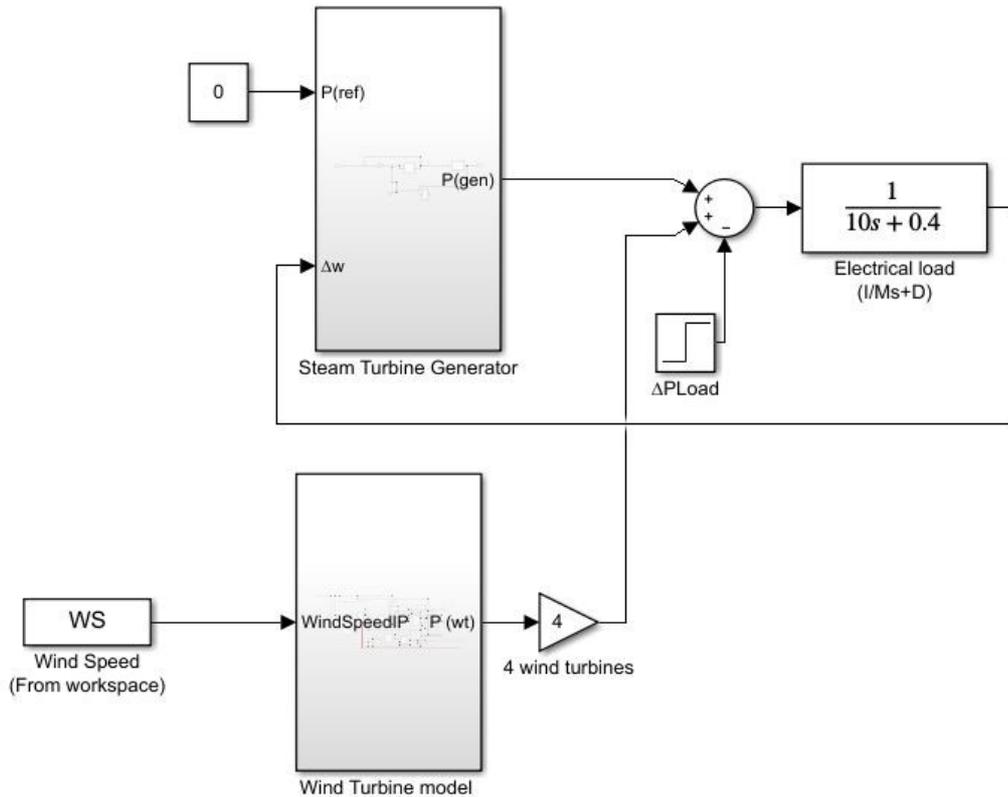


Figure 40. Simulink diagram of isolated power system without contribution of wind turbine in frequency control

4.8. Cause Of Frequency Drop

The frequency drop at the load side occurs due to the loss of generation and in power system studies it can be assumed as a N-1 contingency. Type C and Type D wind turbines can operate at constant frequency mode (i.e. there is a constant frequency input at the grid side convertor) or a system frequency following mode (i.e. grid side convertor controls the V_{dc} (DC link voltage and Q (reactive power)). In this thesis the type D wind turbine is operating at the system frequency following mode where the convertor output's frequency will vary depending on the frequency fluctuations in the system. In the simulations an event of sudden load increase is simulated in the form of a step input. The load increase creates a disbalance between the generation and the consumption which leads to a frequency drop. The conventional generation (steam turbine generator in this case) is equipped with the governor control which tends to bring the frequency back to its nominal value. However, in isolated power systems the maximum load power is intended

to be met by wind turbines because of their low cost and conventional generators are operated at least capacities to save fuel. Therefore, the aim is to meet the frequency stabilization through wind turbine.

In a network a drop in frequency value can result in high magnetizing currents in the frequency sensitive load such as induction motors and the transformer.

4.9. Inertia Controller

The main purpose of the inertia controller is for the wind turbines to use their rotor's inertia to provide the frequency support. It enables the turbine to provide the surge of power for the first few seconds after the disturbance, using the kinetic energy stored in the blades of the wind turbine (wind turbine inertia). The disturbance can be in the form of loss of a major chunk of generation, for example the steam turbine generator in the isolated power system stops producing power or it is also attributed to a sudden increase of a load (which is done here). In the simulation of the isolated power system, a step response equivalent to 0.2 p.u (10 MW) is used to replicate the sudden increase of load.

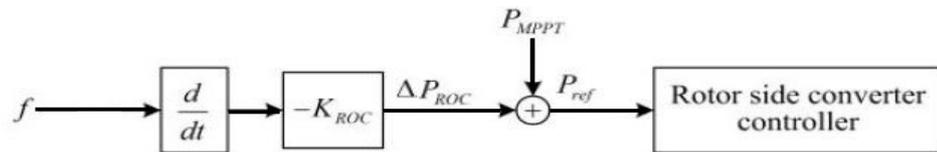


Figure 41. Inertia controller

The inertial controller is meant to control the fast drop in frequency after the disturbance. It consists of a derivative block $\frac{d}{dt}$, which takes the derivative of the falling frequency and multiplies with the gain 'K_{ROC}'.

The output is given by

$$\Delta P_{ROC} = -K_{ROC} \frac{df}{dt}$$

where,

- ' ΔP_{ROC} ' is the output of the inertia controller (expressed in p.u).

- ' K_{ROCOF} ' is the gain.
- $\frac{df}{dt}$ is the derivative of actual frequency (after the disturbance)
- P_{MPPT} is the maximum power output of wind turbine at the given speed.

The derivative of the changing frequency (which is negative for the decreasing frequency) is multiplied to the gain $-K_{ROCOF}$. The output of the branch ΔP_{ROCOF} is the positive momentary power surge added to the otherwise normal power output P_{MPPT} of the wind turbine. The output P_{ref} which is the sum of P_{MPPT} and ΔP_{ROCOF} is then fed to the rotor side converter which controls the torque of the wind turbine generator. It rotates the generator more than its present speed by an amount equal to ΔP_{ROCOF} using the inherent inertia of the wind turbine rotors. The value of gain $-K_{ROCOF}$ is 4 that gives a balance between overshoot and the damping of frequency. The value of the gain is given in Appendix B.

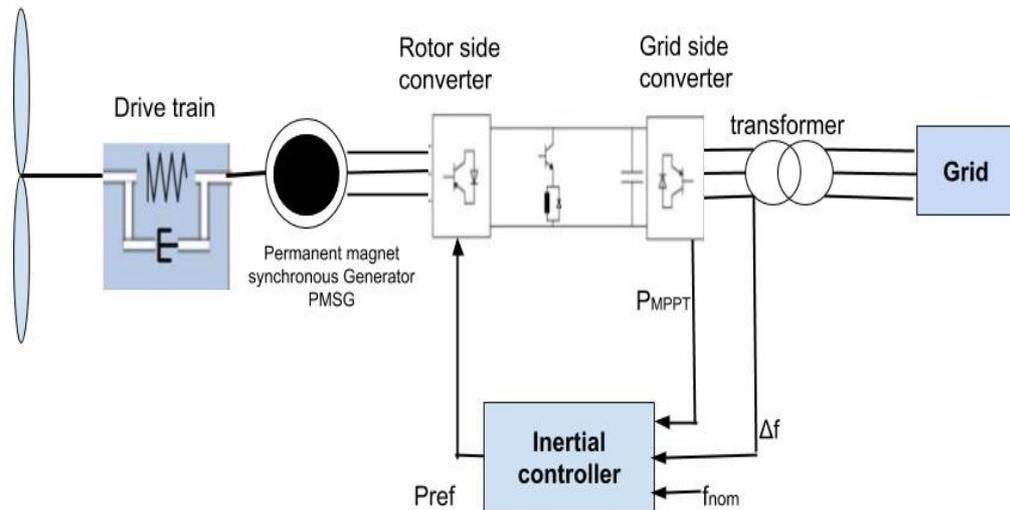


Figure 42. Wind turbine with inertia controller

Figure 42 shows the wind turbine equipped with the inertia controller. In a wind turbine block diagram the inertia controller takes the power input from the MPPT block and feeds the reference power to rotor side converter which in turn feeds it to the generator side of the drivetrain in mechanical block as shown in Figure 43.

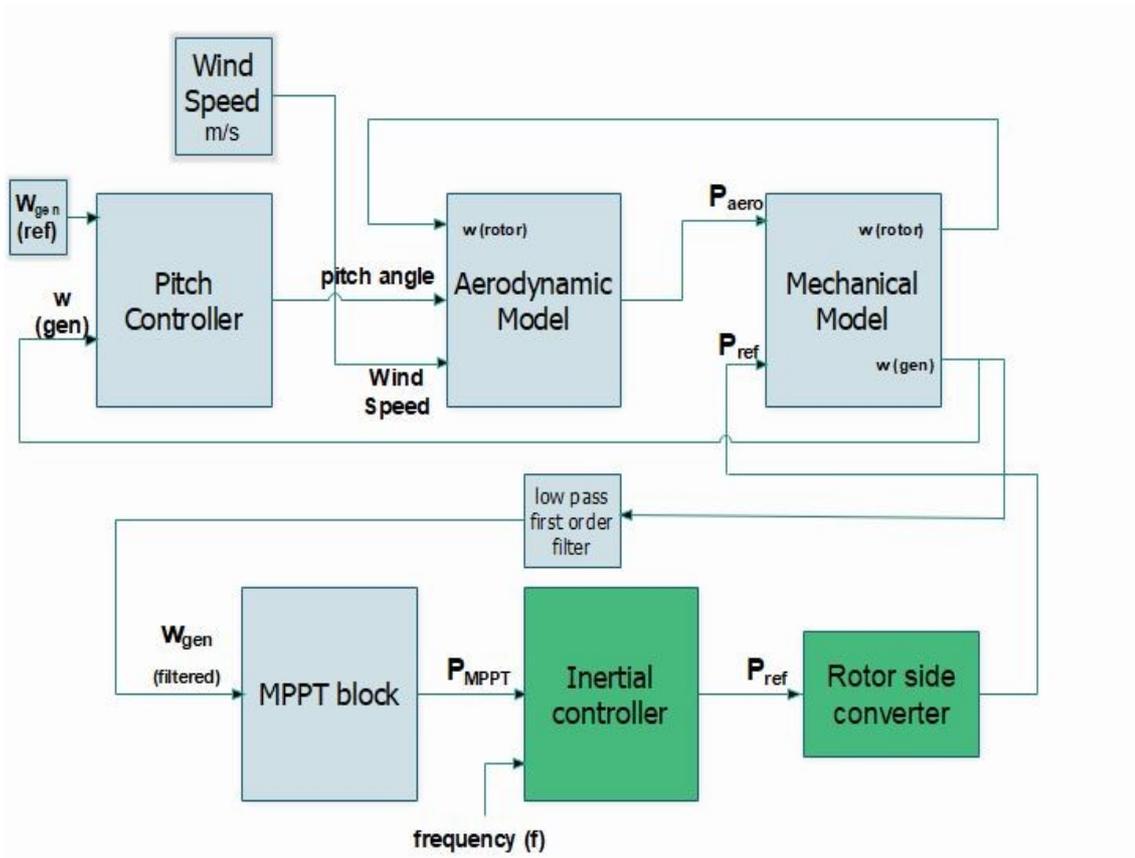


Figure 43. Inertia controller in Wind turbine's block diagram

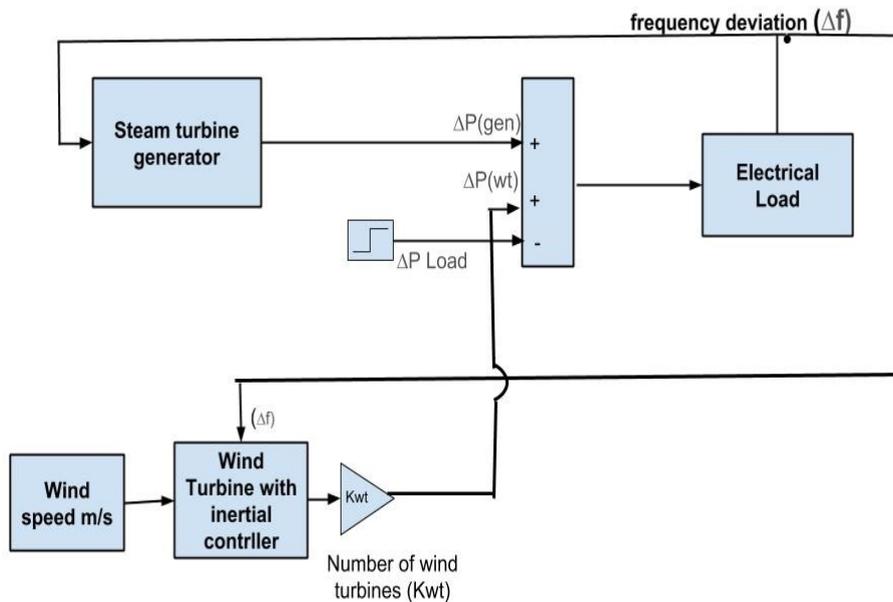


Figure 44. Block diagram of isolated power system with contribution of wind turbines in frequency control through inertia controller

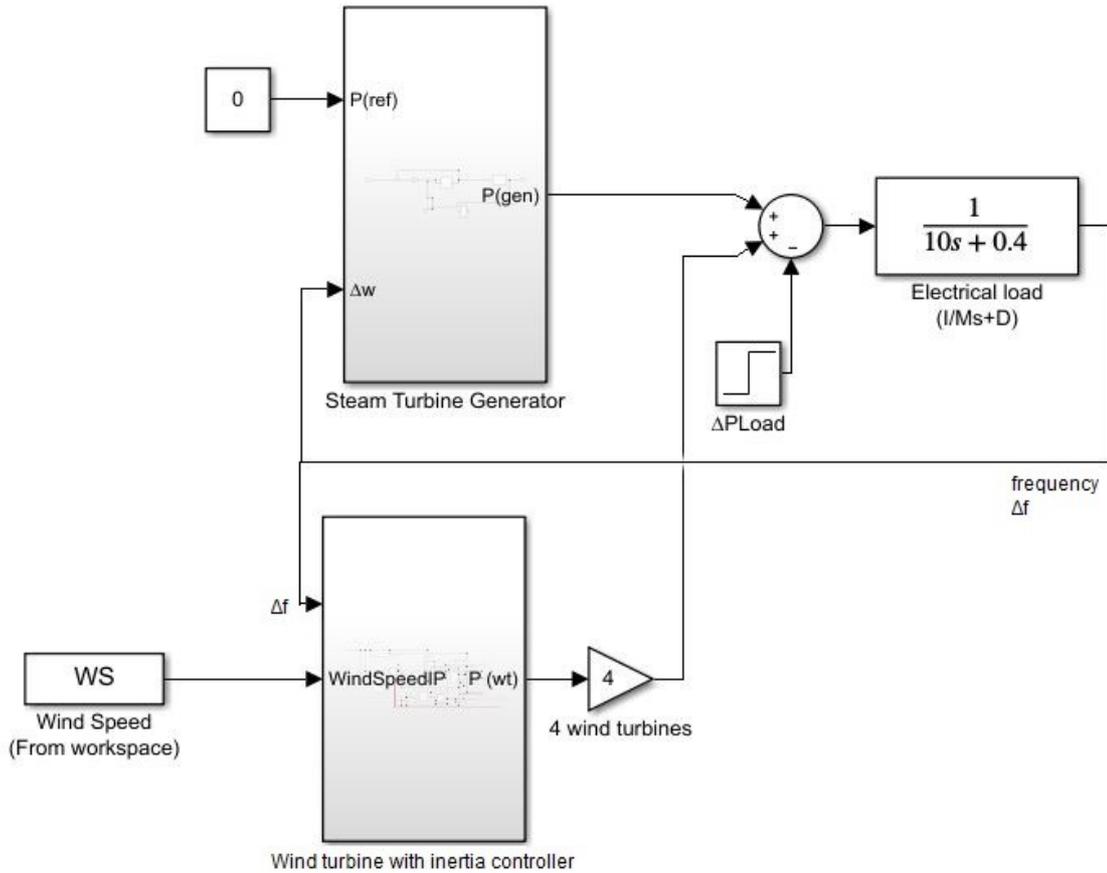


Figure 45. Simulink diagram of Isolated power system with inertia controller

4.10. Droop Controller

While the inertial controller keeps in check the rate of change of frequency (ROCOF) and provides inertia response, the droop controller provides primary frequency control by correcting the offset and helps bringing back the frequency to its nominal value. Its output is proportional to the measured frequency deviation. The output of this loop is given by

$$\Delta P_{dro} = -K_{dro}(f - f_{nom})$$

where

ΔP_{dro} is the power added or subtracted by the droop control loop

K_{dro} is the gain of droop

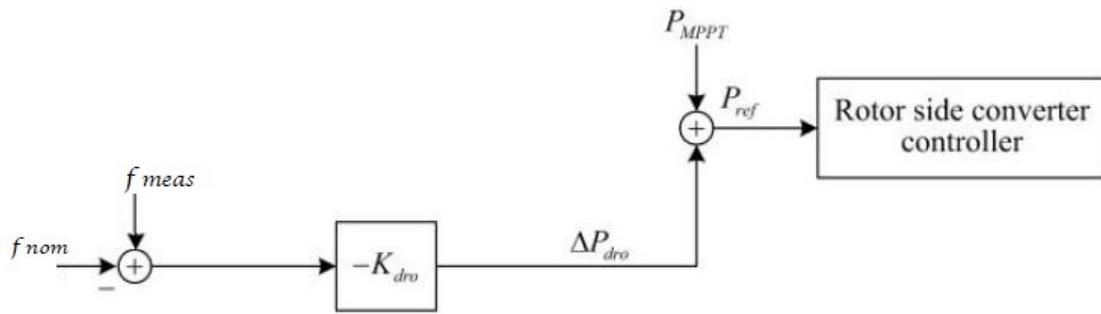


Figure 46. Droop controller

The droop controller tends to correct the frequency offset by multiplying the difference between the actual and nominal frequency with the gain $-K_{dro}$. The output ΔP_{dro} is again the extra surge of power generated by using the inherent inertia of the turbine's rotor added to the turbines normal power output P_{MPPT} at the given wind speed. K_{dro} is optimized to have minimum overshoot and damping of the frequency.

The power output from the inertial controller P_{ref} is fed to the rotor side of converter which rotates the generator more than its present speed using the inherent inertia of the wind turbine rotors.

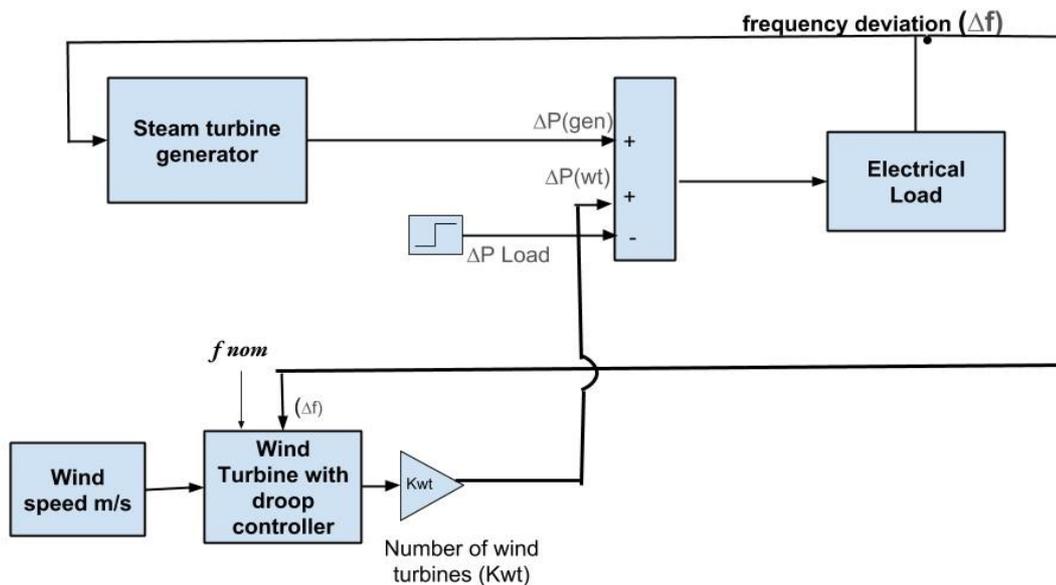


Figure 47. Block diagram of isolated power system with contribution of wind turbines in frequency control through droop controller

4.11. Recovery Mode Of Wind Turbine

After the overproduction period, the wind turbine's rotor slows down and enters the recovery mode. This means that the output of the turbine falls the optimal output level P_{MPPT} for a while and restores back to it after some time.

4.12. Simulations and Results

4.12.1. Effect Of Disturbance On Frequency

The effect of disturbance on frequency is simulated for the three cases:

- i) Without any contribution to frequency control from wind turbines.
- ii) With contribution to frequency control from wind turbine with inertia controller.
- iii) With contribution to frequency control from wind turbine with droop controller.

A disturbance in the form of a unit step input was applied at time 10 sec and the frequency of the system at the load end was measured for three cases. The wind speed input is constant at 10.8 m/s.

Figure 49 shows the frequency deviations for all the three cases. For the case of no frequency control contribution from the wind turbine, the frequency drops to 49.83 Hz. In this case the primary frequency control is provided completely by the conventional generator. The frequency oscillates until 20 seconds before becoming stable at 50Hz.

For the case of wind turbine contribution through inertial controller the frequency drops to 49.91 Hz which means that by emulation of inertia from the wind turbine the

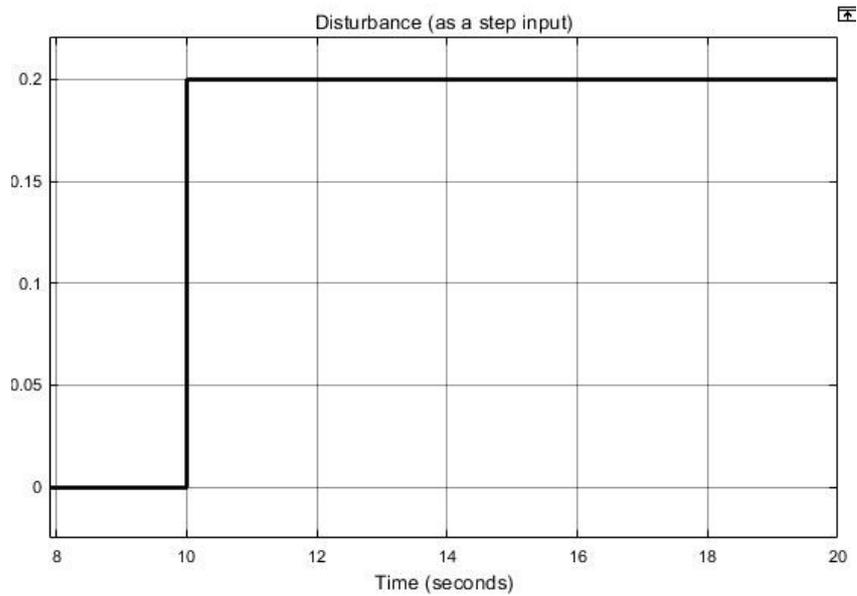


Figure 48. A load increase (disturbance) in the form of unit step

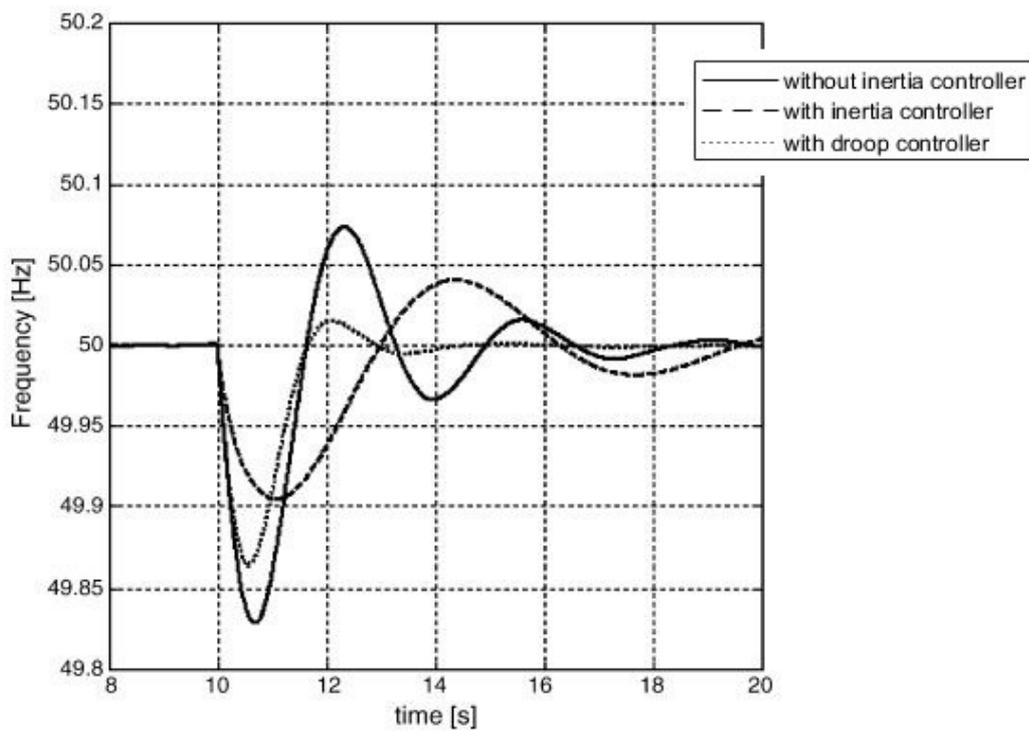


Figure 49. Frequency deviation after disturbance. a) Without inertial controller – *solid line*
 b) with inertial controller – *dashed line* c) with droop controller – *dotted line*

drop in frequency is less for the same amount of disturbance. The oscillations are more in this case as the turbine goes in to recovery mode.

For the case of droop controller, the drop in frequency is 49.87 Hz but in this case there is no over shoot in the frequency.

4.12.2. Effect Of Disturbance On Turbine's Power Output

Figure 50 shows the power output of the wind turbine for the case of inertial and droop controller. Before the disturbance the wind turbine is producing a power equal to 0.9 p.u corresponding to a wind speed of 10.8m/s. As soon the disturbance occurs the inertial controller provides a surge in power up to 1.23p.u. This surge is provided by using the inherent inertia of the turbine rotors and plays a part in controlling the frequency drop. After the surge, the turbine enters a recovery phases and the speed of rotor drops

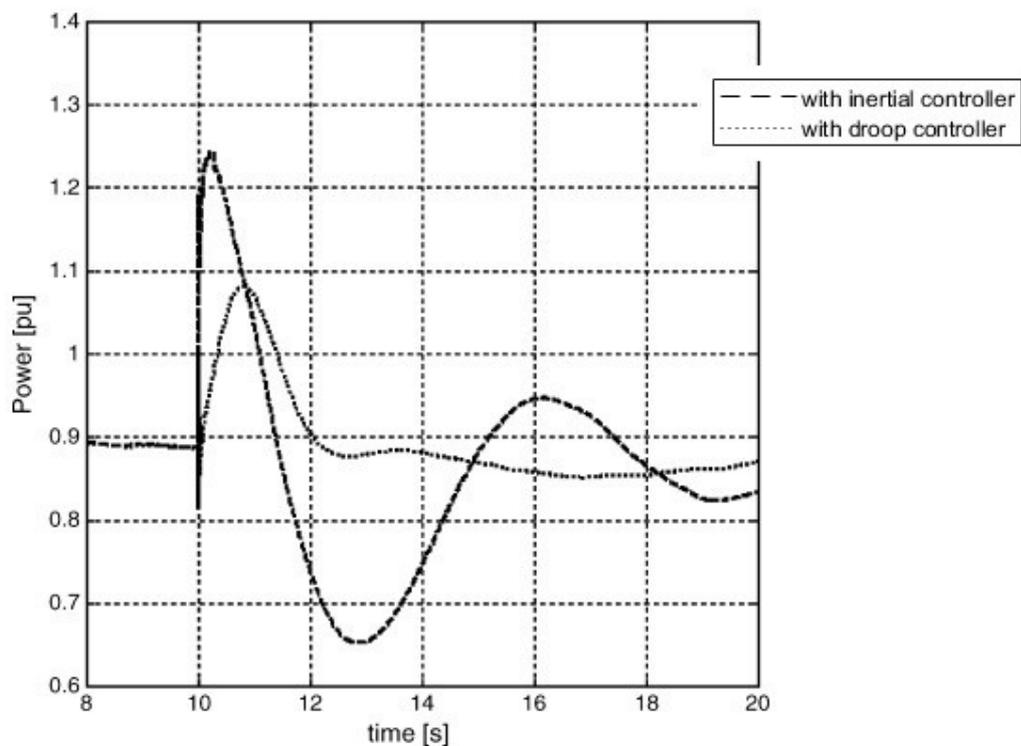


Figure 50. Power output of wind turbine [p.u] for inertia and droop controllers

Likewise for the droop controller, the turbine provides a surge of power and increases its output from 0.9 p.u to almost 1.1 p.u. However, the recovery phase in this case is less severe than inertial controller.

4.13. Discussion

When comparing the two controllers, the droop controller performs better than

the inertia controller. The drop of frequency in droop controller is slightly more than the inertial controller but there is no over shoot in the frequency response. Looking at the power output from wind turbine, in the case of droop controller the required power is smaller and the mechanical and electrical stress on the drive train and power electronics is less. However, both the controllers give a favorable result as compared to the case of no frequency support from the wind turbine. Therefore, in an isolated grid containing significant portion of wind power, the individual wind turbines in the wind farms can be provided with these controllers for better frequency stabilization in the grid. The momentary surge in the power of the wind turbine comes at the cost of the kinetic energy stored in the rotating blades. However, this surge of power may also cause extra stress on the drive train. The limits for the drive train and mechanical model also need to be considered.

4.14. Future Work

In this thesis the wake effect between the wind turbines in a wind farm was not considered. The output of one turbine was multiplied by 4. It was assumed that the four wind turbines in the wind farm are located at enough distance to not cause any wake disturbances. However, this is an ideal case and a wake model between the turbines can be considered for future studies. Also, an isolated power system was considered to have only steam turbine generator and wind generation. However, the modern isolated systems are equipped with solar panels, Battery Energy Storage Systems (BESS) and may contain other Distributed Energy Resources as well. The inertia of the system in the presence of these other components will be different which will affect the grid's frequency in a different way. The implementation of inertial and droop controller considering these other components of suitable rating is recommended as future research work.

CHAPTER 5

CONCLUSION

The use of high percentage of wind power in isolated grid can cause severe frequency stabilizing problems. There is therefore a need of inertia emulation from the wind turbines. The inertial controller and a droop controller for providing such frequency control are designed and the performances of both the controllers are compared. The droop controller tends to have better frequency stabilization performance while the inertial controller has the least amount of frequency dip in the case of a disturbance. There were various assumptions made during the simulations: the most important is zero wake affect within the wind farm, which rarely is a case.

The results show that inertial or a droop controller in a wind turbine help support a dropping frequency which becomes vital in isolated power systems with less conventional generation and hence less conventional inertia response. This contribution from the wind turbines not only eases the pressure from the conventional generator but can also lead to reducing reserve generation requirements in the case of a large power system cutting economic costs as a result.

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APPENDICES

APPENDIX A.

PARAMETERS FOR WIND TURBINE MODEL

The wind turbine that is used in this thesis is variable speed wind turbine with 11m/s rated wind speed. The wind turbine parameters used in the modelling are given in the table below.

Table A.1 Parameters of wind turbine

<i>Pitch Control Block</i>			
Actuator			
Blade angle controller gain	K_{pitch}	(deg/pu)	1.4
Blade angle controller time constant	T_{pitch}	(s)	2.2
Generator speed nominal	ω_{nom}	(rpm)	1500
Servo mechanism			
Servo time constant	T_{servo}	(s)	0.1
Minimum blade angle	Pitch_min	degrees	0
Maximum blade angle	Pitch_max	degrees	30
Rate of change	Rate ($\frac{d\beta}{dt}$)	(deg/s)	10/-10

Table A.2 Aerodynamic power block

<i>Aerodynamic power block</i>			
Air density	Rho	(kg/m ³)	1.225
Rotor radius	R	m	40

Table A.3. Two mass mechanical block

<i>Two mass mechanical block</i>			
Nominal power	P_n	(MW)	2
Number of pole pairs	N_{pp}	-	2
Gear ratio	N_{gear}	-	96

Inertia of generator	I_{gen}	(kgm ²)	151
Inertia of rotor	I_{rot}	(kgm ²)	8682000
Low speed shaft stiffness	K_{sh}	(Nm/rad)	111360000
Shaft damping	C	(Nm/rad/s)	329760

Table A.4. Power control block

Power control block			
Active power control gain	K_p	-	1
Power measurement filter time constant	T_{pf}	(s)	0.001
Active power control gain	K_p	Deg/unit	0.1
Active power control time constant	T_p	(s)	0.1
Max active current reference	I_{max}	p.u	1.3
Min active current reference	I_{min}	p.u	-1.3

Per unit values of mechanical block			
Equivalent inertia constant	H_{eq}	p.u	0.91
Inertia constant of generator	H_{gen}	[s]	0.75
Inertia constant of rotor	H_{rot}	[s]	4.5
Shaft stiffness	K	p.u	84.4
Shaft damping	C	p.u	4

MATLAB code for wind turbine model

```

%% Wind Turbine Model
% close all; clear all; clc;
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Variable Inputs defined by user
% [m/s] Initial wind speed >5m/s Only for stand alone use
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Data
%-----
% Wind Turbine
Pn=2*10^6; % [W] Nominal power [W]

```

```

D=80; %[m] Rotor diameter
vtip_nom=70; %[m/s] Tip speed at rated power
Igen=151; %[kg m2] Generator inertia
Irot=8682000; %[kg m2] Rotor inertia
Kls=111360000; %[Nm/rad] Low speed shaft stiffness
C=329670; %[Nm/rad/s] Shaft Damping
Npp=2; % [-]Number of pole pairs
Ngear=96; %[] Gear Ratio
rho=1.225; %[kg/m2] Air density %[1.225]
%-----
% Pitch Controller Data
Tservo=0.1; %[s] Sevro time constant
Kp_pitch_control=1.4; %[deg/pu] Blade angle controller (Kpitch)
%[2,0.9]
Ti_pitch_control=2.2; %[s] Blade angle controller time constant
(Tpitch)
theta_min=0; %[deg] minimum blade angle (picth_min) ...theta_min
theta_max=30; %[deg] maximum blade angle (picth_max)
dtheta_max=10; %[deg/s] opening rate of change (rate_max)
dtheta_min=-10; %[deg/s] closing rate of change (rate_min)
%-----
% Speed Filter
tsf=0.2; %[sec]
%-----
% Power Control
Kp_power_filter=1; %[pu] Power measurement filter gain
Ttr=0.01; %[sec] Power measurement time constant
Kp_power_control=1; %[pu] Active power control gain %[1]
Ti_power_control=0.1; %[pu] Active power control time constant %[0.1]
iref_max=1.3; %[pu] Maximum active current reference
iref_min=-1.3; %[pu] Minimum active current reference
% Filter
tif=0.1; %[sec]
%% Calculation of rated (nominal) generator and rotor speed
n_gen_nom=1600.32; % [rpm]
omega_gen_nom=n_gen_nom*2*pi/60;
omega_rot_nom=omega_gen_nom/Ngear; %[rad/sec]
% % omega_rot_nom=vtip_nom/(D/2); %[rad/sec]
% % omega_gen_nom=Ngear*omega_rot_nom; %[rad/sec]
%% Bases
Pbase=Pn; %[W]
omega_gen_base=omega_gen_nom; %[rad/sec]
omega_rot_base=omega_gen_base/Ngear; %[rad/sec]
%% PU values
omega_gen_nom_pu=omega_gen_nom/omega_gen_base; %[pu]
Hrot_pu=0.5*Irot*omega_rot_nom^2/Pn; %[pu]
Hgen_pu=0.5*Igen*omega_gen_nom^2/Pn; %[pu]
Heq_pu=Hrot_pu*Hgen_pu/(Hrot_pu+Hgen_pu); %[pu]
% Calculation of pu stiffness nd damping
Ieq=(Irot*Igen*Ngear^2)/(Irot+Igen*Ngear^2);
f_free_free=(0.5/pi)*sqrt(Kls/Ieq);
f_free_fast=f_free_free*sqrt(Ieq/Irot);
Ksh_pu=4*(pi^2)*(f_free_free^2)*Heq_pu; %[pu] stifness
Csh_pu=4; % [pu] damping
%-----
%% Implementation of MPPT control
load CpRisoe;
load Table_MPPT;
%Final Curve - Look up table
maxP=data.power_vector_pu;
omega_gen_vector_pu=data.omega_gen_vector_pu;

```

```

%% Initial conditions and limitations
wind_init=6; %[m/s]Initial wind speed value
% Pitch Control - Actuator
theta_init=interp1(data.wind_vector,data.pitch_vector,wind_init);%initial
value for the integrator in the Actuator
% Pitch Control
xinit=theta_init/(Kp_pitch_control/Ti_pitch_control); %initial value
for the integrator in the pitch controller
xmax=theta_max*Ti_pitch_control/Kp_pitch_control;
xmin=theta_min*Ti_pitch_control/Kp_pitch_control;
% Mechanical Model
omega_gen_init_pu=interp1(data.wind_vector,data.omega_gen_vector_pu,wi
nd_init);
omega_gen_init=omega_gen_init_pu*omega_gen_base;
omega_rot_init=omega_gen_init/Ngear;
omega_rot_init_pu=omega_rot_init/omega_rot_base;
% P_init_pu=interp1(data.wind_vector,data.power_vector_pu,wind_init);
P_init_pu=0.5*rho*pi*(D/2)^2*wind_init^3*interp2(Cp.pitch,Cp.lambda,Cp
.values,theta_init,omega_rot_init_pu*omega_rot_base*0.5*D/wind_init)/P
n;
omega_gen_init_pu2=interp1(data.power_vector_pu,data.omega_gen_vector_
pu,P_init_pu);
thk_init_pu=(1/Ksh_pu)*(P_init_pu/omega_gen_init_pu);
% Power Control
iref_init=P_init_pu; %[pu]
zinit=iref_init*Ti_power_control/Kp_power_control;
zmax=iref_max*Ti_power_control/Kp_power_control;
zmin=iref_min*Ti_power_control/Kp_power_control;
%-----

```

APPENDIX B.

PARAMETERS OF ISOLATED POWER SYSTEM

Table B.1. Parameters of isolated power system

<i>Wind Turbines</i>	
Number of Wind Turbines	4
Installed capacity of wind turbines	8 MW
Equivalent inertia constant of WT	0.91 pu

<i>Steam turbine generator parameters</i>	
Prime mover time constant	2
Governor proportional parameter	20
Governor integral parameter	2
Damping	0.40 pu
Droop	0.04
Delta P _{ref}	0

<i>Inertial and Droop controller gains</i>	
K _{ROC}	4
K _{dro}	4