Power Quality Analysis of Offshore Wind Farms

Evaluating how different turbulence spectra will affect the power quality from offshore winds farms using FAST, TurbSim and MATLAB/Simulink.

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Abstract

As wind power is a variable power source, depending on the wind speed and turbulence, the output power will vary with the changes in wind conditions. Therefore, the aim of this study is to perform power quality analysis from an offshore wind farm with different wind spectra with the purpose to see which conditions that will affect the output power.

The study is done by comparing three different turbulence spectra and wind speeds, with the IEC and NORSOK requirements for offshore operations. First, TurbSim is used to generate wind files with different turbulence spectra and wind speeds. Next, a model named FAST is used to run a simulation with a wind turbine generator. Finally, this FAST model is integrated with a doubly fed induction generator model in Simulink to obtain all the relevant power quality measurements.

Analysing the results of voltage, active and reactive power, the results are indicating that the WTG model works as intended. The wind files created in TurbSim are dependable and variations in wind speed due to turbulence spectra and mean wind speeds, are visible in the result plots. The measurements from the wind turbine generator are within the requirements of NORSOK and IEC.

A functional control system together with power quality improving devices, such as converters, inverters, etc., are necessary in order to obtain a stable and high-quality output power. The voltage in this case within the requirements, but in real cases with changes due to turbulence and wind speed, variations outside the requirements shall quickly be adjusted back to the desired values. As for further work a more detailed model, with higher capacity, located offshore with wave spectra as well as turbulence spectra, would give more comparable results for offshore operators. Another feature of a more detailed model would be including frequency variations.

Preface

Throughout my bachelor's degree in Energy Engineering at Western Norway University of Applied Sciences in Bergen, Norway, the enthusiasm increased for renewable energy sources. During my final year and bachelor's thesis about offshore wind turbines in cooperation with Equinor, my idea of the main field of interest was confirmed – offshore wind energy.

This study is a result of my master's thesis in the study program Renewable Energy at the University of Agder in Grimstad, Norway, which has had a duration of two years. The master's study corresponds to 30 ECTS which represents a workload of 810-900 learning hours. Throughout the study, output power quality and stability from offshore wind farms and the relating problems and difficulties will be addressed. The target group for which this study was written for are those that are involved in development of offshore wind, wind/gas hybrid systems, operators and project owners as well as everyone interesting in power management and power quality analysis of offshore wind turbines.

As a result of the increasing interest in offshore wind, it was desirable to gain a more complex understanding of the challenges and considerations related to operating an offshore wind farm regarding power quality. The master's study period has been an exciting, challenging and interesting time. This semester has contributed to a steep learning curve regarding analyzation of power systems, operations of offshore wind farms, and independent work in general.

I wish to thank my supervisors Professor Van Khang Huynh and Post Doctor Surya Teja Kandukuri, both at UiA Grimstad, for guidance and valuable inputs regarding my study. It has been a different and challenging study time due to the Covid-19 pandemic, which has resulted in guidance and follow-up based on web-based communication. Further, I wish to thank my leader Trygve Sandvik at Siemens for giving me the opportunity to write this study in cooperation with Siemens. Additionally, I want to thank my external supervisors Sigmund Bakka, an engineer at Siemens, together with the rest of the people at Siemens for ideas, contact networks, and discussions. Finally, I want to thank my family, partner, and friends for support and encouragement throughout the whole master period.

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Notations

σ	Standard deviation
ω	Rotational speed [RPM]
ω_r	Rated rotational speed [RPM]
E	Potential energy [J]
f	Frequency [Hz]
H	Inertia constant [s]
I_n	Rated current [A]
P	Rated power [W]
p	Number of pole pairs
P_n	Rated power [W]
Q_n	Reactive power [VAr]
S	Velocity spectra
S_n	Apparent power [VA]

Abbreviations

AC	Alternating Current
CO_2	Carbon Dioxide
CSC	Current Source Converter
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DOF	Degree of Freedom
EMS	Energy Management System
FAST	Fatigue, Aerodynamics, Structures, and Turbulence
FC	Fuel Cell
GTG	Gas Turbine Generators
GTO	Gate Turn-Off
HAWT	Horizontal-Axis Wind Turbine
HRES	Hybrid Renewable Energy System
HWRT	High Wind Range Through
IGBT	Insulated Gate Bipolar Transistor
LQGC	Linear Quadratic Gaussian Controller
MPPT	Maximum Power Point Tracker
MW	Megawatt
O&G	Oil and Gas
OOGP	Offshore Oil and Gas Platform
PI	Proportional Integral (Controller)
PMIG	Permanent Magnet Induction Generator
PMS	Power Management System
PQ	Power Quality
PU	Per Unit
SOP	State of Charge
SR	Spinning Reserve
STATCOM	Static Compensator

SVC	Static VAr Compensator
TSO	Transmission System Operator
UiA	University of Agder
UPQC	Unified Power Quality Conditioner
VSI	Voltage Source Inverter
VSWT	Variable Speed Wind Turbine
WRIG	Wound Rotor Induction Generator
WTG	Wind Turbine Generator

1 Introduction

1.1 Motivation and Background

The oil and gas industry moves toward a higher penetration of renewable energy in power production, attracting new projects with hybrid energy systems. As a result of increasing carbon dioxide (CO_2) taxes and fees, the oil and gas (O&G) installations, both rigid and mobile, must look into more environmentally friendly solutions to run their operations. This is based on the Norwegian Continental Shelf regulated by the Norwegian Government and the Petroleum Safety Authority Norway. The emissions which are considered taxable are those open to the air. The majority of these emissions originate from the combustion of natural gas or diesel turbines, engines and boilers, flaring of natural gas for safety reasons, and storage and loading of crude oil [1].

As wind power is a variable power source, thorough planning is crucial when integrating this type of energy into an isolated power system. Due to the variations in wind energy, the power system will be imbalanced when increasing wind power penetration. This can affect the frequency quality or system stability and decrease the efficiency and power balance in the system. Hence, a modern system must be able to operate and deliver power with sufficient power quality and stability.

The integration of wind energy in a power system with natural gas turbines results in a different operational pattern than conventional thermal power plants. Therefore, an understanding of how the integration of wind energy will affect the stability of the power system is very important for the system operator. Securing an excellent power quality output from the wind turbines is crucial as the hybrid system in this specific case often is an isolated grid located far out at sea. A more thorough description of the motivation case for a hybrid system will be described in Section 1.1.1. If the power consumption is larger than the capacity of the power production, load shedding is used to avoid blackouts. Another feature could be to automatically start and stop consumer units (e.g., diesel generators or gas turbines) under variable loads.

This study presents the master thesis which is carried out in cooperation with Siemens' office in Stavanger, Norway. Siemens is a technology company that offers solutions to multiple industries disciplines, and the largest among the disciplines, the oil and gas industry. The three main areas of competence at Siemens, are electrification, digitalization, and automation. This study will conclude my final year as a master student in renewable energy at the University of Agder (UiA).

1.1.1 Background Motivation Case

Equinor has decided to build a wind farm in the North Sea to provide oil and gas installations with electricity which will reduce the CO_2 emissions from the already operating gas turbine generators (GTGs). This project, named Hywind Tampen, will also reduce the dependence on gas turbines to have a smooth power supply to the installations [2].

The idea is to have 11 wind turbine generators (WTGs) with a rated capacity of 8.6 megawatts (MW) each giving a total capacity of 94.6 MW. 6 of the wind turbines will provide electricity to the two Snorre installations, and 5 wind turbines to the three Gullfaks installations. There are also several gas turbines installed on the oil platforms. The plan for Hywind Tampen is shown in Fig. 1-1.

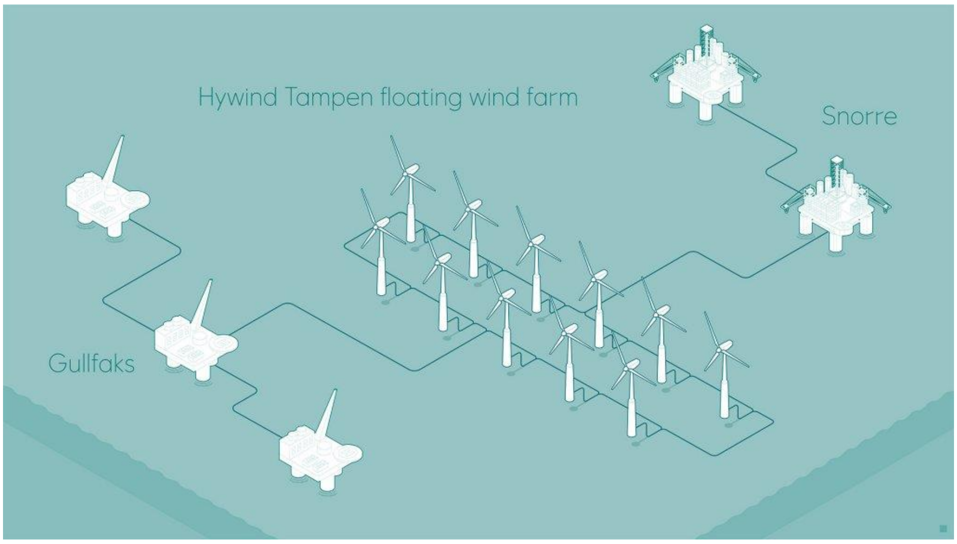

Figure 1-1: Hywind Tampen [2]

There will be an isolated grid for the 5 O&G installations and the 11 wind turbines, and all the electricity demand will need to be provided from wind turbines and gas turbines located on the offshore oil and gas platforms (OOGPs).

The wind turbine chosen for the Hywind Tampen project is Siemens Gamesa’s 8.6 MW offshore turbine. The rotor diameter is 167 meter and the turbine will be placed on top of Hywind floating foundation developed by Equinor, making the turbine well suited for rough Norwegian offshore conditions.

From this motivation case by Equinor, the interest and motivation of studying and analysing power quality from offshore wind farms, or offshore wind turbines specifically, increased. The essentiality of the output power quality can affect how the whole power system has to be structured.

1.2 Preliminary Study

This study is somewhat based on preliminary work [3] done in the second semester of 2019 and will, therefore, be briefly be described before the problem of this study. The preliminary study was a research project of power management systems on hybrid power systems installed on offshore oil and gas installations. The goal was to define the main challenges and important factors in order to obtain a stable power supply to the consumer which in this case was the offshore oil and gas installations as shown in Fig. 1-1. In Simulink, two separate systems, one for the offshore wind farm, and one for the gas turbine were created. The ideal case was to run the two systems together, in a combined / hybrid power system. To be able to do that, a detailed controller was necessary.

It was not within the time frames to create and develop this controller for a hybrid system and was suggested as further work for the project. Such a controller would need detailed control functions which takes time to develop and fine tune in order to get smooth operation of the hybrid system.

The learning outcome of the preliminary study was that these control systems or power management systems of hybrid systems on offshore oil and gas installations are still immature. This can easily be explained because the issue is somewhat novel to in the industry due to the increasing penetration of renewable energy combined with fossil energy production. Hybrid systems onshore cannot directly be compared as they normally are connected to the main grid and do not experience the same difficulties and challenges when it comes to stability. In isolated grid cases, the power quality on the output energy from the wind farm has to be carefully monitored to avoid voltage drops and frequency deviations being fed into the grid.

1.3 Problem Definition

In order to get a complete understanding of how a wind farm is being operated, it is necessary to analyse which aspects and conditions that will influence the power production and power quality from the wind farm. This power quality from the wind farm will then again be a major contribution to a hybrid system. As a hybrid power system consists of multiple power generating units and multiple consumer units, balanced and controlled power management of the system is crucial. In order to predict the gas generator start-up or shut-down time, a detailed and thorough understanding of the wind farm is necessary. This leads to the main goal for this study, and it is formulated as follows.

- Perform power quality analysis from an offshore wind farm with different wind spectra, with the purpose to see which conditions that will affect the output power.

This work intends to evaluate and analyse which external influences in addition to technical devices, that affects the output power quality from an offshore wind farm. By testing different wind and turbulence spectra, it is desirable to analyse how to predict a steady power supply from the wind farm. The main goal applies to offshore wind farms, preferable with floating foundations.

In order to address the research question of this study the following sub-goals were formulated:

- Establish wind turbulence scenarios for the wind farm to be tested in.
- Integrate the FAST simulation model with a Type-3 WTG model in Simulink.

- Test if there are significant differences in power quality and power production during both the IEC turbulence spectra, and the SMOOTH spectra.
- Determine if the power quality can be improved or stabilized even more by devices, such as inverters, converters, etc.

The first goal considers the wind input selection from a technical perspective. The second sub-goal is necessary to measure all the relevant parameters from the offshore wind turbine and further analysis on the results. The third sub-goal allows evaluation of differences in power production and power quality during different turbulence conditions. The fourth sub-goal includes an evaluation of technical improving devices and how they can contribute in this specific case.

1.4 Limitations and Assumptions

In order to complete the problem of this study several limitations and assumptions needs to be considered.

- For this study, a 1.5 MW wind turbine was chosen when building a model in Simulink. The reason for choosing this turbine is that there is a lot of data available for the model, as well as thorough documentation of integrating the Simulink model with FAST. If performing this study on a bigger turbine (higher output power), is desirable, this can be done through scaling up the model created here. Due to time constraints, this will not be included in this study.
- In this study, only 1 wind turbine has been considered instead of a whole wind farm with multiple turbines. This is because the only changes when simulating a wind farm instead of a single wind turbine, is that the rated capacity of the wind turbine is multiplied with the number of turbines in the farm. Therefore, it has been considered as sufficient to only use 1 wind turbine for this analysis.
- The operator requirement listed in NORSOK is assumed to be valid for a 60 Hz system, even though the limits are listed for 50 Hz system. This is because 50 Hz is normally used in the North Sea at offshore oil and gas installations, but as the values are given in per unit (pu) base, it is assumed that they are similar for 60 Hz per unit values.

Further restrictions and assumptions regarding this study will be stated throughout the study.

1.5 Outline of the Study

The structure of this study is organized as follow.

In Chapter 2, the theory that supports the method will be presented. In this study, some of the theory is based on the theory chapter in the preliminary study in [3]. This applies for the major subsections in Chapter 2, except for Chapter 2.1, Chapter 2.8, Chapter 2.9 and Chapter 2.10. Additionally, there has been some changes and updates in the other sections as well.

In chapter 3, a literature review will be presented starting with previous studies on power quality from wind farms. Energy management systems and control of the power distribution and consumption are presented.

In chapter 4, the method will be described. This chapter includes how data was generated and gathered for both turbulence-model in TurbSim and the simulation of the wind farm in FAST. How the FAST model was integrated in Simulink is also described. Finally, a description of the model's specifications, operations and verification process will be presented.

In Chapter 5 the results are given, including a discussion part for each section.

In Chapter 6, the conclusion summing up the findings will be reviewed followed by recommendations for further studies.

2 Theory

This chapter will give the theoretical background for the topic of this master study. Evaluating the output power quality from an offshore wind farm is important when the farm is connected with other power producing units in a hybrid system.

Section 2.1 will give an introduction of wind power generation and the generator type used in this study, as well as basic control functions for wind turbines. Section 2.2 will give an introduction on the integration of wind power in the power systems. This is in order to highlight the complexities that have to be considered at all time when integrating wind power. Section 2.3 introduces the topic of power system stability and reliability. Section 2.4 and 2.5 will give an introduction to frequency and voltage stability and control, both for hybrid systems and offshore wind farms in specific. In Section 2.6, load shedding in power systems is described. Further, energy management system will be described more in details in Section 2.7. Energy management systems are presented in Section 2.8. Section 2.9 presents a typical choice of offshore wind turbines. In Section 2.10, power quality and power quality improving devices will be briefly explained and presented.

Parts of this chapter are redrafts of reference [3], which was been written as a research project and named “Preliminary study on hybrid power management systems”. The theory of the research project is to a certain degree applicable in this study and therefore it is desirable to use some of the work done in the preliminary study.

2.1 Wind Power Generation

2.1.1 Wind Power

A basic system point of view is that wind speed is the input and electrical power is the system output. The wind turbine generator can only extract a fraction of the power in the wind and the turbine output power is decided by Eq. 2.1.

$$P = \frac{1}{2} * \rho Cp A U^3 \left(\frac{\lambda}{\beta}\right) \tag{2.1}$$

P is the active output power, ρ is the density of air which is assumed to be 1.225 kg/m^3 (standard conditions at sea-level and 15°C), *A* is the rotor swept area in m^2, *Cp* is the conversion efficiency, *U* is the wind speed in m/s, and β is the pitch angle.

λ is defined by:

$$\lambda = \frac{\omega_r * r}{U} \tag{2.2}$$

Where ω_r is the rotational speed of the rotor, and *r* is the radius of the rotor.

As the wind speed is powered to the third in the equation above, it is clear that this input parameter has a huge effect on the total output power.

Further equations beyond those mentioned in this section which are used in Simulink, when building the model, will be further explained in Chapter 4.4.2 where the integration of a Type 3 DFIG model is described.

2.1.2 Doubly Fed Induction Generator (DFIG)

There are many types of generators used in wind turbines. One of the most popular generator being used today, is the DFIG. The DFIG consist of a wound rotor induction generator (WRIG) where the stator windings are directly connected to the constant-frequency three-phase grid and with the rotor windings mounted to a bidirectional back-to-back insulated gate bipolar transistor (IGBT) voltage source converter.

The term "doubly fed" originates from the fact that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter. This type of system allows a variable-speed operation over a large restricted range. A rotor current with a variable frequency is injected by the converter in order to compensate the difference between the mechanical and the electrical frequency. The behaviour of the generator is governed by the power converter and its controller during normal operation and faults.

The power converters for the DFIG consists of two converters, the rotor-side converter and grid-side converter and they are controlled independently of each other. It is beyond the scope of this study to go into detail regarding the control of converters. The main logic is that the rotor-side converter controls the active and reactive power by controlling the rotor current components, while the grid-side converter controls the DC-link voltage and ensures a converter operation of unity power factor (i.e. zero reactive power).

The advantages of the DFIG are many. It has the capability to control reactive power and to decouple active and reactive power control by independently controlling the rotor excitation current. The DFIG does not necessarily have to be magnetised from the power grid, it can also be magnetised from the rotor circuit. Another feature is that it is capable of generating reactive power that can be delivered to the stator by the grid-side converter. Nevertheless, the grid-side converter usually operates at unity power factor and is not involved in the reactive power exchange between the wind turbine and the grid. In a scenario with a weak grid, e.g. with an isolated grid, where the voltage may fluctuate, the DFIG may be ordered to produce or absorb an amount of reactive power to or from the grid. The purpose of this function is voltage control.

The size of the converter is not directly related to the total generator power but to the selected range of speed, and hence to the slip power. Thus, the cost of the converter increases when the speed range around the synchronous speed becomes wider. [4]

2.1.3 *Wind Turbine Control Functions*

Control systems may dynamically adjust blade pitch settings and generator torque to control power in high winds on variable-speed wind turbines. Without functions of controlling the output power of wind turbines, a wind turbine cannot produce power successfully and safe.

There are two levels of wind turbine control; supervisory and dynamic control. The first kind, supervisory control, manages and monitors turbine operation and sequences control actions. This can be e.g. brake release and contactor closing. The other kind, dynamic control, manages other things like those aspects of machine operation in which the machine dynamics affect the outcome of control actions. This can be e.g. changing blade pitch in response to turbulent winds.

Variable-speed wind turbines can be operated at different speeds; pitch-regulated turbines can change the rotor or blade geometry, and turbines which have yaw drives or yaw orientation system can control yaw error. In a variable-speed, pitch-regulated wind turbine, the torque produced by the generator can be varied independently of the aerodynamic torque and other system variables. This is:

$$Variable\ speed\ generator\ torque = f(generator\ torque\ control\ system) \tag{2.3}$$

The control system components are shown in Fig. 2-1.

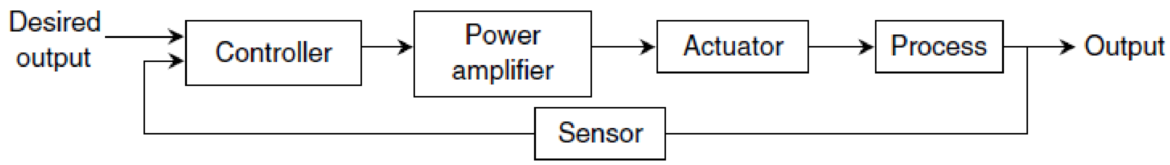

Figure 2-1: Control system components

For the “controller” in Fig. 2-1, usually a *proportional-integral* (PI-controller) or *proportional*, *derivative*, and *integral* (PID-controller) is used for wind turbines. The function of a PI-controller is to reduce the power error to zero, i.e., the difference between the actual electrical power and the reference active power.

The sensor in the control system shown in Fig. 2-1 could be measurements of speed, temperatures, position, electrical characteristics, fluid flow parameters, etc.

The controllable processes in a wind turbine includes, but are not limited to:

- The development of aerodynamic torque
- The development of generator torque

Further and more detailed control of wind power operation can be found in [5].

Grid-side converter control system is a control system used to control the voltage of the DC bus capacitor, but it can also be used to control the C_{grid} converter to generate or absorb reactive power. Such type of system is used for the doubly-fed induction generator which will be explained later in Chapter 4.4.

In a control system it is possible to choose the control function to run in two different modes, *Voltage regulation* or *Var regulation*. Voltage regulation is set as default in the model for the simulation later in the study and will be used throughout the whole analysis. [6]

2.2 Integration of Wind Generation in Power Systems

2.2.1 Hybrid Power Systems

Hybrid power systems usually includes conventional thermal power plants and at least one renewable energy source [5]. Wind turbines can be added to complement the power produced from the thermal power source. The integration of wind turbines into these hybrid power systems presents unique system design challenges.

For isolated power system, the terms “wind penetration” and “renewable penetration” are used to characterize the magnitude of the wind or renewable power in the system compared to the rated load [5]. In isolated power systems, or “island grids”, wind turbines may significantly affect the operation of the system dependent on the amount of wind penetration.

The classic hybrid systems include both a direct-current (DC) bus for the battery bank and an alternating-current (AC) bus for the engine generator and distribution. Large power systems, such as e.g. OOGPs, are focused around the AC bus and incorporate both AC-connected wind turbine generators and diesel engines [7].

2.2.2 Integration of Wind Turbines

As the wind turbines delivers a substantial portion of the total system load, the difference between the wind power and the load is called net load. This load gap has to be covered by thermal power plants, which in this case are gas turbines.

Because of wind- and load fluctuations, the net load may also fluctuate. σ_{load} and σ_{wind} are the standard deviations of the load and wind respectively. The standard deviation of the net load, σ_{net} is given as [8]:

$$\sigma_{net} = \sqrt{\sigma_{load}^2 + \sigma_{wind}^2} \tag{2.4}$$

By implementing wind energy into the power system, the variability in the net load will increase because of the variability of wind power. Further, the uncertainty of the net load will increase in the future. This leads to an increased need for power system operators to make decision based on predictions of the load and available wind energy. As a result of uncertainty of these factors, the power system operators require additional spinning reserve to deal with increased net load variations [5].

2.2.3 Power Balance

When integrating renewable energy sources into isolated or islanded power supply systems, the amount of variable energy sources will highly affect the power quality. The amount of instantaneous wind power penetration is defined as the ratio of instantaneous wind power output, P_{wind} to instantaneous primary electrical load, P_{load}:

$$Instantaneous\ power\ contribution = \frac{P_{wind}}{P_{load}} \tag{2.5}$$

Thus, it is the ratio of how much of the load is being supplied by wind energy at any moment. When the instantaneous power contribution increases from the wind farm, the variation of wind power output increases and therefore the power system operators have to be more caution to ensure that the gas turbines are capable of controlling the gas turbine production and hence the power quality [4].

2.2.4 Effect on Gas Turbine Operation

For the motivation case described in Section 1.1.1, the hybrid system consists of a wind farm and gas turbine generators and it is therefore necessary to see how the penetration of wind turbine will influence the gas turbine operation.

The frequency stability of a hybrid power system mainly depends on relevant factors such as load fluctuations, total system inertia, and the responsiveness and control system of the prime mover in the system [9]. In most cases of island grids, the prime mover is gas generators. To be able to have a proper regulation of frequency, the prime mover has to respond to variations in wind power and load fluctuations rapidly. The better responsiveness of the prime mover, the better frequency regulation [5]. If the wind power penetration reaches a very high level, the prime mover may not be able to respond fast enough to the power fluctuations. This introduces the need for additional buffers, such as energy storage in form of battery packages, to balance the system [9].

Hence, it is essential to consider the response time of the prime mover when integrating wind power in an isolated power system. Gas turbines can be incorporated online but need start-up time, which vary from 3-6 minutes, depending on whether it is a cold start or if the engine was already running. Another element with high wind penetration is the gas turbine efficiency which decreases as the load is lowered [9].

Low levels of loading make it more difficult for the gas turbine to regulate frequency and maintain an adequate power quality. The manufacturers lower the operating limits in which the gas turbines should not operate below. Usually, this is around 30-35% of rated power. If operating the turbine below its limit for longer periods, it reduces the governor’s ability to control the frequency. The governor works at cooler temperatures which causes increased carbon build up, maintenance requirements and poor emissions regulation [4].

By lowering the operating level, the amount of wind power contribution, which is possible to have in the system, becomes limited. In periods with low load, the wind turbine can be regulated to limit its output to ensure that the gas turbine does not operate below its lower limit.

Also, maintaining the proper level of spinning reserve is an issue with high levels of wind penetration. Experienced power system operators are required to confront significantly power variations.

2.2.5 Grid Control

In a power system, the generated power must be balanced with the consumed amount of power. It is crucial to maintain the frequency within its limit, and the power system operators need some generation capacity which is committed to load following. Variation in load and changes in wind power output must be matched rapidly by the thermal power plants [8].

If large load changes occur during the day, more gas turbines need to be brought online. Large gas turbines usually need approximately 45 minutes to prepare for power generation. Hence, a certain amount of “spinning reserve” is required to be kept online to respond to power fluctuations [5].

2.3 Power System Stability

IEEE/CIGRE [10] gives the following definition of power system stability:

“Power system stability is the ability of an electric power system, for a given initial operating condition, the regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact”.

System stability is mainly a function of the initial operating condition and system disturbances. Instability in the power system can appear due to various disturbances. Variations in the load can occur frequently and behave as small disturbances, and the power system will have to adapt to these changes in operating conditions. Furthermore, the system has to recover from large disturbances such as loss of generators or short-circuits. Constant changes in the power system makes it a nonlinear system. Power system stability is mainly divided into three categories; rotor angle stability, frequency stability and voltage stability as shown in Fig. 2-1.

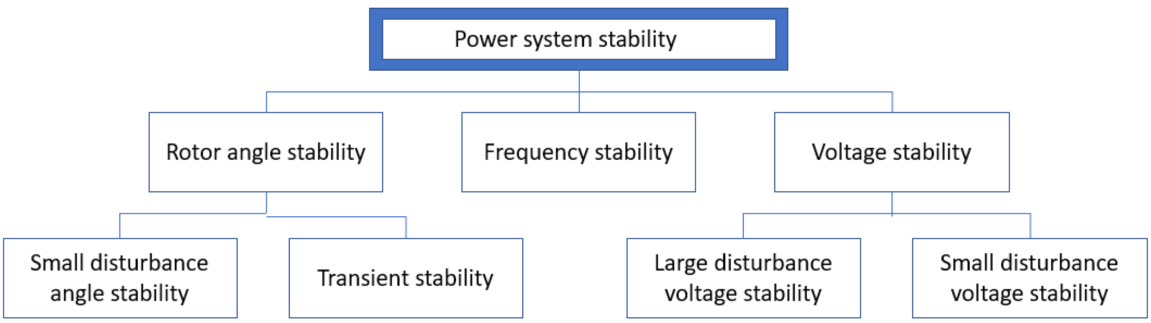

Figure 2-2: Classification of power system stability, based on IEEE/CIGRE report [10]

One way of improving the stability of a power system, is to apply energy storage technologies, such as batteries. Large scale battery packages have to improve their cost efficiencies and be developed further in order to become a viable addition [11].

2.4 Frequency Stability and Control

Variations in wind power available for wind farms, has to be monitored and predicted in order to ensure a stable power output quality.

IEEE/CIGRE defines frequency stability as [10]:

"The ability of a power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. It depends on the ability to maintain/restore equilibrium between system generation and load, with minimum unintentional loss of load."

The flows of active and reactive power in a power system are somewhat independent of each other. There are different controls for active and reactive power in order to be able to study the individually. Reactive power is closely related to frequency control, and active power is closely related to voltage control [12].

As described in [13], the power system response can be divided into four stages and easily be explained by an example. Where: a generator disconnects from the system.

- Stage I: rotor swings will occur in the other generators (first few seconds)
- Stage II: the frequency will drop (a few seconds to several seconds) because the speed of the other generator in the system will slow down. The frequency drop is only dependent on the inertia in the system
- Stage III: the primary frequency control is activated by the governing system (several seconds)
- Stage IV: the secondary control brings the frequency back to its initial value (several seconds to a minute)

Conventional generators ensure frequency stabilization by having directly connected synchronous generators. In other words, this means that there is a coupling in the generators between the power system frequency and the electromagnetic torque. When the power system's frequency quickly decreases, the electrical active power suddenly – and temporarily – increase due to this coupling. This reaction is known as the "natural" inertial response of the generator.

WTGs and VSWTs have technologies where they can have a generator speed as low as 0.7 pu, while conventional generators on the other hand, only can go down to 0.95 pu. This means that from two installations of the same rating and the same inertia, the VSWTs would have 4.12 times more kinetic energy than the conventional installations. The perk of this kinetic energy is that it could be utilized to provide temporary primary frequency control. [14]

2.4.1 Primary Frequency Control

When the total power generation is equal to the load demand (including losses), the frequency is constant. If there is a change in frequency due to increase or decrease of load, the primary frequency control is activated by the governing system. The aim is to obtain a balance between power generation and power demand. Primary frequency control action will result in a steady state frequency deviation, which is dependent on the system frequency response, R, expressed in Eq. 2.7 [13]. The droop, ρ, specifies how much the frequency change as a function of change in power.

$$\frac{\Delta f}{f_N} = \rho \frac{\Delta P}{P_N} \tag{2.6}$$

$$\frac{P_N}{\rho f_N} = \frac{\Delta P}{\Delta f} = R \tag{2.7}$$

2.4.2 Secondary Frequency Control

Without any additional action, the governing system is not able to return the frequency to its initial value after a change in load. As shown in Fig. 2-3, the load reference set point has to be shifted in order to return the frequency to its initial value [13]. The operators performs a secondary control by adjusting the speed-changer motor which changes the speed reference set point by moving the speed-droop characteristic up or down [8].

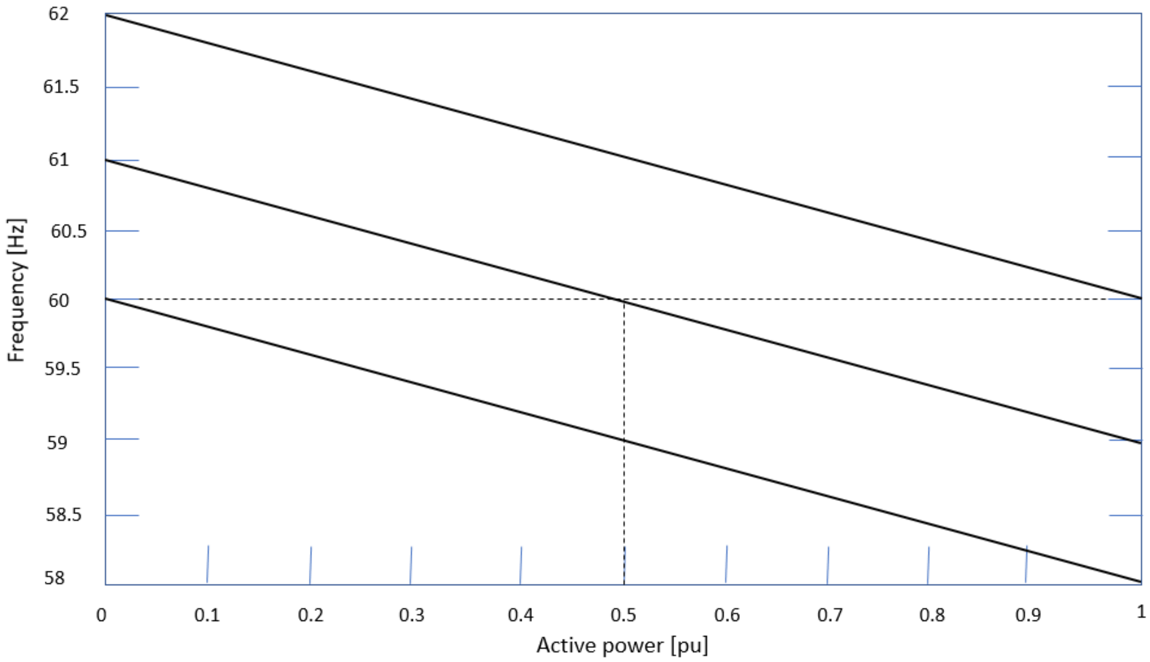

Figure 2-3: Effect on speed-changer setting on governor characteristics

Note: other droop characteristics can be found for a frequency of 50 Hz, but for this study and the motivation case, 60 Hz will be used as this is the normal for older OOGPs [15].

2.4.3 Frequency Control of Wind Farms

The increasing penetration of intermittent energy sources in power system generation can introduce large uncertainties and instability problems into the grid. Conventional generators are equipped with primary and secondary voltage controls in order to control frequency deviations, load changes or other contingency functions. In wind power generation, there are other ways to contribute to the frequency regulation than by the generator directly. Variable-speed wind turbines are able to support the grid during frequency deviations as when the share of VSWTs in the power system increases, the momentum of the system increases, and thereby the frequency in the system may drop/increase very rapidly. Connected between the share of VSWTs and the grid, is a supplementary control loop, i.e., frequency controller, which emulates a virtual inertia for the VSWTs, which gives the ability to support the grid [16].

When a wind farm is connected to the grid, a large disconnection can result in power system oscillations. In order to cope with these oscillations, modern wind farms are often equipped with VSWTs as they have back-to-back power electronic converters for the grid connection. All wind farms have to be able to meet the frequency response requirements of primary, secondary and high-frequency responses. The following scenario will be described with the requirements in The U.K. If the frequency drops with a deviation of e.g. 0.5 Hz, the generator output should ideally increase by an amount equal to primary response within a time interval of 0 – 10 s, and be sustained for a further 20 s. Then the generator should keep the power output at the secondary response from 30 s to 30 min in order to stabilize the frequency. The high-frequency response will be activated in cases where the frequency is increased. The generator output power should then be decreased by an amount equal to high-frequency response within the time period 0 - 10 s. [14].

2.4.4 Spinning Reserve in Gas Turbines

Another important aspect in a hybrid power system, which may not be directly relevant to the power quality from offshore wind farms, but still of huge impact for the complete system, is spinning reserve (SR) in gas turbines. Spinning reserve in gas turbines helps system operators to compensate for unpredictable imbalances between load and power generation, caused by sudden disruptions of generating units, errors in load forecasting or unexpected deviations by generating units [17]. The system must at all times have sufficient active power in reserve to control the frequency and re-establish a balance between load and generation in case of disturbances [8]. Primary frequency control is an automatic response which is not controlled by the operator, and a sufficient amount of SR must be reserved for this control. Secondary control on the other hand, uses SR and is controlled by the system operator in this case [13].

2.5 Voltage Stability and Control

In general, voltage instability problems and collapse are normally associated with heavy loaded power systems which are not able to meet the demand for reactive power. Hence, voltage stability may also be called load stability [11].

Typically, such voltage drops are common in longer distribution lines between an offshore wind farm and the onshore converter station. However, for this case, the distribution lines will not be that long, as the wind farm will deliver electricity to the nearby OOGPs.

A classic voltage (V) criterion is based on how the system is capable of supplying the load with reactive power (Q) for a given real power demand. This criterion is often described as the $d\Delta Q/dV$ criterion, and to explain this criterion it is simpler when separating the reactive power demand from the real power demand. A gradual increase in the demand from the system, such as due to the normal daily load variations, can lead to two detrimental effects on the voltage stability. [13]

For high voltage systems, the reactive power transfer is the dominant factor for the voltage-profile. Large wind farms should be connected to higher voltage networks to reduce the voltage drop (also called regulation) [18].

It is customary at oil platforms that the power generation units are equipped with Automatic Voltage Regulators (AVR) which controls the system voltage by changing the magnetization in the rotor of the synchronous generator [19]. In [20] it is described how to implement voltage control in several ways. One efficient choice would be the voltage droop control. With this type of control, the reactive power supplied by the wind turbines follows the slope or characteristic in Fig. 2-4.

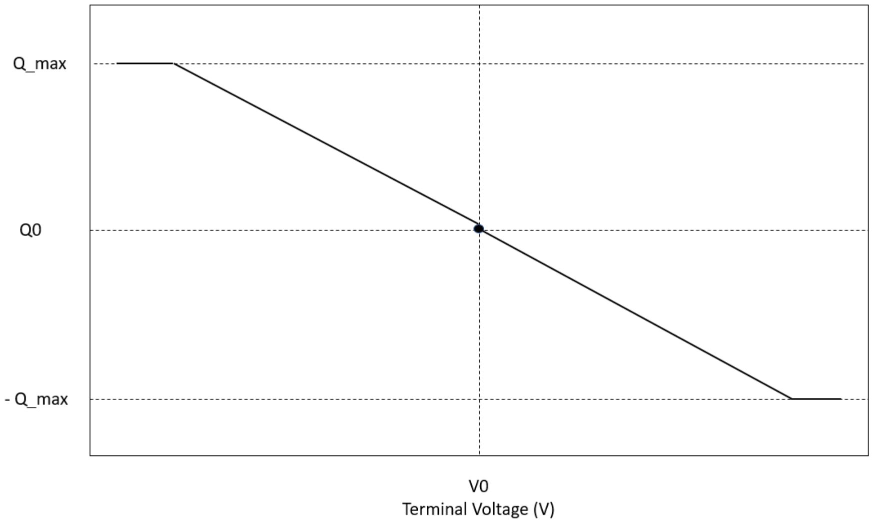

Figure 2-4: Voltage-droop characteristics based on [19]

V_0 is the reference voltage where the desired reactive power production is Q_0. If the voltage is decreased, the sensor will notice, and the reactive power is increased proportionally to the voltage decrease. To ensure that the reactive power does not exceed Q_{min} and Q_{max} , there are limiters present according to Eq. 2.8.

$$P^2 + Q^2 \leq V^2 i_{rated}^2 \tag{2.8}$$

A well-known challenge with this type of voltage control, is that the current has to be kept lower than the limit i_{rated} [20]. This is equivalent to Eq. 2.8.

2.6 Load Shedding

Under-frequency load shedding is a common practice to maintain stability in a power system. This technique is implemented in power systems when power imbalance (disturbances or overload) occurs [21].

In other types of power systems, it is possible to transfer power from the neighbouring systems to avoid a decrease in frequency. This is not possible in an isolated grid, which again makes the grid more vulnerable to disturbances and load changes due to lower inertia and smaller spinning reserves [22]. In events with under-frequency and if the generators are unable to increase their output power, load shedding arrangement are employed to reduce the load demand to a secure level [13]. It is crucial that the decrease in frequency does not reach the stage where the generator units trip due to under-frequency protective delays [12].

There are two main problems or challenges associated with the operation of a power system at low frequency, both related to generating units. The first problem is related to power systems that are operated at low frequencies. This leads to problems due to thermal power plants, e.g. vibratory stress on the long low-pressure turbine blades. The second problem is related to the severity of operating induction motors below rated frequency and how it affects the output power.

Prime movers have the following limitations which affect their ability to control such frequency decay:

- The generation can only be increased up to the limits of available spinning reserve.
- The load which can be picked up by a thermal unit is limited by thermal stress in the turbine.
- The speed delay of the speed governing system.

As a result of the limitations listed above, the generation reserve available for controlling the frequency is limited to a portion of the remaining generation [12].

Load shedding is implemented using under-frequency relays. These relays detect the decrease in frequency and disconnect the convenient amount of load until the system regains stability. Normally the significant loads are the first to be disconnected [13].

2.7 Power System Operator

The main task for the power system operator is to ensure a power production which is equal to the demand at all times. Also, it is crucial that the frequency is within required limits for stable power supply. Operators should control and observe among other things the following information: generator power, generator frequency, spinning reserve and wind power. To cope with potential disturbances, the system operator needs to ensure that the system is secure and well equipped. In order to combat the increasing wind power due to higher wind energy penetration in the system, more spinning reserve can be required. The system operator determines how many generators they want to operate and hence the amount of available spinning reserve. If the amount of spinning reserve is inadequate when disturbances occurs, automatic load shedding could be a solution to prevent overloading of the generators. [13, 23]

2.7.1 NORSOK and IEC Standard

NORSOK standard E-001 contains provisions for electrical installation on offshore units [24]. According to NORSOK the standard requirements for system frequency is 50 Hz and the allowed deviations in system frequency is gathered from IEC 61892-1 standard. IEC 61892-1 is an international standard for electrical installations on mobile and fixed offshore units [25].

Table 2-1: Requirements for frequency deviations on offshore units according to [25]

Operation case	Frequency deviations (Δf)
Steady state	± 5 %
Transient	± 10 %
Cyclic	± 0.5 %

According to [15], IEC 61892-1 is one of the most used IEC Standard in the offshore industry for the current case.

2.7.2 Operational Grid Requirements

The transmission system operator (TSO) normally has a set of written requirements which all units that wish to connect to the power grid have to accommodate. These requirements are called grid codes and defines voltage and frequency limits for continuous operation as well as fault capabilities. The grid codes in Norway are specified by Statnett, and found in [26]. The Norwegian requirements are given in Table 2-2.

Table 2-2: Operational requirements for wind power production, Norway

Frequency (Hz)	Voltage (pu)	Duration
47.5 – 49.0	0.90 – 1.05	> 30 minutes
49.0 – 52.0	0.90 – 1.05	Continuous

2.8 Energy Management System

It is important to distinguish between the two main types of grid; isolated and connected to the onshore main grid. The reason for this, is the stability which is provided from the main grid. For an isolated grid, both frequency and voltage stability are ensured by the gas generators conventionally.

The definition of an isolated grid or microgrid is according to [27]:

"that is a miniaturized version of self-sustained energy model which can be used to generate, distribute and control the bi-directional flow of power within its boundary of operation in a coordinated control, intelligent and efficient way with a focus on integration of green energy sources."

With multiple generators that are both conventional and non-conventional, and are interconnected physically by different interfacing devices, the energy management is the solution for control within the complete system. Energy management system (EMS) are built up of monitoring and forecasting consumption and generation of energy.

To cope with different kinds of power quality related issues in the isolated grid, different controllers and devices are applied. Some of these devices use unified power quality conditioner (UPQC) as a compensating device, series voltage source inverter (VSI) mitigates supply side disturbances and shunt VSI mitigate load side disturbances. In addition to the examples of devices mentioned above, control strategies are central to make a system work [27].

A basic version of an EMS can be built up like illustrated in Fig. 2-5 where the two most central contributors are the monitoring and the forecast systems. On the bottom line, the main objectives for an EMS are listed choosing to focus on either one simple target, or multiple at the same time.

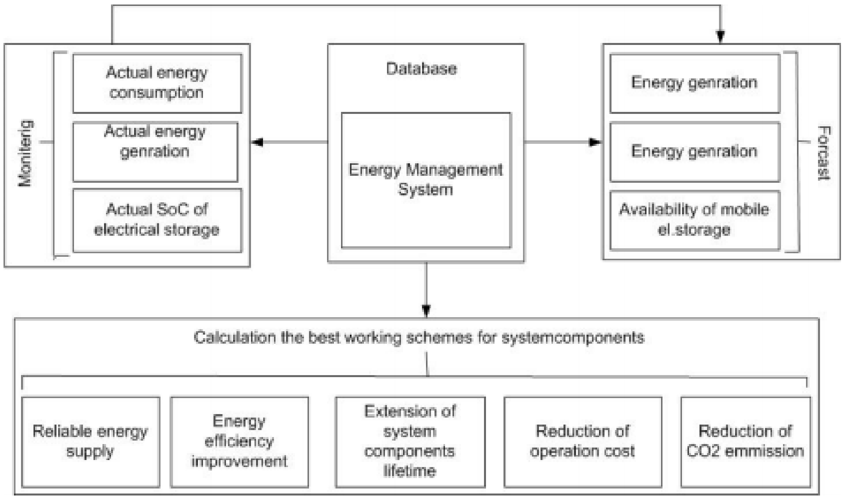

Figure 2-5: Main concept of Energy Management System @2017 IEEE [27]

Fig. 2-6 illustrates a hybrid power system with a renewable energy source, a conventional gas turbine with generator, long-term energy storage in form of a battery package and a grid. The wind farm and the gas turbine(s), together with the battery package, are connected to a common busbar.

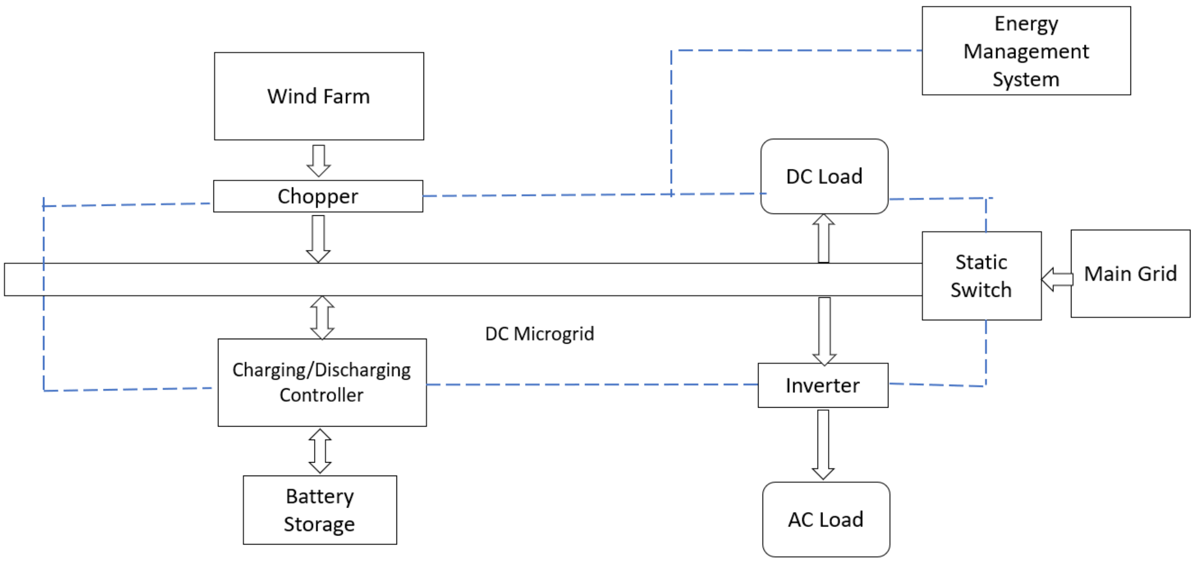

Figure 2-6: Microgrid with EMS based on [27]

Some typical inputs for an EMS system are as follows:

- Power generated by the wind farm
- Power generated by the gas turbines

- State of charge of battery
- Non controllable load
- Controllable load

Some of the typical output signals from the EMS are listed as:

- True/false for charging of battery
- True/false for discharging of battery
- True/false for grid on/off
- True/false for load to switch on/off

2.9 Typical Offshore Wind Turbine

For the motivation case described in Section 1.1.1, Equinor has decided to use Siemens Gamesa WTGs. The turbine model has the following manufacturer data [28]:

Table 2-3: Manufacturer data for the actual wind turbine

Siemens Gamesa 8.6-167 DD	
Rotor Diameter	167 m
Nominal (rated) power	8.6 MW
Gear	None. Direct drive
Blade length	81.5 m
Swept area	21,900 m^2
Power regulation	Pitch-regulated, variable speed

This generation of wind turbine is recommended for high wind circumstances at offshore locations. They are designed for the most challenging offshore sites and extracting maximum power for projects at sea. With new types of technologies implemented in the newest generation of offshore wind turbines, the efficiency and reliability of these turbines increases.

The operating principles of this type of generator are comparable to that of synchronous machines, except that these machines are run asynchronous. Asynchronous means that they are not normally connected directly to the AC network. The power produced by this generator is initially variable voltage and frequency. This AC is often immediately rectified to DC which again is either directed to DC loads or battery storage, or else is inverted back to AC with a fixed frequency and voltage. The last operating principle is the one applied for the power system in this case.

Direct drive technology makes the maintenance easier by reducing the number of rating and wear-prone components. By using a permanent magnet induction generator (PMIG) which needs no excitation power, the efficiency increases as well.

Another improving and innovative factor according to Siemens Gamesa, is The High Wind Range Through (HWRT) system. Normally, when the wind speed exceeds 25 m/s, the turbine will shut down for self-protection and to avoid casualty. However, the new HWRT technology allows the turbine to slowly ramp down power output instead of shutting it down, enabling smoother production ramp-down and thereby a more reliable electrical grid [28].

2.10 Power Quality and Power Quality Improving Devices

In order to analyse the power quality, it can be helpful to have a quick introduction to the characteristics which normally are measured when monitoring and regulating the power quality.

Rated power, P_n, is the maximum continuous electric output power which a WTG is designed to achieve under normal operating conditions. Another characteristic is the reactive power, Q_n, from the wind turbine at rated power and nominal voltage and frequency. Next is the apparent power, S_n, given for operations at rated power and nominal voltage and frequency. Then it is the rated current, I_n, also given for operations at rated power and nominal voltage and frequency. Finally, it is characteristics like flicker coefficient, maximum number of wind turbine switching operations, flicker step factor and harmonic current which have an impact on the wind turbine output power quality. [4]

The most usual grid interferences that occurs in wind turbines or wind farms with variable-speed wind turbines are given in Table 2-4, this table is based on [4].

Table 2-4: Grid interferences caused by wind turbines and wind farms

Parameter	Cause
Voltage rise	Power production
Voltage fluctuations and flicker	Switching operations Tower shadow effect Blade pitching error Yaw error Wind shear Fluctuations of wind speed
Harmonics	Frequency inverter Thyristor controller

Reactive power consumption	Inductive components or generating systems (asynchronous generator)
Voltage peaks and drops	Switching operations

Introducing devices which can improve the power quality from power producing units. Initially it is helpful to know that converters convert AC to DC, while inverters on the other hand, convert DC to AC. The technical symbols are respectively given in Fig. 2-7.

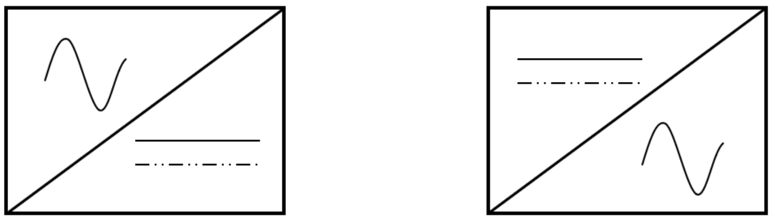

Figure 2-7: Technical symbols of converter (left) and inverter (right)

2.10.1 FACTS Devices

Flexible AC transmission system (FACTS) devices are expensive and therefore it is necessary to ensure that their functionality is required before specifying them. The devices perform four basic functions and they can be divided into:

1. Power transfer between electrically separated systems
2. Active power management
3. Reactive power management
4. Waveform quality management

The devices will be described in sections considering current and voltage separately.

The current source converter (CSC). Normally, this is a line-commutated device which means that the thyristors are switched on by a gate control but remain on until the current reaches zero.

Self-commutated current source converters have been developed and constructed using gate turn-off (GTO) or insulated-gate bipolar transistor (IGBT) technology. In-line commutated devices are normally built as 6- or 12-pulse bridge. Twelve-pulse bridge provides smoother AC or DC waveforms compared to 6-pulse bridges. For these converters to operate successfully, they need commutation overlap periods and hence have short periods in each cycle when two phases are effectively short circuited. The effects are more compelling in inverter operation. If the system is weak, the system voltage will collapse during these periods and the inverter control will drop its commutation reference. Therefore, CSCs can only be used when both systems are relatively strong in an electric matter.

The voltage source converter (VSC). This type of converter can produce AC voltage which is controllable in magnitude and phase comparable to a synchronous generator or synchronous compensator. The reason why VSC is well suited for wind farm connection, connection of oil platforms etc., is that the device commutates independently of the AC-side voltage and therefore the VSC can be used on a load-only system. A load-only system means a system with zero fault level.

Wind farms often require reactive compensation for voltage regulation under normal conditions, and to assist ride-through under fault conditions. Two relevant devices are:

Static Var compensator (SVC). This device is a combination of thyristor-switched capacitor banks and thyristor-controlled inductor banks. Placed in systems with low voltage, the device will produce reactive power, that is, delivering capacitive current. On the other hand, when placed in high voltage systems, it will absorb reactive power, similar to an inductor. The objective of this device is to *rescue* a dangerous high voltage condition and allowing time for other system action. The two basic areas of usage: to regulate bus voltage at a node, and, placed in the mid-point of a line, to allow the line impedance to be compensated, hence extending its rating.

Static compensator (STATCOM). This device is based on a VSC rather than a thyristor-controller capacitance. The VSC DC terminals are connected to a small capacitor which is being maintained at some voltage level. As the output voltage from this device lags the system voltage by a small angle to maintain the capacitor charged, the reactive power (VAr) injection in the system is determined by the angle. The advantage with this device is that it can maintain the reactive power at a constant level down to 0.2 per unit system voltage, after which it falls off proportionally to 0 at zero voltage. [18]

2.10.2 UPQC

UPQC is built up by series and shunt active power filter for mitigating power quality issues. Two VSIs are used to operate as series and shunt active power filters, which is realized by using 6 Insulated Gate Bipolar Transistors (IGBTs) for each VSI. The series component of UPQC can allay the supply side disturbances like voltage swells, voltage drops, voltage unbalances, harmonics and flickers. These problems are solved by injecting voltage. The shunt component on the other hand, helps to allay the current quality problems which occurs on the load side. Such problems can be low power factor, unbalance, harmonics in load currents in the connected load etc. The shunt component ensures the current to be balanced and sinusoidal and in phase with the source voltage by injecting current. [27]

2.10.3 Network Issues of Concern

Typical issues which are to be solved or improved by the devices explained above, are:

1. Dips
2. Harmonics
3. Flicker

Dips. The major source of dips other than starting conditions, is the variations in the wind. As wind energy variability is neither fixed or continuously variable, and some is IGBT switched, the performance should be assessed to determine if the variation exceeds the standard at any point.

Harmonics. All devices containing power converters are appropriate to produce harmonic voltage distortion. Normally, power system planners and operators will attempt to ensure that installations do not diminish harmonics on the power system. There may be requirements not to exceed total harmonic distortion of the voltage waveform and limits on the distortion due to specific harmonics.

Flicker. It can be a challenge to give a direct and specific definition of flicker. Usually it is considered to be a discernible regular increase and decrease in the luminescence of incandescent luminaires connected to the system. A phenomenon called 3P describes a power oscillation at three times the blade turning speed. The 3P frequency is usually about 1 Hz. If the frequency oscillations cause significant distortion of customer voltage waveform, utilities are likely to receive complaints.

2.10.4 Power Quality Measurement Requirements

Wind turbines and their power quality are certified on the basis of measurements according to national and international guidelines. The certifications are an essential basis for utilities to evaluate the grid connection of wind turbines and wind farms. In order to ensure correct and valid measurements of the power quality, three guidelines have been developed, and these are:

- International Electrotechnical Commission (IEC) guideline IEC 61400-21: 'Wind Turbine Generator Systems, Part 21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines' (IEC, 2001);
- MEASNET guideline: 'Power Quality Measurement Procedure of Wind Turbines' (MEASNET, 2000);
- The German Fördergesellschaft Windenergie (FGW) guideline: 'Technische Richlinie für Windenergieanlagen, Teil 3: Bestimmung der Elektrischen Eigenschaften' (Technical guidelines for wind turbines, part 3: determination of the electrical characteristics; FGW, 2002).

IEC 61400-21 is the most central guideline for power quality measurements of wind turbines. The guideline gives an overview of which characteristics that are important to measure and monitor regarding the output power quality from wind turbines (e.g. flicker, harmonics, power, switching operations). The institute behind IEC 61400-21 has created a data sheet to follow when performing measurements on wind turbines, normally this is done on the prototype and the other wind turbines of the same kind are compared with the prototype.

MEASNET is the name of a measuring network of wind energy institutes which aims to harmonize measuring procedures and endorsements in order to achieve common recognition of the measurement results by its member institutes. MEASNET (2000) has some vulnerability regarding harmonic currents which calls for more extended measurements.

The FGW in Germany developed a technical guideline in 2002 which is used for measurements on power quality of wind turbines. The guideline has continuously improved and been updated in order to match new research and development in the wind farm technology. Most of the principles are somewhat similar with the principles in IEC 61400-21, although the data collected in the two different systems are not directly comparable.

In Appendix A, an overview of the requirements of the guidelines is given based on [4].

3 Review of Literature

Power quality of wind farms have, to a certain extent, been researched and written about in academic articles and thesis' earlier. In hybrid power systems where wind power is responsible for a large part of the power contribution, it is crucial to ensure a stable and secure energy supply to the grid system. A selection of of the previous work done on power quality analysis and energy management system (EMS) / power management system (PMS) will be presented in this section.

During the last years with a rapid development of offshore wind farms, there has been an urgent and increasing demand for research on the power quality of grid-connected wind farms and their impact on the operation of the power grid. Considering the intermittent nature of the wind generators and the tower-shadow effect imposed on the downwind turbines in an offshore wind farm, the electrical power output delivered by this type of generation possesses similar intermittent and fluctuant features.

In [29], they have considered a 50 MW offshore wind farm and its output power quality at a given point of connection in the simulation model in PSCAD/EMTDC. Static Var Compensator (SVC) is used in this study to compensate for the reactive power generated. The focus was the measurement method for power quality and analysis of the effect of offshore wind farm connected to the main grid. The model applies power quality indices to quantify the degree of power quality disturbances. The study performs measurements on active and reactive power together with voltage in order to check for three different indices for power quality: voltage unbalance, voltage harmonics, and lastly; voltage fluctuations and flicker. The obtained measurements are then compared with the national limits of power quality for the case, and the researchers claims that STATCOM will improve the power quality if implemented. Furthermore, the active power filter detection method will be able to reduce the harmonics.

In [30], Yildiz *et al.* have focused on power quality of a wind farm that is connected to a distribution grid. Their main focus has been supply-waveform problems, its frequency and magnitude. As harmonics disturbances are considered to be one of the major power quality problems in power systems and harmonic indices have been developed to assess the service quality of a power system corresponding to harmonic distortion levels. These indices can be applied on both current and voltage and the most common ones are the Total Harmonic Distortion (THD) and Total Demand Distortion (TDD), used respectively for voltage and current harmonics. The study has considered a 36 MW wind farm in Turkey with a total of 12 WTGs where the turbines are connected to a substation, which ensures that the electric power generated from the wind farm is delivered to the transmission line at constant voltage at 154 kV and 50 Hz. For a three-months period they have observed and analysed the following measurements: voltage, current, frequency, active, reactive, apparent power, power factor and harmonic distortions. The output frequency at wind farm feeder is crucial and has to have a constant value of 50 Hz which is the nominal value at the Turkish distribution system. Results from the analysis shows that the THD is usually less than the limit specified by IEEE Std. 519-1992 for industrial harmonic loads. The conclusion from the study is that the harmonic values of wind farms have a marginal impact on the medium level of transmission network although the other parameters are mainly good.

Ghiasi *et al.* presents in [31] an analytical and detailed approach to evaluate the technical and economic performance of the strategy for power quality (PQ) changes. They state that the most important factors in power quality changes in distribution networks are inflation, voltage changes, power outages, imbalances, and harmonics. The main objectives of this article is described as follows: to begin with, a worldwide PQ planning issue by considering technical and economical perspectives that several PQ phenomena have been taken into account simultaneously are defined; then, an objective function which incorporates technical and economical perspectives into optimization for development of worldwide solution is presented; and at the end, an optimisation-based worldwide PQ planning approach to mitigate a range of critical PQ phenomena to different required levels across the grid simultaneously is developed and analysed. Such PQ phenomena includes voltage sags, unbalance, and harmonics phenomena.

In the article, Ghiasi *et al.* presents two solution for PQ mitigation: equipment-based and grid-based solutions. Equipment refers to FACTS devices which have experienced a good development process. STATCOM, SVC and DVR are the FACTS devices which are considered for PQ mitigation in this article. Moreover, Passive Filters (PFs) are widely used to reduce harmonics in industrial facilities and electric power networks. For the grid-based solutions, short circuit faults in the transmission and distribution grids results in voltage disturbances. It is feasible to mitigate this type of voltage disturbance by reducing the possibility of fault occurrence. By using Lagrangian relaxation together with MATLAB and DigSilent software for the optimization, the study concludes that applying these FACTS devices will be highly beneficial in the long term.

In [27], Borase and Akolkar have performed a study on power quality improvements on an isolated microgrid. A microgrid is a miniaturized version of a self-sustained energy model and can to a certain degree be compared to an isolated offshore grid. Energy management is a way of controlling all kinds of energy generation and production within an enterprise, and an energy management system monitors and forecasts actual energy generation and consumption. In order to meet different types of power quality related issues, different controllers are used. One such controller is the Unified UPQC as explained in Section 2.9.2, and the device is used for compensation. Series VSI mitigate supply side disturbances and shunt VSI mitigate load side disturbances. The main objective of the study is to evaluate the beneficial contribution of Unified UPQC with regards to voltage swells, voltage sags, voltage unbalance, harmonics and flickers as well as other issues due to fault or distortion due to switching power electronic devices. The simulations have been performed under various conditions of power generation and load distribution and an example of a condition is minimum solar generation and maximum wind generation. Test results in the study for the UPQC under all three conditions indicates that the UPQC device can mitigate the supply and demand side disturbance like voltage sag. The conclusion of the study when integrating DC-microgrid with both EMS and UPQC is that the performance of the microgrid will improve. EMS contribute to better utilization of manpower, non-breakdowns in the system, savings in the energy consumption etc. In order to cope with low voltage side disturbances, UPQC is used to provide good power quality control. A combination of the two systems is claimed to give a better yield than using each system individually. Finally, the authors end the study with: *"Integration of EMS with UPQC gives better energy management with better power quality control".*

In [32] Haritza Camblong *et al.* have presented a linear quadratic Gaussian controller (LQGC) designed to allow the contribution of wind turbines to the primary frequency regulation of an island power system. The simulated power system is built up of multiple power plants, some of them based on renewable resources and some of them with conventional generators. Wind farms are modelled as a simplified aggregated model reduced to one-machine equivalent and the wind turbines shaft flexibility is taken into account when the simplified aggregation model of the wind farm is used. Classical wind turbine controllers have different operation strategies and the generated power depends only on the available wind power. For low wind speeds, this controller will try to maximize the power production by applying the maximum power point tracker (MPPT). When the wind speed is higher than the rated wind speed (FL operating region), the generated power will be limited to its rated value. This is thanks to the pitch regulator. For the controller to contribute to frequency regulation in FL, rotational speed has to be regulated to its rated value and electrical power needs to be controlled depending on the frequency. When simulating a scenario where the contribution from a big power plant is lost, the grid frequency is analysed. Simulation results shows that the dynamic behaviour of wind turbines with respect to contribution of primary frequency regulation is good. Simulations also indicates smaller oscillations produces by the LQGC compared with the PI controller which can be explained by the fact that PI controller diminish less low frequency wind speed variations. Further simulation comparison of LQGC and PI controllers shows that LQGC allows for a higher wind energy integration in the grid with contribution to primary frequency regulation as well as indicating that the maintenance costs would decrease as a result of this.

A study performed by Xue Yingcheng and Tai Nengling [14] has focused on the role of wind generation in a system's primary frequency control. Wind turbine control methods are presented in the report together with advantages and disadvantages. According to the study, there are mainly three methods where VSWT participate effectively in system frequency regulation which are: Intertial Control Method, Power Reserve Control Method, and the Communication Method. The study presents a method where a supplementary inertia loop integrated in an active power control loop, and this loop is activated during frequency deviations. Such deviations occur when there is an imbalance between demand and generation. The inertia control loop reduces the imbalance by injection more power from the wind turbine to the grid, until governor increase mechanical power of conventional plant. The next method is the power reserve method, and this is based on the need for a compensation of the imbalance between demand and generation. The generated power should decrease as a result of an increasing frequency, and vice versa. This can be done by implementing power reserve and can be categorized in e.g. pitch control and speed control. The third method is based on a combination of several solutions. One of them is the possibility to combine wind energy with fuel cells. The study concludes that more research is necessary on the topic, but they hope that their evaluation of different methods can help the industry towards primary frequency control. Further, they suggest rethinking secondary control since frequency disturbances due to wind generation tend to fall within the traditional time-scale boundary between primary and secondary control actions.

In [4], John O. Tande has performed a case study considering a 5 x 750 kW wind farm on a 22 kV distribution feeder and analyses the power quality characteristics. The study also presents possible voltage quality problems from a wind farm in many cases can be solved just by changing the control parameters. IEC 61400-21 became the standard when determining the power quality characteristics of a wind turbine and is also the basis for this study. Different power quality characteristics are explained thoroughly, before their impact on voltage quality is evaluated. The discussion section of the article considers the differences from the simplified evaluation of power quality before the IEC 61400-21 was developed and the conclusion of this issue is that the simplified assessment unnecessarily narrows the acceptable wind farm capacity. Therefore, the simplified assessment is not recommended for dimensioning the grid connection of a wind farm.

Further, it is also desirable to see what studies and workload performed on energy management systems (EMS), especially for wind farms in hybrid systems. EMS is related to planning, controlling, and monitoring energy-related processes in addition to conserve energy recourses, protect the climate, and finally, save energy-related costs. EMS is a multidisciplinary method that includes technical, economic, geopolitical, and political issues regarding both consumption and production of energy. An energy management system collects data and measurements for planning and control the power production and generation, as mentioned earlier. Power quality is one of the aspects that is constantly being assessed.

In [33], Pablo García *et al.* have considered a stand-alone hybrid renewable energy system (HRES) with both a wind turbine and solar panels as primary energy sources. A hydrogen subsystem (fuel cells) and a battery are the energy storage solutions for the hybrid system. The study mainly focuses on the state of charge (SOC) and depth of discharge (DOP) for the battery solution, as this is a crucial part of the hybrid energy system as it has to ensure a sufficient power supply if there is low wind or no sun. The EMS is set up with an initial control which determines the power in the battery and FC/electrolyser, while aiming to keep the utilization costs at a minimum. There is also a supervisory system based on “fuzzy logic” that is used to control the battery SOC and the hydrogen tank level. The supervisory system communicates with the initial control system. Furthermore, the authors have created an additional EMS based on control states in order to check the performance of the EMS explained in the beginning. The conclusion of the study is that EMS based on fuzzy logic and utilization cost ensures the optimization of the utilization cost and reduces the number of elements through the considered lifetime of the hybrid system, which is set to 25 years.

P. Pinceti *et al.* have in [34] studied the control functions necessary for regulating a microgrid including both conventional and renewable sources. The given definition of a PMS in this study is:

"A supervisory control and data acquisition (SCADA) that implements a set of specific functions necessary for controlling an industrial power system, or in more general terms, any electrical system that contains both loads and generators."

Included in a typical industrial power system of this kind are one or more connections to the main grid at high or medium voltage, one or more step-down transformer, a distribution network at medium and low voltage, and one or more generators both from conventional energy sources (gas and steam turbines) and from renewable sources (wind or photovoltaic). The study [34] presents design criteria for a PMS, and specifies the differences for islanded grids and main grids on shore. Presented are two different operation modes for the PMS, where the first is valid when the system operates in parallel mode, then the target is the power exchange control, the reactive power balance, the maximization of the renewable sources. For the second operation mode, which is valid during islanded mode, the target is regulating the island frequency and voltage. Simulation results of the study shows a satisfactory performance of the PMS during normal operation (in parallel with the grid), and in islanded mode. Additionally, during the simulation it was confirmed that the PMS detects all events that may cause the separation of the microgrid from the main grid and actuates the necessary emergency actions such as e.g. load shedding and generator shedding.

Having read through some of the previous studies and reports, it is safe to say that the field has to some extent, been investigated in the past. Nevertheless, it is desirable to investigate further how new wind turbine technology and new solutions due to floating foundations, will be affected by different wind spectra and wave conditions. The overall main object of the study is to cover the "gap" in the literature and be a contribution to the development of offshore wind farms and their power quality.

4 Methods

In this section, the setup of the simulation software will be thoroughly explained. As mentioned earlier, there are three different software involved, and these will be presented in this first sub-chapter. Further, all the central inputs will be explained or mentioned if not considered to be central/important. Finally, the integration of a wind turbine generator model in Simulink/SimPowerSystems will be described. This integration is experienced to be far more time-consuming than first expected, due to difficulties in integrating the FAST model into the SimPowerSystems model. In order to evaluate how the power production will be affected due to different turbulence spectra, the evaluation of active power and voltage, along with reactive power, will be the main focus.

4.1 Introduction of Software

The simulation and generation of turbulence time-series are done by applying TurbSim and the wind power generation, among other characteristics, into FAST. Both software are developed by the National Renewable Energy Laboratory (NREL). A brief introduction to TurbSim software and FAST software are given in the two following sub chapters respectively. Next, the FAST model has to be integrated with a SimPowerSystem model in Simulink in order to obtain all relevant parameters, which will be described in Chapter 4.4. Finally, the simulation and evaluation of different turbulence spectra and wind scenarios will be explained and described.

4.1.1 TurbSim

TurbSim is a stochastic, full-field, inflow turbulence simulator which generates an output summary which can be used in AeroDyn-based codes such as FAST simulation software. FAST will be further described later in Section 4.1.2. AeroDyn's InflowWind modules uses Taylor's frozen turbulence hypothesis to obtain local wind speeds, interpolating the TurbSim-generated fields in both time and space. In Fig. 4-1, the TurbSim simulation model is summarized with an illustration.

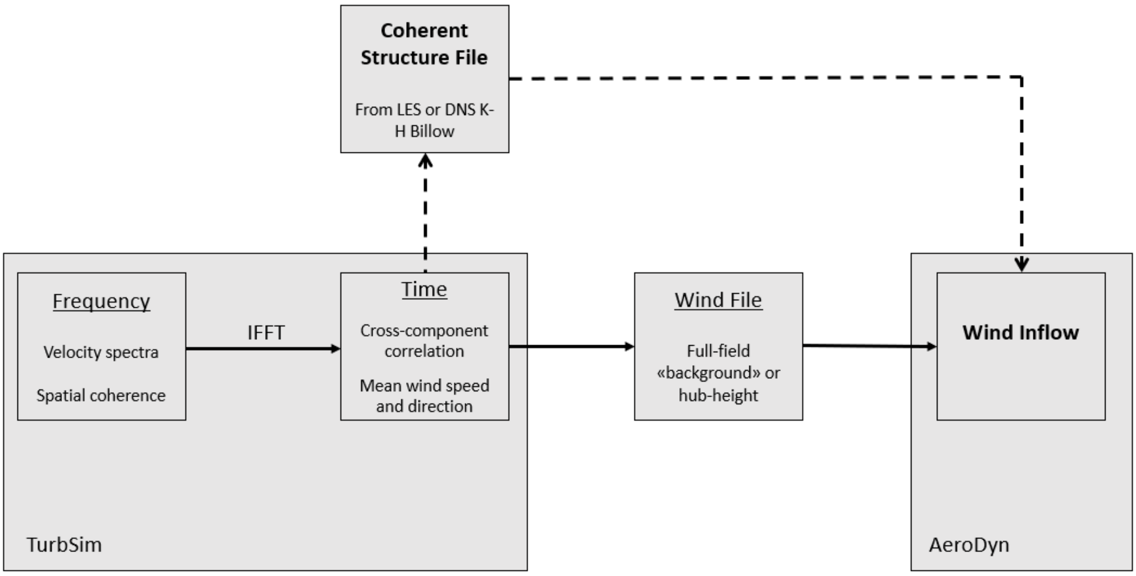

Figure 4-1: TurbSim simulation model

A transformation from the frequency domain to time domain producing wind output compatible with AeroDyn; optional coherent structures are written to a separate file and superimposed in AeroDyn (the software requires a full-field background wind file).

TurbSim starts off by reading a text input file to set the parameters required for the program to execute. Parameters like hub height, hub width, grid points in x, y and z directions, as well as the turbulence spectra are all input values for the input text file. An example of making a grid structure for the turbine rotor is shown in Fig. 4-2. The circles pictured in the figure are the rotor diameters assumed by TurbSim; the actual rotor diameter(s) will be smaller than pictured. This is because TurbSim must interpolate within the grid for any point at which it needs wind speeds, the *GridHeight and GridWidth* should be larger than the actual rotor diameter.

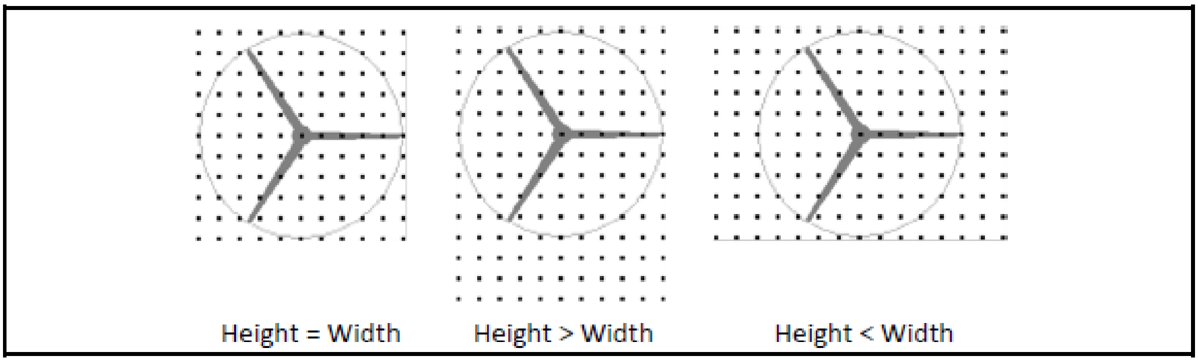

Figure 4-2: Example grid and rotor placements in TurbSim

For floating wind turbines which moves more during the simulation than rigid turbines, the grid needs to be even larger. For this simulation, an onshore wind turbine generator model will be used. Further explanation of this choice of wind turbine will be given later in this study.

In the input text file, it is also required that a turbulence spectra model is chosen. The different spectra models are based on IEC standards and are as follow:

- IECKAI: The ICE Kaimal Model
- IECVKM: The IEC Von Karman Isotropic Model
- SMOOTH: The Risø Smoorth-Terrain Model
- NWTCUP: The NREL National Wind Technology Center Model
- GP_LLJ: The NREL Great Plains Low-Level Jet Model
- WF_UPW: The NREL Wind Farm, Upwind Model
- WF_14D: The NREL Wind Farm, Downwind Model (14 Rotor Diameters)
- WF_07D: The NREL Wind Farm, Downwind Model (7 Rotor Diameters)
- TIDAL: The NREL/UW Tidal Channel Model

One of the great features of TurbSim is the ability to add coherent turbulence events that are based on data obtained from numerical simulations. The spectra models listed above, all create a velocity spectra, *S*. These values of *S* are further used to calculate the standard deviation, σ, as shown in Eq. 4.1.

$$\sigma^2 = \int_0^\infty S(f)df \tag{4.1}$$

In Appendix B the input file is shown. Note that none of the inputs in Appendix B are updated to fit the desired scenarios in this study. Parameters have to be changed in order to create different turbulence spectra, wind speeds, turbulence intensities, etc. A further description and introduction of the TurbSim input file is given in Section 4.2.

TurbSim can generate different sets of output files which are specified in the root name of the TurbSim input file, as well as a summary file for all runs after the file is run. The outputs are further implemented as input for FAST simulation software.

4.1.2 FAST and Simulink

NREL has also developed FAST (Fatigue, Aerodynamics, Structures, and Turbulence) Code which is a comprehensive aeroelastic simulator that is capable of predicting both the extreme and fatigue loads of two- and three-bladed horizontal-axis wind turbines (HAWTs). FAST can be run together with other software, and in this study, an interface with Simulink will be used.

The FAST subroutines have been linked with a MATLAB standard gateway subroutine in order to use the FAST equations of motion in a S-Function that can be incorporated in a Simulink model. In Simulink, an open loop model is created, and the model is shown in Fig. 4-3.

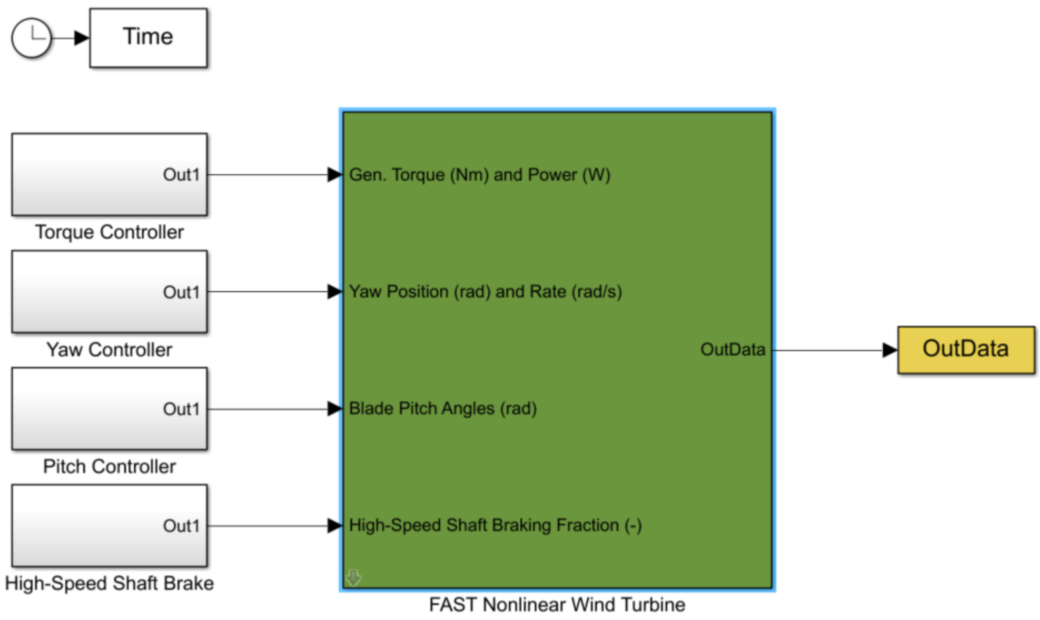

Figure 4-3: OpenLoop model in Simulink

In Fig. 4-4, the wind turbine model in Simulink is illustrated. The S-Function block is pictured as the pink block in the Simulink model. It collects data from four input signals and collects them in an "OutData" list. This "OutData" list can further be used to e.g. plot the simulated results in MATLAB.

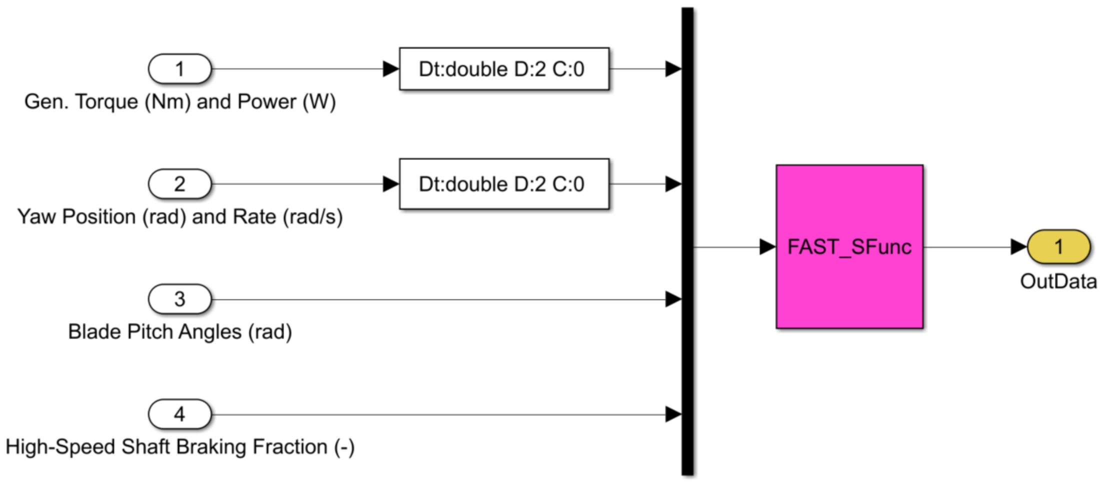

Figure 4-4: S-Function in Simulink

The block also integrates the degree of freedom (DOF) accelerations to get velocities and displacements. Thus, the equations of motion are formulated in the FAST S-Function but solved using one of the Simulink solvers.

The FAST program generates one or more output files based on the settings in the input file. In this case, parameters that are of interest will be added in an output list named "OutList" and can then be further analysed.

4.2 TurbSim Input

Setting all the parameters in TurbSim is experienced to be a time-consuming task if not all the different options are well-known. As shown in Appendix B, the number of input parameters are many. The program reads a text input file in order to set the parameters required for the program to perform. In the user guide for the TurbSim software, a comprehensive description is found for all the parameters and includes the name of the parameter, a description, and the units for that parameter. Another rather import thing is the coordinate system the software operates with, with wind-component coordinate direction in x, y, z directions which in this case is u, v, and w. An illustration of how the wind components are defined in two separate coordinate systems is described in Table 4-1.

Table 4-1: Definitions of TurbSim wind-component coordinate system

Inertial Reference Frame		Aligned with the Mean Wind	
U	Along positive X (nominally downwind)	*u*	Streamwise (longitudinal)
V	Along positive Y (to the left when looking along X)	*v*	Transverse (crosswise)
W	Up, along positive	*w*	Vertical

It is found unnecessary to explain each single parameter in the input file as all of them are not equally important and crucial for the simulation. The most central parameters are the inputs required to create the grid, which includes number of grid points in z an y-directions, hub height for the turbine, grid width and height. Another group of important factors are the meteorological boundary conditions where the reference height for the turbulence model, the turbulence intensity, the mean velocity for the wind at reference height and of course, the input turbulence model. An overview of the most central inputs is given in Table 4-2.

Table 4-2: TurbSim Inputs

Input Name	Description	Input Value
NumGrid_Z	Number of grid points to generate in the vertical direction. Must be greater than 1 and can be both odd and even numbers.	21

NumGrid_Y	Number of grid points in the vertical direction. Must be greater than 1. If the value is an odd number, points fall along the undeflected tower centerline.	21
HubHt	The hub height of the turbine for which the inflow is being generated. TurbSim uses the metric system, so the value must be entered in meters. This parameter is used as a reference height for determining the grid location.	84 [m]
GridHeight	The distance (in meters) between the top and bottom of the grid. The top of the grid is assumed to be aligned with the top of the rotor disk (see Fig. 4-2), and because all points of the grid must be above ground level, ½ *GridHeight* < *HubHt*	150 [m]
GridWidth	Gives the grid width in meters. The rotor is assumed to be centered horizontally on the grid.	150 [m]
TurbModel	This parameter tells TurbSim which spectral model it should use. Enter the six-character input value of the desired spectral model which are listed in Chapter 4.1.1.	Different spectral models will be simulated and analysed throughout the study. Therefore, this field is left empty in this table.
RefHt	This parameter specifies the height (in meters) of the	84 [m]

	corresponding reference wind speed (parameter *Uref*). TurbSim uses this reference height and wind speed with the wind profile type to calculate the mean wind speed.	
Uref	Is the mean streamwise wind speed at the reference height. It is the mean value for wind speed at *RefHt*.	- [m/s] Different values for *Uref* will be used in order to simulate different wind- and turbulence scenarios

The grid mentioned in this context can be illustrated in Fig. 4-2.

There are several possible parameters that can be changed in the TurbSim input file, but these are considered as not central in this setup.

4.3 FAST Input

For FAST there are multiple input files, and the primary input file is used to describe the wind turbine operating parameters and basic geometry. Nevertheless, the blade, tower, furling, and aerodynamic parameters and wind-time histories are read from separate files.

For this study, “Test13” is the master input file for the chosen turbine model. This file is specific for a 1.5 MW wind turbine which is placed onshore. This “Test13” file works as a master file and gather inputs from multiple other input files as mentioned above. These other files are listed in Table 4-3.

Table 4-3: Input files for FAST

Name of Input File	Description
Test13_ElastoDyn	Name of file containing elastic dynamic input parameters
WP_Baseline_InflowWind_12mps	Name of the file where the wind condition parameters are given
WP_Baseline_AeroDyn_Dynin	Name of input file for aerodynamic parameters, such as air foils, some tower and foil parameters etc.

Tesr13_ServoDyn	Name of the file containing control and electrical-drive input.

The most central inputs are inputs such as max simulation time, reference height for horizontal wind speed, reference height for wind turbine hub, mean wind speed and which output parameters that are desirable to summarize. The outputs that are being listed in the "OutList" in MATLAB workspace can further be used to plot results and make analysis.

4.4 Integrating FAST with a Type 3 WTG model

In MATLAB, an "OutList" with the simulated results from FAST simulation is presented, but not all of the interesting values are being read from the FAST model initially. The list of parameters is enclosed, and a wind turbine generator model has to be added to the FAST model to produce the necessary/desirable detailed parameters of the generator. This means that the FAST model has to be integrated with a wind turbine generator model in the MATLAB/Simulink library under Simscape > SimPowerSystems. The how-to guide for this integration is given in [35].

4.4.1 Choice of Wind Turbine Generator Model for Simulation

For the integration of a WTG model in Simulink, it was found to be beneficial to choose a wind turbine model that could simulate different turbulence spectra. Due to time constraints and limited skills in MATLAB, a 1.5 MW WTG was chosen. This is a relatively small turbine for offshore use, but the generator operation conditions are similar as for e.g. a 5 MW WTG model. Therefore, a 1.5 MW model is fully compatible to use for this case. The main objective of this study is to analysis the output power quality from a wind turbine generator based on wind scenarios, and this can be done with the chosen wind turbine.

Some general properties for the NREL 1.5 MW WP Baseline wind turbine are given in Table 4-4.

Table 4-4: Properties for NREL baseline wind turbine

NREL WindpACK (WP) 1.5 MW Baseline Wind Turbine	
Rated Capacity	1.5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Rated Tip and Generator Speed	75 m/s and 1200 rpm
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor Diameter, Hub Diameter	70 m, 3.5 m

Hub Height	84 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.5 m/s, 25 m/s

Compared with the wind turbine mentioned in Chapter 1.1.1, the simulation turbine is smaller and not placed offshore. Nevertheless, as explained earlier, the main focus is the power quality and that can be analysed with the 1.5 WTG as well.

In Fig. 4-5 the power curve for the given wind turbine is illustrated. When the wind speed is below 3 m/s there is no power produced as this wind speed is below the cut-in wind speed for this turbine. From 3 m/s the power production rises all the way up to 1500 kW at 11.5 m/s which is the rated wind speed, i.e. wind speed where the wind turbine reaches its rated capacity. The power curve flattens out and keeps steady until 25 m/s, where the turbine shuts down in order to prevent casualties.

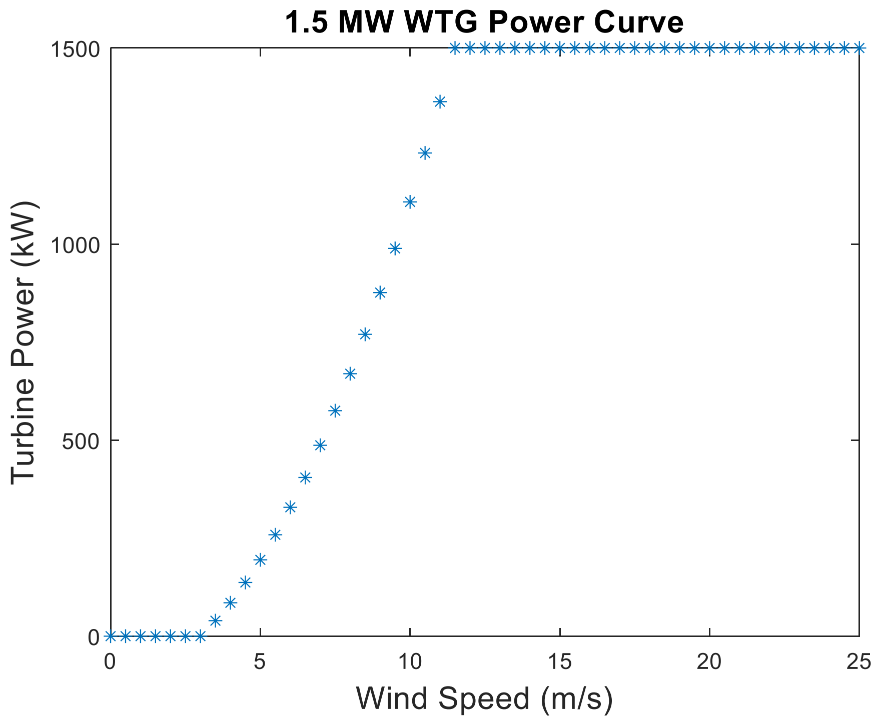

Figure 4-5: 1.5 MW WTG power curve

4.4.2 Integration

The wind turbine used in this model has a doubly fed induction generator (DFIG) and is considered by MATLAB developers to be solid for performing simulations and use the results for analysis. The initial parameters for the wind turbine are obtained from the user manual of integrating a WTG model with FAST and are valid for a 1.5 MW WTG with a nominal voltage of 575 V and frequency of 60 Hz. In Fig. 4-6, the input parameters for the wind turbine generator are given.

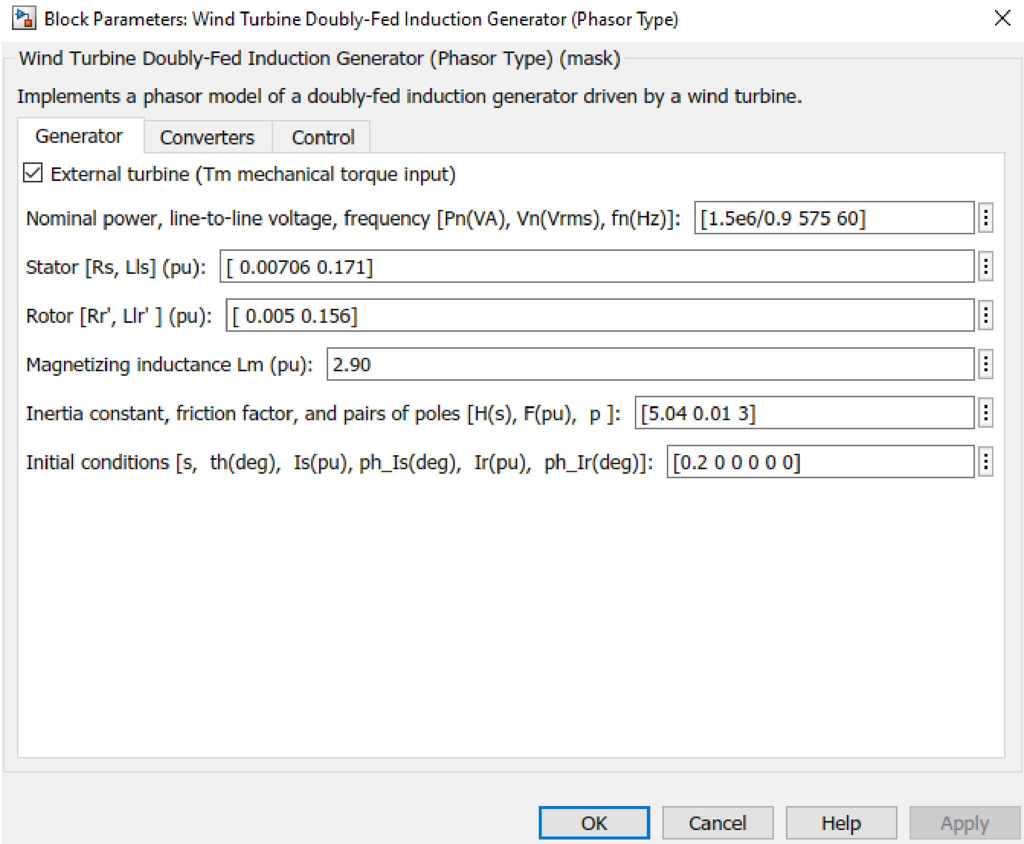

Figure 4-6: Parameters for a 1.5 MW DFIG

The WTG model in SimPowerSystems is a phasor model, which means that the power system is treated as a balanced three-phase fixed-frequency network. This is similar to how the offshore operators wants to operate their isolated grid out in the North Sea for example. This type of wind turbine model can be modelled by using a three-phase representation so that the unbalanced conditions can be simulated. Such unbalanced conditions may origin from the grid unbalanced voltage (faults, dips, or other transient events) or unbalanced grid impedance. The model does not account for these factors, but measurements of voltage, active and reactive power among other parameters can be read from the simulation and then further analysed.

Note that the Type 3 WTG can handle much higher wind speeds than for example a Type 1 WTG. Thus, a sufficiently large amount of kinetic energy can be stored and restored in the rotating blades and other mechanical components of a wind turbine. This characteristic makes the output of the generator not as easily affected by the wind fluctuations and turbulence.

As the wind turbine model of the SimPowerSystems is bypassed, the power-speed characteristic of the turbine is necessary. This characteristic has to be provided in terms of the maximum power points in the power-speed plot as shown for the 1.5 MW wind turbine in Fig. 4-7.

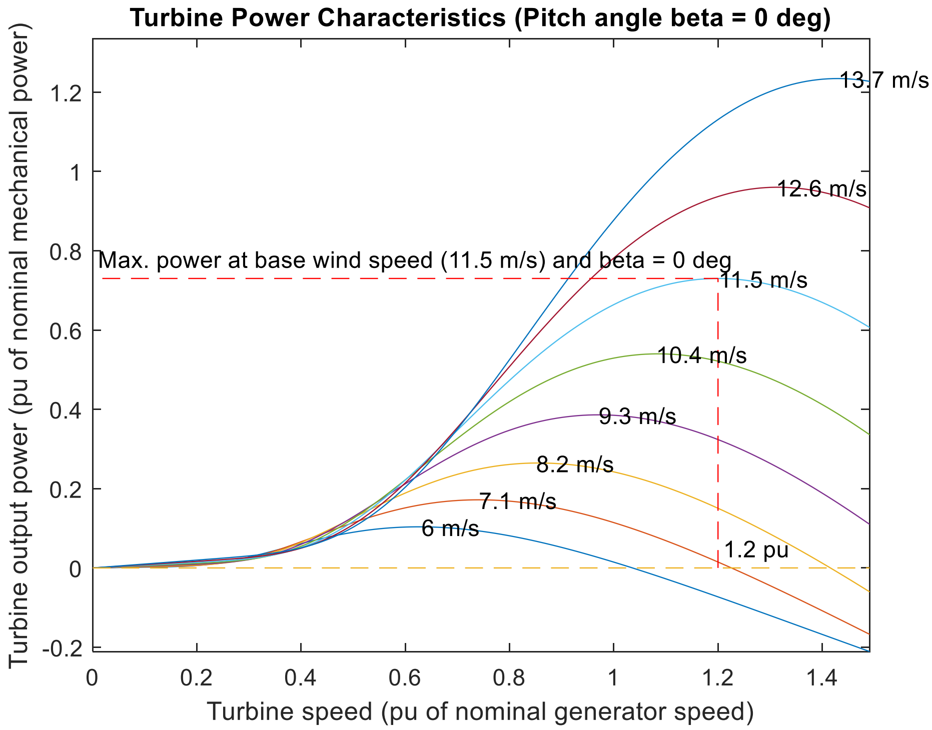

Figure 4-7: Turbine power characteristics

In Fig. 4-8, the connection diagram of the DFIG is shown. The generator operates in a variable-speed mode by using a partial-size power converter connected to the rotor winding of the wound-rotor induction generator. The stator winding is then connected to a 60 Hz grid. This type of wind turbine generator is usually operated between 30% slip (sub synchronous speed), and the converter is typically at approximately 30% of rated output power. Back-to-back ACDC-AC of the power converter is done by using two pulse-width modulation-switched voltage-source inverters which are coupled with a DC link. In variable-speed modus, the torque characteristic of the DFIG is a quadratic function of its rotational speed. This specific WTG authorizes maximal extraction of wind power because its output power is electronically controlled to follow the optimal curve, which is a function of the generator rotational speed.

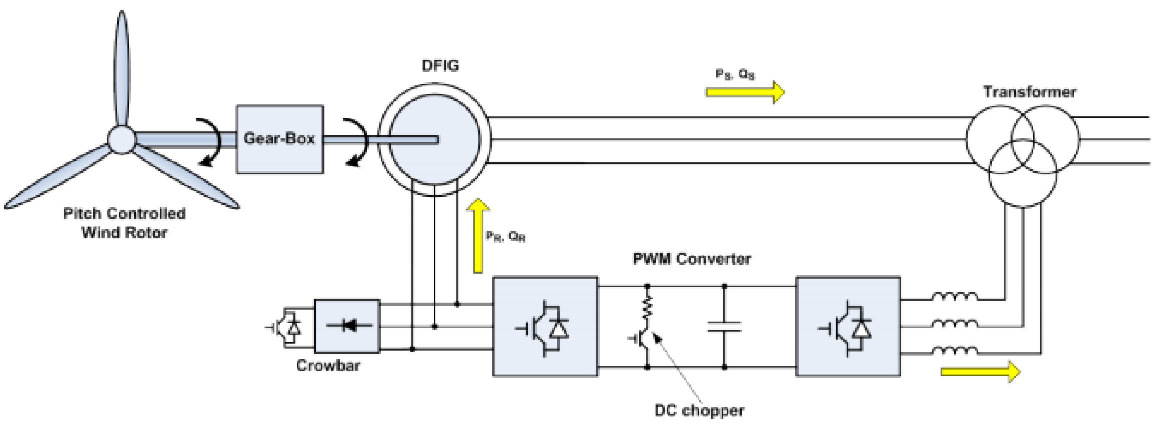

Figure 4-8: Type 3 wind turbine connection diagram

By bypassing the wind turbine model, the SimPowerSystems DFIG model will take the torque as the input. This torque input normally gets transmitted from the high-speed shaft of the gearbox. Nevertheless, the generator has to take the generator (high-speed shaft) rotational speed from FAST and deliver the generator electromagnetic torque and output power to FAST.

The complete SimPowerSystems wind turbine model is shown in Fig. 4-9. The model uses the generator speed in RPM as an input, where this torque is produced by the high-speed shaft of the gearbox.

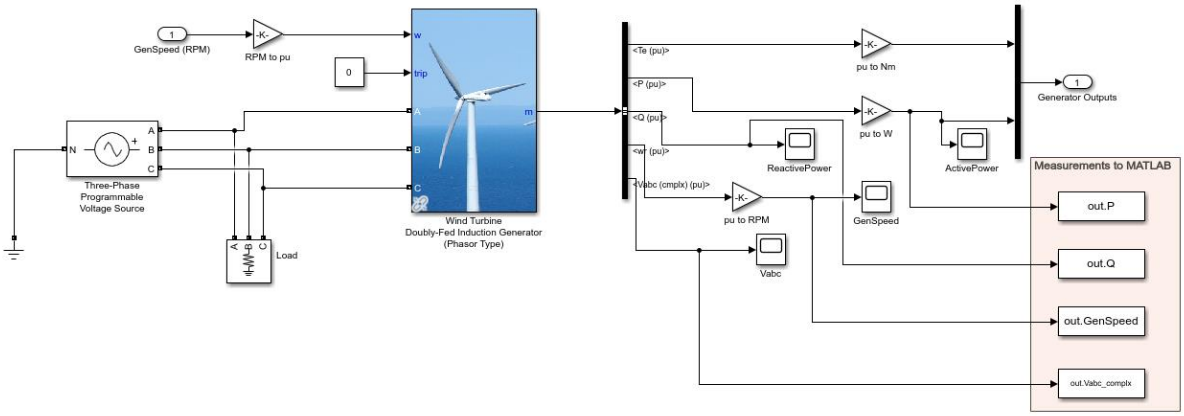

Figure 4-9: Wind turbine DFIG model

The three-phase programmable voltage source requires Vrms (rms value of voltage) which has to be of same value as the nominal voltage for the turbine generator. The nominal voltage of the WTG is found in the parameter sheet and the value is given in line-to-line rms value. The three-phase load connected to the three-phase programmable voltage source, has a nominal voltage of 575 V and frequency of 60 Hz.

The Simulink model mostly use pu values which have to be converted back and forward as desired. On the right side of the wind turbine model, two gains are required in order to convert the outputs from pu back to SI units. This conversion is done by rearranging the expression given in Eq. 4.2 and solve for the quantity expressed in SI units.

$$base\ value\ in\ p.u. = \frac{quantity\ expressed\ in\ SI\ units}{base\ value} \tag{4.2}$$

The “RPM to pu” gain shown located to the left of the wind turbine model in Fig. 4-9, is used to convert the input generator speed in RPM to pu which is preferred for the wind turbine generator model.

$$w_{base} = \frac{120 * f}{2 * p} = \frac{120 * 60}{2 * 3} = 1200\ rpm \tag{4.3}$$

Where f is frequency and p is number of pole pairs.

The gain input is simply to insert the expression in Eq. 4.4.

$$\omega \; in \; pu = \frac{1}{base \; value} = \frac{1 \; rpm}{1200 \; rpm} \tag{4.4}$$

The value of “1” represents the input value of rpm signal from the FAST OutData. The conversion between pu and SI units are done by applying a base value and the expression given in Eq. 4.2.

In the parameter sheet for the wind turbine generator, the base voltage and base power are given. The parameter sheet can be found in [35].

V_{base} = 575 V (line-to-line rms)

Apparent power, *S*, is found by:

$$S = P * PF \tag{4.5}$$

Where *PF* is given a value of 0.9 in [35].

S_{base} = (1.5/0.9) MVA

Further, the base values for current, and the base value for impedance are calculated in Eq. 4.6 and Eq. 4.7 respectively.

$$I_{base} = \frac{S_{base}}{V_{base} * \sqrt{3}} = \frac{\left(\frac{1\,500\,000}{0.9}\right) VA}{575 \, V * \sqrt{3}} = 1673.48 \, A \tag{4.6}$$

$$Z_{base} = \frac{V_{base}}{I_{base} * \sqrt{3}} = \frac{575 \, V}{1673.48A * \sqrt{3}} = 0.1984 \, \Omega \tag{4.7}$$

These are parameters which are to be inserted in the box illustrated in Fig. 4-6. The following parameters calculated in Eq. 4.8 and Eq. 4.9 are resistances calculated to cross check that the above parameters are correct, by comparing them with the given pu values in [35].

Stator winding resistance:

$$R_s = \frac{1.556 * 10^{-3} \Omega}{0.1984 \, \Omega} = 0.00706 \, pu \tag{4.8}$$

Rotor winding resistance:

$$R_r = \frac{1.102 * 10^{-3} \Omega}{0.2204 \, \Omega} = 0.005 \, pu \tag{4.9}$$

The remaining parameters required in the box shown in Fig. 4-6 are directly inserted from the parameter sheet.

In the same parameter block, illustrated in Fig. 4-6, the inertia constant, *H*, must be inserted. This can be calculated by applying the following expressions given in Eq. 4.10 throughout Eq. 4.14.

$$H = \frac{E\ (J)}{P\ \left(\frac{J}{s}\right)} \tag{4.10}$$

Where *E* is the potential energy stored in the rotor at nominal speed in Joule, and *P* is the nominal power in W (J/s).

$$E = \frac{J\ (kgm^2) * \left(\omega\left(\frac{rad}{s}\right)\right)^2}{2} \tag{4.11}$$

Where *J* is the moment of inertia and has a value of 1063.25 kgm^2 for this 1.5 MW NREL offshore wind turbine.

$$\omega = \frac{2\pi\ \left(\frac{rad}{rev}\right) * \omega\left(\frac{rev}{min}\right)}{60\left(\frac{sec}{min}\right)} = \frac{2\pi * 1200}{60} = 125.7\frac{rad}{s} \tag{4.12}$$

When inserting rotational speed in Eq. 4.11, the result of potential energy, *E*, becomes:

$$E = \frac{1063.25 * 125.7^2}{2} = 8\ 400\ 000\ J \tag{4.13}$$

Finally, the inertia constant is calculated by applying the expression given in Eq. 4.10:

$$H = \frac{8\ 400\ 000\ J}{\left(\frac{1\ 500\ 000}{0.9}\right)\frac{J}{s}} = 5.04\ s \tag{4.14}$$

By clicking on the wind turbine model (pictured block in Fig. 4-9), the internal components for the wind turbine are set. In Fig. 4-10 the internal components of the DFIG model are shown. The yellow blocks represent the simplified models of the power electronics. The green block represents the WTG model. Either, the value of the Wind_On block is of interest, or the “Tm (pu)” and one of the signals are being transmitted into the blue Generator & Converters block.

By double clicking on the “Generator and Converters” block, all the measurements/outputs are shown in a green inner block. Here it is possible to create sinks/scopes or simply send the desired measurements to workspace in MATLAB where the results easily can be illustrated by graphs and plots. These results will be further presented and discussed in Chapter 5.

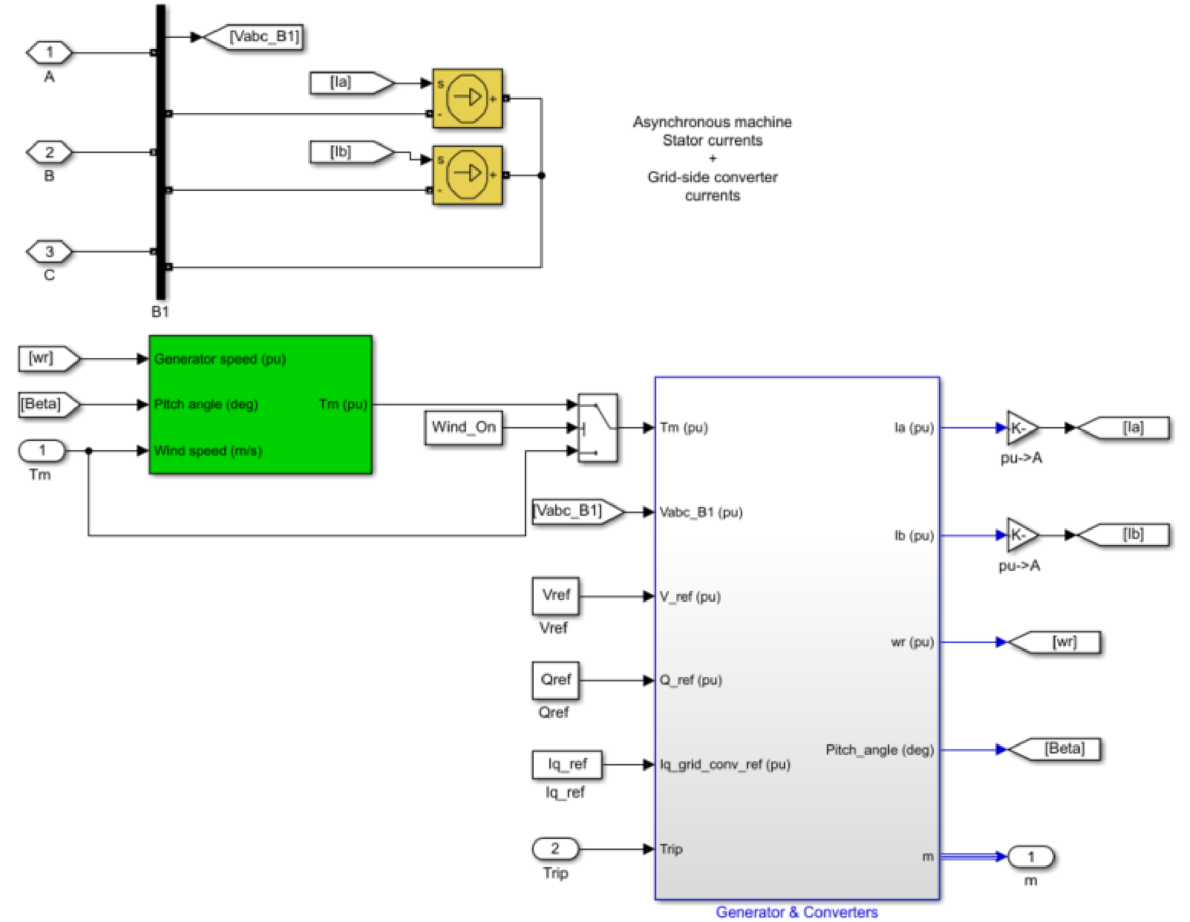

Figure 4-10: Internal components of the SimPowerSystem DFIG model

As this model nearly gives all values in per unit, the values can be converted into SI-units which are easier to relate to.

Note: “Tm” is updated to be “w” as input to the green block in Fig. 4-10.

Now the integration of the DFIG model in the Simulink environment can start, and the complete system is shown in Fig. 4-11.

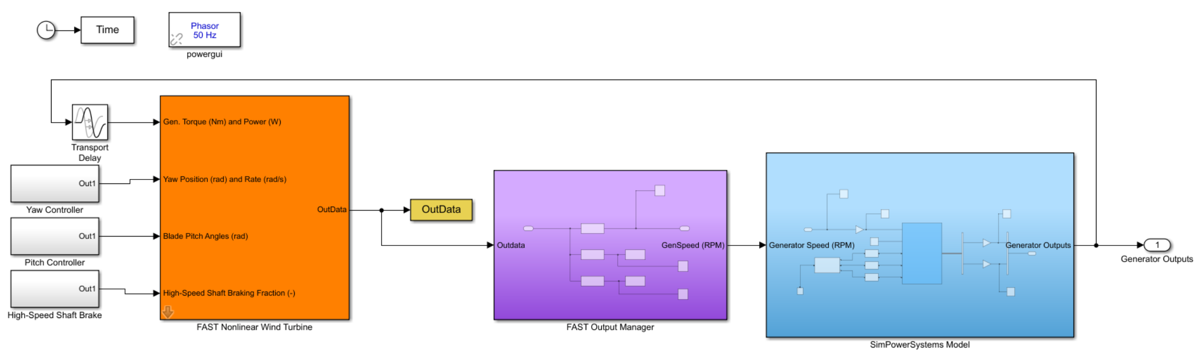

Figure 4-11: Complete Simulink model

The SimPowerSystems model shown in Fig. 4-11 is in the blue block. The FAST S-Function block is the orange block. This block is readily available within the downloaded FAST package as the *OpenLoop.slx*. The Pitch and Yaw Controllers block are not affected by this integration. The Torque Controller, which gives the torque and power inputs to FAST, is now replaced by the generator model.

The purple block represents the FAST Output Manager Block which contains parallel Interpreted MATLAB Function blocks, as shown in Fig. 4-12. It is possible to generate a function block like these for every parameter of interest in the "OutList" in MATLAB. The "GenSpeed" is absolutely necessary as the WTG model (blue block) uses the generator speed as the input signal, so this function block is therefore not optional.

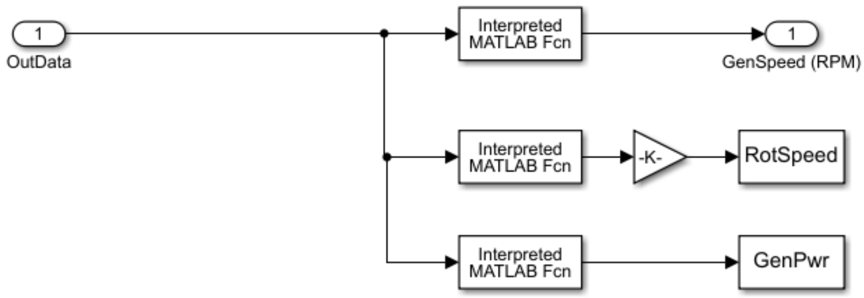

Figure 4-12: FAST Output Manager block

Each function block can be used to isolate a variable of interest from the array of FAST outputs. In the "Interpreted MATLAB Fcn" blocks, an expression calling for the specific parameters is required. For the rotor speed the expression looks like:

u(strcmp('RotSpeed',OutList'))

A "Powergui" block is a requirement in every simulation using SimPowerSystems models and is shown on the top left corner in Fig. 4-11. It is important to place the "Powergui" block at the top level of the model in Simulink for optimal performance, and a maximum of one Powergui block is allowed per model. Some changes are necessary, as the default setting of this block is Continuous and phasor model is the recommended setting for this simulation. For physical models, such as this one of SimPowerSystems, MathWorks recommend implicit global solvers. These can be ode14x, ode23t, or ode15s, and for this case it is chosen ode23tb(stiff/TR-BDF2).

4.5 Verifying the WTG Model in Simulink

After integrating the WTG model with FAST in Simulink, it was desirable to check and verify the integration. This was done by comparing the output results from FAST with the output results from the WTG model. It is considered to be sufficient to check and compare results for only one turbulence spectra, but with three different wind speeds; 8.2 m/s, 10 m/s and 14 m/s. The reason for choosing these wind speeds exactly, will be further explained in the next section, Chapter 4.6.

The results of the verification are presented in Chapter 5.1.

4.6 Simulating Different Turbulence Spectra

In order to see how the power production and power quality will be affected under different turbulence spectra, different scenarios were simulated. Each relevant turbulence spectra, as well as wind speeds and turbulence intensity are tested and described in the following sections. In this sub chapter, the different turbulence spectra will be presented, and the simulation methodology will be described.

For all turbulence spectra, *"power law"* wind profile is used. This is an input parameter in the TurbSim input file and is often used in wind power assessments where wind speeds at the height of a turbine (≥ 50 metres) needs to be estimated from near surface wind observations. The wind profile can also be used in cases where wind speed data at various heights must be adjusted to a standard height prior to use. TurbSim also asks for *"IECturb"* which is the turbulence intensity and can have an input of *A*, *B* or *C* where *A* is the most turbulent input. *A* is chosen to represent the rough conditions in the North Sea.

All turbulence spectra will be tested with 3 different wind speeds; 8.2 m/s, 10 m/s and 14 m/s. The reason for choosing 8.2 m/s as a test wind speed is because it is the mean wind speed over a year at the Gullfaks oil field. The wind conditions there will be a good representation of the conditions offshore. If choosing a wind speed at approximately 4 m/s and experience turbulence, the wind speed can get below 3 m/s which is the cut-in wind speed for the WTG model, and the simulation fails. Therefore, a range of higher wind speeds are chosen. 10 m/s is just a random chosen wind speed which occurs quite often in the wind data spread sheet from Gullfaks oil field. It is also desirable to choose a wind speed above the rated speed for the wind turbine. Hence, 14 m/s was chosen.

The resulting plots of the simulation together with an analyse of power quality will be evaluated in Chapter 5.

4.6.1 IECKAI

The first step in order to simulate a case is to set the turbulence spectra in the TurbSim input file, in this case; IECKAI. This turbulence spectra is found in IEC 61400-1 2nd ed. for offshore conditions. It is also of interest to see how the WTG model will react to different wind speeds at hub height.

In this model, the Kaimal spectra describes the energy in the turbulence wind field.

4.6.2 IECVKM

This IEC model is defined in IEC 61400-1 2nd edition for isotropic turbulence and neutral atmospheric stability. Isotropic turbulence is an idealized version of the realistic turbulence where the statistical properties are invariant for a full rotation and reflections of the coordinate axes.

4.6.3 SMOOTH

TurbSim also offers the Risø Smooth-terrain model which is based on work performed by Højstrup *et. al* [36] and Olesen *et. al* [37]. Special for this spectral model, is that it has separate equations for stable/neutral and unstable flows. The SMOOTH model defines the velocity spectra using local height and wind speed which is different from the IEC models which use the wind speed and height of the hub to define the spectra at all points.

4.7 Creating Plots in MATLAB

As explained in the beginning of this chapter, the results will be plotted using MATLAB. All parameters are being sent to workspace through the "sinks" shown in Fig. 4-8. "To workspace" is a block in Simulink which sends the simulated results to workspace in MATLAB. This has been done for all turbulence spectra, and for all the 3 chosen wind speeds as mentioned above. This means that in the end there will be, in total, 9 simulation results. From these results, the desirable parameters can be plotted, which are; active power, reactive power and three-phase voltage. Also, the wind speed will be included for each turbulence spectra and wind speed.

The results of the three-phase voltage from the WTG model are being sent to MATLAB as complex numbers. This means that the value is split into a real part and an imaginary part on the following form (just an example):

$$1.0 + 0.00012\mathbf{i}$$

Where ***i*** represents the imaginary part of the number.

The results are plotted with only the real part of the number, this means, only the magnitude of the voltage. The phase of the voltage has been considered to be redundant to plot as the WTG model is a phasor model with balanced voltage. This means that there is 120° phase difference.

The MATLAB code can be found in Appendix C.

4.8 Operational Requirements

As mentioned in Chapter 2.5.2, the grid requirements that operators have to follow are given in Table 2-2. To get a better understanding of these limits, the voltage can be found in SI units by turning Eq. 4.2 and make an expression as shown in Eq. 4.15. SI units may be more convenient in comparison of values, and easier to relate to.

$$Voltage\ in\ SI\ unit = \frac{Voltage\ in\ p.u}{Nominal\ Voltage} \tag{4.15}$$

The requirements are once again given in Table 4-5 but are identical to the requirement limits presented in Table 2-2.

Table 4-5: Operational requirements NORSOK

Frequency (Hz)	Voltage (pu)	Voltage (V)	Duration
47.5 – 49.0	0.90 – 1.05	855 – 997.5	> 30 minutes
49.0 – 52.0	0.90 – 1.05	855 – 997.5	Continuous

These are the values that the three-phase voltage will be compared with.

5 Results and Discussion

In this chapter, the simulation results together with a discussion part for each result, will be presented. As described in Chapter 4.6, different turbulence spectra are simulated in order to see how the wind and turbulence conditions will affect the power quality of offshore wind farms.

The power quality and stability of the system will be evaluated based on frequency and voltage deviations. These deviations have to be within certain limits, as described in Chapter 2.6.2. If the values are outside the limits, measures are necessary to ensure power stability to the power system/grid.

As this is a fixed frequency system, the measurements of voltage will be analysed to see if the system operates within or without the requirements. Both the active and reactive power are also included, as these gives an indication on how the power production from the wind turbine generator varies based on different turbulence spectra and wind speeds.

5.1 Comparing Results from FAST with WTG Model

To evaluate how accurate the WTG model developed in Simulink is working when being integrated with FAST, it would be beneficial to compare the output results Simulink model with the output generated from FAST alone. For this comparison it is chosen to look at active power, rotational speed of the generator and reactive power.

It has been chosen to only compare for 10 m/s wind speed in the IECKAI turbulence spectra. The plots are plotted over each other for the same parameters in a common plot, resulting in a total of 3 plots. The comparison plots for generator power, generator speed and wind speed are given in Fig. 5-1, Fig. 5-2 and Fig. 5-3 respectively.

Due to some difficulties running plots of both FAST simulation results and DFIG WTG model simulation results at the same time, it was decided to copy the results into an Excel spreadsheet and make the plots from there. In order to make the comparison of results, and hence verification of the Simulink model easier, the results for the same parameters have been plotted in stacked plots. All plots have been simulated for 600 s with timesteps of 0.005, which equals just above 120,000 rows in Excel.

In Fig. 5-1 the generator power is given in kW for both FAST (top plot) and the DFIG model (bottom plot). It is clear that both models follows the same wind curve to a certain degree, but due to internal losses in the generator, converters, etc., the power curves will not be identical. The DFIG model in Simulink produces more active power than the FAST wind turbine model. However, the models seem to operate after the same principles and that the differences in active power can be explained by different wind turbine control systems, loads resistances, converter losses, etc. These are considered to have a minor effect on the overall behaviour of the FAST wind turbine.

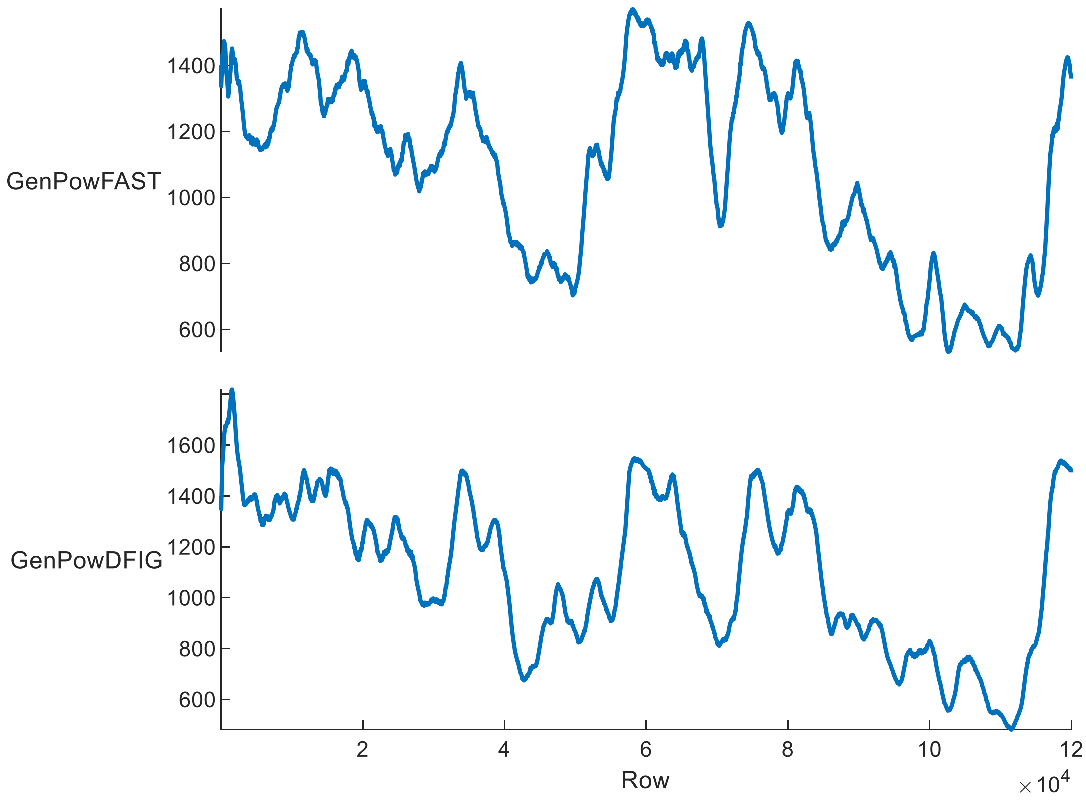

Figure 5-1: Generator power in kW

In Fig. 5-2 the generator speed for both wind turbine models are shown. For the Simulink model (DFIG), the generator speed has a large overshoot just after start-up, followed by a more stable speed for a while, before experiencing new oscillations. For the FAST model, the generator speed seems to not be so easily affected by the changes in wind speed. Or at least, not as fast as the DFIG model, as the generator speed curve doesn’t have any large overshoots. At approximately 60,000 on the x-axis, the two plots somewhat follow the same pattern.

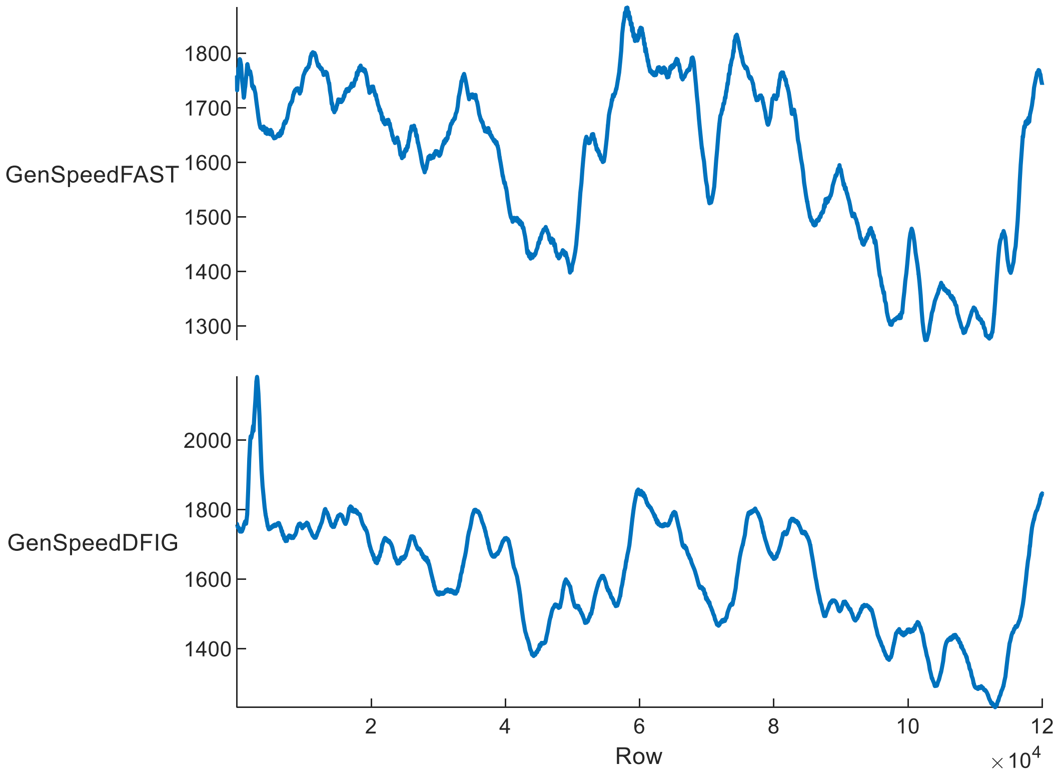

Figure 5-2: Generator speed in RPM

In the final figure of this comparison part, Fig. 5-3, the input wind speeds are given. These values are generated in *"TurbSim"* and "*WP_Baseline_InflowWind_12mps"*. The top plot is for the DFIG model in Simulink, while the bottom plot is wind speed in x direction in FAST. It is worth noticing that the mean value for the two plots are different, as the DFIG wind speed initially is higher than the FAST wind speed. However, the FAST wind speed has higher peak values at approximately 16 m/s.

Overall, the wind speed input may be one of the parameters with the biggest effect on the output power referring to Eq. 2-1 where the wind speed is given by (U (m/s))^3. Therefore, the accuracy, or at least the magnitudes should be somewhat identical. Despite some differences in the wind speed, it is reasonable that the output power will be comparable and have the same values to a certain degree as the wind speed is set to almost meet the requirement for rated wind speed at 11.5 m/s.

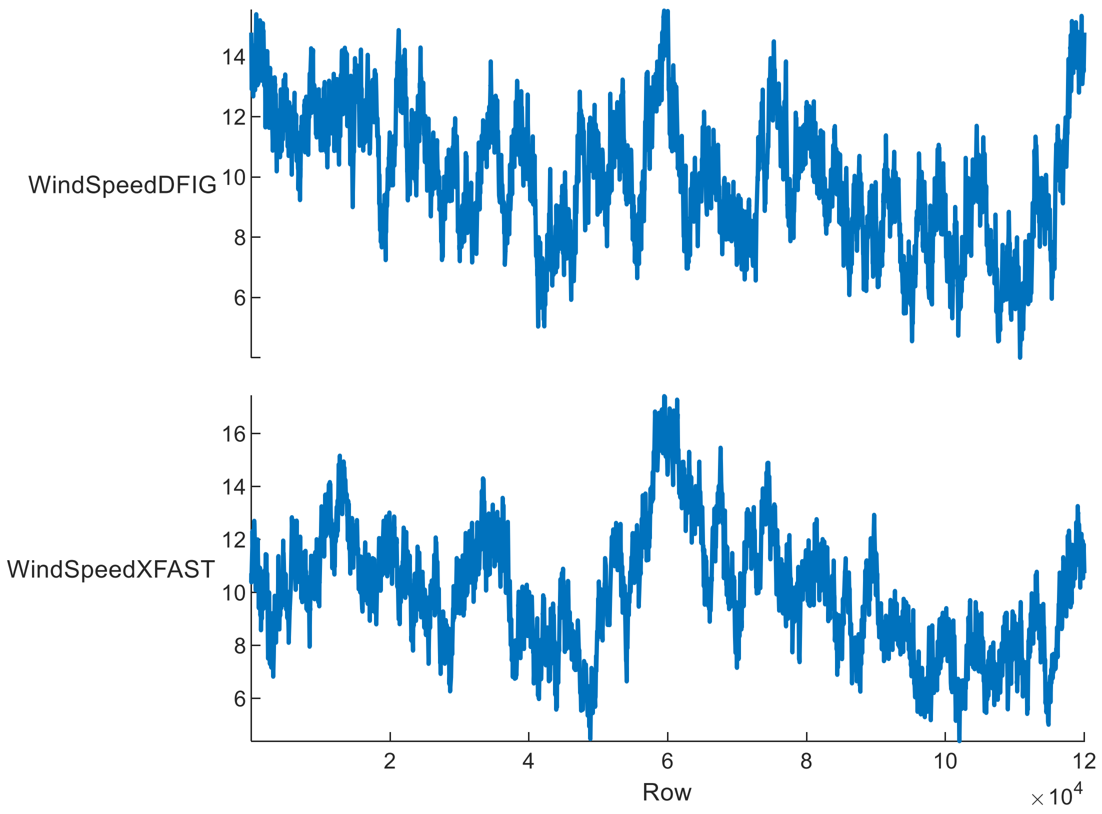

Figure 5-3: Wind speed in m/s

Summing up this comparison plots, the model developed in Simulink (DFIG) behaves similarly to the FAST model which works as a master model. Therefore, it is concluded that the models are integrated successfully.

5.2 Simulation of Different Turbulence Spectra

In Chapter 4.6, the simulation of different turbulence spectra was explained, and the results will be presented in this chapter. Discussion for each result plot will also be included throughout this chapter.

In Appendix D, one can see result plots of the generator speed for all wind speeds at different turbulence spectra. Reminding that the rated generator speed is 1200 rpm.

5.2.1 IECKAI

5.2.1.1 10 m/s wind speed

The wind speed at 10 m/s with IECKAI turbulence spectra is shown in Fig. 5-4. The wind speed variations are reasonable as the turbulence intensity is set to be *"A"*, which is the highest level of turbulence intensity in TurbSim.

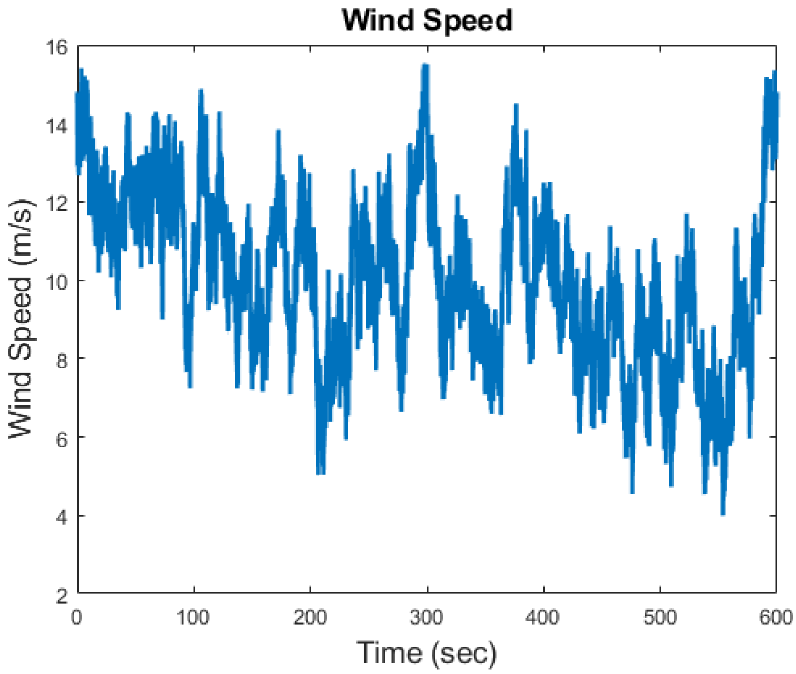

Figure 5-4: IECKAI 10 m/s wind speed

When having a wind speed of 10 m/s, it is expected that the WTG model will produce power close to its rated capacity as the rated wind speed for this wind turbine is 11.5 m/s. All wind speeds above 3 m/s should result in power production as it is the cut-in wind speed, and as proven in Fig. 5-5, the power curve/line is reliable.

In the next figure, Fig. 5-5, the active power output from the WTG model is illustrated. The output power is very close to the rated output power at 1.5 MW and is experienced to be a satisfactory result. An output power close to the rated capacity indicates that the WTG model is solid and works as intended.

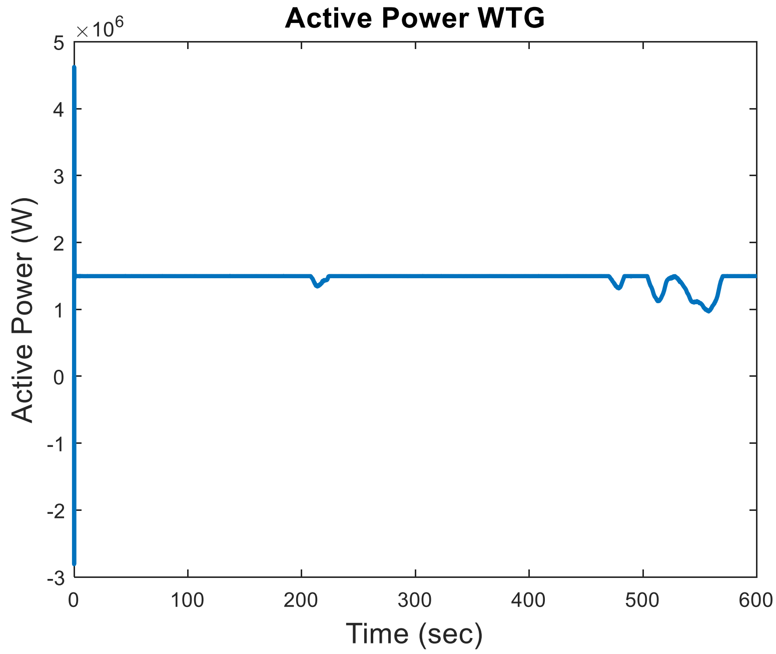

Figure 5-5: Active power IECKAI 10 m/s

How close the output power is to the rated value is better illustrated in Fig. 5-6 where the x-axis has been zoomed in to a time interval of 16 seconds. The output power is just below 1.5 MW, or more precisely, 1.497 MW.

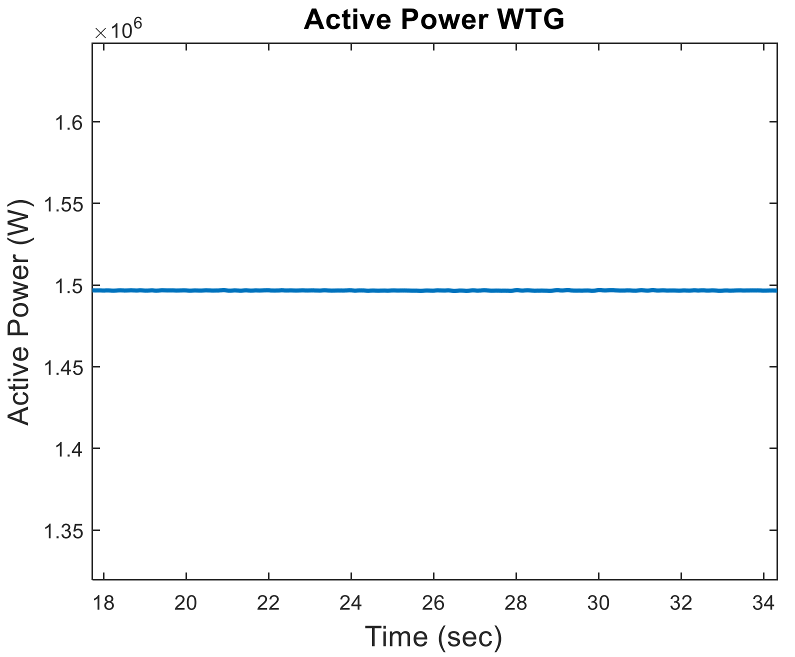

Figure 5-6: Zoomed in active power IECKAI 10 m/s

The rest of the result plots will be given in pu and not SI-unit as it is easier to analyse the data this way. Reminding that 1 pu is the rated value of a device, in this case the wind turbine generator, which for active power would mean;

1 pu = 1.5 MW

Following, in Fig. 5-7, the active power is given in pu. The perfect scenario would be a stable line at 1 pu, but as the output power is just below rated value, the same is for the pu value.

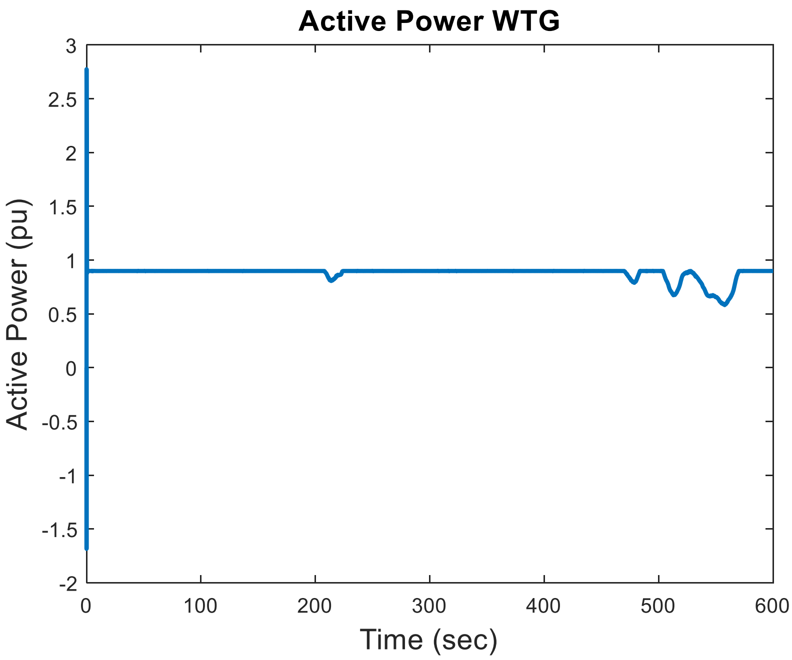

Figure 5-7: Active power in pu IECKAI 10 m/s

The reactive power of the generator is shown in Fig. 5-8. As explained in Chapter 2.1.2, the power convert for DFIG shall ensure that the reactive power stays at zero.

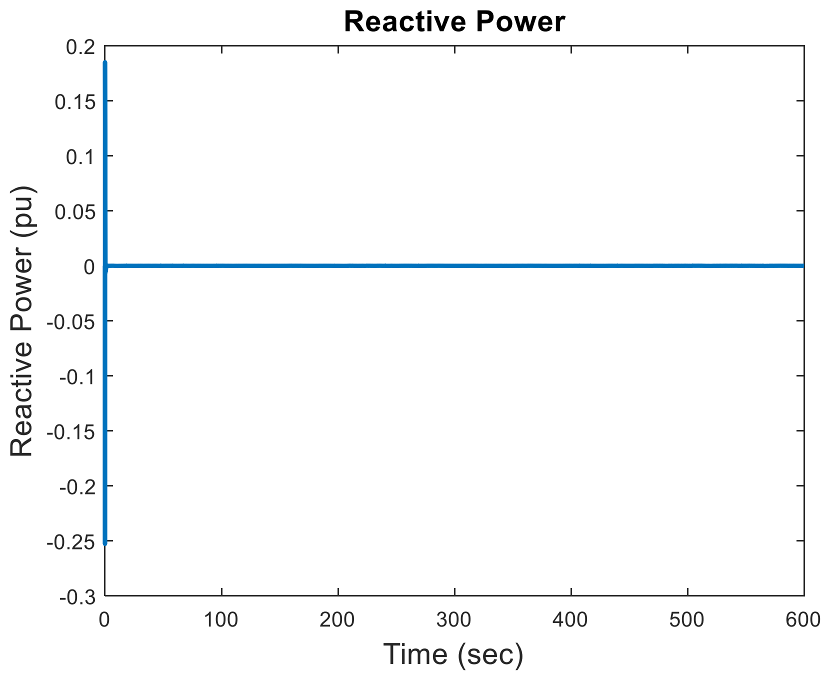

Figure 5-8: Reactive power IECKAI 10 m/s

Reactive power is directly proportional to the excitation of the generator. The excitation is the process to generate the magnetic field, so the generator rotor becomes magnetic in nature. When the reactive power is positive, the generator produces reactive power which means that the generator is over-excited. Similarly, when the reactive power is negative, which means that the generator consumes reactive power, the generator is under-excited. Reactive power stabilizes the power system, and as the active power output is steady and balanced, the need for reactive power in this case is limited. Further, reactive power is closely related to frequency control of a system as explained in Chapter 2.3. This is a fixed frequency system so the need for reactive power in order to control the frequency is redundant.

The converter on the grid side of this DFIG model is assumed to have unity power factor which can be explained by injection of reactive power from the converter. Further, the reactive power given in Fig. 5-8 is the reactive power absorbed by the DFIG rotor, but this power is given by the converter, and the reactive power absorbed from the grid by the converter is zero – unity power factor.

In Fig. 5-9, the three-phase voltage is illustrated. As the voltage consists of a real part and an imaginary part, only the magnitude will be visible in the plot. That all phase voltages, *Va, Vb* and *Vc* are 1 pu means that they are at the rated value of 575 V.

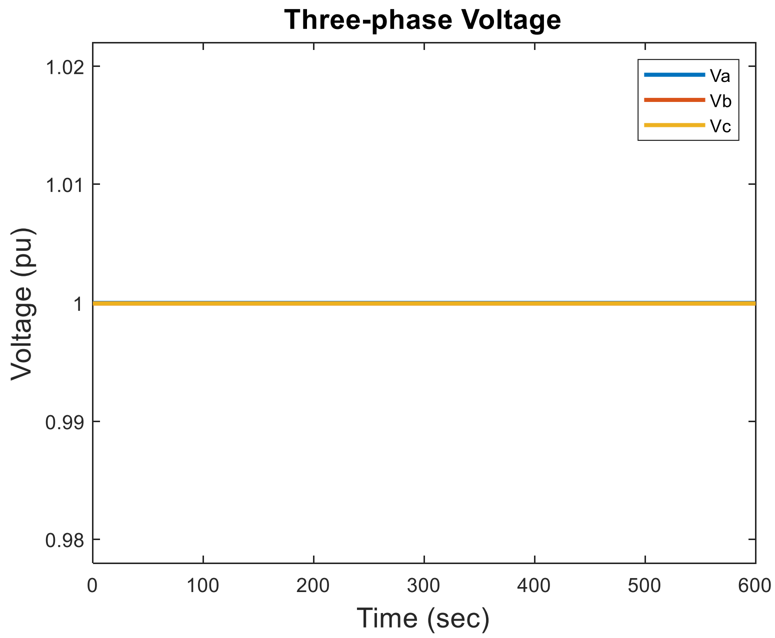

Figure 5-9: Three-phase voltage IECKAI 10 m/s

5.2.1.2 8.2 m/s wind speed

The next wind speed to be simulated in this turbulence spectra is 8.2 m/s which is the mean wind speed over a year at Gullfaks oil field in the North Sea. The wind speed is illustrated in a plot in Fig. 5-10. Again, the turbulence intensity "*A*" is chosen and the variations in the wind in the plot is accurate and swings up/down from the given wind speed at 8 m/s.

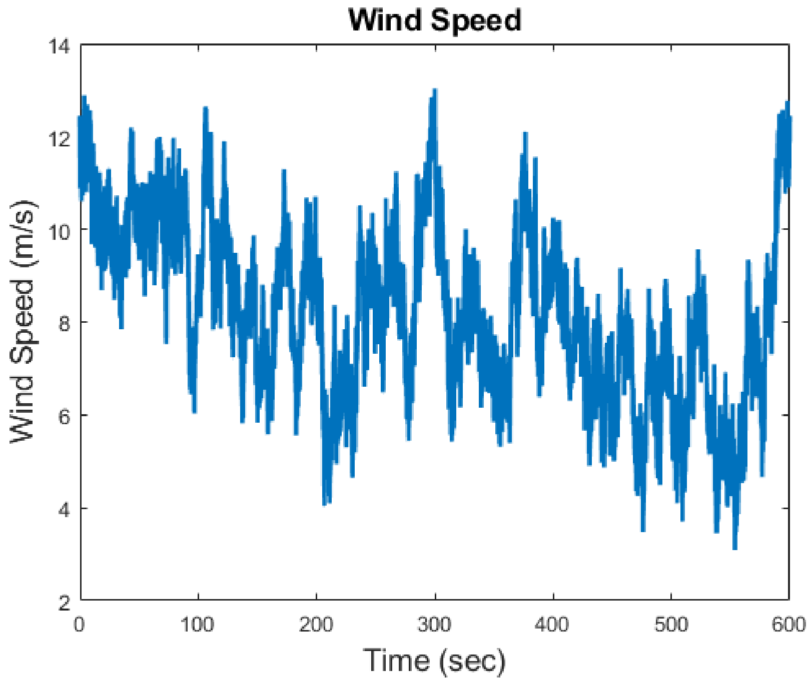

Figure 5-10: Wind speed IECKAI 8.2 m/s

In the next plot, in Fig. 5-11, the active power output at 8 m/s wind speed is shown. Due to a lower wind speed, the active power output is lower than the rated power at 1 pu. This is because the wind speed is lower than the rated wind speed. The active power plot is showing satisfactory results.

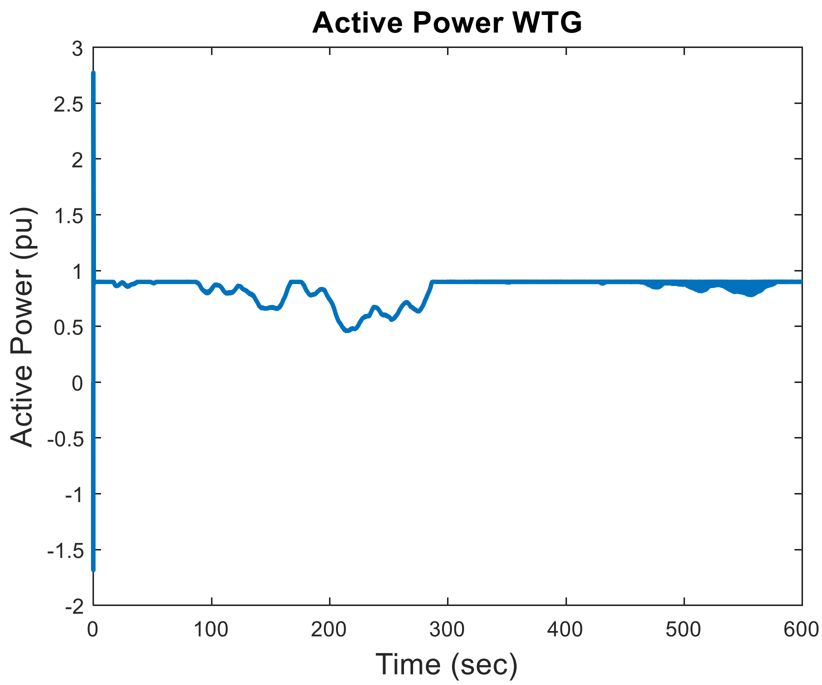

Figure 5-11: Active power IECKAI 8.2 m/s

The reason for some dips in the output power is the variations in wind speed due to turbulence.

Next up, the reactive power is shown in Fig. 5-12. Similarly, to the reactive power at IECKAI 10 m/s, the value becomes zero. Again, this is due to the power converter specific for DFIG and the result is satisfactory.

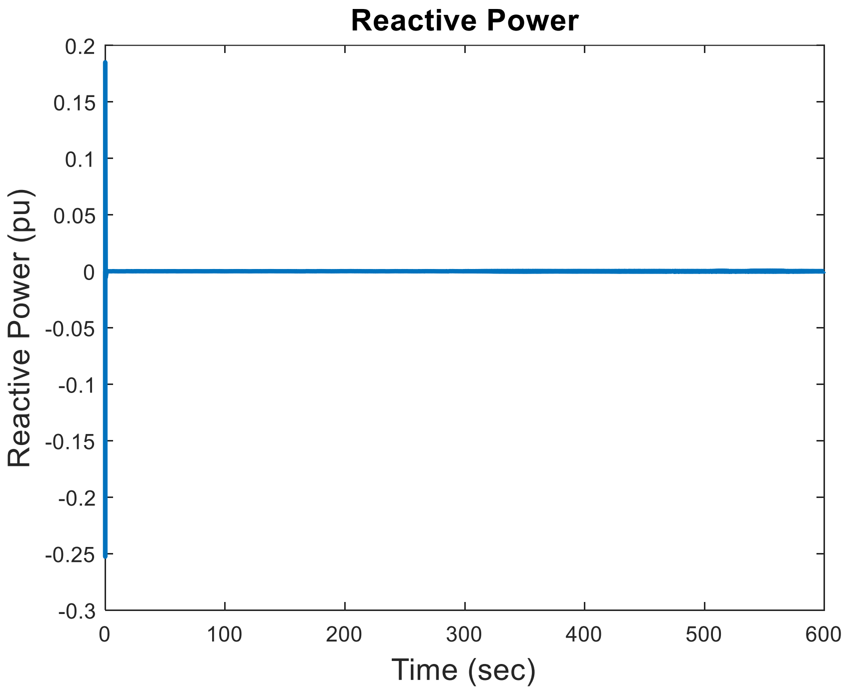

Figure 5-12: Reactive power IECKAI 8.2 m/s

Further, the three-phase voltage is given in Fig. 5-13. Again, the value stays at 1 pu which is the rated/nominal voltage for the generator.

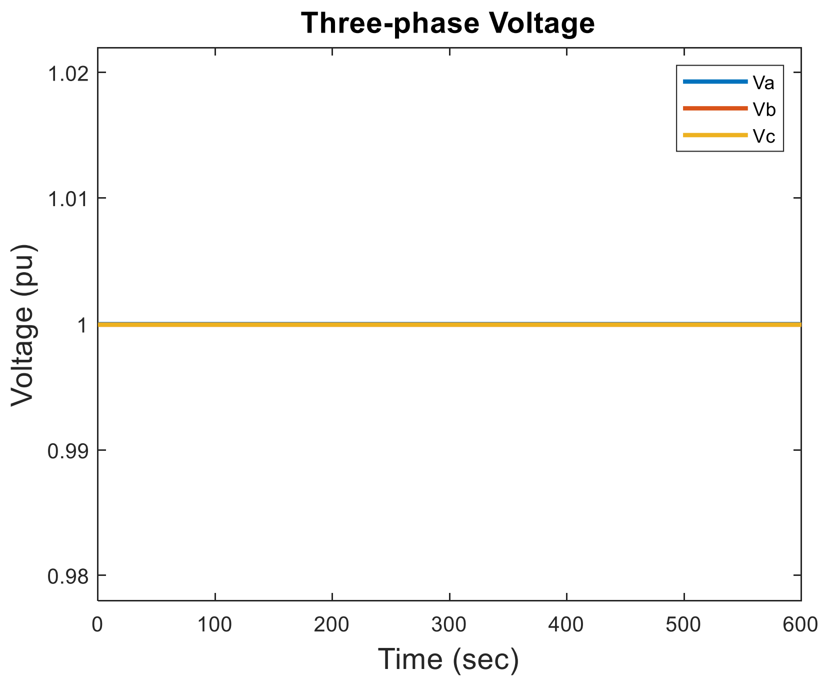

Figure 5-13: Three-phase voltage IECKAI 8.2 m/s

5.2.1.3 14 m/s wind speed

The last wind speed scenario for this turbulence spectra is representing a rougher condition of turbulence. The changes in wind speed is illustrated in Fig. 5-14.

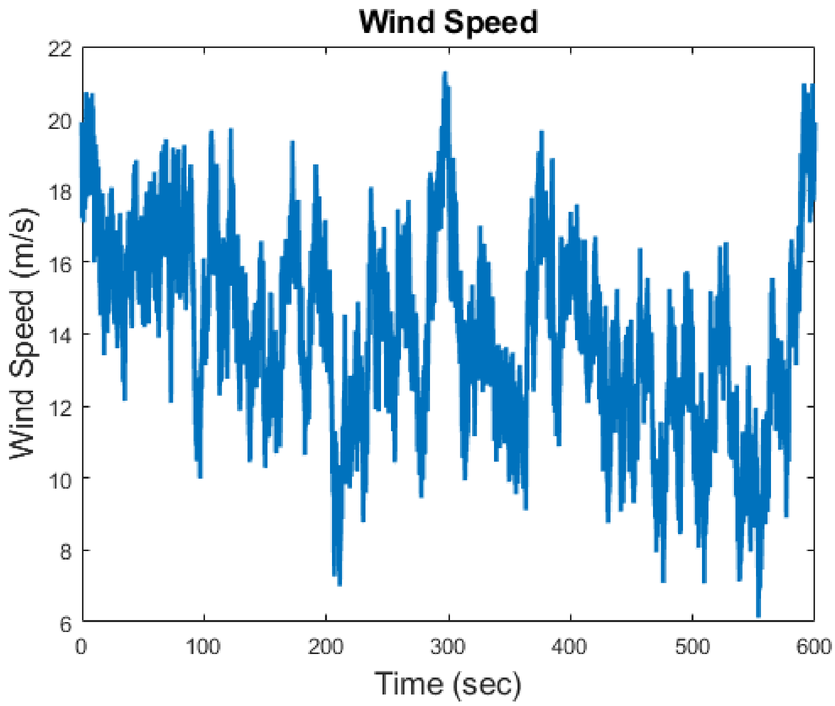

Figure 5-14: Wind speed IECKAI 14 m/s

The output active power at 14 m/s is shown in Fig. 5-15.

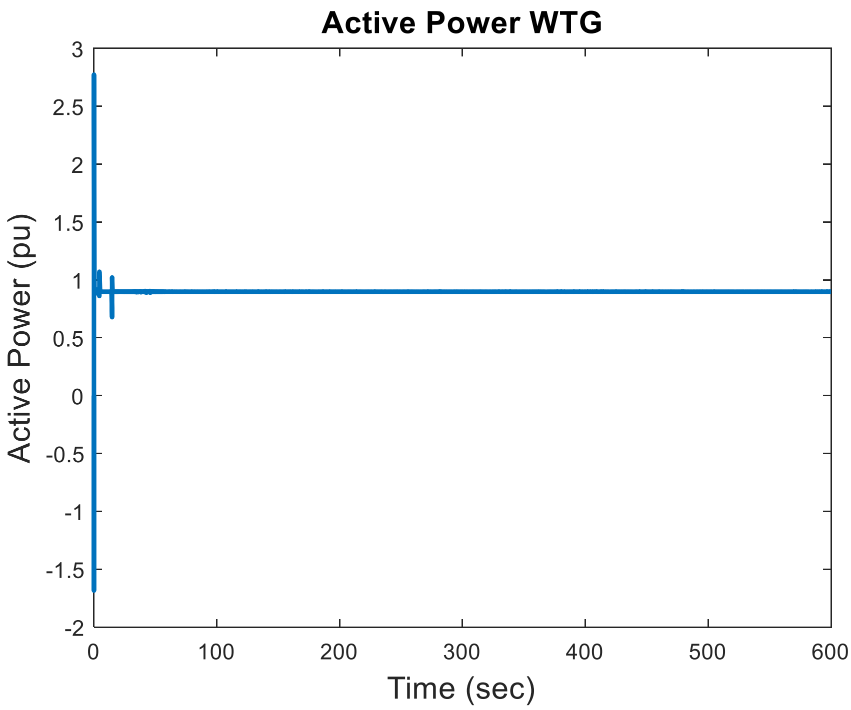

Figure 5-15: Active power IECKAI 14 m/s

The wind speed as above rated wind speed for the wind turbine and the output power reaches it maximum value at 11.5 m/s wind speed. This is the reason why the output power stays at 1 pu for the given wind speed, except for some oscillations early in the simulation period.

Further, the reactive power and voltage at 14 m/s with the constant value of zero and 1, is shown in Fig. 5-16 and Fig. 5-17 respectively.

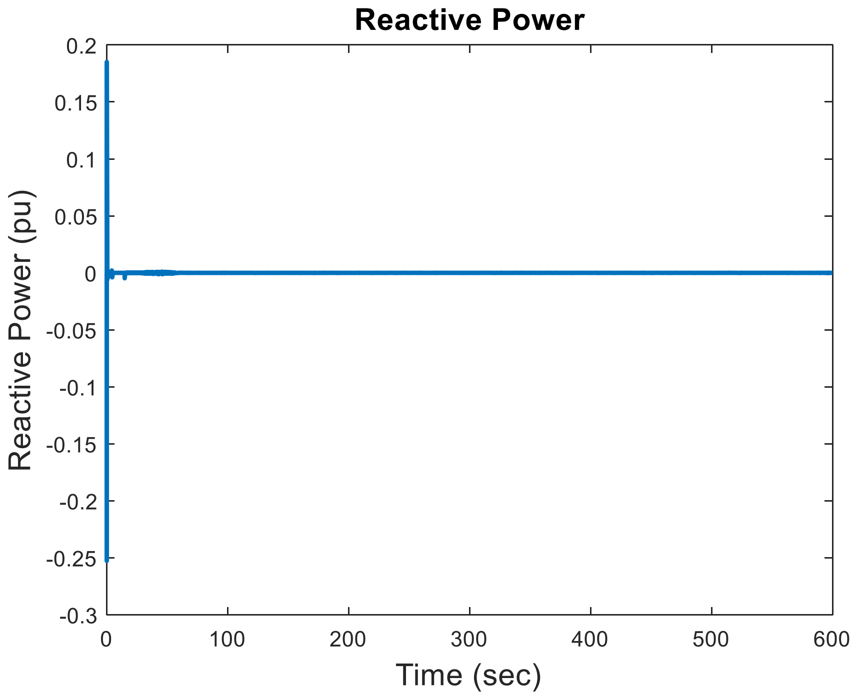

Figure 5-16: Reactive power IECKAI 14 m/s

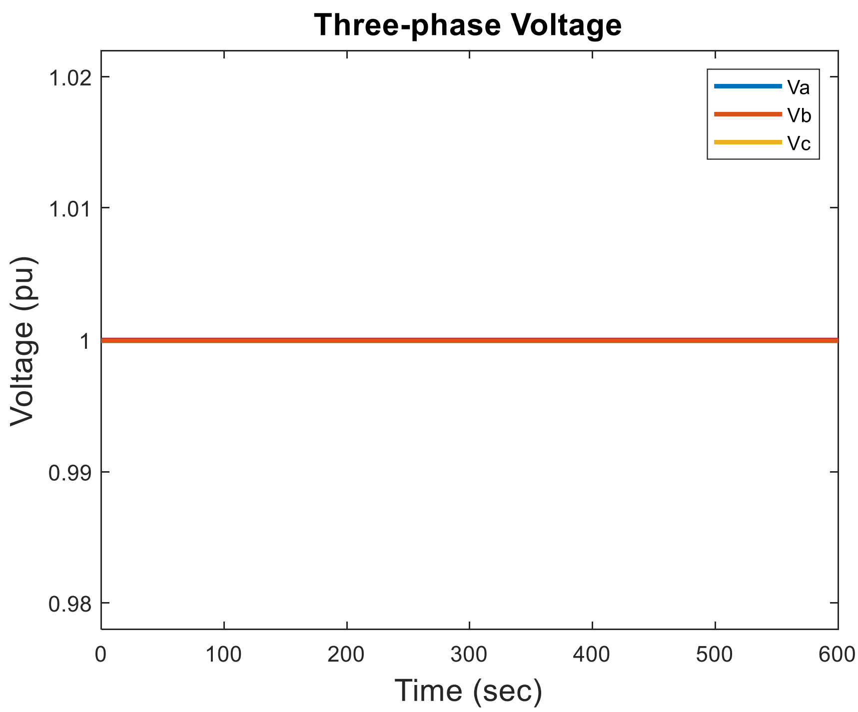

Figure 5-17: Three-phase voltage IECKAI 14 m/s

Note: For the rest of this result chapter, plots of reactive power and three-phase voltage will not be given if the value is constant at 0 and 1, respectively. Then it is referred to plots that are identical further up in the study.

5.2.2 IECVKM

5.2.2.1 10 m/s wind speed

Starting at 10 m/s wind speed the resulting plot is given in Fig. 5-18. The turbulence intensity is still "*A*" which should results in big variations in wind speed. This is confirmed when studying Fig. 5-18.

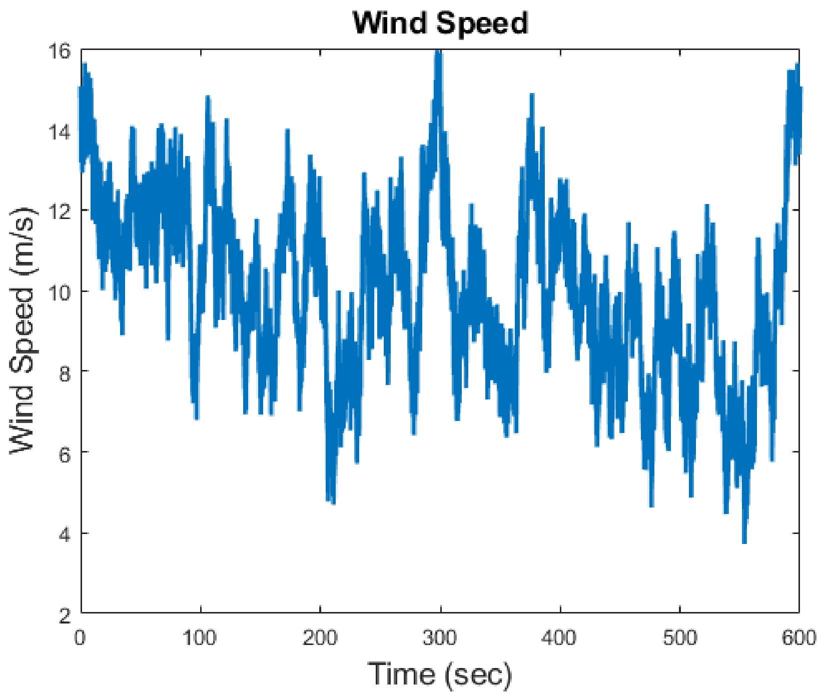

Figure 5-18: Wind speed IECVKM 10 m/s

When comparing the wind speed at 10 m/s in the IECVKM spectra with 10 m/s in IECKAI spectra, the variations in IECVKM are bigger. Looking at the minimum and maximum values in the plot, as well as the frequency of the variations, the IECVKM gives more variations in wind speed due to turbulence.

The active power is given in Fig. 5-19 and has a value of almost 1 pu. The reason for this is the same as mentioned before, the rated speed is higher than the simulated speed. Nevertheless, the plot is showing desirable results, and is a good reflection of how well the DFIG wind turbine model in Simulink is working.

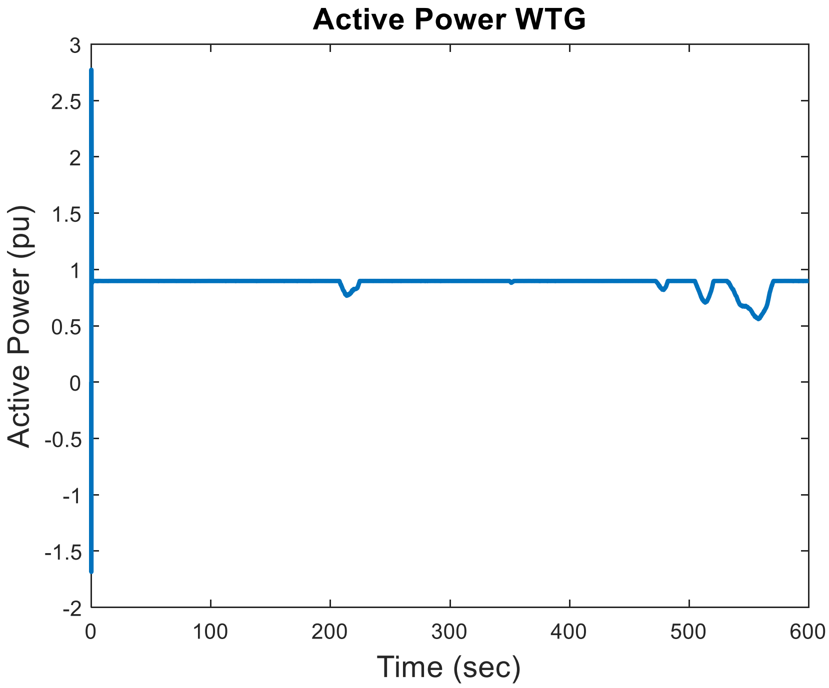

Figure 5-19: Active power IECVKM 10 m/s

The reactive power and the three-phase voltage are not shown in plots presented in this section because they are identical to Fig. 5-16 and Fig. 5-17 respectively.

5.2.2.2 8.2 m/s wind speed

The result plot for wind speed, given in Fig. 5-20, looks very similar to the wind speed at 8 m/s in the IECKAI turbulence spectra, shown in Fig. 5-10.

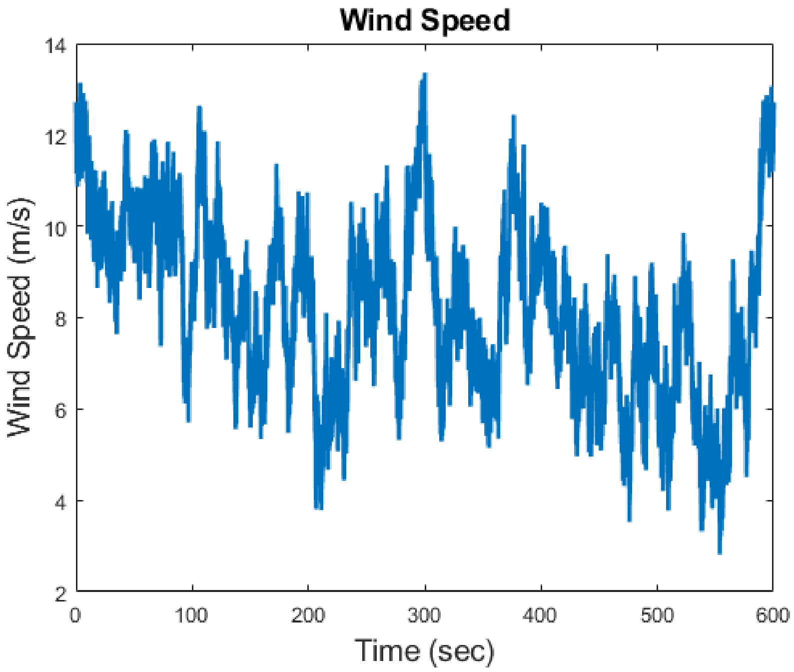

Figure 5-20: Wind speed at IECVKM 8.2 m/s

The plots of wind speed for 8 m/s are almost similar for IECVKM and IECKAI turbulence spectra.

In the next figure, the active power at 8.2 m/s wind speed in the IECVKM turbulence spectra is shown.

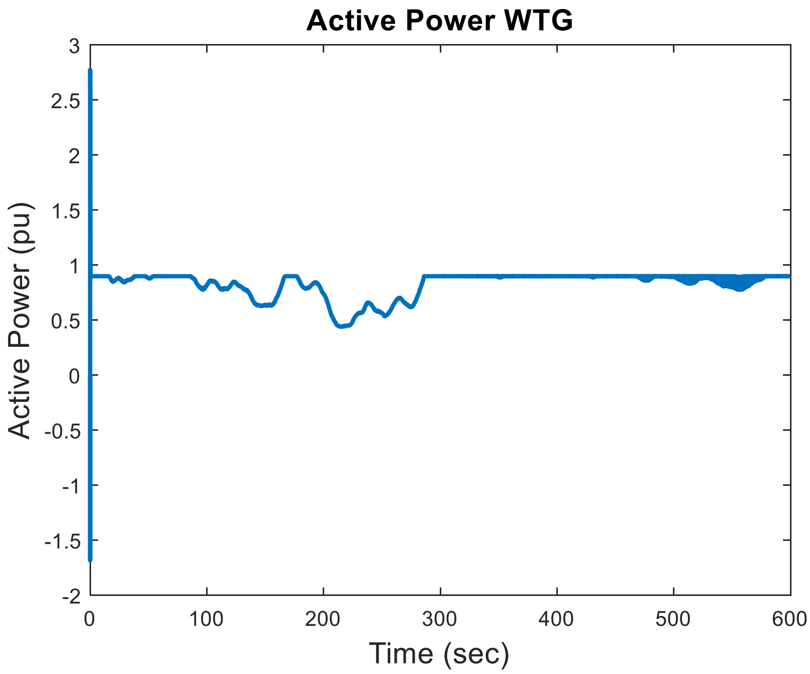

Figure 5-21: Active power at IECVKM 8.2 m/s

The active power plot in Fig. 5-21 experiences some dips around 100-300 seconds of simulations, and it is not directly related to the variations in wind speed when comparing the variations with Fig. 5-20. However, what is clear, is that when the wind speed reaches its lowest value in the interval between 100 and 300 seconds, and at approximately 500 seconds, the output power is reduced. This is a natural result of lower wind speed.

However, even if the active power has oscillations, the reactive power and the three-phase voltage are being kept constant at 0 pu and 1 pu respectively. The plots are identical to Fig. 5-16 and Fig. 5-17 for reactive power and voltage respectively.

5.2.2.3 14 m/s wind speed

Wind speed at the highest simulated value at IECVKM, at 14 m/s, is given in Fig. 5-22. The variations are quite high, and compared with the wind speed plot for IECKAI at 14 m/s, the plots look similar.

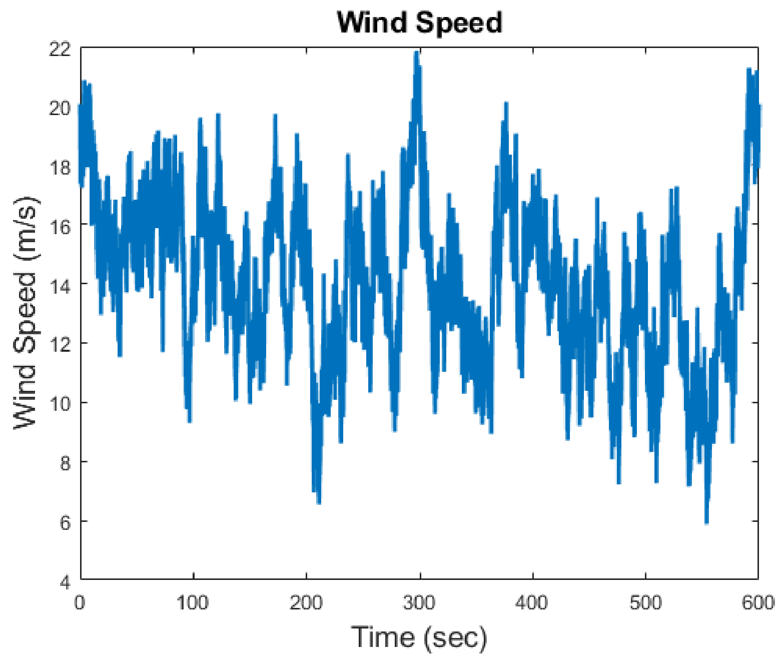

Figure 5-22: Wind speed IECVKM 14 m/s

In Fig. 5-23, the active power is given in a result plot. The value is stable at 1 pu due to the high wind speed. The wind speed is above rated wind speed and the high output active power is expected.

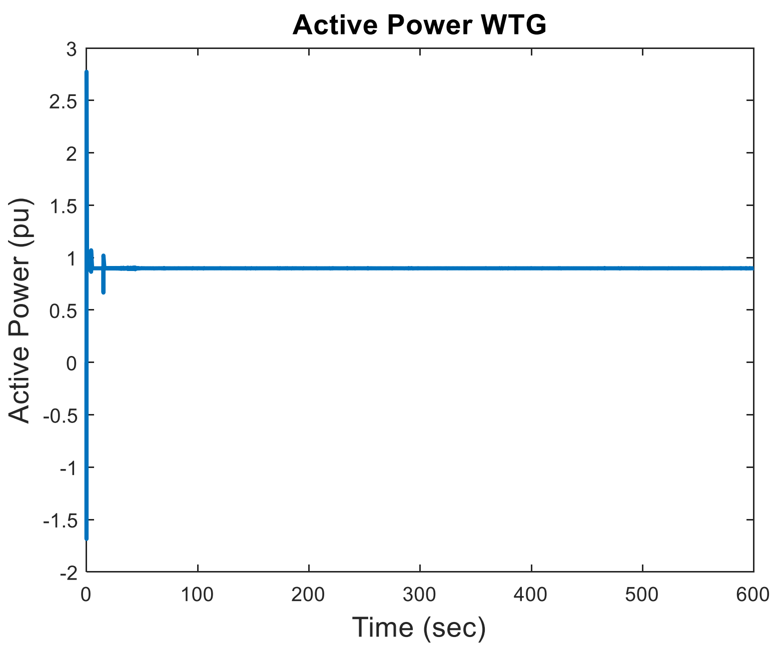

Figure 5-23: Active power IECVKM 14 m/s

The reactive power, given in Fig. 5-24 (zoomed in) experiences some oscillations initially before the PI-controller rapidly adjust the value back to zero. Tuning the controller further could result in even lower oscillations and variations in reactive power.

The three-phase voltage has a constant value of 1 pu and the plot looks identical to Fig. 5-17.

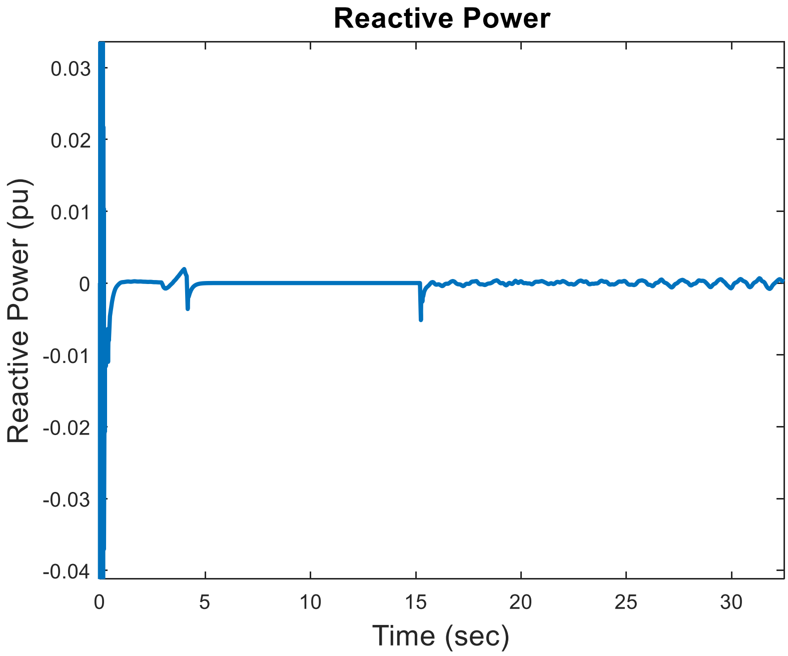

Figure 5-24: Reactive power IECVKM 14 m/s

Tuning of the PI-controller is considered to be outside the scope of this study and is therefore not being investigated further.

5.2.3 SMOOTH

5.2.3.1 10 m/s wind speed

Simulating the final turbulence spectra at 10 m/s, the wind speed result plot is given in Fig. 5-25.

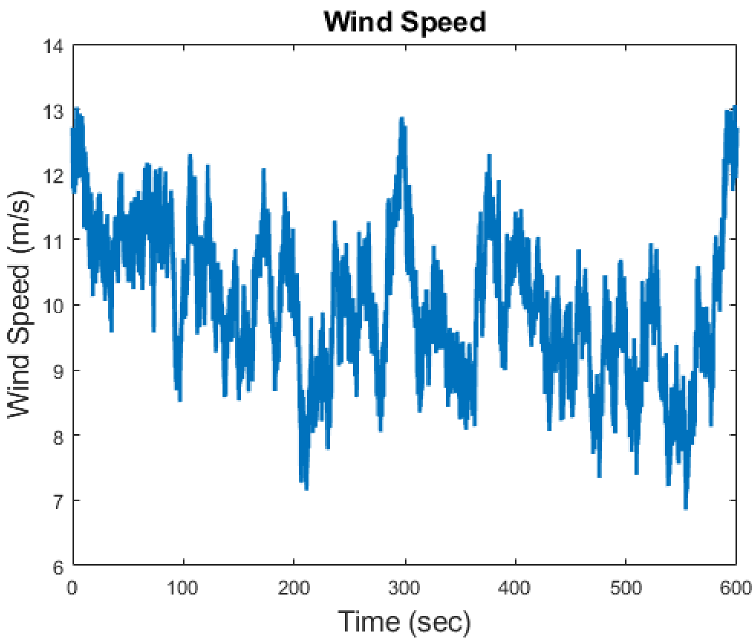

Figure 5-25: Wind speed SMOOTH 10 m/s

The mean value of this turbulence wind plot is much lower than for the two other plots at 10 m/s at IECKAI and IECVKM turbulence spectra. When comparing these three 10 m/s wind speed plots, the variations are between 22 m/s and 7 m/s for the IECKAI and IECVKM, but for the SMOOTH, the variations are between approximately 13 m/s and 7 m/s. This confirms that the SMOOTH turbulence spectra has less and smaller variations, resulting in a smoother wind turbulence.

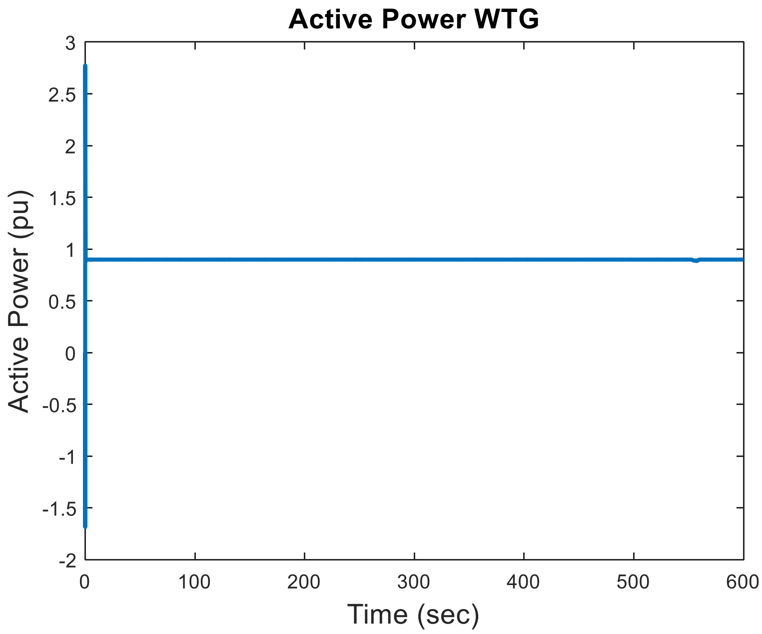

Figure 5-26: Active power SMOOTH 10 m/s

The active power in Fig. 5-26 remains at a constant value of almost 1 pu, more precisely the output power is 1.497 MW which is almost rated output power.

The reactive power has a constant value of zero here as well, and the plot is identical to Fig. 5-16 and therefore considered as unnecessary to attach.

The three-phase voltage is being held constant at nominal value, equivalent to 1 pu and the plot looks identical to Fig. 5-17.

5.2.3.2 8.2 m/s wind speed

The next wind speed, 8.2 m/s is simulated in the SMOOTH turbulence spectra as well, and the result plots are given in Fig. 5-27. Again, the variations are smaller than for the other two turbulence spectra. This was also the case for the 10 m/s wind speed.

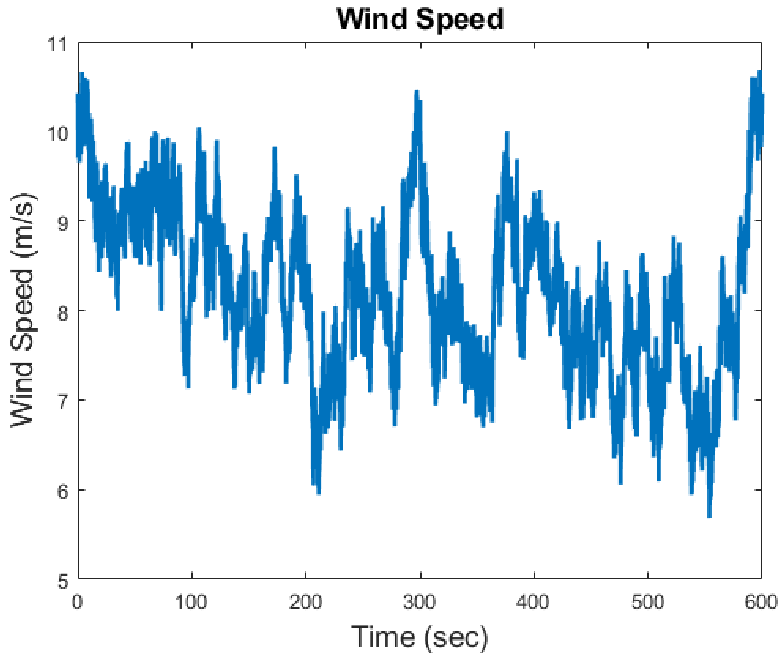

Figure 5-27: Wind speed SMOOTH 8.2 m/s

Active output power is given Fig. 5-28. Unlike the other active power plots, this wind speed at this turbulence spectra results in variations throughout the whole simulation period. This combined with smaller variations in the wind speed doesn't seem to be directly related.

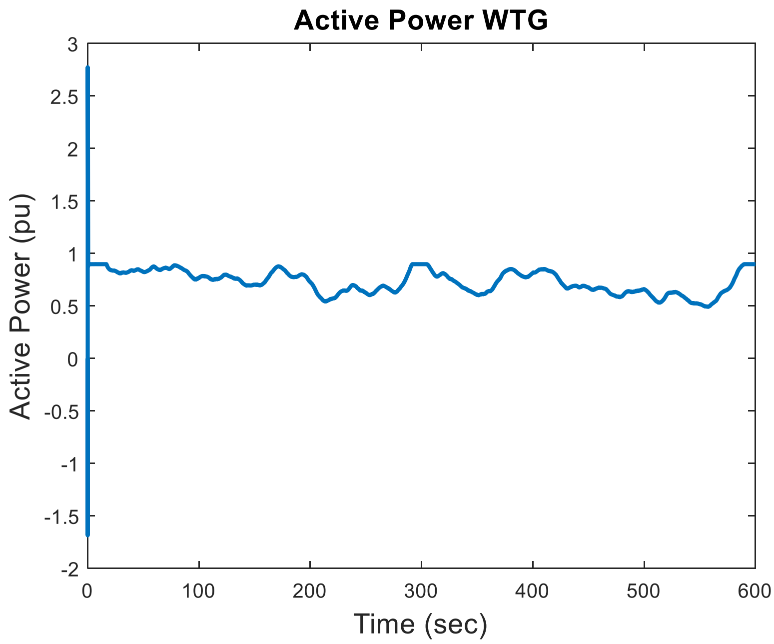

Figure 5-28: Active power SMOOTH 8.2 m/s

The variations are not too big, and the output power stays at a high value for the given wind speed at all time. However, some regulation of the power stability will be necessary, and spinning reserve in gas turbines could be the solution in this case if the wind farm was connected in a hybrid system with multiple power producing units.

The reactive power and three-phase voltage are constant at 0 and 1 pu respectively. The plots are identical to Fig. 5-16 and Fig. 5-17 respectively.

5.2.3.3 14 m/s wind speed

The final wind speed, at the final turbulence spectra, 14 m/s at the SMOOTH spectra, is simulated and shown in Fig. 5-29.

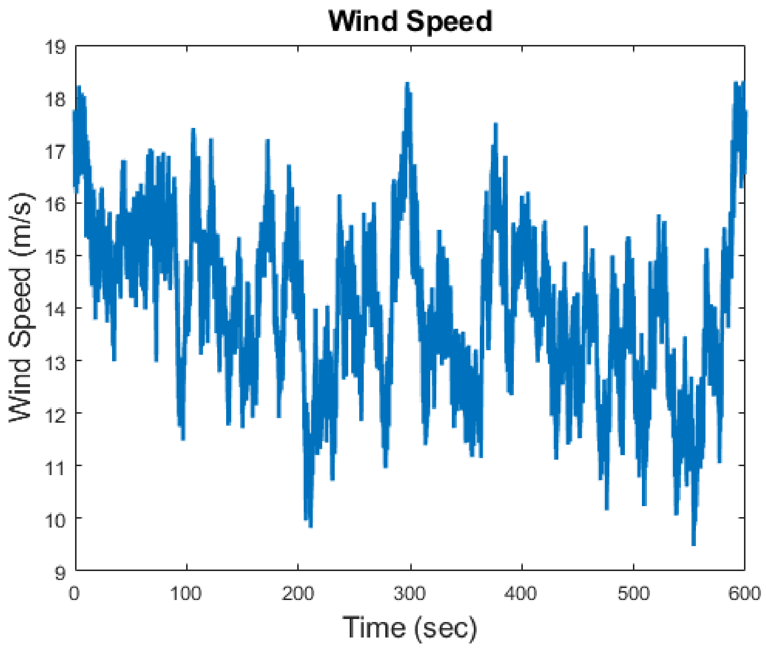

Figure 5-29: Wind speed SMOOTH 14 m/s

Similar as the rest of the SMOOTH turbulence wind speeds, the variations are smaller than for IECKAI and IECVKM turbulence spectra. This will result in a smoother power production in reality.

It is not directly visible in Fig. 5-30, that the active power has a smoother curve than the two other turbulence spectra.

Nevertheless, the active power is stable at 1 pu as the simulated wind speed is above the rated wind speed for the WTG.

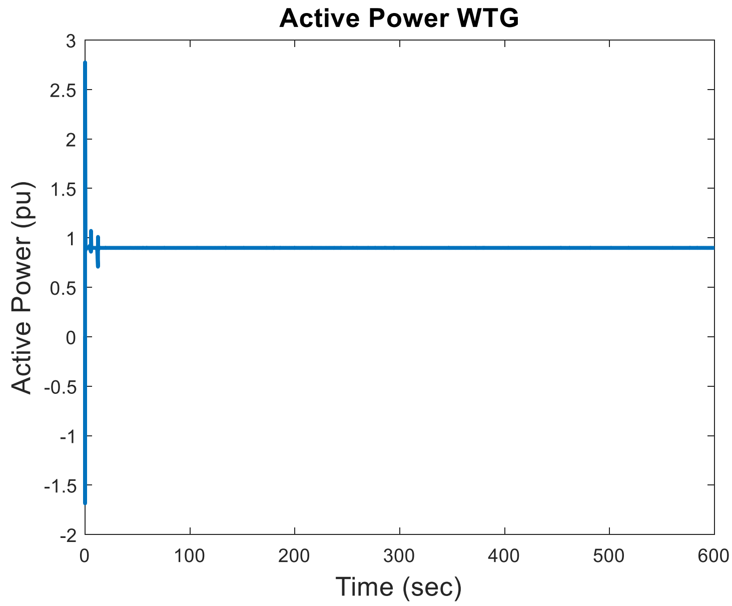

Figure 5-30: Active power SMOOTH 14 m/s

The reactive power is experiencing some oscillations initially at the simulation time, which is illustrated in Fig. 5-31. These oscillations are rapidly being controlled by the PI-controller of the generator control system.

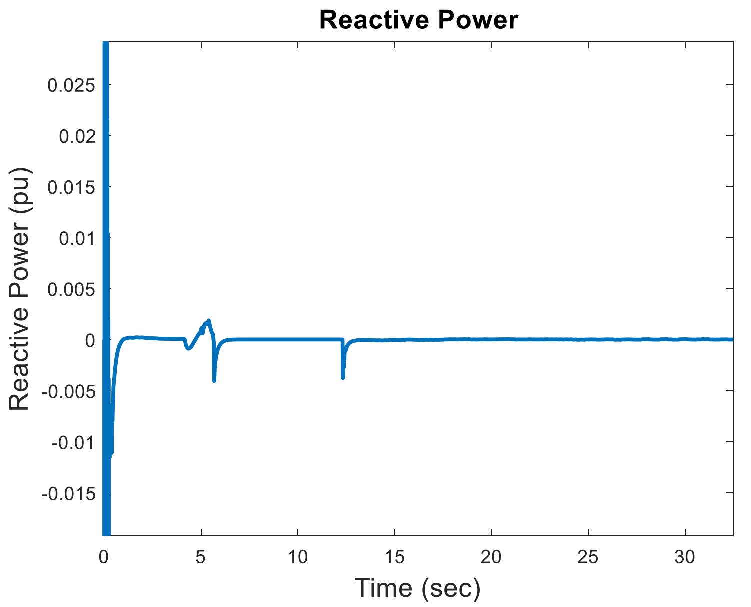

Figure 5-31: Reactive power SMOOTH 14 m/s

The voltage keeps a constant value of 1 pu, and the plot is identical to Fig. 5-17 and therefore considered to be unnecessary to include in this section.

5.3 NORSOK and IEC Requirements

As this is a fixed frequency system, deviations in the frequency will not be found in this study. Further, when looking at the requirements explained in Chapter 2.7.2, they are;

Table 5-1: Operators requirements

Frequency (Hz)		Voltage (pu)	Duration
~~**47.5 – 49.0**~~	~~**57.5 – 59.0**~~	~~0.90 – 1.05~~	~~> 30 minutes~~
49.0 – 52.0	**59.0 – 62.0**	0.90 – 1.05	Continuous

These limits are assumed to be valid for a 60 Hz system as well as for 50 Hz. This is because a generator designed to work at 50 Hz, normally also runs at 60 Hz, and therefore, it is assumed that the pu values of the voltage deviations can be used in this analysis.

The two first columns in Table 5-1, have been copied in order to match a 60 Hz frequency system. The top line has been rejected as the fixed frequency in this system doesn't match the frequency range.

When analysing the voltage results from the simulations, which all have an output value of 1 pu, the measurements are within the requirements and satisfactory. There are some oscillations in the power output, but these are not limited by the requirements shown above in Table 5-1. If these power oscillations increases, the voltage could experience a rise as shown in Table 2-4.

6 Conclusion and Recommendations for Further Work

6.1 Conclusion

Due to the increased use of offshore wind turbines in hybrid power systems in isolated grids, the power quality from the power producing units in the system have to be analysed. This study has considered output power quality and stability of a 1.5 MW wind turbine tested in the Simulink environment. This was done by applying a FAST wind turbine model with the same rated capacity. The FAST wind turbine model has been integrated with a double fed induction generator model in Simulink and was then run for different wind turbulence spectra and wind speeds. These wind scenarios were generated in TurbSim, a stochastic, full-field, inflow turbulence simulator.

Turbulence spectra models chosen for this study was IECKAI, IECVKM and SMOOTH which were all tested with the highest possible turbulence intensity. This was done in order to match the rough weather conditions found offshore in the North Sea. Further, three different wind speeds have been chosen when the turbulence spectra were simulated, and these are 8.2 m/s, 10 m/s and 14 m/s.

The accuracy of the Simulink wind turbine model was verified and compared with the FAST wind turbine model, by comparing the output results from the two wind turbine generator models. In general, it was found that the Simulink DFIG model worked as intended with only minor differences in generator speed and active power from the FAST model. After verifying the model, output results were forwarded to MATLAB and then plotted in graphs to visualise the results.

When comparing the three-phase voltage in pu with the offshore operator's requirement, the values stayed at 1 pu throughout the whole simulation, which means, at nominal voltage (575 V). It is assumed that the requirements for a 50 Hz system also is valid for a 60 Hz system. Smaller voltage dips are considered to be fixed by installing AC/AC inverters. The oscillations in the output active and reactive power can be smoothened by adding an inverter or by tuning the control system of the wind turbine.

Based on these findings, the turbulence spectra and wind speeds did not manage to get the voltage to go beyond or below the requirements stated by NORSOK and IEC for offshore operation requirements. A more similar wind turbine generator, i.e. higher rated capacity, bigger turbine diameter could have other results with the same wind speeds and turbulence spectra, and other actions would then be necessary in order to keep a stable power quality.

6.2 Recommendations for Further Work

The wind turbine model used in this study is a relatively small wind turbine with low rated capacity that is not often preferred for offshore use. The offshore wind farm developers and operators would like the turbines to be as big as possible, located far out at sea with floating foundation.

As for further research, it would be interesting to develop a DFIG model in Simulink with 5 MW rated power, or even higher, located offshore, to make the simulation more reliable and relatable for the offshore wind operators. Then the model could be used for simulating offshore conditions and predict the behaviour of offshore wind farms. Offshore oil and gas operators could also benefit from this type of model, when planning the power management system for the hybrid system, including both gas/steam turbines and wind turbines. Including wave spectra in addition to turbulence spectra could give a more realistic outcome of the simulation for operators having their power production offshore.

Taking advantage of the power quality improving devices as presented in Chapter 2.10, the oscillations and variations in power and voltage respectively, could be reduced to a minimum. The control system could be tuned further to have a more rapid adjustment of oscillations. Investigating if a PID-controller would result in better stability is also suggested as further studies.

Taking advantage of real historical weather measurements from wind sensors located out at the wind farm site could give a true representation of the wind scenarios and the following power production variations.

With these points, the following suggestion to improve the similarity and reliability of the wind turbine model of the purpose to predict power quality and power stability from offshore wind farms are:

- Use wind turbine generators more similar to the wind turbine introduced in Chapter 2.9 with higher rated capacity and larger rotor diameter.
- Tuning control system in order to reduce the active and reactive power oscillations.
- Use real historical wind data obtained from the Gullfaks oil field for the whole simulation (or another preferred weather measuring station).

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Appendix A – Measurement Requirement of the Guidelines

Requirement	**IEC 61400-21**	**MEASNET**	**German Technical Guideline**
Instantaneous power peaks	Average value of 0.2 s	Identical to IEC 61400-21	Average value over 8 to 16 line periods
1-minute power peak	Included	Included	Included
10-minute power peak	Maximum permitted power, based on manufacturer's information	Identical to IEC 61400-21	Measurement at 10-minute intervals
Reactive power or power factor	Reactive power as 10-minute average value	Identical to IEC 61400-21	Power factor as 1-minute average value
Flicker in normal operation	10-minute intervals	Identical to IEC 61400-21	1-minute intervals
Integer harmonic currents	Up to 50th order, 10-minute average values	Up to 50th order, grouping, 10-minutes average values	Up to 40th order, 8 line period value
Interharmonic currents	No	Up to 2 kHz, grouping, 10-minute average values	Up to 2 kHz, 8 line period
Current distortion in the higher frequency range	No	Frequency range 2-9 kHz, grouping, 10-minute average values, bandwidth 200 Hz	Frequency range 2-9 kHz, 8 line period value, bandwidth 200 Hz
Flicker and voltage change during switching operations of the wind turbine	For switching operations: • Cut-in at cut-in wind speed • Cut-in at nominal wind speed • Switching between generator stages Separate evaluation of flicker and voltage change	Identical to IEC 61400-21	For switching operations: • Cut-in at cut-in wind speed • Cut-in at normal wind speed • Cut-off at nominal wind speed • Switching between generator stages Same evaluation of flicker and voltage change

Appendix B – TurbSim Input File

```
TurbSim Input File. Valid for TurbSim v1.50, 4-Aug-2009

---------Runtime Options-----------------------------------
2318573   RandSeed1     - First random seed (-2147483648 to 2147483647)
RANLUX    RandSeed2     - Second random seed for intrinsic pRNG, or other pRNG: "RanLux" or "RNSNLW"
False     WrBHHTP       - Output HH turbulence parameters in GenPro-binary form?  (Generates RootName.bin)
False     WrFHHTP       - Output HH turbulence parameters in formatted form?  (Generates RootName.dat)
False     WrADHH        - Output hub-height time-series data in AeroDyn form?  (Generates RootName.hh)
False     WrADFF        - Output FF time-series data in TurbSim/AeroDyn form? (Generates Rootname.bts)
True      WrBLFF        - Output FF time-series data in BLADED/AeroDyn form?  (Generates RootName.wnd)
False     WrADTWR       - Output tower time-series data? (Generates RootName.twr)
False     WrFMTFF       - Output FF time-series data in formatted (readable) form?  (RootName.u, .v, .w)
True      WrACT         - Output coherent turbulence time steps in AeroDyn form? (Generates RootName.cts)
True      Clockwise     - Clockwise rotation looking downwind? (Used only for FF binary files w/ BLADED)
  0       ScaleIEC      - Scale IEC turbulence models to exact target std deviation? [0=none;1=hub;2=all]

--------Turbine/Model Specifications-----------------------
13        NumGrid_Z     - Vertical grid-point matrix dimension
13        NumGrid_Y     - Horizontal grid-point matrix dimension
0.05      TimeStep      - Time step [s]
630       AnalysisTime- Length of analysis time series [s] (program will add time if necessary)
630       UsableTime    - Usable length of output time series [s] (program adds GridWidth/MeanHHWS seconds)
84.30     HubHt         - Hub height [m] (should be > 0.5*GridHeight)
80.00     GridHeight    - Grid height [m]
80.00     GridWidth     - Grid width [m] (should be >= 2*(RotorRadius+ShaftLength))
0         VFlowAng      - Vertical mean flow (uptilt) angle [degrees]
0         HFlowAng      - Horizontal mean flow (skew) angle [degrees]

--------Meteorological Boundary Conditions-------------------
"SMOOTH"  TurbModel     - Turbulence model (IECKAI, IECVKM, GP_LLJ, NWTCUP, SMOOTH, WF_UPW, WF_07D, WF_14D)
"1-ED2"   IECstandard - Number of the IEC standard (61400-x, x=1,2,3) with optional 61400-1 ed. number
"A"       IECturbc      - IEC turbulence characteristic ("A", "B", "C" or TI in %) or KHTEST
"NTM"     IEC_WindType- IEC turbulence type ("NTM", "xETM", "xEWM1", or "xEWM50" for x=class 1, 2, or 3)
default   ETMc          - IEC Extreme turbulence model "c" parameter [m/s] (or "default")
"IEC"     ProfileType - Wind profile type ("JET"=Low-level jet, "LOG", "PL"=power law, "IEC", "default")
84.30     RefHt         - Height of the reference wind speed [m]
18.2      URef          - Mean wind speed at the reference height [m/s]
450       ZJetMax       - Height of the low-level jet [m] (70-490 m or "default", only for "JET" profile)
default   PLExp         - Power law exponent (or "default")
default   Z0            - Surface roughness length [m] (or "default")

--------Non-IEC Meteorological Boundary Conditions------------
default   Latitude      - Site latitude [degrees] (or "default")
0.05      RICH_NO       - Gradient Richardson number
default   UStar         - Friction or shear velocity [m/s] (or "default")
default   ZI            - Mixing layer depth [m] (or "default")
default   PC_UW         - Mean u'w' Reynolds stress (or "default")
default   PC_UV         - Mean u'v' Reynolds stress (or "default")
default   PC_VW         - Mean v'w' Reynolds stress (or "default")
default   InCDec1       - U-component coherence parameters ("a  b" in quotes or "default")
default   InCDec2       - V-component coherence parameters ("a  b" in quotes or "default")
default   InCDec3       - W-component coherence parameters ("a  b" in quotes or "default")
default   CohExp        - Coherence exponent (or "default")

--------Coherent Turbulence Scaling Parameters-------------------
"M:\coh_events\eventdata"  CTEventPath     - Name of the path where event data files are located
"Random"  CTEventFile - Type of event files ("LES", "DNS", or "RANDOM")
True      Randomize     - Randomize the disturbance scale and locations? (true/false)
 1.0      DistScl       - Disturbance scale (ratio of wave height to rotor disk).
 0.5      CTLy          - Fractional location of tower center from right to L of dataset looking downwind
 0.5      CTLz          - Fractional location of hub height from the bottom of the dataset
30.0      CTStartTime - Minimum start time for coherent structures in RootName.cts [s]

==================================================
NOTE: Do not add or remove any lines in this file!
==================================================
```

Appendix C – MATLAB Script

C.1 Wind Turbine Power Curve

```
%% Wind Turbine Power Curve
prated = 1.5e3;       %wind turbine rated power [W]
vin = 3;              % cut-in speed [m/s]
vr = 11.5;            % rated output speed [m/s]
vout = 25;            % cut-out speed [m/s]

velAvg = mean ([datavals],2);
dv = 0.5;
vbins = 0:dv:ceil(max(velAvg));

%Calculating power curve
powervbins = prated*(vbins.^2 - vin^2)/(vr^2 - vin^2);
powervbins (vbins <= vin) = 0;
powervbins (vbins > vout) = 0;
powervbins (vbins >= vr & vbins <= vout) = prated;

%Plotting power curve
figure;
plot (vbins, powervbins,'*');
xlabel ('Wind Speed (m/s)','Fontsize',14);
ylabel ('Turbine Power (kW)','Fontsize',14);
title ('1.5 MW WTG Power Curve','Fontsize',14);
xlim ([0 25]);
```

C.2 Comparison Plots

```
%% Data collection
Time = Comparisonofresults(:,1);
P_FAST = Comparisonofresults(:,2);
P_DFIG = Comparisonofresults(:,3);
w_FAST = Comparisonofresults(:,4);
w_DFIG = Comparisonofresults(:,5);
W_DFIG = Comparisonofresults(:,6);
W_FAST = Comparisonofresults(:,7);

%% Generator power
figure (1)
stackedplot(Comparisonofresults,{'GenPowFAST','GenPowDFIG'},'LineWidth',1.5);

%% Generator speed
figure (2)
stackedplot(Comparisonofresults,{'GenSpeedFAST','GenSpeedDFIG'},'LineWidth',1.5);

%% Wind speed
figure (3)
stackedplot(Comparisonofresults,{'WindSpeedDFIG','WindSpeedXFAST'},'LineWidth',1.5);
```

C.3 Results Plots

```
%%Wind speed
Time = simlnkout.Time;
plot (simlnkout.WindSpeed,'LineWidth',2);
title ('Wind Speed','Fontsize',14);
ylabel ('Wind Speed (m/s)','Fontsize',14);
xlabel ('Time (sec)','Fontsize',14);

%% DFIG outputs

OutData = simlnkout.OutData;
Dfigout = simlnkout.Dfigout;
Qmva = Dfigout.Q__pu_.Data*1.5e6/09;
Pmva = Dfigout.P__pu_.Data*1.5e6/0.9;
w_r = Dfigout.wr__pu_.Data*1200;
V = Dfigout.Vabc__cmplx___pu_;
Time = simlnkout.Time;

% figure (1)
% plot (Time, Pmva,'LineWidth',2);
% title ('Active Power WTG','Fontsize',14);
% ylabel ('Active Power (W)','Fontsize',14);
% xlabel ('Time (sec)','Fontsize',14);

figure (2)
plot (Time, Pmva/(1.5e6/0.9),'LineWidth',2);
title ('Active Power WTG','Fontsize',14);
ylabel ('Active Power (pu)','Fontsize',14);
xlabel ('Time (sec)','Fontsize',14);

% figure (3)
% plot (Time, Qmva,'LineWidth',2);
% title ('Reactive Power','Fontsize',14);
% ylabel ('Reactive Power (VAr)','Fontsize',14);
% xlabel ('Time (sec)','Fontsize',14);

figure (4)
plot (Time, Qmva/(1.5e6/0.9),'LineWidth',2);
title ('Reactive Power','Fontsize',14);
ylabel ('Reactive Power (pu)','Fontsize',14);
xlabel ('Time (sec)','Fontsize',14);
```

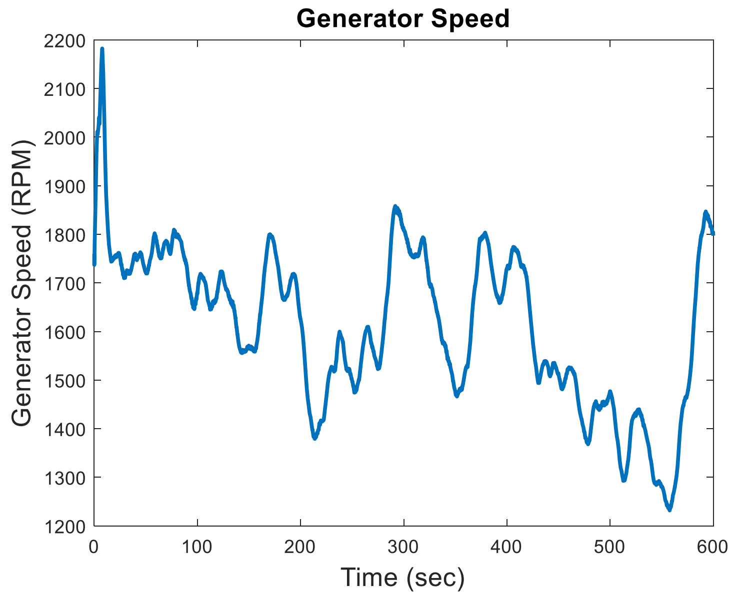
```
figure (5)
plot (Time, w_r,'LineWidth',2);
title ('Generator Speed','Fontsize',14);
ylabel ('Generator Speed (RPM)','Fontsize',14);
xlabel ('Time (sec)','Fontsize',14);

figure (6)
Va = V.Data(:,1);
Vb = V.Data(:,2);
Vc = V.Data(:,3);
plot (Time, abs(Va),'LineWidth',2);
hold on;
plot (Time, abs(Vb),'LineWidth',2);
plot (Time, abs(Vc),'LineWidth',2);
legend ('Va', 'Vb', 'Vc');
title ('Three-phase Voltage','Fontsize',14);
ylabel ('Voltage (pu)','Fontsize',14);
xlabel ('Time (sec)','Fontsize',14);
```

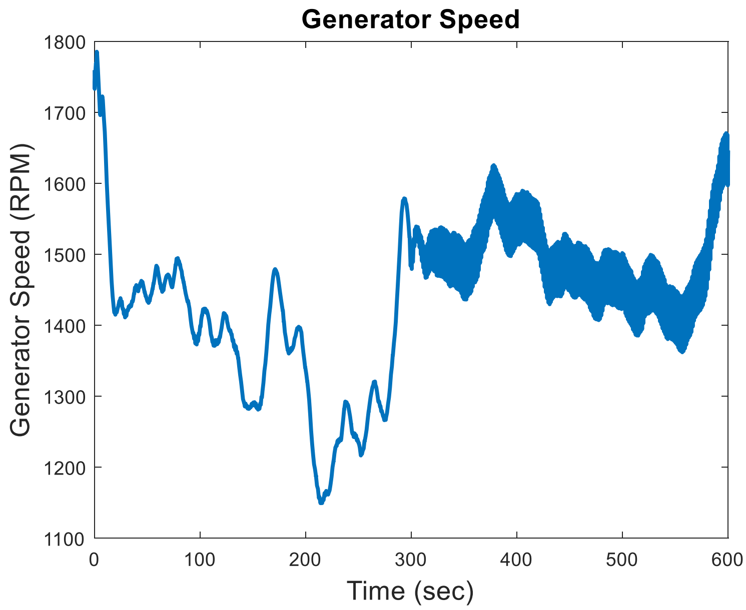
Appendix D – Results of Generator Speed

IECKAI Turbulence Spectra

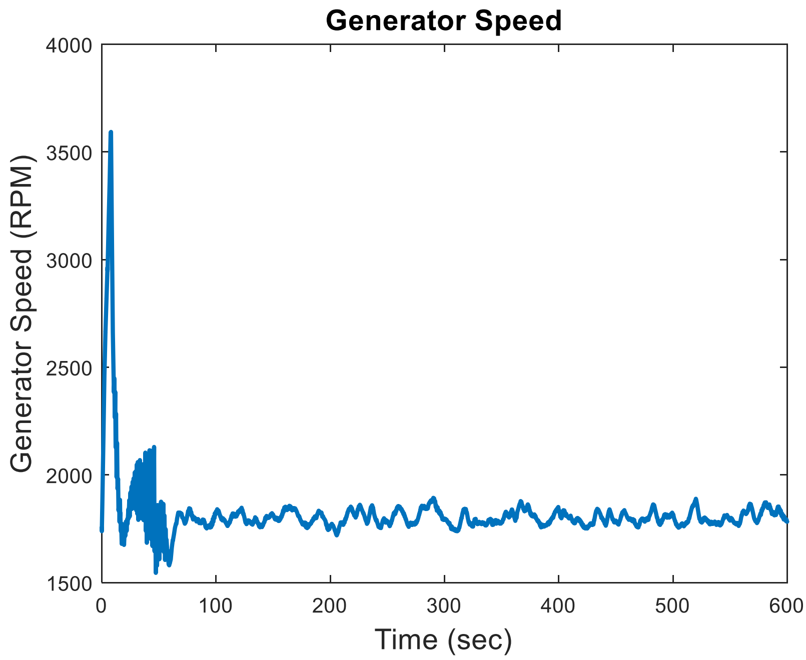
10 m/s



8.2 m/s

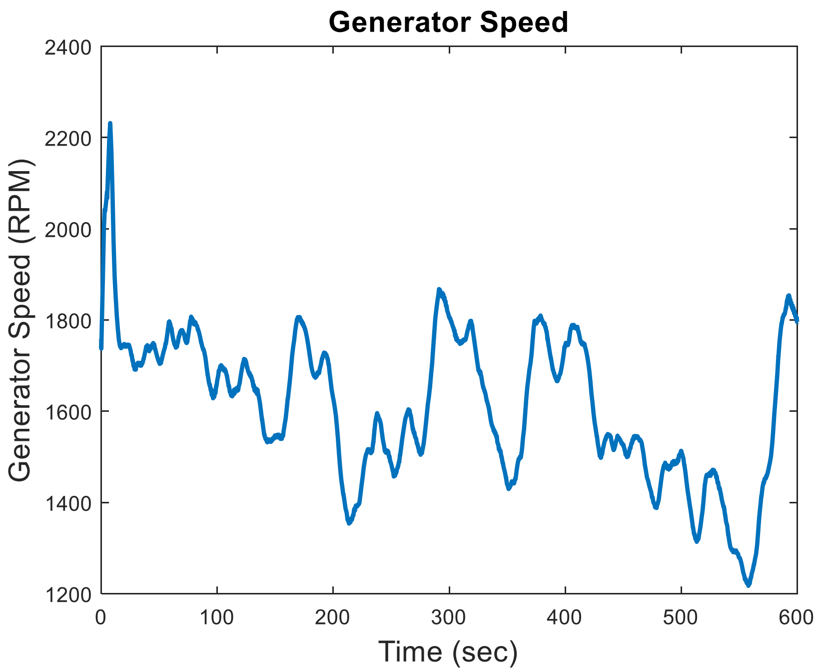


14 m/s

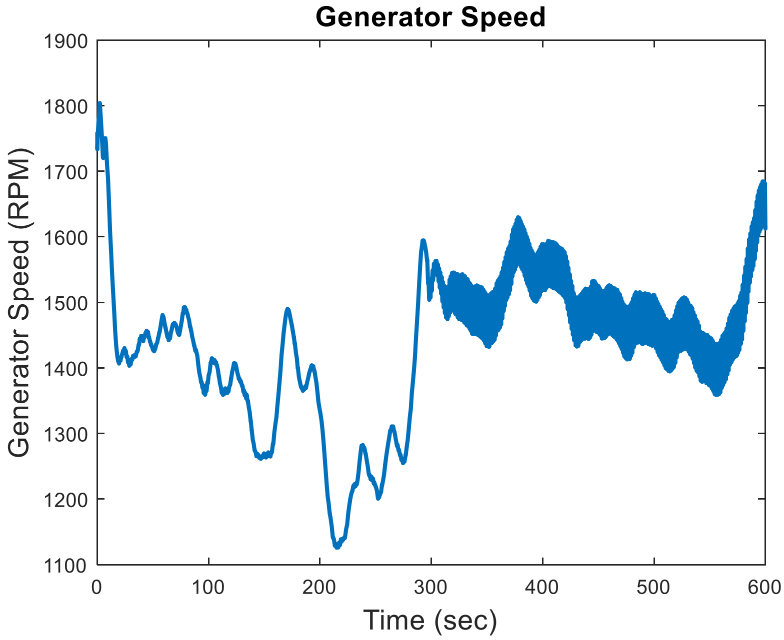


IECVKM Turbulence Spectra

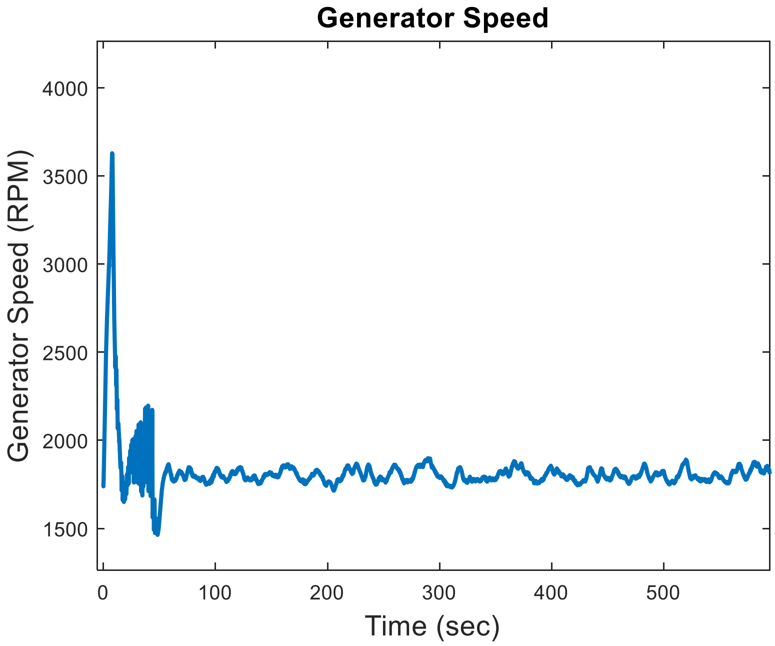
10 m/s



8.2 m/s

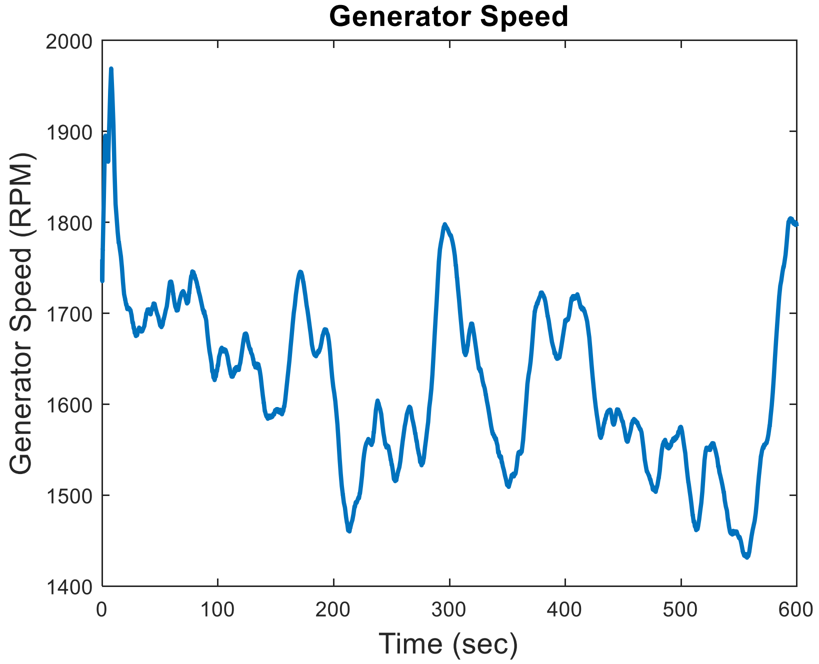

Generator Speed
Generator Speed (RPM)
1900
1800
1700
1600
1500
1400
1300
1200
1100
0
100
200
300
400
500
600
Time (sec)

14 m/s

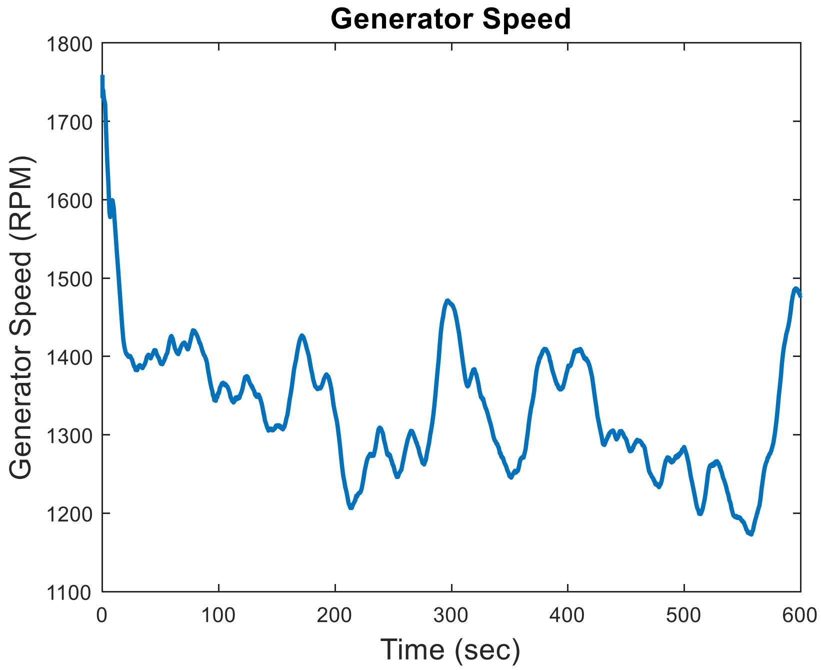

Generator Speed
Generator Speed (RPM)
4000
3500
3000
2500
2000
1500
0
100
200
300
400
500
Time (sec)

SMOOTH Turbulence Spectra

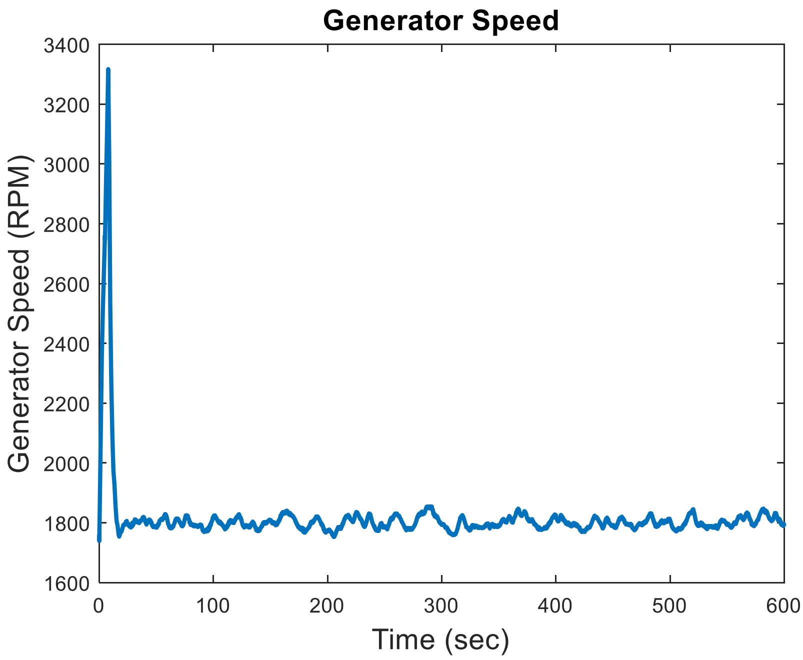
10 m/s



8.2 m/s



14 m/s


Generator Speed
Generator Speed (RPM)
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
0
100
200
300
400
500
600
Time (sec)