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OPERATIONAL STRATEGIES FOR WIND FARMS UNDER EXTREME WIND CONDITIONS

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Abstract:

Control strategies for shutting down wind turbines are essential to improve the reliability of offshore wind energy under extreme wind conditions, which are expected to become more frequent in the North Sea area. The main objective of this thesis is to investigate and verify operational storm strategies for offshore wind farms. These strategies involve coordinated shutdowns of wind turbines to avoid disturbance in the utility grids. The proposed storm strategies are tested using a MATLAB Simulink wind farm model based on the Horns Rev I wind farm. The shutdown performance is tested with several proposed wind profiles to evaluate its correct operation in different meteorological conditions. The power and voltage responses resulting from different shutdown procedures are thoroughly analyzed and discussed to determine the optimal shutdown strategy for the specific case study. The chosen strategy aims to strike a balance between achieving a rapid shutdown of the entire wind farm, minimizing voltage drops, and ensuring a smooth transition to the idle state.

Preface

This report presents the Thesis of the Master in Wind Energy Systems at the AAU Department of Energy, Aalborg University, Denmark.

The topic of this thesis is to investigate, propose and verify operational shutdown strategies for wind farms under extreme wind conditions. This purpose has been motivated by the growing expansion of offshore wind energy in the North Sea as well as the high wind speeds that are expected to become more frequent in the future.

I would like to express my gratitude to my supervisor Florin Iov, for his invaluable help, support, guidance, and motivation provided during the last three semesters of supervising my projects.

Mónica Sanz García Salmones

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Chapter 1

Introduction

1.1 Background and Motivation

In recent years, it has become evident that more active steps must be taken in order to shift to a low carbon society due to the significant impacts of climate change [1]. The marine environment provides a great opportunity for transition, as it holds a massive energy potential; and in Europe, the North Sea is the most resourceful area for exploiting marine renewable energy [2].

Since 2017, Energinet and the North Sea Wind Power Hub consortium have been researching and developing the idea of two energy islands: one in the North Sea and one in the Baltic Sea, in order to drive the increased and ongoing expansion of offshore wind energy. As a result, in June 2020, the Danish Parliament decided to commence the construction of the two energy islands, which are expected to be finished by 2030, each providing 6 GW of energy [3].

The Baltic Sea energy island is planned to be located at 20 km off the coast of Rønne, and will be connected to Bornholm, Zealand, and at least one other country [4]. Meanwhile, the North Sea energy island will be connected to Denmark via the west coast of Jutland, and at least 50 km offshore from Thorsminde. With a minimum of 3 GW in 2033, the aim is to reach 10 GW by 2040, which allows to power 10 million households and support the further electrification of Denmark and its neighboring countries [4].

On the other hand, the expected dynamics of wind energy in the North Sea until the end of the 21st century have been analyzed by the following study [5], thus motivating the purpose of this thesis. It focuses on the assessment of average and extreme wind conditions over three-time windows: the near future (2021-2060), the distant future (2061-2100), and the past (the last 40 years).

Data from a Regional Climate prediction model has been used in the study, with two distinct scenarios considered: a realistic one, which presumes a growth in greenhouse gas emissions until 2040, followed by stagnation and a decline afterwards; and a pessimistic one, which assumes an ongoing increase in emissions throughout the 21st century.

The results of the study [5] have revealed that extreme wind conditions, with maximum wind speeds exceeding 30 m/s, are expected to become more frequent in the future.

In the realistic scenario, it is shown that these extreme events are likely to occur more often, with maximum wind speeds even surpassing 40 m/s, which corresponds to a second-category hurricane level (>43 m/s) [6]. In the pessimistic scenario, maximum wind speed values up to 35 m/s have been observed, corresponding to a first-category hurricane level (>30 m/s).

From this study [5] can be concluded that average wind speeds will likely increase in the near future in the North Sea area, and therefore actual and future installed wind turbines must be able to withstand wind profiles of such magnitude. The reliability of offshore wind energy production in extreme wind conditions has thus been the main motivation for this project.

1.2 SoA on Storm Control Strategies

At very high wind speeds, wind turbines are shut down in order to avoid damage from extreme mechanical loads and stresses for which the turbine is not designed [7]. The cut-off limit for the average wind speed is established based on the cost-efficiency criteria of the turbine and is typically 25 m/s. However, wind turbines are capable of operating at speeds greater than the cut-out speed through derating.

Derating is the ability of a wind turbine or wind plant to function below maximum capacity during periods of high wind speed. This is achieved through various control methods, such as adjusting the pitch of blades and regulating generator torque. By implementing these solutions, turbines are able to continue producing energy at wind speeds greater than the cut-off limit, although at reduced levels. All approaches involve a gradual ramp control of power in relation to increasing wind speed, with the possibility to use ramp speed control or dynamic control.

In ramp speed control, the power is gradually reduced as wind speed increases until zero power is reached. Thus, hysteresis effect is eliminated, as operation continues back and forth as wind speed increases and decreases [8]. This process is depicted in figures 1.1 and 1.2, which will be explained below.

In the dynamic control, an algorithm is used that estimates the state of the wind turbine and predicts the worst-case wind speed. The algorithm evaluates all wind speeds possessing set characteristics and selects the one that yields the highest loads. Then, the wind turbine power or rotor speed is adjusted to ensure that, even in an extreme case, the design loads remain within the predefined limits [9].

Since grid companies are interested in ensure the energy production under storm situations, several storm control strategies are available to cope with wind turbine operation during very high wind speeds.

The considered as *Hard Storm Transition* (HST) control shuts down the wind turbine when the 1-minute average nacelle anemometer wind speed reaches 25 m/s, and restarts it when the average wind speed drops below 25 m/s.

However, this approach leads to abrupt shutdowns of the entire wind farm, resulting in harmful consequences for the electricity grid. Additionally, it makes it very difficult to estimate energy production at high wind speeds, because a slight misjudgment in wind speed forecasting could lead to a huge error in power prediction [9]. That is why, in order to prevent frequent shutdowns and restarts that cause considerable losses in power output, *Hysteresis Storm Transition* is usually applied [10].

This process entails that the wind turbine will only start up when the average wind speed exceeds a value lower than the cut-off limit, typically 20 m/s [11]. This is not an issue in areas where wind speeds rarely exceed the cutoff speed; however, can be useful in areas with short wind gusts above the cut-off limit and with high turbulence.

Other storm control strategy is the one developed by ENERCON, denoted as *Soft Storm Transition* (SST). When this storm control is activated, the power is linearly decreased starting at a predetermined wind speed denominated Vstorm, smaller than the cut-off limit, also set between 28m/s and 34m/s [12].

In addition, the shutdown considers the 10-min average measurement, instead of only 1-minute average, which also smooths the transition.
The comparison between both strategies -SST and HST- can be seen in figure 1.1.

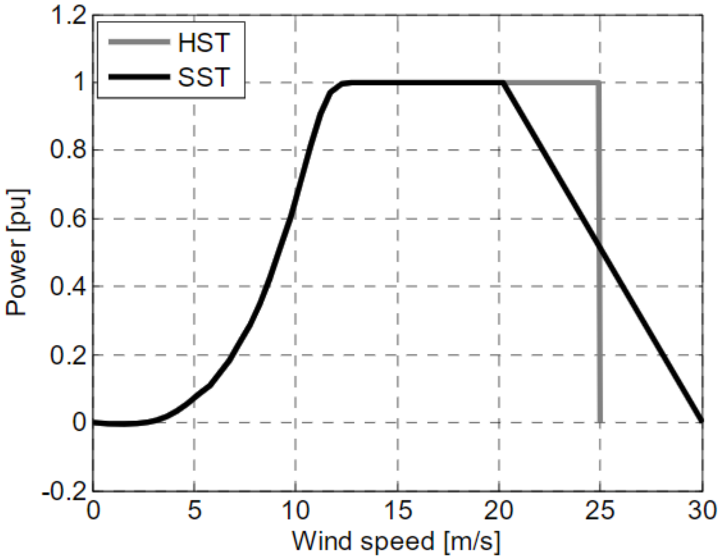


Figure 1.1. HST and SST power curves [13].

Siemens also implements SST storm control in their wind turbines, the *High Wind Ride Through* (HWRT) system [14], gradually derating instead of shutting down abruptly. Figure 1.2 shows a typical power curve without (left graph) and with (right graph) HWRT.

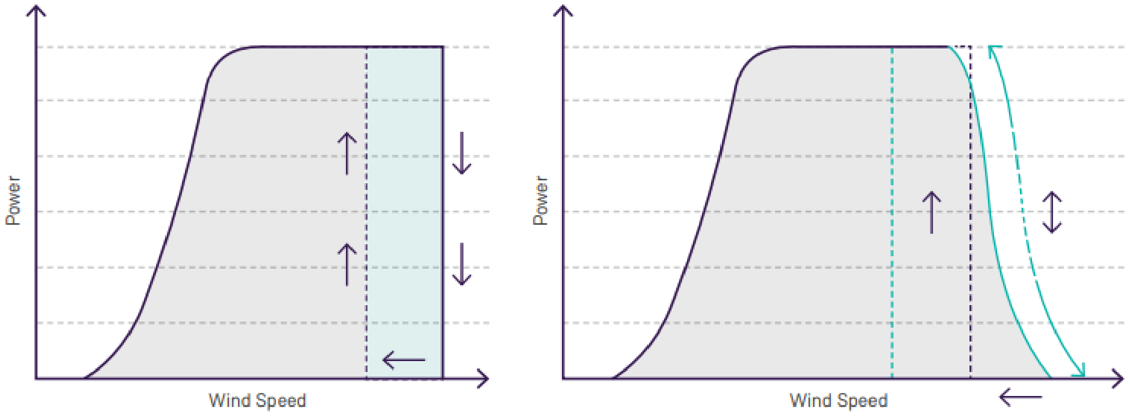


Figure 1.2. Siemens power curve without and with High Wind Ride Through control.

It is evident that the hysteresis loop is reduced with the HWRT control, thus increasing the production time. Consequently, this functionality renders the wind turbine more grid-friendly, as the quantity of electricity sent into the grid is more stable and foreseeable. When an assurance of a certain level of energy production is essential, this is beneficial. Additionally, the reduction of shutdowns of the wind turbine leads to less wear and tear on its components.

1.3 Project Formulation

A storm represents the most variable wind speed situation, and therefore this challenge adds to the already existing variability and difficult predictability of wind energy.
As explained in 1.2, when a big storm situation occurs, the shutdown of the wind turbines may be postponed but not unavoidable, and therefore the wind farm controller must be prepared to coordinate a shutdown operation.

It can be assumed that in cases of extreme wind speeds, all wind turbines in the park are subjected to winds of approximately the same magnitude -although taking into account the speed variations due to the wake effect-, but it is to be assumed that all units must be shut down. The success of this operation depends on the control strategy implemented in the farm controller, as it must communicate to each WT and coordinate the entire park.

This operation presents some challenges because a sudden and complete shutdown of the whole park will lead to power system imbalance and generate disturbances in the utility grids. Therefore, shutdown control strategies as well as the coordination between the controllers are essential for enhancing the reliability of offshore wind power production, especially from now on, since average wind speeds seem to increase in the near future.

Since large wind energy companies in Denmark, such as Vestas or Siemens Gamesa, do not publicly expose their storm control strategy, this thesis aims to properly investigate it, develop and verify a strategy for a typical offshore wind farm located in the North Sea area, so that the challenges intrinsic to it can be analyzed.

1.4 Project Objectives

The objective of this thesis is to investigate, propose and verify operational shutdown strategies for wind farms under extreme wind conditions. These operational strategies should account for a coordinated shutdown of the wind turbines in such a way as to avoid disturbance in the utility grids.

In order to achieve this goal, the following tasks must be accomplished:

- A literature review of current control strategies for wind turbines in storm conditions should be performed.
- The layout of the wind farm model to be simulated must be defined and planned.
- The requirements and functionalities required in the model need to be investigated and considered.
- Several wind profiles must be found or created in order to simulate different weather conditions.
- A representative wind farm model of the layout chosen needs to be built.
- This wind farm model should be verified for proper operation.
- The typical shutdown procedure of a pitch-regulated, variable-speed wind turbine needs to be investigated.
- The shutdown control must be developed, including its logic and implementation in the model.
- Several shutdown coordination strategies should be proposed.

1.5 Outline

- *Chapter 1:* Presents an introduction that provides the context for the motivation and objectives of this project.
- *Chapter 2:* Presents the overview of the system on which this project is based, including the model requirements and the conditions under which the system is tested.
- *Chapter 3:* Presents and explains the two subsystems that make up the wind farm model under study, necessary to simulate the wind farm shutdown.
- *Chapter 4:* Verify the correct operation of the model, by means of different tests that analyze each of the subsystems separately.
- *Chapter 5:* Presents and proposes several operational strategies for the control and coordination of a wind farm shutdown.
- *Chapter 6:* Presents the simulation results belonging to the implemented shutdown strategies in the wind farm model.
- *Chapter 7:* Contains the conclusions drawn from the study and proposes future works.

Chapter 2

System Definition

This chapter introduces the reader to the system on which this project is based.
The requirements necessary to build the model are presented, as well as the conditions under which the system is tested. The following sections cover the basics prior to the development of the wind farm model.

2.1 Wind Farm Layout

As this project is motivated by the growing extreme wind conditions in the North Sea, the wind farm model proposed in this project is based on the actual one, Horns Rev I, located on the west coast of Denmark. This park, established in 2002 as part of the Danish government's offshore wind energy initiative, was the first offshore wind farm in the North Sea to be built [15]. Figure 2.1 shows where the WF is located, about 20 kilometers off the coast of Denmark.

Figure 2.1. Horns Rev I WF location [15].

With a power capacity of 160 MW, it consists of a total of 80 variable-pitch variable-speed Vestas V80/2MW wind turbines [16]. As shown in figure 2.2, the wind turbines are set up in a regular array of 8 by 10 WT, where the vertical rows are referred to as columns from 1 to 10, and the horizontal rows from A to H [17].
It can be seen that each wind turbine is separated from the others by a certain distance, usually measured in rotor diameters. Each column forms a 16 MW feeder -8 WTs-, and each feeder is connected to the offshore transformer of 33/150 kV [15].

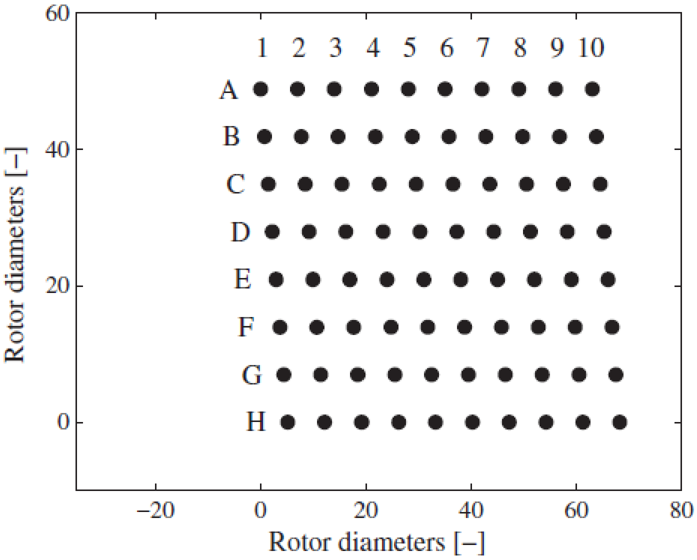


Figure 2.2. Layout of the Horns Rev I offshore WF [17].

As the purpose of this thesis is to incite the wind farm to shut down and evaluate how this process can be coordinated, it would not be necessary to model the entire park, as a single row would be sufficient to capture the strategy. Thus, the first line of the park will be simulated and will serve as the basis for this study, i.e wind turbines A_1-H_1. The proposed layout of the electrical diagram to be modeled is shown in figure 2.3.

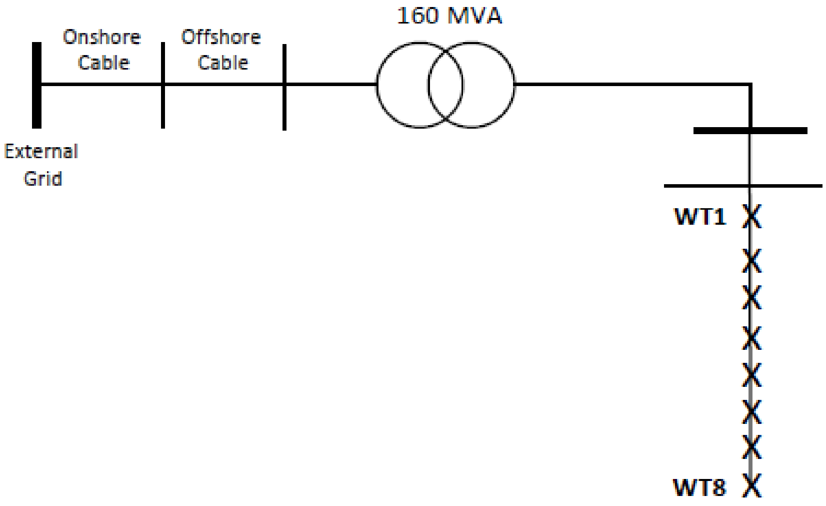


Figure 2.3. Single line diagram of the WF to be modeled.

2.2 System Requirements

This section aims to highlight the essential requirements that must be considered during the model development. To achieve this, the first step is to identify the diverse categories that wind power plants can be classified into.

Four categories of wind power plants can be distinguished by their nominal power capacity and voltage magnitude at the *Point of Connection* POC. According to the technical regulation for wind power plants above 11 kW [18] these categories are as follows:

- A2: Comprising of plants with power output greater than 11 kW and less than or equal to 50 kW.
- B: Comprising of plants with power output greater than 50 kW and less than or equal to 1.5 MW.
- C: Comprising of plants with power output greater than 1.5 MW and less than or equal to 25 MW.
- D: Comprising of plants with power output greater than 25 MW or connected to a voltage level exceeding 100 kV.

Given that Horns Rev I has a capacity rating of 160 MW, it is only necessary to consider the requirements relevant to wind power plants type D during the modeling process.

2.2.1 Active power constraint functions

To avoid instabilities or disturbances in the utility grid during operation or shutdown, the WF must be equipped with constraint functions, i.e. active power control functions.
The following functions are essential to ensure grid stability and reliability [18]:

Absolute power constraint

An absolute power constraint is employed to restrict the active power from the WF within a defined maximum power limit at the POC, to avoid overloading in critical situations. If there is a need to change the parameter for the absolute power constraint, the control must begin within two seconds of receiving the order and must be completed within 10 seconds.

Delta power constraint

The delta power constraint is used to limit the active power of the WF in proportion to the available active power to maintain a constant value. If the delta power constraint parameter needs to be changed, the control must start within two seconds after receipt of the command and be completed within 10 seconds.

Ramp rate constraint

The ramp rate constraint limits the maximum rate of change of active power when changes in wind speed, e.g. sudden gusts that would soar the power. Therefore, this constraint aims to prevent negative impacts on the grid stability caused by power fluctuations.

If the active power ramp rate constraint parameter needs to be changed, the control process must start within two seconds of receiving the command and be completed within 10 seconds. The implementation of this limitation in the model is highly significant, where the standard maximum value of 100 kW/s for the ramp rate, outlined in [18], will be used.

2.2.2 Voltage deviations

It is also important to consider the voltage requirements when modeling a wind farm connected to the external grid, as the voltage level of the power system must be maintained within acceptable limits to ensure an stable and reliable operation.

The voltage level of a wind power plant at the *Point of Common Coupling* (PCC) and POC is determined by the *Transmission System Operator* (TSO), and it must be within the voltage limits specified in the technical regulations [18]. Depending on the location, the normal operating voltage may vary, and the electricity supply undertaking must communicate this value as nominal voltage Uc to the wind power plant.

According to the grid codes, the permissible range of normal operating voltage for the connection point allows a deviation of ±10% of the nominal voltage. However, for the point of common coupling (PCC), the voltage deviation is limited to ±2.5% of Uc.

Deviations from the prescribed limits may result in voltage instability, equipment damage, and blackouts. Several factors, such as load demand, system impedance, and wind farm power output, can affect the voltage level. Therefore, although this project does not focus on grid voltage control, it must ensure that the developed model of the wind farm and the control strategies used do not adversely affect the external grid and respect the limits established in the grid codes.

2.3 Test Cases

Different wind profiles can have a significant effect on the energy output of a wind farm, which is why it is important to have access to several wind profiles that accurately reflect real conditions.

In this regard, real wind data from the summer period from Horns Rev I are available and will be used in the first place in order to validate the normal operation of the model.
Later on, since the purpose is to lead the wind farm to a shutdown due to extreme wind conditions, a high wind speed profile that exceeds the operating limits of the wind turbines will be used to feed the model.

2.3.1 Horns Rev I Wind Profile

24 hours of wind data are available from the 11th of July 2016 with a sample time of 2 minutes. Anemometer data are available for each of the wind turbines, therefore the application of *Hellmann exponential law* [19] to extrapolate the wind speed reading from the mast to the height and distance of the nacelle is not necessary.

For simplicity, and because this wind profile will be used simply to verify the correct operation of the model, the same profile will serve as input to every WT in the model, although it could be possible to calculate how the wind affects each wind turbine differently depending on its location in the park.

Figure 2.4 shows the data set covering the entire day, from which the time interval corresponding to the initial three hours is used for the simulation. The data reveal that wind speeds ranged from 7 to 15 m/s throughout the day, which corresponds to a low wind profile.

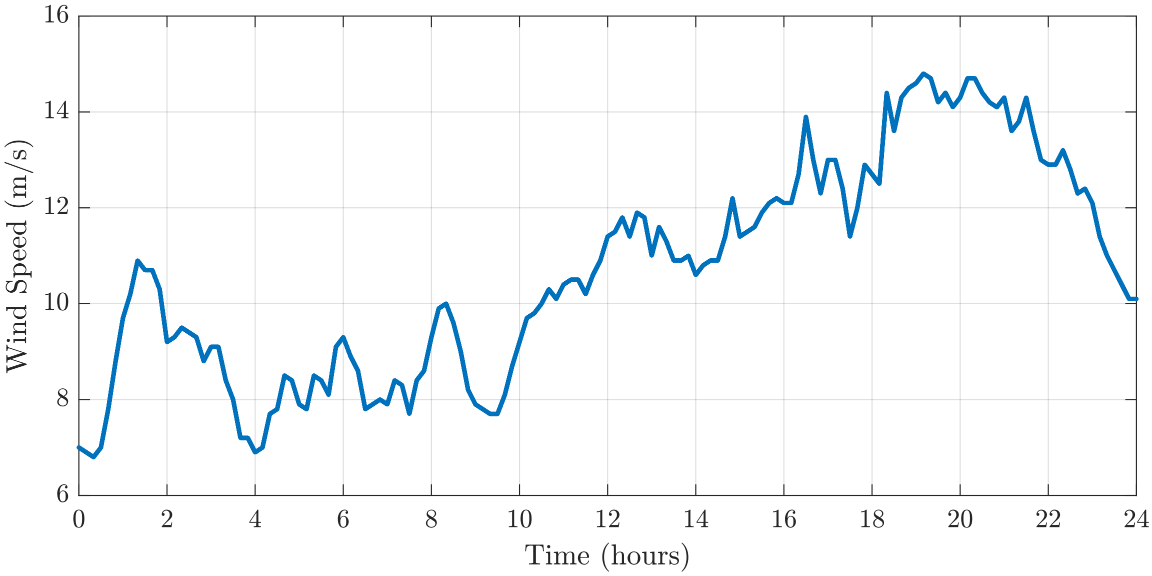


Figure 2.4. Horns Rev I wind profile.

Since the sample time of 2 minutes can not be reduced, in order to obtain a more realistic wind profile, these data will be processed using a wind model before being fed into the WF model. In this way, a more fluctuating wind profile is generated that better reflects reality. This wind model is in the public domain and can be found at [20].

2.3.2 High Wind Profile

The objective of using a high wind profile is to lead the wind turbines to shut down. In order to accomplish this task, it is imperative to know the circumstances that result in the shutdown of a wind turbine. As mentioned in the SoA 1.2, the cut-off limit is typically established at 25 m/s, and according to the SST, shutdown and startup procedures are only activated considering the 10-min average measurements, in order to prevent frequent shutdowns and restarts in the WF.

Since no actual extreme wind data is available, the following wind profile has been generated by scaling other lower wind profiles. In this way, it is intended to simulate the sequences of standard operation, shutdown, and startup in a relatively short time of 9000 seconds. To do this, the wind speed has been first raised to exceed the cut-off limit and cause a shutdown. Then, the speed has been significantly decreased to bring the turbine back to standard operation, as shown in the figure.

Up to 3 hours of data with a sample time of 10 seconds will be simulated, during which time the rotor wind speed will exceed several times the cut-off limit of 25 m/s, as can be seen in figure 2.5. In orange, the 10-minute moving average measurement is depicted and will be used to trigger the shutdown and startup procedures.

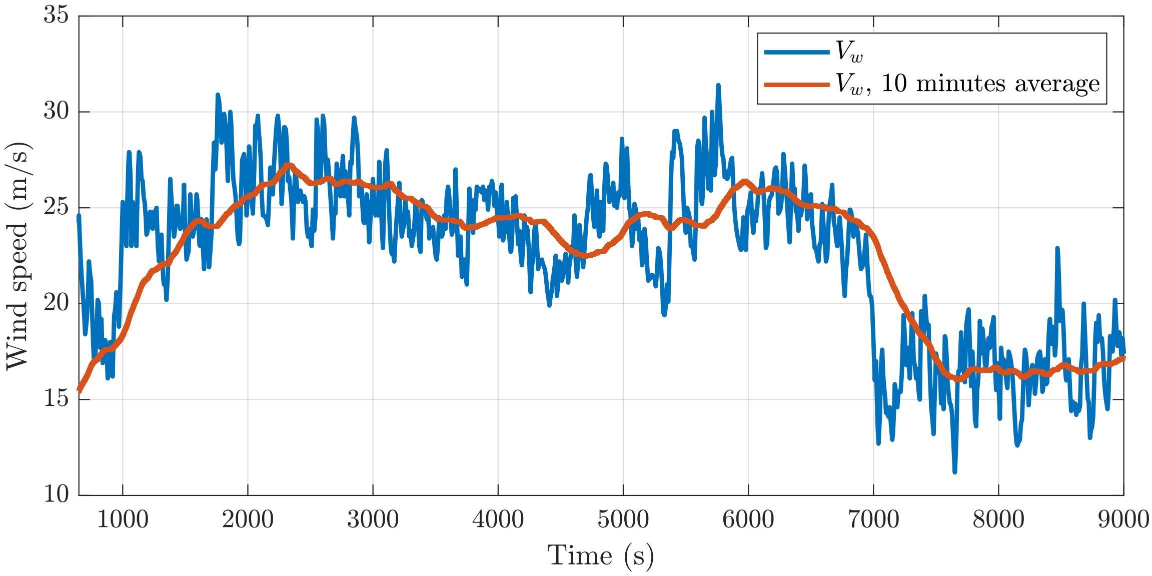


Figure 2.5. High wind profile.

This wind profile will subsequently be used as a reference to feeding the wind farm model for the purpose of developing and testing the various proposed shutdown strategies. Additionally, it will be used to verify the model response and performance in high wind conditions.

2.3.3 Wind Gusts Profile

According to the definition of *extreme wind conditions* given by the IEC International Electrotechnical Commission standard [21], these are defined as wind speeds of short duration and loads that result from significant variations in wind direction and vertical shear.

The maximum wind speed that a wind turbine can withstand over 3 seconds with a recurrence period of 50 years is calculated in 2.1 given the height and hub height of 80 meters for Horns Rev I wind turbines. Considering also the highest average cut-off wind speed of 25 m/s, Horns Rev turbines should be shut down any time the wind gusts reach 35 m/s.

$$V_{e50} = 1.4 \cdot V_{ref} \cdot \left(\frac{z}{z_{hub}}\right)^{0.11} = 1.4 \cdot 25m/s \cdot \left(\frac{80m}{80m}\right)^{0.11} = 35m/s \tag{2.1}$$

According to 2.1, a wind gusts profile has been created with the objective of showing in a relatively short period of time numerous gusts that would cause the wind farm to shut down. In this way and together with the two previous profiles, the shutdown strategy to be developed will contemplate several possible test cases.

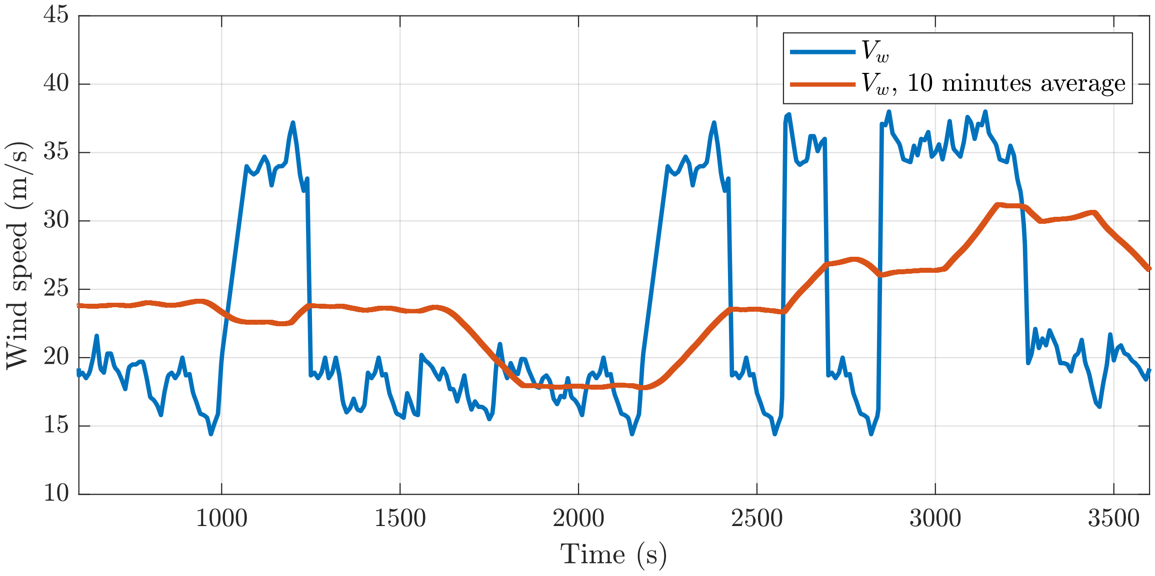


Figure 2.6. Wind gusts profile.

2.4 Summary

This chapter provides an overview of the Horns Rev I wind farm and the system that will be used. Relevant Danish grid codes that need to be taken into account during the modeling are discussed. Furthermore, three wind profiles created to test the model performance during normal operation and to assess the effectiveness of the shutdown strategy are presented.

Chapter 3

Wind Farm Model

This chapter presents and explains the two subsystems that make up the wind farm model, i.e. the wind turbine models and the external grid model. These elements are necessary to study and simulate the wind farm shutdown, and their explanation aims to provide a better understanding of how to create an accurate model for simulating the wind farm operation.

3.1 Wind Turbine Model

A simplified WT public model developed by Aalborg University is used to build the wind farm model according to the layout of Horns Rev I. This WT model [22], provides a simple yet accurate approach to capture wind speed fluctuations in active power output, and alterations in active and reactive power; while reflecting the dynamics of Type III and Type IV wind turbine generators.

The advantage of using a simplified model is that allows the system to be simulated in a reasonable period of time without increasing unnecessary the computational burden of the model, which in the case of an 8-turbine wind farm model is very useful.
Additionally, it is not always possible to obtain the specific data required for all physical and control systems of a wind turbine generator. Therefore, simpler performance models based on open data sheets such as the one proposed, provide a solution to this problem.

The main blocks comprising the wind turbine model are represented in a simplified form in figure 3.1. While the measured wind speed V_{wind} and power references P_{ref} and Q_{ref} are the inputs, the available active power P_{ava} and generated powers P_{out} and Q_{out} are the obtained outputs.

In the rotor inertia effect block, a first-order low-pass filter with transfer function shown in equation 3.1 replaces the mechanical damping of the WT, where the rotor inertia smoothes the wind fluctuations transmitted to the system. The time constant τ used for smoothing the wind speed is obtained in equation 3.2 with the rated speed v_{rated}, the measured wind speed v_{wind}, and the natural time constant τ_0, i.e. the time it takes for the wind turbine to achieve its rated speed from standstill.

$$G(s) = \frac{1}{1 + s\tau} \tag{3.1}$$

$$\tau = \tau_0 \cdot \frac{v_{rated}}{v_{wind}} \tag{3.2}$$

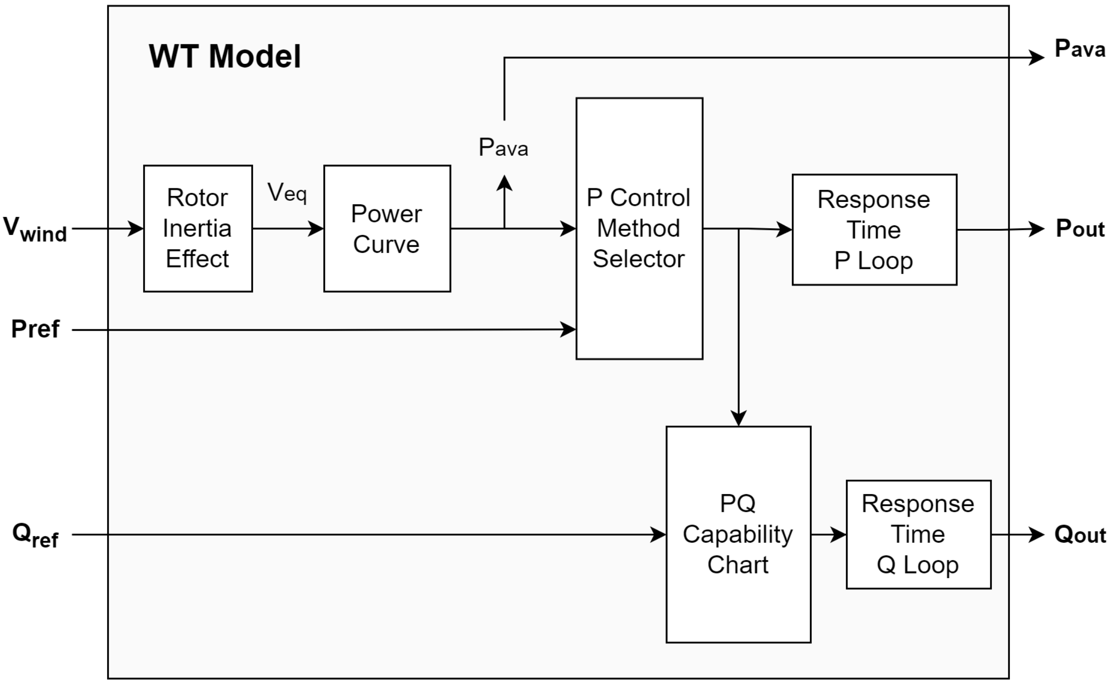


Figure 3.1. WT model, adapted from [22].

The equivalent wind speed value obtained from the smoothing effect is then interpolated on the power curve through a lookup table, giving the available power P_{ava}.

The parameters from the lookup table that form the power curve are represented in figure 3.2, where it can be seen that for wind speeds under the cut-in limit of 4 m/s and higher than the cut-off limit of 25, i.e. region 1 and 4 respectively, the WT does not produce any power.

On the other hand, in Region 2, i.e. from the cut-in limit until the rated speed, the available power is calculated according to the theoretical power shown in equation 3.3, which depends on the air density ρ, power coefficient -function of pitch angle (θ) and tip speed ratio (λ)-, blades swept area and wind speed cubed.

$$P_{ava} = \frac{1}{2} \cdot \rho \cdot Cp(\lambda, \theta) \cdot \pi R^2 \cdot V_{wind}^3 \tag{3.3}$$

While in region 2 the aim is to maximize the power output, in region 3 the wind turbine adjusts the pitch angle and mechanical torque in order to limit the power and keep the rated value, 1 pu in figure 3.2.

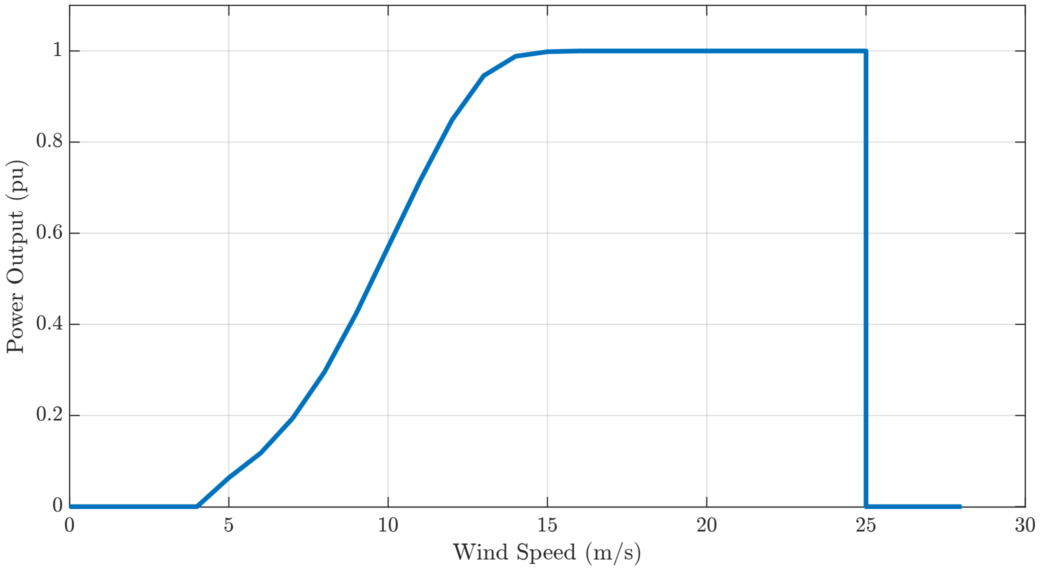


Figure 3.2. WT model power curve.

Thus, depending on which power region the wind turbine is operating, the P control method selector block selects the active power control for the WT, either injecting all P_{ava} in the grid or the maximum limit P_{ref} of 1 pu. The model also incorporates a PQ chart feature, that relates to the P over Q ratio of the WT system.

Finally, the time response for injecting active and reactive power into the POC by the wind turbine considers the internal control loops for both active and reactive power, with transfer functions shown below.

$$\frac{1}{1+s\tau_P} \tag{3.4}$$

$$\frac{1}{1+s\tau_Q} \tag{3.5}$$

3.2 External Grid Model

The external grid model is modeled as a MATLAB function block in Simulink. This model contains the layout of the park, represented in figure 3.3. The single line diagram consists of 11 buses, which are highlighted in red in the figure.

Bus number one serves as the slack bus to represent the external grid, while bus number 2 serves as the PCC, and bus number 3 represents the POC. All the buses, except for the slack bus, are modeled as PQ loads, with both active and reactive power known as variables.

As previously mentioned, the current model only contains wind turbine models for the first feeder of the wind farm. However, the remaining generation units are included as an additional PQ source, which is connected to bus 3. This approach enables the model to reflect the overall load of the park without increasing the computational burden.

The grid model block operates based on several inputs, including the reference voltage of the external grid -set at 1 pu-, the apparent power generated by the wind turbines, and two crucial grid parameters: the short circuit ratio SCR and the XR ratio. In this case, the parameters are set to 7 and 5, respectively, to represent a stiff grid [23]. The model includes the primary characteristics of the transformer, as well as medium voltage cable calculations.

The outcome of these calculations is a detailed voltage profile for every point along the transmission line. This data is particularly valuable for the purpose of verification and comparison, as it allows for effective analysis of the wind farm model and the different strategies applied to it.

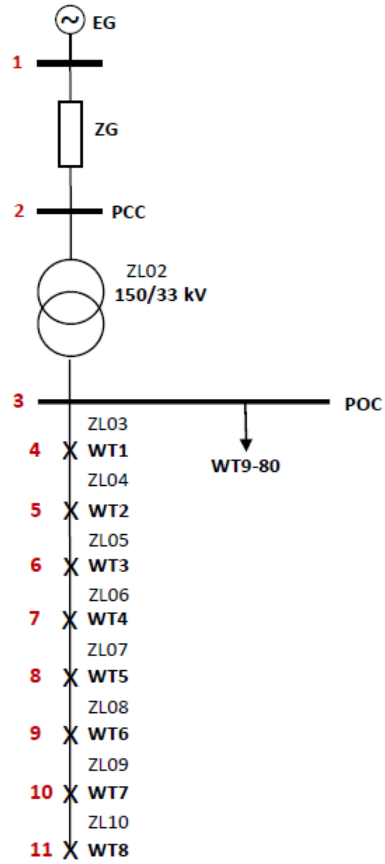


Figure 3.3. Single line diagram of the WF model.

3.3 Summary

The two subsystems that form the wind farm model are presented. A simplified public wind turbine model developed by Aalborg University is used for the wind turbine model. The second subsystem refers to the external grid model, which includes the wind farm layout and is based on an arrangement of 11 buses. The model provides a detailed voltage profile for each point along the transmission line, useful for verifying the wind farm model and the different shutdown strategies applied to it.

Chapter 4

Verification of the model

The following chapter aims to verify the correct operation of the model, by means of different tests that analyze each of the subsystems separately. In this way, it is possible to confirm whether the model as a whole has the essential characteristics to ensure an accurate simulation and; therefore, the reliability of the conclusions drawn from the simulations can be valid.

4.1 Wind Turbine model

In order to verify the wind turbine model explained in the previous chapter, it has been decided to compare it with the very famous NREL offshore 5-MW baseline wind turbine model from Aeolus SimWindFarm Toolbox. This model of a conventional three-bladed upwind variable-speed variable-pitch wind turbine has been developed by the National Renewable Energy Laboratory [24] and is considered a reference by research teams around the world to standardize baseline offshore wind turbines.

The NREL model can be found in the public domain [25] and contains all the aerodynamics and mechanical parameters as well as a 1st-order pitch actuator. Therefore, it is suitable for testing whether the simplified model used still captures the same dynamics of the NREL.

The objective is to find out how the models will respond to the entire wind speed range if they have the same dynamic performance. For this purpose, both models are fed with the same step signal input, with the idea to compare how long it takes to reach the new steady state at a given time.

Figure 4.1 shows the power response in per unit values for the step input signal applied. Starting at 0, it can be seen that the power is increasing in small increments where it is reaching the steady-state intermediate points.

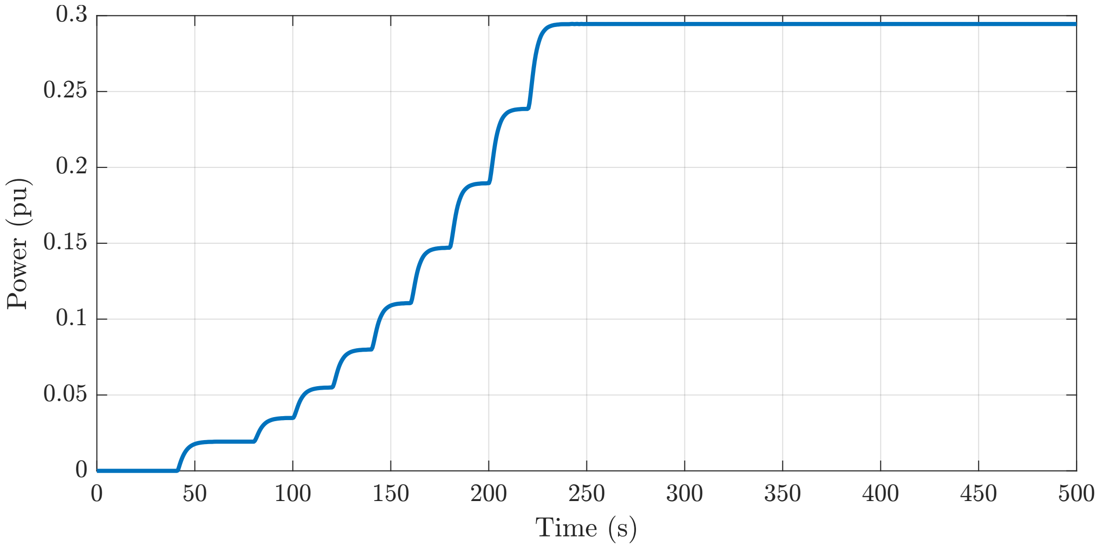


Figure 4.1. NREL system response to unit step input.

Looking at the graph, every increment can resemble a first-order system output for step input signal, where according to control theory, the gain k, i.e. the final value that the response reaches, is the nominal power of the wind turbine.

By calculating the *Relative Error* (RE), it can be measured how accurate the simplified model is, compared to the 'true value', i.e. the NREL model.

$$\text{RE} = 1 - \frac{\text{Simplified model}}{\text{NREL model}} \cdot 100\% \tag{4.1}$$

An RE of 9% has been obtained from equation 4.1. Therefore, the simplified model shows 91 % of accuracy when compared to the benchmark model. This is a significant but an acceptable difference.

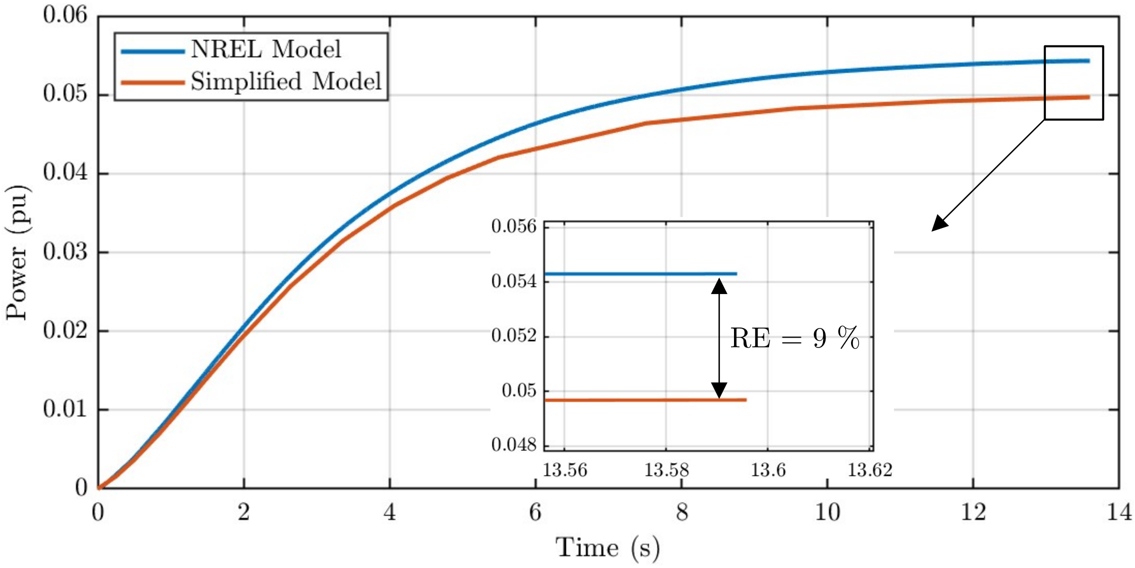


Figure 4.2. Time response comparison.

4.2 Wind Farm Model

To verify the proper operation of the wind farm model as a whole, i.e. the wind turbine model and the grid model, it must be ensured that its operation does not disturb the voltage at any point in the system. Incorporating the voltage requirements into the model allows an accurate assessment of the impact of the wind farm on the power system and helps to ensure safe and effective operation within the power grid.

According to the grid codes [18], the normal operating voltage range established for the point of connection permits a ±10% deviation from the rated voltage (Uc).
However, for the purpose of the point of common coupling (PCC), the voltage deviation is limited to ±2.5% of Uc.

Knowing that the voltage on the slack bus, representing the external power grid, operates at 1 per unit voltage; the following table outlines the maximum and minimum allowable voltage values for both POC and PCC buses.

Table 4.1. Voltage deviations allowed in the model.

Bus	Voltage range	Minimum Voltage (pu)	Maximum Voltage (pu)
PCC	Uc ±2.5%	0.975	1.025
POC	Uc ±10%	0.900	1.100

Subsequently, the voltage level at each of the 11 buses within the system will be measured in accordance with the limiting values specified for PCC and POC, first under normal conditions and then under high wind conditions.

4.2.1 Normal operating conditions

Figure 4.3 shows the voltages along the feeder when the wind farm is running in normal operation. For this case, the wind profile from the actual measurements of the Horns Rev wind turbines given in section 2.3.1 is fed into the model. The objective is to test that in normal conditions, the model works properly and in accordance with the voltage limits established by the grid codes stated in section 2.2.

It is known that when the wind is low, the available power and therefore the active power generated by the wind turbines is small, which keeps system voltages close to 1 pu.
As shown in the legend of Figure 4.3, the voltage levels of each bus of the system are represented, starting at the PCC and ending at bus 11, where WT8 is connected.

It can be seen that the further it goes into the buses along the feeder, the higher the voltage is. At the same time, the wind turbines closer to the POC have a lower per-unit voltage than those further away. This is in line with the expected outcome as the wind turbines introduce power into the grid, leading to a higher voltage level in order to achieve 1 pu voltage at the slack bus, due to the line losses.

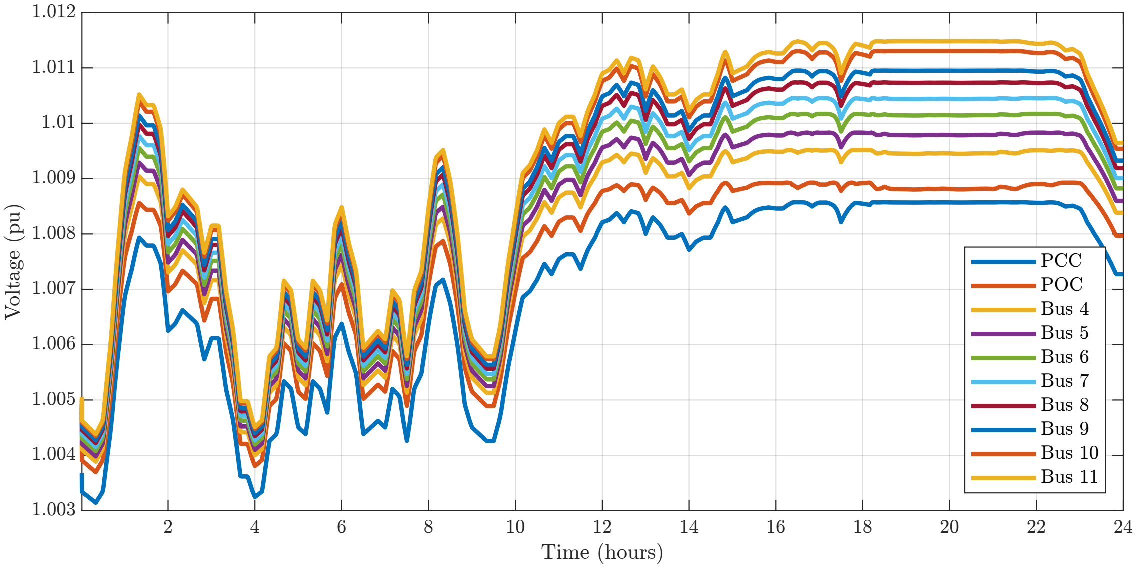


Figure 4.3. Voltage levels for normal operating conditions.

According to the graph, the voltage levels during the day are oscillating between 1.003 and 1.012 pu. Therefore, at no point in the system are the voltage levels stipulated by the grid codes exceeded. It can be assured that the model operates properly under normal wind conditions.

4.2.2 High wind conditions

The model is now tested with the high wind speed profile from 2.3.2. As explained before, wind speeds of these magnitudes lead to the shutdown of the wind farm. However, figure 4.5 show the voltages before applying any shutdown strategy to the model, to better understand the possible implications of high wind conditions on the model and the system.

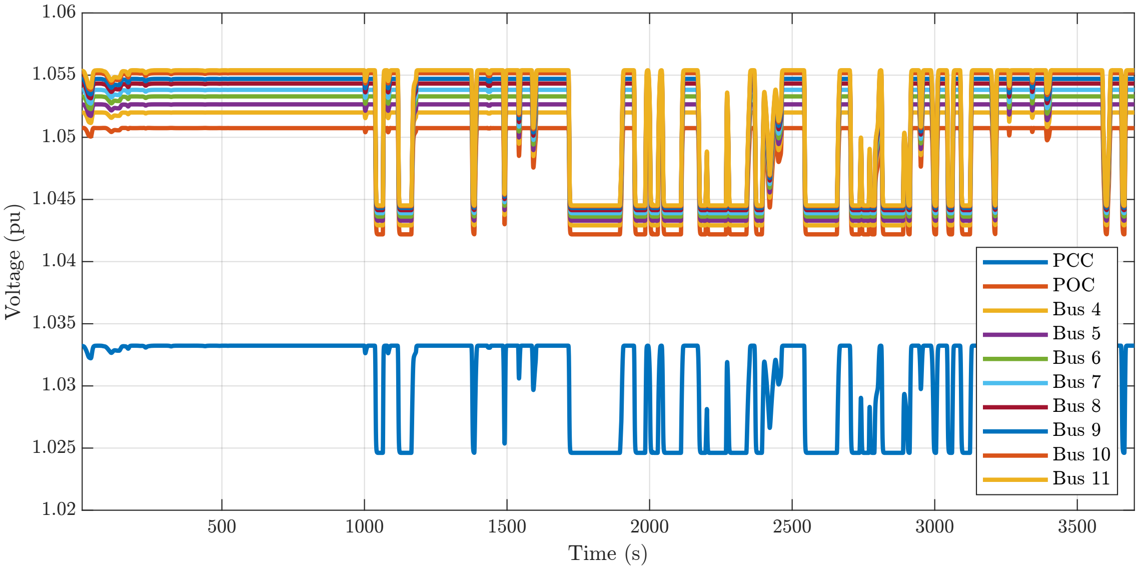


Figure 4.4. Voltage levels for high wind conditions.

As figure 2.5 from this profile shows, the wind is exceeding several times the cut-off limit of 25 m/s. Whenever this wind speed is entered into the WT model lookup table block -figure 3.1-, the corresponding power curve output gives an available power output of 0. As a result, the wind turbines shut down. Once the wind speed drops below this margin again, they start up, generating the rated power of 1 pu.

This repetitive pattern of sudden stops and subsequent restarts is very detrimental. Apart from generating additional stress to its components which increases the risk of mechanical failures, generates huge power losses, and negatively affects the voltage.

It can be seen in figure 4.5, that the voltage level in the PCC is only within the limits -below 1.025- during those moments when the wind farm is disconnected. Moreover, these fluctuations can be easily propagated to neighboring areas, affecting the quality and stability of the voltage supplied to nearby consumers.

4.2.3 Wind Gusts conditions

When the gust profile from section 2.3.3 is fed into the model, the same voltage response can be observed as with the other high wind profile. The PCC voltage is only within the limits at times when the wind farm is not operating.

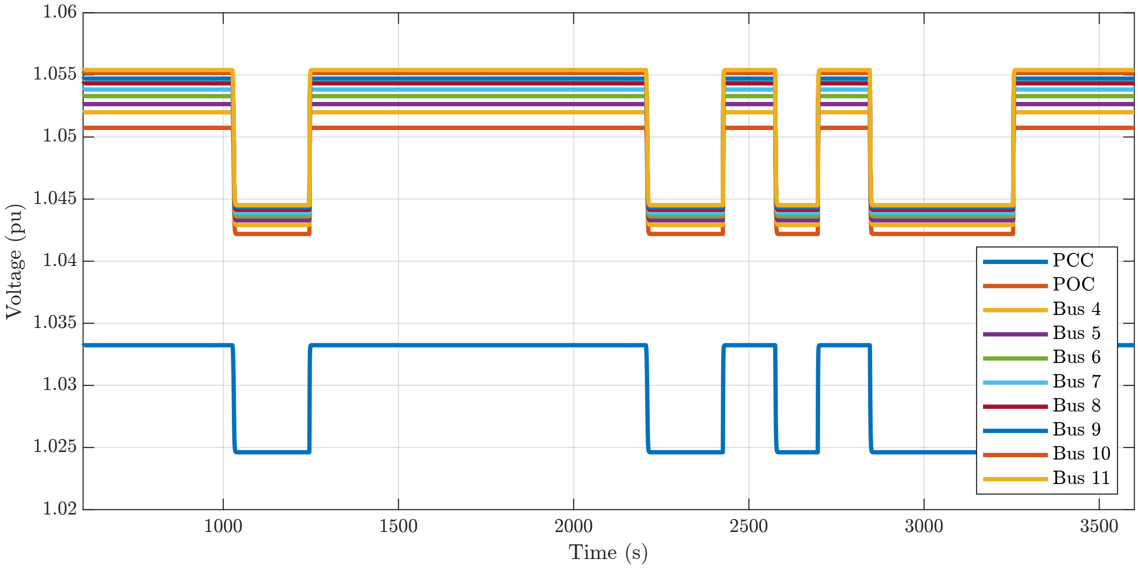


Figure 4.5. Voltage levels for wind gusts conditions.

Overall, it is evident that a storm control strategy needs to be applied to this model since its performance with high wind profiles is not adequate.

4.3 Summary

The wind turbine model performance is compared to the NREL offshore 5 MW benchmark model. From the grid model, voltages from every bus are analyzed to determine when the permissible voltage limits are exceeded. The three test cases proposed in section 2.3 are used to evaluate the model under normal operating conditions and under extreme wind conditions.

Chapter 5

Proposed Strategies

This chapter presents and proposes several operational strategies for the control and coordination of a wind farm shutdown. First, the classical approach used in the industry is reviewed. The logic chosen for the shutdown control is then explained, followed by its implementation in the model. Furthermore, different shutdown coordination strategies are proposed.

5.1 Classical Procedure

According to the literature, pitch-regulated, variable-speed wind turbines brake the rotor by pitching the blades. This process involves braking the rotor by adjusting the angle of the blades [21], [26]. The control operation relies on two different but interconnected systems: a *generator torque controller*, and a *collective blade pitch controller*.

In the event of a shutdown, two critical instructions are issued to the controller. First, the generator torque must be set to *zero*. This is important because it cuts off the power production. Second, the blade pitch angle must be adjusted to aerodynamically brake the turbine. This is achieved by setting the blades to their maximum inclination angle, typically *90°*. This adjustment sets the blade in a position nearly perpendicular to the wind, which causes the blades to catch less wind, slow down and eventually stop turbine rotation.

The torque and pitch controllers continuously communicate with each other and the overall turbine control system, as the pitch controller is enabled by the torque controller according to the power demand. When the rotor speed has decreased substantially after pitching the blades and when the torque is minimized, it may be necessary to apply mechanical brakes to bring the rotor rotation to a complete stop.

The yaw control system is also involved in the shutdown procedure. By adjusting the turbine orientation and moving it away from the wind direction axis, it also effectively reduces tower loads and mechanical damage.

As the model used in this project lacks an aerodynamic system, including parameters such as pitch angle or generator torque, a simpler approach is employed. The objective is to disconnect the wind turbines by setting the active and reactive power output to zero.

After reviewing the various shutdown strategies outlined in section 1.2, the aim is to select a strategy that shuts down the wind turbines only when absolutely necessary. This strategy should minimize continuous shutdowns and restarts while avoiding abrupt processes.

5.2 Shutdown Control Logic

According to the specifications of the V80/2MW, as well as for most wind turbines, the cut-off limit of 25 m/s will be the threshold value for initiating the shutdown. After the turbine has been shut down, as explained in 2.3.2, it should not be immediately restarted just below the cut-off limit. If the turbine were to activate every time the wind speed falls below the cut-out limit or even below a lower value like 20 m/s, it would result in frequent restarts and stops, since the typical pattern of a high wind day is rapid and sharp changes.

For this reason, the shutdown procedure will only be triggered based on the 10-minute average data collection. This approach ensures that the turbine is not prematurely shut down due to temporary fluctuations in wind speed. However, there is one exception as per the standard mentioned in 2.3.3, which allows for shutdown in cases of wind gusts reaching up to 35 m/s. These gusts are measured on a per-second basis, providing an additional safety measure for the control system.

Therefore, the shutdown control will be implemented in the wind farm model using the following logical approach, as depicted in figure 5.1.

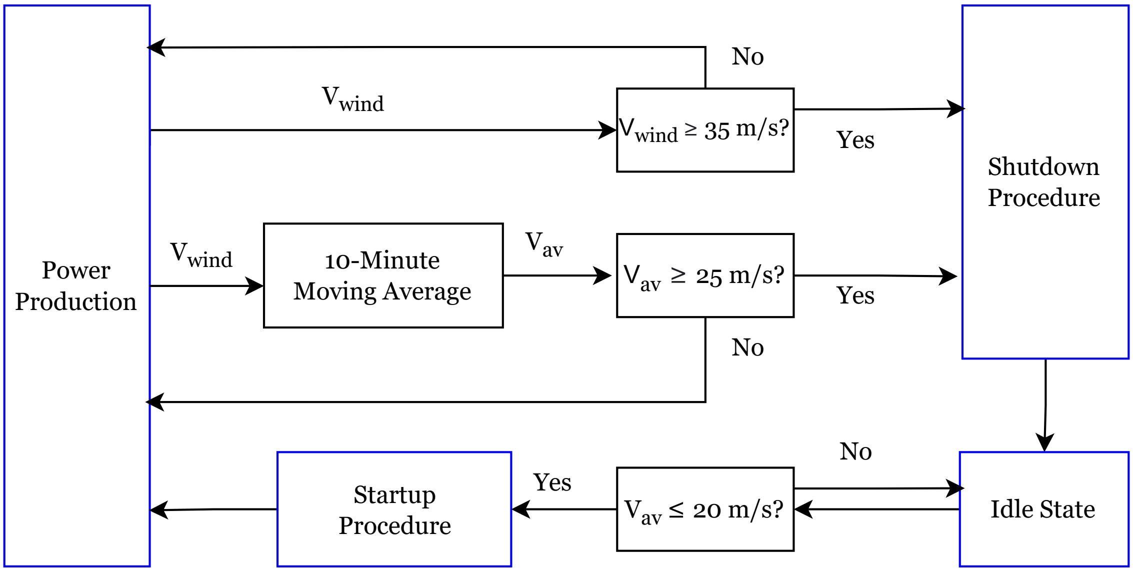


Figure 5.1. Shutdown control logic flowchart.

5.3 Shutdown Control Implementation

The previously proposed shutdown *Control Logic* has been implemented in the Simulink model as a MATLAB function together with a second block *Sequential Groupwise Shutdown*. The interaction of the two blocks together forms the so called *Shutdown Control* implementation in this project and allows the model to operate and switch between the different operating modes of the turbines: *production, shutdown, idle state, and startup.*

Hereunder a brief explanation of how the model performance under each of these states is provided. Figure 5.2 represents the structure of the Simulink model with all its contents. The specific block of *Sequential Groupwise Shutdown*, belongs to the shutdown coordination section and will therefore be explained in the next section.

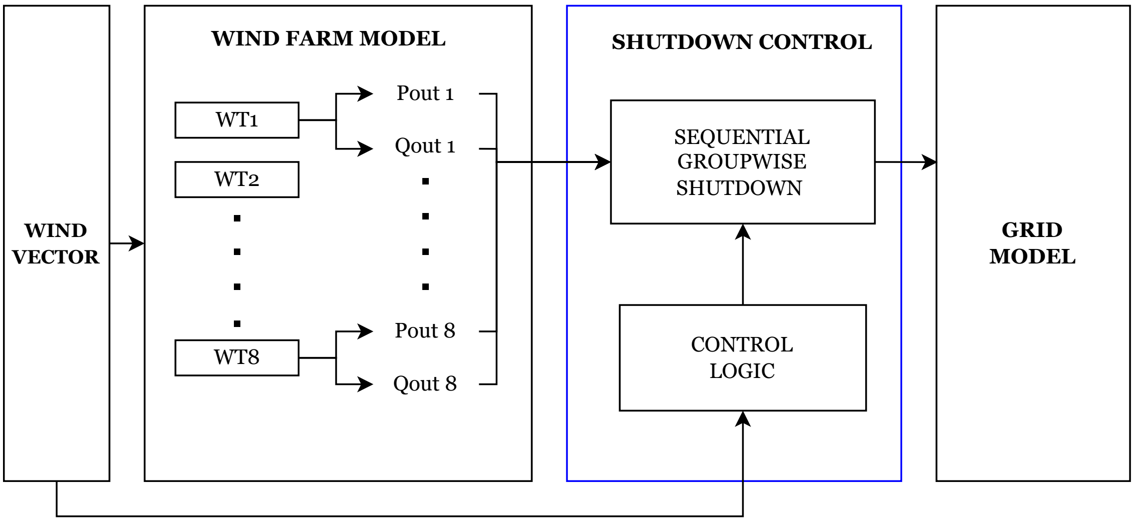


Figure 5.2. Shutdown control implementation flowchart.

Power production

The wind vector is feeding the wind farm model and the shutdown control block. When the model is operating under normal operation, i.e. for wind speeds below the safety margins, the wind turbines are producing and the sequential groupwise shutdown block is injecting the available apparent wind power into the grid model.

Shutdown procedure

The wind vector contains values that exceed the predetermined thresholds. The control logic block computes these values and triggers the shutdown procedure. The sequential groupwise shutdown block receives the command and coordinates the shutdown procedure for the whole wind farm as will be explained further in the next section.

In this state, the sequential groupwise shutdown block changes the reference power for each wind turbine to 0. Subsequently, a ramp rate is employed to progressively decrease the power output until it reaches 0.

Idle state

Once the power outputs are set to zero, there is no injection of active or reactive power into the grid. The wind turbines are completely shut down, indicating a full disconnection from the grid. This state represents the real stage where the turbine blades are pitched out of the wind, and the mechanical brake is applied to ensure their immobilization.

Startup post shutdown

Once the wind drops below the safety limits, the control logic block sends the order to start up, and the sequential groupwise shutdown block restores the reference power values. This allows the wind turbines to leave the idle state and start producing and injecting power into the grid. To ensure a smooth transition, a ramp limiter is also used to gradually increase the power output.

5.4 Performance Verification

Before implementing and developing the shutdown coordination, the shutdown logic is assessed to determine if the model effectively shuts down and starts the wind farm model as planned in 5.1 and required by the available high wind profiles.

High Wind Profile

According to the *Shutdown Control Logic* outlined in section 5.1, the model should be running in normal operation, producing the rated power of 1 pu; and when the controller detects either a 10-minute average wind speed of 25 m/s or a wind gust greater than 35 m/s, the shutdown process will be activated. Then, it will remain turned off until the 10-minute average wind speed decreases below 20 m/s. Then it is, according to the literature, considered safe to start up again.

This process is shown in figure 5.4, where it can be seen that the shutdown coordination procedure starts when the orange curve in figure 5.3 reaches 25 m/s, i.e. instant 1882 seconds. Then, the wind farm model remains in an idle state until the average wind speed decreases again below 20 m/s, -instant 7226 seconds in picture 5.3-.
The *Shutdown Control* operates as intended.

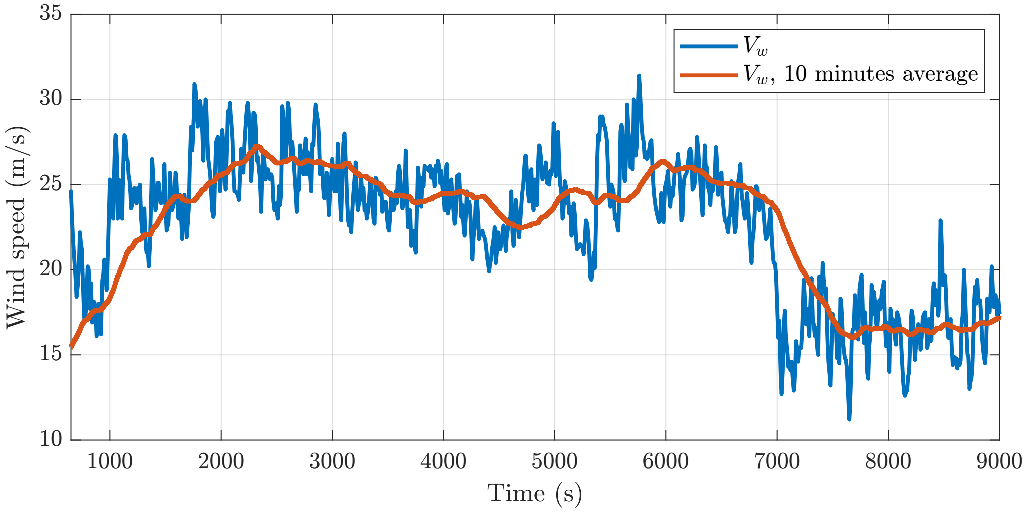


Figure 5.3. Wind Speed (m/s).

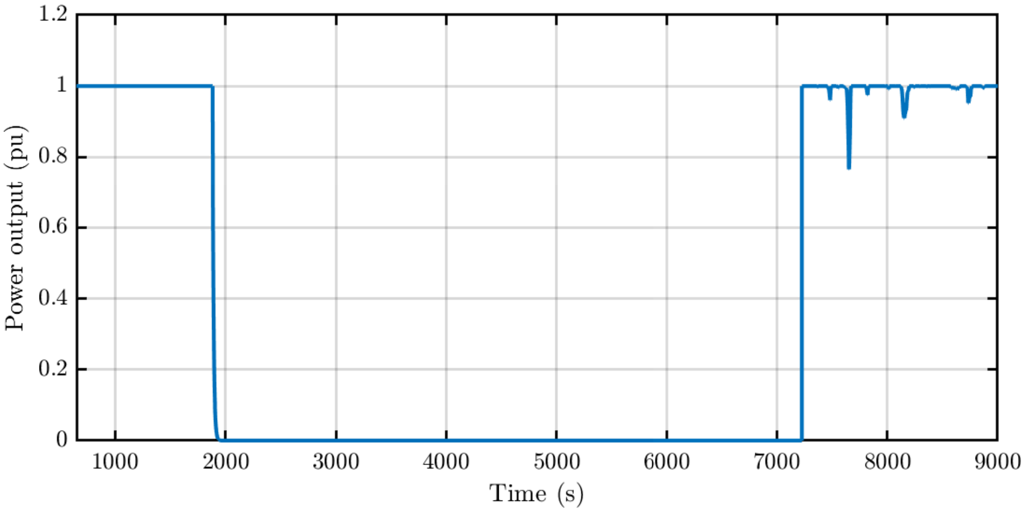


Figure 5.4. Power output (pu).

Wind Gusts Profile

The same strategy is now tested with the wind gust profile. The purpose of this profile is to assess whether the shutdown control also accounts for rapid wind variations.

It can be seen, that this time, the 10-minute average wind speed remains below the cut-off limit until the last part of the simulation. However, the wind vector contains high values that exceed the permissible threshold of 35m/s; therefore, the model should be shut down.

Figure 5.5 shows two shutdown actions that align correctly with the wind gusts profile. The first shutdown occurs when the wind initially crosses the 35 m/s threshold, at the first prominent blue peak. After the shutdown, the model remains in an idle state until the mean speed -represented by the orange curve- drops below 20 m/s, which does not occur again until the instant of 1760 seconds.

After that, there is one more shutdown during the next big peak, and the model remains disconnected until the end of the simulation because the mean wind does not fall below the safety threshold of 20 m/s again. The *Shutdown Control* also operates properly under the presence of rapid high wind gusts.

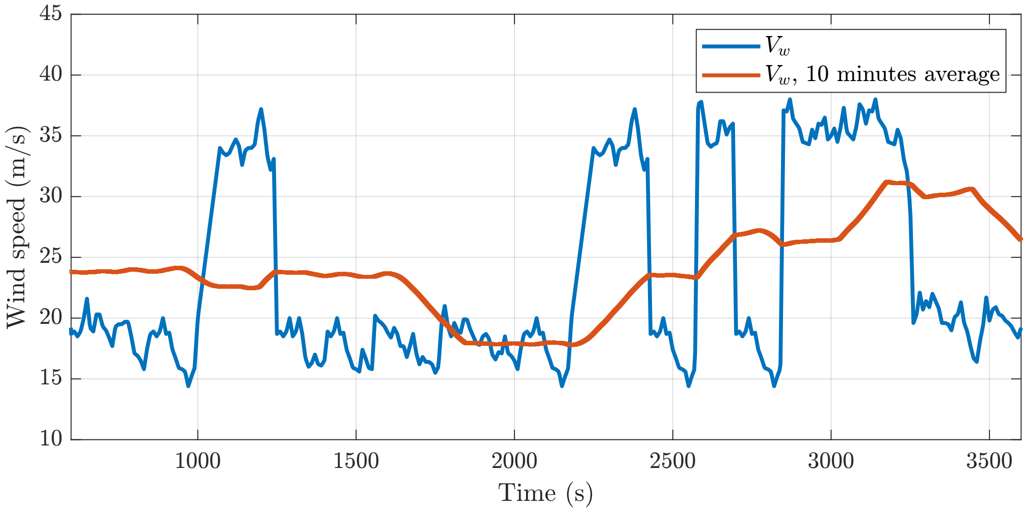


Figure 5.5. Wind Gusts profile.

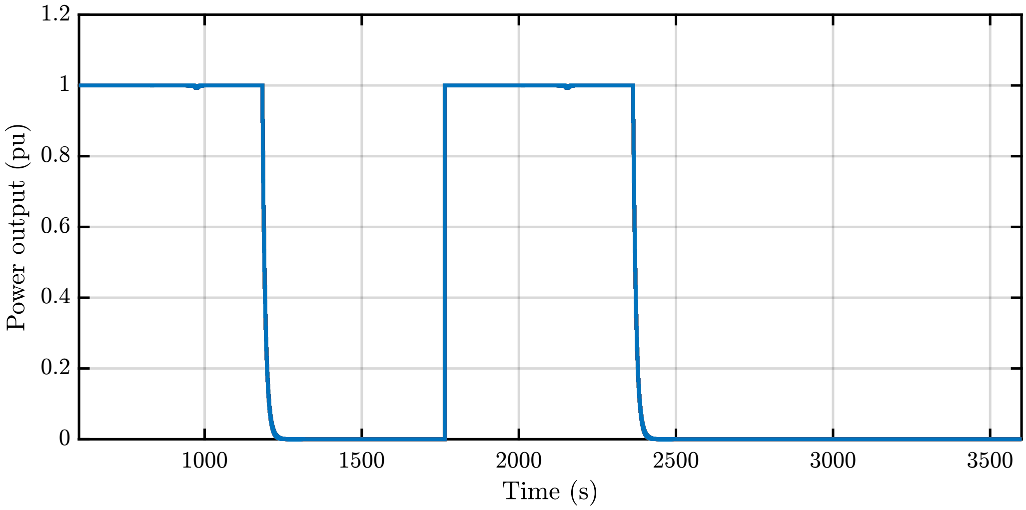


Figure 5.6. Power output (pu)

5.5 Shutdown Coordination

Once the shutdown logic is defined and correctly implemented in the model, the coordination of the shutdown process for the eight wind turbines that form the first feeder needs to be ensured. The objective of this coordination is, as far as possible, to avoid sudden drops in power production and to minimize negative impacts on grid stability.

A shutdown strategy often involves a coordinated sequence. The number of turbines that shut down depends on several factors. These may include the overall size of the wind farm, the WT capacity, the stability of the local power grid, and specific weather conditions at the time. Since the sequence to be followed in this particular case is unknown, different sequences will be proposed and compared with each other.

As explained in section 4.2, voltage levels will serve as a critical reference point in the decision making process for this project. By looking at the voltage, it will be possible to determine which shutdown strategy is the most appropriate and efficient to apply in this case study.

On the other hand, as explained in section 1.3 of the problem formulation, it is assumed that all wind turbines of the park are subjected to the same wind speed magnitudes. Therefore, situations in which wind eddies are affecting only some areas of the wind farm are not considered. All wind turbines are being fed with the same wind vector and need to be shut down.

The wind profile designated to test the different proposed coordination scenarios will be *High Wind Profile*, as outlined in 2.3.2. Specifically, the first hour of data will be simulated in order to observe the system response to the first shutdown, i.e. second 1882.

Sequential groupwise shutdown with controlled ramp down

This MATLAB function implements a sequential shutdown procedure for the whole wind farm according to a specific condition. In the shutdown process, a ramp rate is added, to control the ramp down instead of performing an abrupt disconnection.
The turbines are grouped -NT turbines at a time- and shut down one group at a time, beginning with the last group, i.e. the group furthest from the POC.

When a shutdown command is received from the *Control Logic* block, the function initiates the shutdown process starting from the last group of turbines. The power ramp down rate can be predefined, but according to the specifications of the model [27], the maximum ramp rates for external control of active and reactive power are 0.1 pu/sec and 20 pu/sec, respectively. Therefore, these are the maximum ramp rates that can be applied.

Once the shutdown process of a group of turbines has started, a timer starts counting the time elapsed since the start of the shutdown process. When the timer reaches a predefined time interval, the next group initiates its shutdown sequence, regardless of whether the previous group has fully completed its shutdown process.

This design choice arises from the understanding that it is not necessary to wait for the full shutdown of the previous group. By this stage, the power output and hence voltage from the earlier group would have significantly decreased, posing minimal risk to the grid and the turbines themselves.

Conversely, if the shutdown order is revoked before all groups reach a complete shutdown, -for example, due to the wind returning to safer levels- the function restores all variables to their original states. Consequently, the turbines revert to their initial states, effectively resuming power generation.

In summary, three parameters can be easily modified in the block code:

- *NT:* Number of turbines to form a shutdown group. Therefore, the number of turbines that shut down at a time.
- *Ramp Rate:* Power ramp down rate, reflected in the time it takes for a turbine to shut down.
- *Time Wait:* Time interval to wait before starting the shutdown process for the next group of turbines.

These three parameters control critical aspects of the shutdown process. By varying them, it is possible to create a wide set of scenarios that make it feasible to identify the most appropriate shutdown strategy for this model.

Two perspectives arise with this control, the grid perspective and the turbine perspective. From the grid perspective, it is beneficial to avoid big voltage drops and surges; therefore, an escalating shutdown strategy for the wind turbines is deemed desirable.
From the turbine safety perspective, delaying shutdowns may not be advantageous as it could potentially damage the turbines that are last in line to be shut down.

This project presents an electrical perspective, thus, mechanical loads or stress measurements are not considered. Furthermore, it is assumed that the turbines have a safety factor greater than one [28], which indicates they can endure loads greater than what they are realistically expected to handle.

Hence, the implemented strategy involves a time delay between each group shutdown, as opposed to initiating shutdowns simultaneously at varied ramp rates. To compensate this and minimize the waiting time for the last turbines to shut down, the maximum ramp rate of 0.1 pu/sec will be used for all the scenarios. This approach will bring forward all turbine shutdowns while avoiding large power and voltage drops in the grid.

5.6 Shutdown Test Cases

As mentioned, the maximum ramp rate will be implemented in every case. Four main scenarios have been proposed, where different *NT* shutdown groups are simulated. For each of these scenarios, different *Time Wait* values are considered. The results of these simulations will be analyzed in the next chapter with the intention of establishing the optimal shutdown strategy.

Table 5.1. Shutdown scenarios list.

Scenario	NT	Time Wait (sec)		
A	8	-	-	-
B	4	10	30	180
C	2	10	30	180
D	1	10	30	180

5.7 Summary

The shutdown control logic is only triggered based on the cut-off limit, using a 10-minute average data acquisition. This approach ensures that the turbines are not prematurely shut down due to temporary fluctuations in wind speed. The logic also allows for shutdown in the event of wind gusts of 35 m/s, providing an additional safety measure. The correct operation of the shutdown is checked prior to the development of the coordination strategy to avoid cascading failures.

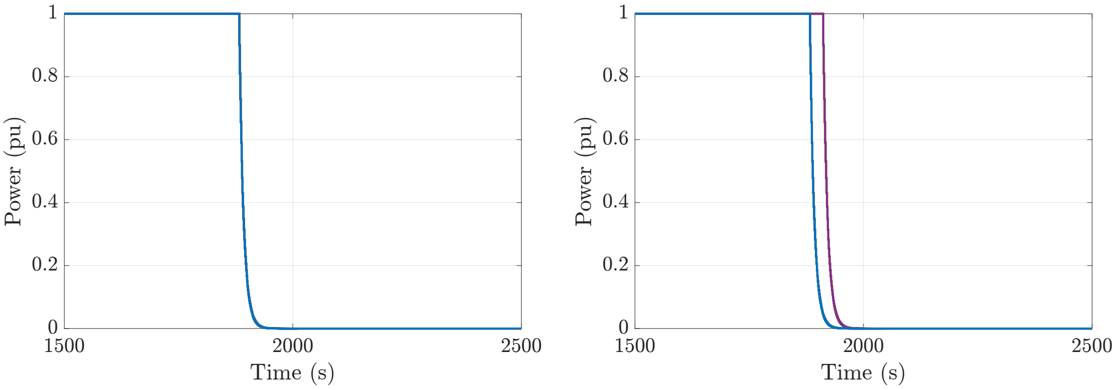
The implementation of the shutdown logic is done in the Simulink model using a MATLAB function, along with the Sequential Groupwise Shutdown block. This block is responsible for coordinating the shutdowns of the entire wind farm, ensuring a proper sequence, and avoiding abrupt drops in voltage and power production. Several shutdown test cases are presented and proposed by trying different NT shutdown groups and different Time Wait values to determine the optimal shutdown strategy.

Chapter 6

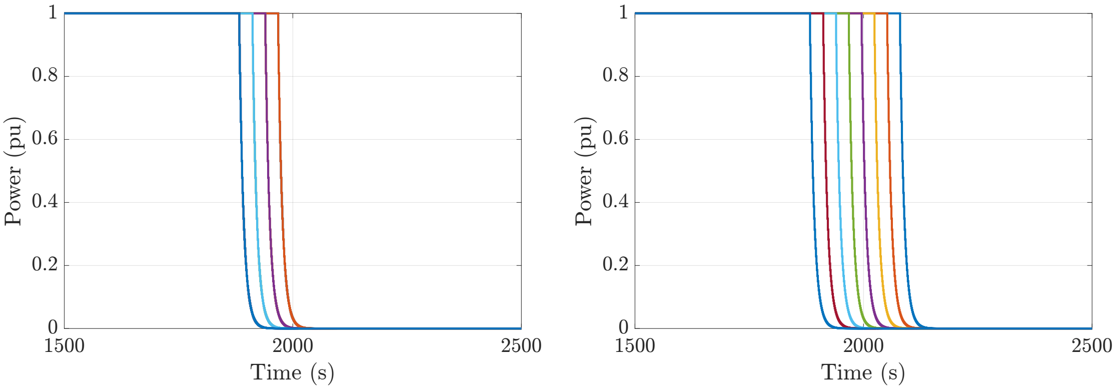
Simulation Results

The following chapter presents the simulation results belonging to the implemented shutdown strategies in the wind farm model. Power outputs and voltage levels are analyzed in order to select the ultimate shutdown strategy.
This strategy is then tested with both wind profiles introduced in chapter 2: the High Wind Profile 2.3.2 and the Wind Gusts Profile 2.3.3. This evaluation is carried out to determine whether the model appropriately shuts down and starts up as required.

6.1 Power output



(a) Scenario A ***(b)*** Scenario B



(c) Scenario C ***(d)*** Scenario D

Figure 6.1. Grouped shutdown, four NT combinations.

Figure 6.1 shows the shutdown procedure for the four scenarios under study. In this particular case, a time wait example of 30 seconds is implemented solely for the purpose of visualizing the operation of the different shutdown scenarios. The scenarios are labeled as *A, B, C,* and *D*, with the corresponding *NT* being 8, 4, 2, and 1, respectively.

It is important to note that the initial group of turbines to shut down always commences on the second of 1882, which is the precise instant when the moving average of the *High Wind Profile* 2.5 triggers the shutdown control. the power output gradually decreases until the wind turbines are disconnected, depending on the selected groups.

6.2 Voltage Levels

Hereafter, all the test cases proposed in table 5.6 are simulated, and the voltage responses are displayed to provide a comprehensive analysis. Each scenario *A, B, C, D*, is analyzed by three different *Time Waits*, which are presented in detail within each corresponding subsection.

6.2.1 Scenario A

The initial scenario under evaluation does not require a time wait since all wind turbines are simultaneously deactivated, eliminating the need for coordination. Figure 6.2 shows the voltage levels at each point of the feeder. It can be seen that after the shutdown, *PCC* voltage recovers within the permissible limits (0.975 - 1.025, table 4.1).

However, the abrupt voltage drop observed when the wind turbines are shut down is unfavorable for both internal connections and the external grid. This sudden voltage decrease can adversely affect the quality of the electrical power supply, among other detrimental effects. Thus, this scenario is discarded and will be skipped to analyze the rest of the scenarios.

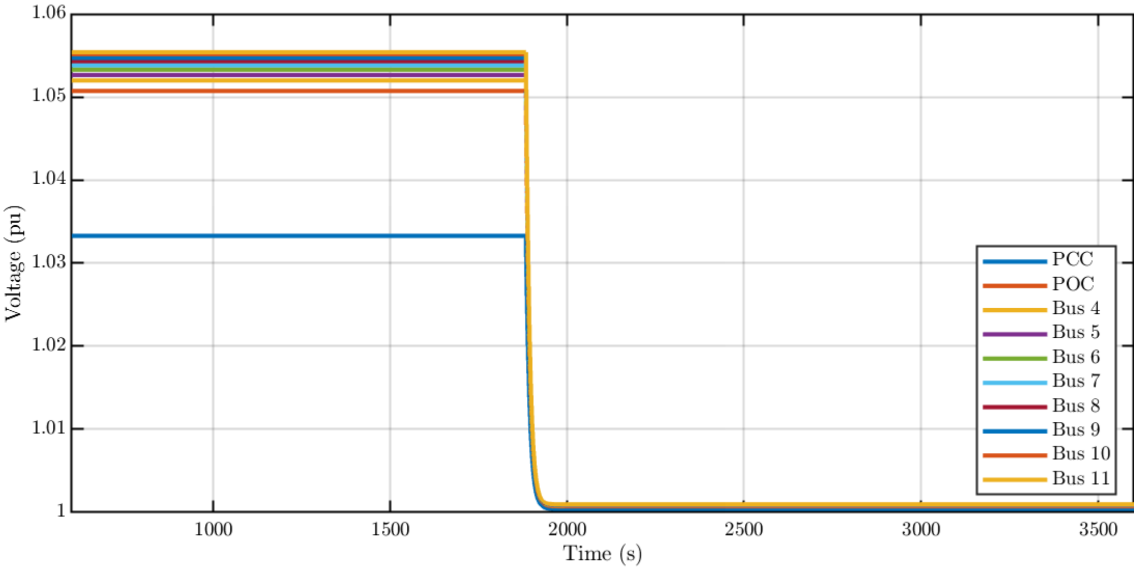


Figure 6.2. Scenario A.

6.2.2 Scenario B

In this scenario, NT is fixed to 4. Therefore, the wind farm is shut down by groups of 4 turbines. According to the layout that is being modeled -figure 3.3-, the feeder is shut down in two groups. Figures 6.3, 6.4 and 6.5 represent scenario B changing the time interval to 10, 30, and 180 seconds respectively.

As the PCC is the most vulnerable point of the scheme -the other points are not exceeding the recommended values-, a gray dashed line is added to accurately delineate the permissible voltage range for the PCC, as specified in Table 4.1.

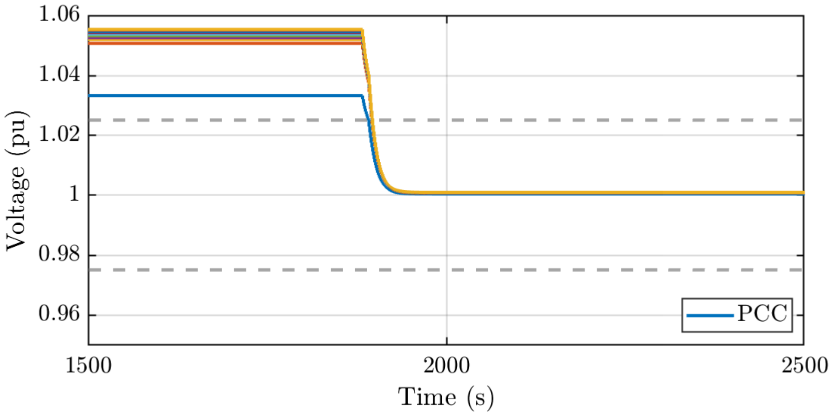


Figure 6.3. Scenario B, Time Wait 10 seconds.

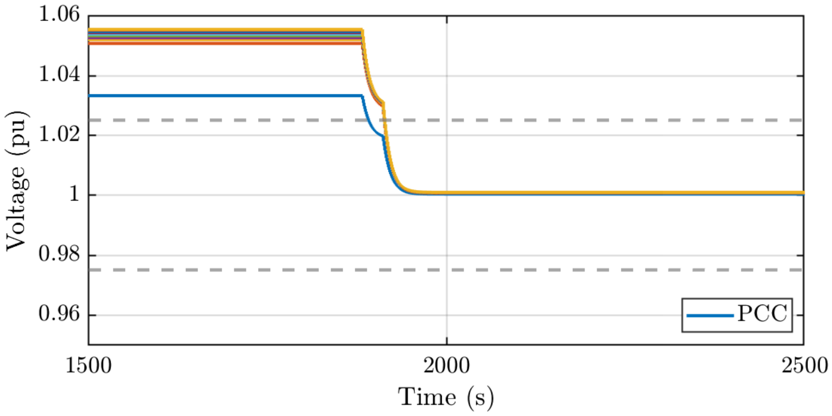


Figure 6.4. Scenario B, Time Wait 30 seconds.

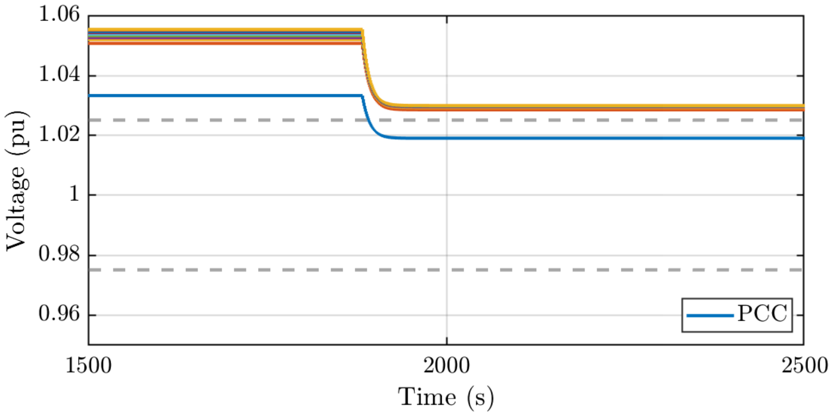


Figure 6.5. Scenario B, Time Wait 180 seconds

While the test depicted in Figure 6.5 exhibits a faster voltage recovery compared to the other tests, prolonging the waiting time for the subsequent group of turbines results in a significant accumulation of voltage that take a considerable duration to restore to 1 pu.

On the other hand, when comparing tests 6.3 and 6.4, it can be deduced that a time wait of 30 seconds appears to be a more favorable option. This choice enables the voltage at the PCC to be restored to 1 pu around the same time as the 10 seconds option, while also showing a slight step down that could be advantageous for the grid.

6.2.3 Scenario C

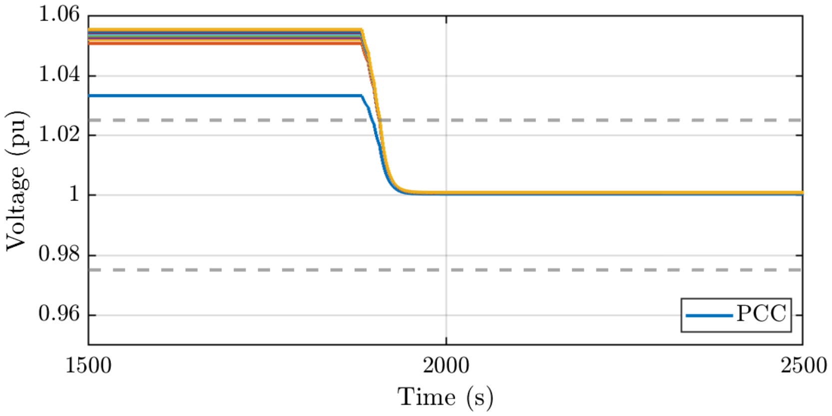


Figure 6.6. Scenario C, Time Wait 10 seconds.

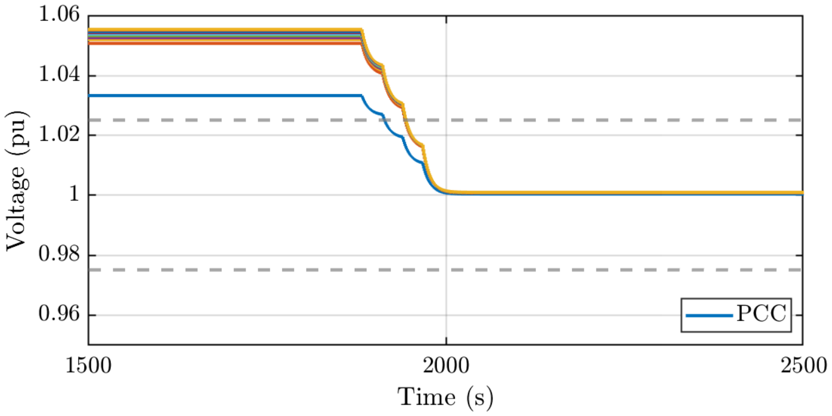


Figure 6.7. Scenario C, Time Wait 30 seconds.

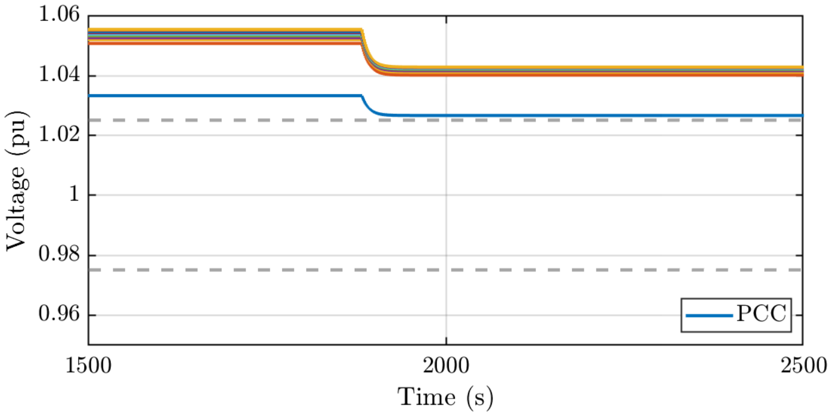


Figure 6.8. Scenario C, Time Wait 180 seconds.

In scenario C, NT is fixed to 2. Therefore, the wind farm is shut down by four groups of 2 turbines. Figures 6.6, 6.7, and 6.8 represent scenario C changing the time interval to 10, 30, and 180 seconds respectively.

Similar to the previous scenario, a time wait of 180 seconds seems excessively long to await the activation of the next group shutdown. In this case, the voltage at the PCC does not even stabilize within the permissible range. The combination of NT=2 and time wait of 3 minutes is discarded.

When comparing tests 6.6 and 6.7, the time wait of 30 seconds once again emerges as the more advantageous choice. In the 30 seconds test, voltage at the PCC drops immediately under the maximum permissible voltage, while the voltage drop steps are slower and more progressive compared with the 10 seconds test.

6.2.4 Scenario D

In the last scenario, NT is fixed to 1. The turbines are shutting down progressively one by one. Again, figures 6.9, 6.10, and 6.11 represent scenario D for a time interval of 10, 30, and 180 seconds respectively.

Regarding the third test, the same conclusion is obtained. Waiting for 3 minutes to shut down the next group is an excessively long time, especially considering that the turbines are shutting down one at a time. While this option may be more suitable for scenario B, where the wind farm is shut down in two groups, allowing the production to gradually reduce to safe levels within three minutes, it proves impractical for the current scenario.

In this scenario, the last turbine of the row would begin its shutdown process 21 minutes after the first one, which is an unreasonably long period of time. As a result, Test 6.11 is dismissed, along with scenarios B and C for this time wait.

Once again, the decision lies between the 10-second and 30-second options. The initial test presented in figure 6.9 shows a similar response to those depicted in figures 6.6 and 6.3. In other words, there appears to be minimal variation observed across the scenarios when employing the same 10 second time wait.

Regarding the 30 seconds test shown in 6.10, it demonstrates a more gradual decrease compared to 6.7 and 6.4 for this time wait. As expected, the PCC voltage requires additional time to stabilize. However, within a few seconds, the voltage drops under the permissible range, i.e. falling below the gray dashed line depicted in the figure.

Therefore, a trade-off situation arises from these results, where a time wait of 30 seconds emerges as the most favorable option. This duration provides a reasonable time frame to gradually reduce the voltage and power output while other generation units connected to the grid can compensate for this lack of generation.

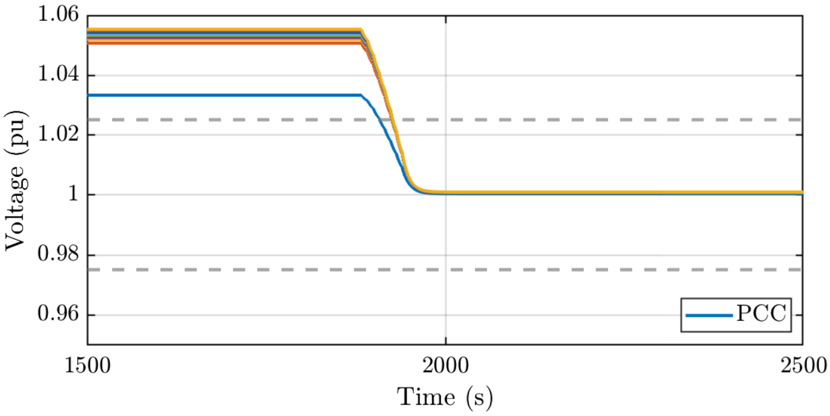


Figure 6.9. Scenario D, Time Wait 10 seconds.

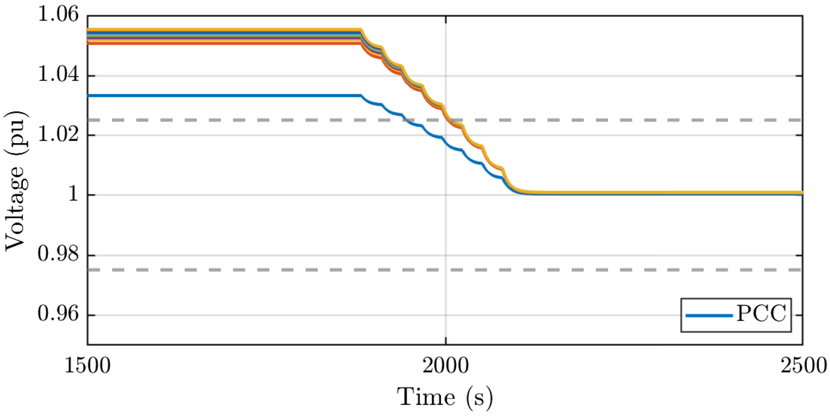


Figure 6.10. Scenario D, Time Wait 30 seconds.

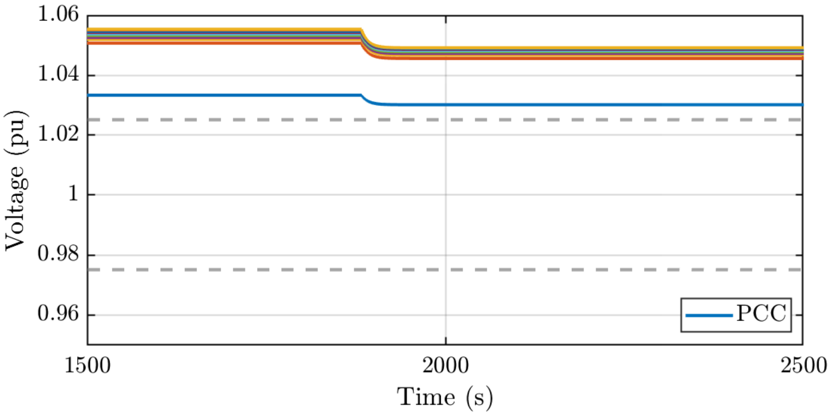


Figure 6.11. Scenario D, Time Wait 180 seconds.

6.3 Selected Strategy

After analyzing the results and conclusions derived from various scenarios and test cases in this chapter, it can be concluded that the optimal waiting time for each shutdown group is 30 seconds. This time interval corresponds to three possible scenarios: NT=4, NT=2, and NT=1.

When making this decision, it is essential to consider both perspectives, the voltage stability and the safety of the individual turbines.

The objective is to minimize the impact on the grid while avoiding unnecessary delays in the shutdown procedures. In the case of NT=1, the last turbine would start to shut down 3 minutes after exceeding the critical wind speed. Conversely, in the case of NT=2, all turbines would have reduced their power within one and a half minutes of reaching this wind speed.

Both options are considered grid-friendly, but in order to achieve a balance between voltage stability and power reduction, the faster scenario, NT=2, is selected.
The strategy selected is **Scenario C, Time Wait of 30 seconds** -figure 6.7, 6.1c-. This choice ensures a fast response while maintaining voltage stability.

6.4 Summary

In this chapter, the results obtained from the different shutdown test cases proposed in the previous chapter are presented and analyzed. The power and voltage responses to the different shutdown procedures are discussed in detail and the optimal shutdown strategy is selected.

Chapter 7

Conclusions and Future Work

7.1 Summary and Conclusions

The main objective of this thesis is to propose storm strategies for shutting down offshore wind farms due to extreme wind conditions. This project is motivated by multiple factors. First, average wind speeds are expected to increase in the near future in the North Sea, and therefore actual and future installed wind turbines in this area must be able to withstand extreme wind conditions.

In addition, the unpredictable and variable nature of the wind during storms poses a significant challenge, as sudden shutdowns of wind farms can lead to power system imbalances and grid disturbances. It is therefore necessary to implement shutdown control strategies and ensure effective coordination between controllers to improve the reliability of offshore wind energy production.

The system has been developed using a wind farm model in MATLAB Simulink to test the proposed strategies. This model is based on the actual Horns Rev I wind farm, located on the North Sea coast of Denmark. With a generating capacity of 160 MW, this wind farm comprises a total of 80 Vestas V80/2MW pitch-regulated, variable-speed wind turbines.

It has been considered to simulate only the first line of the wind farm, i.e. eight wind turbines, since this is sufficient to capture the shutdown strategy. However, the remaining generation units have been included as additional loads in the grid model, to reflect the overall load of the park without increasing the computational burden.

The development of the Simulink model consists of four main subsystems that collectively create the wind farm model simulation environment: the wind profiles, the wind turbine model, the external grid model, and the shutdown controller.

To accurately represent real world conditions, three wind profiles have been created. The first profile uses actual wind data from Horns Rev I during the summer period. This profile is used to validate the normal operation of the model, as it represents a low wind scenario, with wind speeds ranging from 7 to 15 m/s.

The second profile simulates high wind conditions that result in the shutdown of the wind turbines. It has been generated by scaling lower wind profiles and is specifically designed to replicate sequences of standard operation, shutdown, and startup within a relatively short time frame.
The third wind profile includes wind gusts according to the definition of extreme wind conditions given by the IEC International Electrotechnical Commission standard.

The wind turbine model has been developed using a simplified wind turbine public model provided by Aalborg University. Despite being a simplified version that lacks an aerodynamic system, this model was chosen over a more complex alternative such as the NREL offshore 5-MW baseline wind turbine model.
This decision was made to avoid excessive computational load and prolonged compilation times, which would occur when simulating eight turbines using the more complex model. The simplified model has shown good performance in capturing wind speed fluctuations and power variations, thus serving the purpose of the study.

A public grid model, provided by Aalborg University, has been also used. This model was modified and adjusted to fit the specific study case. Together with the eight wind turbine models, it formed the wind farm model, which was tested with the three wind profiles to evaluate its overall execution.

The wind farm model has shown a good performance under normal wind conditions, ensuring that the voltage levels at each bus remain within the limits stipulated by the grid codes. When the wind is low, and the available power generated by the wind turbines is small, the system voltages stay close to 1 pu, oscillating between 1.003 and 1.012 pu.

Conversely, when the wind farm model was tested with high wind, -without applying any shutdown strategy-, the wind turbines were frequently disconnected and reconnected to the grid as the wind speed exceeded and dropped below the 25 m/s cut-off limit.
This repetitive pattern of sudden stops and restarts has been shown to have a negative effect on the voltage, causing the voltage level at the PCC to exceed the maximum permissible ranges. Moreover, it is known that this repetitive pattern of sudden stops and restarts is detrimental as it puts additional stress on the components, increases the risk of mechanical failures, causes significant power losses, etc. It was therefore concluded that a storm control strategy was necessary.

The storm control strategy was implemented in the wind farm model as two different MATLAB functions, the *Control Logic* block, and the *Sequential Groupwise Shutdow* block.

Since the model used in this project lacked an aerodynamic system, a simpler approach has been used. The objective was to select a strategy that would shut down the wind turbines, by setting the active and reactive power output to zero, only when absolutely necessary, thus avoiding abrupt processes.

The shutdown control logic has been implemented based on 10-minute data collection measurements, to ensure that temporary fluctuations in wind speed do not prematurely shut down the turbine. Additionally, the shutdown has also been allowed in cases of wind gusts up to 35 m/s, providing an additional safety measure for the control system. Shutdown performance has been tested with both high wind profiles to assess correct operation in different conditions.

The *Sequential Groupwise Shutdow* block has been designed to coordinate the shutdown of the turbines. For this purpose, four main scenarios have been proposed, simulating different NT groups. For each of these scenarios, various waiting times, including both short and exceptionally long durations -3 minutes-, have been proposed to assess their impact on the PCC voltage. However, it is unknown whether other alternative values would have been more appropriate as no literature has been found on this specific topic.

The implemented strategy has introduced a time delay between the shutdown of each group, instead of starting the shutdowns simultaneously at different ramp rates. As this decision may not be optimal from the turbine safety perspective -it requires the last turbines in line to wait for shutdown-, the maximum ramp rate has been employed for all scenarios. This approach has brought forward all turbine shutdowns mitigating significant power and voltage drops.

Voltage levels have been a critical reference point in the decision making process, particularly when selecting the optimal shutdown strategy. The analysis has primarily focused on the PCC voltage, considering it the most vulnerable point of the system.

Out of the 10 analyzed test cases, Scenario C, with a wait time of 30 seconds has been identified as the preferred strategy. This selection strikes a balance between achieving a fast total shutdown response of the wind farm (increasing NT and physically protecting the turbines by shutting them down as soon as possible), while minimizing the voltage drop (decreasing wait time) and ensuring a smooth transition.

In comparison and returning to the objectives set at the beginning of the project, it can be said that all the proposed tasks have been fulfilled, with the following achievements:

- The different storm control strategies found in the literature have been investigated.
- The layout of the wind farm has been clearly defined, including dimensions, capacities, and connection points.
- Ramp rates and voltage limits have been established in accordance with the requirements specified in the grid codes.
- Three wind profiles have been created to simulate the wind farm model under normal, high wind, and extreme conditions.
- A wind farm model including wind turbine models and an external grid model has been developed and verified.
- The control logic and shutdown control have been developed and verified using the two high wind profiles.

- Several shutdown strategies have been proposed and analyzed, concluding with the selection of the most suitable strategy for this case study.

7.2 Future Work

Following the work of this thesis, some studies are proposed:

- **New scenarios:** Additional scenarios can be simulated, to include a wider range of variables and explore different ramp rates. This will provide a more comprehensive understanding of the behavior of the system under different conditions.
- **Complex WT model:** That includes advanced aeromechanical subsystems, such as pitch and torque controllers. The classical shutdown procedure by means of pitch and yaw control could be implemented.
- **Wake effect model:** With a wake effect model, more accurate estimates of how the wind propagates along the wind farm can be obtained. This approach can provide more accurate assessments of local variations in wind speeds, enabling selective turbine shutdowns in the park.
- **Wind prediction model:** Forecast tools can be used to predict extreme wind periods. The predictive model could help to assess the wind uncertainty and to coordinate a planned wind farm shutdown in advance.

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