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Power System Operation on Oil and Gas Installations with Integration of Offshore Wind

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Preface

This master´s thesis concludes the final work of the Master Programme Electric Power Engineering, at the Faculty of Information Technology and Electrical Engineering, at the Norwegian University of Science and Technology (NTNU). I would like to thank my supervisor, Professor Kjetil Uhlen, for valuable guidance and helpful insights during the work with my master's thesis. I would also like to thank my co-supervisor, Dr. Wei He at Statoil AS for her guidance during my master thesis.

June 13, 2017, Trondheim

Pål M. Berge

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Abstract

This thesis investigates the operational aspects of integrating wind energy with the power supply to offshore oil and gas (O&G) installations. The use of wind energy is an environmentally friendly and efficient way of supplying power to O&G installations to reduce the dependence on gas turbines and lower the CO2 emissions. Wind measurements indicate excellent wind conditions offshore, and thus there is great potential to install wind energy to an O&G installation. Wind power is a highly variable power source, and therefore the focus of this thesis is on frequency stability.

High wind penetration in the power system results in a different operational pattern for the system operators compared to conventional thermal power plants. Therefore, it is essential for the power system operator to understand how the integration of wind energy affects the power system stability. These impacts are investigated by conducting dynamic power system simulations.

A hybrid power system has been modeled consisting of two 13 MW gas turbines, a 6 MW wind turbine, and several loads. The level of complexity of the models is kept simple to reduce the computational requirements. The thesis presents dynamic models of the wind turbine and gas turbines, and how the components models are combined to generate the complete model. The system includes mechanical models of gas turbines and wind turbine. Wind model subsystems consist of wind turbine, drive train, blade pitch controller and maximum power point tracking controller. Gas turbine subsystems consist of governor, turbine and drive train.

A operator training simulator has been modeled and implemented in Simulink to give the power system operators knowledge on how wind power penetration affects the frequency variability on O&G installations. The modeled operator training simulator gives the power system operators the chance to monitor and observe how the wind turbine and gas turbines perform under different load and wind variations. The power system operators also have the opportunity to execute simple control actions, for instance adjusting the speed reference set point of the gas turbine, perform load shedding and start or stop gas turbines.

In the simulation study, one gas turbine replaced either a 6 MW or 2.3 MW wind turbine. The wind turbine contributes with 10-45 % of the total installed system capacity. The dynamic study investigates transient, steady state and periodic frequency deviations produced by variable operating conditions due to wind variations.

Wind events are simulated to study transient frequency deviations for different ramping capabilities of the gas turbine. Simulation results indicate that when the wind turbine operates at moderate wind speeds (10-16 m/s), it might cause undesirable periodic frequency deviations due to periodic power oscillations. All other dynamic studies indicate that integration of the 6 MW wind turbine to an oil and gas installation is feasible.

Sammendrag

Denne oppgaven undersøker de operative aspektene ved å integrere vindenergi med kraftforsyningen til offshore olje- og gassinstallasjoner. Bruk av vindenergi er en miljøvennlig og effektiv måte å levere kraft til olje- og gassinstallasjoner for å redusere avhengigheten av gassturbiner og redusere CO2-utslippene. Vindmålinger indikerer gode vindforhold offshore, og dermed er det et stort potensial for å installere vindkraft til en olje- og gassinstallasjon. Vindkraft er en svært variabel energikilde, og derfor fokuserer denne oppgaven på frekvensstabilitet.

Høy vindpenetrasjon i kraftsystemet resulterer i et annet driftsmønster for systemoperatørene sammenlignet med konvensjonelle termiske energikilder. Derfor er det avgjørende for systemoperatørene å forstå hvordan integrering av vindenergi påvirker kraftsystemets stabilitet. Disse effektene undersøkes ved å utføre dynamiske kraftsystemsimuleringer.

Et hybrid-kraftsystem er modellert bestående av to 13 MW gassturbiner, en 6 MW vindturbin, og flere laster. Nivået på kompleksiteten til modellene holdes enkelt for å redusere beregningskravene. Oppgaven presenterer dynamiske modeller av vindturbin- og gassturbiner, og hvordan komponentmodellene kombineres for å generere hele modellen. Systemet omfatter mekaniske modeller av gassturbiner og vindturbinen.
En treningsoperatorsimulator har blitt modellert og implementert i Simulink for å gi systemoperatørene kunnskap om hvordan økt vindkraft penetrasjon påvirker frekvensvariasjoner på olje- og gassinstallasjoner. Den modellerte treningsoperatorsimulatoren gir systemoperatørene sjansen til å overvåke og observere hvordan vindturbin- og gassturbiner opererer under forskjellige belastnings- og vindvariasjoner. Systemoperatørene har også mulighet til å utføre enkle kontrollhandlinger, som for eksempel å justere referansepunktet til hastighetsregulatoren på gassturbinen, koble ut laster, og starte eller stoppe gassturbiner.

I simuleringene erstattes en gassturbin med enten en 6 MW eller 2,3 MW vindturbin. Vindturbinen bidrar med 10-45 % av den totale systemkapasiteten. Den dynamiske studien undersøker transiente, stasjonære og periodiske frekvensavvik produsert av variable driftsforhold grunnet

vindvariasjoner.

Ulike vindhendelser er simulert for å studere transiente frekvensavvik for forskjellige rampehastigheter på gassturbinen. Simuleringsresultater indikerer at når vindturbinen opererer ved moderate vindhastigheter (10-16 m/s), så kan det forårsake uønskede periodiske frekvensavvik på grunn av periodiske effektvariasjonene påført av vindturbinen. Alle andre dynamiske studier indikerer at integrering av en 6 MW vindturbin til en olje- og gassinstallasjon er mulig.

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Chapter 1

Introduction

1.1 Background and Motivation

Statoil has discussed the possibility to move the Hywind wind turbine to an oil and gas (O&G) installation as a solution to reduce dependence on gas turbines and to lower CO2 gas emissions. This thesis investigates the operational aspects of integrating wind energy with the power supply to O&G installations. The idea is to reduce the operating time for the second gas turbine on the O&G installation and replace it with a 6 MW or 2.3 MW wind turbine. Wind measurements show that there are excellent wind conditions offshore which give a real potential to move the Hywind wind turbine to an O&G installation.

Wind energy is a variable power source and integrating wind power into an isolated power system needs planning. Due to the wind variability, the occurrence of power imbalance will increase with more wind power penetration. These factors can increase the frequency variations and worsen the frequency quality. The system should be able to operate and deliver power with adequate power quality and robustness.

Integration of wind energy results in a different operational pattern for the system operators compared to conventional thermal power plants. Therefore, it is essential for the power system operators to understand how integration of wind energy affects the power system stability.

This thesis will focus on frequency stability related challenges of connecting wind power to O&G installations. The objective is to build a operator training simulator model which can give the system operators knowledge about how the power system performs when implementing wind energy in the system, and it gives the opportunity the run simulations in real-time or faster.

1.2 Scope of Work

The scope of work is the following;

- Model a wind turbine with blade pitch control, mechanical drive train and maximum power tracking controller. Only mechanical model, the electrical dynamics are neglected
- Model gas turbines based on dynamic mechanical models. The electrical dynamics are neglected
- Model a operator training simulator that can run simulation in real-time or quicker
- Implement load shedding scheme and start and stop function of gas turbines in the operator training simulator
- Simulation for both overfrequency and underfrequency events
- Simulation to analyze periodic frequency deviation for different wind speed intervals
- Compare frequency and power quality for a 6 MW and 2.3 MW wind turbine

1.3 Limitations

The limitations of this thesis is the following;

- This thesis focuses on active power and system frequency. Not voltage stability and control
- The model is only valid for slow power system dynamics in the range of seconds and slower

- The modeled power system is a simple and hypothetical system
- The system load is modeled based on assumptions and not on measured data
- The load shedding scheme are based on simple algorithms to give the power system operator an impression on how the system responds when loads are disconnected from the system and are not based on advanced algorithms

1.4 Structure of the Report

The rest of the report is organized as follows:

Chapter 2 explains the basic theory behind the study performed in this thesis. The first section gives an introduction to the integration of the wind in power systems. The second section provides an introduction to the topic of power system stability.

Chapter 3 gives a description of the modeled power system. The first section provides a description of the modeled power system used for simulation in Simulink. The second section gives a description of the wind turbine components. The third section provides a description of the gas turbine components. Finally, the last section provides a description of the operator training simulator model.

Chapter 4 presents the simulation results and discussion.

Chapter 5 includes conclusion and recommendation for further work

Chapter 2

Theory

Parts of this chapter are redrafts of reference [17]. This chapter explains the basic theory behind the study performed in this thesis. The first section gives an introduction to the integration of the wind in power systems. The second section provides an introduction to the topic of power system stability.

2.1 Integration of Wind in Power Systems

Wind energy is an uncontrollable variable power source and integration of wind into an isolated power system brings challenges to the power system operator. These problems can include:

- Operation and control with large wind penetration
- Power balance
- Need proper techniques to predict the wind
- Grid integration technologies to meet grid code requirements

2.1.1 Hybrid Power Systems

Power systems which consist of conventional thermal power plants and at least one renewable energy source are called hybrid power systems[10]. Wind turbines can be added to complement the power from the thermal power plants. When integrating wind power into these power systems, some unique system design challenges can present themselves.

In isolated power systems, the terms “wind penetration" and “renewable penetration” are used to characterize the magnitude of the wind or renewable power in the systems compared to the rated load [10]. Wind turbines in isolated power systems can significantly affect the operation of the system dependent on the amount of wind penetration.

2.1.2 Integration of Wind Turbines

If the wind turbine supplies a substantial portion of the total system load, the difference between the wind power and the load is called net load. This load needs to be produced by the thermal power plants, in this case, the gas turbines.

Because of wind- and load variations, the net load, may 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 by[10]:

$$\sigma_{net} = \sqrt{\sigma^2{}_{load} + \sigma^2{}_{wind}} \tag{2.1}$$

By introducing wind energy into the power system, the variability of the net load will increase due to the variability of wind power. Also, the uncertainty of the net load will increase in the future. This means that the power system operators need to make decisions based on predictions of the load and available wind energy. Because of the uncertainty of these factors, the power system operators require additional spinning reserves to deal with increased net load variations[10].

2.1.3 Power Balance

When installing renewable energy sources into an isolated power system, the amount of variable energy sources will highly effect the power quality. The amount of instantaneous wind power penetration in the system is defined as the ratio of instantaneous wind power output P_{wind} to the instantaneous primary load P_{load}:

$$\text{Instantaneous power contribution} = \frac{P_{wind}}{P_{load}} \tag{2.2}$$

The ratio is how much of the load is being supplied by wind energy at any moment. When the instantaneous power contribution from the wind turbine increase, the variation of the wind power output increases and therefore the power system operators need to be more caution to ensure that the gas turbines are capable of controlling the power quality. Fig. 2.1 displays the power balance of the modeled wind-gas power system. From the figure, it can be seen that the wind power contribution is 46 % when the wind speed is above rated wind speed (14 m/s) and the load is 1 per unit [23].

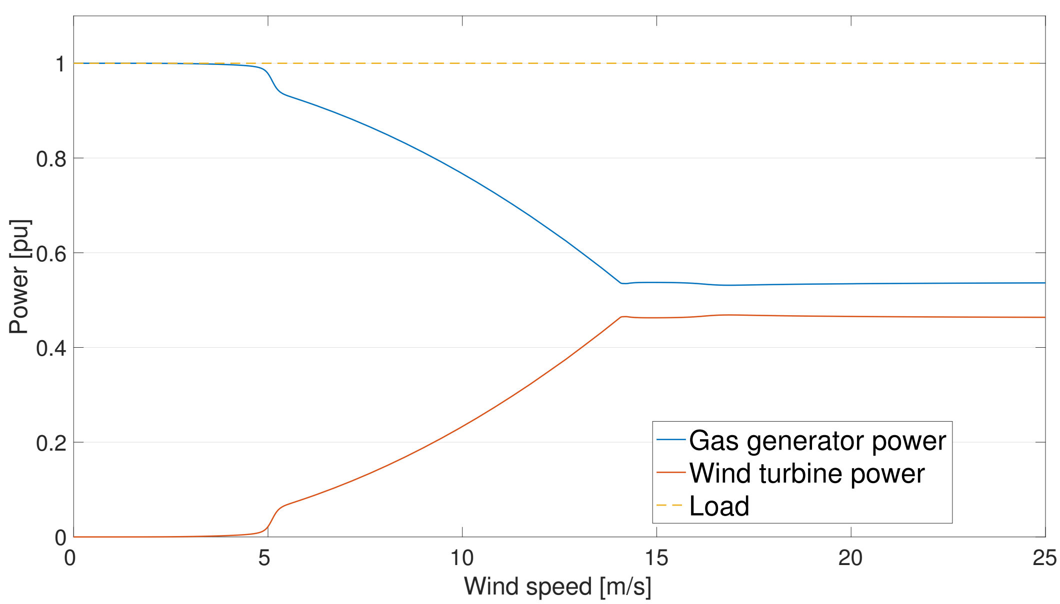

Figure 2.1: Power balance of wind-gas power system

2.1.4 Effect on Gas Turbine Operation

The frequency stability of a hybrid power system depends on relevant factors such as load fluctuations, total system inertia, and the responsiveness and control system of the gas generators in the system [7]. To be able to have a proper regulation of frequency, the gas turbine needs to respond to changes in wind power and load fluctuations rapidly. The better responsiveness of the gas generator, the better frequency regulation [10]. If the wind power penetration is too high, the gas turbine may not be able to respond fast enough to the power fluctuations.

For these reasons, it is important to consider the response time of the gas turbine when integrating wind power in an isolated power system. Additional gas turbines can be brought online but need start-up time which can be up to 45 minutes. Another factor with high wind penetration is the gas turbine efficiency which decreases with lower loading [7].

Low loading levels make it more difficult for the gas turbine to regulate frequency and maintain an acceptable power quality. The manufacturers set lower operating limit in which the gas turbines should not operate below. This is usually around 30-35 % of rated power. Operating the turbine below its lower limit during longer periods, reduces the governor's ability to control frequency, it works at cooler temperatures which cause increased carbon build up, higher maintenance requirements and poor emissions regulation [23].

This lower operating level limits the amount of wind power contribution it is possible to have in the system. At times with low load, the wind turbine can be regulated to limit its output to ensure that the gas turbine doesn't operate below its lower limit.

Maintaining the proper level of spinning reserve is also an issue with high levels of wind penetration. This requires experienced power system operators to cope with significant power variations.

2.1.5 Grid Control

In a power system, the consumed power must be balanced by the generated power. To keep the frequency within its limit, the power system operator needs some generation capacity which is committed to load following. Fluctuating load and changing wind power output must be matched quickly by the thermal power plants. The mechanism to control the power balance is primary and secondary control which are explained in Chapter 2.3.

If there are large load changes during the day, more gas turbines need to be brought online, but usually, large gas turbines need between 45 minutes to prepare for the generation. Therefore, a certain amount of 'spinning reserve' are required to be kept online to react to power fluctuations[10].

2.2 Power System Stability

IEEE/CIGRE [19] give definition of power system stability:

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

The system stability depends on the severity of the disturbance as well as the initial operating condition. Power system instability can appear after various disturbances. Load variations occur consistently and behave as small disturbances, and the power system needs to adapt to these changes in operating conditions. The system also needs to recover from large disturbances such as loss of generators or short-circuits. The power system is a very nonlinear system that is constantly changing. Power system stability is divided into three categories; Rotor angle stability, frequency stability and voltage stability as shown in Fig. 2.2. This thesis focuses on frequency stability, and a more detailed description of the subject is given in the next sections.

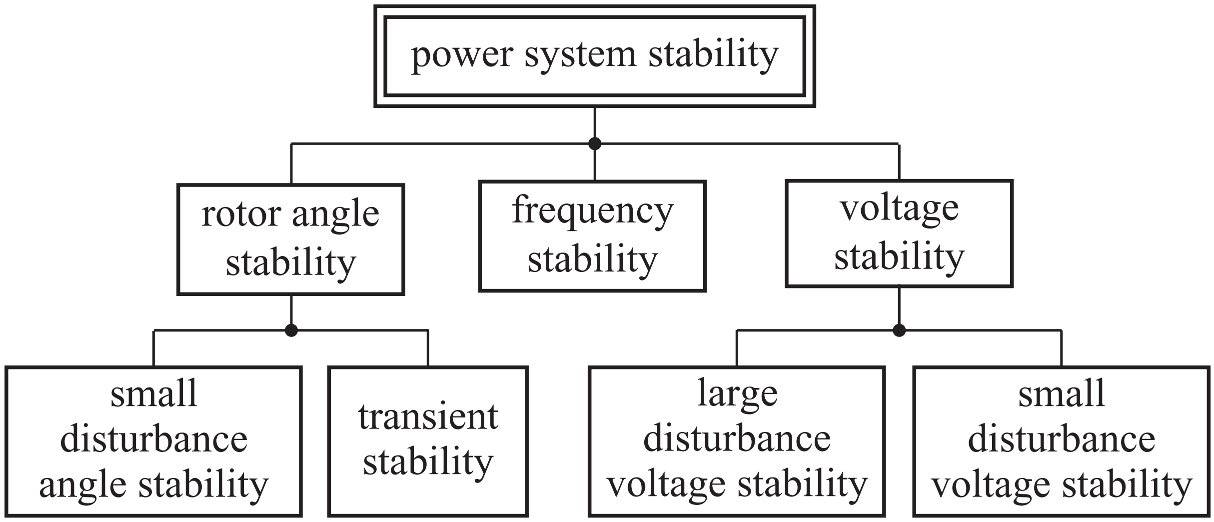

Figure 2.2: Classification of power system stability, based on IEEE/CIGRE report [19]

2.3 Frequency Stability and Control

IEEE/GIGRE defines frequency stability as [19]:

“The ability of a power system to maintain steady state 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 a minimum unintentional loss of load."

The active and reactive power in a system is relatively independent of each other. There are different controls for active and reactive power so that they can be studied individually. Reactive power is related to voltage control, and active power is related to frequency control [18]. In this thesis, only active power is considered.
The power system response can be divided into four stages:

- Stage I: Rotor swings in the generators
- Stage II: Frequency drop
- Stage III: Primary control by governing systems

- Stage IV: Secondary control

The system response can be explained by an example where a generator disconnects from the system. First rotor swings will occur in the other generators in the system. Then at stage II, a frequency drop will occur because the speed of the other generators in the system will slow down. The frequency drop is only dependent on the total inertia in the system. In stage III, the primary frequency control is activated by the governing system after the frequency drops. In stage IV, the secondary control brings the frequency back to its initial value [12].

2.3.1 Primary Frequency Control

If the power generation is equal to the load demand, 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 to obtain a balance between power generation and demand. Primary frequency control action will result in a steady state frequency deviation, which is dependent on the system frequency response, R, expressed in (2.4) [12]. The droop, ρ, specifies how much the frequency change as a function of a change in power.

$$\frac{\Delta f}{f_N} = \rho \frac{\Delta P}{P_N} \tag{2.3}$$

$$\frac{P_n}{\rho f_N} = \frac{\Delta P}{\Delta f} = R \tag{2.4}$$

2.3.2 Secondary Frequency Control

The governing system is not able to return the frequency to its initial value after a change in load, without extra control actions. According to Fig. 2.3, the load reference set point has to be shifted to return the frequency to its initial value. [12]. The operators perform secondary control by adjusting the speed-changer motor, which changes the speed reference set point by moving the speed - droop characteristic up or down [18].

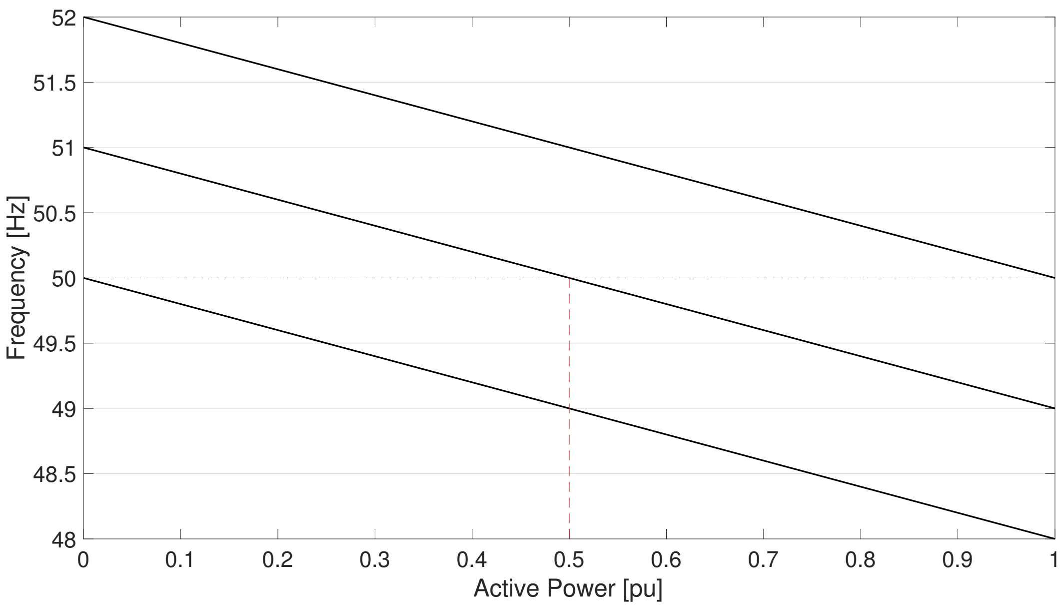

Figure 2.3: Effect on speed-changer setting on governor characteristic

2.3.3 Spinning Reserve

Spinning reserve is unused capacity which is synchronized to the system and able to affect the active power. The system must at all time have enough active power in reserve to control the frequency and re-establish a balance between load and generation in case of disturbances [26]. Primary frequency control is an automatic response that is not controlled by the operator, and a sufficient amount of spinning reserve must be reserved for this control[12]. Secondary control uses spinning reserve and is controlled by the system operator in this case.

2.4 Swing Equation

Newton's second law can be used to explain the relationship between mechanical and electrical torque, rotor shaft speed and the inertia of the machine.

$$J\frac{\mathrm{d}\omega_m}{\mathrm{d}t} + D_m\omega_m = \tau_m - \tau_e \tag{2.5}$$

J is the total moment of inertia, ω_m is the rotor shaft speed, D_m is the damping torque and τ_m and τ_e is mechanical and electrical torque. τ_m changes rather slowly, due to long time thermal constant related to the turbine, but τ_e can almost change instantaneously. If a disturbance occurs, the rotor accelerates if $\tau_m > \tau_e$ and decelerates if $\tau_m < \tau_e$. By normalizing (2.5) in terms of per unit, H becomes the inertia constant and S_n is the rated power of the generator. This gives: $J = \frac{2HS_N}{\omega_s^2}$. The swing equation then becomes:

$$\frac{2HS_N}{\omega_s^2}\dot{\omega}_m + D_m\omega_m = \tau_m - \tau_e \tag{2.6}$$

By setting $\omega = \frac{\omega_m}{\omega_s}$, where ω is the speed in per unit. Then swing equation becomes:

$$\frac{2HS_N}{\omega_s}\dot{\omega} + D_m\omega\omega_s = \tau_m - \tau_e \tag{2.7}$$

Setting the torque in per unit gives: $\tau_b = \frac{S_N}{\omega_s}$.

$$2H\dot{\omega} + \frac{D_m\omega\omega_s^2}{S_N} = \tau_m - \tau_e \tag{2.8}$$

If $D = \frac{D_m\omega_s^2}{S_N}$, and then inserting D into the equation:

$$2H\dot{\omega} + D\omega = \tau_m - \tau_e \tag{2.9}$$

The active power is, $P = \omega\tau$. By linearizing, $\omega = 1$, then $P \approx \tau$. Also, $\frac{\mathrm{d}\delta}{\mathrm{d}t} = \omega - \omega_s = \Delta\omega$. Then the final expression of the swing equation can be represented as two first-order equations [12].

$$\frac{\mathrm{d}\Delta\omega}{\mathrm{d}t} = \frac{1}{2H}(P_m - P_e - D\Delta\omega) \tag{2.10}$$

$$\frac{\mathrm{d}\delta}{\mathrm{d}t} = \Delta\omega \tag{2.11}$$

2.5 Load Shedding

Under-frequency load shedding is a technique that is commonly used to maintain stability in the power system. This is implemented when disturbances or overload in the system occur [15].

In isolated systems where it is not possible to transfer power from neighboring systems when the area degenerates, there will be a decrease in frequency. Isolated systems are more vulnerable to disturbances due to lower inertia and smaller spinning reserves [6]. In cases with under-frequency and where the generators are unable to increase their power output, load shedding schemes are employed to reduce the load demand to a safe level [12]. It is important that the frequency decline does not reach the level where the generator units trip due to under-frequency protective relays [18].

Operating power systems at low frequency lead to problems related to thermal power plants, such as vibratory stress on the long low-pressure turbine blades. Prime movers have several limitations which affect their ability to control frequency decays.

- The generation is limited by the available spinning reserve.
- The thermal limit on the turbines sets the limit of how much load that can be picked up by due to thermal stress.
- The governing systems time delay

As a result of the factors listed above, the available generation to control the frequency is limited to a portion of the remaining generation [18].

Load shedding is implemented using under-frequency relays. The relays detect the frequency decay and disconnect the appropriate amount of load until the system regains stability. Usually, the load shedding scheme is implemented in stages where the least significant loads are disconnected first [12].

2.6 Power System Operator

The power system operate must ensure that the power generation is equal to the demand at all times and that the frequency is within its required limits. Operators monitor among other things the following information; generator power, generator frequency, spinning reserve and wind power. The system operator is needed to ensure that the system is secure and equipped to withstand potential disturbances. The operator decides the number of generators to operate and the amount of available spinning reserve. With increased variable wind power in the system, more spinning reserve can be required. If there is insufficient amount of spinning reserve when a disturbance occurs, automatic load shedding is used to prevent overload on generators.[12] [3]

2.7 Norsok and IEC Standard

Norsok standard E-001 includes provisions for electrical installations on offshore units[1]. Norsok standard requirements for system frequency is 50 Hz and give reference to the IEC 61892-1 standard regarding frequency deviations. IEC 61892-1 is an international standard for electrical installations on mobile and fixed offshore units [2].

Table 2.1: Requirements for frequency deviations on offshore units according to IEC 61892-1 standard

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

Chapter 3

Modelling

Parts of this chapter are redrafts of reference [17]. The first section gives a description of the modeled power system used for simulation in Simulink. The second section gives a description of the wind turbine components. The third section provides a description of the gas turbine components. Finally, the last section gives a description of the operator training simulator model.

The software's used for modeling are Matlab and Simulink. The power system components and operator training simulator are modeled using the Simulink graphical block diagram environment. The model is build using blocks from the standard library and Matlab function blocks.

3.1 Hybrid Power System

The modeled hybrid power system used in the operator training simulator and for the dynamic power system study is illustrated in Fig. 3.1, and it consists of a 6 MW wind turbine with a back to back converter, two 13 MW gas turbines and several loads. The wind turbine can operate in parallel with one or two gas turbines.

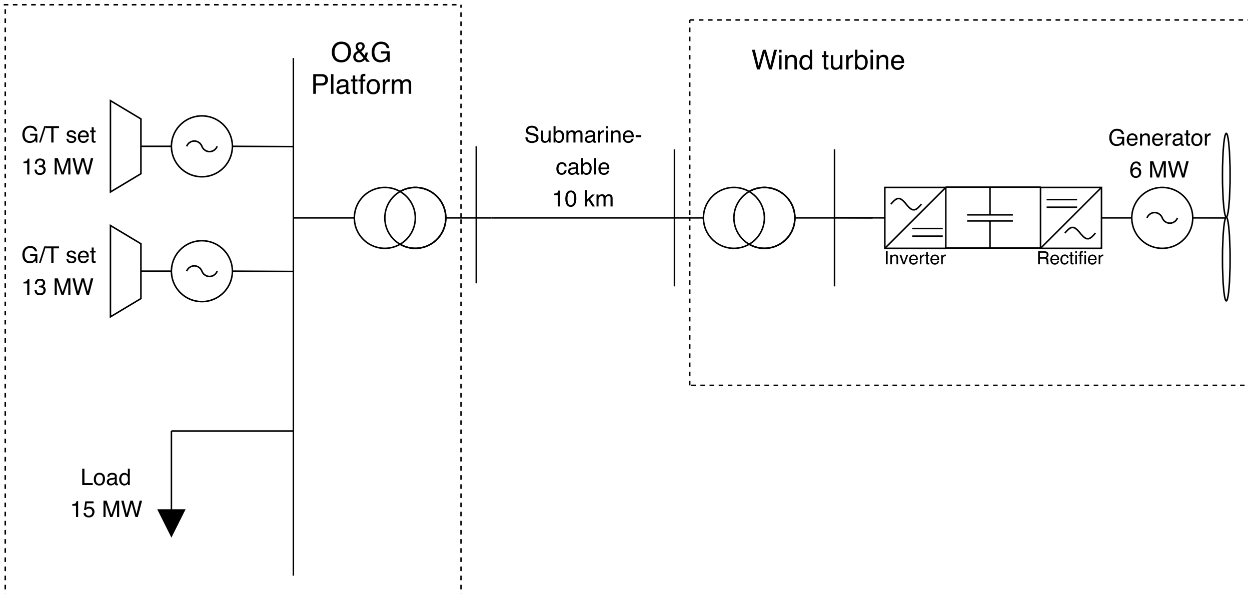

Figure 3.1: Hybrid power system O&G installation connected to a offshore wind turbine

3.2 Offshore Platform

The electrical power system on the offshore platform is depicted in Fig. 3.2. The system consists of two 13 MW gas turbines with a synchronous generator, seven induction machines and three passive loads and two transformers. This is an example of a power system on a platform. There are seven circuit breakers in the power system which the power system operators can control in the operator training simulator. The loads in the training simulator can be altered for different scenarios.

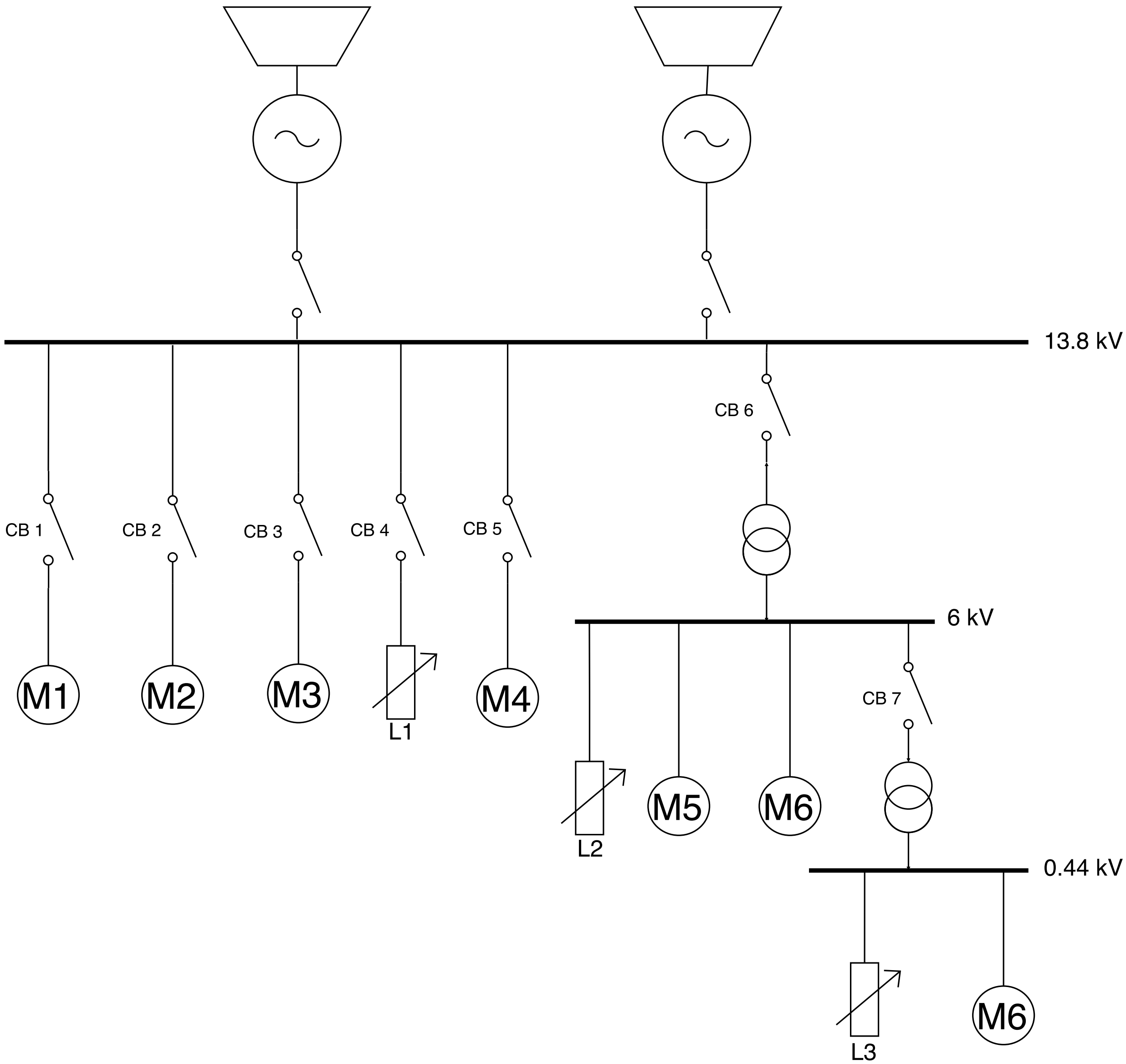

Figure 3.2: One-line diagram of offshore platform

3.3 Wind Turbine

This section represents the modeled wind turbine system used in operator training simulator and simulation study. The first section describes the model functional structure and the second section describes the model's components. The model only consists of mechanical models to reduce the complexity of the model and reduce the computational requirements. The wind turbine model functional structure is illustrated in Fig. 3.3. Wind turbine parameters are listed in Table A.3 in Appendix A.

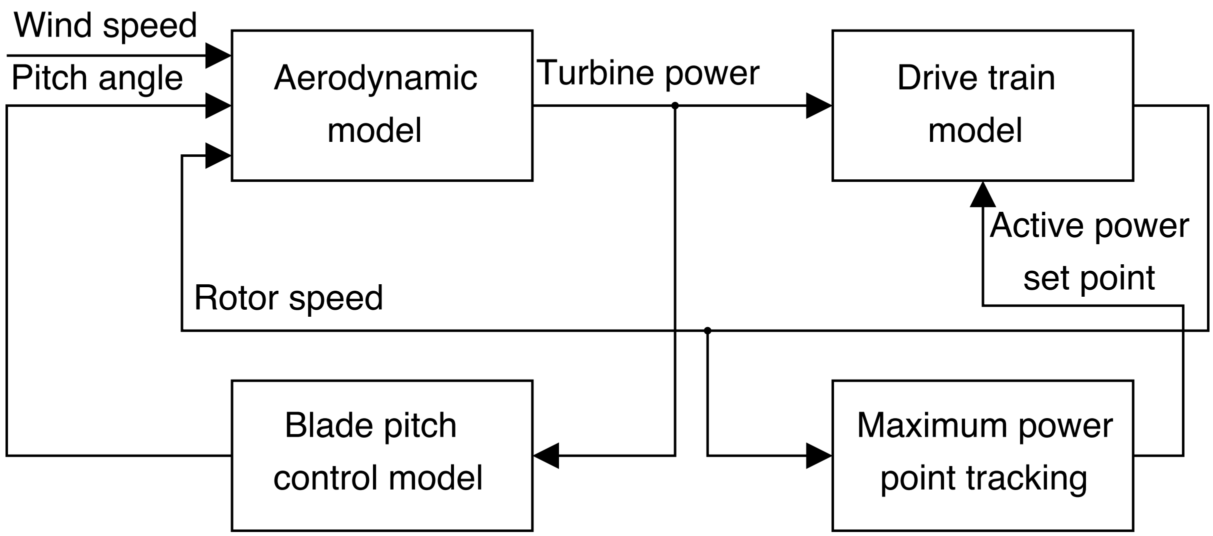

Figure 3.3: Wind turbine model functional structure

3.3.1 Aerodynamic Model

The subject of modeling wind turbine aerodynamics is treated in depth in literature [10]. In this thesis, a simple empirical method is used to model the wind turbine aerodynamic model [20]. It is the kinetic energy in the wind that drives the wind turbine. The wind turbine can only extract a fraction of the power in the wind and the turbine output power is given by:

$$P = \frac{1}{2}\rho A c_p(\lambda/\beta) v_w^3 \tag{3.1}$$

Where ρ is the air density, A is the swept area of the turbine, c_p is the coefficient of performance of the turbine and V_w is the wind speed. c_p varies with the tip speed ratio, λ and pitch angle, β [10].

λ is defined by:

$$\lambda = \frac{\omega_r r}{v_w} \tag{3.2}$$

Where ω_r is the rotational speed of the rotor and, r is the radius of the rotor. The generic equation used to model $c_p(\lambda/\beta)$ is [20]:

$$c_p(\lambda/\beta) = c_1(\frac{c_2}{\lambda_i} - c_3\beta - c_4)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \tag{3.3}$$

With λ_i given by:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.4}$$

The c_p/λ curves are unique for different wind turbine designs, but studies show that c_p/λ curves from different wind turbines are quite similar [11]. Therefore the general approximation (3.3) is used in this thesis. The c_p $/\lambda$ curve is plotted in Fig. 3.4 for different values of pitch angle, β.

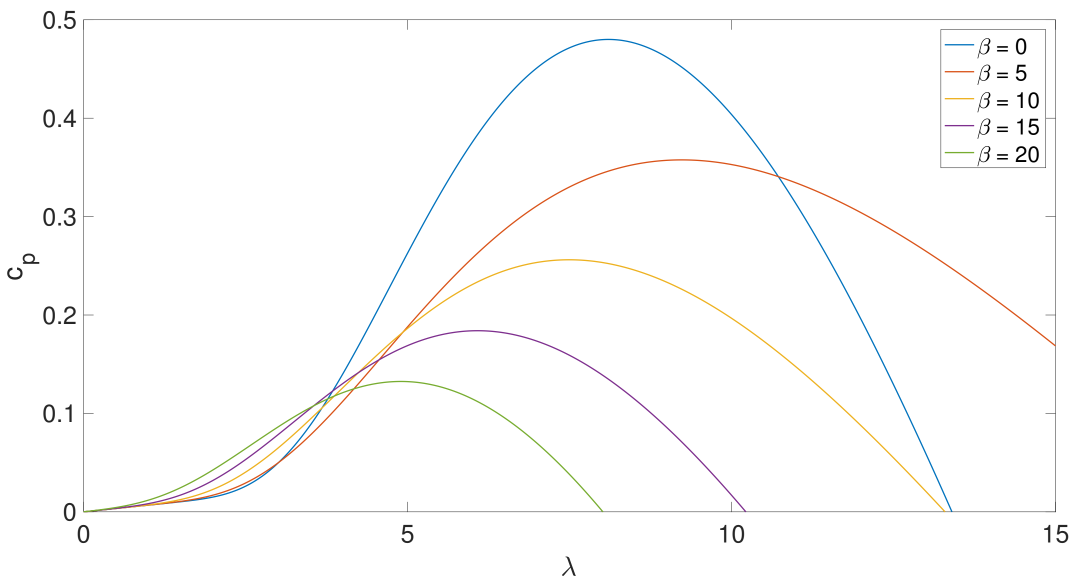

Figure 3.4: c_p/λ curve for different values of β

The c_p/λ curve, (3.1) and (3.2) are used to calculate the power as a function of rotor speed for any wind speed [12]. The turbine must operate at the peak of the curve to extract the maximum power from the turbine, which is called maximum power point tracking [12]. This is further explained in Section 3.3.2. Fig. 3.5 represent the power as a function of rotor speed for different wind speeds.

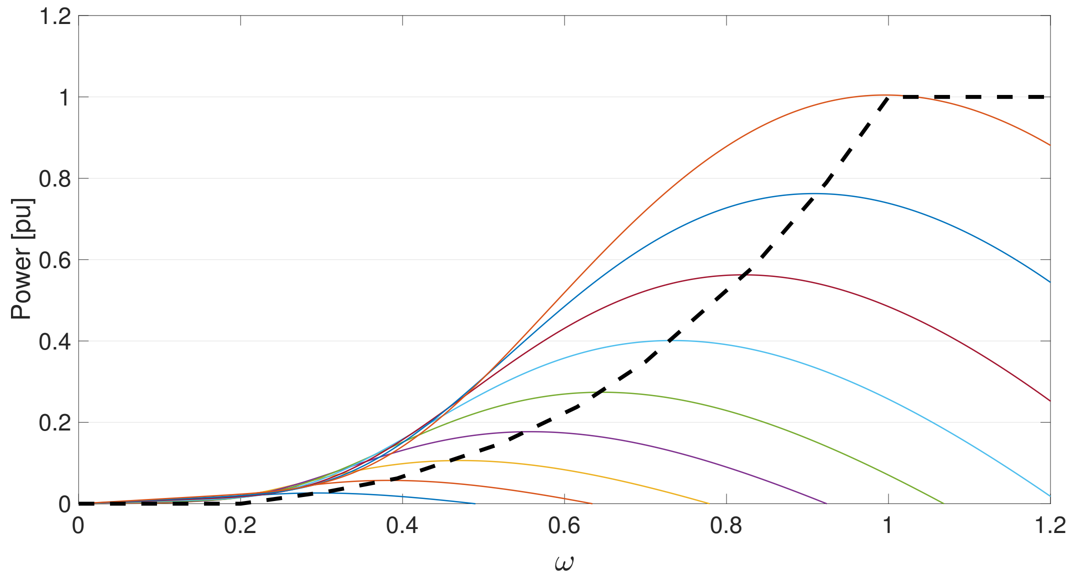

Figure 3.5: Maximum power tracking curve

The wind turbine model which is implemented in this thesis is the variable pitch wind turbine block in Simulink [16]. The wind turbine is modeled based on the mathematical equations on aerodynamics presented in Section 3.3.1. The input variables to the model are generator speed, pitch angle, and wind speed. The output variable is mechanical torque. Fig. 3.6 presents the Simulink block diagram of the wind turbine.

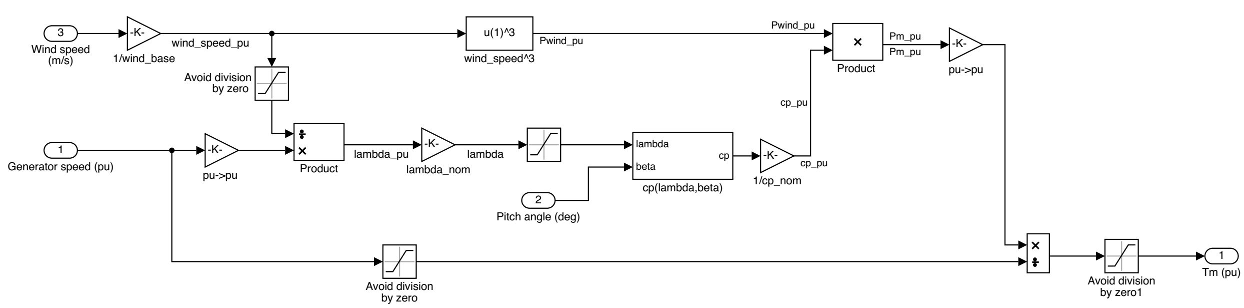

Figure 3.6: Simulink variable speed wind turbine block [16]

3.3.2 Maximum Power Point Tracking Controller

To obtain the highest energy yield, it is desirable to determine the optimal generator speed that gives the highest power output. A controller needs to be implemented to track the maximum power peaks regardless of wind speed. The controller operates between cut-in and cut-out wind speed for variable speed wind turbines[24]. The maximum power is extracted at a specific ratio that is called the optimum tip speed ratio (TSR). The wind turbine needs to change its rotational speed to maintain optimal TSR when the wind speed instantaneous changes.

There are several maximum power point tracking (MPPT) techniques[14]. The algorithm implemented in this model is optimal torque (OT) control. The principle of this method is to adjust the wind turbine torque to the maximum reference torque at a given wind speed. To present turbine power as a function of λ and ω, (3.2) from Section 2.6.1 can be rewritten into:

$$V_w = \frac{\omega_r R}{\lambda} \tag{3.5}$$

By substituting (3.5) into (3.1), the expression becomes:

$$P_m = \frac{1}{2}\rho R^5 \frac{\omega_m^3}{\lambda^3} C_p \tag{3.6}$$

When the rotor is operating at λ_{opt}, it means that it operates at C_{Pmax}. Therfore it is possible to replace, $\lambda = \lambda_{opt}$ and $C_p = C_{pmax}$ into (3.6). The expression is then:

$$P_{m-opt} = \frac{1}{2}\pi R^5 \omega_m^3 \frac{C_{Pmax}}{\lambda_{opt}^3} = K_{p-opt}\omega_m^3 \tag{3.7}$$

Since $P_m = \omega_m\ T_m$, T_m can be reorganized as follows:

$$T_{m-opt} = \frac{1}{2}\pi R^5 \omega_m^2 \frac{C_{Pmax}}{\lambda_{opt}^3} = K_{p-opt}\omega_m^2 \tag{3.8}$$

Fig. 3.7 shows how the controller is implemented in the model. The method proves to be simple, fast and efficient[14].

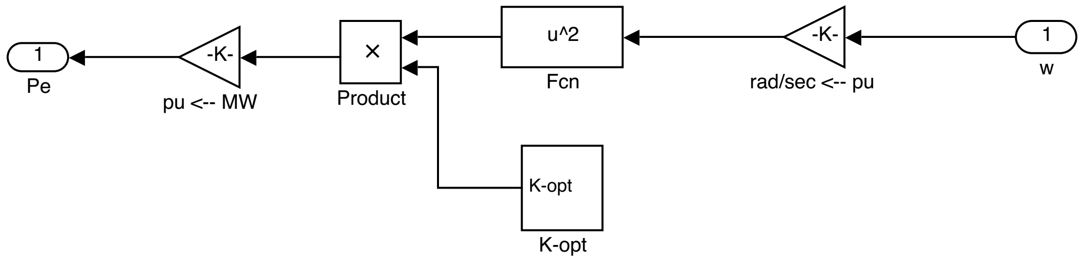

Figure 3.7: Maximum power tracking controller

3.3.3 Drive Train

The drive train can be modeled as a single mass when assuming an ideally stiff shaft [9]. The swing equation (3.9) is used to model the drive train. The inputs are mechanical and electrical power, and the output is generator speed. The electrical power is extracted using MPPT controller.

$$\frac{\mathrm{d}\Delta\omega}{\mathrm{d}t} = \frac{1}{2H}(P_m - P_e) \tag{3.9}$$

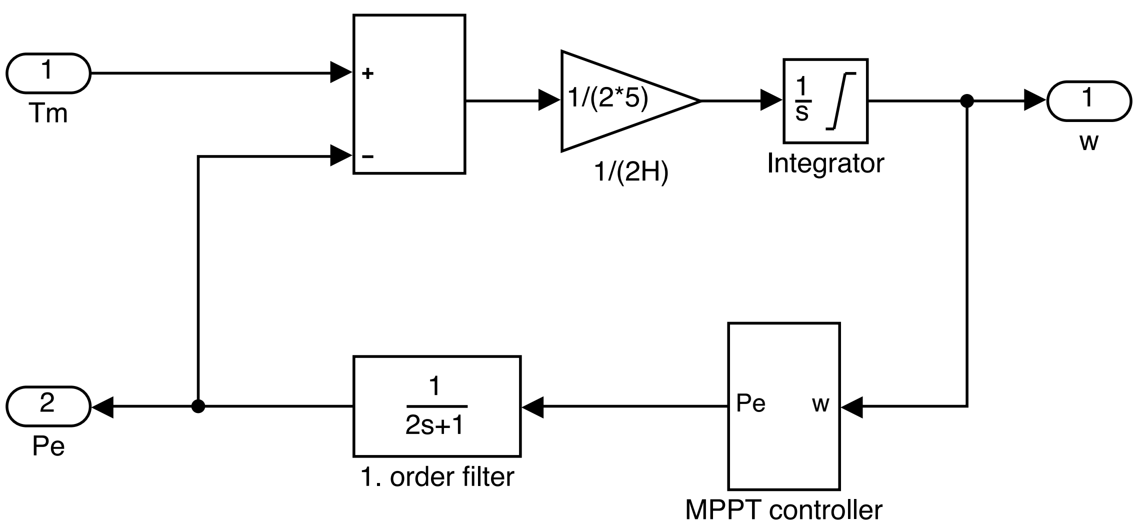

Figure 3.8: Drive train with MPPT controller

3.3.4 Blade Pitch Controller

The pitch angle controller is active at high wind speeds. The blade pitch angle is changed to limit the aerodynamic efficiency of the rotor and limit the turbine output power to its rated value. The pitch controller operates when the turbine power exceeds the fixed reference value to prevent overloading of the generator.

Several pitch controllers are investigated in [5]. The pitch controller implemented in this model uses a PI controller with gain scheduling. At higher wind speed, the pitch controller is more sensitive to changes, therefore are gain scheduling implemented to reduce the proportional gain at higher wind speeds to prevent oscillations from the pitch controller. The block diagram of the pitch controller is shown in Fig. 3.9.

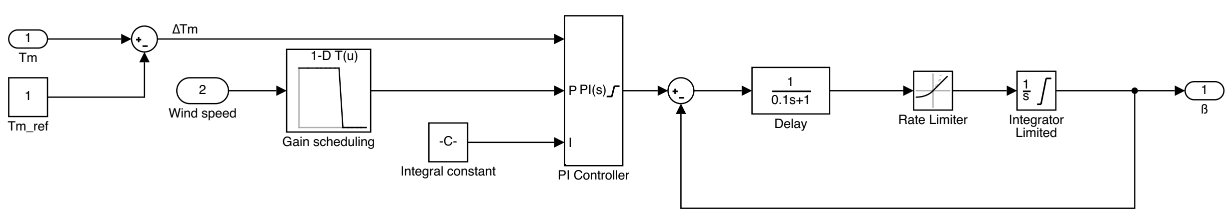

Figure 3.9: Blade pitch controller

3.4 Gas Turbine

The electrical energy which is produced by the synchronous generator is driven by a gas turbine. By using hot turbine exhaust gas, the thermal energy is converted into mechanical energy. If the fuel is natural gas, the working fluid is generally air. Fig. 3.10 displays a typical gas turbine system called open regenerative cycle, and it consists of a compressor C, combustion chamber CH and turbine T. The fuel which gets supplied through the governor valve is burned together with air supplied by the compressor in the combustion chamber. It is then transferred from the combustion chamber to the turbine where it's get expanded and transfers its energy to the shaft which drives the synchronous generator [12].

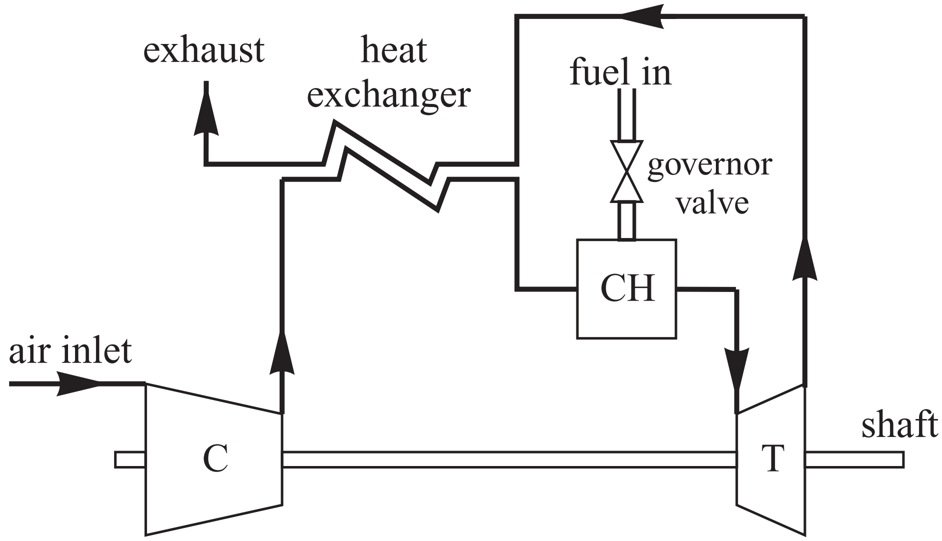

Figure 3.10: Open regenerative cycle of the gas turbine, Fig. from [12]

3.4.1 Governing System

All turbines are equipped with a governing system which controls the speed or power output according to a power-frequency characteristic. A schematic diagram of an electro-hydraulic governing system is illustrated in Fig. 3.11. When the mechanical torque is equal to the generators electromagnetic torque, the rotational speed of the turbine-generator is constant. If the electromagnetic torque increases, due to load changes, the rotational speed decrease because the mechanical torque is lower than the electromagnetic torque. The valve position gradually opens, and the turbine power increases. The governing system has two feedbacks, the one through the speed measurement device and the second from the servomotor to the pilot valve to ensure a negative slope of the static power-frequency characteristic as shown in Fig. 2.3. The turbine needs operate within thermal and mechanical limits and the governing system control that the turbine doesn't exceed these limits [12].

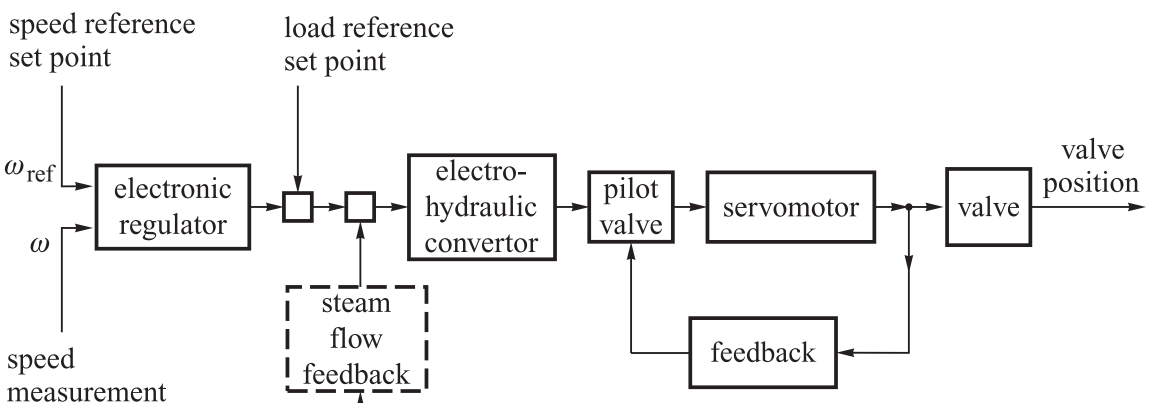

Figure 3.11: Schematic diagram of the electro-hydraulic governing system, Fig. from [12]

The governor controller which are used in this model is Proportional-Integral-Derivative (PID). The output signal is the sum of the three terms, where the proportional term is the error signal multiplied by the gain, the integral term is proportional to the integral of the error signal, and the derivative term is proportional to the derivative of the error signal. The parameters of the controller are the proportional gain K, integral time T_i and derivative time T_d. In the model the parameters are noted trough the standard form where, K_p = K, $K_i = \frac{K}{T_i}$ and $K_d = KT_d$ [13].

The controller input is the difference between the reference speed, ω_{set} and the change in generator speed, $\Delta\omega$. The deviation in mechanical power ΔP_m is multiplied with the droop through a feedback loop. The output signal is the valve position of the turbine, Δc.

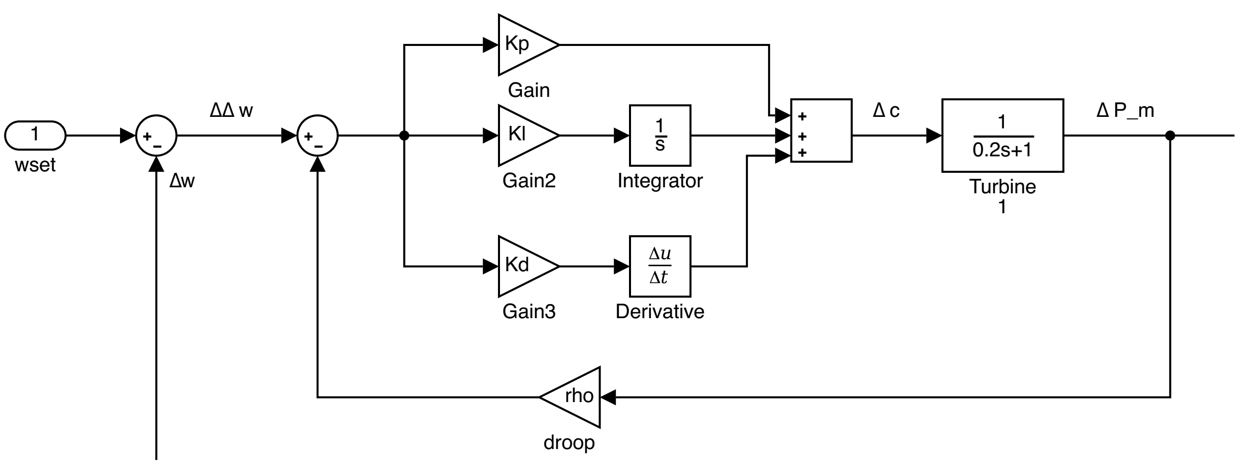

Figure 3.12: PID governor

3.4.2 Drive train

The block diagram for drive train model is presented in Fig. 3.13. The inputs to the model are mechanical power, electrical power and frequency dependent load noted as P_m, P_e and P_d. The output is the change in generator speed, $\Delta\omega$. The block diagram is based on the swing equation (2.10).

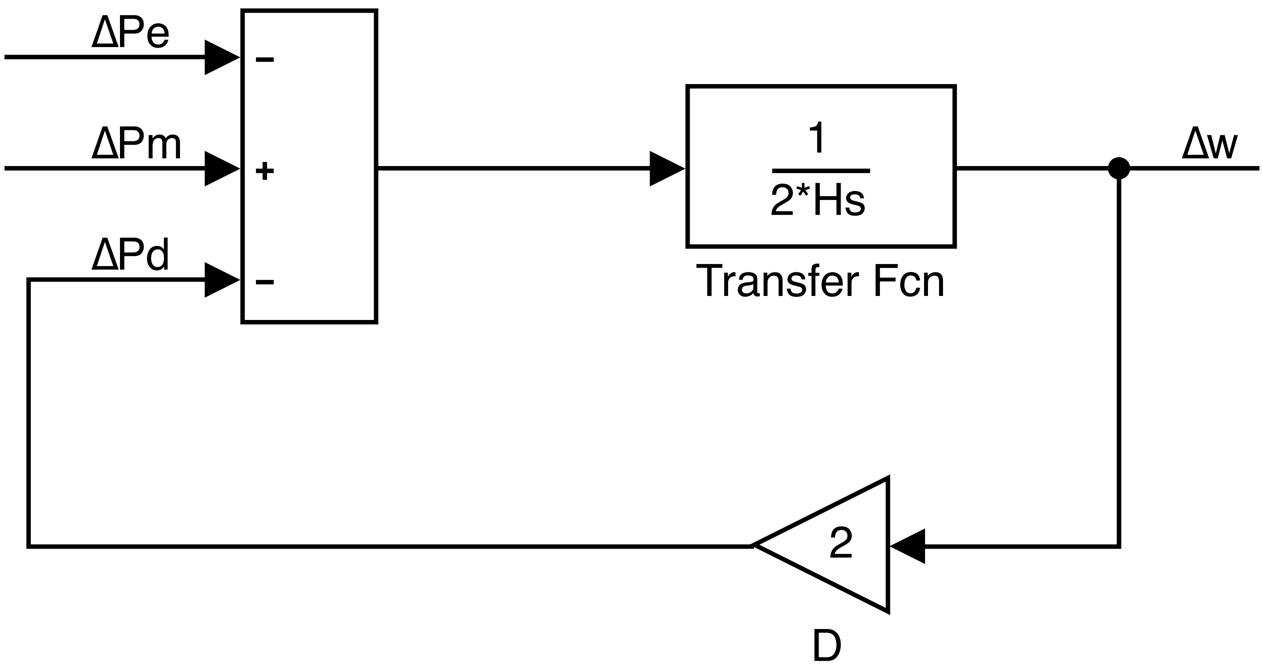

Figure 3.13: Drive train

3.4.3 Parallel Operation of Generators

The block diagram for the control loops for operating generators in parallel is illustrated in Fig. 3.14. It takes the change in generator speed times the standard formulation of the electrical frequency, $2\pi f_n$ as input and gives the change in rotor angle as output. K_e is the synchronizing torque coefficient and ΔP_{12} represents the power division between the generators [18].

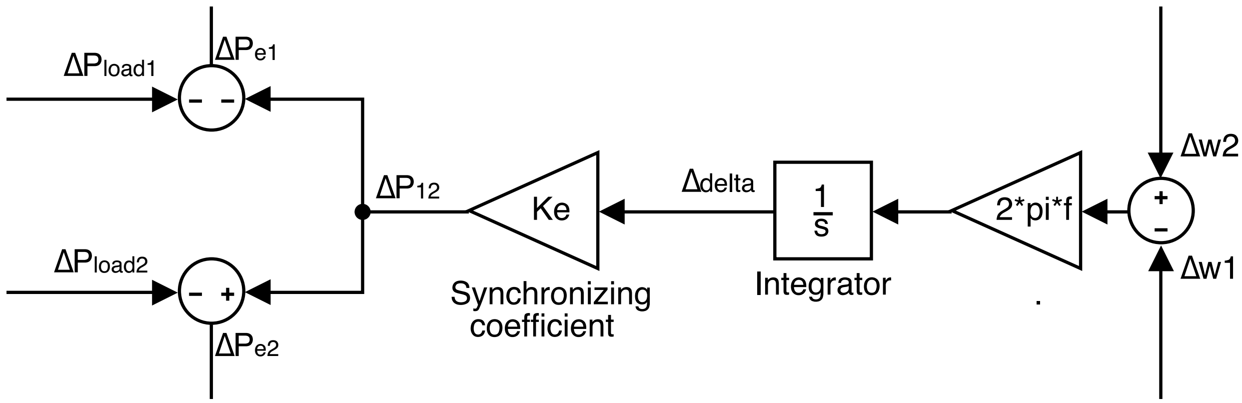

Figure 3.14: Parallel operation of generators

3.5 Operator Training Simulator

A operator training simulator is developed and implemented in Simulink which gives the power system operators an opportunity to simulate the modeled power system in real time or quicker. This gives the power system operators the possibility to simulate how the system respond and operates under different scenarios. With the simulator, it is possible to change the wind speed input and load inputs. The system configuration and one-line diagram can be modified to fit any given system configuration. In the training operator control, it is included features such as automatic and manual load shedding which is further explained in Section 3.5.2. Another feature is the start and stop of gas turbine 1 and 2 which is explained in Section 3.5.3.

3.5.1 User Interface

The user interface of the control center is illustrated in Fig 3.15. The user interface consists of:

- Instruments that measures:
  - Frequency on generator 1 and 2
  - Electric power on generator 1 and 2
  - Electrical load
  - Electrical wind power
- Switch to control circuit breakers

- Lamps for low-frequency alarms
- Knob to adjust the speed changer for gas turbine 1 and 2
- Switch to start or stop gas turbine 1 and 2
- Clock that shows simulation time and real time
- One-line diagram
- Graphs that show power measurements last 10 minutes
- Graphs that show frequency measurements last 10 minutes
- Graphs that show wind measurements last 10 minutes and wind forecast next 15 minutes

The graphs that show power measurements, frequency measurements, wind measurements and wind forecast are illustrated in Appendix B.

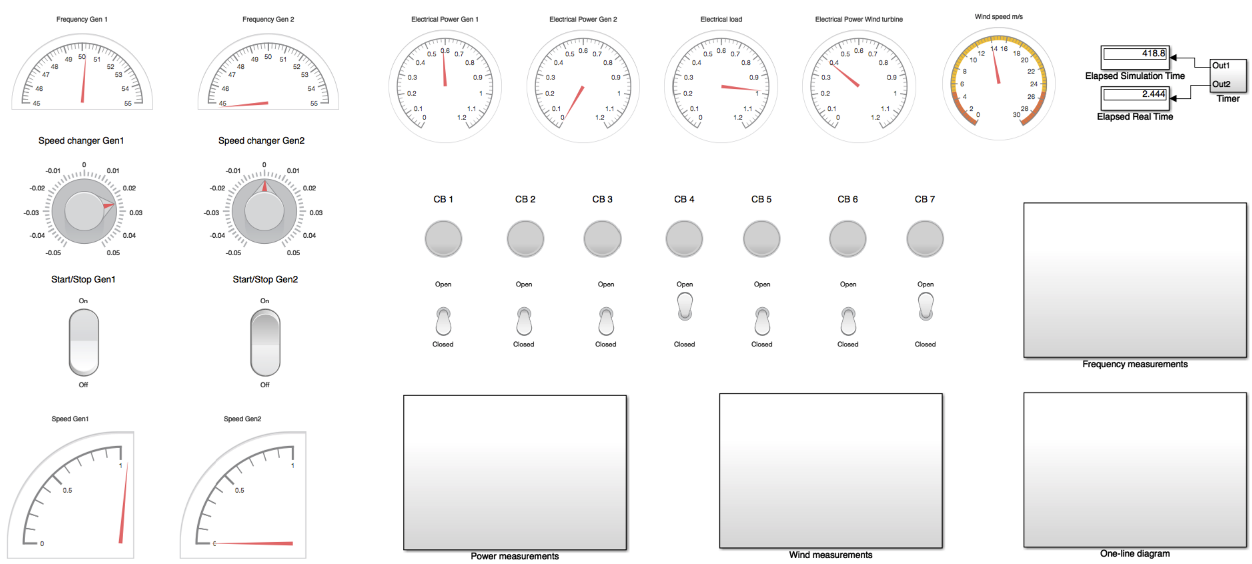

Figure 3.15: Operator training simulator

3.5.2 Load Shedding Scheme

An important function in the operator training simulator is the automatic and manual load shedding scheme. The automatic and manual load shedding scheme is presented in Fig. 3.16. If the power exceeds the maximum loadability of the generator, load shedding is performed. The load shedding algorithm disconnects the load that are closest to the minimum amount of required load which needs to be disconnected to keep the system stable.

The manual load shedding scheme is active if the system frequency is below specified limits. If the frequency drops below the specified limit, the power system operator receives an alarm in the form of a red light in the control system, and this indicates which loads are recommended to be disconnected from the system.

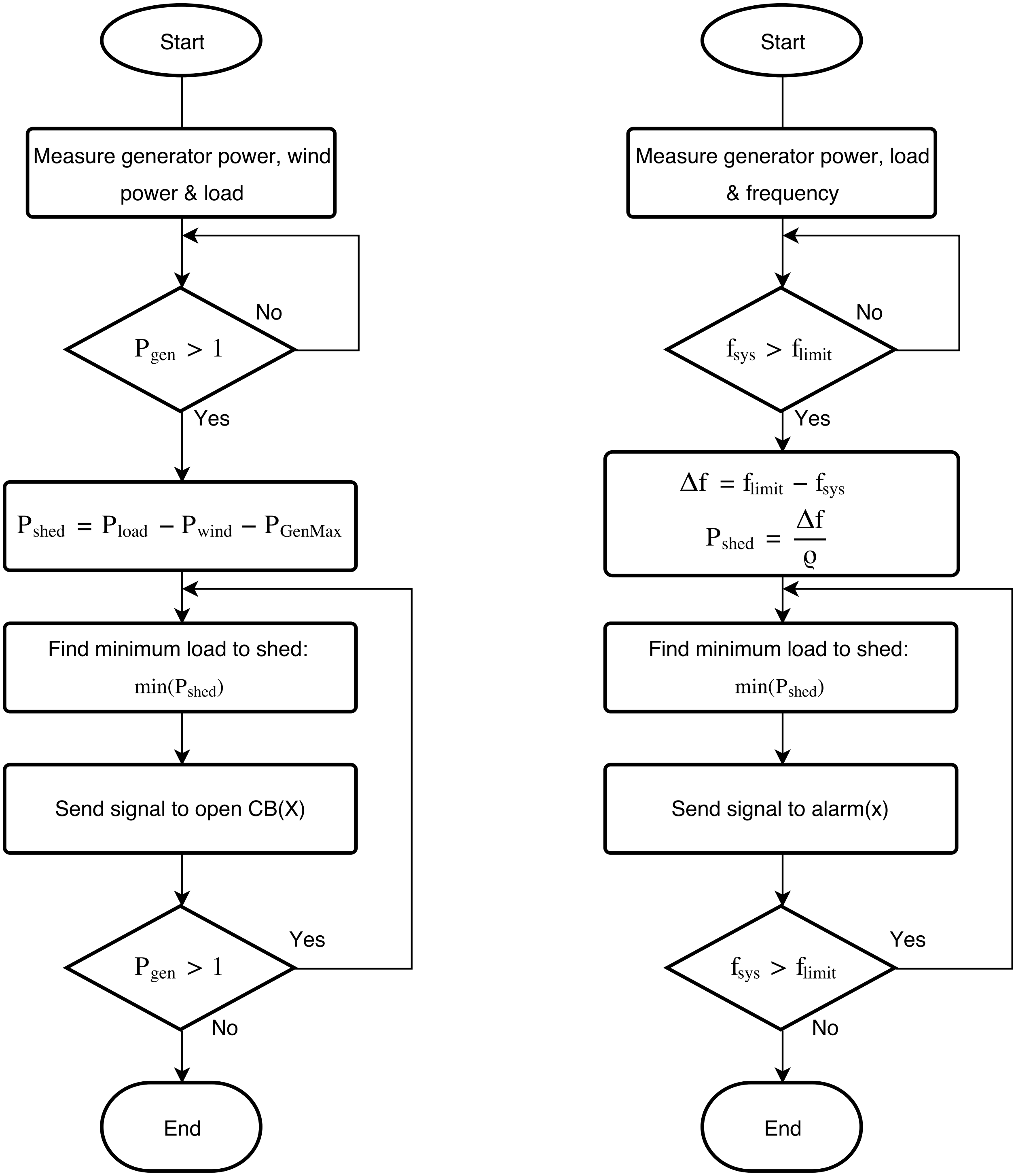

Figure 3.16: Automatic & manual load shedding algorithm

3.5.3 Start & Stop of Gas Turbine

A central function in the operator training simulator is the start and stop function. The start and stop functions that are implemented can be operated by the operator in a manual process or as an automatic process. The frequency is monitored by the control algorithm developed in Matlab and are presented in Fig. 3.17. When the operator decides to start an extra gas-generator, the frequency of the second generator is controllably ramped until it reaches the system frequency. The control actions after the second generator is started, depends on if it is in manual or automatic operation.

If the control is set to automatic, the synchronization is realized automatically. This is accomplished by the control system by measuring the frequency of generator 1. Then the control system sends a signal to act on the speed reference set point to adjust the frequency of generator 2 to match the frequency of generator 1. When the frequency and rotor angle of both generators are equal, the control system sends a signal to close the generator circuit breaker to complete the synchronization. When synchronization is complete, the control system sends signal to adjust the speed reference set point to share the load equally between the two generator sets.

If the control is set to manual, the operator decides when to close circuit breaker and can manually adjust the speed reference set point on the gas turbine to control the load sharing between the two generators.

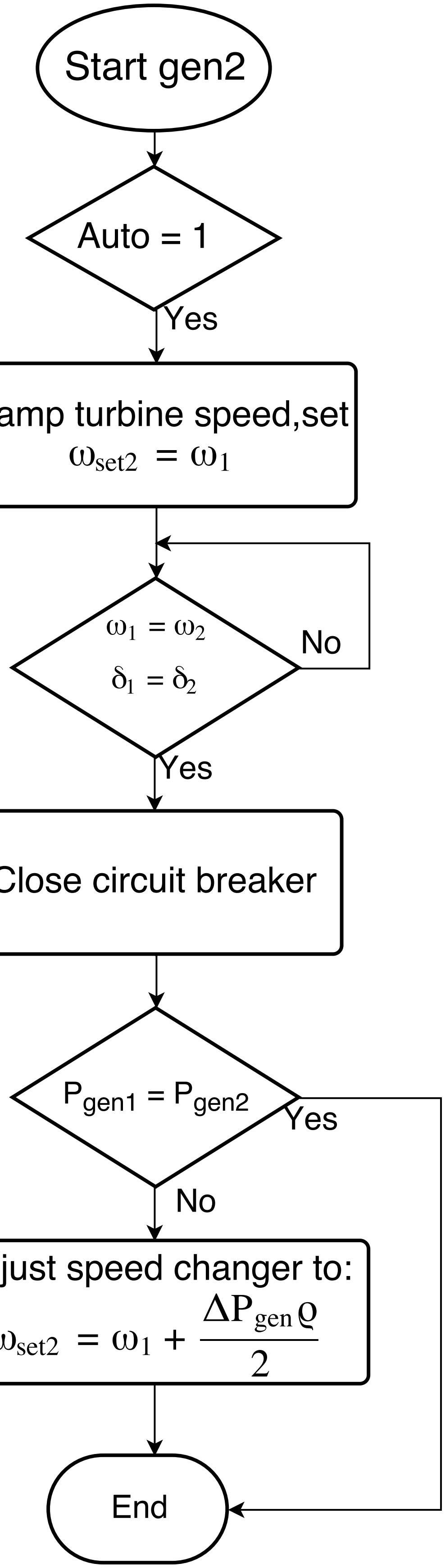

Figure 3.17: Start & stop algorithm for generator turbine sets

Chapter 4

Results and Discussion

This chapter presents a number of cases where the system in Fig. 3.1 in Chapter 3 is exposed to disturbances. All dynamic power system simulation is performed in Simulink. Wind and load inputs are modeled using Matlab. Simulations were conducted with a gas turbine and wind turbine operating at various wind conditions. The system base power is 13 MW, and the system frequency is 50 Hz.

The selected cases were chosen because it is highly significant to analyze how different wind speeds influence the frequency quality in an isolated system and how the amount of wind penetration impact the frequency stability.

4.1 Case 1 - Wind Turbine

In this case the performance of the wind turbine is examined with regard to active power output at different wind speeds. Wind speeds of interest are low, moderate and high wind speeds which highly effect the power output from the wind turbine. In the Section 3.3.1, the c_p/λ curve and MPPT scheme where explained and how this results in highly variable power output in some wind speeds regions.

4.1.1 Low Wind Speed

Fig. 4.1 shows the active power output from the 6 MW wind turbine when the wind speed varies between 4 - 8 m/s. At this wind speed, it can be seen that the wind power output is low and there are small power variations.

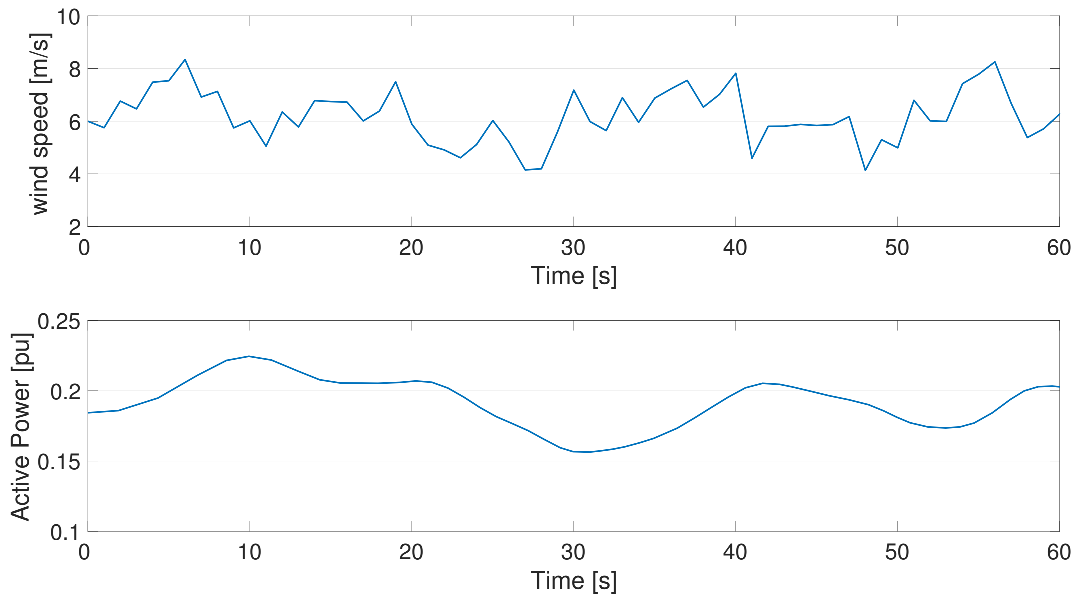

Figure 4.1: Wind turbine power output for low wind speeds

4.1.2 Moderate Wind Speed

Fig. 4.2 shows the active power output from the 6 MW wind turbine when the wind speed varies between 10 - 16 m/s. This region induces the largest fluctuations in wind power. The figure shows that the MPPT controller has a very good performance and controls the power output very good. This case with rapid changes in wind speed around 14 m/s are the area the power system operator is most concern about because the rapid change in wind turbine power has to be dealt with by the gas turbine.

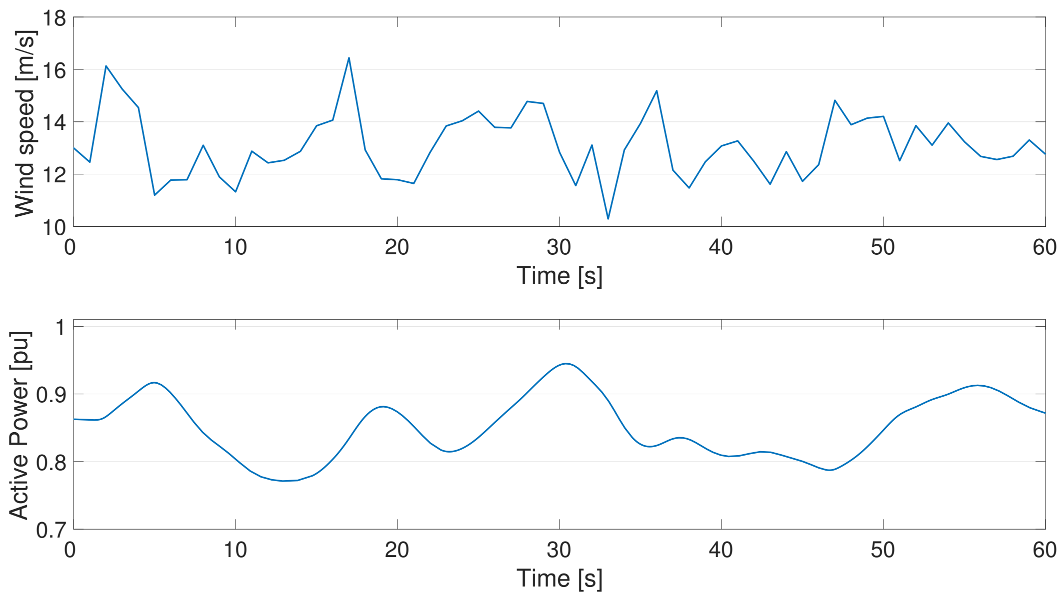

Figure 4.2: Wind turbine power output for moderate wind speeds

4.1.3 High Wind Speed

Fig. 4.3 shows the active power output from the 6 MW wind turbine when the wind speed varies between 16 - 20 m/s. Above rated wind speed, the blade pitch mechanism is active to regulate the power by pitching the blades to control that the power does not exceed rated power. The figure demonstrates that the pitch controller regulates the power with a good performance. As expected the power fluctuates around rated power due to the mechanical slowness in the pitch regulator.

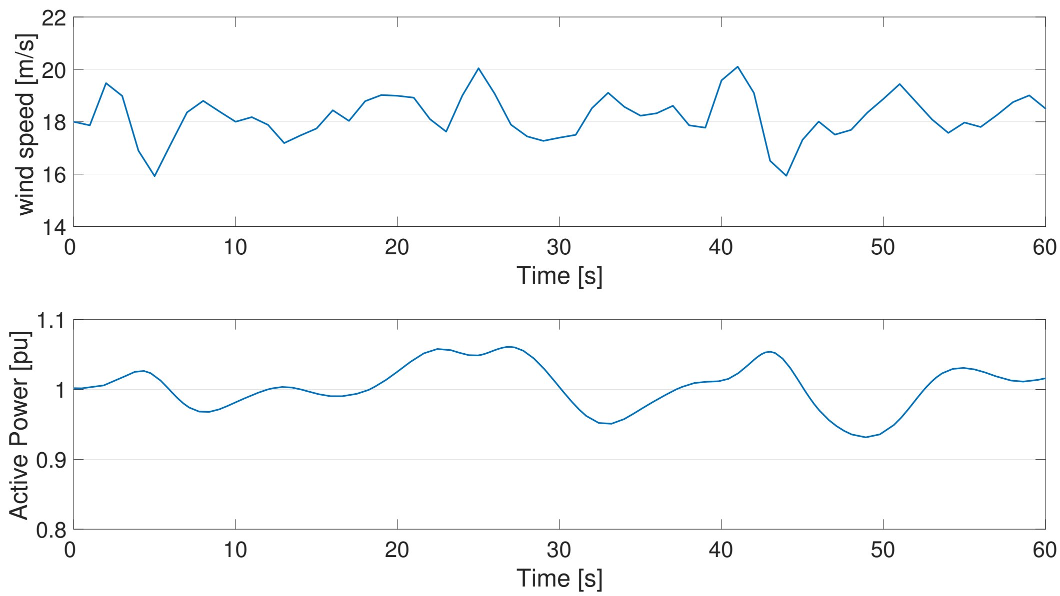

Figure 4.3: Wind turbine power output for high wind speeds

4.2 Case 2 - Wind Events

Four different wind events are dissipated in Fig. 4.4. Sinking wind speed is a drop in wind speed that results in that the wind turbine power is ramped down until it becomes zero when it is below cut-in wind speed. Wind rise is when there is a ramp in wind speed that creates a ramp in wind turbine power. The ramping time for sinking wind speed and wind rise is 15 seconds. In some cases, the ramping time can last for minutes, but a fast ramp is simulated to analyze worst case scenarios. When a sinking wind speed is followed by the wind rise it forms a wind lull, and these are more common than sinking wind speeds and wind rises. The opposite of a wind lull is a wind gust [8]. In the next section, an analysis of how the wind ramps impact the power system will be performed.

Sinking wind speed

In this section, the system response to sinking wind speed events is analyzed to look at which risks this scenario brings to the power system operator. The power system is equipped to handle a fast ramp in load, and the gas turbine is usually able to handle steep load ramps. The wind

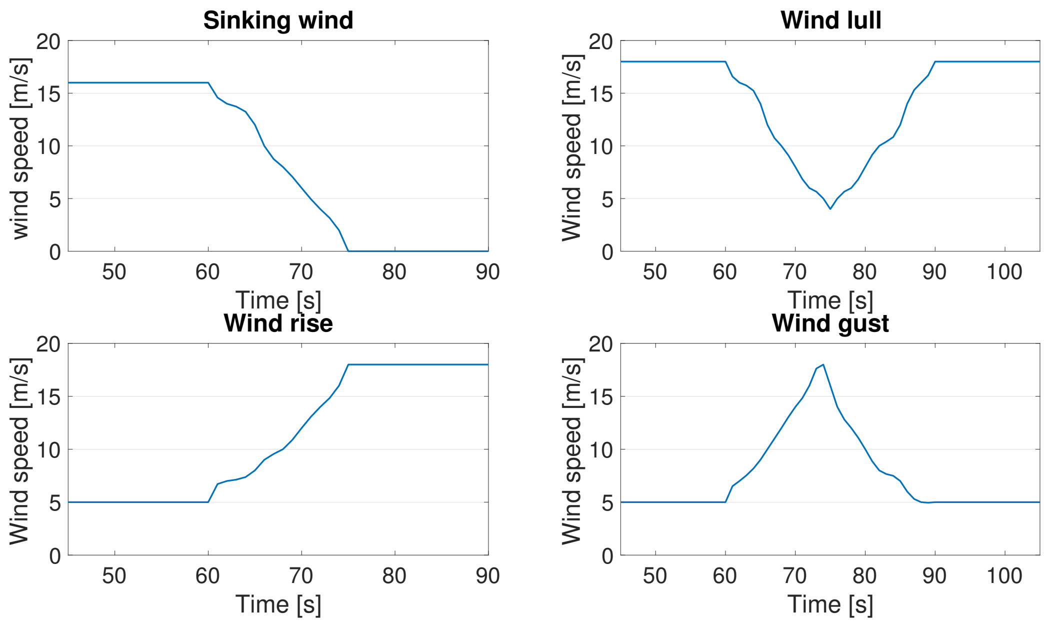

Figure 4.4: Wind events

turbine power, load, and gas generator power are presented in Fig. 4.5. The lost wind turbine power needs to be produced by the gas generator.

Since information on the gas turbine maximal ramp rate is not available, the frequency response of the gas turbine is simulated with different ramping rates to analyze how this affects the frequency response.

Fig. 4.6 shows that a drop in wind turbine power results in a steady state frequency error of 2 % (i.e., $\pm 1 Hz$), which are within the steady state frequency requirements set by IEC [2]. Moreover, it is interesting to analyze the frequency response for different ramping capabilities of the gas turbine. The ramping capability of the gas turbine greatly affects how the system response to rapid changes in wind turbine power. The IEC requirements for transient frequency deviation are ±10% (i.e., $\pm 5 Hz$) and to ensure that the system are within these limits, the minimum ramping capability of the gas turbine should be no less than 0.035 $[\frac{pu}{s}]$ or 455 $[\frac{kW}{s}]$.

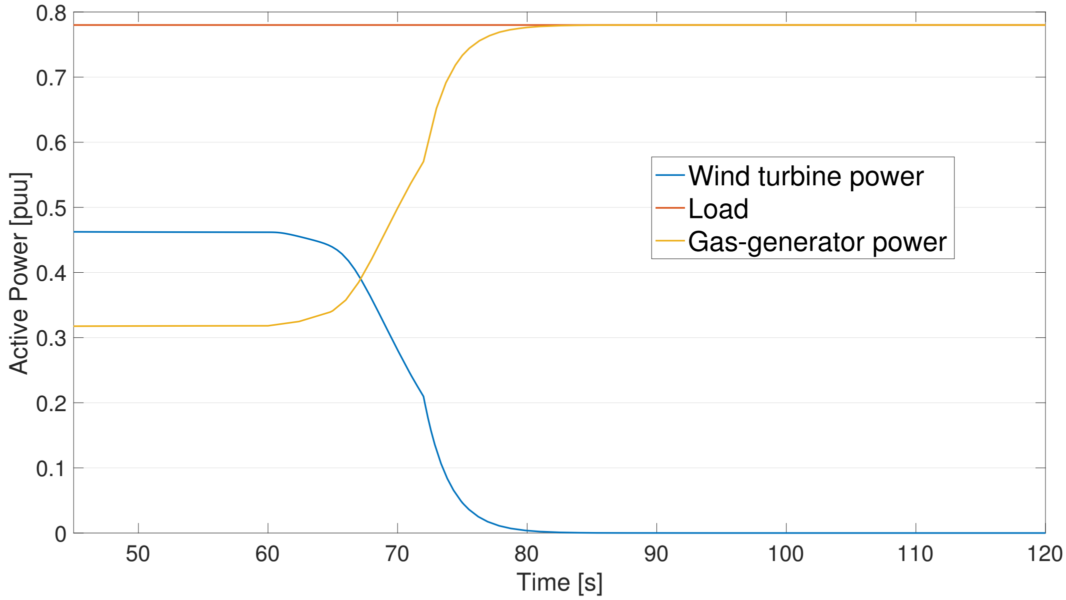

Figure 4.5: Power from wind turbine, gas-generator and load

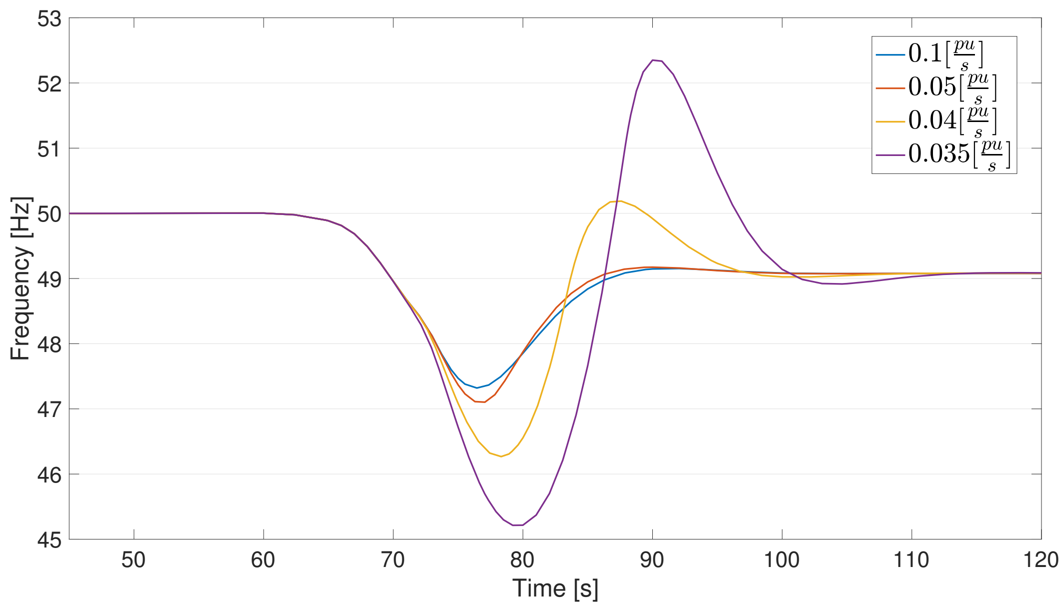

Figure 4.6: System frequency response to a sinking wind speed event

Sinking wind speed with Load Shedding

To ensure that the steady state frequency and transient frequency does not drop below acceptable limits, load shedding is an option to comply with the requirements set by IEC. Frequency response to the a sinking wind speed event with different ramping capabilities on the gas turbine is dissipated in Fig. 4.7. The figure shows that when load shedding is applied, the frequency drop is smaller and the minimum ramping capability of the gas turbine can be 0.025 [$\frac{pu}{s}$] or 325 [$\frac{kW}{s}$] and still be within the requirements set by the IEC standard.

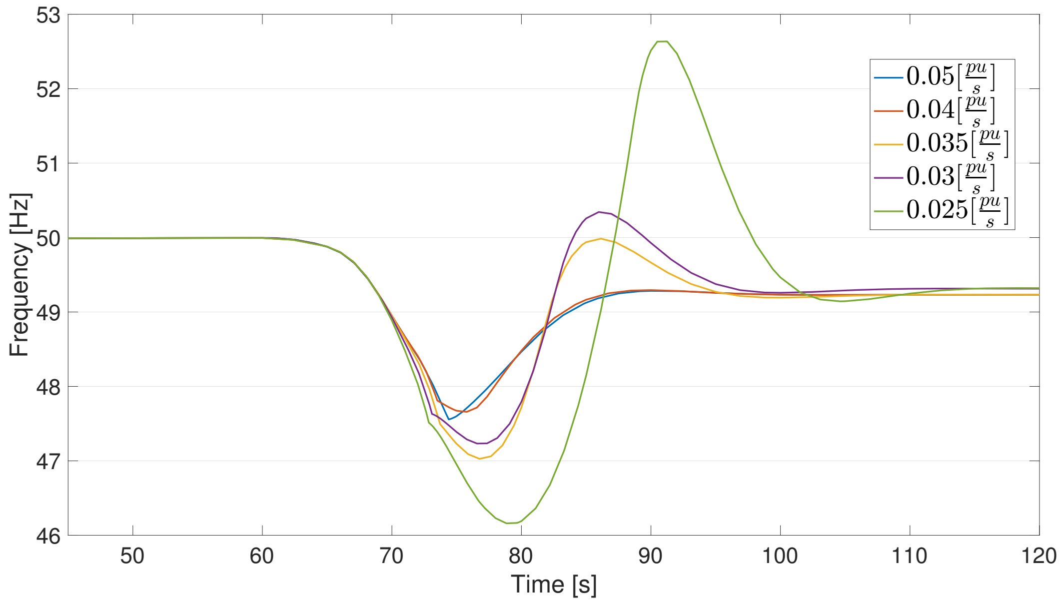

Figure 4.7: System frequency response to a sinking wind speed event with load shedding

Fig 4.8 displays the amount of load which is disconnected in the load shedding event. If the gas turbine has low ramping capabilities, more load is disconnected from the system.

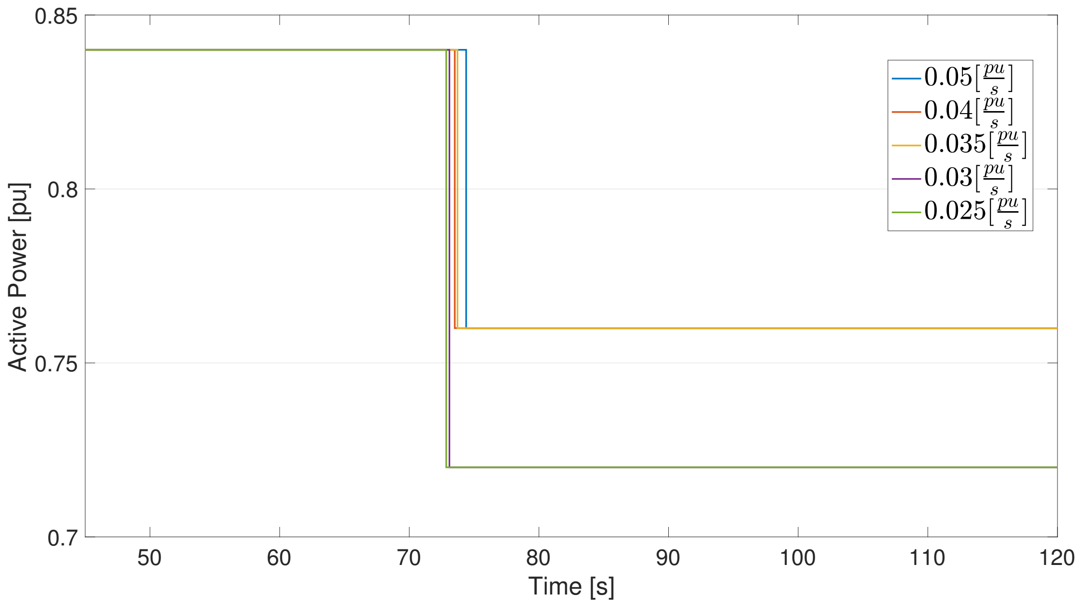

Figure 4.8: Amount of load disconnected from the system

Rise, lull and gust wind events are displayed in Fig. 4.9, 4.10 and 4.11. In these cases, the gas turbine rate ramp is set to 0.05 $[\frac{pu}{s}]$, and the figures show that these wind events produce small risks on the power system operation since the gas turbine response is fast enough to handle the power deviation these events produce on wind turbine power output.

Rise Wind

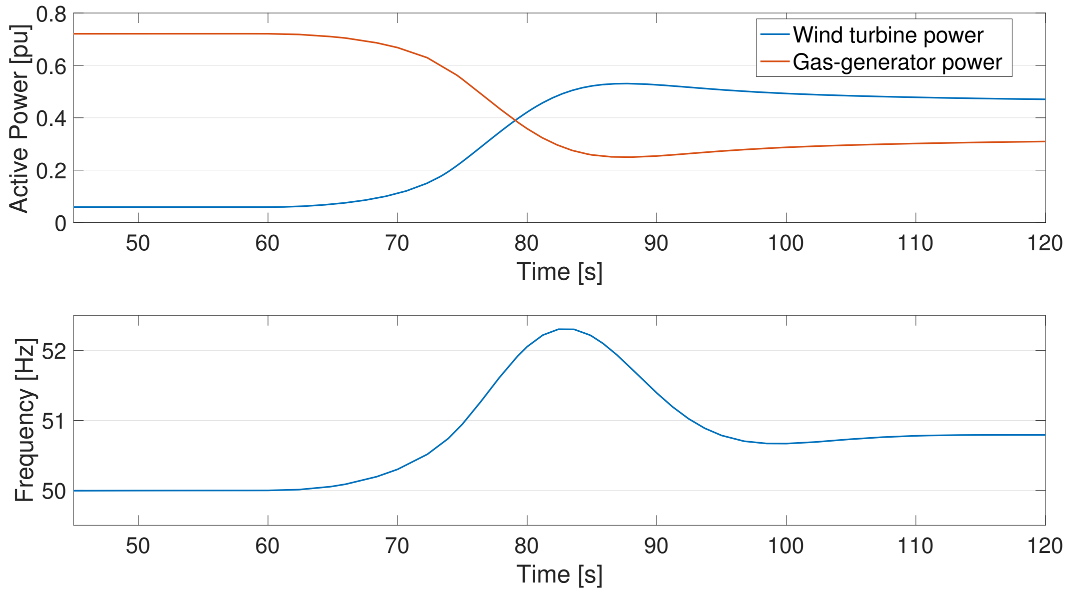

Figure 4.9: Wind turbine power, gas-generator power and system frequency response to rise wind event

Lull Wind

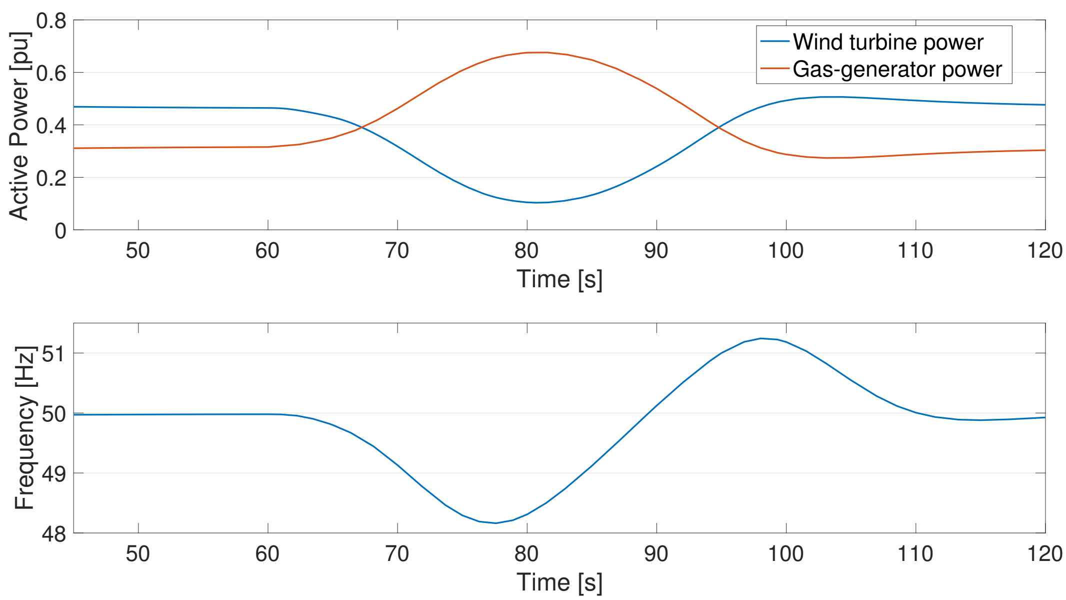

Figure 4.10: Wind turbine power, gas-generator power and system frequency response to lull wind event

Gust Wind

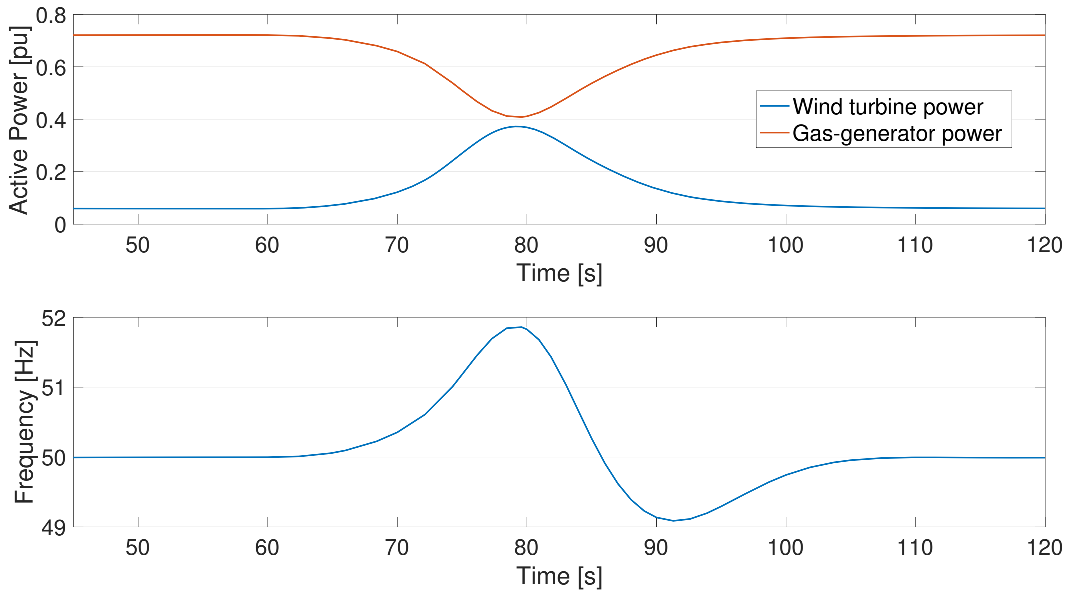

Figure 4.11: Wind turbine power, gas-generator power and system frequency response to gust wind event

4.2.1 Wind Speeds Around Cut-out Wind Speed

If the wind speed becomes too low or too high, the wind turbine will automatically stop. At high wind speed, the wind turbine will stop to avoid mechanical stress [4]. At high wind speeds, the impact is large since the wind turbine produces rated power. When the turbine is stopped, the power decrease from rated power to zero in a short moment of time. The cut-out wind speed is 25 m/s in the model used in this thesis. The blade pitch controller is used to limit the power before the mechanical breaking are used to park the wind turbine. Fig. 4.12 shows the simulated wind speed series.

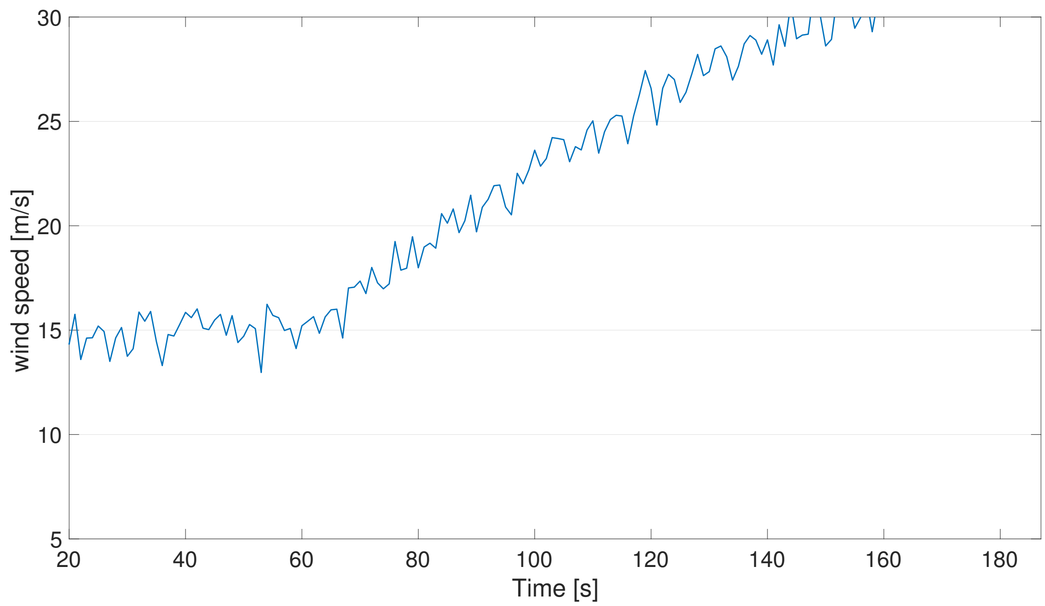

Figure 4.12: Simulated wind speed series

Fig. 4.13 shows the wind turbine power during the storm stop event, and it shows that the power decrease from rated power to zero power in about 20 seconds.

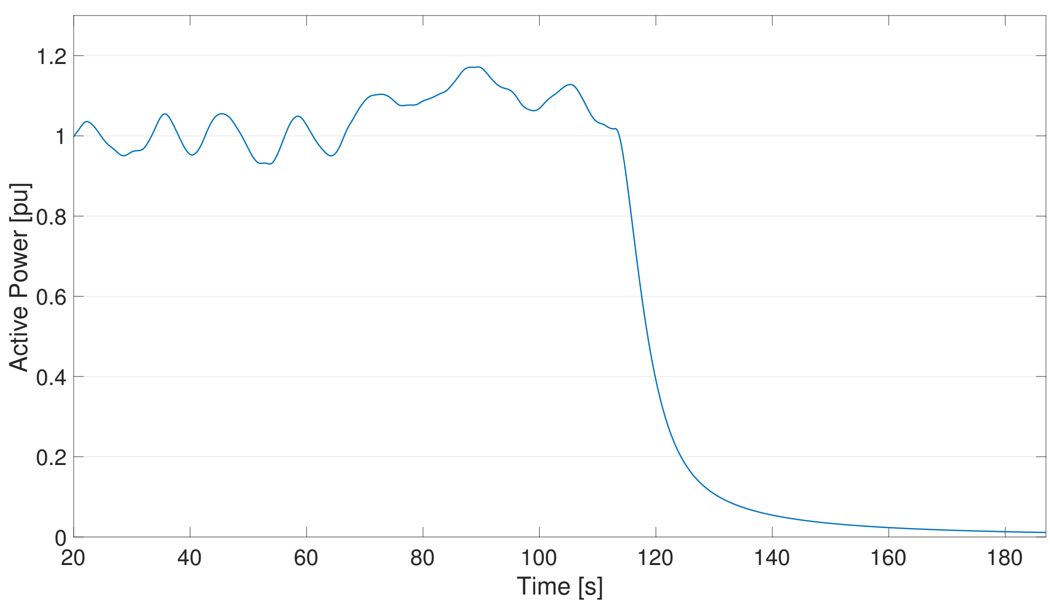

Figure 4.13: Active Power wind turbine during storm stop

Wind turbine shut down will affect the power system stability as a result of losing 6 MW production within 20 seconds. The gas turbines have to compensate for the lost wind power generation by quickly increase their power output. As shown in Fig. 4.14 the active power from the generator increases when the active power from the wind turbine decreases. The figure also indicates that the gas turbine has a fast enough ramp rate to deal with the lost wind power production without disconnect loads if the total load is below 1 per unit.

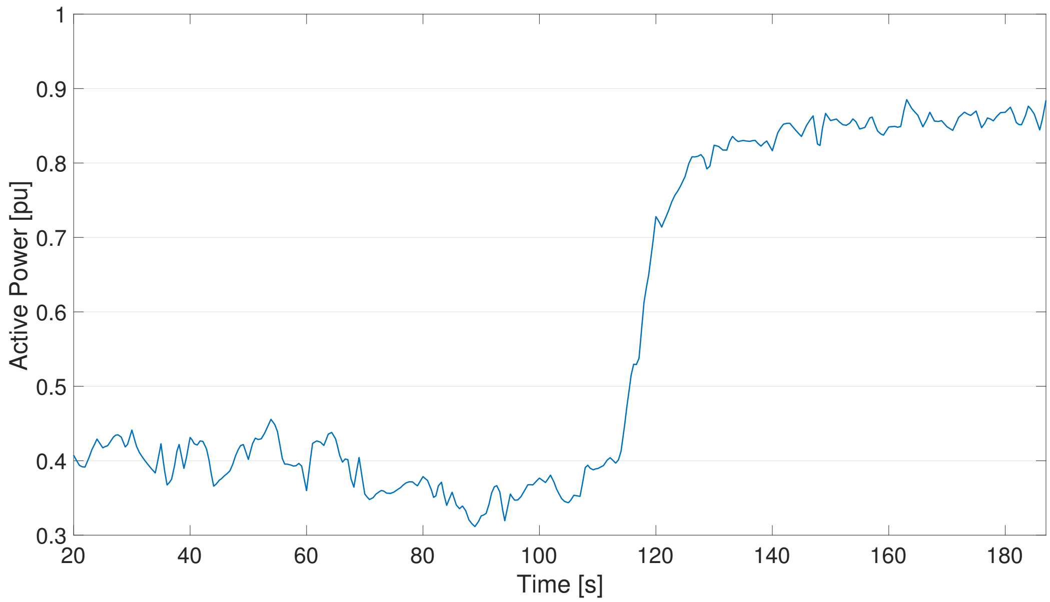

Figure 4.14: Active power output from gas-generator on O&G installation

Fig. 4.15 shows the power system frequency response on the O&G installation. There is a drop in frequency due to the rapid increase in mechanical power from the gas turbine. The governing system recovers the frequency to 49 Hz. After the wind turbine shut down, the loading of the gas turbine is high, and the power system operator should take measures to bring the power system to a more secure state. These actions can be to start another gas turbine, adjust the speed reference set point to bring the frequency up or disconnect loads.

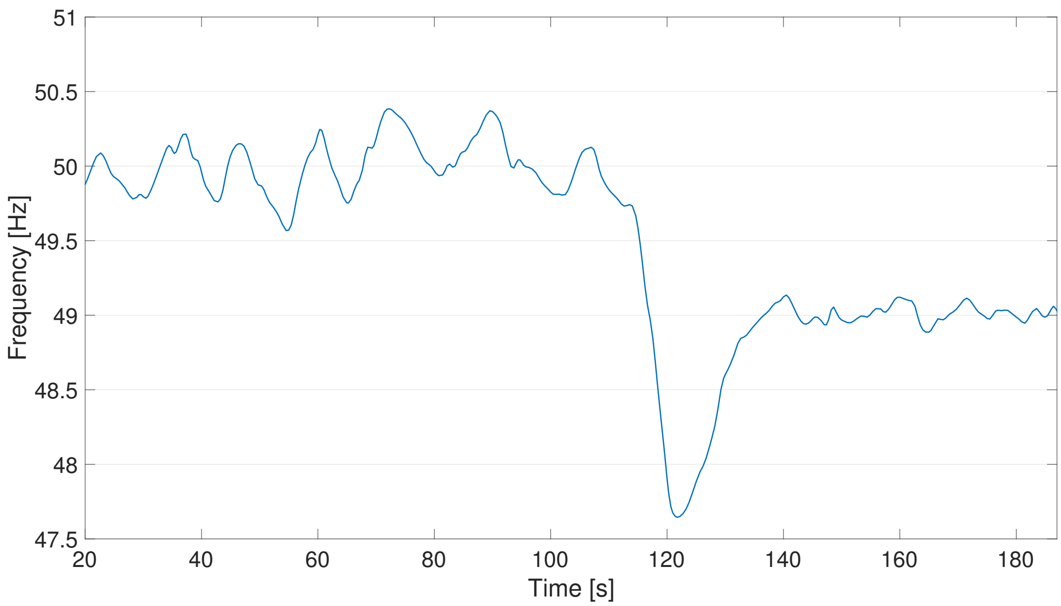

Figure 4.15: System frequency on O&G installation

When operating at high wind speeds where it is likely that the wind turbine shuts down, it is important for the power system operators to have sufficient amount of spinning reserve to avoid automatic load shedding due to overloading of the gas turbine.

4.3 Case 3 - Comparison of the 6 MW and 2.3 MW Wind Turbine

In this case the 6 MW wind turbine is compared with the 2.3 MW wind turbine to simulate variations in wind turbine power, gas generator power and system frequency. The comparison is relevant as the the Hywind portfolio consist of both wind turbines. It is also of interest to analyze how the different turbine capacity affects the frequency stability on the O&G installation. Finally, frequency quality and power quality are compared and analyzed.

The simulation time is 30 minutes, and the wind speed series is displayed in Fig. 4.16. The mean wind speed is 12 m/s with a standard deviation of 1.5 m/s and turbulence intensity of 0.05. Fig. 4.17 shows the load demand on the O&G installation.

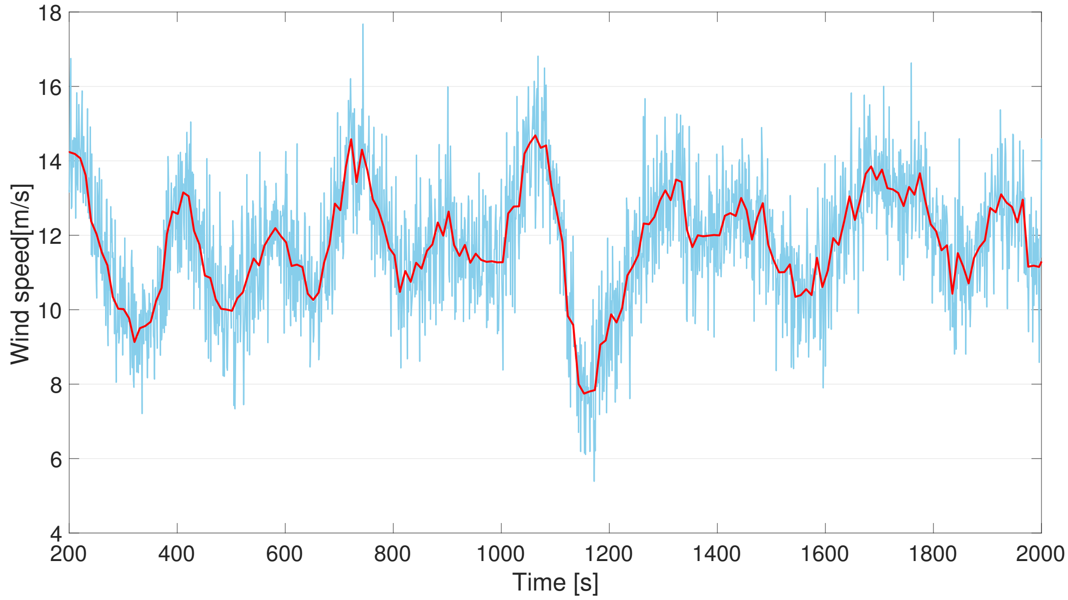

Figure 4.16: Red line: Mean wind speed with standard deviation of 1.5 m/s, Blue line: Simulated wind speed serie with added turbulence intensity of 0.05

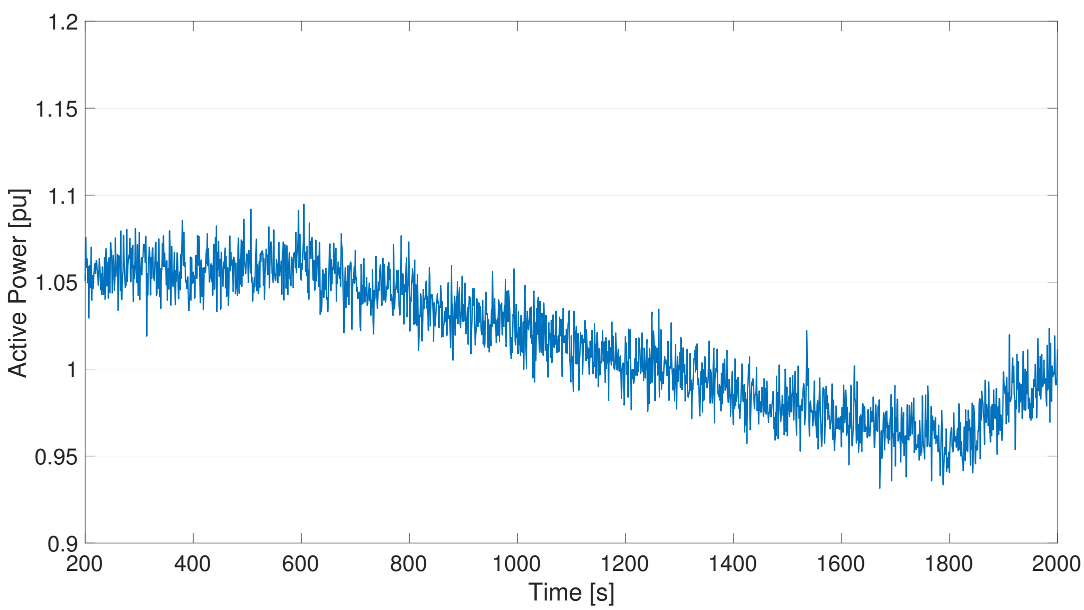

Figure 4.17: Total load on O&G installation

Fig. 4.18 shows the active power output from the 6 MW wind turbine. From the figure, it is possible to observe that the power change corresponds to the changes in wind speed. This particular wind speed spectrum generates substantial changes in wind turbine power output. Fig. 4.19

displays the power output from the 2.3 MW wind turbine. The tendency is the same as with the 6 MW wind turbine but the power variations are obviously much lower.

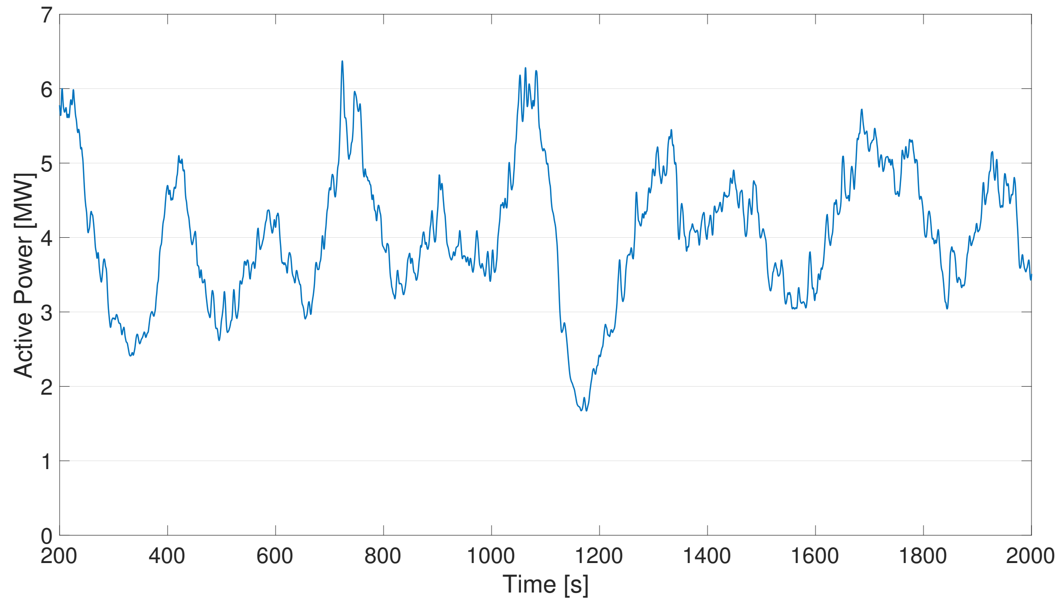

Figure 4.18: Active Power from 6 MW windturbine

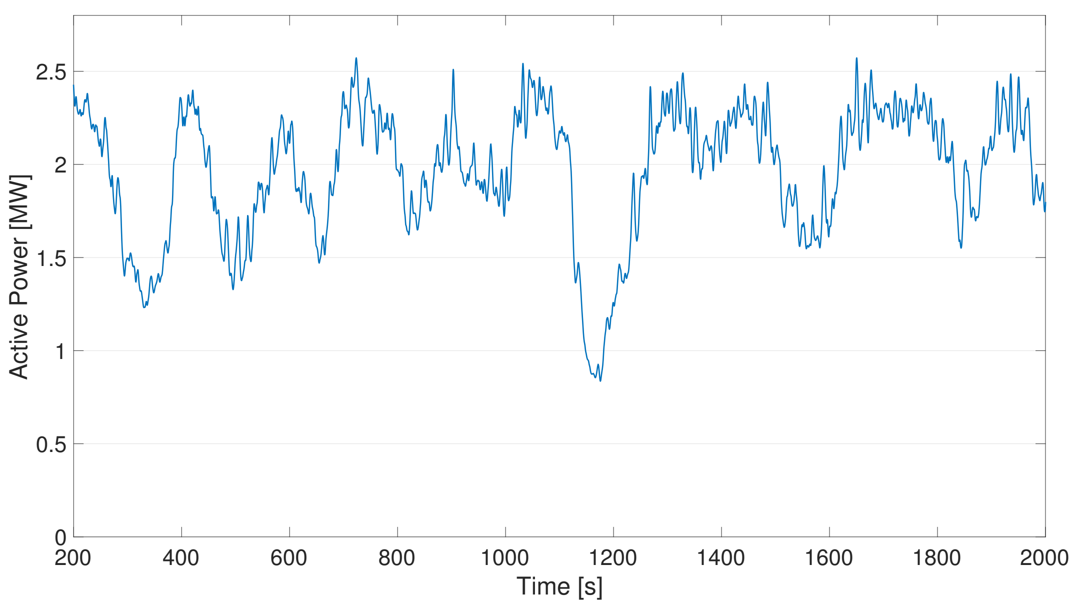

Figure 4.19: Active Power from 2.3 MW windturbine

As shown in Fig. 4.20 the loading of the gas turbine fluctuates in correlation with the wind turbine output. As expected the 6 MW wind turbine introduce larger power deviations into the power system and in consequence large frequency deviations in the system as seen in Fig. 4.21. The steady state frequency deviation is within the ±5 % limit set by the IEC standard for both the 6 MW and 2.3 MW wind turbine.

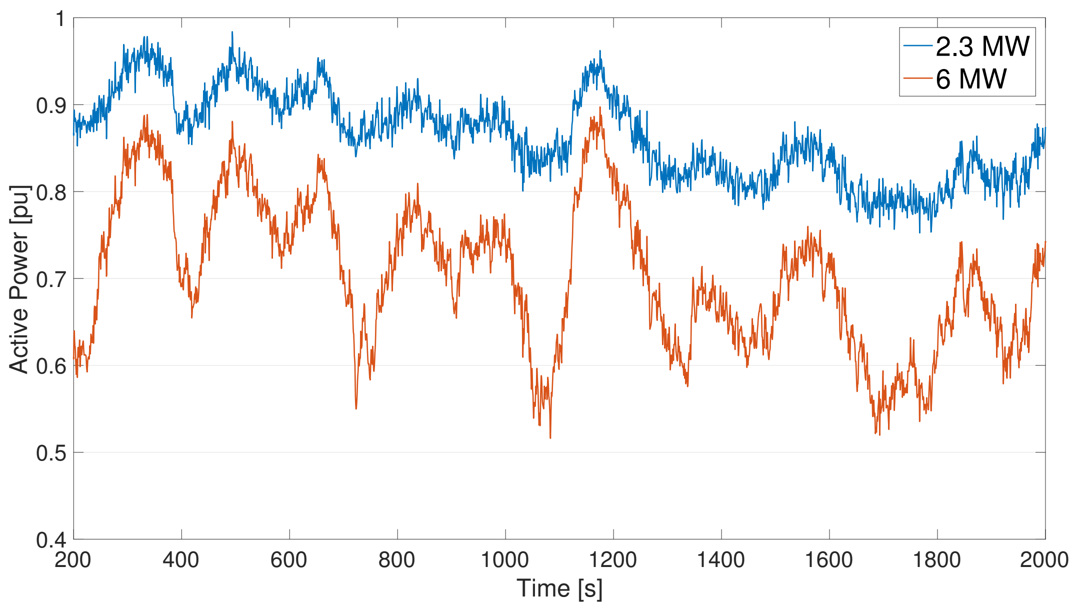

Figure 4.20: Gas-generator power O&G installation with integration of 6 MW or 2.3 MW wind turbine

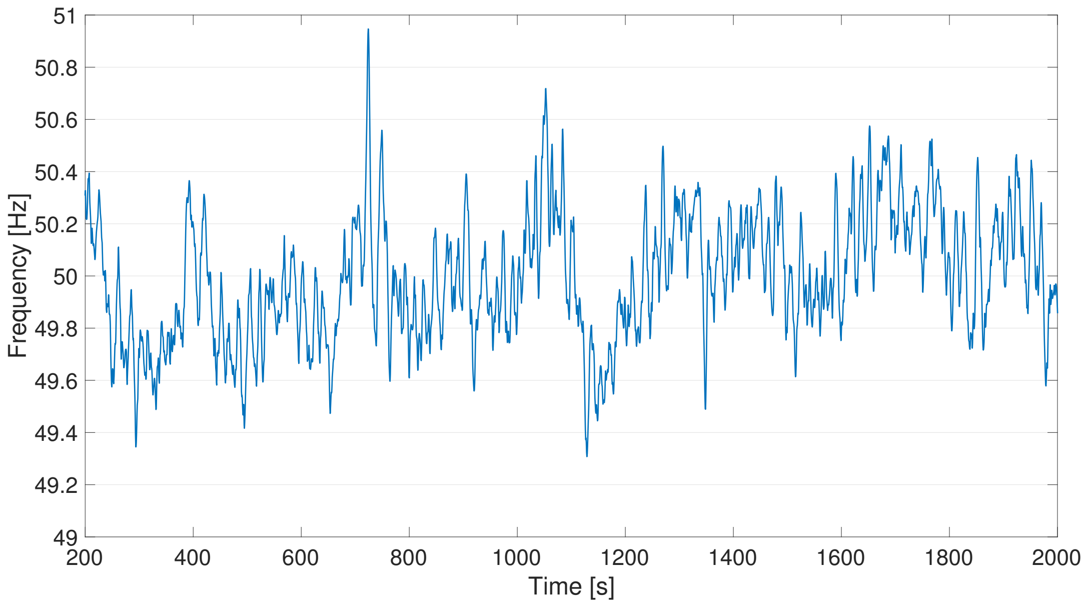

Figure 4.21: System frequency on O&G installation with integration of 6 MW wind turbine

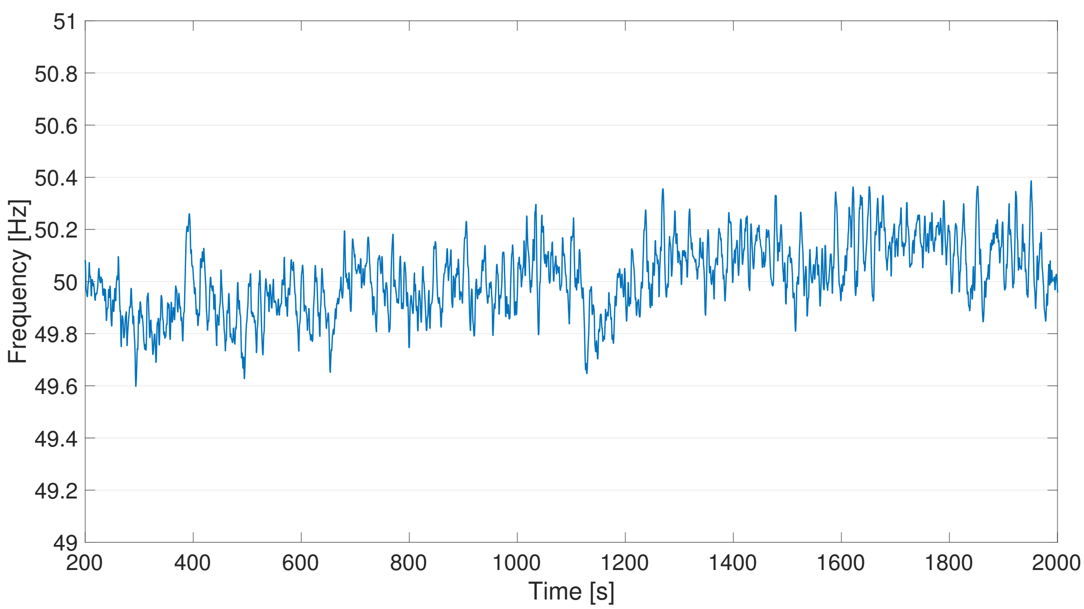

Figure 4.22: System frequency on O&G installation with integration of 2.3 MW wind turbine

4.3.1 Power Quality

Fig. 4.23 and 4.24 gives a graphical representation of the distribution of active power in form of a histogram. This provides information on the expected power deviation if the 6 MW or the 2.3

MW wind turbine is introduced into the power system. This has an impact on power quality and operation of the power system. The power quality affects the voltage and frequency fluctuation.

The power quality also depends on the different types of loads in the system. Induction motors need a large amount of reactive power, which the system needs to provide [23]. This issue is not analyzed in this thesis, but highly relevant to consider.

In this power system, the gas generator provides all the power quality service in this system. The gas turbine governor controls the frequency by responding to changes in active power. The automatic voltage regulator controls the reactive power and voltage, but this is not implemented in this thesis [23].

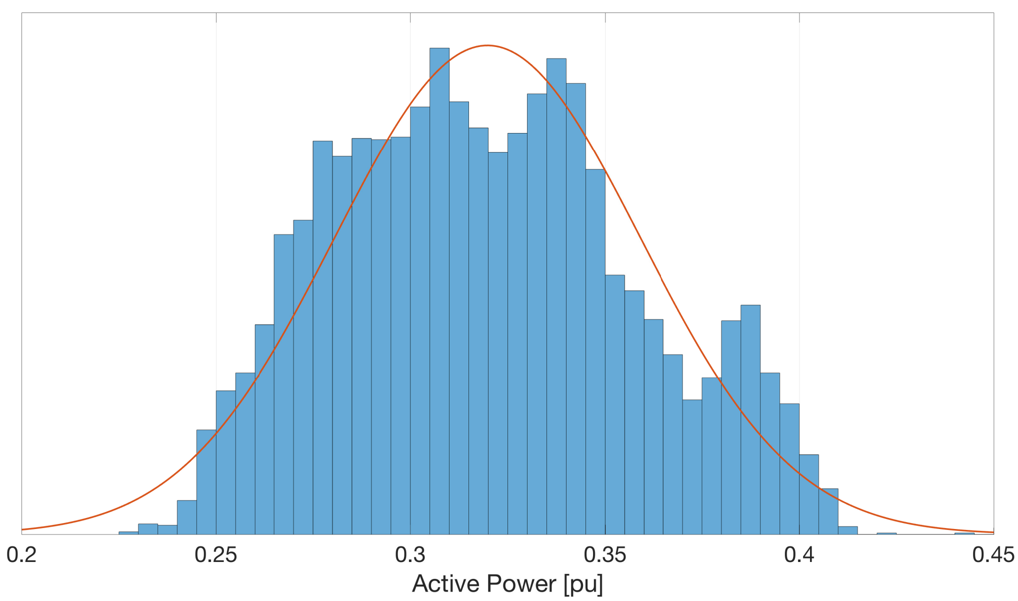

Figure 4.23: Probability density function for produced power from 6 MW wind turbine converted to base value

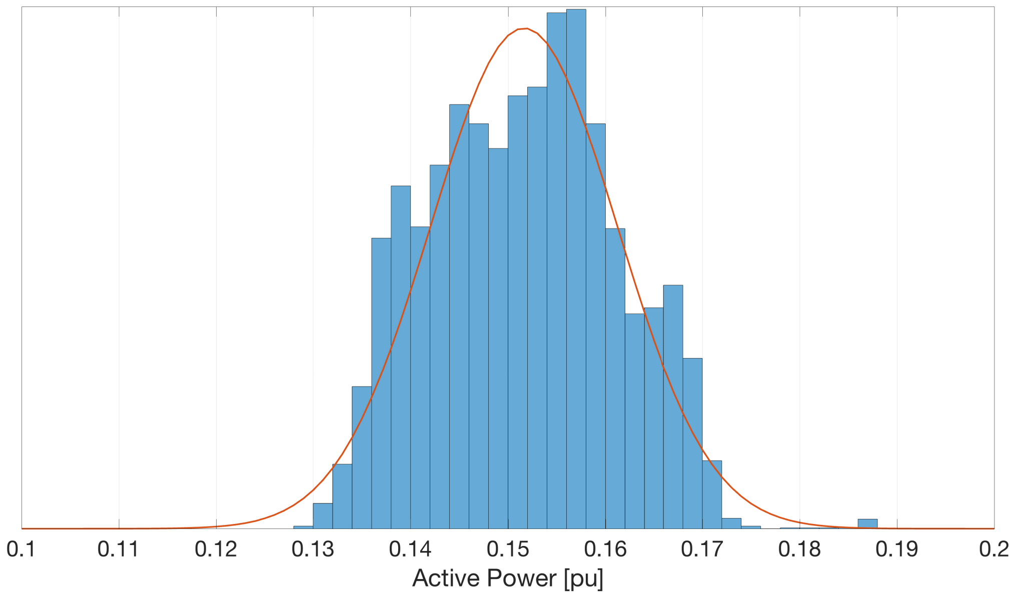

Figure 4.24: Probability density function for produced power from 2.3 MW wind turbine converted to base value

4.3.2 Frequency Quality

It is of interest to compare how the frequency quality is affected by different wind turbine size. A histogram and a probability density function are plotted for the 6 MW and 2.3 MW wind turbine in Fig. 4.25 and 4.26. The figures show that the frequency variations are larger for the 6 MW wind turbine then the 2.3 MW wind turbine.

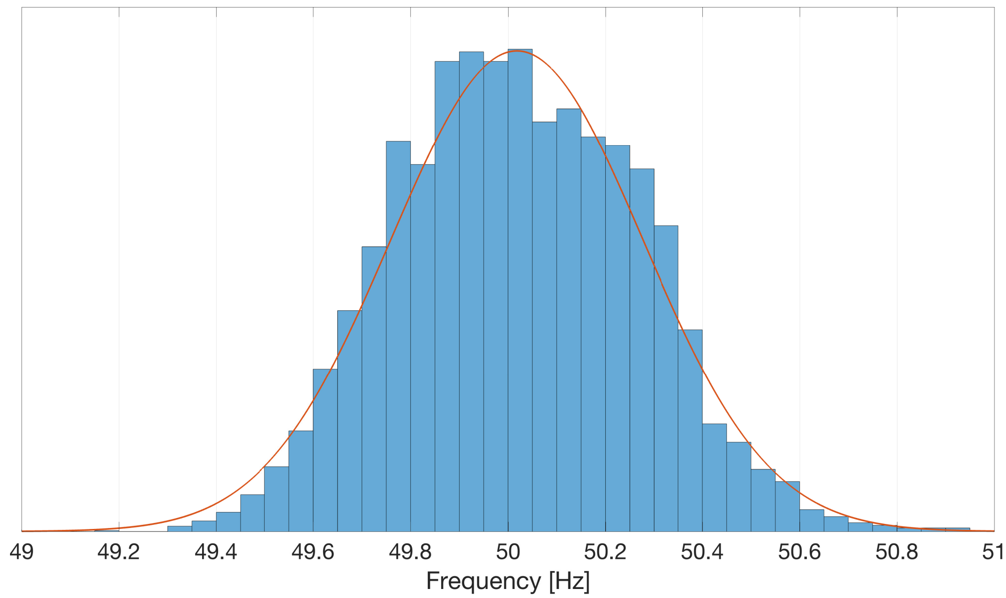

Figure 4.25: Probability density function for frequency with 6 MW windturbine

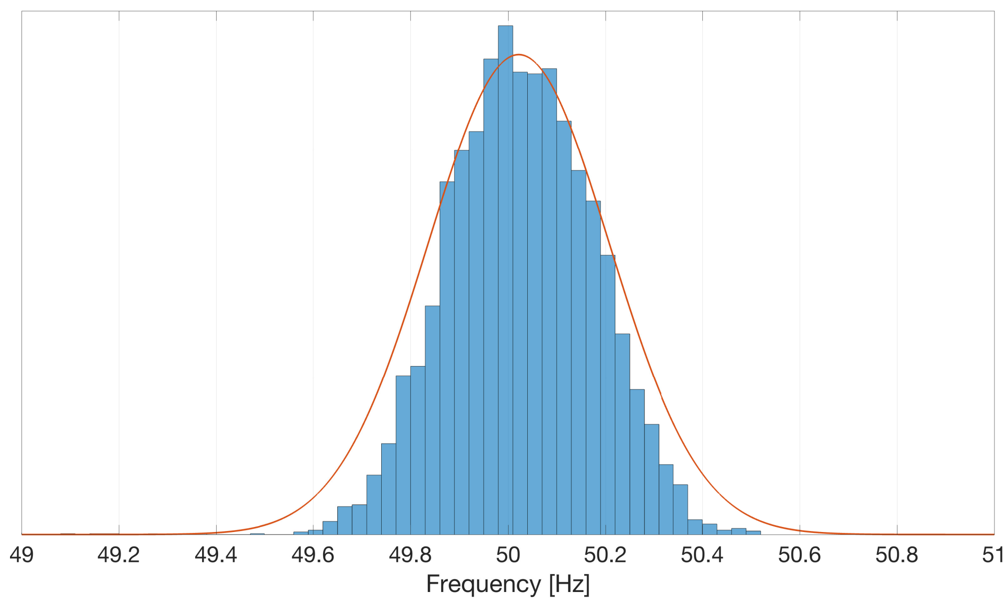

Figure 4.26: Probability density function for frequency with 2.3 MW windturbine

4.4 Case 4 - Amount of Wind Penetration

The objective for this case is to analyze the cyclic frequency variation during normal operation such is caused by variable power from the wind and regularly repeated loading. It is of interest to investigate how different wind speeds and the amount of wind penetration in the power system affects the periodic frequency deviation on the O&G installation. Simulations are performed for three different wind speed intervals with a period of 10 minutes. The periodic frequency deviation is given by [2]:

$$\text{Cyclic frequency variation} = \frac{\pm(f_{max} - f_{min}) \times 100}{2 f_{nominal}} \% \tag{4.1}$$

4.4.1 Low Wind Speed

In this first case, a wind speed just above cut-in wind speed is simulated. The wind speed is illustrated in Fig. 4.27 and varies between 6 – 11 m/s.

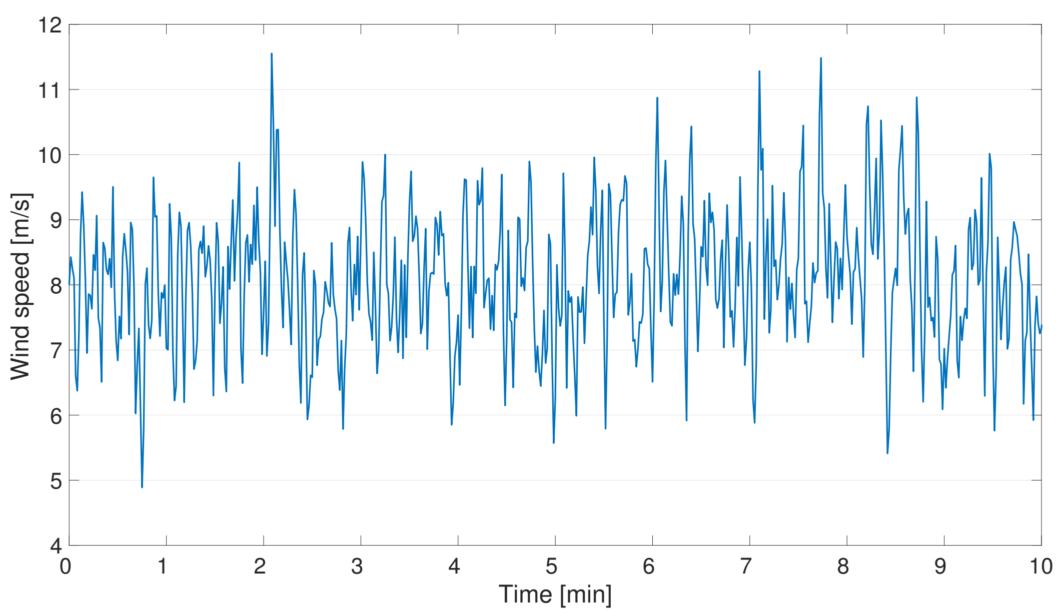

Figure 4.27: Low wind speed series

In Fig. 4.28 the gas generator power, wind turbine power, and load are shown. The figure shows that with a load around 1 per unit, the wind penetration is around 15 % in this wind speed interval.

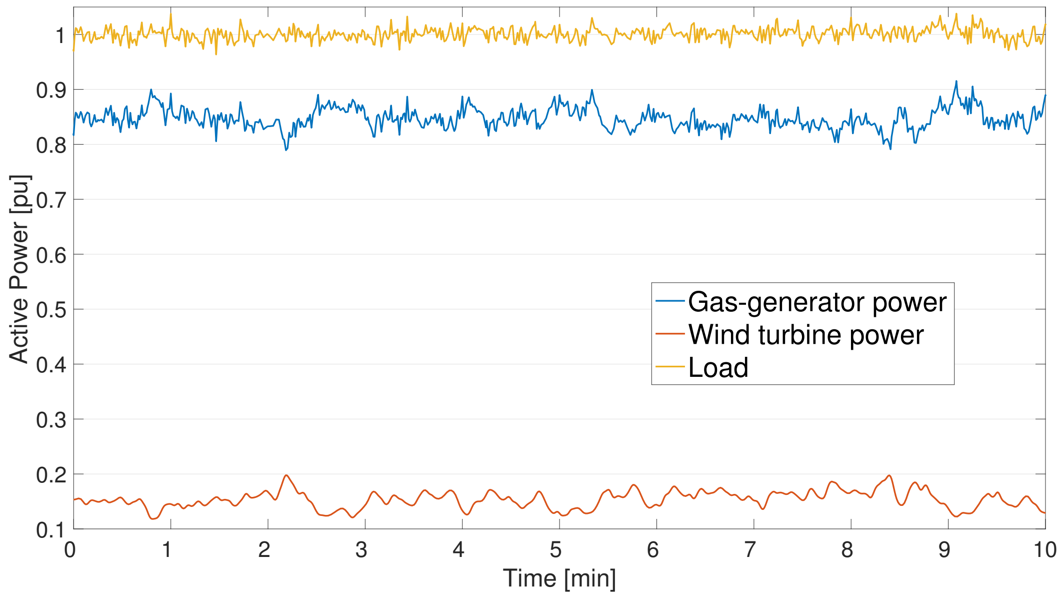

Figure 4.28: Power from wind turbine, gas-generator and load for low wind speeds

The power system frequency is displayed in Fig. 4.29. This show that the gas generator can handle wind power and load variations well. The cyclic frequency variation is around 0.5 – 0.6 % and does not bring problems to the power system operation.

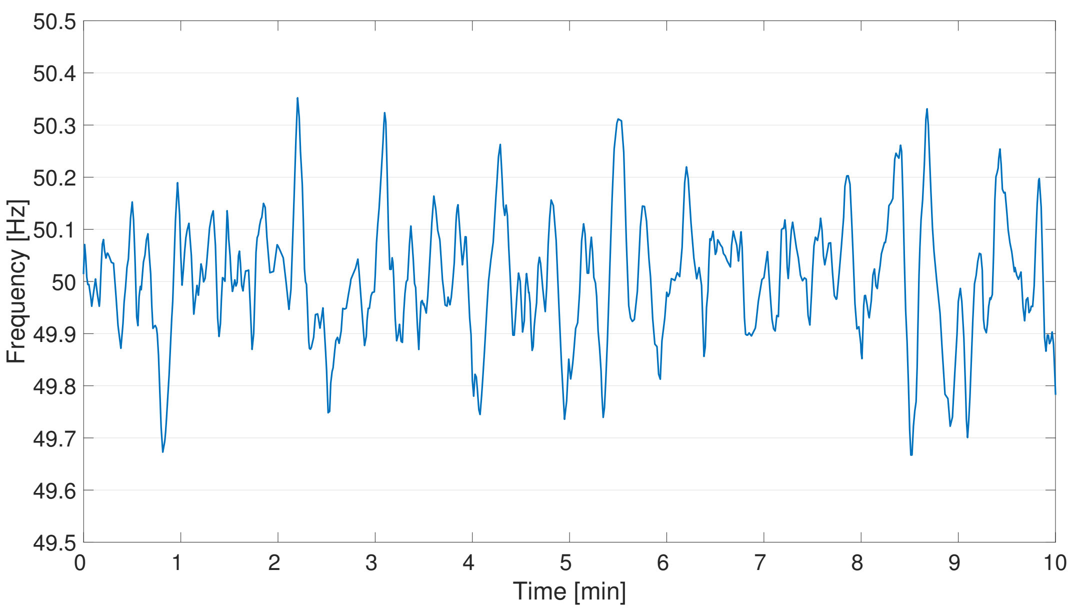

Figure 4.29: System frequency on O&G installation with low wind speeds

4.4.2 Moderate Wind Speed

In this case, a wind speed around rated wind speed is simulated. The wind speed is illustrated in Fig. 4.27 and fluctuates between 10 – 16 m/s. The wind turbine power fluctuations are largest when the turbine operates just below rated wind speed, therefore is this wind speed interval the worst case scenario when considering power variations.

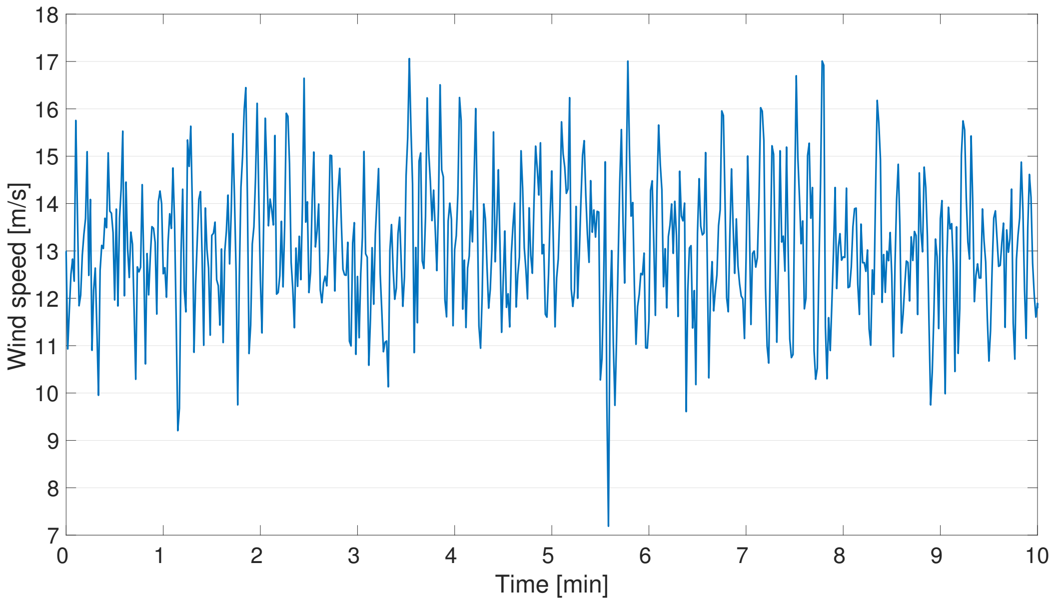

Figure 4.30: Moderate wind speed series

In Fig. 4.31 the gas generator power, wind turbine power, and load are shown. The figure shows that with a load around 1 per unit, the wind penetration is around 35 – 40 % in this wind speed interval.

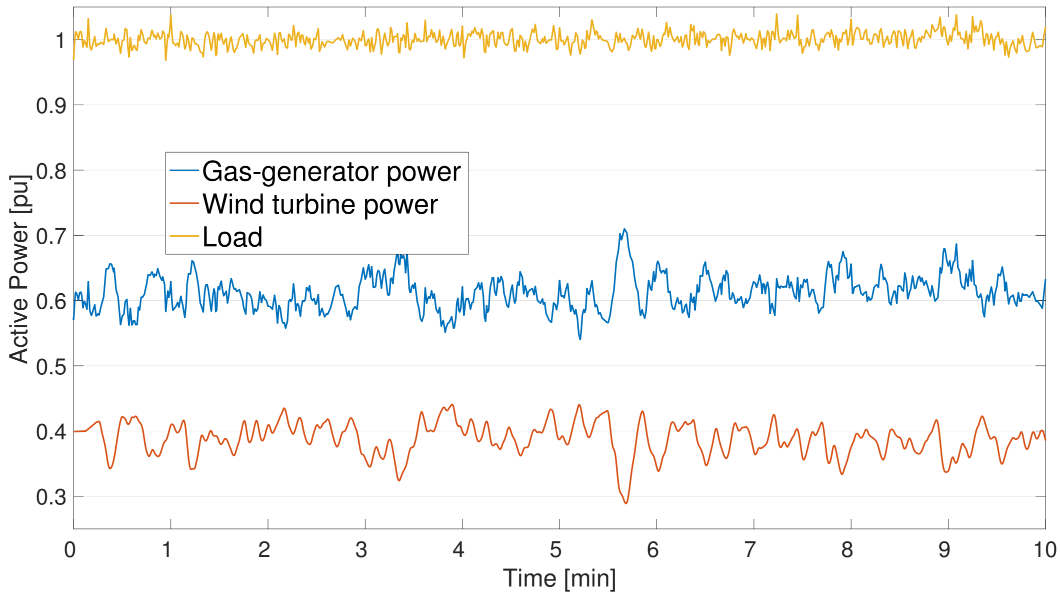

Figure 4.31: Power from wind turbine, gas-generator and load for moderate wind speeds

The power system frequency is displayed in Fig. 4.32. In this case, the cyclic frequency variation is between 0.5 – 1 %. This shows that high wind power penetration and wind speed just below rated wind speed leads to greater periodic frequency deviations.

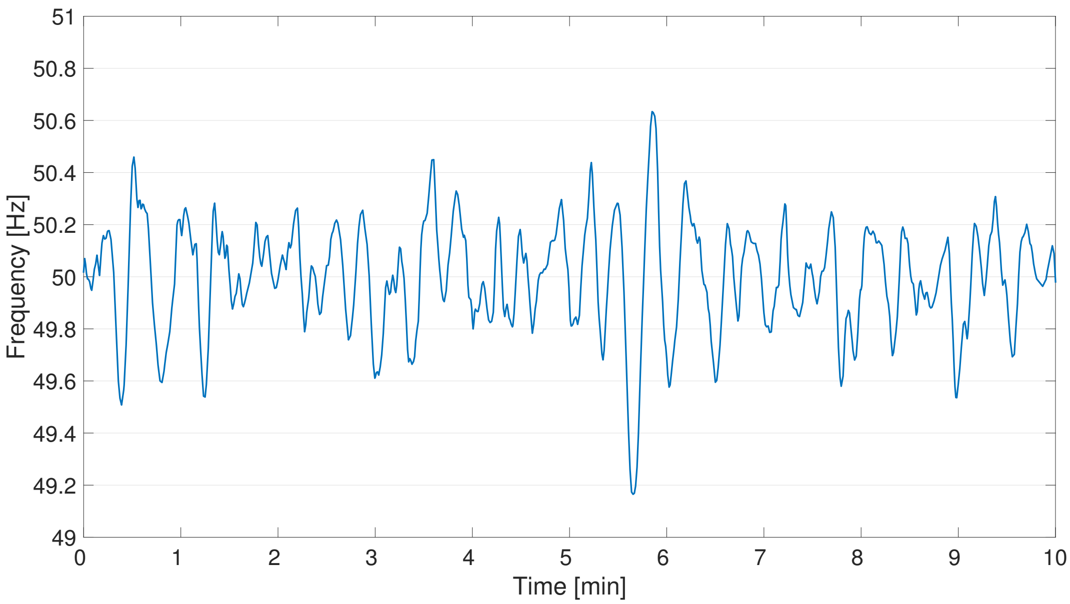

Figure 4.32: System frequency on O&G installation with moderate wind speeds

4.4.3 High Wind Speed

In this case, a high wind speed between 16 – 20 m/s is simulated and is displayed in Fig. 4.33. When the wind speed is above rated wind speed, the blade pitch controller is activated to limit the power to rated power.

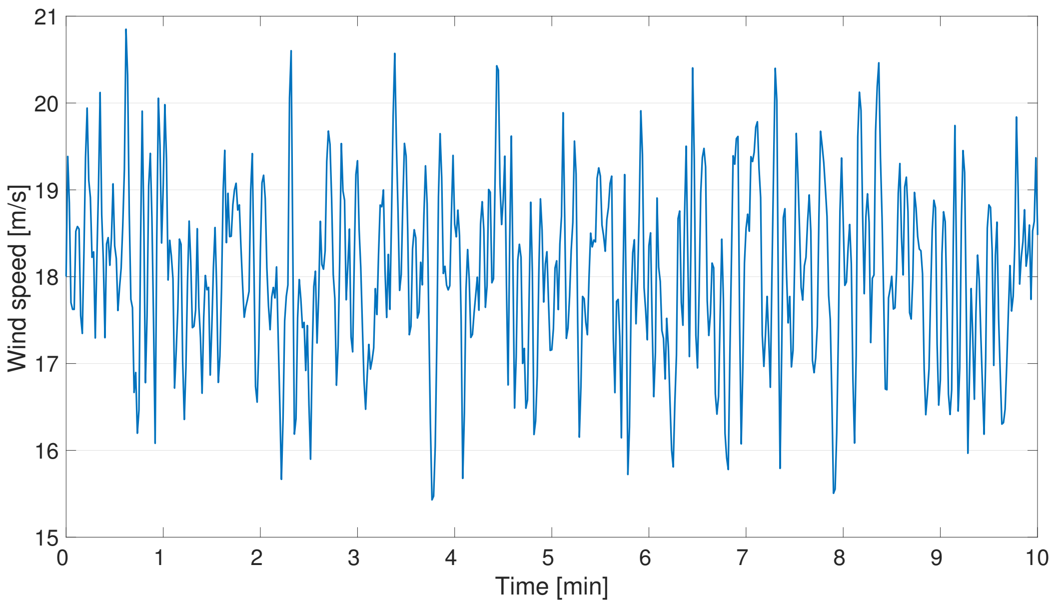

Figure 4.33: High wind speed series

In Fig. 4.34 the gas-generator power, wind turbine power, and load are shown. The figure shows that with a load around 1 per unit, the wind penetration is around 42 – 50 % in this wind speed interval and the wind turbine almost produce the equal amount of power as the gas-generator.

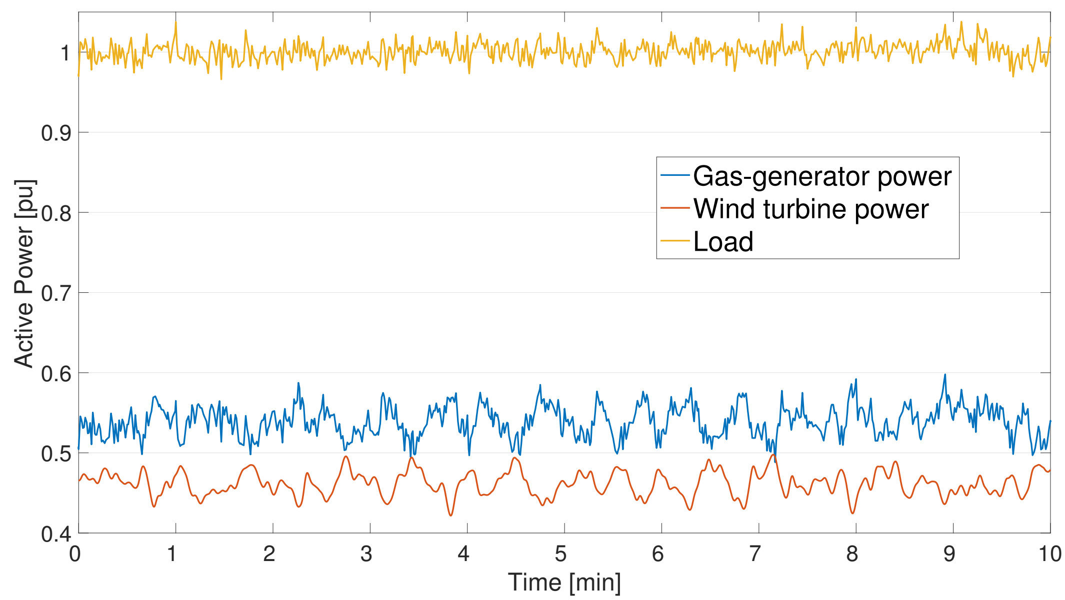

Figure 4.34: Power from wind turbine, gas-generator and load for high wind speeds

The power system frequency is displayed in Fig. 4.35. In this case, the cyclic frequency deviation is between 0.5 – 0.6 %. The frequency deviation is smaller than with moderate wind even with higher wind penetration in the system.

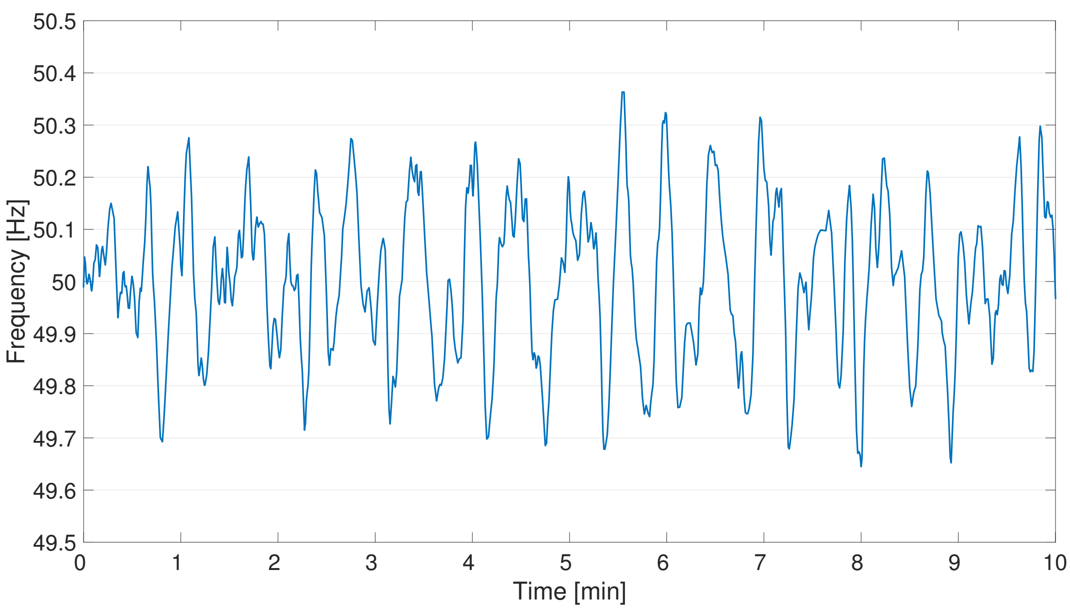

Figure 4.35: System frequency on O&G installation with high wind speeds

4.4.4 Frequency Quality

In Fig. 4.36 a probability density function is plotted for different wind speed intervals. This illustrates the probability for a power system frequency for the different cases. The figure shows that the frequency variations are relatively similar for the two highest wind speed intervals and lower for the lowest wind speed. The probability density data are collected from the previous frequency plots.

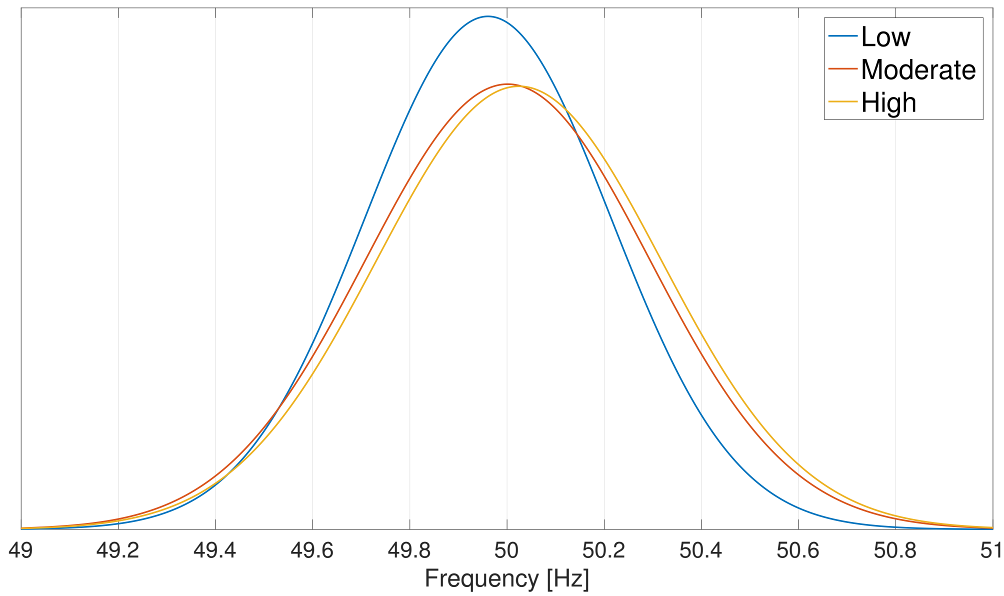

Figure 4.36: Wind events

4.5 Case 5 - Long Term Simulations

In the longer term it is interesting to run simulations for longer time periods to analyze factors related to wind turbine capacity and wind power penetration during a whole year. Fig. 4.37 and 4.38 displays system load, gas turbine power, wind turbine power and percentage of wind penetration over a period of one year. Load data and wind speed data are received from Statoil AS. Load data has a sample rate of one hour and wind speed data has a sample rate of 10 minutes. The sample rate is reduced to one day in the figures presented below.

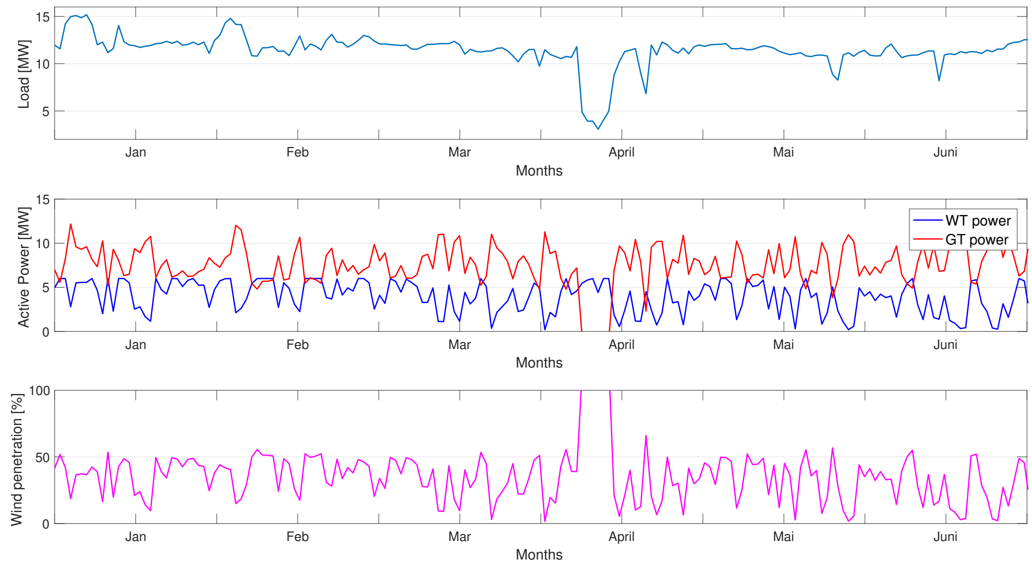

Figure 4.37: Top:Total system load. Center: Wind turbine power and Gas generator power. Bottom:Wind penetration in the power system. From January to June

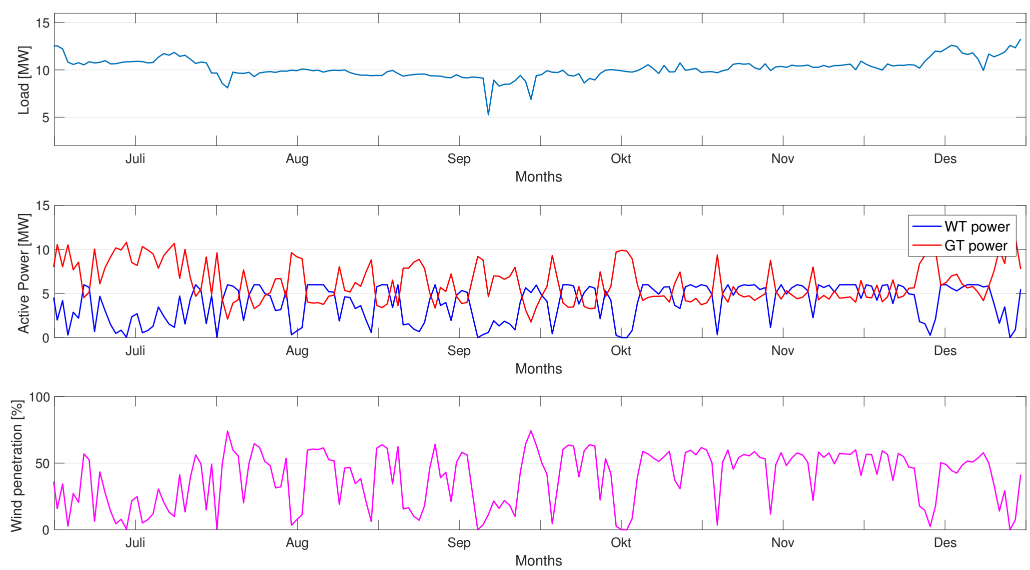

Figure 4.38: Top:Total system load. Center: Wind turbine power and Gas generator power. Bottom:Wind penetration in the power system. From July to December

4.6 Discussion

Wind penetration Issues and Frequency Quality

In Chapter 4.4 the periodic frequency variations are analyzed for different wind speed intervals due to wind variations and amount of wind penetration in the system. Simulation results show that lower wind speed and wind penetration gives the smallest periodic frequency deviations. This is well presented in Fig. 4.36 that show periodic frequency deviations are similar for moderate and high wind speeds. The requirements for cyclic frequency deviations for offshore units is given by an IEC standard and is $\pm 0.5\%$. Results indicate that for low and high wind speeds the cyclic frequency deviations comply with the requirements. For moderate wind speeds, the cyclic frequency deviation is around 0.8 % and therefore don't comply with the IEC requirements. A method to secure that the cyclic frequency deviation is within its limit is to bring another generator online, but this will result in lower loading of the gas turbine, around 30 % which is not recommended. A method is to reduce the wind power output in this wind speed interval by using the pitch regulator to limit the power output. Another method is to install short-term battery storage to reduce the frequency deviations without having to limit the wind turbine power. Battery storage will also reduce maintenance cost and time of the gas turbines due to lower heavy cycling periods since the batteries contributes to lower the periodic power oscillations [25]. The downside to battery storage is the high capital investment cost and it requires space on the O&G installation. A cheaper solution is to install a dump load to limit the power variations on the gas generator, but this solution does not utilize the total available wind power.

Wind Events and Limitation on Gas Turbine Power Variation

In chapter 4.2 wind events are simulated to analyze how the gas generator respond to rapid changes in wind power output. If the wind turbine produced rated power and the wind suddenly drops to zero, the power system loses around 0.45 per unit of power. For the system to have a proper regulation of frequency, the gas turbine needs to respond to these wind events rapidly. Fig. 4.6 illustrates how the frequency response changes with different ramping capabilities on the gas turbine and this show the required ramp rate for the gas turbine to comply with the IEC standard requirements for transient frequency deviation. The ramp rate can easily be changed in the operator training simulator model and this can give the power system operator valuable knowledge how to handle wind energy in the system.

If the ramping capabilities of the gas turbine are slow, load shedding is essential to keep the system stable after a disturbance. This is showed in Fig. 4.7 and proves that the responsiveness of the gas turbine and control system is essential when integrating wind power into an isolated power system.

A different scenario when load shedding is necessary is if the load is above the rated power of the gas generator and there is a rapid drop in wind power. Since the gas generator cannot operate above rated power, load shedding needs to be applied to keep the power system stable. In the case of load shedding, the least critical loads will be disconnected initially. If the wind speed forecast predicts that the wind speed will remain low, resulting in that the wind turbine and the gas generator is unable to supply the total load, the power system operator needs to bring additional gas generator online to cover the total load. The start-up sequence for gas turbines is about 45 minutes and regularly start and stop sequences is damaging for gas turbines. Therefore, the second gas turbine needs to operate for a certain amount of time before it is taken offline. This will further result in the need to limit the wind turbine power or park it to prevent that the loading of each gas turbine is below 30 – 35 %. This proves that it is essential with good wind speed prediction for the power system operator to plan for when to operate one gas turbine and wind turbine, or when to run two gas turbines.

Comparison of the 6 MW and 2.3 MW Wind Turbine

In chapter 4.3 a comparison of integrating the 6 MW and 2.3 MW wind turbine into the power system is performed. When comparing the two wind turbines concerning frequency quality, the 6 MW wind turbine induced higher frequency variation on the power system as expected. The comparison of frequency quality is illustrated in Fig. 4.25 and Fig. 4.26 in Section 4.3.2. On the other side, the 2.3 MW only covers between 0.13 – 0.17 per unit of the total load, whereas the

6 MW wind turbine covers between 0.25 – 0.4 per unit of the total load. This is represented in Fig. 4.23 and 4.24 in Section 4.3.1. From an environmental and economical point of view it is beneficial to utilize the maximum possible power from the wind, therefore is the 6 MW wind turbine the best option in that regard. In the case of frequency quality, the 2.3 MW wind turbine is the better solution.

Chapter 5

Conclusion and Further Work

5.1 Conclusions

A operator training simulator has been modeled to give the power system operators knowledge on how wind power penetration affects the frequency stability on an O&G installation. The modeled operator training simulator gives the power system operators the opportunity to monitor and observe how the wind turbine and gas turbines perform under different load and wind variations. The power system operators also have the possibility execute simple control actions like adjust speed reference set point of the gas turbine, perform load shedding and start or stop gas turbines.

A hybrid power system has been modeled consisting of two 13 MW gas turbines, a 6 MW wind turbine, and several loads. The level of complexity of the models is kept simple to reduce the computational requirements. The system only includes mechanical models of gas turbines and the wind turbine. Wind model subsystems consist of a wind turbine, drive train, blade pitch controller and MPPT controller. Gas turbine subsystems consist of governor, turbine and drive train.

The emphasis in this thesis is on frequency stability of the power system due to the variability of wind power. High wind penetration have large impacts on the power system stability and it essential for the power system operator to understand how integration of wind energy affect the power system stability.

The dynamic study investigates frequency stability. Transient, steady-state and cyclic frequency deviations are analyzed and compared with the requirements in IEC 61892-1 standard for electrical installations on mobile and fixed offshore units. Simulation is performed to examine the necessary ramping capability of the gas turbine to comply with transient frequency deviations requirements from the IEC 61892-1 standard. The required ramping capability of the gas turbine if load shedding is performed are also analyzed. The results indicated that the required ramping capabilities of the gas turbine in case of loss of wind power is 455 [$\frac{kW}{s}$] or 325 [$\frac{kW}{s}$]. High wind penetration causes periodic frequency deviation problems in moderate wind speed because of periodic power oscillation. High wind penetration at high wind speeds and low wind penetration at low wind speed does not cause cyclic frequency deviations problems.

Although there are some problems related to moderate wind speeds, integration of a 6 MW wind turbine is a feasible solution if some control actions are implemented to control the wind turbine at moderate wind speeds.

5.2 Recommendations for Further Work

The recommendation for further work is;

- Implementation of frequency control in the wind turbine model
- Analysis on frequency quality by implementing frequency support
- Modelling of synchronous generator based on fully rated converter wind turbine
- Modelling of classic synchronous generator with AVR
- Focus on voltage stability and control
- Improve user interface of the operator training simulator

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Appendix A

Model parameters

The parameters used in the model are listed below. The system base is 13 MVA.

Table A.1: G/T set

Rated Power	13 MW
H	5s
D	2
T	0.2s
K_p	5
K_i	1.2
K_d	0.8
ρ	0.04
K_e	1

Table A.2: 2.3 MW wind turbine model parameters [21] [16]

Type	Siemens SWT-2.3-108
Rated Power	2.3 MW
Base wind speed	12 m/s
Blade diameter	108 m
Speed range	6-16 rpm
Cut-in wind speed	3-4 m/s
Cut-out wind speed	25 m/s
c1	0.5176
c2	116
c3	0.4
c4	5
c5	21
c6	0.0068
H	5s

Table A.3: 6 MW wind turbine model parameters [22] [16]

Type	Siemens SWT-6.0-154
Rated Power	6 MW
Base wind speed	14 m/s
Blade diameter	154 m
Speed range	5-11 rpm
Cut-in wind speed	3-5 m/s
Cut-out wind speed	25 m/s
c1	0.5176
c2	116
c3	0.4
c4	5
c5	21
c6	0.0068
H	5s

Table A.4: Blade pitch controller

K_p	15-20
K_i	3.1
T	0.1s
T_{Mref}	1
β_{max}	60
β_{min}	0
$\dot{\beta}$	5

Appendix B

Figures

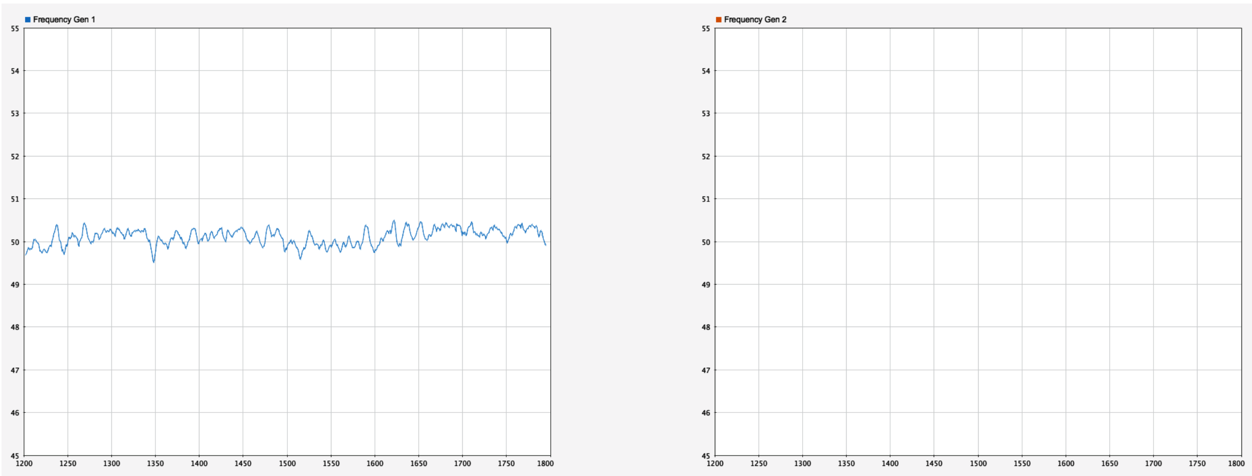

Figure B.1: Frequency on generator 1 and 2

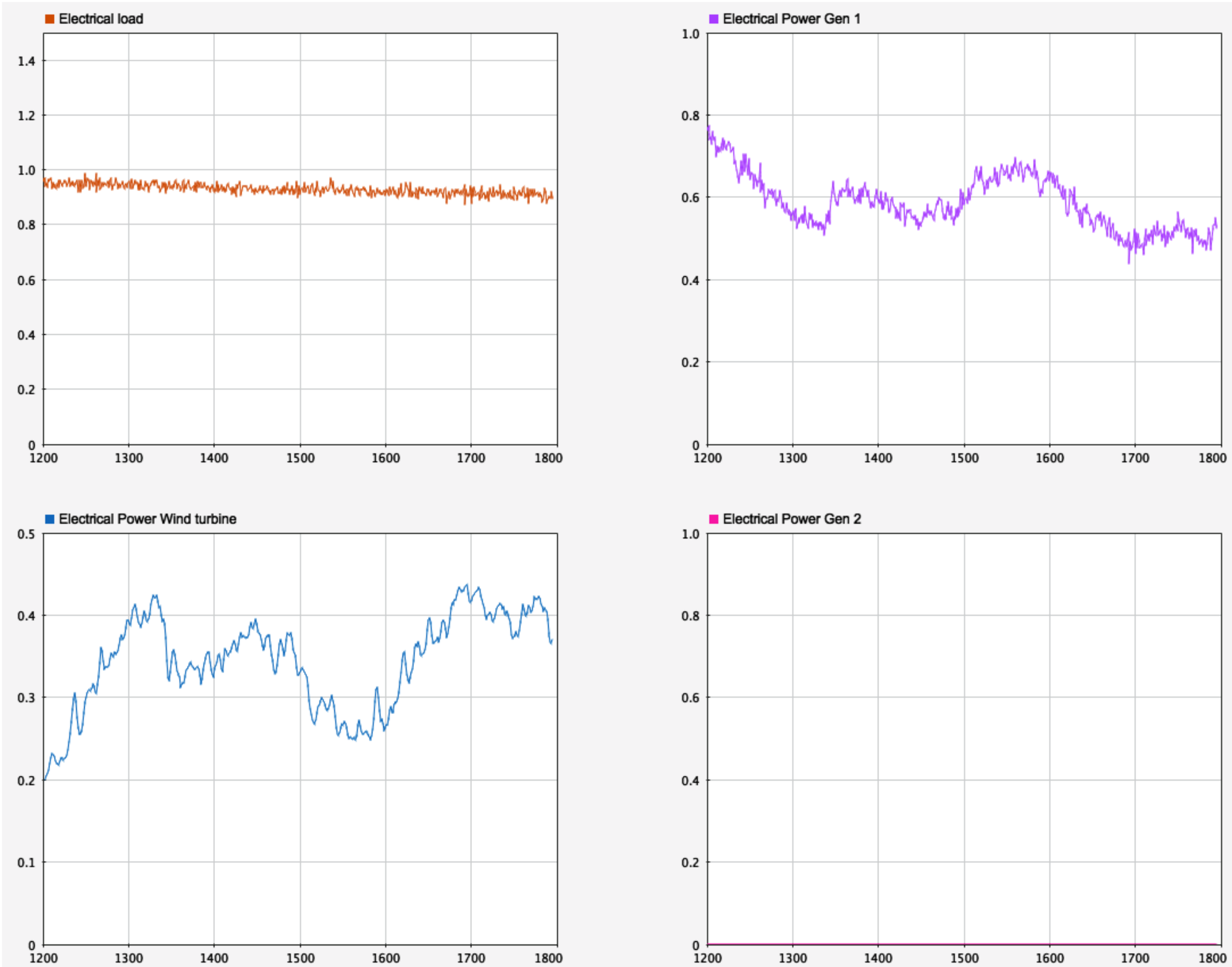

Figure B.2: Electrical load, Electrical power on generator 1 and 2, and electrical wind turbine power

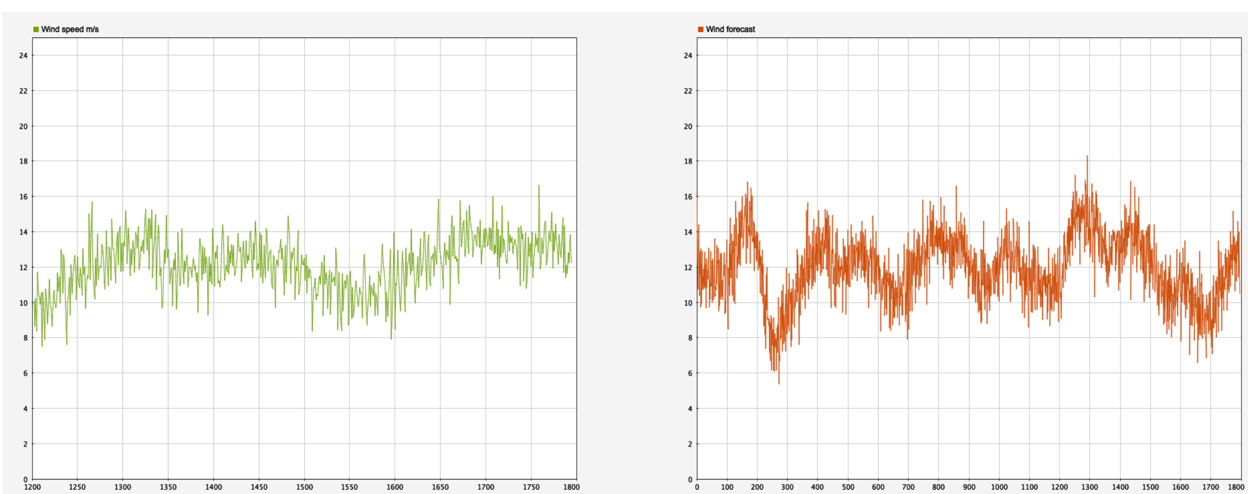

Figure B.3: Wind measurements and wind forecast