Connection of large-scale wind power generation to the Dutch electrical power system and its impact on dynamic behaviour

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Preface

This thesis describes the dynamic effects of wind power integration on the Dutch electrical power system, and is carried out as a final work for my MSc Electrical Power Engineering. During my studies electrical engineering my interest in sustainability grew and therefore I decided to follow several courses in the framework of the minor 'technology in sustainable development' and integrate this subject into my thesis.

Via prof. ir. W.L. (Wil) Kling I became acquainted with the Dutch Transmission System Operator TenneT and was given the opportunity to work on a dynamic study on wind power parallel to, and partly overlapping with, an international study TenneT already participated in. During the period of my thesis I was given a workplace at TenneT within the business unit Asset Management. Next to my thesis I was invited to join several meetings of the business unit and the *netstrategie* cluster from which I also learned a lot.

I would like to thank ir. E.F. (Ernst) Wierenga who put a lot of time and effort in the dynamic generator models and often helped me with the PowerFactory software. Ir. C.P.J. (Kees) Jansen was of great help in getting insight in the dynamic generator models and important aspects regarding dynamic modelling. I would also like to thank ing. F.J.C.M. (Frank) Spaan, my daily supervisor at TenneT with whom I had regularly discussions on my thesis and who advised me in the direction to be followed. My thanks also goes to all the other people in the cluster *netstrategie* who were very interested in my work, were helpful wherever they could, and made me learn a lot about the electrical power system by involving me in their activities.

Prof. ir. W.L. (Wil) Kling I would like to thank for the information he provided for my thesis, and the meetings he invited me to. For the chapter I wrote on the local selection environment of wind parks, in the scope of the sustainability minor, dr. L.M. (Linda) Kamp helped me to define the main question and gave helpful feedback on my work. Ir. R.L. (Ralph) Hendriks I would like to thank for giving me feedback and useful tips in his role as my daily supervisor at the TU Delft.

Finally, but definitely not in the last place, I would like to thank Inge and my parents for their support during the period of this thesis and my entire studies.

Jorrit Bos
Arnhem, August 2008

Summary

Installed wind power world wide is increasing rapidly, driven by the shrinking oil supplies, increasing oil prices, and increasing environmentally awareness. The increase in wind power in the European electricity grid is expected to have its impact on the system behaviour. A European study, European Wind Integration Study (EWIS), was thus set up to study the impact of wind power. This thesis was carried out in parallel with EWIS and overlaps at some points. The impact of large scale wind power integration on transient stability in the Dutch grid was studied. An increase in installed wind power is assumed to cause a (relative) reduction in large coal and gas fired power stations, and thus increasing system instability.

For the simulations the Dutch part of the UCTE interconnected system load flow model was used. Speed controls and excitation controls were added to the thermal power plants, and at the interconnections equivalent generators were placed to represent the external grids.

A validation of the grid model was carried out by reproducing calculations from a previous dynamic stability report. From these calculations it was concluded that the grid representation used creates a very stable situation. This is mainly caused by the representation of the external grids.

Nine connection points were defined and all installed wind power was aggregated in wind parks at those nine connection points. The distribution of wind power amongst turbine type and location was determined to get a realistic distribution.

Several simulation cases were then taken into account, first a comparison was made between the dynamic grid behaviour of the year 2008 and the year 2015, when no changes in the current regulations regarding fault-ride-through capabilities are made. This means that all wind power will be disconnected from the grid on a voltage drop below 0.8 p.u..

Secondly a comparison of the dynamic grid behaviour of 2008 and the year 2015 was made, with no wind included in this case. In this way a comparison between the stability of the different grid structures could be made.

As a third case, different connection requirements were applied, so the wind turbines had to stay connected to the grid in case of a fault. These 'new' regulations were applied to the 2015 grid situation.

From the calculations it followed that the 2015 grid without wind power installed shows a less stable behaviour than the 2008 grid. Voltage oscillations that occur have a larger amplitude and are damped slower. This difference is mainly caused by the fact that for the year 2015 about 2000 MW more generating capacity, that starts to oscillate on a fault, is installed.

In the 2008 situation a short circuit in the centre of the grid may cause

the disconnection of up to 1258 MW of wind power. For the 2015 situation this can become over 5000 MW. A disconnection of such a large amount of wind power is leading to voltage oscillations and oscillations at interconnection power flows. These oscillations however damp out fast and do not increase in amplitude. In the 2008 situation the oscillations at the interconnections are still within the limits of the line capacities, but for the 2015 situation several lines will get overloaded. The voltage recovery time also increases enormously between these years. Applying new regulations, where all variable speed wind turbines will have to stay connected to the grid during a short circuit, reduces the oscillations. Voltage recovery time however will generally increase slightly, caused by the reactive power absorbed by the wind turbines after the fault has cleared.

As can be concluded from the calculations, a rather stable grid situation is created. This is mainly caused by the fact that the external grids are not taken into account, but modelled as an equivalent. In this way a very large amount of power is available directly at the borders and oscillations at the interconnections do not cause oscillations in the neighbouring countries. When a larger part of the surrounding UCTE grid will be implemented the results will be different and most probably show a less stable behaviour.

Local selection environment

This thesis also looked into the large differences in wind power penetration in Europe. Several countries have a leading position in installed wind power, whilst a country like the Netherlands stays behind. Wind resources and room for turbines play an important role in this, but socio-economic factors are also of great importance. When the local selection environment for onshore wind parks in Germany, Spain, and the Netherlands is compared, it can be concluded that governments in Germany and Spain are very supportive and show a stable position towards renewable energy. Furthermore social acceptance is high in Germany and Spain, and both have a large local wind turbine production. These are important explaining factors for the differences in local selection environment and increase in installed wind power.

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Chapter 1

Introduction

Sources of renewable energy are playing an increasing role in the world's electricity supply, for two reasons. One is the decreasing amount of fossil fuels. It is known for long that the fossil reserves are limited, but for years it seemed as if they were not. Oil has played and still does play a huge role in the modern society since e.g. cars, planes, and power plants run on oil. Because of the growing awareness of the fast decreasing oil supplies, the interest in alternatives for oil is increasing. The decreasing amount of oil causes the prices to increase, thus making it more and more viable to look for alternative fuels. The other very important factor in the increasing role of alternative fuels is the increased environmental awareness of the people.

A very plausible, but still debatable, explanation for the global warming is the CO_2 exhaust caused by cars, planes, power plants etcetera. This CO_2 exhaust has to be reduced and alternative, sustainable[1] solutions will have to be found to replace the burning of oil and gas. Wind energy is one of the alternative sustainable energy sources that has a large potential. The amount of world wide installed wind power is thus increasing rapidly, 19.7 gigawatt was added in 2007 to a total of 93.8 gigawatt, Europe plays a leading role with 61% of the total [2]. In the Netherlands about 1700 megawatt of wind power is installed today and it may be assumed this will increase to over 7000 megawatt in the year 2015.

The increasing amount of wind power in the electricity grid has effect on the behaviour of the grid. Wind power output is variable and less predictable than thermal power, resulting in a different way of grid operation. Furthermore the technical characteristics are different from thermal power plants and a large amount of wind power in the electricity grid can cause stability problems [3].

To study the effects of the increasing amount of wind power in Europe, a European wide study was set up by the European TSOs (Transmission System Operators). The first phase of this study, the European Wind Integration Study (EWIS), was set up as a load flow study for the year 2008, to get more insight in the effect of wind power on power flows across Europe. The second phase of EWIS is still ongoing and is looking at the impact of wind power on the dynamic behaviour of the European grid, for the years 2008 and 2015. This thesis follows a parallel path alongside the second phase of EWIS with some overlap, as only

[1] sustainability has many definitions, the most commonly used is the one defined by the 1987 Brundtland report [1]: *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

the Dutch grid is studied.

Local selection environment

As a second part of this thesis, the large differences in installed wind power across Europe are studied. Countries like Germany and Spain have a leading position in installed wind power, whilst for example the Netherlands stays behind. Wind resources and space for turbines play an important role in this, but socio-economic factors are also of great importance. This thesis will look into these factors and a comparison between selection environments in three European countries will be made.

1.1 Research objectives

The increasing wind power penetration in the Dutch electrical power system will have its impact on the behaviour of this system in several aspects. In this thesis the main goal is to determine the effect of large scale wind power integration on transient stability. Transient stability is defined as follows [4]:

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance

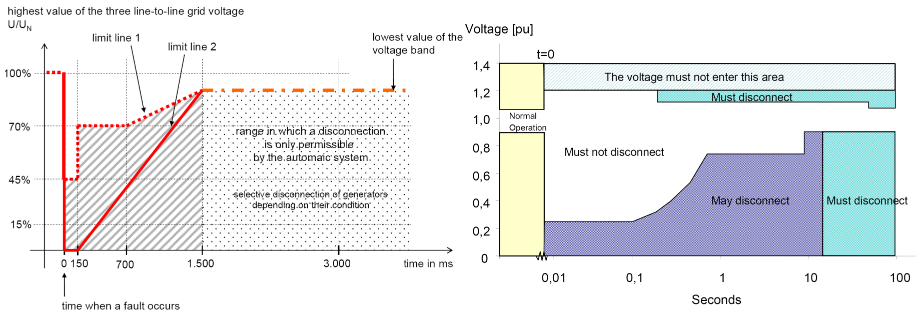
The behaviour of different wind turbine types plays an important role in transient stability. Each turbine type has a different behaviour and effect on the power system during and after a fault. Major factors of influence on voltage and power oscillations, like reactive power demand and fault behaviour, are studied and described. Furthermore, it is examined whether fault-ride-through capabilities improve the system behaviour compared with the disconnection of wind parks during the fault.

Another objective of this thesis, apart from the system stability issue, will be to determine the difference in local selection environment for wind power in Germany, Spain, and the Netherlands.

1.2 Expected results

To get insight in the effects and problems associated with a higher penetration of installed wind power in the Dutch grid, several aspects are taken into account. An increase in installed wind power is assumed to cause a (relative) reduction in conventional thermal power, e.g. large coal and gas fired power stations. Since conventional generation plays an important role in system stability, by means of its control capability and large inertia, it is to be expected that system instability will increase with the increase of wind power penetration. System damping is expected to be less because of the smaller inertia in wind turbines. Reactive power flows are also expected to increase due to the larger amount of wind power and locations where wind power is installed.

Current Dutch grid connection requirements ('grid codes') do not include any special prerequisites regarding the fault ride-through behaviour. Most wind turbine manufacturers thus do not include (or enable) voltage-ride-through capabilities in their wind turbines. In the future these regulations may change, according to the Danish or German model (see figure 1.1). These technical requirements prescribe a certain time the wind power plant has to stay connected at a certain voltage drop. In this way the disconnection of a large amount of wind power during a fault in the system is prevented.



(a) German (b) Danish

Figure 1.1: German and Danish grid code requirements for wind turbine connection (source: E.ON Netz and Energinet.dk)

Power oscillations with neighbouring countries on the interconnections are expected after the disconnection of wind power. These kind of oscillations could lead to the switching off of lines at the interconnections.

1.3 Research methodology

The turbine types used in this thesis, and aggregation techniques will be studied by literature and subsequently (simplified) models will be created. The behaviour of the different turbine types and their aggregated models will be tested and validated in small test grids.

For the Dutch electrical power system a dynamic model will be set up, constructed out of a load flow model, by adding speed and excitation controls. External grids outside the Dutch system will be represented by equivalent models and the model will be validated by a known simulation case. To implement the wind parks in the model a distribution will be determined for the years 2008 and 2015. This distribution is divided up into location, turbine type, and connection to distribution or transmission grid. Finally, several test cases will be determined and calculated for the years 2008 and 2015 to determine the behaviour for both years and to make a comparison.

Software

For simulations, the software-package DIgSILENT PowerFactory will be used. PowerFactory is a simulation tool used for calculations in electrical networks and is suitable for a broad range of simulations including load flow and dynamic calculations.

1.4 Structure

This thesis will first describe the different turbine type models, aggregated models of wind parks and the Dutch electrical power system model for the years 2008 and 2015 in chapter 2. In this chapter also a test case is described, where the various turbine types are connected to a small grid and the behaviour is studied. Chapter 3 describes the distribution of wind power in the Netherlands and gives the substations used for the connection of wind parks. The different simulations cases and results of the calculations are described in chapter 4. A description of the local selection environment for wind energy in Germany, Spain, and the Netherlands will be given in chapter 5. Finally, chapter 6 gives conclusions and recommendations for further work.

Chapter 2

Model description and validation

This chapter describes the models that are used in the simulations. First the turbine and aggregated wind park models are described and validated in a small test grid. After that the dynamic model of the Dutch electrical power system, its construction and a validation method is described.

2.1 Turbine models of aggregated wind parks

The Western Electricity Coordinating Council (WECC, USA) has defined four generic models for the representation of wind turbines. Three turbine models used in this thesis are described, type 1: squirrel cage turbine, type 3: doubly fed induction machine, and type 4: direct drive turbine. Each of these types is modelled as an entire wind park, aggregated into one single wind park model instead of using separate turbine models. The wind park models are validated with reports from EWIS and several papers, to obtain realistic models.

Validation of turbine models

To validate the PowerFactory models for the three different turbines, the same test grid is used for each turbine type (see figure 2.1). All turbines are scaled to an output level of 45 MW (see Appendix A for parameters that need to be adjusted) and connected to a 0.69-kV terminal, via a transformer to a 20-kV terminal, and finally to the 150-kV level. The parameters used in the test system are given in appendix B, table B.1 and table B.2. These parameters are the same as described by the EWIS guideline for wind turbine validation [5], only a grid voltage of 150 kV was chosen instead of 110 kV, to better reflect the Dutch situation. No changes are made in the other model parameters.

Aggregation

For the simulation of larger wind parks aggregated models are needed, because calculation times get high in case every turbine is implemented separately. Aggregated wind park models are required to represent the behaviour of the wind

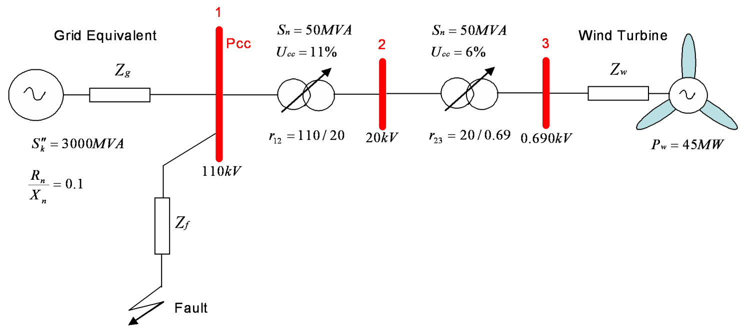


Figure 2.1: Wind park test model (figure from [6])

park during normal operation and during disturbances. An aggregated wind park therefore usually consists of three modules: the wind speed, a model of an individual turbine, and a specification of the park layout. However for the scope of this report the wind speed is assumed to be constant, because of the simulation time of only several seconds. Constant wind speed means that park layout is also ignored, as all wind turbines are assumed to have the same turbine speed. Because of this assumption modelling of turbine parameters, e.g. the amount of energy extracted from the wind, and pitch control is not needed. The $C_p(\lambda, \beta)$ curve, describing the proportion of power extracted from the wind based on pitch angle and rotor speed, is taken at its maximum meaning the turbine produces maximum power.

Furthermore the impedances of cables within the park are neglected, a single equivalent cable model is included to account for all cables within the wind park array [7, 8].

Simulation type

A balanced positive sequence rms-calculation is used in the simulations, thus assuming a symmetrical network. This assumption is made since only three-phase faults are taken into account, as they are the most severe disturbances and therefore represent a worst-case situation. PowerFactory's rms-simulation uses third order models for the generators, thus omitting the exact transient behaviour. This simulation method is chosen instead of instantaneous value simulation because the exact transient behaviour plays a less important role in grid studies and takes up much more calculation time with large systems.

2.1.1 Squirrel cage induction generator

Squirrel cage induction generators (figure 2.2) are the most basic kind of wind turbines. The rotor blades are connected to the generator via a gearbox and the generator is directly coupled to the grid. Because of this, squirrel cage turbines have a fixed operating speed, which means the rotor has to turn at a certain fixed speed in order to generate a frequency of 50 Hz at the output.

The rotor blades of squirrel cage turbines are designed for passive stall control, which limits the rotor speed at high wind speeds by turbulence. Induction

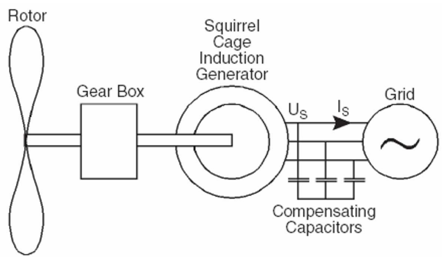


Figure 2.2: Type 1: squirrel cage turbine (figure from [5])

machines always consume reactive power caused by the rotor slip. This reactive power is compensated for by means of a capacitor directly at the generator terminal. Squirrel cage turbines are not equipped with any controls regarding active or reactive power output.

A validation of the aggregated squirrel cage turbine PowerFactory model was carried out in [9], this paper describes the simulation results and turbine parameters (see table B.3). Two different models were validated in this paper, a lumped mass and a two mass-model. The two-mass model represents the coupling between turbine and generator, modelled as a spring and a damper. The spring constant K_{shaft} does not only represent the shaft between the turbine and generator but also the flexibility of the rotor blades [10]. This gives the most accurate results in the simulations, because oscillations in the shaft are taken into account. During short-circuit situations these oscillations play an important role, and thus the two-mass model will be used. The squirrel cage PowerFactory model consists of an asynchronous machine and a compensating capacitor (see figure 2.3).

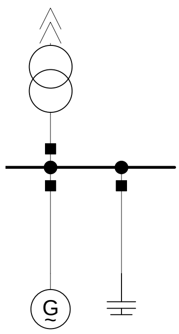


Figure 2.3: Squirrel cage induction generator model in PowerFactory

Figure C.1 shows the SCIG turbine control frame[1], as used in PowerFactory. When the squirrel cage turbine is modelled as a lumped mass model, the prime mover is left out. This means the interaction between generator and rotor (by means of the shaft and gearbox) is not modelled, and the total inertia of the

[1]control frames are used by DIgSILENT PowerFactory for modelling the controls of all grid components of a specific model (see Appendix C)

turbine and generator are added up as one equivalent inertia. To simulate a two mass model, shaft and gearbox are taken into account. In the model a complete wind park is aggregated and implemented as one generator. The active power, reactive power and inertia constants of the single turbines are added.

Protection

Squirrel cage turbines are usually disconnected from the grid in case of a voltage drop below 0.8 p.u.. Currently this yields for all turbine types in the Netherlands, since there are no specific regulations regarding the behaviour of wind turbines during fault situations [11]. The circuit breaker is assumed to have an operation time of 40 ms and will be triggered after 50 ms, resulting in a total disconnection time of 90 ms. A protection block and voltage measurement at the 0.69-kV bus are added to the PowerFactory control frame (see figure C.1).

2.1.2 Doubly-fed induction generator

A doubly fed induction generator (DFIG) is an asynchronous machine with a three-phase wound rotor of which the windings are lead out to terminals via slip rings. In this way the voltage on the rotor can be controlled in both amplitude and frequency using a pulse width modulator. Usually a gearbox is used to connect the rotor of the generator to the turbine rotor (prime mover) of the wind turbine (see figure 2.4).

The DFIG has two converters, one at the rotor-side and one at the grid-side with a DC bus in between. The rotor-side converter (RSC) transforms the direct voltage into a controlled rotor voltage and frequency, which determines the rotor current. The grid-side converter (GSC) converts the AC voltage at the grid-side to a predefined direct voltage. In the PowerFactory model the frequency of the rotor current is not controlled. The frequency is set to an initial value by enforcing a slip percentage in the order of a couple percent.

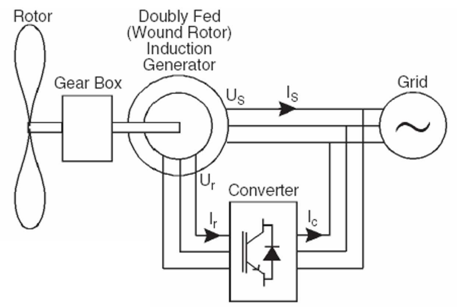


Figure 2.4: Type 3: doubly fed induction machine (figure from [5])

In a doubly fed induction generator only about 25 percent of the total power is lead through a power converter, which makes it possible to dimension the converter small compared to the turbine rating.

PowerFactory has a standard DFIG model available, with the rotor-side converter included in the asynchronous generator model and the grid-side converter added as separate component (see figure 2.5).

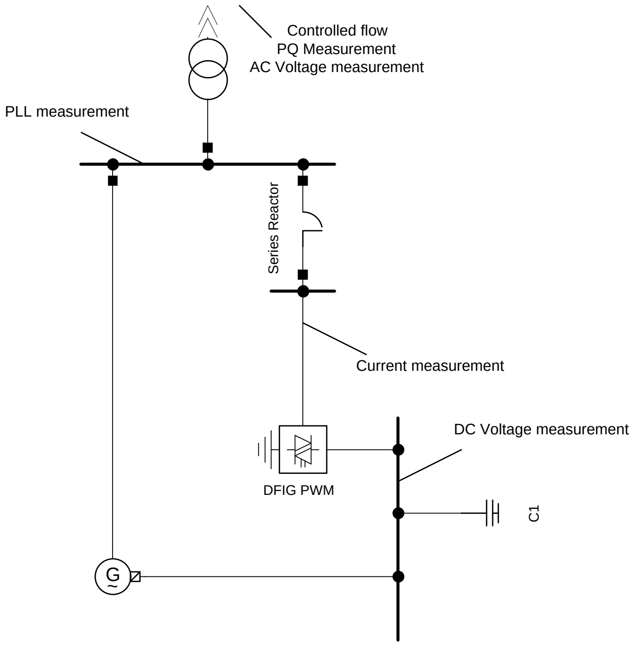


Figure 2.5: DFIG grid in PowerFactory

Both grid-side converter and rotor-side converter have a separate control frame in PowerFactory. The rotor-side converter control frame (see figure C.3) includes the prime mover model and protection. The prime mover consists of three parts: pitch control, turbine and shaft. As mentioned before the pitch angle control and turbine (representing the conversion from wind power to mechanical power) are not included in the model because of the relatively short simulation time. The shaft model can mechanically be approximated by a two-mass model, as with the squirrel cage turbine. In the model a complete wind park is aggregated and implemented as one generator. The active power, reactive power and inertia constants of the single turbines are added. Appendix B, table B.6 shows the parameters of the mechanical –prime mover– part of the turbine model as described by [12].

Protection

The DFIG protection system consists of three different parts. One for over and under speed, one for over and under voltage, and one for overcurrent in the rotor. Both speed and voltage protection have two stages, the first stage reacts very fast on large errors in speed or voltage whilst the second stage is a slower one. The second stage is only triggered after a longer period, but reacts to smaller errors. When one of these two protections is triggered, the wind turbine will be disconnected from the grid by opening the circuit breaker at the 20-kV terminals of the 20/0.69-kV transformer [10]. Only the the voltage protection plays a role in the calculations carried out in this thesis; the speed protection has not been taken into account in the simulations. A system to reconnect the turbine to the grid again when the fault is cleared is also not present in this model.

If the current through the converters becomes too large (≥ 1.5 p.u.), the rotor current protection mechanism is triggered. This protection disconnects the converters from the rotor windings in order to reduce the current in both the rotor windings and converters. If the protection is triggered, the rotor windings are short circuited through resistances that increase the overall rotor resistance, which reduces the rotor current and turns the DFIG into an asynchronous machine. This protection mechanism is named the crow bar (see figure 2.6). When the short circuit is cleared, the crow bar will disconnect, thus re-enabling the controls [13]. In the model used the crow bar is disconnected when the short circuit is cleared and the rotor current has returned to a value below 1.2 p.u. for at least 10 ms. The criteria to trigger and disconnect the crow bar can play an important role in the grid behaviour of the DFIG.

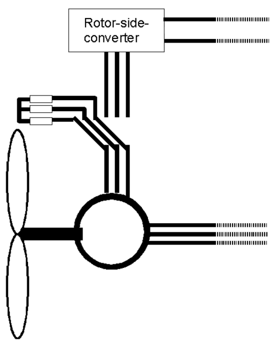


Figure 2.6: DFIG crow bar protection

2.1.3 Direct drive generator

Direct drive turbines have no gearbox, which means the generator runs at the same low speed as the turbine (typically 10 to 25 rpm) and have a high number of pole pairs. These generators have a high rated torque and are thus heavier and less efficient than conventional generators, but have the advantage of the absent gearbox. The generator is directly connected to the grid via two converters with a DC bus in between (see figure 2.7). Direct drive turbines are because of that also known as full converter turbines. A common generator in direct drive turbines, and the type used in this thesis, is the permanent magnet synchronous generator (PMSG). Synchronous machines are used instead of asynchronous because asynchronous generators with a large number of pole pairs, and thus a small pole pitch, have a very low magnetizing reactance and therefore a very large magnetizing current is needed [14]. Permanent magnets instead of an excitation system are used because of the high efficiency and the superfluousness of a DC excitation system. A permanent magnet system does have two disadvantages: the uncontrollability of the excitation and the high costs of permanent magnets.

The direct drive model has been constructed according to the model described in [14] and is implemented in PowerFactory as shown in figure 2.8.

Three control frames are included in the PowerFactory model for the direct drive turbine: one for the grid-side converter, one for the rotor-side converter, and one for the generator. Figure C.4 shows the generator control scheme.

The direct drive turbine is also modelled as complete wind park, aggregated and implemented as one generator. The active and reactive power are summed up and the inertia constant H is taken equal to the inertia constant of a DFIG turbine with the same rated power. This can be done even although a direct drive generator weights about three to ten times more than a DFIG generator [15, 16] but most of the total inertia is determined by the rotor blades. The rotor blade inertia is about 50 000 times larger then the generator inertia [12].

Pulse-width-modulation (PWM) converters

Two converters together form the power converter of the direct drive turbine. These converters operate at the same principle as the DFIG-converters, only here dimensioned at the full generator power. The grid-side converter is a PWM converter that controls the active and reactive power flow to the grid, by means of a given set-point to maintain the direct drive's constant power factor.

A fast current controller is integrated in the model, which reacts on sudden changes in power flow. A slower controller, which defines the reference parameters for the current controller, is included in the PQ-control frame (see figure C.5). The grid-side converter is set to a reactive power output such that the reactive power produced at the output terminals of the wind park will be zero. Appendix B, table B.8 shows the parameters of the PQ-controller as given by the EWIS guideline for wind turbine validation [5]. (The last four parameters are not described by this guideline, but are limiting parameters to keep the control signals within a certain boundary.)

The generator-side converter (see figure C.6) controls the ratio between the direct voltage and the voltage at the generator side. This is accomplished by given reference values for the AC and DC voltage. In this way the stator voltage of the synchronous generator is being controlled. A fast current controller is integrated in this converter also, to react to sudden changes in the voltage. The second stage, slower voltage controller defines the voltage reference parameters for a longer time span [17]. Appendix B, table B.9 gives the parameters for the voltage-controller, and table B.10 the parameters for the integrated current controllers. These parameters are determined by the simulations and are chosen such that in case of a disturbance the DC and AC voltage return to their nominal values fast and with little oscillations.

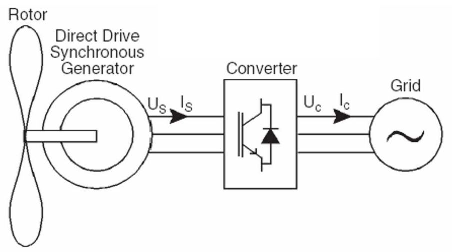


Figure 2.7: Type 4: direct drive turbine (figure from [5])

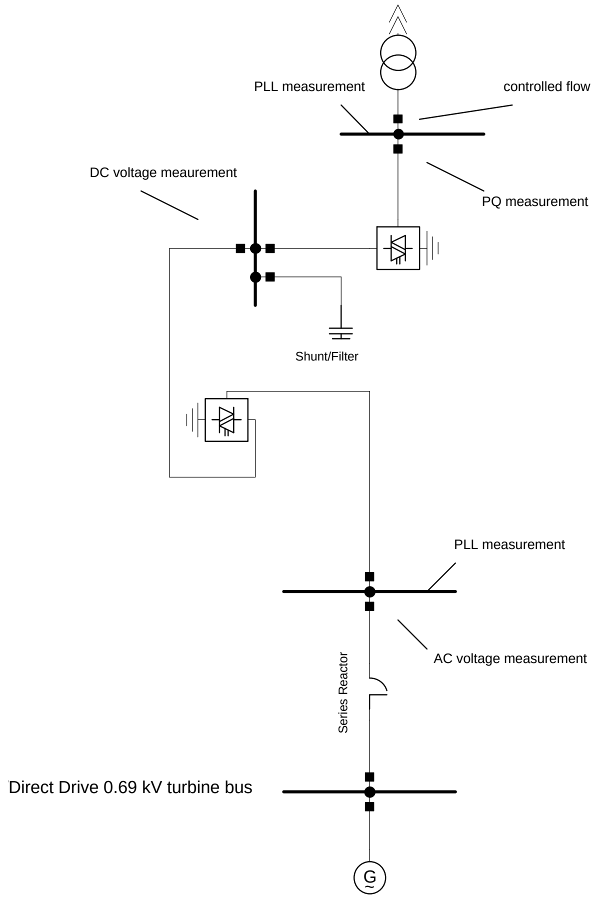


Figure 2.8: Direct drive grid in PowerFactory

Both converters are rated at the power output of the wind park and the AC voltage on both sides of the DC-link is 0.69 kV. The DC-link voltage itself is set to 1.15 kV, so the converters can operate at modulation index $m = 1$. The relation between AC and DC voltage is given by [14]:

$$U_{DC} = |U_{AC}| \frac{2\sqrt{2}}{m\sqrt{3}} \tag{2.1}$$

with:

$\lvert U_{AC} \rvert$	rms line-line voltage
m	modulation index of the PWM converter

The converters are assumed to have an infinitely high switching frequency and are considered to be lossless. A DC-capacitance is included at the DC bus to keep the DC voltage at a constant value and to prevent voltage collapse during a grid fault. Between the generator bus and the bus connected to the AC-side of the generator-side PWM converter, a series reactor has been placed to limit the current from the generator in case of a short circuit at the grid side.

2.2 Validation of the wind park model in PowerFactory

To simulate the behaviour of a grid with different wind park models and conventional generation, and to verify the expected behaviour, about 2000 MW of wind power in different compositions is connected at substation Eemshaven. Eemshaven was chosen in this test, because a large amount of thermal power plants exists near Eemshaven and it is expected that a large amount of wind power will be connected. The wind park is connected to this node as well via 2 km of 20-kV cable, a 20/150-kV transformer, 5 km of 150-kV cable, and a 150/380-kV transformer to the 380-kV level. By means of the calculations that are carried out at substation Eemshaven a prediction of the dynamic grid behaviour of a substation in the Dutch grid with large scale wind integration can be made. Substation Eemshaven is modelled together with the nearby conventional generation (Eemscentrale, (EC3 to EC7, total 1750 MW) and two equivalent external grids (total short circuit power 15 000 MVA) to represent the 220-kV and 380-kV grid of the Netherlands. The load flow values and short-circuit parameters for the equivalent external grids are determined by load-flow calculations in the complete Dutch model. Active and reactive power flows at Eemshaven of all connections not included in the separate Eemshaven model are thus calculated. For the equivalent short-circuit current a short-circuit calculation is carried out, with all generation at substation Eemshaven disconnected. In this way the external grid's short-circuit power was found. Figure 2.9 shows the layout of substation Eemshaven with the wind park connection point at 150 kV and a busbar at 380 kV where also a wind park can be connected.

The generators EC4 to EC7 are equipped with excitation control and a speed governor. Since these generators are all similar steam turbines, controls are the same for all generators. A detailed model (GAST2A, see figure D.4) is being used for the speed governor, since the parameters were known from [18]. For the excitation control the EXST1 model (see figure D.2) is being used, a controller where the excitation voltage is obtained by rectifying the voltage from the generator terminals.

2.2.1 Single turbine type 2000 MW wind park

First, three separate wind parks of 2000 MW and different type are connected one by one to substation Eemshaven. The size of 2000 MW was chosen such that the amount of wind power would be larger than the amount of power produced by thermal power plants at the substation. For this situation a short circuit of 100 ms at the 380-kV terminal is simulated and the the output signals of the wind park and reaction of the EC7 unit are studied. Because all EC generators are equal, only one at the 380-kV bus was chosen to study, since the voltage drop is worst there.

Figure 2.10 and 2.11 show the output of the wind park, for a SCIG wind park (red, solid line), a DFIG wind park (green, dashed line), and a direct drive wind park (blue, dotted line). The fault is initiated at t=0.5 sec and lasts 100 ms.

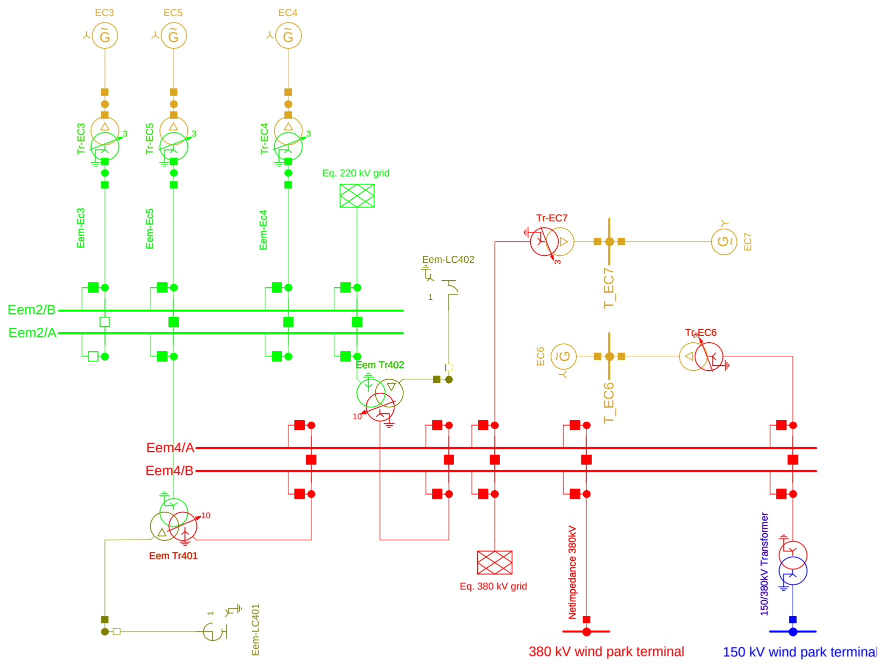


Figure 2.9: Grid situation at substation Eemshaven

Looking at the 380-kV bus voltage (figure 2.10), it can be seen that in case of a DFIG wind park the voltage recovers slower than in the other cases, because of the crow bar connection. Until the crow bar is disconnected, 10 ms after the fault has cleared, the DFIG turbine acts as an induction generator and absorbs reactive power. Once the crow bar is disconnected the turbine still absorbs reactive power for a short time to be able to return to its pre-fault slip. The response of the direct drive wind park shows some oscillations in the bus voltage. These oscillations are caused by the fast controls of the direct drive's grid-side converter. The case with the squirrel cage wind park shows a slight increase in voltage after the fault is cleared, caused by the cables of the park. This is caused by the fact that the cables act mainly as capacitors when they are not loaded, and thus produce reactive power.

The current output of the wind parks (figure 2.10) shows some differences between the turbine types. The SCIG turbine first shows an increase in current, since the turbine will absorb reactive power as soon as the short circuit occurs. This current decays until the turbine disconnects (after 90 ms) and increases a bit because of the reactive power production of the cables, once the short circuit clears. The DFIG also shows a peak in, mainly the imaginary part of, the current (figure 2.11), but only for a very short time since the connection of the crow bar limits the current. The current then decays until a steady state is reached. As the short circuit clears the current starts to return, and shows some small oscillations as the crow bar disconnects. At this time instant a small overshoot in active power and real current can be noticed, caused by fact that the rotor current is still larger than 1 p.u..

In the original simulations with the direct drive turbine, the turbine started

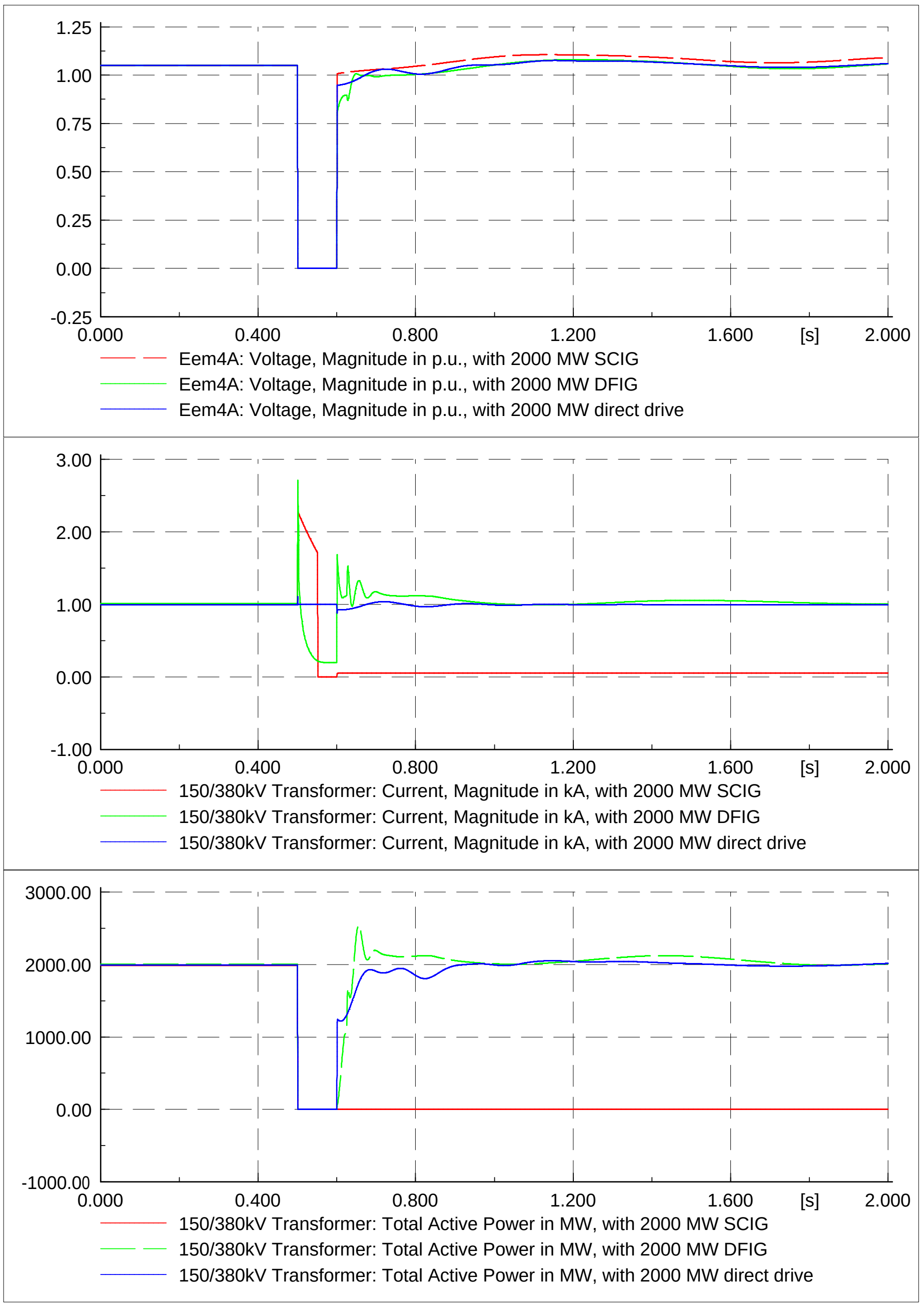


Figure 2.10: Voltage at substation Eemshaven 380-kV terminal, current magnitude and active power of wind park, with 2000 MW different turbine types connected at Eemshaven. Response to 100 ms three-phase fault.

absorbing active power for a short time once the short circuit cleared. This problem occurs only with the 2000 MW wind park and is not seen in simulations with smaller wind parks (below 1000 MW). This problem has to do with

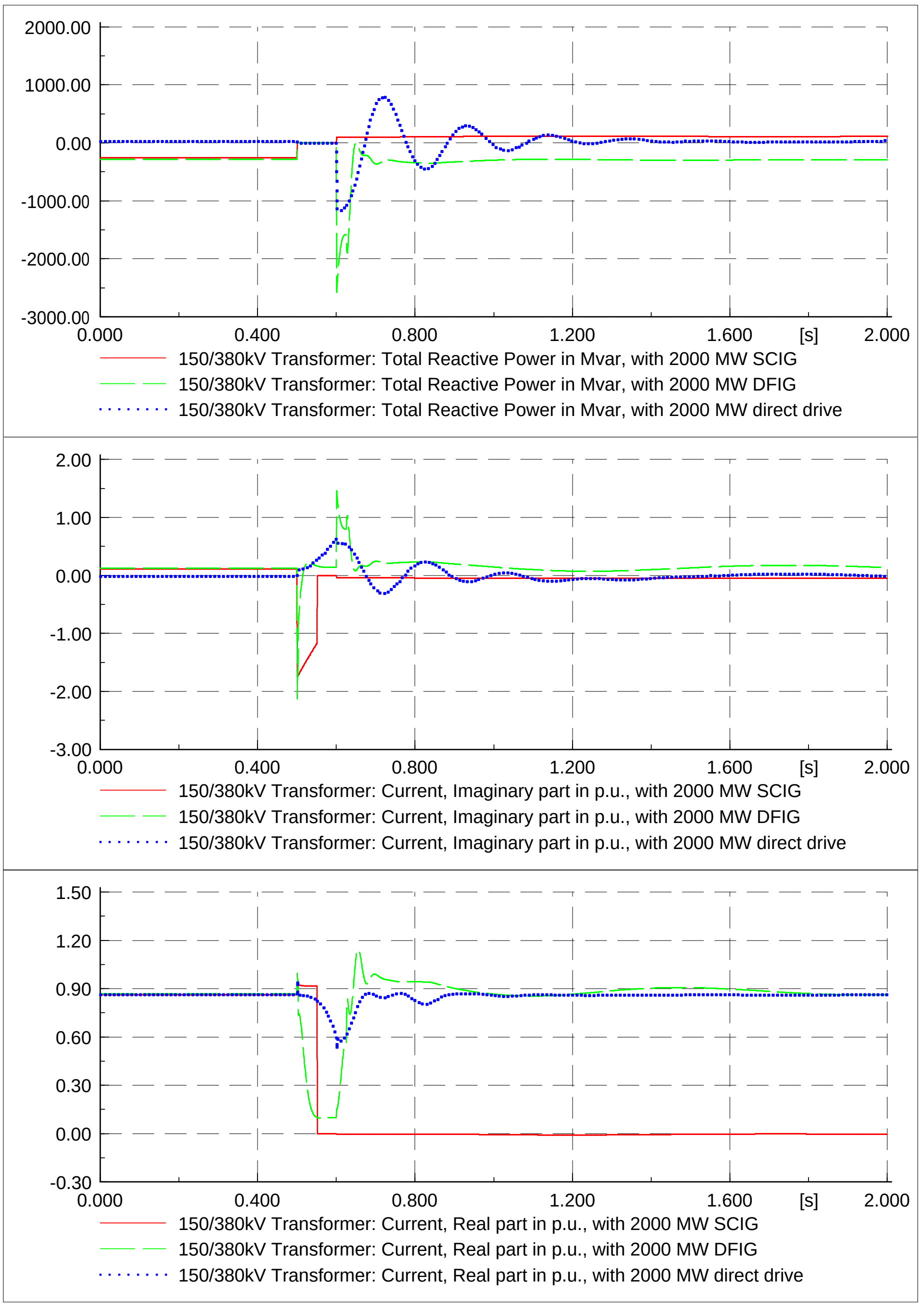


Figure 2.11: Reactive power, imaginary and real part of the current of three different 2000 MW wind parks connected at substation Eemshaven. Response to 100 ms three-phase fault.

the settings of the controller, but could not be determined exactly. In further simulations this problem does not exist, since the largest direct drive wind park in the Dutch grid is only about 350 MW. To still be able to compare the three turbine type wind parks at substation Eemshaven, the direct drive turbine is scaled to 1000 MW and the outputs are nominated on the 2000 MW values.

The direct drive only shows a very small peak in the current as the short circuit occurs and gets cleared (see figure 2.10), because the controls are able to react fast enough and can control the complete output power. Active power output is restored fast, as the direct voltage is still high and the controllers are able to restore the power output quickly. The reactive power output (see figure 2.11) shows some large oscillations once the short circuit is cleared, caused by the reactive power demand of the converter at this moment.

Figure 2.12 shows the reaction of EC7. An absorption of reactive power can be noticed here in the case of the squirrel cage wind park. This absorption of reactive power is caused by the disconnection and resulting reactive power production of the cables as mentioned before. The turbine power of EC7 also shows a small increase for this case, since 2000 MW of production is lost. Between DFIG and direct drive turbine only small differences can be noticed in figure 2.12, the direct drive park's fast controls cause some fast oscillations in the EC7 outputs. The excitation voltage shows a decrease instead of an increase during the fault in all situations. This is caused by the fact that the generator is equipped with a static excitation system.

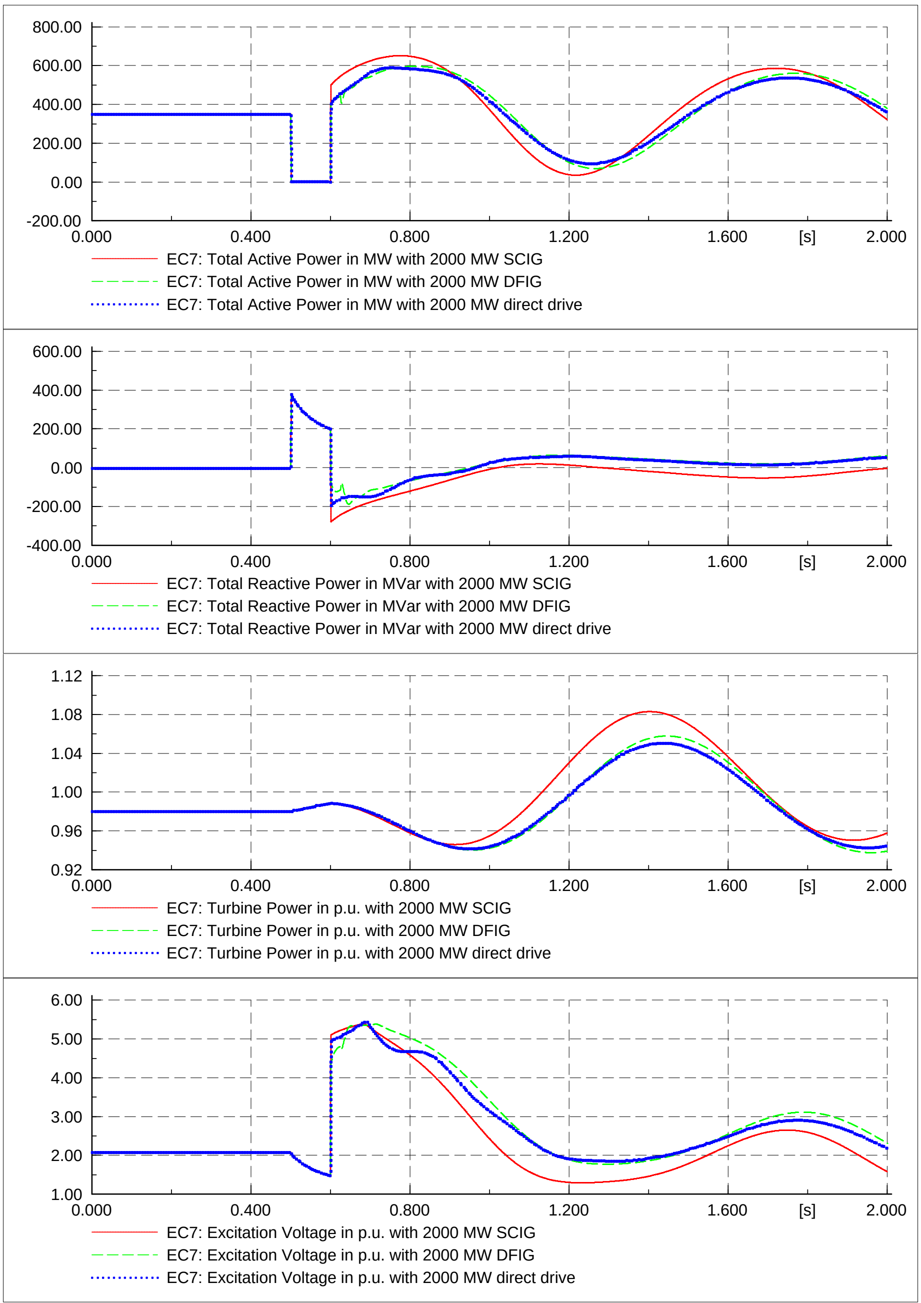


Figure 2.12: Active power, reactive power, turbine power, and excitation voltage of EC7 with 2000 MW different turbine types connected at Eemshaven. Response to 100 ms three-phase fault.

Reduced short-circuit power

Figure 2.13 shows the response of EC7, for the case where the total short-circuit power of the external grids is brought back to 2500 MVA and a wind park of

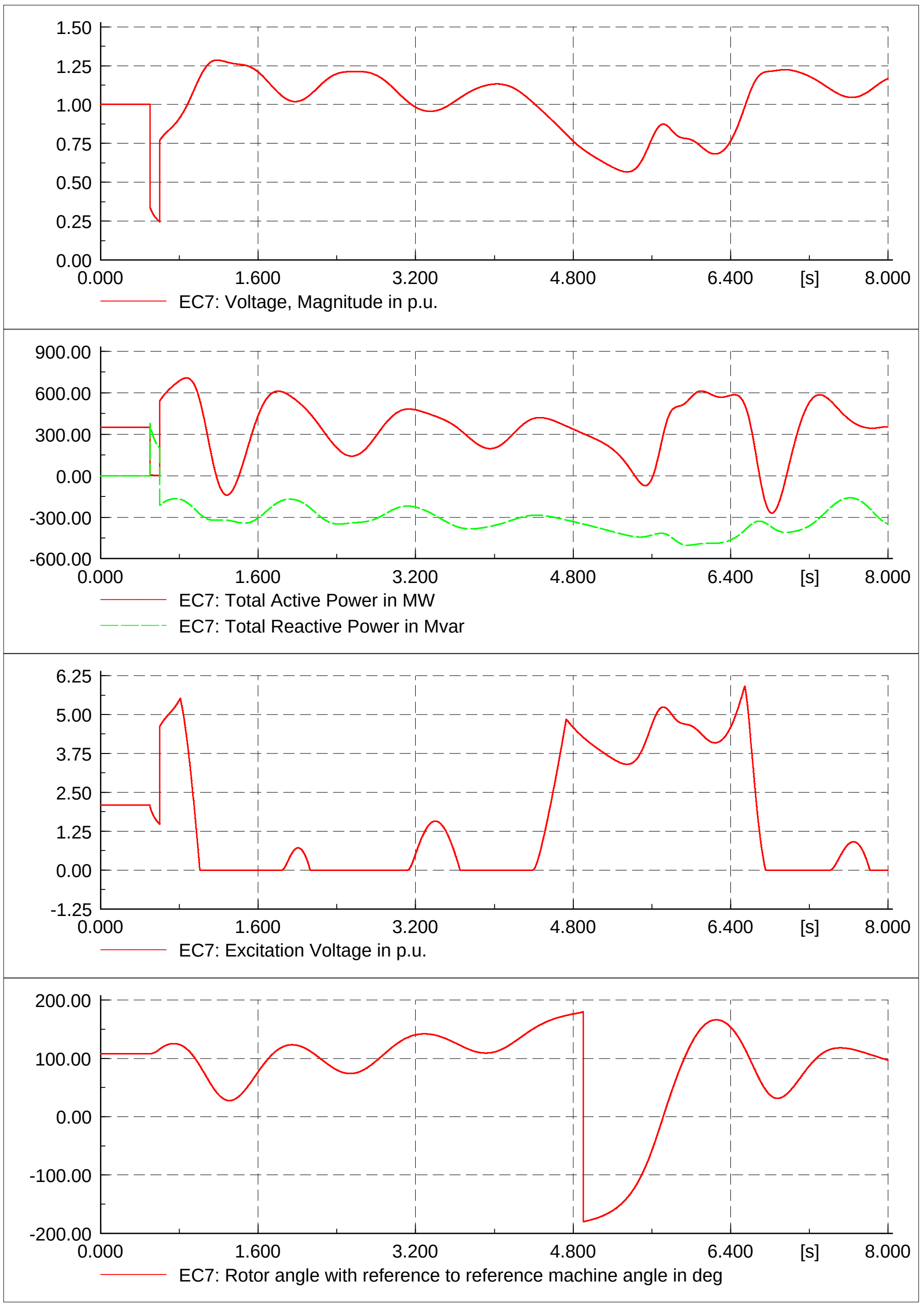


Figure 2.13: Response of EC7 with 2000 MW SCIG turbines and total external grid short-circuit power of 2500 MVA

2000 MW with only squirrel cage turbines is connected to the system. The short-circuit power in this situation is only about 4% of the actual available short-circuit power in the entire UCTE interconnected system and is the highest value which creates an unstable sitation. The same short circuit as before is applied, the turbines disconnect after 50 ms, and it can be seen that a pole slip occurs as the rotor angle becomes too large and the power plant becomes unstable when looking at a longer time span. The voltage also shows an oscillatory behaviour. From this calculation it can be concluded that only in a situation where the short-circuit power of the equivalent external grids is brought back to 4%, an unstable situation occurs.

Conclusions

From these simulations it can be concluded that voltage recovery will be the fastest when the wind turbines are disconnected (as in the induction machine case), this however does cause large oscillations.

When looking at the DFIG and direct drive, the direct drive turbine results in the best voltage recovery for the model used. Active power output is restored fastest in case of a DFIG turbine, since the direct drive generator responds like a synchronous generator. Oscillations in the reactive power flow are smallest for the direct drive turbine, but are damped slower. Taking all this into account the grid behaviour of the DFIG and direct drive turbine does not differ very much, both have the same kind of impact on system stability and similar control capabilities (see table 2.1). It has to be taken into account that these results strongly depend on the assumptions for converter ratings and control parameters. These conclusions can thus only be drawn for the models used.

Table 2.1: Comparison behaviour wind turbines and thermal power plant

	Voltage support	I_k'' **(p.u.)**
Squirrel cage	not possible	≈ 2
Direct drive	possible, not implemented	≈ 1
DFIG	possible, not implemented	≈ 3
Thermal plant	depending on exciter	≈ 5

2.2.2 Combined turbine types 1900 MW wind park

As a second test, a wind park of 1900 MW, consisting of 70% DFIG (1350 MW), 24% direct drive (450 MW), and 6% squirrel cage induction turbines (110 MW) is connected to 380-kV substation Eemshaven. The value of 1900 MW instead of 2000 MW as before was chosen for scaling reasons. A short circuit of 100 ms at the 380-kV terminal is simulated and the the output quantities of the wind park and reaction of the EC7 unit are studied.

The first graph in figure 2.14 shows the voltage at the Eemshaven 380-kV bus, for the situation when a short circuit occurs at t=0.5 sec and is cleared at t=0.6 sec. The figure shows the reaction for the case where all wind is disconnected on the fault (red, solid line), only the squirrel cage turbine is disconnected (green, dashed line), and the situation without wind (blue, dotted line). It can be seen that in the case when the wind turbines are not disconnected during the fault, the recovery of the voltage is a bit slower than in the other cases. This is caused by the reactive power the wind park absorbs once the fault clears (see figure 2.15).

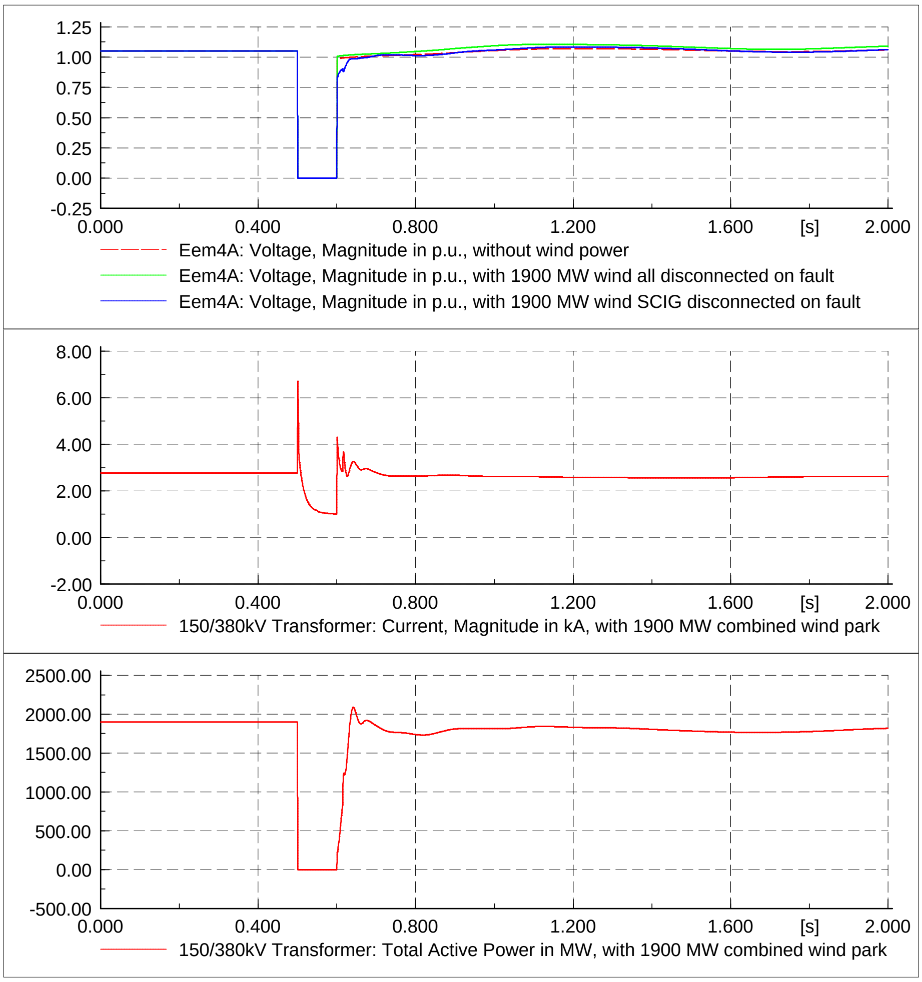


Figure 2.14: Voltage at Eemshaven 380-kV terminal, wind park current magnitude, and active power with 1900 MW wind park. Response to 100 ms three-phase fault.

The second and third graph of figure 2.14 and figure 2.15 show the output of the wind park for the case where only the SCIG turbines are disconnected. At the moment the short circuit occurs the current magnitude shows a short peak, mainly caused by the imaginary current (figure 2.15). The peak is caused by DFIG, which has the largest influence in the park. When the short circuit is cleared the same oscillations as occurred in the previous simulations, with only DFIG turbines, can be noticed. The active power, reactive power, and real current also show almost the same reaction as if the wind park consisted of DFIG turbines only.

Figure 2.16 shows the active and reactive power, the turbine power, and excitation voltage of the EC7 unit. The active power response does not show many differences between the three situations, it can be seen however that when the wind turbines get disconnected on the fault the conventional generation

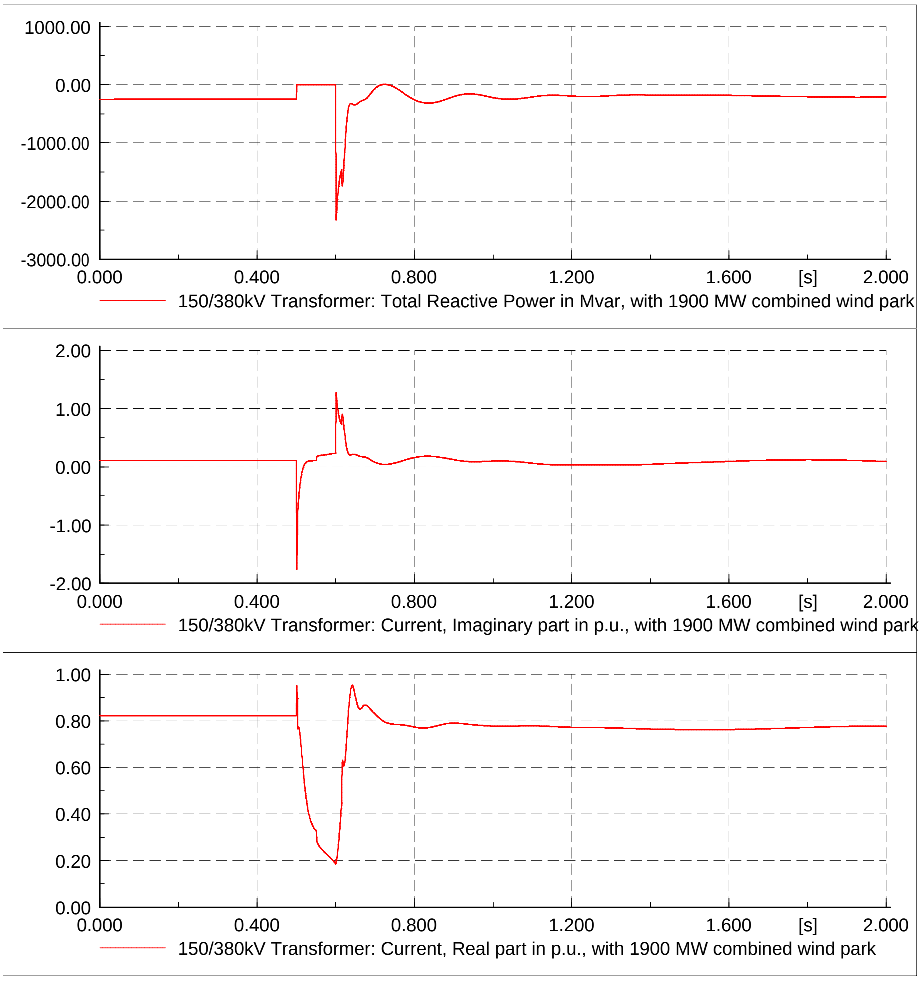


Figure 2.15: Reactive power, imaginary and real part of current of 1,900 MW wind park connected at Eemshaven. Response to 100 ms three-phase fault.

starts to absorb the reactive power produced by the cables of the wind park.

Conclusions

From these simulation it can be concluded that in a wind park with mainly DFIG turbines installed the behaviour is also mainly determined by the behaviour of this turbine type, although the oscillations caused by the direct drive turbine can also be noticed. Furthermore it can be seen that even in a situation with about 1900 MW of wind, 1790 MW of thermal power nearby, and 15 000 MVA short-circuit power in external grids, no (voltage) instability occurs in case of a short circuit. The same sort of calculations were carried out by [19] at substation Beverwijk, where the voltage response shows a similar behaviour as in these calculations.

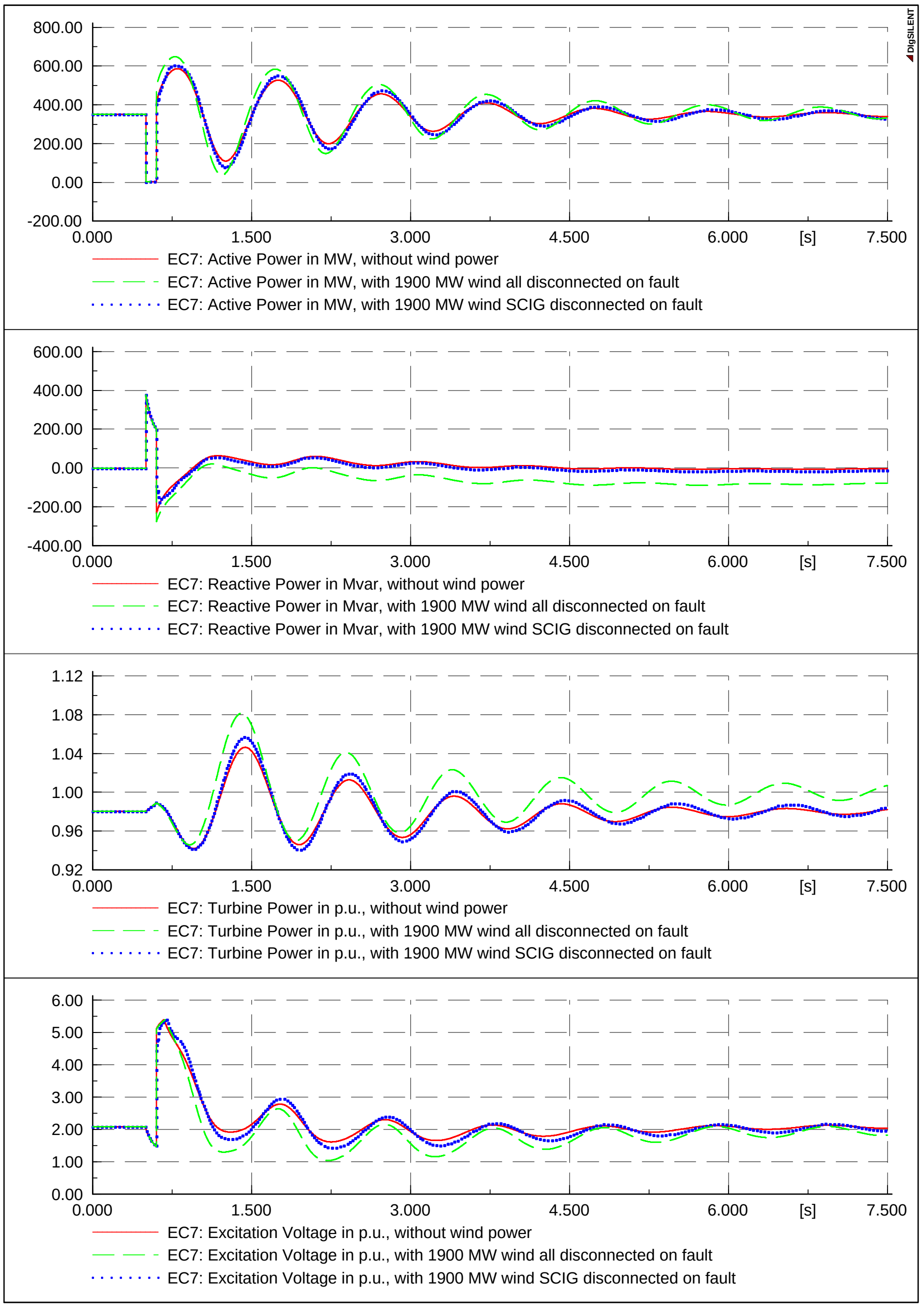


Figure 2.16: Active power, reactive power, turbine power, and excitation voltage of EC7 with 1900 MW wind park. Response to 100 ms three-phase fault.

2.3 Dutch electrical power system model

To be able to carry out dynamic calculations for the two scenarios, a grid model for the year 2008 and a grid model for the year 2015 are needed. These models are constructed from load-flow models with dynamic models for all large generating units included.

For both years the grid model of the UCTE (Union for the Co-ordination of Transmission of Electricity) is used, since this model is used also in the EWIS study. The load flow scenario in this model is based on EWIS scenario A, a high wind production in Northern Europe and maximum load [20]. The model consists of the entire UCTE grid, but for the simulations of this report only the Dutch part of the grid is used.

The Dutch grid is relatively small compared to the entire UCTE grid, it accounts for about 3.5% of the UCTE's total generating capacity. Most generation in the grid is located along the coast, with large power plants near Eemshaven in the North and near Maasvlakte and Borssele in the West. A large part of the load is concentrated in the 'Randstad', the area between the cities of Rotterdam, Amsterdam, and Utrecht. The main structure of the 380-kV grid is a double-circuit ring, from Maasbracht in the South to Zwolle in the North. This 380-kV ring structure is created to improve the certainty of supply. Wind parks are connected to the grid as described in chapter 3.

2.3.1 Grid model 2008

External grids

At the borders of the Dutch grid equivalent grid models are included, which represent the cross-border flows, short-circuit power, system inertia, R/X ratio, and primary frequency control of external grids (see table 2.2). The flows are taken from the load flow calculations of the complete UCTE model and the short circuit power is determined by short circuit calculations at the borders. Eight short circuits are created at the same time at the substations with a connection to Germany or Belgium. In this way the total short-circuit current (power) from outside the Dutch grid will match the actual short-circuit current fed in from abroad. Eventual loops where short-circuit currents from within the Dutch grid contribute to the short-circuit currents at the interconnections are ruled out in this way. The R/X ratio's were calculated with the TenneT 2008 grid model in a previous study by TenneT. Figure 2.17 shows the 2008 grid model, with the eight interconnections where equivalent grids are connected.

Within the UCTE interconnected system every country is responsible for a part of the primary and secondary control, proportional to the amount of locally installed generating power and summing up to a total of about 25 000 MW/Hz for the entire UCTE primary action. This value is used as a total for the external grids. As there are eight equivalent grids on the interconnections of the model, each equivalent grid will contribute to the primary control with 3125 MW/Hz.

To calculate the system inertia constant H, a method previously used in a dynamic grid study by KEMA is applied [22]. With this method the total system inertia J will be normalised on the short circuit power at the interconnections. First the total inertia of the entire UCTE has to be calculated

$$H_{av} = \frac{1}{2}\frac{J_{tot} \cdot (2\pi f)^2}{S''_{total}} \tag{2.2}$$

Figure 2.17: Dutch grid model for the year 2008. Green lines are 220-kV connections, red lines are 380-kV connections, and 1 to 8 are external grids (figure from [21])

with:

H_{av} Average inertia constant of units in the UCTE grid
J_{total} Total inertia of UCTE
S''_{total} Total installed power in UCTE

With an assumed average inertia constant H_{av} of 3.5 seconds and a total installed power S_{total} of 620 GVA, this leads to a total inertia J_{total} of $43.9 \times 10^6\,\mathrm{kgm}^2$.

The total system inertia can then be used to calculate an equivalent value for the inertia constant, using the same formula:

$$H_{eq} = \frac{1}{2} \frac{J_{tot} \cdot (2\pi f)^2}{S''_{k_{total}}} \tag{2.3}$$

with:

H_{eq} Equivalent inertia constant of UCTE grid
$S''_{k_{total}}$ Total short circuit power at Dutch interconnections

With the calculated total inertia J_{total} of $43.9 \times 10^6\,\mathrm{kgm}^2$ and a total short circuit power $S''_{k_{total}}$ of 60 GVA at the Dutch interconnections, this leads to an equivalent inertia constant H_{eq} of 36 seconds.

Table 2.2 gives the external grid parameters used for the calculations, where a negative sign means the export of power and a positive sign power import. The external grid at Zandvliet is set as a slacknode, which means in the load flow situation the active and reactive power at this node are calculated in a way the power balance is maintained. For the dynamic simulations all external grids contribute equally to the power balance.

Table 2.2: Interconnection parameters for the 2008 model

Connection	S_k'' (MVA)	P_{lf}(MW)	Q_{lf}(Mvar)	R/X ratio
Diele1	6 582	1 100	-101	0.13
Diele2	6 582	915	-131	0.13
Gronau	8 293	1 320	-126	0.09
Rommerskirchen	6 121	1 195	-112	0.08
Siersdorf	7 964	910	-185	0.02
VanEyk1	3 488	-792	-64	0.08
VanEyk2	4 871	-331	2	0.72
Zandvliet	16 125	-484	-95	0.06
total	**60 026**	**3 833**	**-812**	

Table 2.3: Key values for the 2008 model

Parameter	**Value**
Installed wind power	1 716 MW
Running thermal power plants	9 216 MW
Load	14 447 MW
Import	3 833 MW
Share of UCTE grid	3.5 %

Generators

The basis for the model used is a load flow model, not suited for dynamic simulations. This means the generators in the model are initially not equipped with a speed and excitation control. These controls are added to the model as generic models with model parameters and generator controls specified by KEMA [18] and the UCTE-IPS study [23] (see see Appendix D for an overview of the used models and parameters). All generators larger than 100 MW are equipped with speed and excitation controllers. If for a certain generator the information is not known, standard model with standard values will be used.

In reality the generators are connected to the grid via a step-up transformer, however to create a more simplified model with less parameters, the generators are directly connected to the transmission voltage level. A short line is included between generator and grid to represent the impedance of the step-up transformer.

Loads

The loads are represented as 100% static loads, with a constant impedance. This yields that in case of a voltage drop, the load current will drop equally, thus causing a quadratic power drop.

Lines

Lines are included as lumped element (π) models instead of distributed parameter line models, since transient phenomena are not being studied.

DC-connections

NorNed, the DC-connection to Norway is not included as a dynamic model. NorNed will usually be exporting power and is thus represented as a static load of 700 MW.

Limitations in applicability of model

The use of equivalent grid models instead of the entire UCTE model brings the advantage of (much) shorter calculation times. A drawback however is the absence of generator models outside the Netherlands, discarding all dynamic information about the cross-border interaction. It is thus not possible to use the model for detailed information about dynamic interaction with the neighbouring countries, only relative differences can be determined. The use of external grid models instead of (a part of) the entire UCTE grid will also probably cause a more stable situation, as no interaction occurs between generators in the Netherlands and generators abroad.

Furthermore, the load-flow model on which the dynamic model is based did not include any dynamic data. This means all controllers of the generators were added separately using the two reports [18, 23] mentioned before. The dynamic data of these two reports was not always consistent, resulting in a final model that is build using a rather quick-and-dirty method. Results that are obtained in the calculations thus do not necessarily give a representative view of the actual situation, but give an indication and can be used for relative comparison.

A validation of the model will be carried out in chapter 4, by comparing the results of a previous stability study with results obtained using the grid model as described.

2.3.2 Grid model 2015

The 2015 model is composed out of the 2008 model, by applying the changes in grid topology described by the TenneT Quality and Capacity (Q&C) plan 2008–2014 [24] (see Appendix E), whilst the representation for the other components has not changed. According to this Q&C document the assumed load in 2014 will be around 21 500 MW. Taking into account an average growth of 2% per year, the total load for the year 2015 becomes 22 000 MW.

As import scenario, the value of 2000 MW from the TenneT ‘green revolution’ scenario is used. It is assumed that the power distribution amongst the different interconnections is the same as in the year 2008. For the thermal power plants, the merit order for all existing and presumed new thermal production

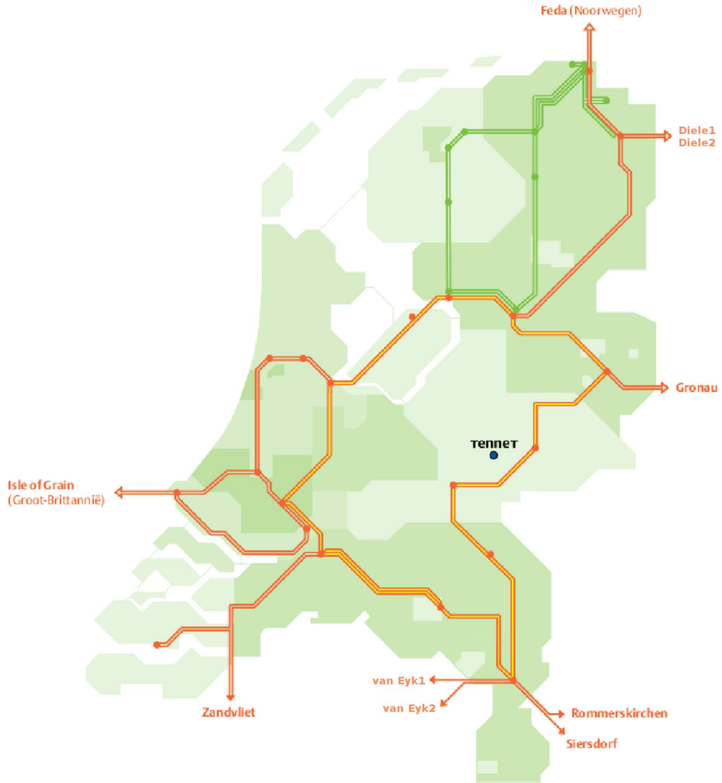


Figure 2.18: Year 2015 grid model. Green lines are 220-kV connections and red lines are 380-kV connections (figure from [21])

for the year 2014 of the Q&C document is being used. It is assumed no new power plants are installed between 2014 and 2015.

From the year 2015 there will be 7302 MW of wind power installed, the percentage thermal power plants is thus reduced drastically and also distributed differently. Especially near 220-kV substation Louwsmeer production has decreased, because of this the reactive power producation and thus voltage support has also become less and low voltages (down to 0.97 p.u.) occur at 220-kV substations Eemshaven, Ens and Louwsmeer. These low voltages are compensated for by changing the tap changers at the 220/380 kV transformers at Eemshaven and Lelystad to -5 and by placing capacitor banks of 150 Mvar at Ens and Louwsmeer. Figure 2.18 shows the Dutch grid for the year 2015. In this figure a DC-connection to Great Brittain (BritNed) can be seen, however this connection was not taken into account in the calculations.

Since the grid layout has changed the short-circuit currents, R/X ratios, and total inertia constant of the external grids have to be re-calculated. The short-circuit calculations are carried out with the TenneT 2014 load flow model as described before and the R/X values are taken from previous TenneT calculations again. The total system inertia J_{total} is calculated again with equation 2.2, resulting in $J_{total} = 53.2 \times 10^6\,\mathrm{kgm}^2$. Using equation 2.3 with a value of $S''_{k_{total}}$ of 59.2 GVA, the 2015 value for H_{total} becomes 44 seconds. Table 2.4 shows all the parameters for the 2015 external grid settings, where again negative sign means the export of power and a positive sign power import.

Table 2.4: Interconnection parameters for the 2015 model

Connection	S_k'' (MVA)	P_{lf}(MW)	Q_{lf}(Mvar)	R/X ratio
Diele1	6 450	568	-53	0.13
Diele2	6 450	473	-68	0.13
Gronau	7 964	682	-65	0.09
Rommerskirchen	618	1 195	-58	0.08
Siersdorf	7 832	470	-96	0.02
VanEyk1	3 488	-409	-50	0.08
VanEyk2	4 805	-171	2	0.72
Zandvliet	16 125	-250	-74	0.06
total	**59 235**	**1 981**	**-462**	

Table 2.5: Key values for the 2015 model

Parameter	**Value**
Installed wind power	7 302 MW
Running thermal power plants	13 238 MW
Load	22 000 MW
Import	1 981 MW

Chapter 3

Distribution of wind power in the Netherlands

This chapter will give an overview of the 220 and 380-kV substations to be used for the connection of aggregated wind parks and the amount of installed wind power at these substations for the years 2008 and 2015. Lower voltage levels of 110 and 150 kV are taken into account for consistency and the connection of loads and thermal generation. For simplification all aggregated wind power has been thought to be connected to the 220 and 380-kV network.

3.1 Connection points

3.1.1 Update of EWIS I distribution

In phase I of the EWIS project the modelling of wind power in the Netherlands for load flow studies was done by dividing the total wind power (in megawatt) over six nodes in the grid (see table 3.1). Phase I was limited to examination of the load-flow situation in 2008, as mentioned before.

The assumed distribution of wind power by the EWIS project is now updated looking at the actual installed wind power according to the Wind Service Holland (WSH) database [25], and its distribution in the Netherlands (see figure 3.1). Information from this database shows to a lower amount of the wind power connected at the nodes Eemshaven and Louwsmeer and a higher amount at Lelystad and Beverwijk (see table 3.1). This update does not have much influence on the results obtained for phase I (load-flow analysis), furthermore this part of the study has already been finished off. However, for the dynamic analysis that will be performed in this thesis and the second EWIS the updated distribution will be used.

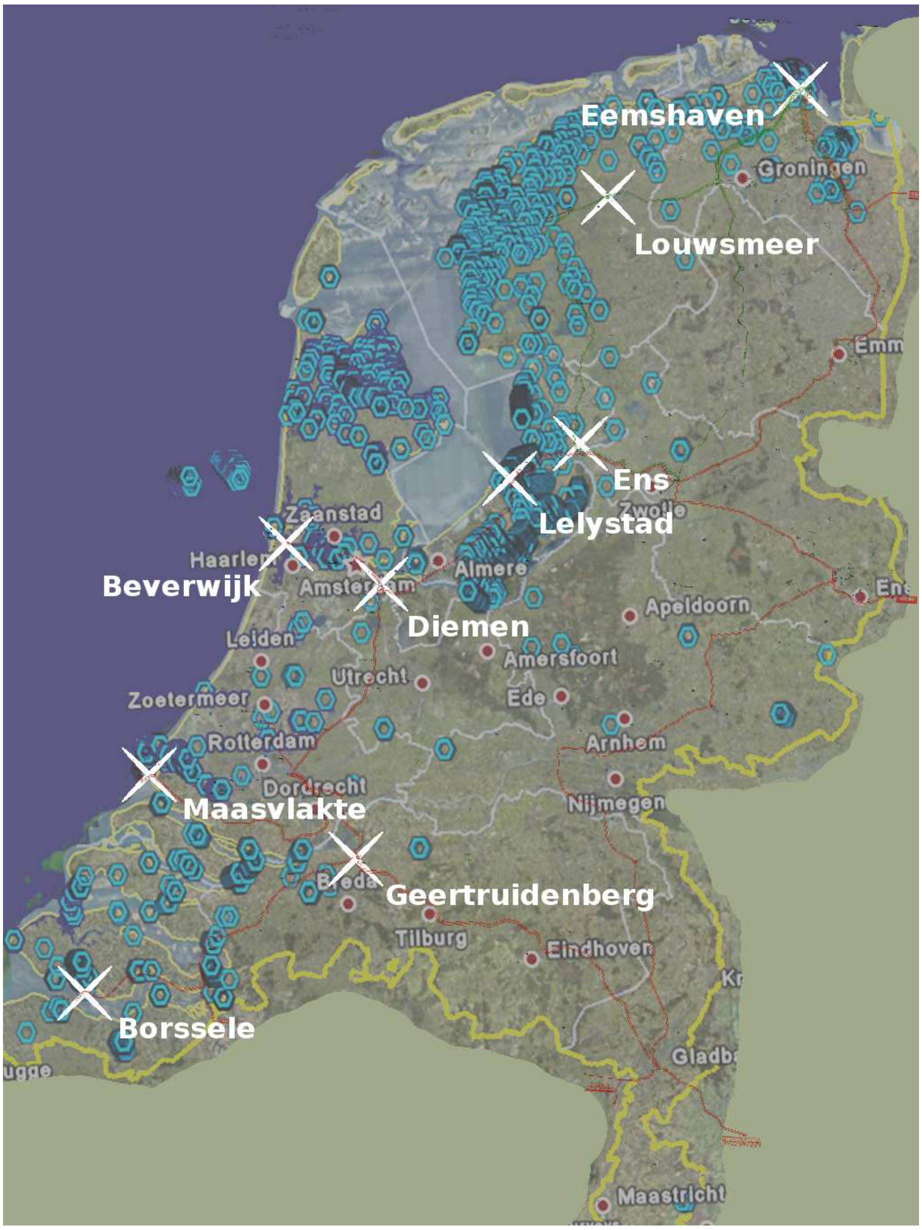


Figure 3.1: Overview of wind turbines (blue circles) and connection points (white crosses) in the Netherlands for the year 2008, with Ens and Diemen added with respect to EWIS I

Table 3.1: Connection points from EWIS phase I: installed power according to EWIS study and actual values for 2008

Substation	**EWIS (MW)**	**Actual (MW)**
NEEM-A2 (North 1 Eemshaven)	350	126
NLSM-A2 (North 2 Louwsmeer)	350	134
NLLS 3 (North 3 Lelystad)	350	598
NBSL.A1 (South 1 Borssele)	250	168
NMVL 3 (South 2 Maasvlakte)	200	289
NVLN 3 (Offshore Velsen/Beverwijk)	220	401
Total	**1720**	**1716**

3.1.2 Additional connection points

The assumed increase of installed wind power related to 2015 is large in the province of Noord Hollland (Beverwijk) en Flevoland (Lelystad). Therefore two additional connection points Diemen and Ens are introduced. Diemen is created as an extra point to distribute the wind power in Noord Holland equally over Diemen and Beverwijk, since at Beverwijk the connection of a large amount of offshore wind power is expected. Ens is created as an extra connection point, because of the plans to install a large wind park in the IJsselmeer, and the already large amount of wind power at Lelystad. Geertruidenberg is used as a collection point for all the scattered onshore wind power in the southern part of the country (see table 3.2).

Table 3.2: Nine connection points with their share of wind power for the year 2008

Substation	**MW**
Eemshaven	126
Louwsmeer	134
Lelystad	519
Ens	79
Borssele	168
Geertruidenberg	169
Maasvlakte	120
Beverwijk	273
Diemen	128
Total	**1716**

3.2 Turbine distribution 2008

Since different turbine types behave differently in case of a disturbance (see chapter 2), it is important to obtain an overview of the distribution in turbine types. This distribution of turbine types at the different connection points is calculated using the data of the WSH database in which the 21 largest parks of the Netherlands are given including their turbine types (summing up to a total of 644 MW). For the year 2008 this gives a distribution of 8% squirrel cage turbines, 64% DFIG turbines and 28% full converter turbines. The remaining power capacity (of 1072 MW) is assumed to be distributed according to figure 3.2, which gives the distribution of technologies worldwide. For the year 2008 this has an estimated distribution of 15% squirrel cage turbines, 60% DFIG turbines and 25% full converter turbines. The variable rotor resistance turbines are not taken into account as a separate group in this study but are included in the squirrel cage group. This is done because the share of variable rotor resistance turbines is very small, the grid behaviour very similar to squirrel cage turbines, and in EWIS also only three types are being used.

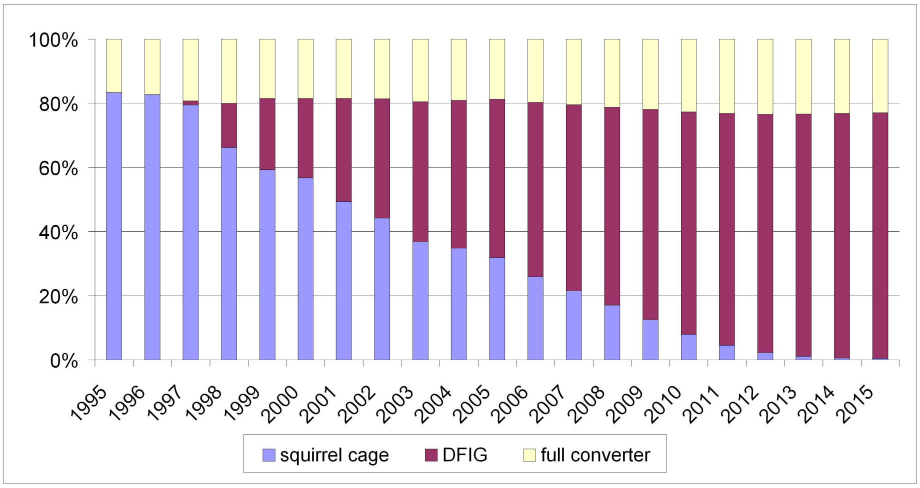


Figure 3.2: World share of cumulative installed wind power (data from [26] extrapolated)

Table 3.3 gives the total installed power per generator type based on the before mentioned percentages for wind parks. A final distribution of 17.5% squirrel cage, 61% DFIG and 21.5% full converter turbines can be found. In 2008 all installed wind power is connected to the distribution and/or sub-transmission network ($\leq$ 150 kV) so even the larger wind parks that exist do not connect directly to the EHV-transmission grid.

3.3 Turbine distribution 2015

3.3.1 Division of wind power over nodes

Several scenarios exist for the growth in wind production in the Netherlands. The government is targeting to have doubled the onshore wind capacity (an increase of 1700 MW) and add to 450 MW in offshore wind parks by 2012. Looking at existing plans and growth, the doubling of onshore wind is a plausible scenario for 2015. At most connection points the amount of wind power will double, but at some points a larger growth is assumed. Repowering near

Table 3.3: Installed wind power and type distribution 2008 (MW)

Substation	**Squirrel cage**	**DFIG**	**Full converter**	**Total**
Eemshaven	34	20	72	126
Louwsmeer	20	80	33	133
Lelystad	127	275	117	519
Ens	28	36	15	79
Borssele	16	125	27	168
Geertruidenberg	27	106	36	169
Maasvlakte	8	100	13	121
Beverwijk	23	211	39	273
Diemen	17	92	19	128
Total	**300**	**1045**	**371**	**1716**

Lelystad and a high potential for new onshore wind near Borssele causes higher numbers (see Appendix F, table F.1). Two new wind parks of 300 MW and 600 MW near Eemshaven and Ens cause an extra increase of 900 MW, bringing the total increase on land to about 2600 MW.

For offshore wind the assumptions of the TenneT Quality and Capacity plan 2008–2014 [24] are used, because there are already a lot of applications filed for offshore wind parks. The government aims at 450 MW extra offshore wind power in 2012 added to the 107 MW (wind park NSW) already installed [27], but current plans show about 950 MW operational in 2012. The Quality and Capacity plan states that in 2014 3000 MW will be installed. 570 MW (including 120 MW realised in 2008 by wind park Q7) of this is taken as the amount desired by the government, which leaves an extra 2430 MW that still has to be distributed by location. A distribution of 15% for the top and bottom coast locations (Eemshaven and Borssele) each and 35% for the other two (Beverwijk and Maasvlakte) is taken into account (see Appendix F, table F.2). This distribution is found by looking at the locations of the currently filed applications [28]. This distribution of the connection of offshore wind power is more detailed compared to the base case of the Quality and Capacity plan where only Maasvlakte and Beverwijk are taken into account.

This assumed additional onshore and offshore wind power installed between 2008 and 2015 amounts 5586 MW, leading to a total assumed installed wind power in 2015 of 7302 MW. Based on the distribution of figure 3.2 0.5% squirrel cage turbines, 76.5% DFIG turbines and 23% full converter (direct drive) turbines are assumed in 2015 (see table 3.4). It is assumed that the distribution in turbine types will be equal at each substation, as the actual distribution is not known.

Table 3.4: Installed wind power (in MW) and type distribution for 2015

Substation	Squirrel cage	DFIG	Full converter	Total new	Total 2015
Eemshaven	4	605	182	665	791
Louwsmeer	1	205	61	134	267
Lelystad	7	1009	303	800	1319
Ens	3	520	156	600	679
Borssele	4	664	200	700	868
Geertruidenberg	2	258	78	169	338
Maasvlakte	5	835	251	970	1091
Beverwijk	8	1295	390	1420	1693
Diemen	1	196	59	128	256
Total	**35**	**5587**	**1680**	**5586**	**7302**

3.3.2 Division among distribution and transmission grid

In 2015 some parts of the total installed wind power will be connected to the EHV-transmission grid instead of the distribution and sub-transmission grid. It is assumed that offshore wind parks and large onshore wind parks ($\geq 200\,\text{MW}$) are connected to the transmission grid, whilst smaller new and repowering projects are still connected to the distribution grid. This leads to the distribution given in table 3.5.

No new squirrel cage turbines will be built any more, which means the squirrel cage turbines that are remaining in 2015 will all be connected to the distribution grid. All new installed wind power, which is listed under transmission in table 3.5, will be divided up into DFIG and full converter turbines according to the percentages mentioned before. The remaining power that is not distributed yet after these steps is listed under the distribution level of the DFIG and full converter turbines, according to the distribution percentages (see table 3.4).

Appendix F, table F.4 gives an overview of the currently installed wind power, the new installed wind power until 2015, and the total amount of wind power in 2015. This table can be used as a general overview, whilst detailed information must be taken from table F.3.

Table 3.5: Additional wind power (MW) from 2008 to 2015, divided into connection to distribution and EHV-transmission grid

Substation	**Distribution**	**Transmission**
Eemshaven	0	665
Louwsmeer	134	0
Lelystad	800	0
Ens	0	600
Borssele	335	365
Geertruidenberg	169	0
Maasvlakte	120	850
Beverwijk	0	1420
Diemen	128	0
Total	**1686**	**3900**

Chapter 4

Results

This chapter describes the results of the calculations that are carried out to study the dynamic behaviour of the Dutch grid, with large scale wind power integration.

4.1 Grid model validation

It is know from previous studies that when in the 2008 situation both circuits between Maasvlakte and Crayestein get disconnected, an unstable situation occurs at the Maasvlakte generators [29]. To validate the model of the Dutch grid, separated from the UCTE model, the simulations from [29] are being reproduced and the results are compared. From these calculations it can be seen that the grid used for the calculations of this thesis shows a much more damped behaviour than observed in previous studies. Only when the short circuit power of the external grids was set to 100 MVA in each external grid, the system became unstable. This is not a realistic value, since the total short-circuit power is in that case about one hundredth of the actual short-circuit power.

The study by [29] uses a larger part of the German and Belgian grid, which plays an important role in system stability. A grid with at the interconnections equivalent external grids with representative short-circuit power modelled will be (much) more stable than a grid where (parts of) the neighbouring grids are included. To get more representative results for the actual grid behaviour it would be necessary to include at least a part of the external system in the model. The model used is thus only usable for making a relative comparison between the results of the different situations.

4.2 Grid situation 2008

Several fault situations are taken into account to get insight in the grid response, this section describes a selection of the situations with most notable results.

First the worst-case response will be described where all wind power generation is disconnected during a fault. Then a case will be described that focusses on a short circuit in the centre part of the grid, which causes the disconnection of multiple large wind parks. Substation Ens was chosen for this situation since a short circuit at Ens causes largest amount of disconnected wind. This was determined by creating one by one short circuits at all substations with wind connected. Another short circuit is calculated at substation Eemshaven to study the effects of a short-circuit at a substation with much large thermal power plants nearby, and to make a comparison with the Eemshaven test case as described in chapter 2.

Finally two N-2 cases are simulated, where one circuit is assumed to be in maintenance and the other is switched off after a short circuit. These N-2 cases are taken into account as they are assumed to have larger impact on system stability because of the increase in impedance and the higher loading of lines.

4.2.1 Artificial worst case

A short circuit of 150 ms is created at all nine wind park substations at the same time. Thus causing a voltage drop to 0 p.u. at those substations and the disconnection of about 1700 MW of wind generation. The largest oscillations in voltage (2%) occur at substations Lelystad, in the center of the grid. This could be expected, since there are few large thermal power plants nearby, the only plant nearby (Flevocentrale) is assumed off in the EWIS model, and for the year 2008 the largest amount of wind power is connected at Lelystad. The oscillations damp out fast, and the voltage restores to above 1 p·u· in about 52 ms. This means that with the grid representation used, the system restores fast from a situation where all wind is instantly disconnected.

At the interconnection Maasbracht-Siersdorf oscillations in the active power flow of about 1300 MW occur. This however does not represent the actual oscillations in power, since equivalent grid models at the interconnections are used. The oscillations will probably be larger in a real situation, as generators in the external grids will also start to oscillate. Furthermore, it can be seen that the interconnection from Geertruidenberg to Zandvliet experiences a swinging in the active power of about 1300 MW. Initially power is exported on this connection, but during the swing period active power is imported from Belgium (see figure 4.1, red solid line). In this way the power balance is restored after about 7 seconds.

4.2.2 Short circuit calculations

150 ms short circuit at Ens

When a short circuit occurs at substation Ens, six substations with wind parks connected experience a voltage drop below 0.8 p.u. and are thus disconnected. These are at Ens, Eemshaven, Louwsmeer, Diemen, Lelystad, and Beverwijk with a total power of 1258 MW. This is a worst case value, since all wind parks are clustered whilst in the real situation the turbines are more spread and thus will not all experience this voltage drop below 0.8 p.u. Voltage oscillations that occur at Ens have disappeared in about 5 seconds in this case, and are just after the short circuit has cleared about 1%. The voltage recovers very fast and after 1 ms it has returned to 1 p.u.

Figure 4.1 is showing the active power flow at the interconnections Diele1, Diele2, Zandvliet and VanEyk1 for the worst-case situation (red, solid line) and a short circuit at substation Ens (green, dashed line). It can be seen that between the worst-case situation and a short-circuit situation at Ens only small

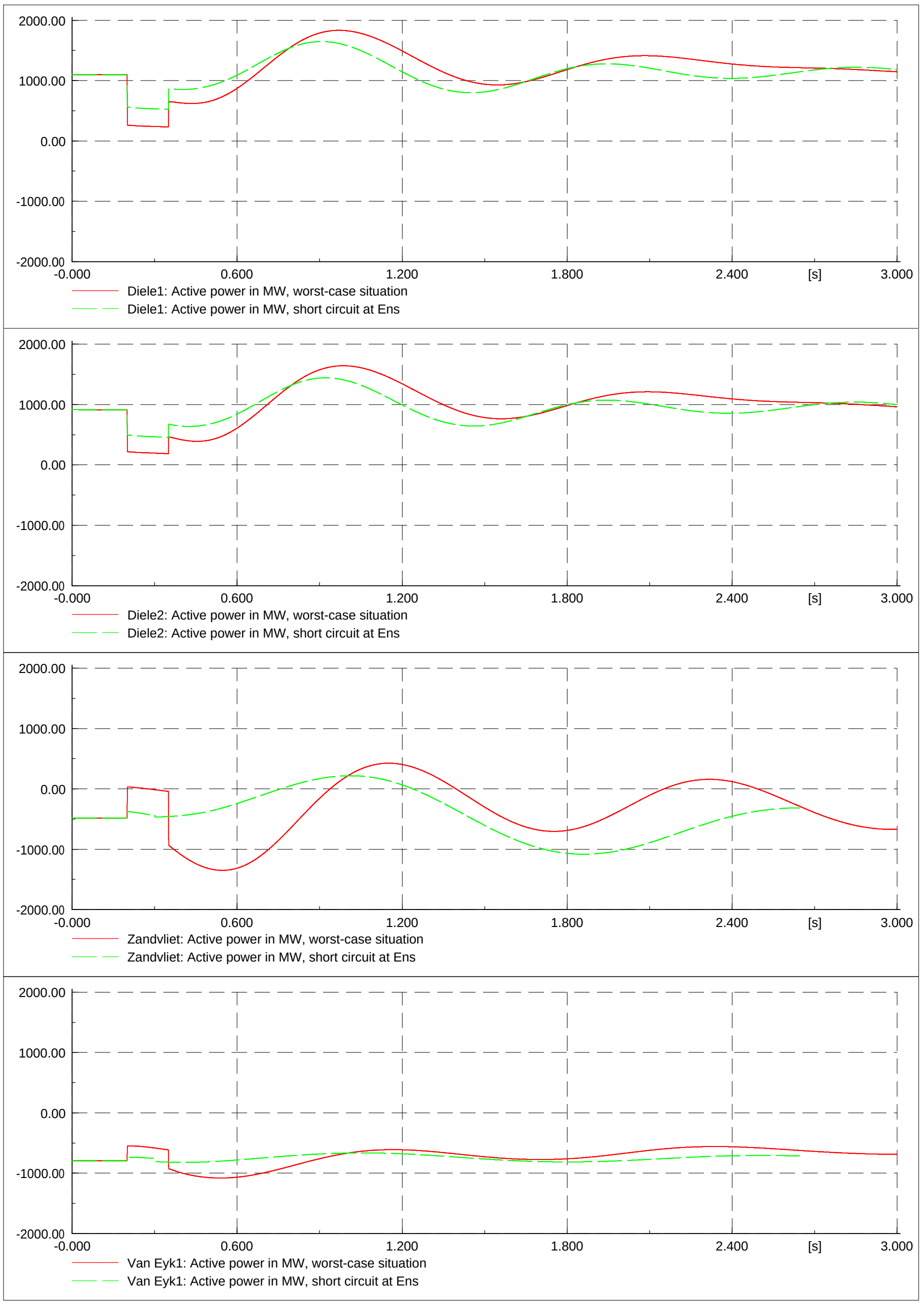


Figure 4.1: Active power flow interconnections, worst-case situation and short circuit at Ens 2008

differences occur at most interconnections. Diele1 and Diele2 show large oscillations in both cases, because of the large amount of disconnected wind generation relatively nearby. The Van Eyk interconnection only shows small oscillations, as there is not much installed wind nearby that connection. Again it should be noted that because of the representation of the external grid, these oscillations may not represent the actual situation, but should mainly be used for comparison.

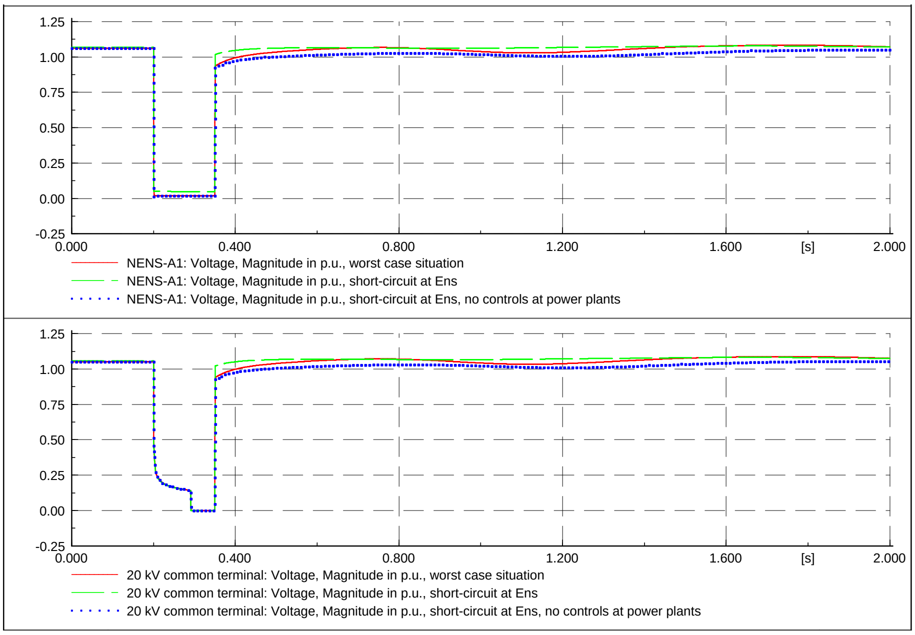


Figure 4.2: Voltage at substation Ens, worst-case situation and short circuit at Ens for the 2008 situation

The voltage at substation Ens (see figure 4.2) only shows a small difference between the worst-case situation (red, solid line) and a short circuit at Ens (green, dashed line). In the worst-case situation the voltage shows a little slower return to its nominal value since more wind power is lost. When looking at the 20-kV bus voltage, a drop can be noticed 90 ms after the short circuit occurs. This drop is caused by the disconnection of the wind park at that time. Before the wind park is disconnected it still provides some voltage support so the voltage at the 20-kV terminal does not drop to zero immediately.

Even in the situation where all excitation controls and governors of the thermal power plants are switched off, no instabilities occur. The voltage at substation Ens though shows a slower voltage recovery and an oscillation that lasts a little longer than in the case where controls are added to the thermal power plants (see figure 4.2, blue dotted line).

From these calculations it can be concluded even a worst-case calculation does not lead to instabilities in the grid. It has to be noted again that the representation of the interconnections play a major role in this stability, and once the actual external grids are included instabilities may occur.

150 ms short circuit at Eemshaven

When a short circuit occurs at substation Eemshaven, the voltages at substations Eemshaven, Louwsmeer and Ens drop below 0.8 p.u., thus causing the disconnection of all wind at these stations with a total amount of 339 MW.

Voltage oscillations in this case are only about 2% (see figure 4.3), since only a relatively small amount of wind power is disconnected. Oscillations that occur in the power flow at the interconnections are the largest at the Meeden–Diele connections and show an amplitude of 800 MW. Steady state in the power flows returns within 6 seconds (see figure G.1).

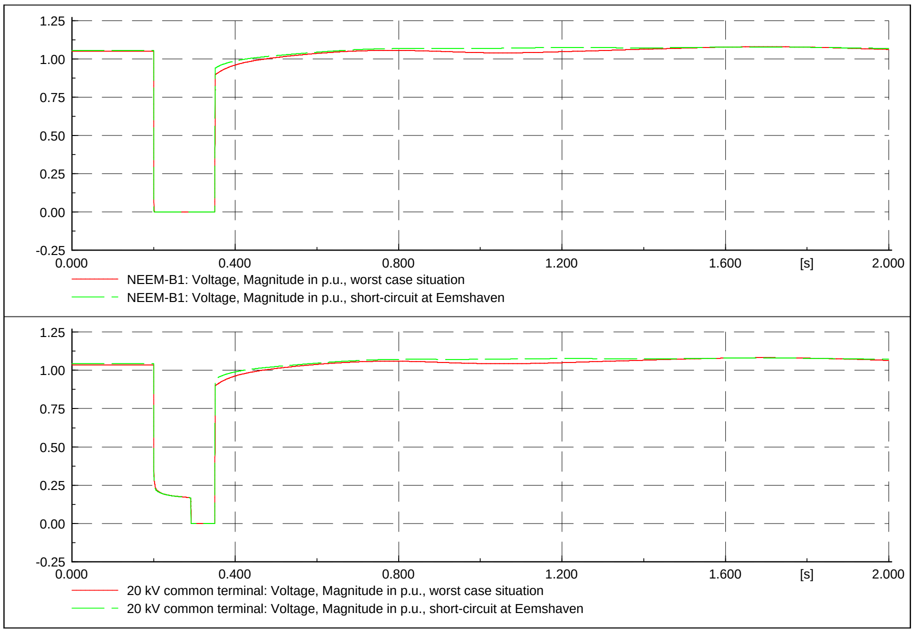


Figure 4.3: Voltage substation Eemshaven, worst-case situation and short circuit at Eemshaven for the year 2008

Figure 4.4 shows the response of the Eemscentrale (EC7). Active power, reactive power, and excitation voltage show a strong resemblance with the reaction of EC7 in previous simulations with just substation Eemshaven. As the short circuit occurs, the active power output drops to zero and the generator begins to produce reactive power. At the moment the short-circuit is cleared the turbine absorbs reactive power and active power production returns after some oscillations. The excitation voltage shows only a small increase when the short circuit occurs, because the excitation is taken from the generator terminals. When the short circuit is cleared an increase in excitation can be noticed. The final value of the excitation voltage lays slightly lower than the initial value as the reactive power output of the EC7 plant is reduced, caused by the reactive power production of the wind park cables.

4.2.3 N-2 situations

To create a more severe situation than in case of a short circuit at one single substation without losing circuits, two N-2 situations are simulated where maintenance is assumed at one circuit and another is disconnected after the clearing of a short circuit.

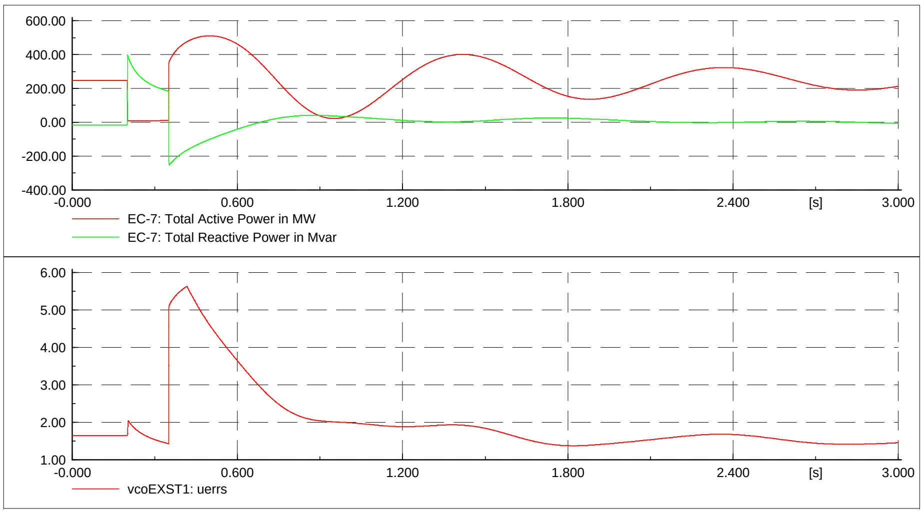


Figure 4.4: Short circuit at substation Eemshaven, response of EC7: active power, reactive power, and excitation voltage

Eemshaven

A N-2 case in around substation Eemshaven is chosen, because there is a large amount of thermal power plants near Eemshaven. Problems could thus be expected when several lines are disconnected.

In this case it is assumed that one of the 380-kV circuit Eemshaven–Meeden is in maintenance. A short circuit occurs at the second line between Eemshaven and Meeden, causing the disconnection of this line after 100 ms.

This short circuit is causing the disconnection of the wind parks at substation Eemshaven and Louwsmeer, with a total power of 259 MW. The largest oscillations in voltage can be observed at substation Eemshaven and are about 2.5%. Osillations at Louwsmeer and Ens are only 1% and 0.5%, and the voltage returns to 1 p.u. in about 1 ms.

Oscillations in active power flows at the interconnections which occur after the line is switched off are relatively small, only up to 400 MW at both Meeden–Diele circuits. The relative small amplitude of the oscillations is caused by the fact that not much power is disconnected in this case, and only few large power substations experience a large voltage drop.

Lelystad

As a second N-2 case, the circuit between Diemen and Ens is assumed to be in maintenance when a short circuit followed by disconnection of the line Lelystad–Ens. This case was taken into account, as switching off the line Lelystad–Ens causes a disconnection of the 380-kV ring in the grid.

Both of these connections consist only of one circuit, resulting in the situation that Lelystad is only still connected to Diemen (by one circuit). This short circuit results in the disconnection of 1258 MW of wind, wind parks Eemshaven, Louwsmeer, Lelystad, Ens, Beverwijk, and Diemen are disconnected. Voltage oscillations up to 2% are noticeable at substation Diemen, and are damped out after 6 seconds. Since after the short circuit all wind at Lelystad is disconnected and there is no large power plant in operation at Lelystad, no large power flows occur. Lelystad and Ens hardly show any voltage oscillations in this case, and the voltage thus recovers fast (1 ms) to 1 p.u..

In this situation the largest oscillation in active power at the interconnections occurs at Geertruidenberg–Zandvliet, with an amplitude of about 1500 MW. Meeden–Diele also experiences oscillations of 600 MW at both connections. All power oscillations at the interconnections are damped out after about 8 seconds (see figure G.2).

4.2.4 Comparison 2008 fault situations

Table 4.1 gives an overview of the different fault situations. It shows the amount of disconnected wind power caused by the fault, the largest voltage overshoot at a 380-kV substation, the time it takes the voltage to recovers to 1 p.u. at substation Ens and the largest oscillation at the interconnections. Substation Ens was chosen for this comparison as the largest oscillations in voltage occur at Ens. The table shows that the voltage recovery time is worst in the worst-case situation, mainly caused by the fact that because of the short circuit at nine 380/220kV-substations the voltage drops to zero at those nine substations and many power plants have to recover from the fault. Furthermore a large difference in power oscillation occurs between the short circuit at Ens and the N-2 situation near Lelystad, whilst the same amount of wind is disconnected. This difference is caused by the disconnection of the ring structure in the grid, resulting in changing power flows.

Table 4.1: Results 2008 simulations

Fault scenario	**Wind disconnected (MW)**	**Largest voltage overshoot (%)**	**Voltage recovery time Ens (ms)**	**Largest power oscillation on interconnection (MW)**
Worst case	1716	2	52	1300
Short circuit Ens	1258	1	1	750
Short circuit Eemshaven	339	2	1	800
N-2 Eemshaven	339	3	1	400
N-2 Lelystad	1258	2	1	1500

4.3 Comparison grid behaviour 2008 and 2015, without wind power

In this case all the wind power is removed from the grid, and the loads for both years are reduced with the value of the installed amount of wind power (see table 4.2). A comparison between 2008 and 2015 can thus be made, without the influence of wind on the system behaviour. Figure 4.5 shows the voltage at substation Ens, and figure 4.6 shows the power flows at the interconnections for a worst-case situation, where a short circuit occurs at all substations where wind will be connected.

Table 4.2: Comparison grid situation no wind power 2008 and 2015

Parameter	2008	2015
Load (MW)	12 731	14 698
Generation (MW)	9 216	13 238
Total import (MW)	3 833	1 981

It can be seen that for the 2015 situation the oscillation in the voltage at substation Ens is larger than in the 2008 situation. Oscillations that occur in the interconnection power flows are also larger and take a longer time to damp.

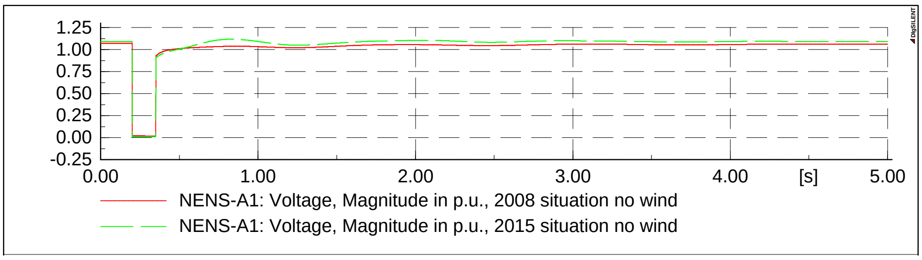


Figure 4.5: Voltage at substation Ens with no wind installed for the 2008 and 2015 situation

These differences are mainly caused by the fact that there is more generation installed in the grid, and thus more power is lost during the short circuit(s). All generators have to return to their normal operating point as the short circuit is cleared and this is accompanied by oscillations.

4.4 Grid situation 2015, with 'old' rules and regulations applied

The following results are obtained by simulations with the 2015 grid, as described in chapter 2.

4.4.1 Artificial worst case

In the 2015 worst-case situation 7302 MW of wind power is being disconnected, causing large oscillations and flows at the interconnections (up to 1500 MW at

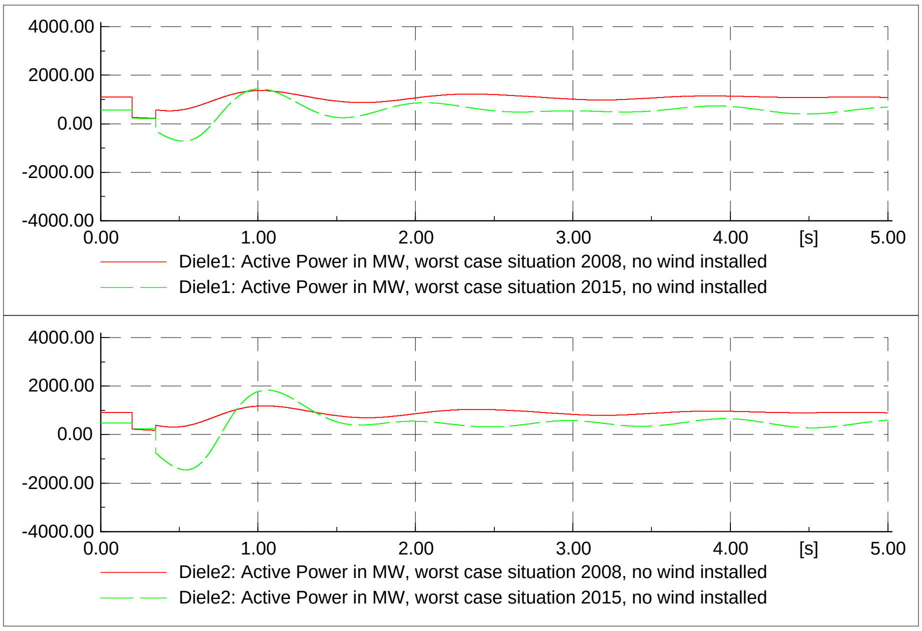


Figure 4.6: Active power flow at interconnection Meeden–Diele, worst-case situation with no wind power installed for the 2008 and 2015 situation

both Meeden–Diele circuits). When this would happen in a real situation, the interconnections get overloaded, since the total import capacity of the Netherlands is only about 5000 MW and the remaining 2000 MW is not available as a national reserve. At substation Ens voltage oscillations of about only 1 % occur, but voltage recovery to 1 p.u. takes 290 ms (see figure 4.7). This could be expected, since over 7000 MW of generating power is disconnected from the grid and the thermal power plants account for only about two third of the total power in operation. The relatively stable situation is again mainly caused by the representation of the equivalant external grids.

4.4.2 Short-circuit calculations

150 ms short circuit substation Ens

When a short circuit occurs at substation Ens 5000 MW of wind power is lost because Eemshaven, Ens, Louwsmeer, Lelystad, Diemen, and Beverwijk experience a voltage drop below 0.8 p.u.. Voltage oscillations that occur at substation Ens are damped within 6 seconds and are about 0.8 % at maximum (see figure 4.7). The voltage recovery time is almost the same as in the worst-case situation.

In this case again large oscillations of up to 1200 MW occur at the Meeden–Diele connections. The interconnection at Zandvliet, which is normally an exporting connection of about 300 MW, starts to import 2000 MW from Belgium (see figure G.3).

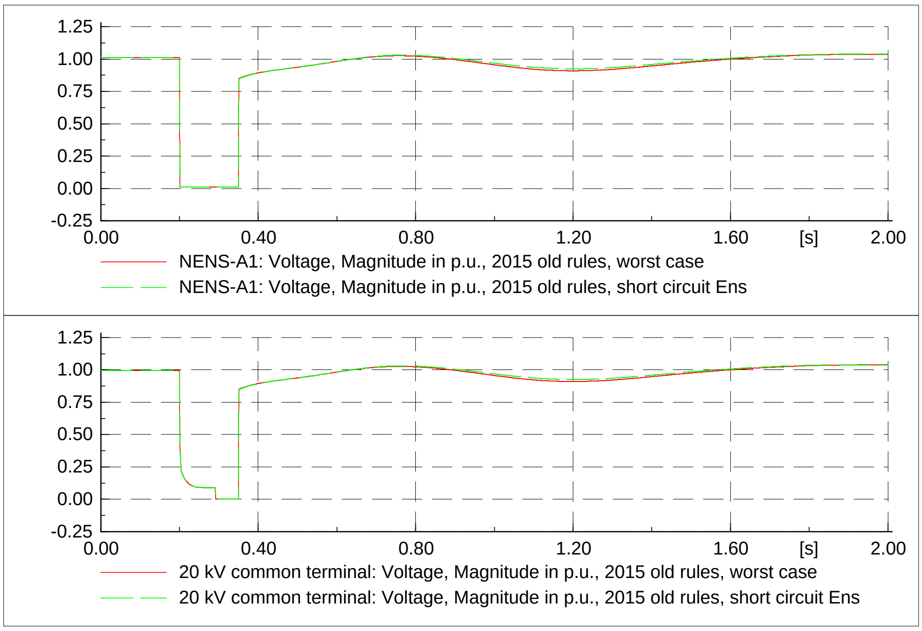


Figure 4.7: Voltage at substation Ens, worst-case situation and short circuit at Ens for the year 2015 with old regulations applied

150 ms short circuit substation Eemshaven

A short circuit at substation Eemshaven shows relatively large oscillations (about 3%) in the voltage, whilst 'only' 1058 MW of wind power is disconnected from the grid. These oscillations are mainly caused by the thermal power plants near Eemshaven, that start to oscillate once the short circuit is cleared.

At the external connections the worst oscillations in the active power flows (more than 2000 MW) occur at both interconnections Meeden–Diele, but they are damped within 6 seconds. This fast damping mainly occurs because of external grid representation, as this results in a very stable grid situation.

4.4.3 N-2 situations

Eemshaven

When the N-2 case at substation Eemshaven is repeated for the 2015 grid with old regulations applied, it results in the disconnection of 1737 MW of wind power. All wind power at Eemshaven, Louwsmeer, and Ens is disconnected from the grid. Since two circuits from Eemshaven are out of service after the short circuit has occurred, the total impedance from Eemshaven to the south has increased enormously. Figure 4.8 shows the voltage results at Eemshaven for the worst case situation (red, solid line) and the N-2 situation (green, dashed line). It can be seen that the voltage recovery is worse for the N-2 situation, only after 476 ms the voltage returns to 1 p.u.. This is caused by the reactive power demand of the heavily loaded lines from Eemshaven to the south in the 220-kV grid.

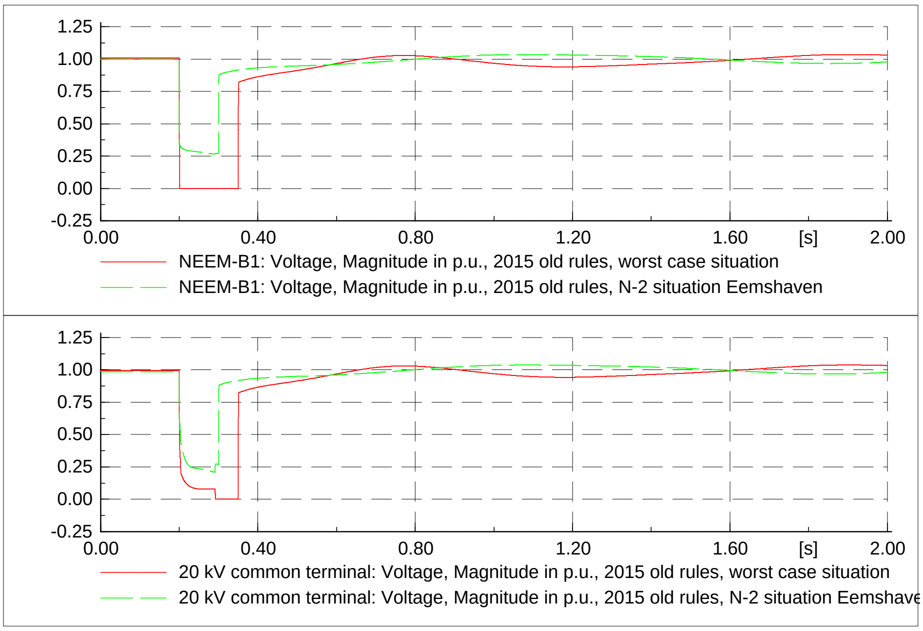


Figure 4.8: Voltage at substation Eemshaven and voltage at 20 kV wind park terminal, N-2 situation near Eemshaven with old regulations applied for the year 2015

4.5 Grid situation 2015, with ‘new’ rules and regulations applied

In this section the ‘new’ rules and regulations are applied. For the calculations this means the wind parks of the direct drive and DFIG types are not disconnected from the grid during a fault of 150 ms, only squirrel cage induction machines are still disconnected since these turbines do not have controls and would absorb large amount of reactive power after the fault. These regulations are part of the requirements as stated by the German grid code, which require that for the first 150 ms of a voltage drop to 0 p.u. a wind park has to stay connected to the grid. Other requirements that are present in the German codes, like the reactive power supply during a voltage dip and frequency support are not taken into account in the calculations.

4.5.1 Artificial worst case

The worst-case situation for the year 2015 with ‘new’ rules and regulations results in the disconnection of only 35 MW of wind power, since only the squirrel cage induction generators are disconnected. Figure 4.9 is showing the voltage at substation Ens for the worst-case situation (red, solid line). Some irregularities can be seen at the moment the short circuit is cleared. These irregularities are caused by the disconnection of the DFIG crowbar, which occurs 10 ms after the voltage has returned. At this moment the controllers are connected again and try to return to the set point.

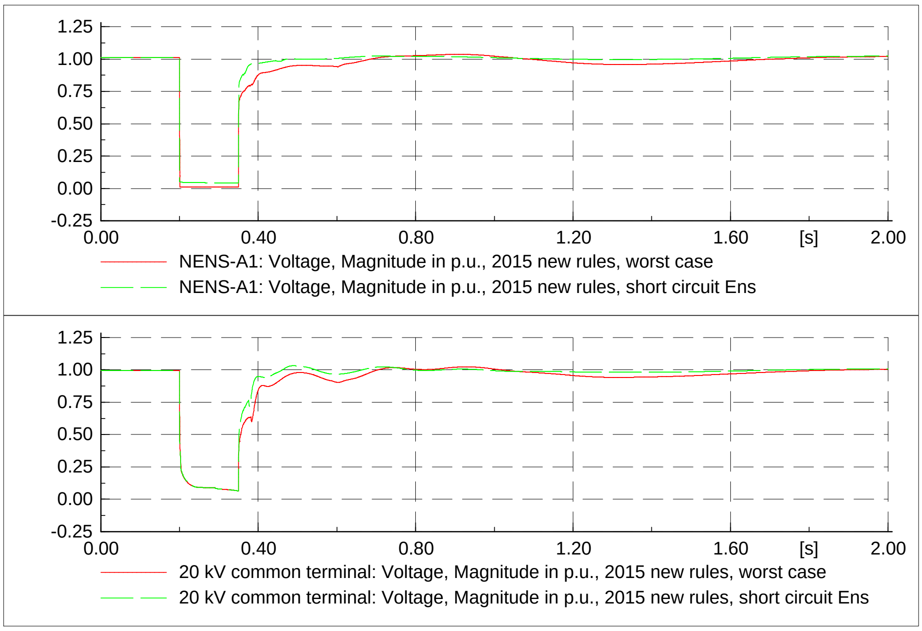


Figure 4.9: Voltage at substation Ens, worst-case situation and short circuit at subsation Ens for the 2015 situation with new regulations applied

Active power flow oscillations of up to 1650 MW (at the interconnection Hengelo–Gronau) occur in this worst-case situation (see figure G.4). These oscillations are mainly caused by the power that is fed into the grid from abroad during the short circuit. Once the short circuit is cleared, the power balance will be restored. All generating units (including wind parks) in the grid have to return to their normal operating points.

4.5.2 Short-circuit calculations

150 ms short circuit at Ens

When a short circuit occurs at substation Ens, the substations Lelystad, Ens, Louwsmeer, Diemen, Beverwijk and Eemshaven experience a voltage drop below 0.8 p.u., resulting in the disconnection of 24 MW in this case. Voltage oscillations that occur at substation Ens are about 1%, and the voltage recovers to above 1 p.u. in 122 ms (see figure 4.9). The irregularities that occur in the voltage just after the short circuit is cleared are caused by the disconnection of the DFIG crow bar again and can also be seen in the power flow and current of the wind park (see figure 4.10). These results again show a strong resemblence with the results obtained before, from the calculations with the substation Eemshaven model.

Oscillations at the external connections are damped fast, within 4 seconds. Largest oscillations that occur are about 750 MW, at the interconnection Meeden–Diele (see figure 4.11, green dashed line). It can be seen that the oscillations are less than in the worst-case situation, since less thermal power plants and wind parks experience a voltage drop, and start oscillating.

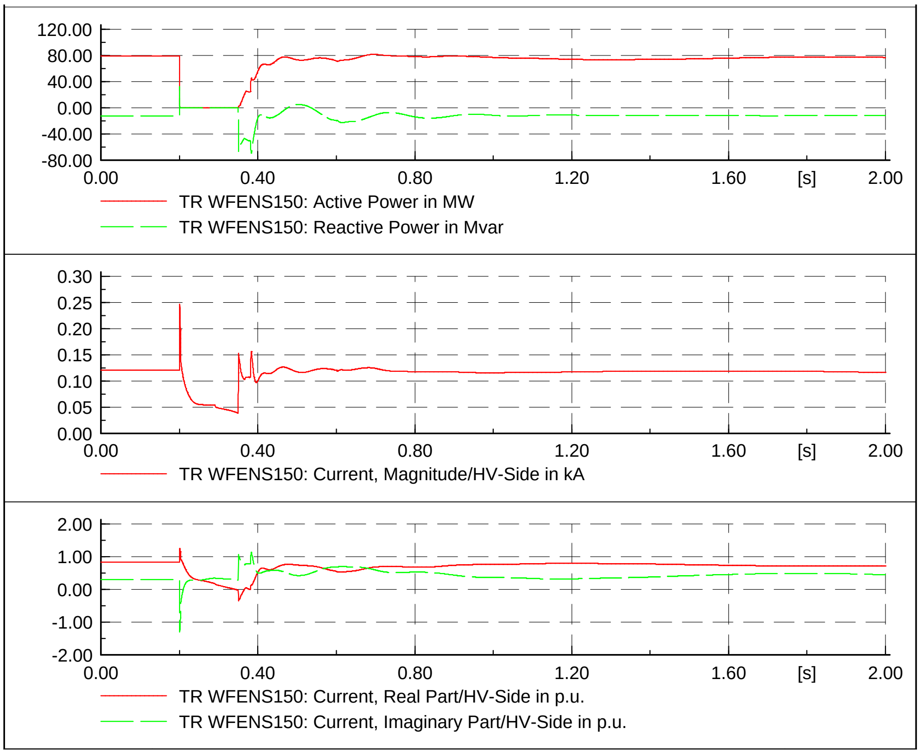


Figure 4.10: Active and reactive power, total, real and imaginary current of distribution grid wind park, short circuit at Ens, 2015 situation with new regulations applied

4.5.3 N-2 situations

Eemshaven

Once again the N-2 calculation in the northern part of the grid is repeated. It can be seen that a small, very slowly damped, oscillation in voltage occurs at substation Eemshaven (figure 4.12, green dashed line). A slow voltage recovery can be noticed, it takes about 859 ms before the voltage reaches the value of 1 p.u.. This again is caused by the heavily loaded lines and in this case the wind parks also absorb reactive power, delaying the voltage recovery. When comparing these results with the worst case situation (red, solid line), it can be seen that the voltage recovery is slower, but the oscillations that occur are about the same.

4.5.4 Comparison 2015 fault situations

A comparison of the different fault situations is given in table 4.3. The table shows the largest voltage overshoot at the 380-kV substations, the voltage-recovery time at substation Ens, and the maximum oscillations in power flow on the interconnections. The results are given for the situation where all wind is disconnected from the grid in a case of a fault (old) and the situation where only squirrel cage induction generators disconnect (new). From these results

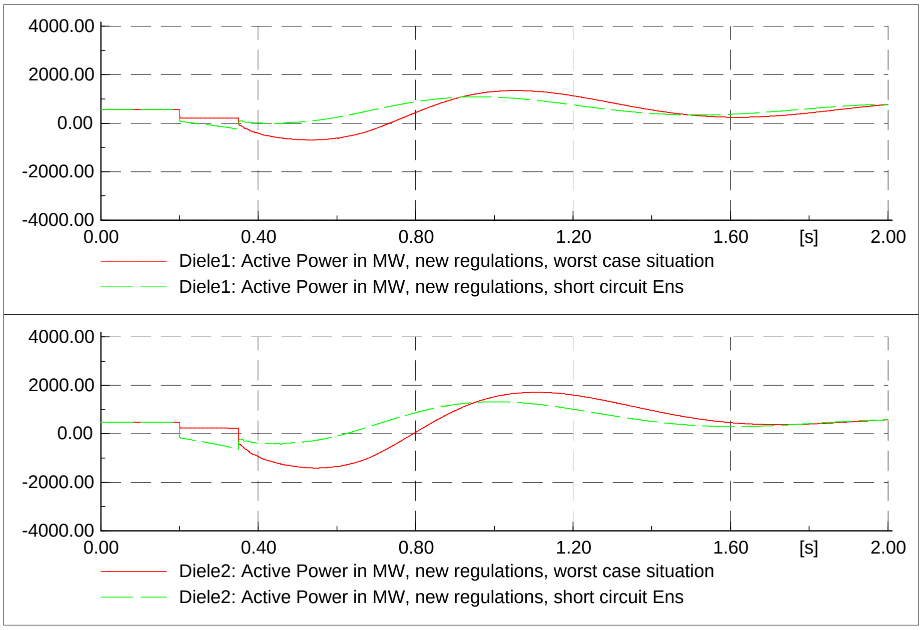


Figure 4.11: Active power flow Meeden–Diele, worst-case situation and short circuit at Ens, for the 2015 situation with new regulations applied

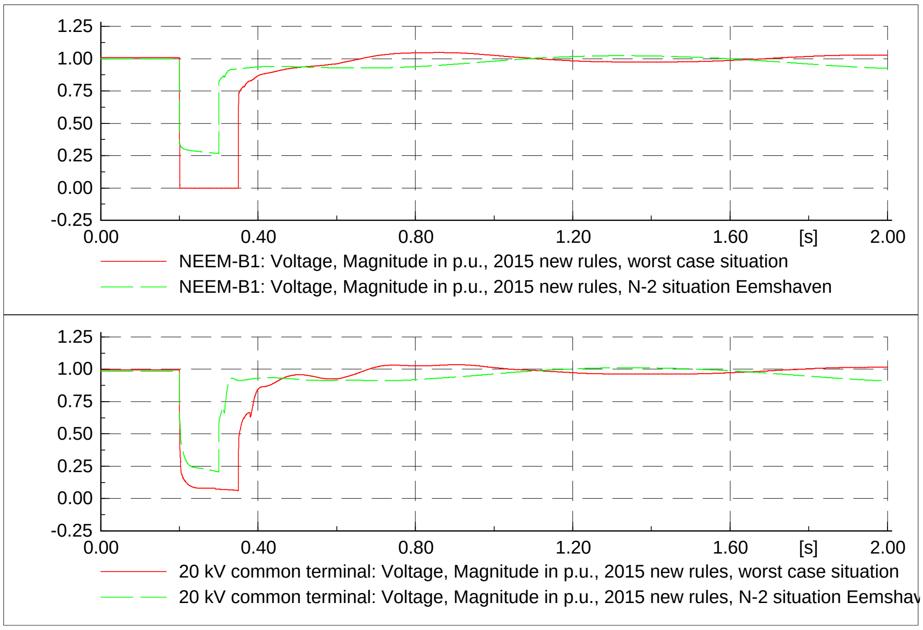


Figure 4.12: Voltage at substation Eemshaven and voltage at 20 kV wind park terminal, N-2 situation near Eemshaven with new regulations applied for the year 2015

it can be concluded that the amount of wind power that is disconnected is not a measure for the oscillations that occur and the voltage recovery time. Largest voltage oscillations occur in the N-2 case, where the transport capacity is limited. For the oscillations in active power flow at the interconnections the location of the short circuit is of major influence. Finally it can be seen that preventing the wind parks from disconnecting from the grid in case of a fault reduces oscillations in voltage and power flows but increases the voltage recovery time, in some cases almost by a factor two.

Table 4.3: Results 2015 simulations

Fault scenario	**Wind disconnected (MW)**		**Largest voltage overshoot (%)**		**Voltage recovery time Ens (ms)**		**Largest power oscillation on interconnection (MW)**	
	old	new	old	new	old	new	old	new
Worst case	7302	35	1	1	290	335	2000	1300
Short circuit Ens	5000	24	3	1	288	122	2000	1000
Short circuit Eemshaven	1058	5	3	3	296	337	2300	1700
N-2 Eemshaven	1737	8	4	2	476	859	1350	1000

4.6 Comparison simulation results

Worst case

Figure 4.13 and 4.14 show a comparison between the 2008 situation (red, solid line), 2015 situation with old regulations, where all wind power is disconnected on a fault (green, dashed line), and the new regulations situation where only the induction machines are disconnected (blue, dotted line). The voltages at substation Ens, and at the wind park 20-kV common terminal show a little slower recovery in the 2015 case with old regulations compared to the 2008 situation. This is mainly caused by the (much) bigger amount of wind power that is disconnected from the grid in the year 2015. When new regulations are applied in the year 2015, and the direct drive and DFIG stay connected during the fault, an even slower voltage recovery can be seen. This slower recovery is mainly caused by the DFIG, since as long as the crowbar is connected, the wind park acts as an induction machine and thus absorbs reactive power once the fault clears. The oscillations are less in this case, since the balance is restored faster as only a few MW of wind power are disconnected from the grid.

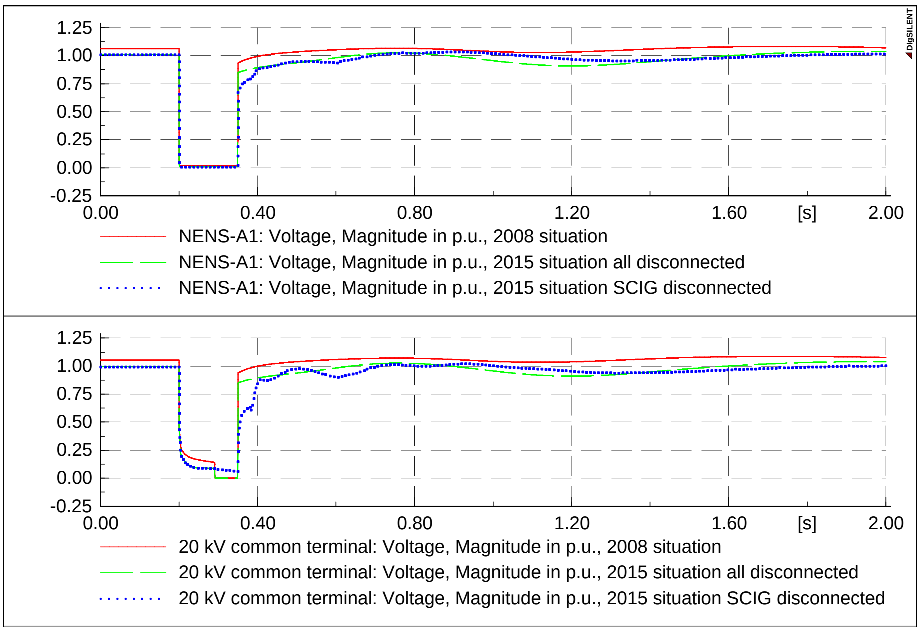


Figure 4.13: Voltage at substation Ens and voltage at 20-kV terminal, worst case situation for the year 2008 and 2015 with old and new regulations applied

Figure 4.14 shows the power flows at interconnection Meeden–Diele for the 2008 situation (red, solid line), 2015 situation with old rules and regulations applied (green, dashed line), and for the 2015 situation with new rules and regulations applied (blue, dotted line). When comparing these results it could be seen that between 2008 and 2015 the oscillations increase, but applying new regulations results in a reduction of the oscillations. It should again be noted that a relative comparison can be made between these results, but a quantitative conclusion on these oscillations can not be drawn, since the external grids are an over-simplified representation of reality.

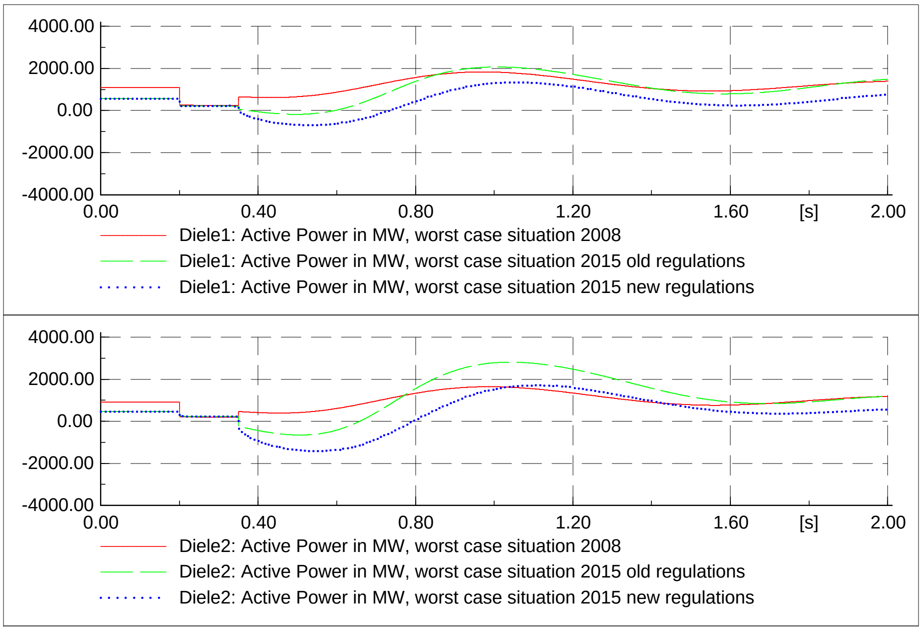


Figure 4.14: Active power flow at interconnection Meeden–Diele, worst case situation for the year 2008 and 2015 with old and new regulations applied

150 ms short circuit at substation Ens

The voltage response at substation Ens after a short circuit is applied shows almost the same results as the worst case situation (see figure 4.15). It can be seen that the oscillations are increasing in the 2015 situation, but once the new regulations are in place almost the same result is obtained as with the 2008 situation. The voltage-recovery time becomes longer for the 2015 situation, but in this case new rules and regulations improve the voltage recovery. This is caused by the fact that there is not much thermal power installed near substation Ens. The amount of power plants that experience a large voltage drop and absorb reactive power for a short time after the fault has cleared is thus small.

At the interconnection Meeden–Diele (see figure 4.16) again an increase in oscillations, caused by the amount of disconnected power, can be seen between the 2008 situation (red, solid line) and the 2015 situation with old rules applied (green, dashed line). Applying new rules and regulations however results in a drastic decrease in oscillations (blue, dotted line), this is mainly because of the fact mentioned before that only a few thermal power plants experience a voltage drop in the case of a short circuit at substation Ens.

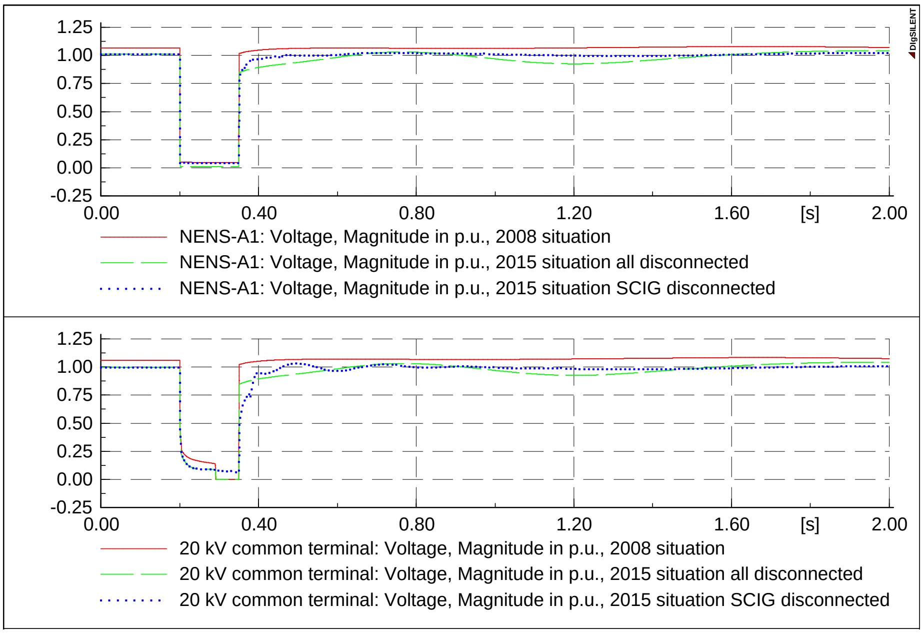


Figure 4.15: Voltage at substation Ens and voltage at 20 kV terminal, short circuit at Ens for the year 2008 and 2015 with old and new regulations applied

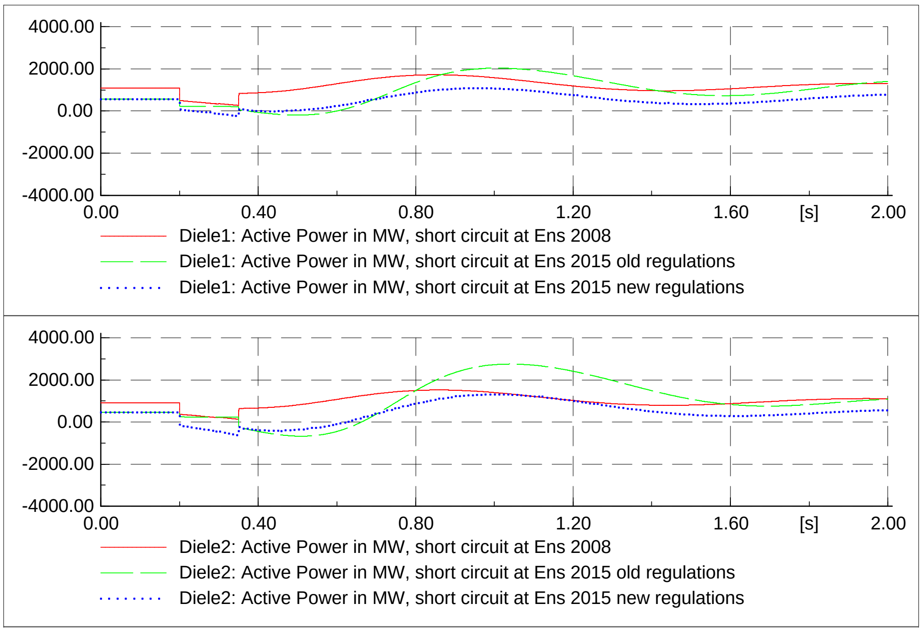


Figure 4.16: Active power flow at interconnection Meeden–Diele, short circuit at Ens for the year 2008 and 2015 with old and new regulations applied

150 ms short circuit at substation Eemshaven

Figure 4.17 shows the voltage response at substation Eemshaven, for the 2008 situation (red, solid line), the 2015 situation with old rules and regulations (green, dashed line), and the 2015 situation with new rules and regulations applied (blue, dotted line). At the 380-kV level not many differences can be seen, only the voltage for 2015 is lower than for 2008, because of the lower thermal regulation. The voltage-recovery time shows hardly any differences, since still the thermal power plants nearby Eemshaven play an important role. Only at the 20-kV level the influence of a larger wind park (slower voltage recovery) and new regulations (more oscillations and a dip in voltage recovery) can be observed.

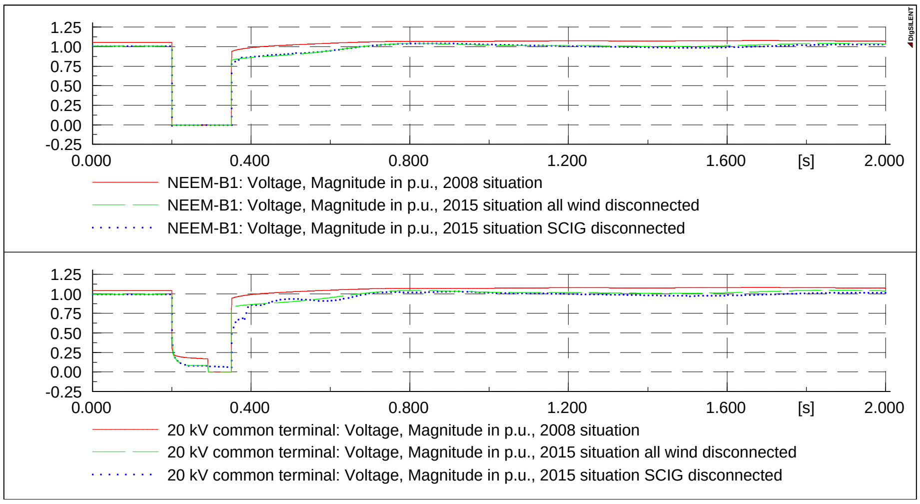


Figure 4.17: Voltage at substation Eemshaven and voltage at 20 kV terminal, short circuit at Eemshaven for the year 2008 and 2015 with old and new regulations applied

Limitations of the used model

Because the interconnections are represented as external grids, there are no actual limits in the amount of active and reactive power that can be supplied or absorbed. When the actual external grids are implemented power oscillations op to several thousands of megawatts can cause instabilities, as these kind of oscillations may cause rotor angle instabilities in generators in the surrounding grid. Also, interconnectors may be disconnected in this case, since they are (heavily) overloaded. Sudden loss of the interconnections will even amplify the oscillations, since the power balance has to be restored locally now.

Conclusions

It can be concluded that the main differences occur between the 2008 situation and the 2015 situation with the disconnection of all wind power (see table 4.4). The oscillations and recovery times of voltages increase as well. Voltage recovery becomes a little slower when the turbines are not disconnected from the grid. This is mainly caused by the DFIG turbines, that absorb reactive power when the short circuit is cleared. A way to limit this effect is to disconnect the crowbar sooner, when the fault has not been cleared yet. Such requirements, where the turbines are required to have voltage support, are already applied by the German TSO E.ON Netz [30].

Table 4.4: Comparison 2008 and 2015 voltage response

Fault scenario	**Largest voltage overshoot (%)**			**Voltage-recovery time Ens (ms)**		
	2008	2015 old	2015 new	2008	2015 old	2015 new
Worst case	2	1	1	52	290	335
Short circuit Ens	1	3	1	1	288	122
Short circuit Eemshaven	2	3	3	1	296	337
N-2 Eemshaven	3	4	2	1	476	859

As already said, the oscillations in the interconnection power flows are enlarged by the disconnection of a larger amount of wind power in the grid and a larger amount of conventional power in the year 2015. The year 2015 situation thus shows larger power flow oscillations than the 2008 situation. New regulations cause a decrease in these oscillations, since almost no wind power is disconnected from the grid in that case.

Chapter 5

Local selection environment for onshore wind parks in Germany, Spain and the Netherlands

Wind power generation is not equally spread over Europe, some areas have large amounts of wind power installed while other areas have almost nothing. These areas with much wind power installed are usually not near high load areas, resulting in large power flows across Europe in case of high wind speeds and low local loads. Factors like wind resources and space for turbines are of course important explaining factors here. But also the socio-economic factors in the local selection environment determine the attractiveness of a location for investors in wind power. These latter factors will be investigated in this chapter.

Local manufacturing of wind turbines (localization) plays an important role in the development of wind power in a certain country. Most of the leading wind turbine manufacturers are established in a country with booming national wind power development, and nine out of the ten largest wind turbine manufacturers are established in the five countries leading on installed wind power [31]. Germany as well as Spain have a big national wind power industry, whilst this industry in the Netherlands has almost vanished over the last years.

Table 5.1 shows the installed wind power in Spain, Germany and the Netherlands for the years 1995 to 2007. It can be seen that large differences between these countries occur in the development of installed wind power. In this chapter a comparison between the selection environments of these countries will be made:
Is it more attractive for investors to install onshore wind parks in Germany, Spain or The Netherlands, looking at subsidies, connection policy, and local social acceptance?
Government targets usually play an important role in subsidy policies and are also taken into account. The current climate for investments determined by these factors may “force” investors to move to a certain location or country and plays an important role in the feasibility of government targets concerning

onshore wind power.

Table 5.1: Installed wind power (MW) in Spain, Germany and the Netherlands (data from www.ewea.org and [32])

Country	**1995**	**1999**	**2001**	**2002**	**2003**	**2006**	**2007**
Germany	1 136	4 445	8 734	12 001	14 609	20 622	22 247
Relative increase		291%	96%	37%	22%	41%	8%
Spain	145	1 530	3 550	4 830	6 202	11 623	15 145
Relative increase		955%	132%	36%	28%	87%	30%
The Netherlands	236	410	523	678	912	1 558	1 746
Relative increase		74%	28%	30%	35%	71%	12%

5.1 Germany

Already in in the year 2006 about 5% of the total German electricty consumption was generated by wind power and by 2007 Germany has the largest world-wide amount of installed wind power. German wind power development started with small and medium-sized companies, because the larger utility companies were initially not allowed to own wind power. This restriction was discontinued later but private individuals, independent power producers, and small companies still own about 90% of the German wind turbines today [33]. Wind parks were usually built in the form of single wind turbines or clusters of several turbines. Development of larger wind parks, of about 100 MW, has only started during the last two to three years [33]. From 2002 to 2006, the annual installed wind power has decreased from 3247 MW to 2100 MW (see figure 5.1). This decrease is caused by the limited number of suitable areas, building limitations for higher wind turbines, decrease of feed-in tariffs and the inability of network companies to reinforce the grid fast enough. Predictions are that the annual installation of onshore wind power will decrease to 1500 MW [33].

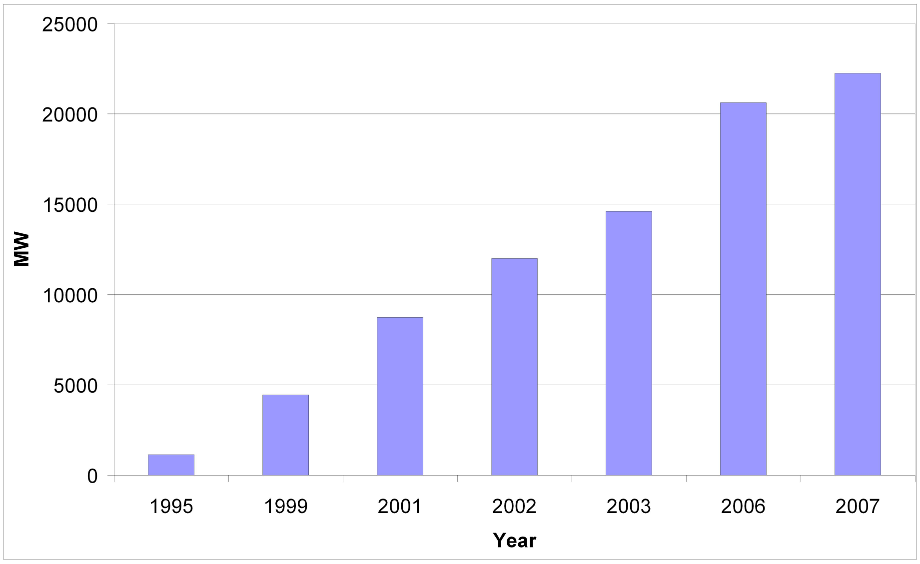


Figure 5.1: Installed wind power (MW) in Germany over the years (data from www.ewea.org and [1])

5.1.1 Government targets

In the 1980s renewable energy was already promoted in Germany by means of R&D programmes and demonstration projects of the Federal Ministry for Research and Technology. Stimulation of wind power began in 1989 when a market stimulation program, with the target of 250 MW of wind, was introduced. This stimulation program gave technology standards in the German wind technology sector a big boost [31, 34, 35]. In August 2004 a new Renewable Energy Sources Act was passed by the German government. This Act was the first which included big targets for the minimum amount of installed wind power;

12.5% of the complete electricity production for 2010 and 20% for 2020 [34]. Altough actual targets for the installation of wind power were set only in 2004, the German government already in the 1980s started to support wind power.

5.1.2 Grid connection procedure

Renewable energy producers in Germany get a special treatment when requesting access to the grid. Conventional producers have to negotiate with the Distribution System Operator (DSO) and Transmission System Operator (TSO) to get access, whilst renewable energy producers are to be connected immediately once they have submitted an application. Germany has four different TSOs and about 700 distribution grid operators, which each have their own operating area. All energy produced by the renewable energy producers should be purchased by the corresponding DSO (or TSO) unless agreed up on otherwise, e.g. in situations where it is better for the system operator if not all energy is always purchased. The Renewable Energy Sources Act states that a renewable energy producer has to be connected to the grid, without the need for a contract between producer and network operator. A recent court decision however realised that a contract is needed for all new renewable energy producers, giving network companies the right to curtail wind power in order to allow more wind parks to connect. In case of a congestion renewable energy producers receive a priority treatment as conventional power plants have to reduce their output first [33].

Network companies have to publish technical requirements on the internet for the grid connection of generation units. These requirements have to describe detailed minimum technical requirements for each voltage level. When conflicts occur the “Bundesnetzagentur” is the arbitrator and has to determine if the wind power producer meets the requirement of the network company. No law exists in Germany on available capacity of the grid, but network companies are legally required to upgrade the network for renewable energy producers if needed [33]. If the renewable energy producer meets all technical requirements access to the grid for producers can be rather fast in Germany, since no special procedures exist for the grid application and renewable energy producers have to be connected immediately.

5.1.3 Policy

The great development of wind power in Germany started with the Electricity Feed-in Act of 1991, which came on top of the 250 MW program and obliged the purchase of all renewable energy. Soft loans, with rates below market rates, also supported German turbine technology and thus the growth of installed wind power [31, 35].

Subsidies

Fixed feed-in tariffs, where the government defines a minimum price for electricity from renewable sources, are being used in Germany since 1991. In the beginning of the 1990s when the target for 250 MW of installed wind power was set, states often offered subsidies for the installation of wind power. It was thus possible for wind power producers to get a national as well as a state subsidy

[33]. German network operators were forced to pay at least 90% of the market kWh prices to renewable energy producers by the Electricity Feed-in Act [34, 35]. Later a cap was included in the act and network operators only had to pay the feed-in tariffs until the share of renewable energy production reached 5% of the total installed capacity. This, together with falling market prices because of the liberalization, eventually started undermining the economic basis for renewable energy sources. To stop this degrading support the Renewable Energy Source Act (RES) was introduced in the year 2000. Under this act the feed-in prices were fixed for 20 years and no longer coupled to market prices as with the 1991 Electricity Feed-in Act, it also abolised the 5% cap. Degression of the tariffs and a stepped nature of the tariffs are two important issues of this act [34]. The degression of the tariffs is included to stimulate manufacturers to reduce production costs and the stepped nature causes payment depending on yield and generation costs. In this way locations with good wind resources get paid less than locations with lower wind resources in order to stimulate wind park development at these lower wind locations. This renewed act also included priority grid access for renewable energy sources, adjusted tariffs, and a lower support level for high wind locations. Furthermore an annual decrease of the feed-in tariffs of 2% is defined [34].

Authorization and regulation of German network companies is done by a regulator, the Bundesnetzagentur. Network companies have to present all their costs to the regulator and propose a tariff based on these costs and a profit. The regulator then may approve this tariff or propose a lower one. When in 2009 another update of the RES will become active, the tariffs will no longer be based on costs but on an incentive regulation. Network upgrading costs then can be completely recovered by network companies, as these costs result in higher network tariffs. Since most wind power in Germany is located in the coastal areas this new act could result in higher network tariffs in these areas [33].

The feed-in tariffs are paid to the renewable energy producers by the network company to which they are connected, who in its turns passes the costs on the the corresponding TSO. The TSO eventually passes the costs on the all the DSOs, which get a share of the costs depending on the number of customers. In this way all electricity consumers pay an equal share of the renewable energy costs [33]. So Germany has had a subsidy system with feed-in tariffs since the beginning of the 1990s that was updated several times to promote growth and innovations in the wind energy sector.

Connection costs

Costs for the connection from the wind park to the grid connection point have to be paid by the wind power producers. Network companies are then obliged to upgrade grid and pay for necessary reinforcements in the grid. Because of this conflicts on the best connection point between producer and network company often arise. The National Energy Act states that network companies have to give access to generation units '*as long as no technical or economic reasons object against it*'.[1] For years the connection point was determined by an understanding that total network connection costs should be minimised.

[1] National Energy Act 2005

This however leaded to several lawsuits and finally a court decision from 2007 defined that even a low voltage network has to be upgraded with overhead lines if required, if this is leading to the lowest network connection costs. Often this is not the most favourable solution as network upgrades can take years and time plays an important role because of declining feed-in tariffs. Wind power producers thus often decide, alone or with several different clusters, to build their own cable connection to a transmission grid substation. No clear grid access application process is described by law, and there are thus no time lines or deadlines for the application procedure. The German Association of network companies has because of that created a guideline that describes the data that has to be delivered to the network companies and which methods network companies should use to calculate the available connection capacity [33].

Grid connection costs have to be paid by the producers. Up till today it is possible for network companies to pass the costs for network upgrades on to the TSO and finally onto the consumer tariff. Generators do not pay for their connection by network fees or tariffs [33].

5.1.4 Social acceptance

A 2003 survey carried out by the EMNID institute and a 2004 study of the analytical institute forsa showed that 66% of the German inhabitatants support the growth in wind power, whilst 30% is against any further growth [3, 36].

In East Germany the support for growth in installed wind power is lower than in West Germany. Citizens of larger cities, as well as people who have not been harmed by wind energy in a direct way, have a bigger support for wind energy than people in the smaller municipalities. Other differences in support can be found in age, 81% of the people under 30 years old have a positive attitude towards wind power, whilst this is only 56% for people aged 60 years or older. People in the North and East of Germany also have a more postive attitude towards wind power than people in other parts of the country [36]. It can be seen that quite some differences in wind power acceptance occur between age groups and areas in Germany, but generally two third of the Germans support further growth in installed wind power.

5.1.5 Conclusions

Although the growth in installed wind power in Germany is decaying, the government has done much the slow the decay down. Already since the beginning of the 1990s Germany knows a system of feed-in tariffs. This system has been updated several times to promote growth and innovations in the wind energy sector, because local development and manufacturing plays an important role in the success of wind power [31]. Even a degression of the feed-in tariff was included to stimulate innovations and make producers introduce more economical models. Wind park grid connection costs have to be paid by the producers, but up till today it is possible for the network companies to include the costs for necessary network updates in the consumer tariff. Renewable energy producers in Germany can obtain access to the grid rather fast, if the producer meets all technical requirements. This is because no special procedures exist for the grid application and renewable energy producers have to be connected immediately by law. Finally social acceptance is quite high in Germany, even though some differences in wind power acceptance occur between age groups and areas in Germany, generally two third of the Germans support further growth in installed wind power.

5.2 Spain

Spain takes a leading position in the management and technical performance of wind parks. This leading position is achieved by large scale wind integration at a high concentration in several areas, 60% to 70% of the total installed wind power is connected at 30 to 40 points in the grid [33]. Spain has a high technological level compared to international standards and social acceptance is usually high. In the years when wind power was not implemented on a large scale, a couple of 'visionary' entrepeneurs played an important role in the development as they saw the (business) potential of wind power [37]. Furthermore in the past decade the electricity consumption in Spain has increased rapidly, thus creating more space in the market for wind power [38]. Because of all these aspects already in the year 2006 wind power accounted for 13% of the total installed generating capacity (see figure 5.2 for the installed wind power in Spain).

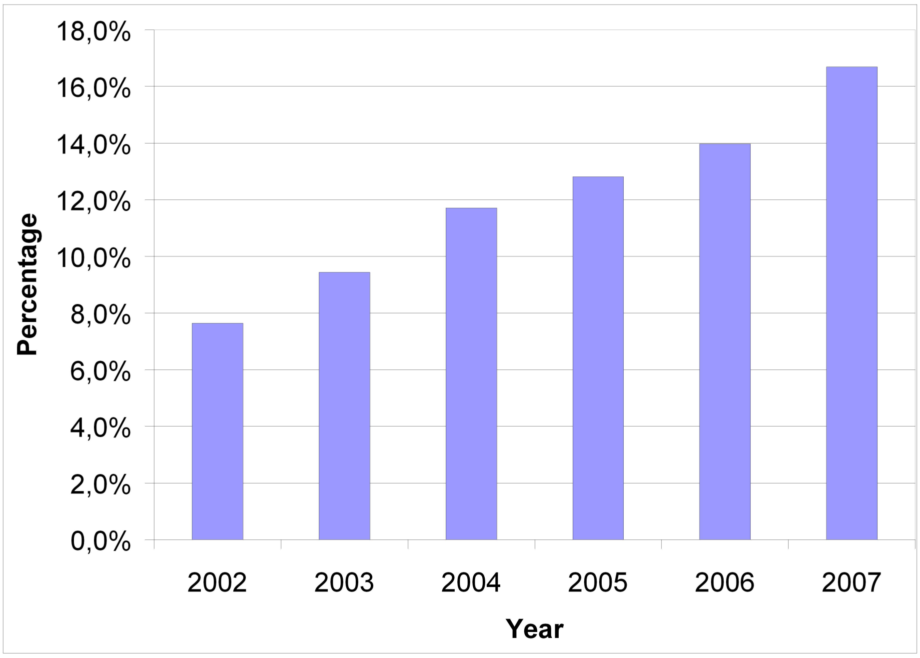


Figure 5.2: Percentage wind power of total installed power in Spain (data from www.ree.es)

Wind power in Spain shows a remarkable difference compared to other European countries. In most countries small clusters of wind turbines are widely spread over the country, whilst in Spain large and medium sized wind parks dominate. This difference is caused by the fact that investors in wind power in

Spain are particularly consortia of power utilities, regional government and turbine manufacturers, as in other countries most investors are private individuals. Another reason for the larger wind parks in Spain is the rather low population density in areas with good wind resources compared to Germany and Denmark [37].

5.2.1 Government targets

Already in 1986 a plan, focused on R&D but without specific targets, was created in Spain to promote renewable energy systems [38]. In December 1999 the plan for renewable energies, “Plan de Fomento de las Energías Renovables” (PFER), was published by the Institute for Energy Diversification and Saving (IDAE) indicating a technical potential for wind power in Spain of 7500 to 15 000 MW. For the year 2006 a target of 5550 MW was set, but already by the end of 2005 the installed capacity reached 10 028 MW (see figure 5.3). The PFER was updated in 2005 by the “Plan de Energías Renovables” (PER), this update defines the political target of 20 166 MW installed capacity by the year 2010 [33, 38]. By the end of 2006 the total installed renewable electricity production in Spain was 13 959 MW. Wind power has experienced the largest growth of all renewable electricity production over the last years and accounted for 23 372 GWh in 2006, or 8.5% of the total electricy demand [33]. As can be seen, the government targets for the amount of wind power to be installed have been updated to a higher level several times since the developments went (much) faster than planned.

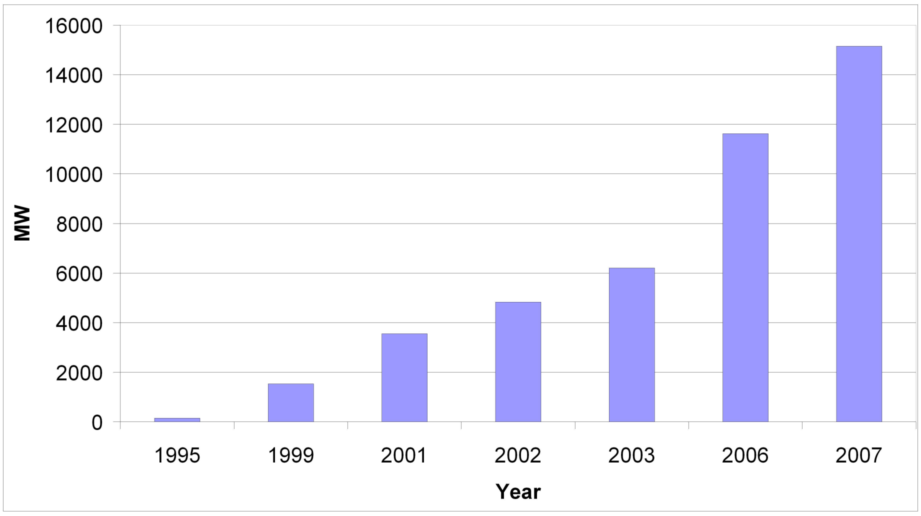


Figure 5.3: Installed wind power (MW) in Spain over the years (data from www.ewea.org and [1])

5.2.2 Grid connection procedure

Legislation in Spain divides energy production into producing technology and energy sources. An ordinary regime which includes conventional energy, and a special regime which includes renewable energy, are specified by this legislation [33, 34]. The special regime is regulated by several different Royal Decrees (RD). These Royal Decrees are legal orders proposed by the government instead of the parliament and have a lower range than laws.

Spanish law uses the criterion of non-existence of reserve of capacity, meaning over-installation at connection points is permitted. The Transmission System Operator (TSO) allows 25% more production capacity based on renewable energy sources without storage than the grid capacity to connect to a connection point, because it is very unlikely that all renewable energy producers will produce at full capacity at the same time [33].

For the development of new wind parks in Spain it is possible to expropriate land if the installations to be installed are declared by the administration as of public usefulness. When a project developer has an agreement with at least 50% of the involved land owners, the rest of the land can be expropriated. To get the administrative license necessary to build the installations an environmental assessment is needed. This assessment process usually takes six to seven months [33].

It is prescribed by a Royal Decree that the TSO can only deny connection to the distribution grid if that connection can cause lack of capacity in the transmission grid. At this moment a large number of wind parks in Spain is producing below their maximum capacity as the grid there still has to be reinforced [33].

Procedure for connection to the transmission grid

When a project developer wants to connect to the transmission grid, an application has to be filed at the TSO and a deposit of 2% of the costs of the complete installation has to be paid to the Ministry. The deposit is returned once the developer gets its administative licence or the licence is not granted. The TSO then sends back a report with eventual anomalies or mistakes and the project developer has to correct the application. Once the application is correct, the TSO has two months to communicate to the developer about the available capacity and proposed connection point. After this the project developer sends its basic project plans and program of execution to the TSO and has to receive the licence within a month. The entire procedure for connection to the transmission grid, from the moment the application is send to the TSO, takes about four months [33].

Procedure for connection to the distribution grid

Project developers demanding access to the distribution grid have to send an application to the DSO in question and have to pay a deposit of 20 Euro/kW to the Ministry. Within ten days the DSO has to reply with eventual anomalies or mistakes and the project developer again has ten days to correct the application. When the DSO has received a correct access application, it has fifteen days to communicate back to the project developer on available connection capacity. If the generation unit to be connected exceeds 10 MW the DSO has to inform the TSO, which in its turn has two months to send a report on the available capacity in its grid. The project developer then has to send basic project information and program execution to the DSO to finally get the application license. This entire process for a connection to the distribution grid takes between two and four months, depending on the size of the installation and thus the involvement of the TSO [33].

5.2.3 Policy

Spain has a policy which supports and promotes renewable energy sources in multiple ways, even though there is no separate ministry for energy. The IDEA, as governmental institute, has implemented several economic support schemes for wind power and other renewables. These support schemes included subsidies on investments, soft loans (with interest below market rate), and investments in renewable energy companies [38]. This section will describe the policy on subsidies, the connection procedures and costs, and market issues related to wind power.

Subsidies

The general subsidy system in Spain consists of a special price paid, above the market price, to the producer of renewable energy in the special regime. Producers of renewable energy are given priority to conventional energy producers, which means they can always sell all their produced energy at the special price. The height of the special price is determined by the government every year. Consumers are the ones that eventually pay for this system by means of a proportional addition to their electricity bill [34]. Installations with a capacity larger than 50 MW are not included in the special regime, but renewable energy producers larger than 50 MW receive a premium equal to a similar smaller installation, multiplied with a factor between 0.2 to 0.8. Up till now no renewable energy installations larger than 50 MW are built in Spain due to this limitation. Because of technical developments and transport capacity, the trend in Spain is to connect larger wind parks directly to the transmission grid. Since installations larger than 50 MW are not included in the special regime, larger installations are divided up into several 50 MW installations [33].

Payment of renewable energy takes place via a fixed regulated feed-in tariff or a combination of the market price for electricity and a premium, between which producers can choose [33, 34, 38]. With the market option a green bonus of 40% and a market bonus of 10% of the average market price is paid to the producer. A penalty has to be paid when the production of plants larger than 10 MW deviates more than 20% from the production announced. About 90% of the Spanish wind power producers have chosen for this market option, because it is expected that the bonus more than compensates for eventual penalties [38].

Connection costs

No clear legislation is available in Spain on the costs required to connect installations to the grid. These costs are paid by the producers, or when they are associated with development of the grid, included in the planning process. The Royal Decree of 2007 states the producers have to pay for costs related to reinforcements of the grid unless the reinforcements are not used by the producer solely. On the other hand the decree does not describe when the grid is solely used by one producer and how the sharing of costs should be carried out [33].

Costs for reinforcements in the distribution grid are sometimes paid by the producers of renewable energy and sometimes socialised, whilst costs for reinforcement in the transmission grid are up till now socialised. These transmission costs are only a small part of the total electricity bill consumers pay. One of the Royal Decrees prescribes that a deposit of 20% of the reinforcement costs for the transmission grid has to be handed in by the developers, but since those costs are socialised such deposits have never been handed in [33]. To speed up developments, the project developers can make agreements with the TSO where project developers will pay for the reinforcements in the transmission grid first and get paid back later when the costs are socialised. These kinds of agreements are not stated in the Spanish law, but completely voluntary. The ministry eventually decides which of the reinforcement costs are to be paid by the project developer and which are to be socialised. Today, renewable energy producers connected to the distribution grid often get a provisional access licence, which means they can already begin to produce electricity even though the necessary reinforcements are not implemented yet [33].

For the distribution grid however, legislation prescribes that the owner of a generating installation has to pay for all costs that follow from the connection of the installation. In practice it is very hard when multiple installations are connected in one area to lay down which costs are caused by what particular installation. Power producers in Spain do not have to pay for their access to the grid, nor for the usage of the grid [33].

5.2.4 Social acceptance

In some regions environmental issues have stopped the development of wind parks, but most regions compete in developing wind parks before the national target is reached. Wind parks ensure an extra income for the municipalities, as exploiters have to pay a tax of about 1% of the income of the installation [33].

A national survey to investigate the nationwide social acceptance has never been carried out in Spain, but some regional research has been done. In the states of Navarra and Castilla, 2000 jobs were generated by the wind power industry. In Navarra over 1300 people were interviewed and an acceptance of 85% for wind power was found. Since this investigation in 2001 the amount of wind power has increased enormously, but the level of social acceptance remaines very high. When looking at the results of different studies in several areas, the acceptance in all areas was higher than 70%. A 2002 study in the province of Tarragona showed that about 83% of the inhabitants preferred wind power over nuclear power or fossil fuel [3]. From the different studies it can be concluded that the nationwide social acceptance of wind power in Spain is rather high.

5.2.5 Conclusions

Spanish government targets for the amount of wind power to be installed have been updated to a higher level several times since the developments went (much) faster than planned. Since 1986 already Spain has a strong governmental support for renewable energy sources. This is, together with the good wind resources, one of the main factors for the enormous increase in installed wind power. Producers can get a connection to the grid within a couple of months, get a good payment by means of feed-in tariffs for their produced energy, and do often not have to pay for their connection to the grid. The high priority wind power producers get means they almost never have to reduce their output power in case of a congestion, resulting in continues payment. Furthermore social acceptance is very high throughout the country, as people benefit economically from wind power by means of tax paid to the municipality, and a vast majority in Spain sees the importance of clean energy. All these factors together have had a very positive influence on the growth of installed wind power and puts Spain worldwide on the third place of installed wind power capacity.

5.3 The Netherlands

The Netherlands have a rather low share of installed wind power compared to other European countries, in the year 2005 only 2.5% of the total electricity consumption was generated by wind power [39]. This low share is not caused by lack of effort, since already in the 1970s there have been many activities to develop and implement renewable energy, but renewable energy never has been top priority in the Dutch policy [40].

If a region is densely populated like the Netherlands, it is difficult to start a wind power project, because more people will be affected than in less densely populated regions and thus possibilities that people will object are bigger. When it becomes apparent at informal level that legal objects will stop the development of a wind park, often the applications are not even filed. About 80% of the total plans for wind parks in the Netherlands are never being built because of this [39]. Municipalities play an important role in the installation of new wind parks, as they can simply refuse to give their permission. Still an increase in installed wind power can be seen in the Netherlands, between 1996 and 2001 the installed wind power increased with more than 40 MW per year. Since the liberalization of the green electricity market in 2001, a growth can be seen. In the year 2002 217 MW of new power was installed, in 2003 233 MW, and in 2006 the new installed power reached 350 MW [41, 42]. (see figure 5.4 for the cumulatively installed wind power in the Netherlands)

5.3.1 Government targets

Renewable electricity generation in the Netherlands has been rising steadiliy since the 1990s [40]. A target of 1000 MW installed wind power for the year 2000 was set by the Ministry of Economic Affairs in 1985 already, but this target was not reached until the year 2004. Further development of the renewable energy targets was done by the 1997 'Action program for Renewable Energy'. The program together with the 1999 Energy Report presented three policy support methods. First the support of R&D, which should increase competitiveness, second greening the fiscal system to stimulate market penetration and finally the streamlining of planning and permitting procedures to reduce the administrative and political bottlenecks. In the year 2002 the target of 1000 MW installed wind power that was set in 1995 was adjusted to 1500 MW of onshore wind power in 2010. This target was laid down by the administrative agreement BLOW (Bestuursovereenkomst Landelijke Ontwikkeling Windenergie) or Governmental Agreement on the National Development of Wind Energy [41].

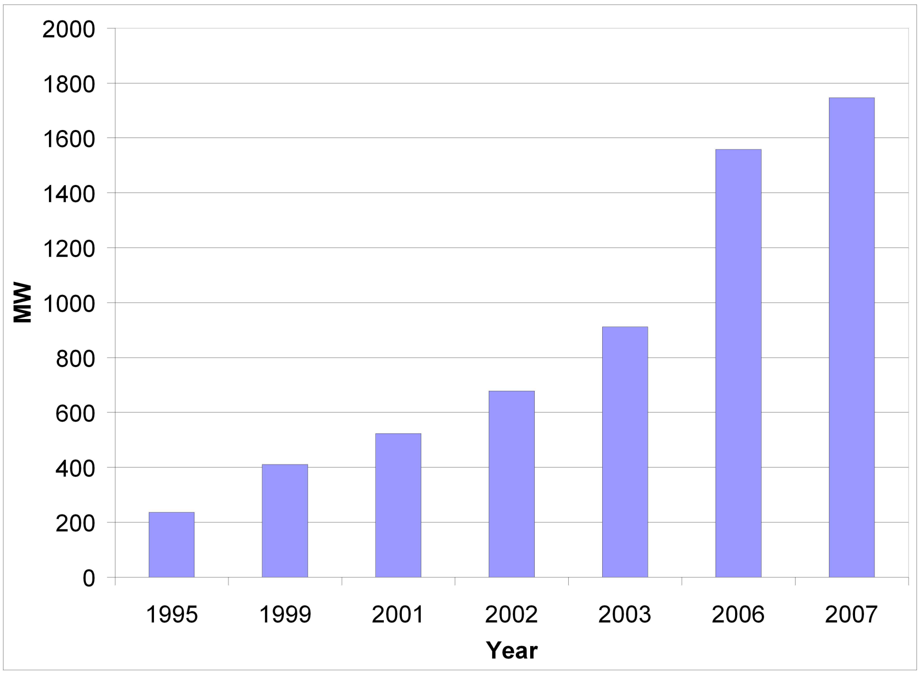


Figure 5.4: Installed wind power (MW) in the Netherlands over the years (data from www.ewea.org and [32])

5.3.2 Procedures

Several procedures have to be followed to get the required permits for the connection of a wind park in the Netherlands. First the project has to fit within the municipal land use plan (MLUP), which states the designated locations for wind turbines, the maximum number of turbines, their maximum heights, and the ratio of mast height and rotor diameter. If the project does not fit within the MLUP the project plan has to be adjusted, an exemption of the MLUP has to be applied for, or the MLUP has to be revised. A revision of the MLUP takes about 60 weeks and and exemption about 48 weeks. Secondly, if the project is larger than 15 MW the authorities have to decide whether an environmental impact assessment is necessary, taking about 48 weeks. After that a construction permit is needed, which can only be obtained if the plans fit within the MLUP, the buildings decree, and building code. A construction permit can be obtained in approximately 12 weeks. Once this permit is obtained, an environmental permit is needed for wind parks larger than 15 MW, which takes 26 weeks to acquire. Projects smaller than 15 MW do not need an environmental permit if the project is placed at least four times the mast height away from the nearest residence. Furthermore depending on the location of the new wind park, a nature conservation permit and dispensation according the law on the protection of wild fauna could be a prerequisite [41]. These last two procedures take respectively between 3 to 9 months and 8 weeks. The entire procedure for the placement of a wind park larger than 15 MW thus takes about 9 months at minimum and over 3,5 years at worst.

In spatial planning the City Council has a veto and can thus block the development of wind parks. Since this council is very sensitive to the public opinion, citizen protests can be of great influence. If wind parks are not indicated in the MLUP, local authorities are often not intended to change the MLUP and building permits are not given [41]. So it is very difficult to get all the permissions needed to build a wind park, when no plans for wind parks are included in the MLUP.

For the actual connection to the grid, an application has to be filed at the TSO or corresponding DSO, depending on the desired voltage level to connect to. Until recently the Dutch TSO TenneT had a 'first come, first served' policy that yielded for every new connection. Since capacity on the grid has become scarcer because of the large amount of distributed generation and a number of new conventional power plants, new connections sometimes have to be postponed or new producers can not transport (all) their energy [43].

5.3.3 Policy

A former barrier for wind parks was the absence of the so called capacity fee. This fee is normally paid to producers by the utilities for their capacity, but utilities refused to pay this fee to wind park producers. Until late in the 1990s this barrier existed. In the year 1990 the international Dutch position on wind energy was very good, but ten years later this leading position disappeared. The Dutch wind turbine industry almost completely vanished and Danish producers took over the market [40].

Subsidies

In the last decade three major policy changes have taken place in the electricity policy. In 1996 an energy tax on renewable energy sources was introduced, in 1998 the liberalisation process of the energy sector started and in 2001 the green electricity market was liberalised for consumers. The liberalisation of the green electricity market together with tax exemptions, caused a favourable situation for the import of foreign green electricity, since this energy was cheap and the generators already written off. Because of this the number of consumers purchasing green electricity increased enormously between 1996 and 2002, causing a big import of renewable energy in the Netherlands as only 26% of the renewable energy was produced locally [40]. Up till 2002 this situation remained and most of the green electricity was imported from abroad. In the year 2002 electricity produced by renewable energy sources almost had the same price as electricity produced by conventional sources [41]. In 2003 the energy tax was ended by the new government and replaced by the 'Environment Quality Electricity generation' (MEP in Dutch), a supply oriented regulation. Renewable electricity producers was offered a fixed feed-in tariff and a degrading tax exemption. This regulation was set for a period of ten years, but after only two years the Economic Affairs minister lowered the subsidies as the budged was exceeded because of a large number of applications for wind parks [42].

In the year 1998 a framework for liberalisation was created by the Electricity Law, wind power producers were from then on free to sell electricity to any other market party [41]. The green electricity market was the first to open, and by July 2001 consumers were able to choose their green electricity company.

Suppliers could now offer their renewable energy to the market for prices equal to or even below conventional energy. Since that day an enormous increase in green electricity consumers started, and by the end of the year 2004 40% of all households was buying green electricity [41].

Since the year 2006 the Dutch government has changed again, and the view on renewable energy also changed. Because of this a new subsidy, stimulation of sustainable energy (SDE) regulation, was launched at the beginning of 2008. This regulation prescribes a fixed subsidy per kWh of produced electricity and a total maximum per renewable energy source [44]. It can thus be seen that, because of the regular changing of the political climate and the absence of long term regulations, a steady policy on subsidies has never existed in the Netherlands.

5.3.4 Social acceptance

There have been no national enquiries regarding the public opinion on wind energy in the Netherlands, but in most municipalities where wind power is planned an action committee against wind power is set up. Also a national critical wind energy platform (*'Nationaal Kritisch Platform Windenergie'*) is raised, which represents local groups, supports opponents of wind power, and warns politicians on the negative effects of wind power [45]. Dutch local and national press often publish negatively of wind energy, thus influencing citizens and authorities [41]. Furthermore local residents increasingly start to protest against wind parks and environmental groups came up with dangers for birds and landscape pollution [40]. Despite all the protests there are still many people in favour of wind energy in the Netherlands, especially long term incentives like the MEP encouraged local ownership and thus local acceptance [46]. Percentages of people in the Netherlands against, and people in favour of wind energy can not be given, be given because of the absence of a local enquiry. It can be seen that on one side there are many local protests against wind power and on the other hand there seems to be a big social acceptance.

5.3.5 Conclusions

It is very difficult and can take quite some time to get all the permissions needed to build a wind park in the Netherlands, especially when no space is reserved for wind parks in the municipal land use plan. A steady long term policy on subsidies has never existed in the Netherlands, because of the regular changing of the political climate. Even though 1985 already a target of 2000 MW was set by the , it took until 1995 before the installed wind power capacity started to grow. This was mainly caused by the liberalisation of the electricity market, which gave producers the opportunity to sell their electricity to every other party and allowed consumers to choose their own green electricity producer. Percentages of people in the Netherlands against and people in favour of wind energy are hard to give, since no national survey has been done on this subject. It can be seen that on one side there are local protests against wind parks, but on the other hand there seems to be a big social acceptance, mainly created by local ownership.

5.4 Comparison and conclusions

Germany and Spain show a big resemblance, both countries have, and have had for many years, a very supporting government towards wind energy. Spanish government targets for the amount of wind power to be installed have been updated to a higher level several times since the developments went (much) faster than planned. The German government has also done much to stop the decaying growth in installed wind power. Both of these country for many years have had a system of feed-in tariffs to promote growth and innovations in the wind energy sector. In the Netherlands the political climate changed regularly and a steady policy on subsidies has never existed. Only since the liberalisation of the electricity market that started in 1995, the installed wind power capacity started to grow faster. The German and Spanish governments also played a bigger role in the local development of wind power than the Dutch government, by means of soft loans and investments in the wind power sector.

Wind energy producers in Spain can get a connection to the grid within a couple of months and do often not have to pay for their connection to the grid. In Germany producers can also obtain access to the grid rather fast, because no special procedures exist for the grid application and renewable energy producers have to be connected immediately by law. In the Netherlands, the grid connection procedure can be rather fast, if there is enough capacity in the grid. However, it is very difficult and can take quite some time to get all the permissions needed to build a wind park in the Netherlands, especially when no space is reserved for wind parks in the municipal land use plan.

Social acceptance levels in the three countries show some differences. In Germany the acceptance of wind energy is rather high, even though some differences in wind power acceptance occur between age groups and areas in Germany. Generally two third of the Germans support further growth in installed wind power. Spain also shows a very high acceptance throughout the country, as people benefit economically from wind power by means of taxes paid to the municipality and a vast majority in Spain that sees the importance of clean energy. Most municipalities where there are plans to install wind power in the Netherlands start an action committee against it, even a national platform against wind power exists. This can be explained by the dense population of the Netherlands; wherever plans are made (many) people live nearby. Even though there are many protests and no national survey has been done on this subject, the overall social acceptance for wind energy seems to be rather high. As can also be seen in Germany and Spain, local ownership and participation in projects play a very important role in creating acceptance.

For investors it would thus be more interesting to build a wind park in Germany or Spain than in the Netherlands, since governments there are very supportive and show a stable position towards renewable energy. The feed-in tariff systems in Germany and Spain are very well developed and the overall social acceptance appears to be higher than in the Netherlands. These, together with the large local wind turbine production and a rather easy procedure for the connection of wind parks in Germany and Spain are important explaining factors for the differences in installed wind power as shown in table 5.1.

Chapter 6

Conclusions and recommendations

6.1 Conclusions

6.1.1 Stability aspects

Several calculations have been carried out to study the influence of a large amount of wind power on the transient stability of the Dutch electrical power system. The calculations were carried out using the Dutch part of the UCTE model with an equivalent representation of the external grids at the interconnections. A validation of this grid model was done by reproducing calculations from an earlier report. From these calculations it was concluded that the situation created showed a much more stable behaviour than the previous calculations. It is assumed this is caused by the representation used for the external grid.

Three different cases were taken into account in the calculations. A comparison between the 2008 situation with about 1700 MW of wind installed, and the 2015 situation with about 7300 MW of wind installed was made. In this case the old regulations were applied, i.e. all wind power is disconnected from the grid if the voltage drops below 0.8 p.u..

Secondly a comparison was made between the 2008 and 2015 grid situation, without wind power installed. The results for the year 2015 showed a decrease in voltage stability and an increase in active power oscillations at the interconnections, caused by the increased amount of thermal power plants in the grid.

For the 2008 situation, a short circuit in the centre of the Dutch power system, at substation Ens, causes a voltage drop below 0.8 p.u. at six substations. This results in the disconnection of 1260 MW of wind power for the model used. The amount of disconnected wind power is a hypothetical worst case, since all wind power is clustered at only nine substations in this thesis, and an assumption has been made for the impedance between wind park and substation. A disconnection of such an amount of wind power causes although only small and fast damped oscillations in the voltages at the substations at the moment the fault clears. At the power flows on the interconnections oscillations occur also, these oscillations damp out within several seconds.

When the same calculation is carried out for the 2015 situation, about 5000 MW of wind power is disconnected. Comparing the results with the 2008 situation shows slightly larger and slower damped oscillations in voltages at the substations. Oscillations that occur in the active power flows at the interconnections are also larger. This is mainly caused by the larger amount of wind power that is lost. Once the oscillations are damped a big increase in import is noticed. In a real situation this would lead to overloaded lines, resulting in switching actions and probably bigger instability problems.

As a third case assumed ‘new’ regulations are applied and most of the turbines are no longer disconnected from the grid during a voltage drop. It can be seen that voltage-recovery time slightly increases, mainly caused by the doubly-fed induction generators that absorb reactive power when the short circuit is cleared. A way to limit this effect is to disconnect the crow bar of DFIG-based wind generators sooner, when the fault has not cleared yet. In the active power flows at the interconnections still some large power oscillations occur, but the oscillations damp out within seconds and the system returns to a steady state.

From these results it could be concluded that the system remains stable, even when about 5000 MW of wind power is disconnected from the grid. Only small oscillations occur in the voltages, but the voltage-recovery time becomes significantly longer for the 2015 situation.

Some remarks should be made on the results, since the interconnections are modelled by a representative external grid. Any effect of thermal power plants or wind power generation from outside the Dutch grid are thus omitted, and a large amount of reserve power is available directly at the borders. As the calculations demonstrate, this external grid representation creates a rather steady situation and a more extended representation would probably result in more oscillatory behaviour.

6.1.2 Local selection environment for onshore wind parks

When comparing the local selection environment for onshore wind parks in Germany, Spain, and the Netherlands, it can be concluded that it would be more interesting for investors to build a wind park in Germany or Spain than in the Netherlands. Governments there are very supportive and show a stable position towards renewable energy. The feed-in tariff systems in Germany and Spain are also very well developed and the overall social acceptance appears to be higher than in the Netherlands. These, together with the large local wind turbine production and a rather easy procedure for the connection of wind parks in Germany and Spain are important explaining factors for the differences in local selection environment.

6.2 Recommendations and further work

In this thesis the grid model used was initially not suited for dynamic simulations. The generator models are included according to two reports, but are not validated with the power producers. To obtain more accurate results, these models and controls have to be described more precise, according to actual parameters.

The grid model used does not include the actual neighbouring grids, but a simplified representation of the external grids. This causes a much more stable model than could be expected and would be representative for the actual situation. To obtain better results, it is recommended to include at least a part of the neighbouring grids and thermal power plants with their controls represented in detail in the simulations. When a validated dynamic model of (a part of) the UCTE is available, the Dutch grid can be separated and parameters for the equivalent grids can be determined more exactly. Interactions between different interconnections will still be ignored, but interaction between Dutch electrical power system and surround grids would be more representative.

The models used for the wind turbines are validated only with previous simulations and papers, but no actual parameters were available. Better validation of the models and further research is needed on the parameter settings to obtain more realistic results.

Finally, all parameters used for the wind turbines are not from an actual turbine and thus the behaviour might differ from the real behaviour. Further research could look into the actual behaviour and control settings of turbine types from different manufacturers. Additional controls like voltage support and frequency control, that are not taken into account in this thesis, could be further looked upon.

Bibliography

[1] G. Brundtland et al. *Our Common Future: The World Commission on Environment and Development. Brundtland Commission. United Nations. World Commission on Environment and Development*, 1987.

[2] *World Wind Energy Association. http://www.wwindea.org/*, attended: 10-07-08, updated: 21-02-2008.

[3] H. Chandler, editor. *Wind Energy -The Facts.* The European Wind Energy Association (EWEA) and the European Commissions Directorate General for Transport and Energy (DG TREN), February 2004.

[4] P. Kundur. *Power System Stability and Control.* McGraw-Hill, 1994.

[5] W. Winter. *Guideline for validation of wind turbines. Final document*, January 2008.

[6] A. Orths. *Validation of wind turbine models. EWIS, Working Group 3*, February 2008.

[7] Network of Experts on Wind Power. *Wind Power in the UCTE Interconnected System.* 2004.

[8] J. G. Slootweg, S. W. H. de Haan, H. Polinder, and W. L. Kling. *Aggregated modelling of wind parks with variable speed wind turbines in power system dynamics simulations. 14th Power Systems Computation Conference*, 2002.

[9] Energinet.dk. *Validation of Wind Turbine Models - SCIG.* December 2007.

[10] J. A. Bos. *Analysis of a dynamic model of a DFIG wind turbine. Work placement report KEMA*, November 2007.

[11] Dienst Toezicht Energie (DTe). *Systeemcode per 4 september 2007.* September 2007.

[12] Energinet.dk. *Validation of Wind Turbine Models - DFIG.* December 2007.

[13] A. D. Hansen and G. Michalke. *Voltage grid support of DFIG wind turbines during grid faults. EWEC 2007*, 2007.

[14] A. D. Hansen, F. Iov, P. Sørensen, N. Cutululis, C. Jauch, and F. Blaabjerg. *Dynamic wind turbine models in power system simulation tool DIgSILENT*. Risø National Laboratory, Technical University of Denmark, August 2007.

[15] Ägir Konsult AB and VG Power AB. *NewGen – a new direct drive wind turbine generator! Nordic Wind Power Conference - NWPC 2006*, May 2006.

[16] Vestas. *V90-3.0 MW Product brochure*.

[17] S. Achilles and M. Pöller. *Direct Drive Synchronous Machine Models for Stability Assessment of Wind Farms. DIgSILENT GmbH, available at http://www.digsilent.de/Consulting/Publications/DirectDrive_Modeling.pdf*.

[18] R. A. C. T. de Groot and C. P. J. Jansen. *Model van het Nederlandse hoogspanningsnet en de omliggende landen ten bate van stabiliteitsstudies aan het 220 en 380 kV net. KEMA T&D Power*, November 2001.

[19] J. G. Slootweg. *Wind Power: Modelling and Impact on Power System Dynamics*. Ph.D. thesis, Delft University of Technology, December 2003.

[20] European Transmission System Operators. *European Wind Integration Study (EWIS) Towards a Successful Integration of Wind Power into European Electricity Grids*. 2007.

[21] TenneT TSO B.V. *Visie 2030*. February 2008.

[22] T. C. M. Bogaert and J. H. Schuld. *Dynamische modelvorming van het Nederlandse transportnet en de daarop aangesloten produktie-eenheden. KEMA Transmission & Distribution*, January 1997.

[23] Tractebel Engineering. *UCTE-IPS project: Validation of Netherlands regulator models*. 2006.

[24] TenneT TSO B.V. *Quality and Capacity Plan 2008–2014*. 2007.

[25] Wind Service Holland. *Wind Energy Statistics NL. http://home.planet.nl/˜windsh/*, attended: 26-11-2007, updated: 22-11-2007.

[26] A. D. Hansen and L. H. Hansen. *Wind Turbine Concept Market Penetration over 10 Years (1995–2004). Wind Energy - Chichester*, 2007.

[27] VROM. *Nieuwe energie voor het klimaat. Werkprogramma schoon en zuinig*, September 2007.

[28] *Noordzeeloket. http://www.noordzeeloket.nl/*, attended: 04-12-2007, updated: 12-11-2007.

[29] H. B. N. Pustjens. *Dynamische stabiliteit van de Maasvlakte eenheden bij netuitbreiding in Zuid-Holland. TenneT*, February 2003.

[30] E.ON Netz GmbH. *Grid Code. High and extra high voltage*, April 2006.

[31] J. I. Lewis and R. H. Wiser. *Fostering a renewable energy technology industry: An international comparison of wind industry policy support mechanisms. Energy Policy*, 2007.

[32] C. Jauch, J. Matevosyan, T. Ackermann, and S. Bolik. *International comparison of requirements for connection of wind turbines to power systems. Wind Energy*, 2005.

[33] E. C. López and T. Ackermann. *Grid Issues for Electricity Production Based on Renewable Energy Sources in Spain, Portugal, Germany, and United Kingdom. Annex to Report of the Grid Connection Inquiry*, 2008.

[34] M. Ragwitz and C. Huber. *Feed-In Systems in Germany and Spain and a comparison. Frauenhofer Institut fur Systemtechni und Innovationsforschung*, 2005.

[35] G. Klaassen, A. Miketa, K. Larsen, and T. Sundqvist. *The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom. Ecological Economics*, 2005.

[36] Gesellschaft für Sozialforschung und statisitsche Analysen mbH (forsa). *Meinungen zur Windenergie*. May 2004.

[37] P. del Río and G. Unruh. *Overcoming the lock-out of renewable energy technologies in Spain: The cases of wind and solar electricity. Renewable and Sustainable Energy Reviews*, 2007.

[38] N. I. Meyer. *Learning from Wind Energy Policy in the EU: Lessons from Denmark, Sweden and Spain. European Environment*, 2007.

[39] D. Toke, S. C. Breukers, and M. Wolsink. *Wind power deployment outcomes: How can we account for the differences? Renewable and Sustainable Energy Reviews*, 2008.

[40] G. P. J. Verbong and F. Geels. *The ongoing energy transition: Lessons from a socio-technical, multi-level analysis of the Dutch electricity system (1960–2004). Energy Policy*, 2007.

[41] S. Agterbosch, P. Glasbergen, and W. J. V. Vermeulen. *Social barriers in wind power implementation in The Netherlands: Perceptions of wind power entrepreneurs and local civil servants of institutional and social conditions in realizing wind power projects. Renewable and Sustainable Energy Reviews*, 2007.

[42] Executive Committee for the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems of the International Energy Agency. *IEA WindEnergy Annual Report 2006*. July 2006.

[43] *TenneT - Hoe werkt het aansluitbeleid? http://www.tennet.org/transport_en_systeemdiensten/Aansluitdiensten/Hoe_werkt_het_aansluitbeleid.aspx*, attended: 31-03-2008.

[44] Minister van Economische Zaken. *Regeling aanwijzing categorieën duurzame energieproductie 2008*. January 2008.

[45] *Nationaal Kritisch Platform Windenergie. http:/www.nkpw.nl/*, attended: 29-04-2008, updated: 21-04-2008.

[46] S. C. Breukers. *Changing institutional landscapes for implementing wind power.* Ph.D. thesis, Universiteit van Amsterdam, January 2007.

[47] H. F. Eleveld, J. H. R. Enslin, J. F. Groeman, K. J. van Oeveren, and M. A. W. van Schaik. *Connect 6000 MW-II: Elektrische infrastructuur op zee. KEMA T&D Consulting*, September 2005.

[48] Wind Generator Modeling Group. *Standard Wind Turbine Generator Models, Western Electricity Coordinating Council. IEEE PES*, 2006.

[49] M. Pöller and S. Achilles. *Aggregated Wind Park Models for Analyzing Power System Dynamics. Proc. 4th International Workshop on Large Scale Integration of Wind Power and Transmission Networks for offshore wind farms, Billund*, 2003.

[50] P. B. Eriksen, T. Ackermann, H. Abildgaard, P. Smith, W. Winter, and J. R. Garcia. *System operation with high wind penetration. Power and Energy Magazine, IEEE*, 2005.

[51] VROM. *Dossier Windenergie Vraag en antwoord. http://www.vrom.nl/pagina.html?id=6985*, attended: 17-04-2008, updated: 2007.

[52] *Connect II: Eindrapport. Ministerie van Economische zaken*, 2005.

Appendices

Appendix A

Adjusted parameters for wind park scaling

- DFIG
  - Rotor frame, PQ measurement
  - Rotor frame, current measurement
  - Rotor frame, protection
  - Load flow parameters of generator
  - DC bus capacitor
  - Reactor, basic settings and load flow settings
  - PWM converter
  - Generator type: inertia, rated mechanical power
  - Transformer rating
- Squirrel cage turbine
  - Load flow parameters of generator
  - Capacitor
  - Transformer rating
  - Generator type: inertia, rated mechanical power
- Direct drive
  - Grid-side frame, PQ measurement
  - Load flow parameters of generator
  - Reactor
  - PWM converters
  - DC bus capacitor
  - Generator type rating
  - Transformer rating
- Rated power of **all** transformers

Appendix B

Test system en wind turbine control parameters

Test system parameters

Table B.1: Parameters of the test system

System component	Parameter	Value
Equivalent grid	S_k''	3 GVA
	R_N/X_N	0.1
Transformer 150/20 kV	U_{1rat}	150 kV
	U_{2rat}	20 kV
	U_K	11%
	S_N	50 MVA
Transformer 20/0.69 kV	U_{1rated}	20 kV
	U_{2rated}	0.69 kV
	U_K	6%
	S_N	50 MVA

Table B.2: Additional test system parameters

System component	**Parameter**	**Value**
Equivalent grid	c-factor	1.
	Voltage magnitude setpoint	1 p.u.
	Voltage angle setpoint	0°
Transformer 150/20 kV	Copper losses - P_{Cu}	0 kW
	No load current - I_0	0%
	No load losses - P_{Fe}	0 kW
	Vector group	YN
	Phase shift	0°
Transformer 20/0.69 kV	Copper losses - P_{Cu}	0 kW
	No load current - I_0	0%
	No load losses - P_{Fe}	0 kW
	Vector group	YN
	Phase shift	0°

SCIG parameters

Table B.3: Parameters of SCIG turbine

Parameter	**Value**
R_s	0.00998 p.u.
X_s	0.12478 p.u.
X_m	3.9931 p.u.
R_r'	0.00998 p.u.
X_r'	0.12478 p.u.

Table B.4: Squirrel cage two mass model mechanical parameters

Parameter	**Value**
K_S [p.u./rad]	0.47748
D_M [p.u.]	0
D_G [p.u.]	0
D_S [p.u.]	0
H_{WTR}	3.4999
H_{GEN}	0.5

DFIG parameters

Table B.5: DFIG electrical parameters

Parameter	Value
R_s	0.008 p.u.
X_s	0.080 p.u.
X_m	3.0 p.u.
R'_r	0.008 p.u.
X'_r	0.080 p.u.

Table B.6: DFIG mechanical parameters

Parameter	Value
Base Power - P_{BASE}	5 MW
Turbine Damping - D_{TUR}	0 Nms/rad
Turbine inertia - J_{WTR}	$6.1 \cdot 10^6$ kgm^2
Generator inertia - J_{GEN}	101.72 kgm^2
Shaft damping - D_{SHAFT}	$1.4 \cdot 10^6$ Nms/rad
Stiffness constant - K_{ms}	$8.3 \cdot 10^7$ Nm/rad
Nominal angular turbine speed	18 rpm

Direct drive parameters

Table B.7: Direct drive synchronous generator parameters

Parameter	Value
Active power	45 MW
Reactive power	6 MVar
Nominal apparent power	55 MVA
Nominal voltage	0.69 kV
Power factor	0.82

Table B.8: Direct drive PQ controller parameters

Parameter	Value
Tr	0,00128 s
KP	0,0000356
TiP	0,0128 s
KQ	0,0000356
TiQ	0,0128 s
yP_min	-2 p.u.
yQ_min	-2 p.u.
yP_max	2 p.u.
yQ_max	2 p.u.

Table B.9: Direct drive voltage controller parameters

Parameter	Value
Kuac	10
Tuac	0.1 s
Kudc	10
Tudc	0.1 s
Min_iqref	-2 p.u.
Min_idref	-2 p.u.
Max_iqref	2 p.u.
Max_idref	2 p.u.

Table B.10: Direct drive PWM integrated current controller parameters

Parameter	Value
Kd: d-Axis, Proportional Gain	2
Td: d-Axis, Integration Time Constant	0.0001s
Kq: q-Axis, Proportional Gain	2
Tq: q-Axis, Integration Time Constant	0.0001s

Appendix C

PowerFactory control frames

DIgSILENT PowerFactory uses so called frames for the control of components in dynamic simulations. These control frames can be created by the user, but several predefined frames are included in the software. The frames consist of blocks, called slots, that can consist of controllers or grid components. Arrows are used to create interconnections between the blocks and define which output signal is linked to which input signal. In this way for example the turbine power of a wind turbine can be calculated and connected to the turbine power input of the generator.

The frames thus provide a way to create a control structure, and a link between controls and components, beside the actual grid. Figure C.1 to figure C.6 show the control frames for the SCIG, DFIG, and direct drive turbine.

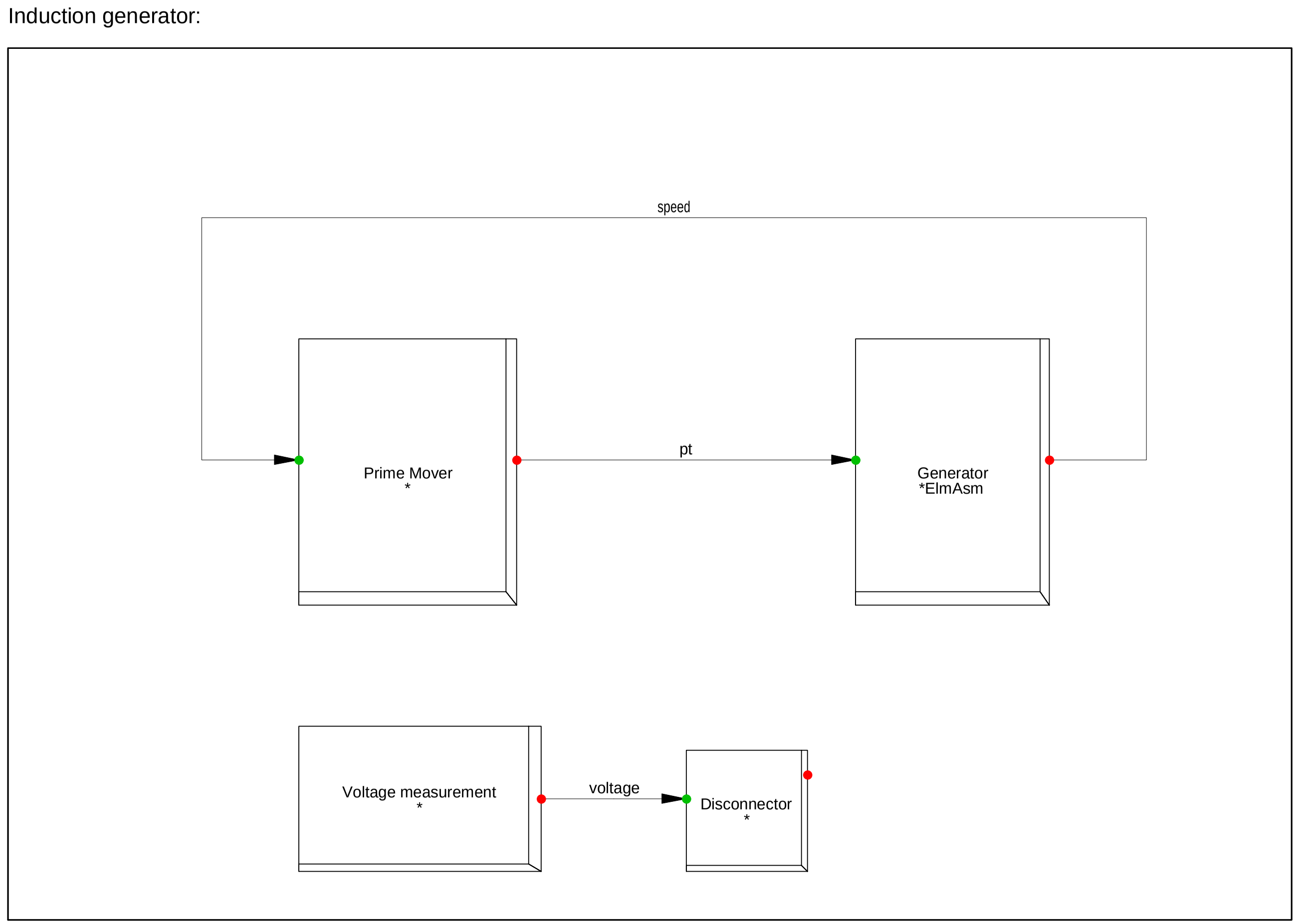


Figure C.1: Squirrel cage induction generator control frame

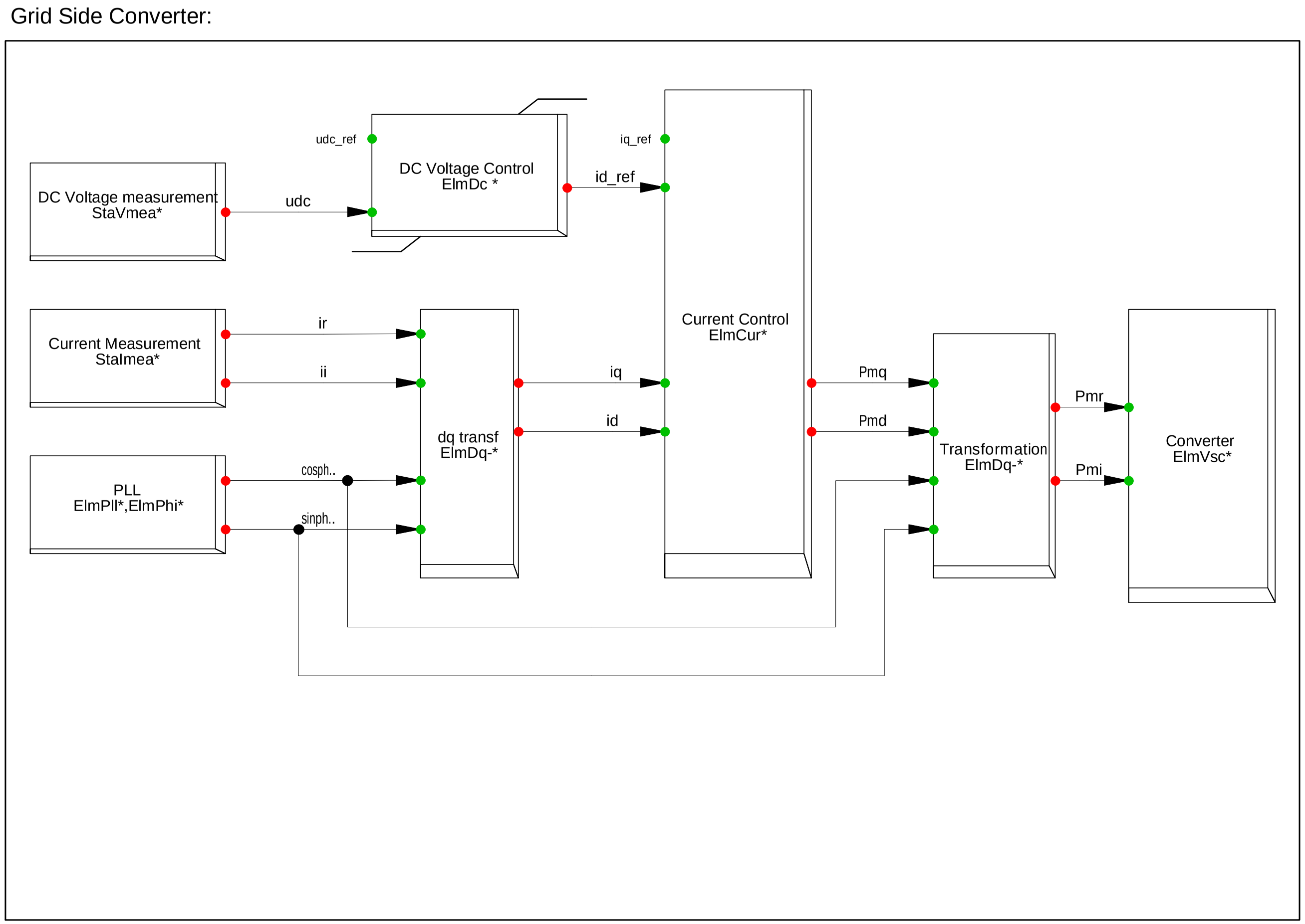


Figure C.2: DFIG grid-side converter frame

DFIG:

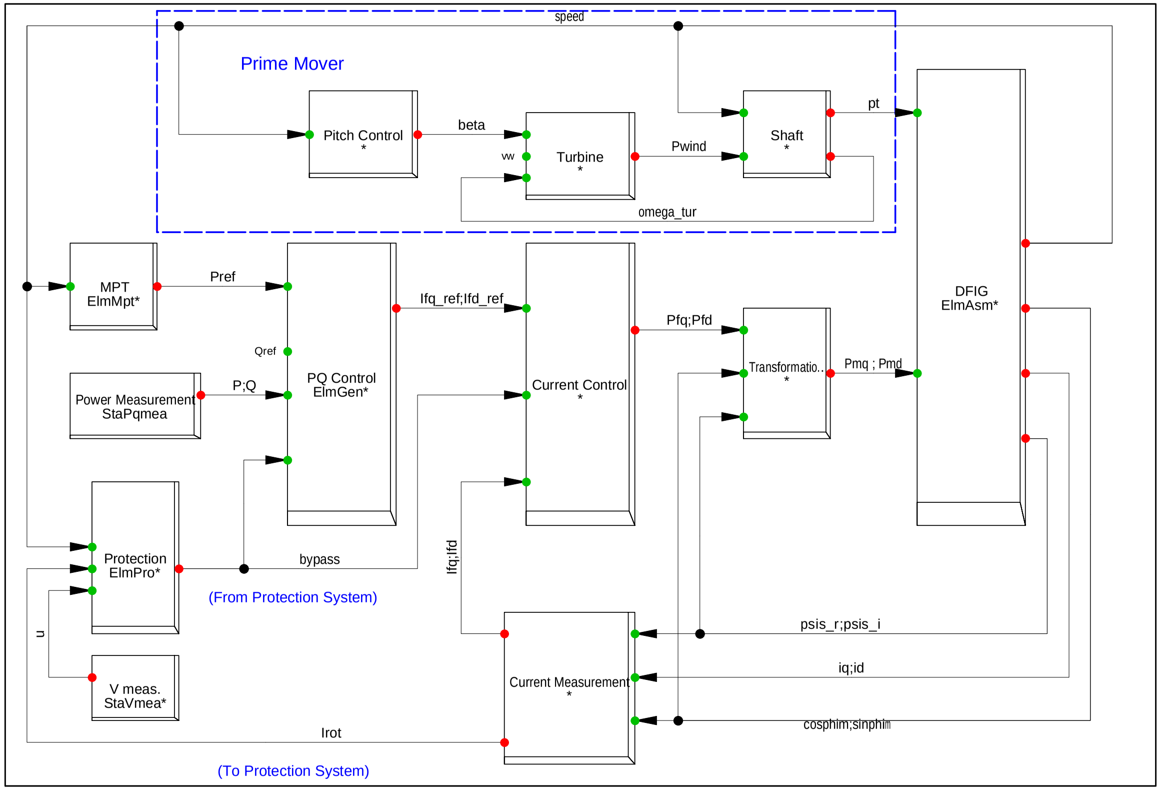


Figure C.3: DFIG rotor-side converter frame

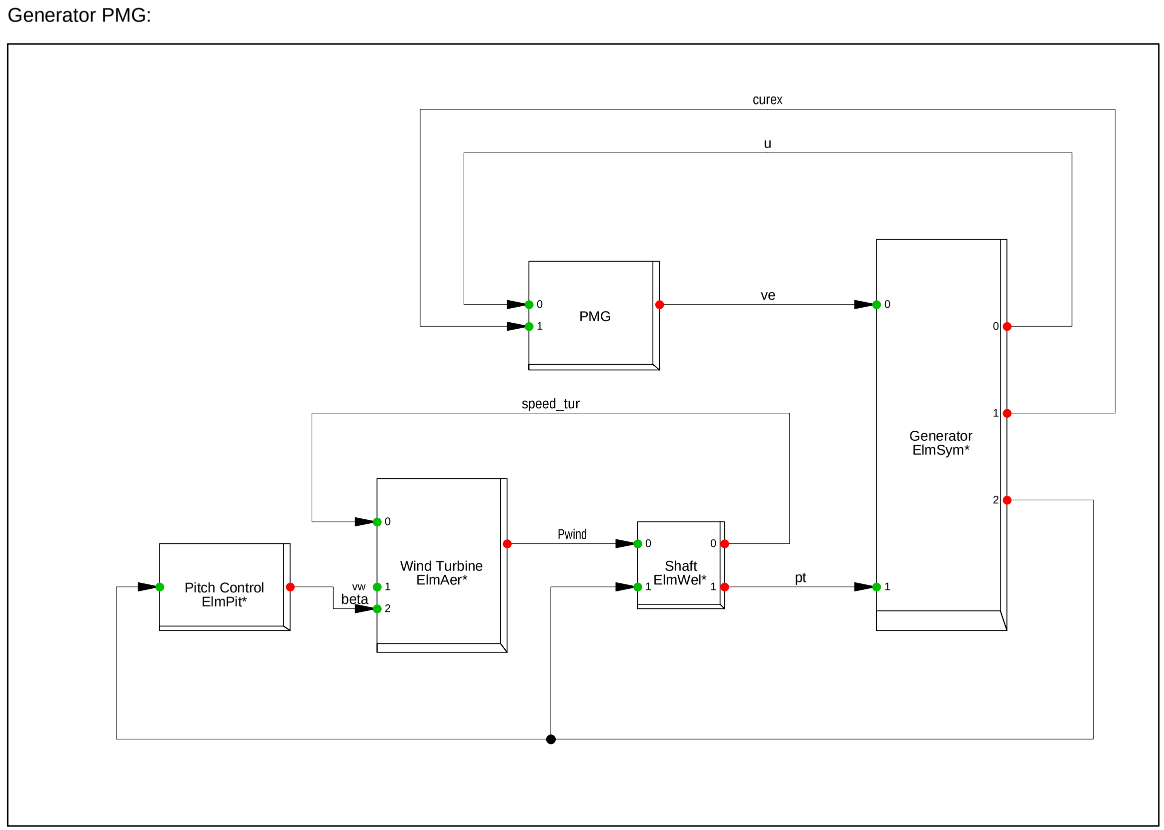


Figure C.4: Direct drive generator control

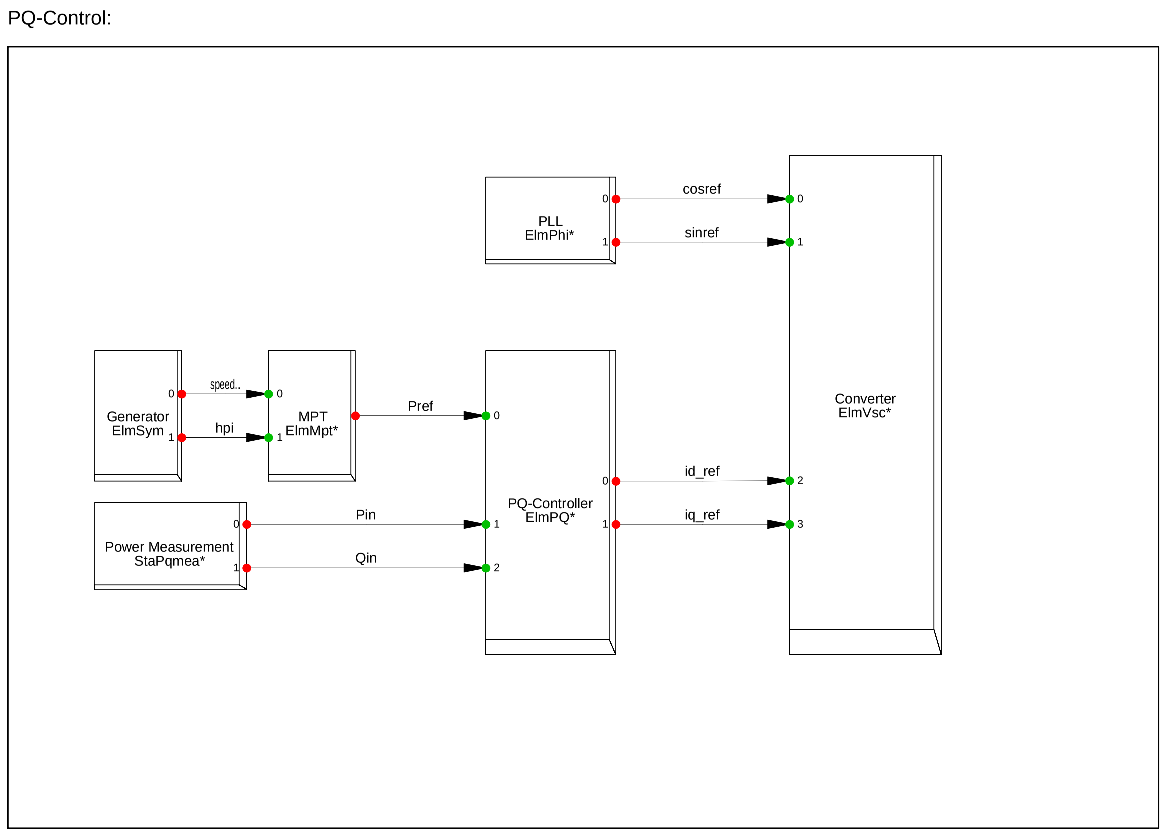


Figure C.5: PQ-Controller diagram

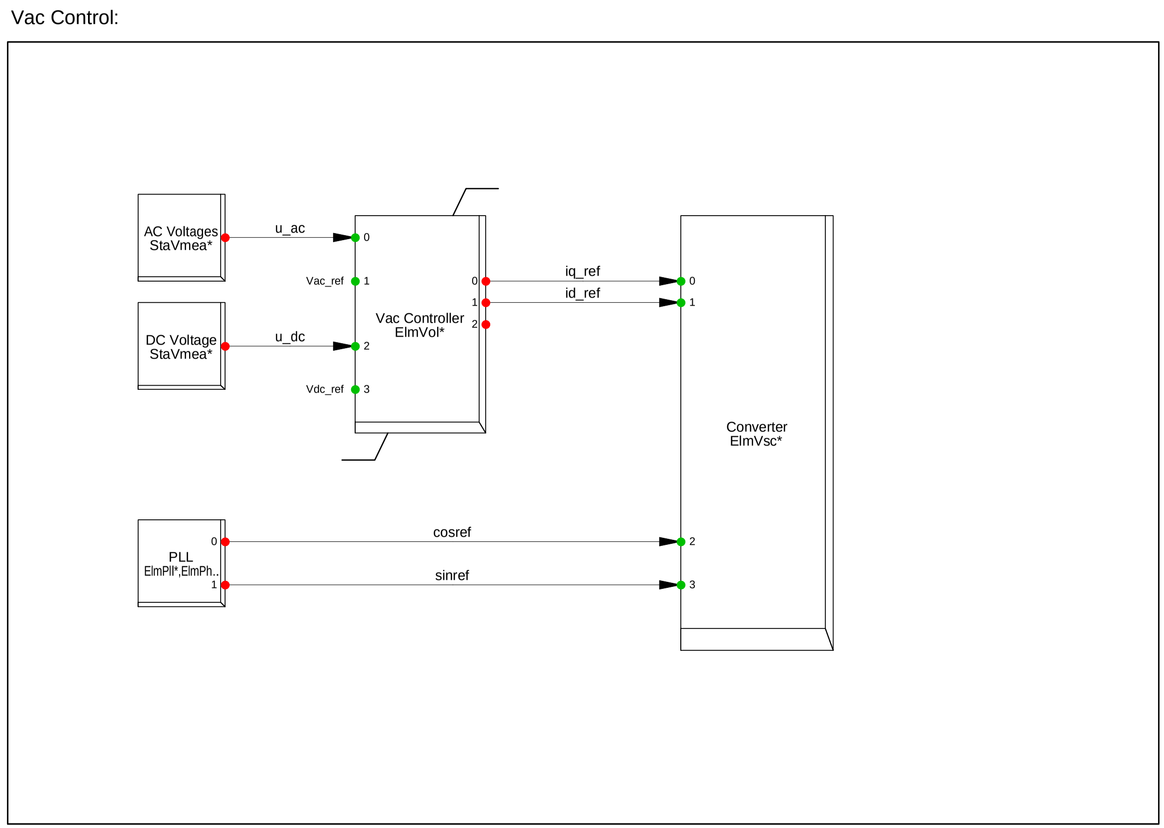


Figure C.6: Voltage-Controller diagram

Appendix D

Power plant controls and parameters

Table D.1: 2008 plants with controls

Power plant	**Excitation control**	**set**	**Speed control**
NA-81	EXST1	2	TGOV1
NA-91	EXST1	2	TGOV1
NBG-102	IEEEX2	1	TGOV1
NBS12	EXST1	4	TGOV1
NBS30	IEEEX2	1	TGOV1
NCC-A	IEEEX2	2	TGOV1
NCC-B	IEEEX2	2	TGOV1
NDES1	EXST1	1	GAST2A
NDES2	SEXS	0	TGOV1
NDGS-13	SEXS	0	TGOV1
NDM33	SEXS	0	TGOV1
NEC-202	SEXS	0	TGOV1
NEC-3	EXST1	1	GAST2A
NEC-5	EXST1	1	GAST2A
NEC-6	EXST1	1	GAST2A
NEC-7	EXST1	1	GAST2A
NES-1	SEXS	0	TGOV1
NFG10-31	SEXS	0	TGOV1
NG-13	IEEEX2	3	TGOV1
NHC60	SEXS	0	TGOV1
NHW-8	EXST1	3	TGOV1
NIJM1	IEEEX2	3	TGOV1
NLWE6	SEXS	0	TGOV1
NMC-7	SEXS	0	TGOV1
NMD1	SEXS	0	TGOV1
NMK12	SEXS	0	TGOV1
NMV-1	IEEEX2	1	TGOV1
NMV-2	IEEEX2	1	TGOV1
NREC113	SEXS	0	TGOV1
NROC3	SEXS	0	TGOV1
NSW-1	SEXS	0	TGOV1
NVN24	IEEEX2	2	TGOV1

Table D.2: 2015 plants with controls

Power plant	Excitation control	set	Speed control
EC4	EXST1	1	GAST2A
EC5	EXST1	1	GAST2A
Gen-NBS30	IEEEX2	1	TGOV1
NMV-1	IEEEX2	1	TGOV1
NMV-2	IEEEX2	1	TGOV1
NA-81	EXST1	2	TGOV1
NBS12	EXST1	4	TGOV1
NBSLD-1	SEXS	0	TGOV1
NBSLSVG-1	SEXS	0	TGOV1
NDM33	SEXS	0	TGOV1
NEN-1	SEXS	0	TGOV1
NEN-2	SEXS	0	TGOV1
NES-1	SEXS	0	TGOV1
NFG10-31	SEXS	0	TGOV1
NG-13	IEEEX3	3	TGOV1
NHW-8	EXST1	3	TGOV1
NIJM1	IEEEX2	3	TGOV1
NLLSEL-1	SEXS	0	TGOV1
NLWE6	SEXS	0	TGOV1
NMC-7	SEXS	0	TGOV1
NMD1	SEXS	0	TGOV1
NMK12	SEXS	0	TGOV1
NMVE-1	SEXS	0	TGOV1
NMVEN-1	SEXS	0	TGOV1
NMVI-1	SEXS	0	TGOV1
NNA-91	EXST1	2	TGOV1
NROC3	SEXS	0	TGOV1
NRWE-1	SEXS	0	TGOV1
NRWE-2	SEXS	0	TGOV1
NSW-1	SEXS	0	TGOV1

Excitation controls

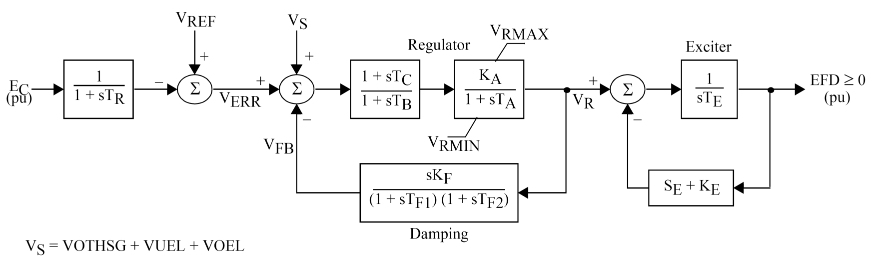


Figure D.1: IEEEX2 control diagram

Table D.3: IEEEX2 parameter sets

Parameter	set 1	set 2	set 3
Tr	0,01	0,01	0,01
Ka	550	1108	500
Ta	0,01	0,01	0,001
Tb	0,001	0,001	1
Tc	0	0	0
Te	0,5	0,5	0,3
Kf	0,022	0,022	0,022
Tf1	0,5	0,5	0,5
Tf2	1,2	1,2	0,2
Ke	1,2	1,2	0
E1	4	4	3,375
Se1	0,7	0,3	1,05
E2	2	2	4,5
Se2	1,5	1,5	1,5
Vrmin	-8	-8	-8
Vrmax	9,8	9,8	9,8

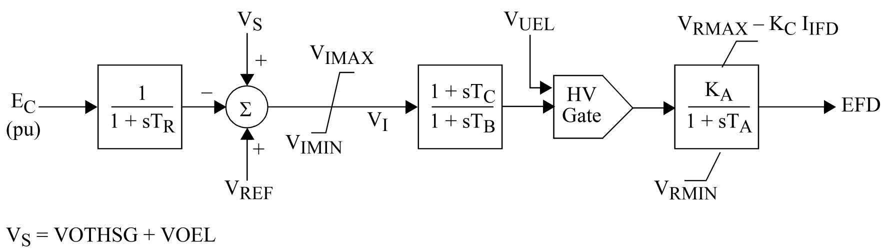


Figure D.2: EXST1 control diagram

Table D.4: EXST1 parameter sets

Parameter	set 1	set 2	set 3
Tr	0	0	0
Tb	0	1	1
Tc	0	1	1
Ka	1000	1000	1000
Ta	1,5	0,01	0,01
Kc	0	0	0
Kf	0,04	0,012	0,015
Tf	1	2	2
Vimin	-0,2	-3	-3
Vrmin	0	-7	-7
Vimax	0,2	10	10
Vrmax	6	8,75	4,9

Table D.5: SEXS parameter set

Parameter	Value
Tb	0,9
Ta	10
K	35
Te	0,05
Emin	0
Emax	6

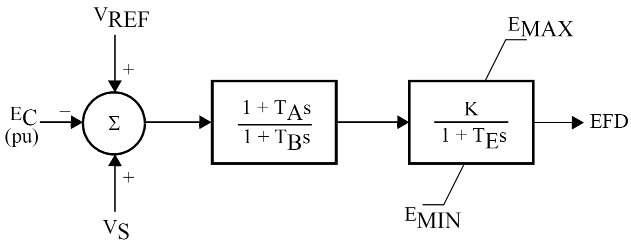


Figure D.3: SEXS control diagram

Speed controls

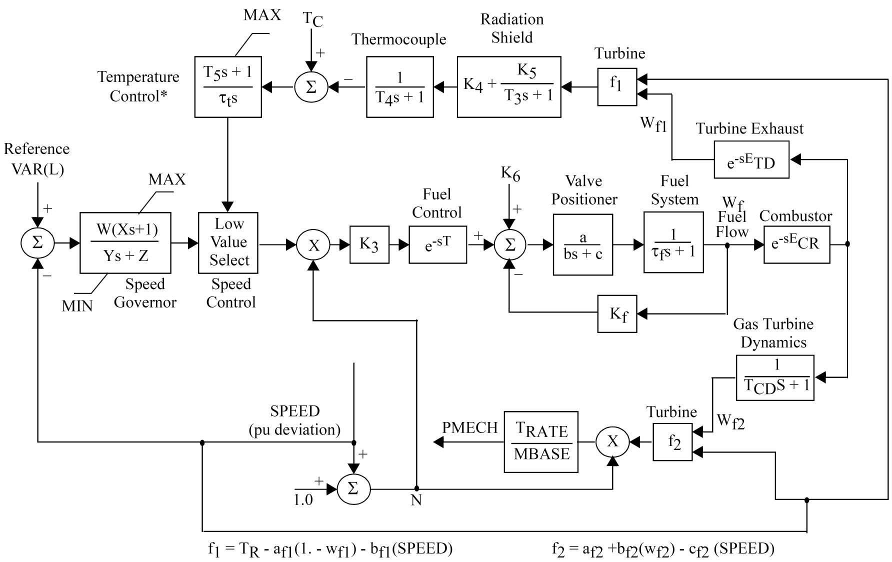


Figure D.4: GAST2A control diagram

Table D.6: GAST2A parameter set

Parameter	Value
Ecr	0,01
T	0
K3	0,77
Tf	0,4
Tcd	0,1
K6	0,23
Kf	0
Trate	358
K4	0,8
K5	0,2
T3	15
W	25
X	0
Z	1
Y	0,05
Tc	980
Tt	250
T5	3,3
T4	2,5
af2	-0,3
bf2	1,3
cf2	0,5
Etd	0,02
Tr	1000
af1	700
af2	550
a	1
b	0,05
c	1
Min	-0,1
Max	1,5

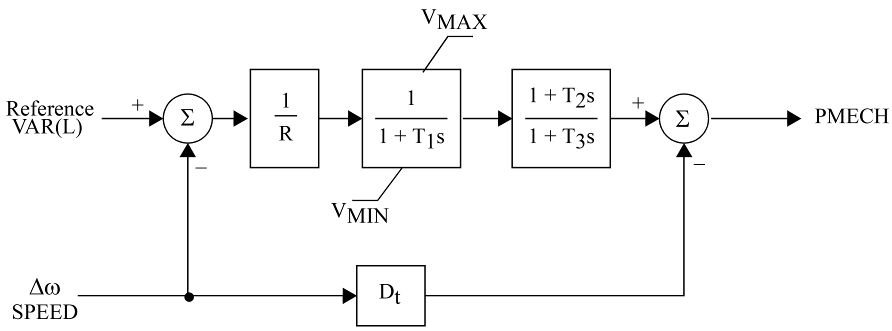


Figure D.5: TGOV1 control diagram

Table D.7: TGOV1 parameter set

Parameter	Value
T3	6
T2	2
At	1
Dt	0
Pturb	0
R	0,1
T1	0,5
Vmin	0,125
Vmax	2

Generator parameters

Table D.8: Parameters for the 2008 generators

generator	Sn	cos fn	Td0'	Td0"	Tq0'	Tq0"	H	D	xd	xd'	xd"	xq	xq'	xq"	xl	S1.0	S1.2
NA-81	775	0,8	7,46	0,04	0,48	0,14	5,14	0	2,6	0,31	0,22	2,49	0,5	0,22	0,18	0,115	0,397
NA-91	813	0,8	5,92	0,03	1,07	0,05	5,3	0	2,267	0,332	0,249	2,216	0,522	0,249	0,214	0,042	0,188
NADM	89	0,8	6,67	0,08	0	0,50	5,96	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAKZ	33	0,8	6,67	0,08	0	0,50	6,13	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAL-1	112	0,8	6,67	0,08	0	0,50	4,07	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAL-2	94	0,8	6,67	0,08	0	0,50	6,57	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAPN	40	0,8	6,67	0,08	0	0,50	3,1	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAVI0	38	0,8	6,67	0,08	0	0,50	6,74	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAVIA	67	0,8	6,67	0,08	0	0,50	6,5	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAVIB	66	0,8	6,67	0,08	0	0,50	5,49	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAVR1	89	0,8	6,67	0,08	0	0,50	6,46	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NAVR2	83	0,8	6,67	0,08	0	0,50	3,55	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NBER	96	0,8	6,67	0,08	0	0,50	5,27	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NBG-102	375	0,8	9,20	0,04	0,5	0,15	2,99	0	2,14	0,38	0,28	1,93	0,5	0,28	0,213	0,09	0,35
NBG-202	375	0,8	9,20	0,04	0,5	0,15	2,99	0	2,14	0,38	0,28	1,93	0,5	0,28	0,213	0,09	0,35
NBS12	600	0,8	11,50	0,03	0,48	0,14	6,61	0	2,26	0,27	0,22	2,05	0,44	0,22	0,2	0,092	0,55
NBS20	52	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NBS30	600	0,8	11,50	0,03	0,48	0,14	6,61	0	2,26	0,27	0,22	2,05	0,44	0,22	0,2	0,092	0,55
NCC-A	770	0,78	11,30	0,05	0,48	0,14	3,51	0	2,3	0,355	0,242	2,07	0,5	0,242	0,18	0,191	0,739
NCC-B	770	0,78	11,30	0,05	0,48	0,14	3,51	0	2,3	0,355	0,242	2,07	0,5	0,242	0,18	0,191	0,739
NCDG	135	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NDES1	448	0,8	4,73	0,04	1	0,15	6,47	0	2,217	0,389	0,276	2,15	0,5	0,276	0,221	0,11	0,449
NDES22	306	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NDGS-13	244	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NDM33	625	0,8	8,36	0,04	0,5	0,15	5,72	0	2,13	0,33	0,245	0,92	0,33	0,245	0,182	0,084	0,235
NDOW-13	70	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NEC-202	725	0,8	8,58	0,08	1,5	0,15	4,11	0	2,36	0,366	0,261	2,12	0,5	0,261	0,196	0,11	0,45
NEC-32	448	0,8	4,73	0,04	1	0,15	6,47	0	2,217	0,389	0,276	2,15	0,5	0,276	0,221	0,11	0,449
NEC-42	448	0,8	4,73	0,04	1	0,15	6,47	0	2,217	0,389	0,276	2,15	0,5	0,276	0,221	0,11	0,449
NEC-52	448	0,8	4,73	0,04	1	0,15	6,47	0	2,217	0,389	0,276	2,15	0,5	0,276	0,221	0,11	0,449
NEC-6	448	0,8	4,73	0,04	1	0,15	6,47	0	2,217	0,389	0,276	2,15	0,5	0,276	0,221	0,11	0,449
NEC-7	448	0,8	4,73	0,04	1	0,15	6,47	0	2,217	0,389	0,276	2,15	0,5	0,276	0,221	0,11	0,449
NENE	73	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NERC0	112	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NES-1	645	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NESM0	312	0,8	6,67	0,08	0	0,50	3,2	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NESS	60	0,8	6,67	0,08	0	0,50	4,5	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NEUR	135	0,8	6,67	0,08	0	0,50	3,49	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NFG10-31	213	0,8	6,67	0,08	0	0,50	6,04	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NFG12-33	170	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NFL30	686	0,9	8,70	0,05	1	0,15	3,09	0	2,67	0,36	0,28	2,4	0,5	0,28	0,21	0,0489	0,303
NG-13	686	0,9	8,70	0,05	1	0,15	3,09	0	2,67	0,36	0,28	2,4	0,5	0,28	0,21	0,0489	0,303
NGAV0	124	0,8	6,67	0,08	0	0,50	6,34	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NGEP	156	0,8	6,67	0,08	0	0,50	4,77	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NGTC0	180	0,8	6,67	0,08	0	0,50	4,97	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NGV15	146	0,8	6,67	0,08	0	0,50	3,86	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NHC60	634	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NHGG1	14999	0,8	6,67	0,08	0	0,50	5,92	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NHKN	138	0,8	6,67	0,08	0	0,50	5,61	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NHMSV	173	0,8	6,67	0,08	0	0,50	4,19	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NHVCA	58	0,8	6,67	0,08	0	0,50	5,53	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NHW-7	938	0,8	6,67	0,08	0	0,50	5,8	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NHW-8	756	0,9	5,92	0,03	1	0,05	5,8	0	2,108	0,308	0,231	2,06	0,486	0,231	0,2	0,042	0,19
NHWG	281	0,8	6,67	0,08	0	0,50	3,44	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NIJM1	686	0,9	8,70	0,05	1	0,15	3,09	0	2,67	0,36	0,28	2,4	0,5	0,28	0,21	0,0489	0,303
NKZV0	112	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NLD12	170	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NLWE6	202	0,8	10,60	0,04	1	0,05	7,38	0	2,48	0,24	0,19	2,31	0,4	0,19	0,17	0,106	0,359
NLYO	120	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMC-7	525	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NMD1	510	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NMK10	188	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMK11	223	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMK12	457	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NMSD0	95	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMV-1	625	0,8	8,36	0,04	0,5	0,15	5,72	0	2,13	0,33	0,245	0,92	0,33	0,245	0,182	0,084	0,235
NMV-2	625	0,8	8,36	0,04	0,5	0,15	5,72	0	2,13	0,33	0,245	0,92	0,33	0,245	0,182	0,084	0,235
NNEF	105	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NPU-1	112	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NREC113	1461	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NROC1	45	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NROC2	45	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NROC3	443	0,8	5,00	0,05	1	0,05	3,5	0	2	0,3	0,2	1,9	0,5	0,2	0,1	0,1	0,4
NSAL0	156	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NSAP	175	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NSCE	108	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NSHL1	188	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NSHL2	263	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NSW-1	190	0,8	12,70	0,04	2,5	0,15	7,38	0	1,86	0,222	0,1872	1,767	0,435	0,1872	0,139	0,137	0,458
NVN24	550	0,8	8,00	0,03	1	0,05	6,4	0	2,37	0,281	0,228	2,1	0,5	0,228	0,193	0,2	0,75
NVN25	550	0,8	8,00	0,03	1	0,05	6,4	0	2,37	0,281	0,228	2,1	0,5	0,228	0,193	0,2	0,75
NWKCE	151	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0

Table D.9: Parameters for the new generators in the year 2015

generator	Sn	cos fn	Td0’	Td0”	Tq0’	Tq0”	H	D	xd	xd’	xd”	xq	xq’	xq”	xl	S1.0	S1.2
NBGMEL-1	568	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NBSLD-1	103	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NBSLSVG-1	1088	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NDZAL-1	145	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NEAP-1	1500	0,8	6,45	0,07	0	0,06	4	0	2	0,4	0,3	2	0,3	0,3	0,2	0	0
NEEB-1	158	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NEEB-2	950	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NEMBNAM-1	163	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NEN-1	440	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NEN-2	1350	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NERWE-x	1000	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NGTES-1	1000	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NLLSEL-1	1125	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMBTES-1	815	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMDKES-1	538	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMVE-1	1315	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMVEL-1	1000	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMVEN-1	1050	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMVI-1	550	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0
NMVNN-1	750	0,8	6,67	0,08	0	0,50	4	0	2	0,3	0,2	2	0,3	0,2	0,1	0	0

Appendix E

Grid changes between 2008 and 2015

Modifications as from the year 2008

- Lelystad: 380 kV-railsystem with both circuits Diemen-Ens connected to station Lelystad
- Borssele: 380 kV-railsystem with bus coupler
- Eemshaven: adding a second 380/220 kV-transformer
- Hengelo: adding a third 380/110 kV-transformer
- Meeden: adding a second 220/110 kV-transformer

Modifications as from the year 2011

- Westerlee: new substation, with two busbars and three 380/150 kV-transformers
- Wateringen: new substation, with two busbars, a bus coupler and three 380/150 kV-transformers
- Bleiswijk: extention to double busbar substation with bus coupler and two additional 380/150 kV-transformers
- Breukelen: new substation with one 380/150 kV-transformer
- Simonshaven: new substation with one 380/150 kV-transformer

Modifications as from the year 2014

- Beverwijk: extention to double busbar substation with bus coupler and two additional 380/150 kV-transformers
- Ens; adding third 380/220 kV-transformer

Modifications in the 380/220 kV grid connections

Modifications as from the year 2011

- Zeyerveen - Hessenweg: 220-kV connection Zeyerveen - Hessenweg upgraded to 1524 MVA
- Krimpen - Bleiswijk: upgrading from 150 kV to 380 kV
- Bleiswijk - Wateringen - Westerlee - Maasvlakte: 380-kV connection

Modifications as from the year 2014

- Vierverlaten - Bergum- Louwsmeer - Oude Haske - Ens: maximum transport capacity of the 220-kV connection raised to 2 x 1524 MVA
- Beverwijk - Oostzaan; upgrading from 150 kV to 380 kV
- Beverwijk - Bleiswijk; double circuit 380-kV connection

Appendix F

Tables wind power distribution

Table F.1: Assumed additional onshore wind power (2008–2015)

Substation	**Motivation**	**MW**
Eemshaven	newly installed and replacement	300
Louwsmeer	doubled	134
Lelystad	large growth because of replacement	800
Ens	large wind park IJsselmeer	600
Borssele	tripled, high potential	335
Geertruidenberg		169
Maasvlakte	doubled	120
Diemen	doubled	128
Onshore total		**2586**

Table F.2: Assumed additional offshore wind power (2008–2015)

Substation	**MW**
Beverwijk (Q7 + 450 MW)	570
Beverwijk (35%)	850
Maasvlakte (35%)	850
Eemshaven (15%)	365
Borssele (15%)	365
Offshore total	**3000**

Table F.3: Total installed wind power by turbine type and grid 2015

Station	**Squirrel cage**		**DFIG**		**Full converter**		**total 2015**
	Distribution	**Transmission**	**Distribution**	**Transmission**	**Distribution**	**Transmission**	
Eemshaven	4	0	94	511	28	154	**791**
Louwsmeer	1	0	205	0	61	0	**267**
Lelystad	7	0	1009	0	303	0	**1319**
Ens	3	0	59	461	17	139	**679**
Borssele	4	0	383	281	115	85	**868**
Geertruidenberg	2	0	258	0	78	0	**338**
Maasvlakte	5	0	181	654	54	197	**1091**
Beverwijk	8	0	203	1092	61	329	**1693**
Diemen	1	0	196	0	59	0	**256**
Total	**35**	**0**	**2588**	**2998**	**776**	**903**	**7302**

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Table F.4: Overview of installed wind power 2008, new installed power, and installed power 2015

Station	**2008**			**New installed**			**2015**		
	Squirrel cage	**DFIG**	**Full converter**	**Squirrel cage**	**DFIG**	**Full converter**	**Squirrel cage**	**DFIG**	**Full converter**
Eemshaven	34	20	72	-30	585	110	4	605	182
Louwsmeer	20	80	33	-19	125	28	1	205	61
Lelystad	127	275	117	-120	734	186	7	1009	303
Ens	28	36	15	-25	484	141	3	520	156
Borssele	16	125	27	-12	539	173	4	664	200
Geertruidenberg	27	106	36	-25	152	42	2	258	78
Maasvlakte	8	100	13	-3	735	238	5	835	251
Beverwijk	23	211	39	-15	1084	351	8	1295	390
Diemen	17	92	19	-16	104	40	1	196	59
Total	**300**	**1045**	**371**	**-265**	**4542**	**1309**	**35**	**5587**	**1680**
	Total 2008: 1716 MW			Total new: 5586 MW			Total 2015: 7302 MW		

Appendix G

Additional simulation results

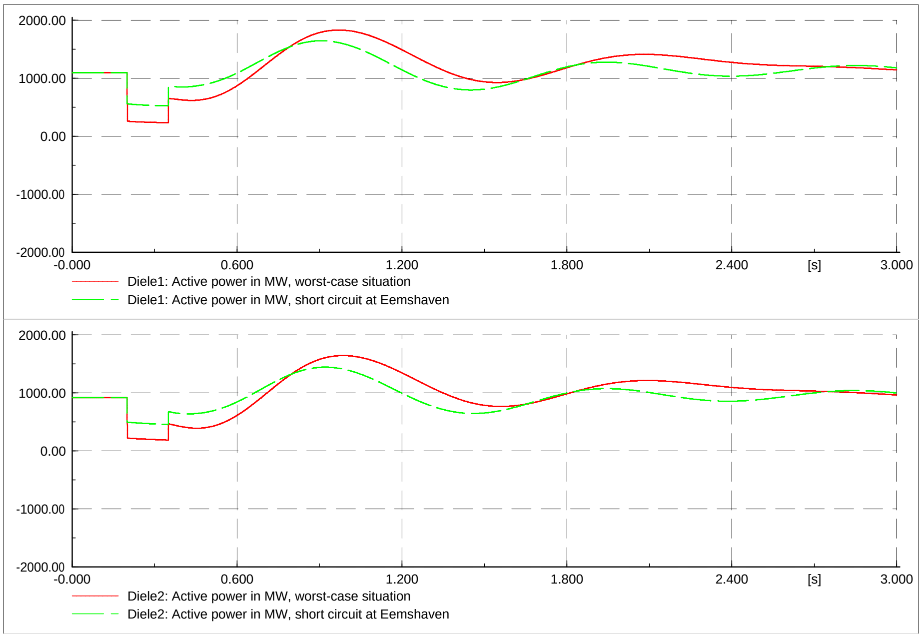

Figure G.1: Active power flow at interconnection Meeden–Diele, for the worst case situation and short circuit at Eemshaven 2008

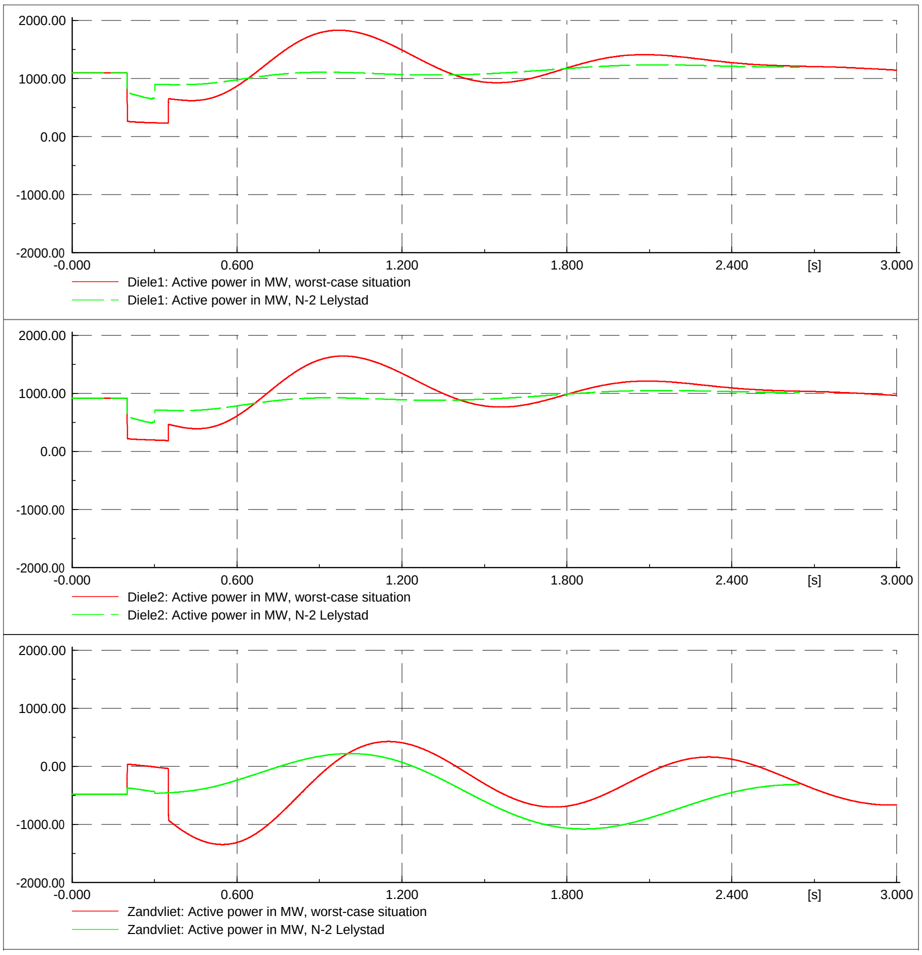

Figure G.2: Active power flow at interconnections, worst-case situation and N-2 situation near Lelystad 2008

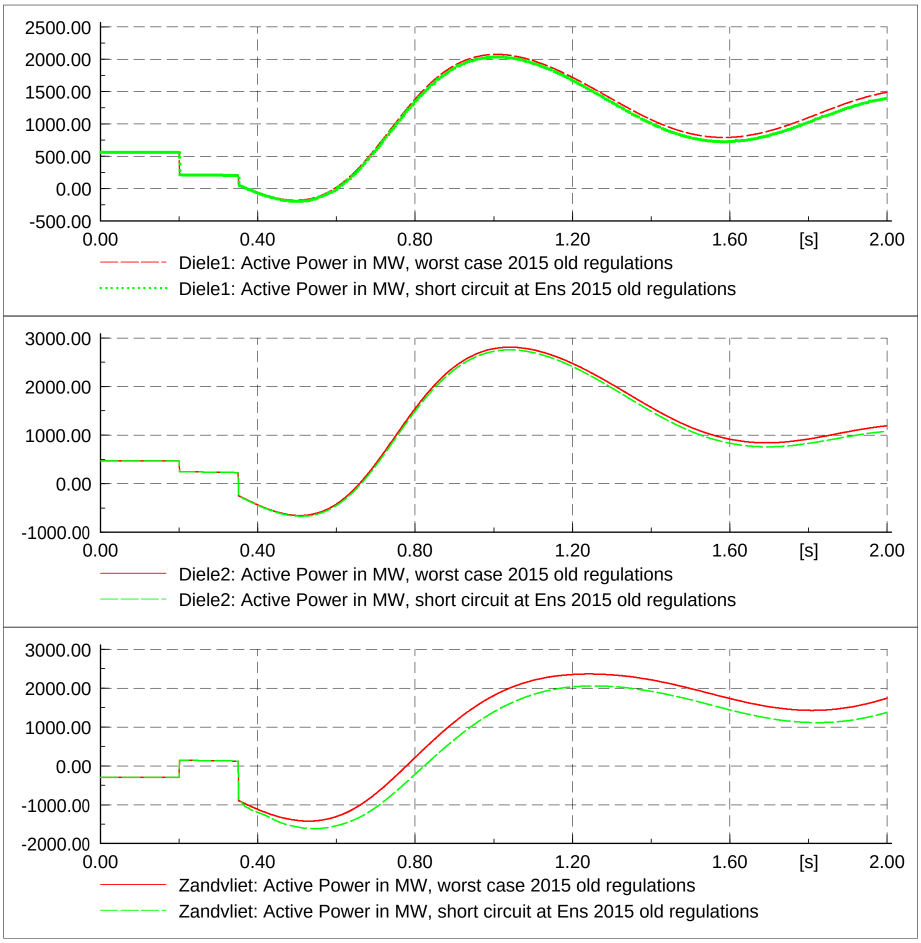

Figure G.3: Active power flow interconnections, worst case situation and short circuit at Ens, old regulations 2015

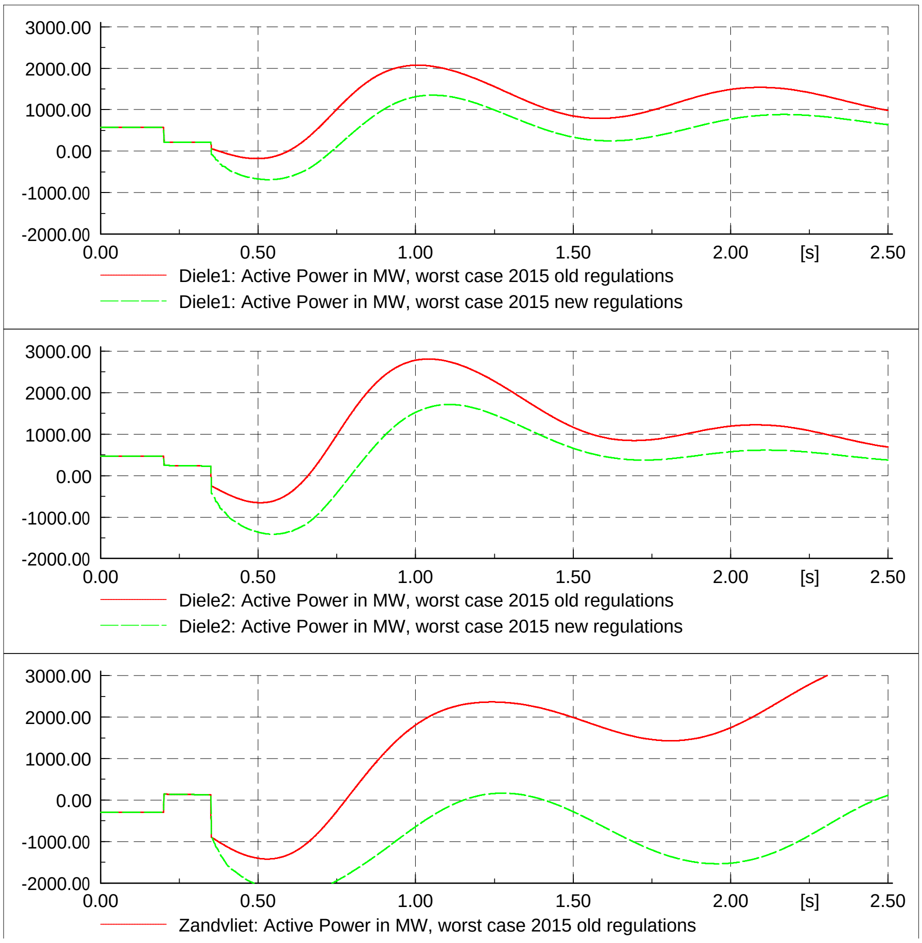

Figure G.4: Active power at interconnections, worst case situation old and new regulations 2015

Appendix H

Thesis proposal

Introduction

Wind power penetration in the Dutch electricity grid is increasing at a fast rate. Optimistic goals are to have 6000 MW of offshore wind power installed by 2020 [47]. Many studies have been carried out already to look at the effects of connecting such a large amount of wind power to the network. Different connection methods, e.g. HVAC and HVDAC, and grid designs have been investigated, but still many questions remain. This thesis will look further into the dynamic behaviour of the electrical power system with large scale wind generation implemented. Issues that will be treated are different rules and regulations throughout Europe regarding the connections of wind parks, short circuit requirements and fault ride through capabilities. Aggregated models will be used as a tool in (dynamic) simulations. A part of the thesis will be carried out in the scope of the second phase of the European Wind Integration Study (EWIS), which is a European study on the effects of wind power on the dynamic grid behaviour in 2008 and 2015.

Thesis description

Distribution of wind power

Today over 1700 MW of wind power is already installed in the Dutch electricity grid, of which the majority (about 93%) is installed onshore. In the scope of the first phase of EWIS a rough distribution of onshore wind power was made by picking six aggregated connection points [20]. A first step in this thesis would be to list the installed wind power in the Netherlands, look at the distribution, and compare this with the aggregated connection points used by EWIS. It will be examined if these six connection points are sufficient for an adequate dynamic simulation, taking into account the current situation and the 2020 situation, with a much higher wind generation penetration.

Wind turbines can be divided up into four types using a general classification created by the Western Electricity Coordinating Council (WECC): type A - fixed speed wind turbines, type B - variable speed wind turbines with variable rotor resistance, type C - variable speed doubly fed induction machines (DFIG) and type D - variable speed turbines with full-scale power converter [48]. For steady-state analysis wind turbines are represented as PQ machines, but this is not accurate enough for dynamic simulations [7]. It is thus important to know the distribution in turbine types, as the grid behaviour of a fixed speed turbine is different from a variable speed turbine. Another difference between turbine types is the fault-current contribution, depending on the turbine type and also mainly on the manufacturer's design. These differences should be taken into account during the simulations and it has to be examined to which extend the differences play a role in the simulations to be carried out.

Aggregated models

For the simulation of larger wind parks, aggregated models are needed, because the calculation times become very long in case every turbine is implemented separately. Another reason for this is that the grid model has a certain detail level, which means the wind park models should not be much more or less detailed than the grid model to be able to get accurate results. Looking at the share cumulative installed wind power world wide (figure H.1), wind parks that will be installed from now on are most likely to have DFIG turbines. But the share of full-scale power converter turbines is also slightly increasing due to decreasing prices of power electronics. In the Dutch electricity grid only about 30% of all installed wind power is clustered into wind parks, the other 70% is scattered throughout the country. This scattered wind power should also be aggregated at several connection points.

Aggregated wind park models are required to represent the behaviour of the wind park during normal operation and during disturbances. An aggregated wind park therefore consists of three modules: the wind speed, a model of an individual turbine, and a specification of the park layout. Several assumptions have to be made to simplify the model. The impedances of cables within the park are neglected, only transformer impedances are taken into account. The wind it is known to consist of four parts: an average wind speed, a ramp component, a gust component, and turbulence. The average value can be assumed to be the same throughout the park, whilst turbulence is assumed to be stochastic and needs to be calculated for each turbine at each simulation time step. For aggregated models though, turbulence is neglected because of the smoothing effect of a larger number of turbines [7, 8]. Fast controls are assumed, which means that the controlled quantities are always equal to their reference values and controls do not need to be implemented in the model [49].

As mentioned before variable and constant speed turbines behave in a different way and thus need to be aggregated separately. Fixed speed wind generators are aggregated by taking one equivalent induction generator in which the mechanical torque of all turbines is summed up. This turbine drives an equivalent inertia. The generator speeds are assumed to be the same, so pitch-angle controllers can be aggregated. A two mass model is needed in dynamic simulations, to take into account the shaft oscillations that can cause considerable power fluctuations. Variable speed turbines can only be fully aggregated if wind speeds and mechanical speeds are assumed to be almost equal throughout the park. Due to non-linearity in the CP(λ,β)- curve and MPT-characteristics, an equivalent wind speed model cannot predict the wind park's behaviour with

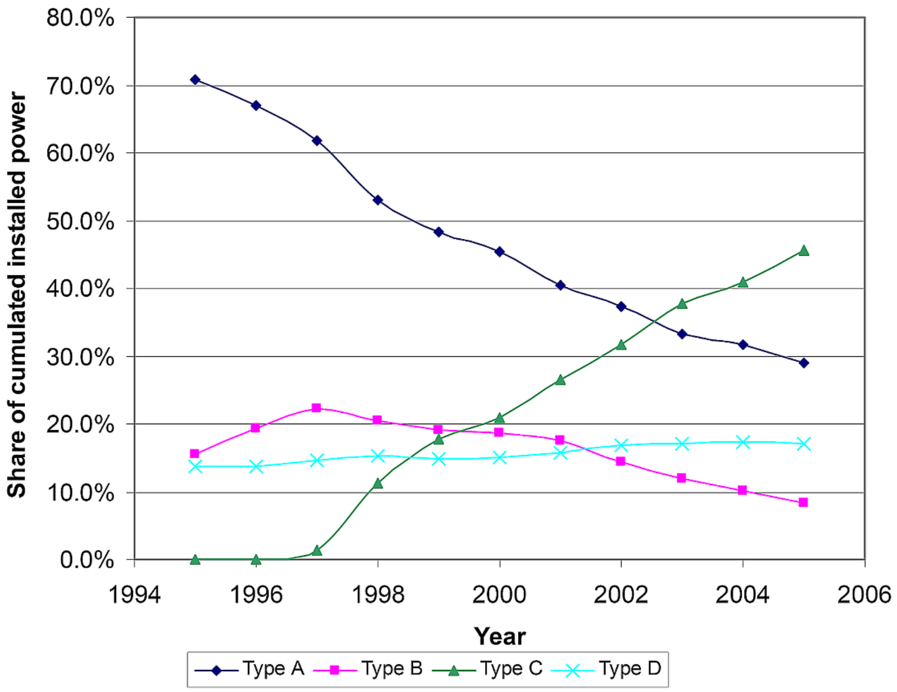

Figure H.1: World share of cumulative installed wind power, type A: fixed speed turbines, type B: variable speed with variable rotor resistance, type C: DFIG, type D: full-scale power converter (figure from [26])

sufficient accuracy when simulating longer term dynamics. A good compromise between accuracy and calculation speed is to aggregate just the electrical system by using one equivalent model for the electrical part of the generators, the controls and power electronic converters. Generator inertia, aerodynamics and pitch-controllers are not aggregated [49].

This thesis will describe the behaviour of wind parks during disturbances in the grid. Reactive power delivery and contribution to short circuit currents will be examined. These phenomena take place in short time spans, which means simulation times are no more than a few seconds and fully aggregated models can be used.

Rules and regulations

Within the UCTE there are many different rules and regulations concerning the connection of wind power to the grid. Each country has its own connection policy, varying from very specific rules to no rules at all concerning wind power [7, 20]. In the Netherlands no specific rules are formulated in the grid code for the connection of wind, thus the same rules as for conventional producers apply [11]:

2.1.16 In case of a short circuit in a grid, it yields for:

- a. Production units that are coupled to a grid with a nominal voltage lower than 110kV decoupling is allowed in case of a voltage drop, if the

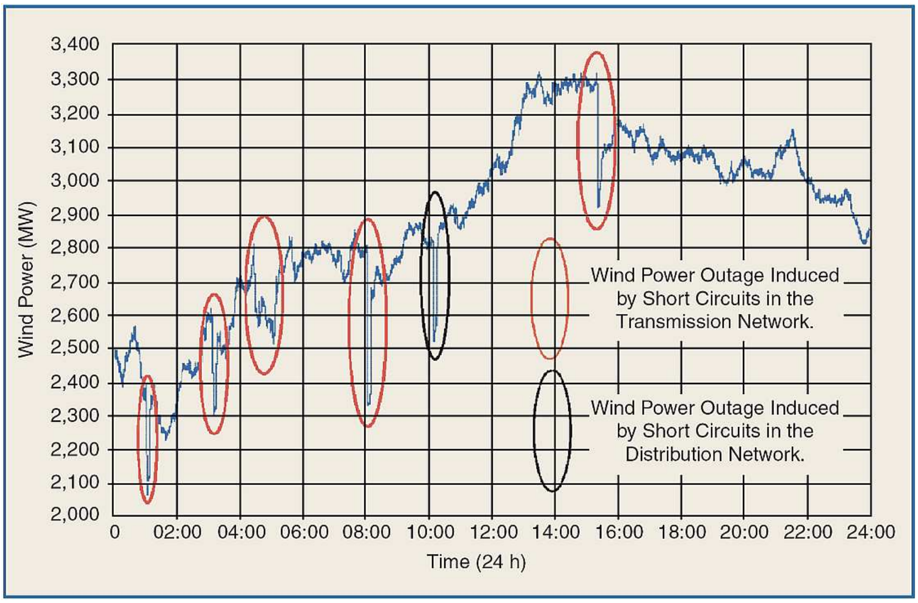

Figure H.2: Wind power trips induced by faults in the Spanish network (figure from [50])

remaining voltage is between 0,8 Un and 0,7 Un after 300 ms. When the remaining voltage has a value less than 0,7 Un, decoupling is allowed after 300 ms or after 90% of the critical short circuit time, if this is less than 300ms.

- b. Production units that are coupled to a grid with nominal voltage of 110kV and higher decoupling is allowed in case of a voltage drop, if the remaining voltage less than 0,7 Un after 300 ms or after 90% of the critical short circuit time, if this is less than 300ms.

An important aspect when looking at the current Dutch grid code is the critical short time of the wind parks, which determines the time after which the park gets disconnected from the grid. Different rules and regulations can have a large impact on the behaviour of wind parks, during these short circuit situations. When no specific rules for the connection of wind turbines exist, every producer can design its turbines in a way he desires. In this situation every wind park would behave differently in case of a voltage dip or short circuit situation and the occurring situation becomes unpredictable.

Figure H.2 shows the situation in Spain, where during high wind speed a voltage dip occurs, which results in the disconnection of a large amount of wind power. The occurrence of these kinds of dips can be diminished or even avoided when regulations are changed and voltage support by wind parks is made compulsory.

A comparison will be made between the current situation "no rules and regulations" according the connection of wind and the situation "new rules and regulations", where the newest German and Danish grid codes are taken into account. When very large differences occur a more sophisticated comparison

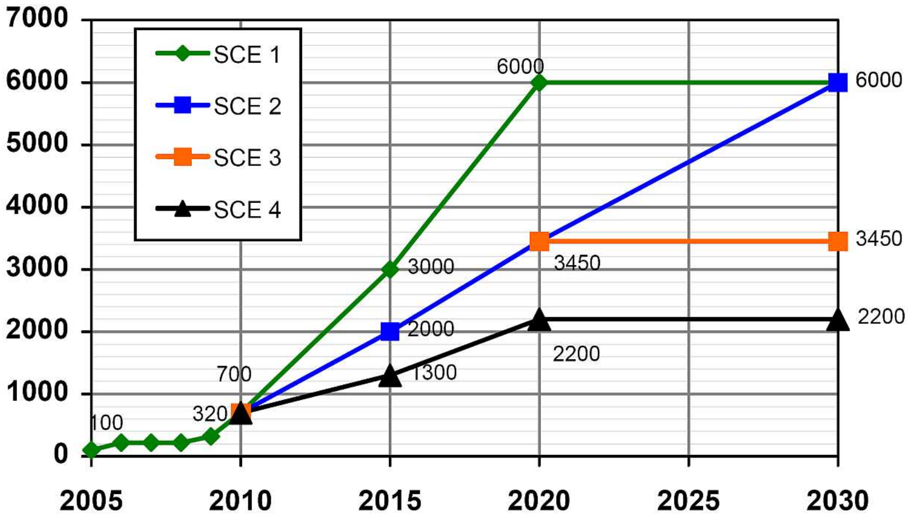

Figure H.3: Scenarios for development of Dutch offshore wind power(figure from [47])

can be made.

Future views

Looking at dynamic behaviour, it is important to know how wind penetration levels in Europe, but especially in the Netherlands will change in the coming years. A good estimation has to be made of the installed wind power in the future, to be able to do accurate simulations. In the year 2020 the installed wind power in Europe is expected to be around 180 000 MW, according to the European Wind Energy Association (EWEA). A five-fold increase compared to the 34 000 MW installed capacity in the year 2004. Such a large amount of wind energy brings some bottlenecks, when looking at Europe as a whole.

For the Netherlands several scenarios have been developed for the amount of installed wind power. In the Connect II studies, four scenarios were created for the year 2030 (see figure H.3).

In the base scenario (government target, see [51]), the targeted 6000 MW offshore wind power will be reached in 2020, in 2015 3000 MW will be installed. The Global Economy scenario (SCE2) assumes that the development of the targeted 6000 MW in 2020 goes at a slower rate than desired, and is only realised in 2030. SCE 3 is the Strong Europe scenario and SCE4 the "less" -scenario, that shows a less ambitious attitude towards the development of offshore wind parks. The scenario describes the addition of one park with an average capacity of 150 MW per year from 2010 on and no new parks after 2020 [52].

Geographical placement

This part of the thesis consists of a chapter written in the scope of the "Technology in Sustainable Development' minor, included in this master thesis to obtain the notice "Sustainable Engineer". The chapter will describe the local selection environment i.e. local acceptance, subsidies etc., for onshore wind parks in the Netherlands, Germany and Spain. The effects of the local selection environments on the placement of wind parks and spreading of wind power across the country, and in a larger European framework, will be determined. Wind power spreading in Europe is not very balanced, some areas have large amounts of wind power installed while other areas have almost nothing. These areas with much wind power installed are usually not near high load areas, resulting in large power flows across Europe in case of high wind speeds. The local selection environment mainly determines the attractiveness of a location for investors in wind energy. In this selection environment rules and regulations, subsidies and social acceptance seem to play an important role. Policy makers and wind project developers do not always seem to sufficiently recognise the nature of tensions at the local level [46]. What role policymakers exactly play, what their targets are, and how changes in selection environment can influence the choice of location for investors, will be examined.

Redundancy

As the wind power penetration level is increasing, wind parks are getting larger. Today the largest wind park in the Netherlands is the OWEZ, which has an installed power of 108 MW [25]. The increasing size of wind parks has influence on the way especially offshore parks are connected.

Different alternative configurations for the connection of offshore wind power described by [47] are: - one 150 kV cable per park to the shore (the base case if the government does not facilitate anything) - 380 kV station at sea with one 380 kV cable to a cluster of three parkss - 380 kV ring, with two stations at sea and closest locations connected directly to shore - HVDC ring, with HVDC station at sea A fifth solution, not described in the Connect 6000 MW studies, would be to use HVAC in combination with Gas Insulated Lines (GIL).

Larger parks means larger losses of power and stability problems in case of a grid fault. Because of that it is important to look at the ideal park or cluster size, to make losses in times with low load and high wind speeds as small as possible and to prevent instabilities in case of a disturbance.

Methods

Distribution of wind power

For listing the installed wind power in the Netherlands the data of [25] will be used to get a view on the distribution. In this database the wind power per province and municipality is given. Also an overview of the 21 largest wind parks in the Netherlands is included. These 21 wind parks account for about one third of the total installed power and the percentage of a certain wind turbine type in a park can be calculated per province. In this way the wind parks can be connected to the grid at or near their actual locations and the remaining wind power will, depending on its size, be connected at one or multiple fictitious nodes. Of these 21 largest only the manufacturer and type number is given in the database, but using the manufacturer's website it is possible to find out the turbine type (fixed or variable speed). The 21 parks can thus be aggregated as mentioned before. The distribution in types of the remaining turbines can be deduced from figure 2.1.

Aggregated models

Aggregated models are to be used depending on the time scale of the simulations, which means for this thesis fully aggregated models will be satisfactory, because simulation times will not become longer than a few seconds. In the scope of the EWIS study, three different aggregations will be made: squirrel cage turbines, DFIG turbines and full converter turbines. All three can be aggregated by taking one equivalent generator in which the mechanical torque of all turbines is summed up and drives an equivalent inertia. To take into account the shaft oscillations, a two mass model is needed. Because of the short simulation time, these simplifications can be used for both fixed speed and for variable speed turbines.

Rules and regulations

An inventory of different rules and regulations concerning the connection of wind power within the UCTE will be drawn up, making use of the information from the different European TSOs. Important aspects are the required fault ride through capability and voltage support of wind parks during disturbances. A comparison of the different rules and regulations can be made by applying them within the simulations. The required level of rules and regulation can be determined to ensure a save operation of the network. 3.4 Simulations

Test grid with nine nodes, representing 380 kV stations. A base case will be created, including the nine 380 kV (or 220 kV) stations. These stations represent the points where wind power will be connected to the grid. Lines between these stations will be the length of the actual length of the total direct and indirect line length between the stations. In the base case the currently installed wind power will be connected to a number of stations, by the distribution determined before. The base case can be extended with the amount of wind power to be installed in the coming years.

Turbine design parameters The short circuit current is depending on the turbine types inside the wind park and on the design chosen by the wind park manufacturer. In the design the power converter is the current limiting factor and mainly determines the short circuit current capability. Before simulations can be started, a plausible value has to be determined by looking at existing models and information available from manufacturers. Another important aspect is the critical short circuit time, the time that a wind park can stay connected to the grid and deliver the short circuit current during a disturbance. This value has to be determined by short circuit simulations with the available models

Power system stability Short circuits at every connection point will be created and the behaviour during and after the short circuit will be studied at all points. Voltage collapse can occur at certain points, when either the short circuit capability of the wind park is too low or the critical short circuit time too short, the parks are completely disconnected from the grid. Rules and regulations determine a certain limit for these properties and can thus have large influence on power system stability. Different rules and regulations of TSOs within the UCTE will be applied to see the effects on the grid.

First all wind parks are connected to the connection points in the 380/220 kV grid determined before. After that the changes in behaviour can be determined when more connection points on the 150/110 kV level are chosen. It can be seen if the results are getting more accurate, or if simulations with only wind connected at the highest voltage levels give results that are accurately enough. The simulation results can be used to make a risk analysis, which describes the bottlenecks in the grid and determines danger situations.

Once the simulations have been done and bottlenecks are determined, Flexible AC Transmission Systems (FACTS) can be used as means of compensation. In this thesis a small inventory will be made up, to determine which compensation is needed at which node to restore the 'normal' voltage profile. This can be done by taking a slack node at every bus that delivers only reactive power and no active power, the profile of the reactive power drawn from this slack node then states the amount and shape of the compensation needed. The information thus collected can be used in a further FACTS study.

Geographical placement

A literature study will be carried out, describing the effect of local selection environment on wind power placement. Rules and regulations across Europe have their influence on plans made by producers. Locations chosen are not always best wind locations, or locations near high load areas, but are usually picked on the most positive selection environment. For this literature study rules and regulations, subsidies and information about social acceptance of the different areas are needed. This information will be collected from (local) governments and papers written with the subject of geographical wind power placement. Once the selection environment is determined for these countries a comparison can be made and the correlation of a certain selection environment to the placement of wind parks will pointed out.