# Wind Power

## Modelling and Impact on Power System Dynamics

## PROEFSCHRIFT

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aan de Technische Universiteit Delft,
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*Dit proefschrift is opgedragen aan*
*Bob en Rietje Paap*

*Voor doorzettingsvermogen en collegialiteit*
*en ter nagedachtenis aan Sebastiaan Paap*

# Preface

Carrying out Ph.D. research and writing a thesis is a lengthy and extensive task, which cannot be completed without the involvement and help of a variety of people and institutions. The first and foremost preconditions to carry out research as well as any other activity are, however, life and health. During my stay at the Electrical Power Systems Laboratory, both my own personal life as well as that of some colleagues have shown that fulfilment of these two preconditions is not at all obvious. All of a sudden, things can happen that turn one's life upside down and put the everyday university routine of teaching, research and publishing in a completely different perspective.
I believe that life and health are not determined by fate or fortune, but that they lie in the hands of the almighty God. I therefore would like to express my gratitude to Him, Who has carried me through the last four years and through my life until now and Who will guide me in the future.

An essential role has been played by my Ph.D. thesis supervisor, prof. ir. W.L. (Wil) Kling. Four years ago, the research project started with the question "What is the impact of new generation technologies on power system small signal stability?". The title of the thesis has finally become *Wind Power: Modelling and Impact on Power System Dynamics*. Starting from the initial, premature research question, we have together travelled a voyage of exploration rather than followed a straight path. During this voyage, we arrived at a number of crossings which forced us to choose how to move on, without knowing very well where each of the possibilities would lead us. Wil was always ready to discuss the different ways to continue the work and to help assessing their merits in order to select the most promising option. Furthermore, our discussions on topics other than the research project, such as the restructuring of the electricity sector and the position of the various players both on a national and international level, family affairs and, at the end of the project, the pros and cons of various job opportunities have also been very stimulating and formative. Thanks a lot, Wil!

I also would like to thank a number of other people at the Electrical Power Systems Laboratory. First, prof. ir. L. (Lou) van der Sluis is acknowledged for giving me the opportunity to join his group in order to obtain a Ph.D., for the ideas and views he expressed during the regular meetings, where Wil Kling, he and I discussed the progress of the research

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Also many people from outside the Electrical Power Systems Laboratory have contributed to this work. Thanks go to ir. S.W.H. (Sjoerd) de Haan and dr. ir. H. (Henk) Polinder from the Electrical Power Processing group of our faculty for explaining me the working principles of variable speed wind turbines and for assisting in developing simulation models during the first part of the project. Prof. dr. ir. G.A.M. (Gijs) van Kuik from the Delft University Wind Energy Institute Duwind is acknowledged for stimulating the exchange of information between Ph.D. students performing research on the various aspects of wind energy, such as aerodynamics, control, electrical and civil engineering and for the many interesting discussions we had together or with the three of us, including Wil Kling. His secretary, mrs. S.M. (Sylvia) Willems is thanked for her hospitality. Drs. M.J. (Mirjam) Nieman is acknowledged for checking the English language.

Ir. J.H. (Johan) Schuld and ing. F.J.C.M. (Frank) Spaan from TenneT bv, Arnhem, as well as ir. H.B.N. (Huub) Pustjens, formerly with TenneT bv and now with KEMA T&D Consulting, Arnhem, are thanked for helping me to get acquainted with the software package PSS/E™ and for providing load flow and dynamic models of the Dutch power system and the UCTE network, which were used for carrying out simulations with a practical power system. Three wind turbine manufacturers, who want to stay anonymous, have provided measurements in order to validate the wind turbine models, which is also very much appreciated. Ir. E.H. (Erik) Lysen, drs. S. (Susan) Agterbosch and drs. H.M. (Martin) Junginger from Utrecht University are thanked for their cooperation in the AIRE project, as a project leader and as fellow Ph.D. students, respectively.

Finally, I would like to thank some people with whom I have a relationship that is not in any way linked to this thesis but is rooted much deeper. Amongst these are my parents, who raised me and financially supported me until I finished my M.Sc. at the age of 22, thus enabling me to devote myself to my studies at Delft University of Technology without having to worry about such things as housing and earning a living. Further, my friend Jurrian Zijl, with whom I have had many discussions when we lived in the same student house and also afterwards, on such topics as being a Ph.D. student and dealing with a thesis supervisor, national and international politics, the church and religion and many other fields. My good friend Alwin Kaashoek is acknowledged for designing the cover of the thesis.

Most of all, thanks go to my wife Hanneke for encouraging me during times when the research was not running smoothly, but even more for sharing my life, as well as to my little daughter Lidewij, who is not even yet aware of the existence of something like a Ph.D. degree and the problems one encounters in obtaining it, but who is busy with much more important things, such as learning to walk and to speak.

Han Slootweg
Delft, October 2003

# Contents

# Introduction

## 1.1 RENEWABLE ENERGY

### 1.1.1 Electricity Supply

The availability of electrical energy is a precondition for the functioning of modern societies. It is used to provide the energy needed for operating information and communication technology, transportation, lighting, food processing and storage as well as a great variety of industrial processes, all of which are characteristics of a modern society. Because the energy for many of the technologies, systems and possibilities that are a property of the developed world is provided as electricity, it can be presumed that there is a link between the level of penetration and consumption of electricity on the one hand and various properties of a society on the other.

Research has indeed shown that there is a significant relation between economic growth and even societal development in general, measured by indicators such as illiteracy and life expectancy, and electricity consumption [1-3]. In figure 1.1 the economic growth, measured by the Gross National Product (GNP) and the electricity consumption in The Netherlands are depicted for the last 55 years as an illustration.

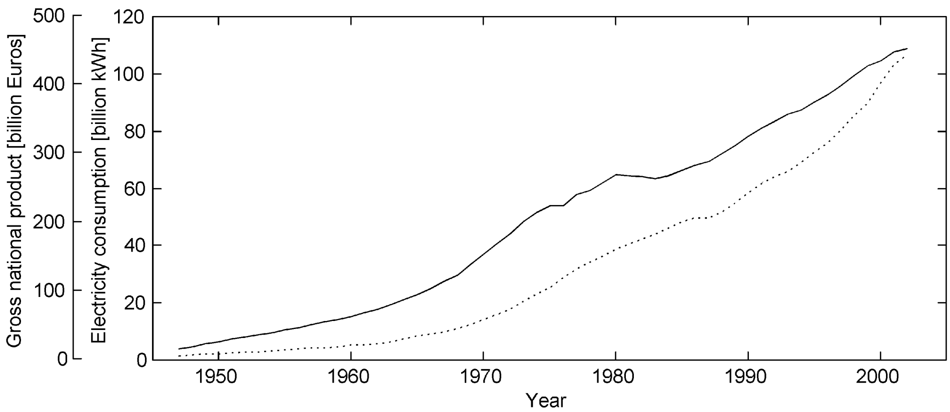


*Figure 1.1 Gross National Product (dotted line) and electricity consumption (solid line) in The Netherlands (source: CBS).*

The relation between economic and societal development and electricity consumption is bidirectional. The availability of electricity greatly facilitates industrialization, because electricity is a convenient way to replace human power by other sources of energy, which are converted into electricity for transmission, distribution and consumption. Further, the availability of electricity enables the application of modern technologies, such as information and communication technology (ICT). All of this leads to large improvements in productivity and thus to an increase in economic welfare. This increase in welfare in turn enables people to pay their electricity bill and to buy goods that consume electricity, such as televisions, computers and fridges, which leads to an increased electricity consumption. Hence, electricity consumption is both a precondition to and a consequence of economic development and growth.

Electricity is an energy carrier. It is generated in power plants, in which a primary energy source is converted into electrical power. Examples of widely used primary energy sources are fossil fuels, falling or flowing water and nuclear fission. An important drawback of generating electricity from fossil fuels and nuclear fission, currently worldwide the most applied primary energy sources for electricity generation, are the adverse environmental impacts, such as the greenhouse effect caused by the increase of the $CO_2$ concentration in the earth's atmosphere and the nuclear waste problem. Further, fossil fuel and uranium reserves are principally finite.
An additional disadvantage of using uranium and fossil fuels to generate electricity, particularly for those countries which themselves do not have supplies of these primary energy sources, is the dependence on other countries for supplying a critically important resource. Countries with large primary energy supplies that are exporting to other countries could use their control over the export as a means to exert pressure on other countries that are dependent on these exports, e.g. to carry out or to stop certain activities or to support or reject certain views. An example of the exertion of such pressure is formed by the oil crises, where Arabian countries 'punished' some western countries for supporting Israel by no longer selling oil to them.

Large scale hydro power plants that convert the energy in flowing or falling water into electricity comprise a valuable alternative for thermal and nuclear power generation, because they do not have the drawbacks of finite primary energy source supplies and emissions and nuclear waste. Nevertheless, it is difficult to supply the world's electricity demand completely with large scale hydro plants. In developed countries, the available hydro power potential has been utilized for a large part. In order to increase the share of hydro power in the electricity generation in these countries, it would be necessary to construct hydro power plants at distant locations, which are often difficult to access.
Further, the transport of the electrical power to the load becomes increasingly difficult, both because the cost and complexity of the transmission system increases due to the long distances to be covered and because in some cases, politically unstable regions must be

crossed, in which the risk of sabotage of the electricity transmission system exists. Finally, the construction of dams and basins for hydro power generation causes the flooding of large areas and thus destroys local ecosystems and sometimes forces many people to move. Thus, although its primary energy supplies are infinite and it does not cause emissions or nuclear waste, large scale hydro power has its own complications and negative environmental impacts.

There exist other electricity generation technologies using renewable primary energy sources that do hence not involve the disadvantages of nuclear and thermal generation. Examples are wave and tidal power, solar power and wind power. In wave and tidal power plants, energy is extracted from the waves and from the water flows caused by the tide. In solar power plants, consisting of solar panels, sunlight is converted into electricity, whereas in wind turbines, the energy contained in flowing air is converted into electricity.
Up to this moment, the contribution of these technologies to the demand for electricity is rather modest. This is caused by two important drawbacks of these technologies. The first is that the electricity they generate tends to be more expensive than that generated by the conventional technologies mentioned above. The second is that in many cases, they are far less flexible than conventional power generation, because the primary energy source from which they generate electricity cannot be controlled. Note that this second disadvantage does not apply to biomass generation.

### 1.1.2 Promoting Renewable Energy

As can be concluded from the last section, the main advantages of conventional thermal, nuclear and hydro power generation are the price of the generated electricity and the controllability and flexibility of their output. On the other hand, the main advantages of renewable power generation are the usage of an infinitely available primary energy source (such as sunlight, wind or biomass) and the less severe environmental consequences. Worldwide, many governments tend to value the advantages of renewable power generation more than those of conventional power generation. Hence, they support the expansion of the renewable energy generation capacity in various ways, which basically aim at reducing both disadvantages of most technologies for renewable energy generation: cost and lack of controllability.

The cost disadvantage is in most cases reduced by socializing the burden by some form of cross subsidy. An example is forcing power companies to buy the power from renewable sources at a guaranteed price which is not based on the actual value of this power, but which is calculated such that the renewable energy project becomes ‘profitable’ for the developer. Unless the power companies are able to sell this power as ‘green power’ at a premium price, arrangements like this will lead to a general increase in the electricity price, as a result of which all consumers pay for the additional cost of electricity generated from renewable sources. Another example are subsidies that are given to the developers of renewable energy projects, which spread the burden associated with renewable energy over all tax payers. One more approach towards reducing the cost disadvantage of renewable electricity is to impose taxes on electricity from conventional plants, thus raising the cost of this electricity and making it easier to compete for renewable energy.

The controllability disadvantage is counteracted by excepting renewable sources from contributing to maintaining the system balance. All generators that want to connect to a network must meet the so-called *connection requirements* of the grid company. These contain requirements that refer to the interaction between the generator and the grid. In order to be able to keep the generation and consumption balanced, which is necessary for correct functioning of a power system, among other things the controllability of generators is addressed in these connection requirements. However, renewable sources are often exempted to a certain extent or even completely from the requirements that concern the controllability of the generated power.

In this way, the drawback of uncontrollability is cancelled, at least seen from the point of view of the project developer, who is now allowed to connect to the system without the need to take additional measures to improve the controllability of the renewable sources, e.g. by using a storage system or backup generator. In reality, the problem is of course transferred to the operators of controllable generators, because the technical precondition that a balance between demand and supply must exist is not affected by administratively changing the connection requirements.

### 1.1.3 Wind Power as a Source of Renewable Energy

One technology to generate electricity in a renewable way is to use wind turbines that convert the energy contained by the wind into electricity. The wind is an infinite primary energy source. Further, other environmental impacts of wind power are limited as well. Although they affect the scenery visually and emit some noise, the consequences of this are small and ecosystems seem hardly to be affected. Further, once removed, their noise and visual impact disappear immediately and no permanent changes to the environment have occurred. A wind turbine generates the energy used to produce and install it in a few months so that the energy balance over the life cycle is definitely positive [4].

Many of the turbine’s components can be recycled. The main environmental problem associated with wind power are the rotor blades, which at this stage cannot be recycled but are used in inferior applications, such as road pavements, after decommissioning of the turbine.

When compared to other renewable energy sources, such as photovoltaics and wave and tidal power, wind power is a relatively cheap source of renewable energy. Therefore, the promotion of renewable energy by a number of governments has led to a strong growth of wind power in the respective countries. Examples are Germany, Denmark and Spain. Figure 1.2 depicts the growth of wind power during the last decade in the US, Europe and the world. As can be seen, the installed wind power capacity shows an approximately exponential growth: during the last five years, annual growth has been higher than 30%. The reason that wind power is the renewable energy source that seems to benefit most from stimulation regimes is that the cost of wind power is relatively low when compared to other renewable energy sources.

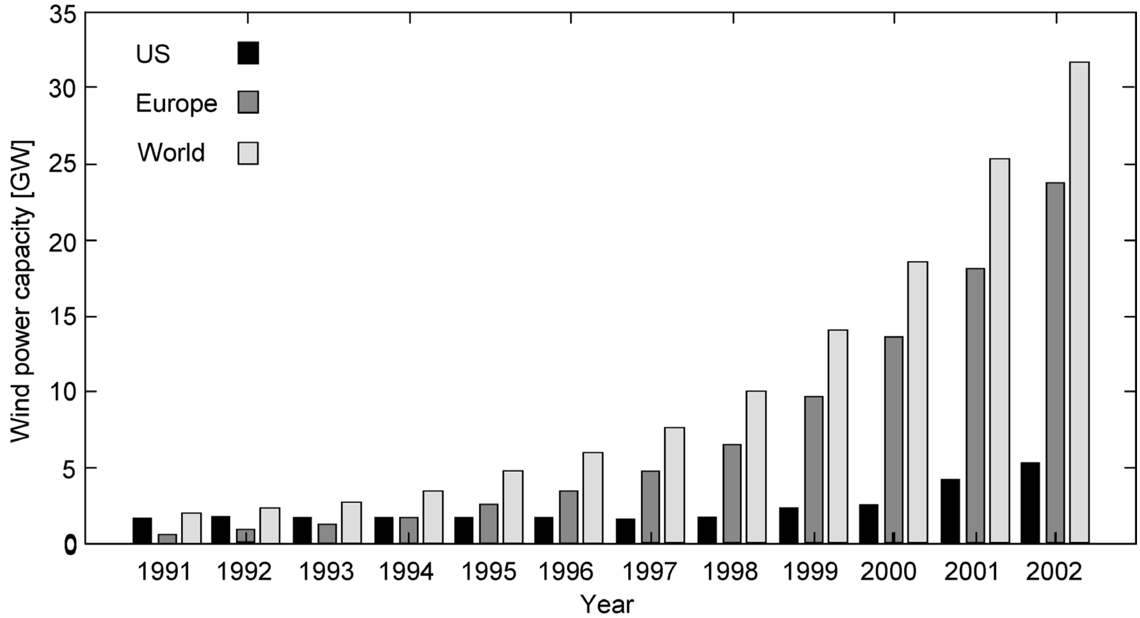


*Figure 1.2 Installed wind power capacity in the US, Europe and the world (sources: European Wind Energy Assocation, Wind Power Monthly).*

## 1.2 WIND POWER STATUS AND CHALLENGES

### 1.2.1 Wind Turbine Technology

Although the fundamental working principle of a wind turbine is straightforward, a wind turbine is a complex system in which knowledge of various fields is combined. The design and optimization of the blades requires profound knowledge of aerodynamics; that of the drive train and the tower knowledge of mechanical and structural engineering, and that of the controllers and the protection system knowledge of electrical engineering and control systems. In this section, we only discuss the recent technological developments in the field. The working principles of constant and variable speed wind turbines are covered in depth in the next chapter.

Two major technological developments have recently taken place in the field of wind power technology. Firstly, a substantial scaling up has taken place to further reduce the cost of wind power: the individual turbine has become larger and so has the typical project scale. For modern wind turbines of the multi-MW class, both the nacelle height and the rotor diameter are in the order of 100 m. Thus, at the vertical position, the blade tip can reach heights of up to 150 m. The development of the scale of individual wind turbines introduced on the market is depicted in figure 1.3 [5].

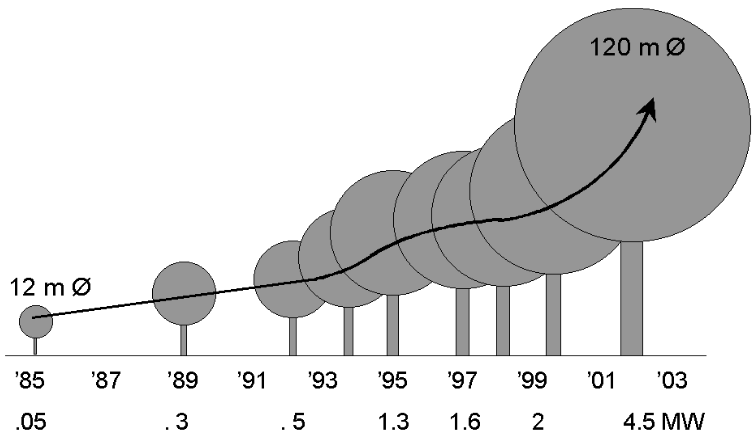


*Figure 1.3 Size and rating of wind turbines at market introduction [5].*

The scale of typical projects has increased as well. The tendency has become to erect wind parks or wind farms instead of solitary wind turbines or small groups of turbines. These parks consist of several tens to even hundreds of wind turbines. Sometimes, these wind parks are constructed offshore. The reasons why wind turbines are grouped in parks are that thus locations with a good resource are used effectively and that the visual impact of the turbines is concentrated in certain regions.

The second important development in the technology of wind turbines is the switch from a constant speed generating system to a variable speed generating system. As is obvious, the difference is that in a constant speed wind turbine, the turbine's rotor revolves at a constant speed whereas in a variable speed wind turbine, the rotational speed of the rotor can vary and can be freely controlled, of course within certain design limits.

As will be discussed in the next chapter, variable speed systems are technically more advanced than constant speed systems. They consist of more components, need additional control systems and are hence more expensive. However, they also have various advantages in comparison to constant speed systems, such as an increased energy yield, a reduction of noise emission and mechanical loads and a better controllability of active and reactive power. During the last years, many manufacturers have switched from the conventional constant speed concept to a variable speed concept.

### 1.2.2 Grid Connection of Wind Turbines

Although stand alone wind-battery or wind-diesel systems do exist, the majority of wind turbines is erected in countries with an extended electricity grid and these are hence connected to this grid. The grid connection of solitary wind turbines is relatively straightforward. The voltage at the turbine's terminals is normally lower than the voltage of the grid to which it is connected, leading to the need for a transformer. Further, switchgear is necessary to disconnect the wind turbine in case of a short circuit or in order to prevent what is called *islanding*, a situation in which a small part of the grid continues to operate with a local balance between generation and load, but without being connected to the main system. A part of a grid operating autonomously is referred to as an (electrical) island. The islanding phenomenon will be treated more elaborately in section 5.3.4.

When wind turbines are grouped and erected in large wind parks, this opens up new possibilities because it enables the integrated design of the three main subsystems of a wind park: the turbines, the infrastructure within the wind park and the grid connection. Further, because wind parks generate larger amounts of electrical power, they are connected at a higher voltage level than solitary turbines. Because high voltage grids are less dense than low voltage grids, this often means that the distance that must be covered to connect to the grid is larger. This particularly applies to offshore wind parks.
As a result, in case of large wind parks, a DC (direct current) connection for connecting the park to the grid may become feasible. First, the losses in conventional AC (alternating current) connections, and thus the operating cost, increase more sharply with the length than is the case with DC connections. Above a certain distance, using a direct current connection is hence more favourable due to its lower operating cost, although the initial investment is higher. This is caused by the fact that power electronic converters are necessary; the cables itself are cheaper in case of DC than in case of AC due to the fact that two cables are necessary instead of three and due to the lower insulation requirements for the same nominal voltage. Further, the reactive current of a long AC cable seems to pose a technical limit to the length of AC connections. Above this limit, DC technology may be the only feasible option.
In the choice between AC and DC for connecting the wind park to the grid, the effect of this decision on the turbines themselves should also be taken into account. When a DC connection is used, the frequency of the power system and the internal wind park grid are decoupled. It becomes therefore possible to vary the frequency of the park grid. This opens up the possibility to operate constant speed wind turbines in variable speed mode, although all turbines within the park have the same speed. Other possibilities are to use variable speed wind turbines with a smaller converter or to use DC for the internal park grid as well [6].

### 1.2.3 Grid Interaction of Wind Turbines

The behaviour of a power system is for the largest part determined by the behaviour and the interaction of the generators that are connected to it. The grid itself consists mainly of passive elements, which hardly affect the behaviour of the system, and as for the loads, only those in which directly grid coupled motors are applied have a significant impact on the behaviour of the system.

In wind turbines, generating systems that differen from the conventional directly grid coupled synchronous generator which is traditionally used in power plants are applied. Due to their different characteristics, these generating systems interact differently with the power system than synchronous generators. This means that they respond to disturbances, such as changes in terminal voltage and frequency or prime mover power, in a different way and that their capability to contribute to grid voltage control may be less. Further, some aspects of the interaction of the wind turbines with the grid are specific for the type of wind turbine that is applied, particularly for wind turbines without and with power electronic converters, i.e. constant and variable speed wind turbines.

As long as the contribution of wind power to the overall demand is small and the wind power penetration is low, the behaviour of the power system will continue to be governed by the synchronous generators, which still supply the largest part of the consumed electrical power. Therefore, it will not differ significantly from the behaviour of power system without wind turbines. However, when large numbers of wind turbines are connected to a system and they replace a substantial fraction of the output of the conventional synchronous generators, they will start to affect various aspects of the system behaviour. This will particularly be the case during periods with low loads and high wind speeds, because in these situations the relative contribution of wind power is at its maximum.

As will be discussed in section 1.3, until this research project, little research had been done on the subject at which penetration level the characteristics of the generating systems used in wind turbines, which differ from those of grid coupled synchronous generators, start to affect the behaviour of the power system. An important topic is for instance in which way wind turbines do affect the system's behaviour and which approaches can be used to mitigate any negative consequences that might occur. This Ph.D. research project tries to answer some of these questions.

### 1.2.4 System Balancing with Wind Power

Electricity cannot be stored in large quantities. Therefore, the amount of generated power must always be equal to the sum of the demand for power and the losses in the power system: the system balance must be kept. A sustained unbalance between generation and load leads to large deviations of the system frequency from its nominal value of 50 or 60 Hz. This endangers correct functioning of the system and leads to the operation of protection devices that disconnect either generators or loads (depending on whether a frequency increase or decrease is registered), in the latter case leading to interruptions of service.

Currently, the balance between generation and consumption, which is essential for the correct functioning of an electrical power system, is for the largest part maintained by adapting the generation to the load. The reason for this is that involving the load in the balancing of the system is difficult, because the demand for electricity is very inelastic and the load is therefore rather inflexible. As long as the power generated by the power plants can be controlled, this is not a principal problem, although the *dispatch* of the generating capacity, i.e. determining which power plants should be operated to supply the load most effectively and efficiently while taking into account fuel prices and the technical characteristics of the plant inventory, is not straightforward at all. However, a significant contribution of generators whose output is not controlled, such as the present wind turbines, poses a principal problem given today's system balancing practices, because such generators cannot contribute to maintaining the system balance.

Generators whose output is not controlled (using either a renewable or a conventional prime mover) can of course supply a certain part of the demand without causing problems for the system balance. However, the more of such generators are connected to a power system, the more controllable generators disappear and the more difficult it becomes to follow the demand for electricity with the remaining controllable generators.

The level up to which generators whose output is not controlled can contribute to the demand for electricity without additional measures and the nature of and extent to which additional measures must be taken in order to allow further growth of the contribution of such generators, depends on many factors, such as:

- the load curve of the system
- the degree of correlation between the load and the availability of the primary energy source used by the uncontrolled generators
- the characteristics of the remaining controllable power plants
- the network topology

It is therefore not possible to make general statements with respect to the amount of uncontrolled generation that can be incorporated in a power system without additional measures, nor with respect to the exact measures that must be taken in order to further increase their penetration level. Nevertheless, it is clear that increasing the penetration of uncontrolled generators such as wind turbines eventually leads to problems in keeping the system balanced.

## 1.3 RESEARCH OBJECTIVE AND APPROACH

### 1.3.1 Problem Statement

***Local versus System Wide Impacts***

As mentioned above, in wind turbines, generating systems different from the conventional synchronous generator are used. The differences between the generating systems used in wind turbines and the directly grid coupled synchronous generator are reflected in their interaction with the grid. The consequences of these differences can be divided in local consequences and system wide consequences. Wind power has thus both local and system wide impacts on the power system.

The distinction between local and system wide impacts is made on the extent to which the *cause* and the *consequences* of a certain change to the system can be located. A local impact is an impact of which the origin(s) can be easily located and which becomes less observable when the (electrical) distance to its origin increases. On the other hand, a system wide impact is an impact of which the origin can not be located and which is equally observable everywhere in the system.

Thus, local impacts of wind power occur at each turbine or park, independent of the overall wind power penetration level in the system as a whole. When the wind power penetration level in the whole system is increased, the local effects occur in the vicinity of each turbine or park, but when the (electrical) distance is large enough, adding wind power on one location does hardly affect the local impacts of wind power elsewhere. Only adding turbines locally increases the local impacts. Further, the local impacts differ for the three main wind turbine types.

System wide impacts, on the other hand, are impacts that affect the behaviour of the system as a whole. They are a general consequence of the application of wind power that can not be attributed to individual turbines or parks. Nevertheless, they are strongly related to the penetration level in the system as a whole. However, in contrast to the local effects, here the level of geographical spreading of the wind turbines and the applied wind turbine type are less important.

***Research Question***

The local impacts of wind power have already been studied extensively and very much literature on the topic exists. Well documented overviews of the various issues that are of importance can be found in text books, such as [7]. The reason that much attention has been paid to the local impacts is that these already occur when one wind turbine is connected to a grid. They must therefore be studied before connecting any wind turbine to a grid and after connection of a turbine, they can be further studied by taking measurements.

On the other hand, the system wide impacts of wind power are only of interest at higher wind power penetration levels. As such high penetration levels have hardly been reached up to this moment, few research efforts have been devoted to the topic. However, given the rapid growth of wind power during the last decade and the expectations for the future, wind power penetration levels may increase to levels where system wide impacts start to occur as well. Note that in this thesis, the penetration level is defined as the share of wind power in the total generation within a synchronously coupled system.

At the start of this research project, hardly any research had been done on the wind power penetration level at which system wide impacts start to occur, the mechanisms that can lead to those impacts, the factors that influence the allowable penetration level and the possible modifications to either the wind turbines or the power system that could be carried out in order to limit these system wide impacts. The central question for this research project is hence:

*In which way do increasing wind power penetration levels affect the behaviour of a power system, and how can negative consequences, if any, be mitigated?*

### 1.3.2 Research Objective

As discussed in the last section, this thesis investigates the impact of wind power on the behaviour of a power system. In technical terms, the behaviour of a power system is normally referred to as the dynamics of a power system. The objective of the research can hence be formulated as:

*To investigate the impact of increasing wind power penetration levels on the dynamics of power systems and to develop measures to mitigate negative consequences, if any.*

In order to achieve the overall research objective, a number of steps must be taken. Each of these steps has its own objective and when all these sub-objectives are reached, the overall research objective is met as well.

The first objective is to clarify the characteristics of wind turbines by analysing their behaviour qualitatively and to investigate the extent to which the differences between the various available wind turbine concepts are reflected in their impact on the dynamics of a power system. General conclusions with respect to the response of wind turbines to disturbances and thus with respect to their impact on the dynamics of a power system should be the result of this exercise.

The second objective is to investigate whether models of the various wind turbine concepts that can be used for power system dynamics simulations are available already. The aim is to identify existing models that can be used for the investigations, possibly with adaptations. If no usable models can be found, the objective becomes to develop these. In both cases, the result consists of models of wind turbines that can be used for power system dynamics simulations, both in the next phases of this research project and in power system dynamics studies in general.

The third objective is to apply the developed models in order to draw more quantitative conclusions with respect to the impact of wind power on power systems. To this end, both transient studies and small-signal analyses of linearised representations of various power systems are carried out. The objective is met by acquiring and analysing the results.

When these three objectives are met, the first part of the research objective as stated above is reached. The fourth objective is related to the second part of the research objective. If any negative consequences are observed in the first and third step, the qualitative and quantitative analysis of the impact of wind power on power system dynamics, measures to mitigate these should be identified.

### 1.3.3 Research Approach

The overall approach taken to reach the research objective was to investigate the behaviour of the various wind turbine types qualitatively, to develop models of wind turbines, to connect these to models of power systems, to compare the responses of power systems with various penetrations of wind power and with various wind turbine types and to explain the observations from the working principles of the wind turbine types and the characteristics of their interaction with the power system.

It proved necessary to investigate the various wind turbine types on the market separately, because it turned out that the impact of an increasing wind power penetration on the dynamics of the power system was not identical for all wind turbine types, but varied between them due to the fundamental differences in their working principles. It was hence impossible to draw conclusions with respect to the impact of an increasing wind power penetration in general and the conclusions had to be qualified for the type of wind turbine being used.

The widely used power system dynamics simulation program PSS/E™, v25.4, was used for the research. At the start of the research project, it was quickly found that no wind turbine models were included in the standard model library of this program. Further study showed that at that time, this also applied to other dynamics simulation packages, and that wind turbine models complying with the assumptions and approaches on which power system dynamics simulation software packages are based, could not even be found in the literature. It was therefore inevitable to first develop wind turbine models for use with power system dynamics simulation packages.

To this end, we studied extensively the assumptions on which power system dynamics simulations are based and the practical aspects of the simulation approach, as well as the working principles of constant and variable speed wind turbines. Then, we developed wind turbine models by selecting those subsystems of the wind turbine that affect the turbine's behaviour in the time frame of interest (a tenth of a second to tens of seconds). Those subsystems whose impact laid above this time frame were neglected by assuming that the associated quantities did not change during the simulation. Those subsystems whose characteristic time constants were well below the time frame of interest (particularly the generator and, if applicable, the power electronics converter) were simplified in order to maintain their characteristic impact on the behaviour of the turbine in the time frame of interest.

Other aspects of the behaviour of these subsystems were cancelled, because they were of limited interest given the intended use of the models. A preliminary validation of the developed models was carried out using measurements, made available by various wind turbine manufacturers under a confidentiality agreement.

In order to facilitate the simulation of high wind power penetrations at the transmission system level without having to model each wind turbine individually, we also developed aggregated wind park models.

In the second part of the research project, the developed models were applied to investigate the impact of wind power on power system dynamics. The impact on the transient stability of power systems was investigated by first analysing qualitatively the response of the various wind turbine types to voltage and frequency disturbances. The conclusions were then illustrated using simulations with models of a widely used power system dynamics test system and a real power system.

The impact of wind power on the small signal stability of power systems was investigated in a similar way. First, the physical origin of power system oscillations was studied. Then, the working principles of the various wind turbine types were related to the origin of power system oscillations, and qualitative conclusions were drawn. These conclusions were illustrated and validated with the results of eigenvalue calculations. These results were obtained with small test systems that showed the various types of power system oscillations. The test systems that were used, have been developed specifically for this study.

## 1.4 THE AIRE PROJECT

The research project that is described in this thesis was carried out within the framework of the AIRE (*Accelerated Implementation of Renewable Electricity in The Netherlands*) project. This section introduces the AIRE project and will appear in all Ph.D. theses resulting from it. Section 1.4.1 contains an introduction to AIRE, written by the project leader. It describes the organization and objective of the AIRE project. Sections 1.4.2 to 1.4.4 contain more detailed descriptions of the three Ph.D. research projects of which the AIRE project consists. Each of these sections has been written the Ph.D. student working on the corresponding project.

### 1.4.1 Introduction to AIRE

*The content of this section was provided by ir. E.H. Lysen, general manager of the Utrecht Centre for Energy Research and project leader of the AIRE project.*

***Organization***

This thesis forms part of the AIRE project: *Accelerated Implementation of Renewable Electricity in The Netherlands*. This multidisciplinary project involves three PhD projects, described below: two at Utrecht University and one at Delft University of Technology. The University of Limburg and the Energy research Centre of the Netherlands (ECN) also participate in AIRE. The project is funded by the Netherlands Organisation for Scientific Research (NWO) and the Netherlands Agency for Energy and the Environment (Novem), as part of the NWO-Novem Energy Research Stimulation Program. The AIRE project is coordinated by the Utrecht Centre for Energy research, at Utrecht University.

***Background***

It is expected that the future electricity supply of the Netherlands will be characterised by a large-scale penetration of renewable energy sources. Various studies have been carried out on this topic, both to explain actual and to predict future implementation rates of renewable energy sources. Studies on potential and future implementation rates commonly stress economical and technical conditions as crucial factors for implementation. Of course, the technological development and accompanying cost reduction of wind turbine technology have contributed significantly to the rapid increase in wind capacity in many countries.

Costs of electricity produced by onshore wind turbines have roughly been reduced by a factor five over the last 20 years. Main reasons for this were the upscaling of the individual turbine, the development of components such as gear boxes, generators etc. specifically designed for wind turbines, increased availability of turbines, lower O&M costs, better siting of wind farms and various other factors. On the other hand there are specific technical constraints related to the impact of wind power on the electrical power system, particularly the dynamic response of the network, the subject of this thesis.

The above studies sometimes mention the importance of non-technical factors in the implementation process, such as governmental policy, attitudes and behaviour of relevant policy makers, government authorities and private players, but these are not incorporated in the models used to calculate future potentials and penetration rates. The underlying assumption is that economical and technical characteristics are the most crucial factors for the implementation rates of these technologies. Studies on actually realised implementation rates cite different conditions that would explain lagging implementation. For wind energy, for instance, resistance to wind turbine siting has been explained by the NIMBY argument (Not In My BackYard) or local public resistance. Other studies state that institutional constraints are more important than public acceptance, or focus on the neglect of the interests of important stakeholder groups. In addition, numerous policy reports stress reasons like lengthy and complex planning issues and approval procedures and lack of financial incentives for faltering implementation.

Clearly, a variety of institutional and social conditions must be studied to be able to explain current implementation rates or to even dare to predict future implementation rates.

***Objective and Focus***

The AIRE project aims at providing an integral analysis of the implementation of renewable energy sources in the Netherlands, taking into account technical, economic, institutional and social conditions. This is expected to support the present Dutch policy in this area and possibly also to accelerate the implementation. The policy is outlined in the Third Energy White Paper from 1995 and aims at a 10% share of renewable energy sources in 2020. The

AIRE project limits itself to the electricity supply, because it is expected that the largest share of the renewable energy contribution will be supplied in the form of grid-coupled electricity. The research focuses on the following three renewable sources: bio-energy, wind energy, and solar PV.

### 1.4.2 Implementation of Wind Power

*The content of this section was provided by drs. S. Agterbosch, Department of Environmental Studies and Policy, Faculty of Geographical Sciences and Copernicus Institute for Sustainable Development and Innovation, Utrecht University, and one of the three Ph.D. students working on the AIRE project.*

***Introduction***

The process by which projects diffuse and get implemented in society can be studied from different perspectives. In the case of wind energy, a technological system perspective is needed, in which different systemic conditions affecting implementation are seen as one societal system. Such a system approach is fruitful because of its focus on the relative importance of these different conditions for the origination and composition of the market. By studying the characteristics of this system, associated with the origination of entrepreneurs attempting to implement a specific product, such as a wind park, thus analysing its chances and bottlenecks and its dynamics in the implementation process, we will be able to estimate the relative importance of different systemic conditions [8, 9].

The development of the wind power supply market is determined by many systemic conditions. These conditions must not be seen as factors that explain the emergence and implementation of new wind power projects that are merely complementary, but exactly their mutual interdependency must be stressed. This mutual interdependency, implicating multi-causal explanations, is analysed with help of the concept *implementation capacity*. Implementation capacity is defined as the total of relevant systemic conditions and mutual interdependencies and gives a picture of the feasibility for wind power entrepreneurs to adopt a technology (wind turbines). It enables to explain, comparatively, changing possibilities over time for different types of entrepreneurs.

***Implementation Capacity***

The implementation capacity consists of four clusters of direct conditions (technical, economic, institutional and social conditions) and two clusters of indirect conditions (governmental policy and societal context). To illustrate the interdependent nature of the different conditions a simplified example is given. Twenty years ago, turbines had a capacity of just 25 kW. Today, the size range sold is 750-1300 kW. Nowadays, large multi-megawatt turbines, 2.5 MW capacity with 80 metre diameter rotors placed on 70 to 80 metre high towers, are commercially available [10].

One of the consequences of these changing technical conditions was that Dutch provincial and local governmental authorities to better protect the landscape increasingly demanded clustering of turbines. Solitary installation is not allowed any longer. This change in institutional conditions almost automatically signifies the involvement of more than one land owner in wind energy development projects. This again implicates a change in social conditions: participation or at least co-operation becomes a prerequisite in these cases. This change in social conditions asks for more co-operative ways of project development.
Some reports mention cases in which exactly this need for co-operation turned out to be a source of conflict with accompanying delays [11]. Another consequence of the need for clustering large turbines is that it becomes more and more common that wind power plants cross borders of municipalities. Therefore, more often, also co-operation between neighbouring municipalities is needed. Another change in social conditions, implicating another complicating factor. The governmental decision making process on the local level is getting more and more complex, requiring more local administrative capacity. Different sources state, however, that local governmental capacity, knowledge about wind energy, about spatial planning processes and procedures and the needed communicative capacity, was and is still one of the main bottlenecks for wind power project development [11].

This example shows two things. First the inclusion of social and institutional conditions is indispensable for a proper understanding of the developments. Second, changes in one cluster of conditions may cause a domino effect: changes in one contextual condition affect other contextual conditions, in the end resulting in an improvement or worsening of the implementation capacity for a specific entrepreneurial group.
On the contrary, actual implementation is the cumulative result of many decisions and activities of different stakeholders, and their foreseen and unforeseen effects on the dynamic configuration of conditions. Changes in one cluster of conditions may cause a domino effect: changes in one contextual condition affects other contextual conditions, in the end resulting in an improvement or worsening of the implementation capacity for a specific entrepreneurial group. It is important for policy makers to consider the interdependencies of the different conditions and therefore to consider the system in its entirety.

***Outline of Research***

In this first PhD. project that is part of AIRE, the dynamic in the configuration of systemic conditions affecting implementation is analysed, to explain the difference in performance on the wind power supply market of the main types of windmill entrepreneurs in the Netherlands, i.e. the electricity sector (energy distributors), small private investors (mainly farmers), co-operatives, and new independent wind power producers. In particular, the coincidence between changes in institutional and social conditions and the presence of differential adaptive behaviour is emphasised in the analysis. The origination and composition of the wind power project market is explained.

The analysis is based on interviews with key stakeholders on the Dutch wind power market including senior policy makers at different ministries, civil servants both on provincial and municipal level, different wind power entrepreneurs and renewable energy consultants. A survey among members of the ‘Association of Wind Turbine Owners North Holland’ (WNWH) (mainly farmers) in the Province of North Holland is used to complement data on this entrepreneurial group. The analysis is complemented with an extensive literature and document study. Data on the number of projects, turbines and total capacity installed are based on the KEMA wind monitor and are complemented with data from Wind Service Holland.

### 1.4.3 Potential and Cost of Wind Power in The Netherlands

*The content of this section was provided by drs. H.M. Junginger, Department of Science, Technology and Society, Faculty of Chemistry and Copernicus Institute for Sustainable Development and Innovation, Utrecht University, and one of the three Ph.D. students working on the AIRE project.*

***Scenarios***

The Dutch policy goal is to achieve a share of 17% renewable electricity in the domestic demand in the year 2020.When analysing the possible acceleration of renewable electricity sources in order to meet this target, it is of importance to analyze the possible quantitative contributions of different technologies until 2020, and the various factors determining their implementation rates. As a first step in this part of the AIRE research project, a number of key factors were identified which influence the possible penetration of renewable electricity technologies:

- the economic viability, i.e. the production costs of electricity in comparison to competing fossil fuel options,
- the technological maturity, i.e. the potential and necessity of further technological development and the associated possibilities of additional cost reductions,
- overall environmental sustainability, i.e. other effects on the environment such as harmful emissions, noise production, visual impacts etc,
- the maximum technical implementation rate, i.e. the maximum rate at which projects may be implemented restricted by technical factors (e.g. the number of workable days offshore, or the maximum production of solar panels),
- institutional and social barriers, i.e. regulating mechanisms influencing the decision-making process, and the perceptions and behavior of relevant actors (see also section 1.4.2).

Using different combinations of these key factors, a number of different scenarios were set up to explore the maximum ranges for renewable electricity penetration until 2020. When assuming very benign boundary conditions for the key factors mentioned above, the total realizable potential for onshore wind until 2020 may reach up to 3100 MW, corresponding to an annual production of approximately 7.4 TWh. In the case of offshore wind, when assuming a maximum of 4000 MW installed capacity, in 2020 about 12.7 TWh may be produced annually [12].

In comparison, the current net domestic electricity production (and imports) in the Netherlands amounted to 107.7 TWh in 2001 (source: CBS). Even when taking into account that the electricity demand may rise up to 145 TWh in 2020, it is clear that wind energy may contribute significantly to the required electricity supply to satisfy this demand. Also when strict economic or environmental criteria are applied, both onshore and offshore wind power contribute significantly to the total renewable electricity production, thus identifying both technologies as robust options.

***Technological Development and Economic Performance of Wind Energy***

Although this part of the AIRE project also comprises other technologies (e.g. large-scale biomass power plants), in the remainder of this section, the economic performance and technological development of onshore and offshore wind power is described. Onshore wind turbines have relatively low production costs compared to other renewable electricity options such as small-scale hydropower or PV.

The cost of electricity produced from onshore wind turbines have roughly been reduced by a factor five over the last 20 years [13]. The main reasons for this were the upscaling of the individual turbine, the development of components such as gearboxes, generators etc. specifically designed for wind turbines, increased availability of turbines, lower O&M costs, better siting of wind farms, and various other factors. With average wind speeds varying in the Netherlands, production costs currently lie between 40-80 €/MWh, also depending on the turn-key investment costs, operation and maintenance (O&M) costs, economic lifetime and interest rate. Yet, in comparison to fossil fuel options with production costs between 20-50 €/MWh, further cost reductions are required to break even. Therefore, the focus of this research lies on analysing the potential for further cost reductions of onshore and offshore wind energy.

A frequently used instrument to analyse historic and possible future cost reductions is the so-called experience curve concept. This concept analyses cost reductions of a product or a technology depending on the cumulative production. On the basis of numerous historical examples, it can be found that with every doubling of cumulative capacity, costs are reduced with a fixed percentage. The progress ratio (PR) is a parameter that expresses the rate at which costs decline each time the cumulative production doubles. For example, a progress ratio of 80% equals a 20% cost decrease for each doubling of the cumulative capacity.

In the case of onshore wind farms, the progress ratio is estimated to be approximately 81% (see also figure 1.4) [14]. When assuming modest global growth rates for the installed wind energy capacity (i.e. four doublings of cumulative capacity over 20 years), this implies that total investment cost may decline by over 50%. Possible driving factors may be the further upscaling of turbines, but also for a large extent the effects of economies of scale, i.e. the mass production of identical turbines.

In the case of offshore wind power, the technical potential is far larger than that of onshore wind energy in the Netherlands, but also the cost of electricity from offshore wind is substantially higher. Investment cost of recent offshore wind farms ranges from 1250-1800 €/kW, substantially higher than onshore investment cost. This is caused by higher cost for foundations, grid connection, transportation and installation [15]. Also O&M costs are higher. On the other hand, offshore wind farms may yield up to 50% more electricity than onshore wind farms of identical size. The electricity cost of future projects is expected to be in the range of 46-68 €/MWh. However, especially for pilot projects in harsher conditions and further away from shore, cost may initially lie higher than these estimates.

The cost reduction potential is likely to be significantly given the relative immature character of this technology. For example, there is an obvious opportunity for learning-by-doing in regard to the transportation and installation of offshore wind farms. While there are too few existing offshore wind farms to devise an offshore wind experience curve, progress ratios from similar industries (e.g. offshore oil and gas industry or submarine electricity infrastructure) may possibly be used to estimate the further cost reduction potential of different offshore wind farm components. For example, a comparison with submarine HVDC cable links shows that a relatively large reduction of electrical infrastructure costs may be feasible with future installation of offshore wind farms [16].

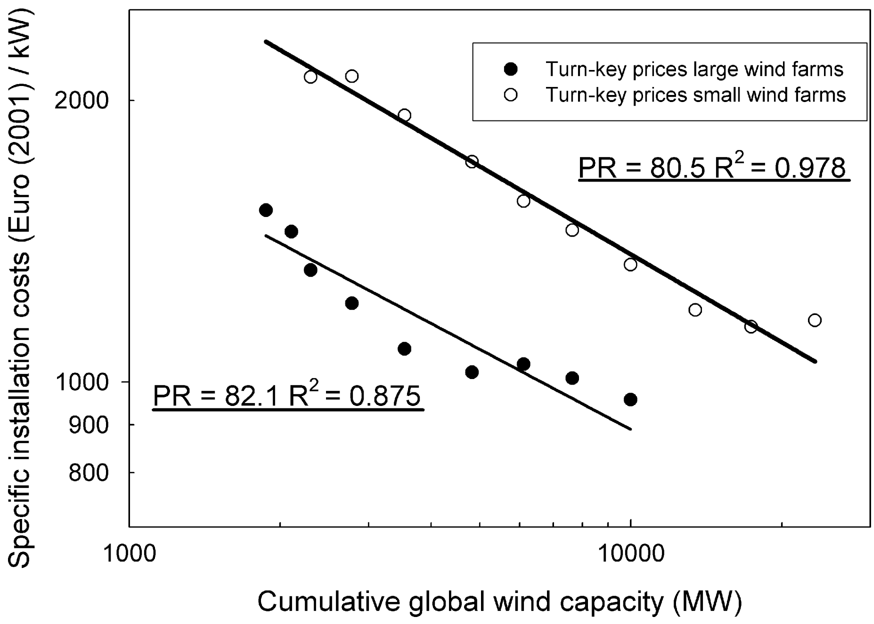


*Figure 1.4 Experience curve for onshore wind farms.*

### 1.4.4 Impact of Wind Power on Power System Dynamics

*This section contains a summary of the background and the contents of the research project described in this thesis. All information in this section can therefore also be found elsewhere in this thesis. However, section 1.4 is meant to give an overview over the complete AIRE project of which this research project was one part. This section will appear in all theses resulting from the AIRE project, so that the research project described in this thesis must be covered.*

***Introduction***

Wind energy is widely seen as one of the most cost-effective ways to generate electricity from renewable sources. As a result, a tendency to erect ever more wind turbines can be observed. Wind turbines may therefore in the future gradually start to replace the output of conventional generators, especially on occasions with low load and high wind speeds. There are, however, fundamental differences between wind turbines and conventional power plants. Conventional power plants use a controllable prime mover, such as fossil fuels or hydro power, whereas the prime mover of a wind turbine is uncontrollable. Presently, the generated electrical power of a wind turbine is not controlled either. Further, conventional power plants use a synchronous generator to convert mechanical power into electrical power. In wind turbines, other generator types are used, namely a squirrel cage or doubly fed induction generator, or a direct drive synchronous generator that is grid coupled by a power electronics converter.

Up to this moment, the energy supplied by wind turbines covers only a minor part of the total demand. Therefore, wind turbines have mainly local impacts on the power system; the overall power system behaviour is determined by the synchronous generators, which cover the largest part of the load. This means that only in the direct vicinity of a wind turbine or park any consequences are observed, whereas overall power system behaviour is hardly affected. Most scientific work carried out to date has been devoted to the local impacts of wind power, such as power quality problems, fault current increases and steady state voltage rises.

If a substantial part of the output of conventional generators is replaced by wind turbines, no longer only local effects will occur, but the overall system behaviour and the operating practices will also change. For correct operation of an electrical power system, it is essential that generation and load are balanced, and that system frequency and node voltages are kept within narrow limits of their nominal values. Further, the dynamic and small signal stability of the system must be assured. If this is not ensured, components could get damaged and/or it could be necessary to disconnect loads interrupting the supply.

In all these issues, generators play an important role. It must therefore be investigated if and in which way the technological differences between conventional generators and the generating systems applied in wind turbines are reflected in their interaction with the electrical power system and in which way they affect voltage and frequency control and dynamic and small signal stability.

***Research Approach***

The topic being investigated in the research project is the impact of large scale wind power on power system transient and small signal stability. The frequency range which is of interest in this kind of problems lies between 0.1 and 10 Hz. The shortest time constants in electrical power systems and power electronics are in the order of 10 μs or even less. If these short time constants were included in the simulations, a small simulation time step would be required. However, in order to observe the phenomena of interest, a relatively long simulation run is necessary. In combination, these two facts would lead to very time consuming simulations.
To avoid this, a special kind of simulation approach has been developed, which is often referred to as power system dynamics simulation. A number of commercial software packages which are based on this approach are available. In this research project, the widely known power system simulation software package PSS/E™ was used. This program contains a large number of standard models of synchronous and asynchronous generators and their controllers. However, no wind turbine models are included. The first step to be taken in order to be able to use this program for the investigation of the impacts of large scale integration of wind power in electrical power systems was therefore to include wind turbine models in the model library of the program as user models.

The next step was to investigate the impact of wind power on power system behaviour. To this end, models of test systems as well as a model of a real power system were used. Using test systems is considered more convenient than using models of real power systems. The latter are not fully documented and tend to be very big, which makes it difficult to distinguish general trends. Moreover, the results obtained with models of real systems are less generic than those obtained with general purpose test systems. However, in order to illustrate the practical applicability of the models, they have also been used in combination with a model of a real power system.

## 1.5 THESIS OUTLINE

The structure of the thesis reflects the research approach discussed above. In chapter 2, a general background will be given. The general working principles of wind power are introduced and the various wind turbine types and their strengths and weaknesses are discussed. The control principle of variable speed wind turbines is elaborated upon. The chapter also contains an overview over the various impacts of wind turbines on a power system. Again, a distinction is made between local impacts, i.e. impacts in the direct vicinity of the turbine, and system wide impacts, i.e. impacts on the system's overall behaviour. Where applicable, the impacts are treated separately for the various wind turbine types.

In chapter 3, models of wind turbines will be developed. First, the modelling approach will be discussed. Then, the approach will be applied to each of the three most important actual wind

turbine types discussed in chapter 2, yielding three different wind turbine models that can be used for power system dynamics simulations. A preliminary validation of the models is carried out and the difficulties associated with wind turbine model validation are shortly commented upon. Further, the impact of each of the wind turbines on node voltages and their voltage control capabilities are analysed in this chapter.
In chapter 4, the developed models are adapted to facilitate their use in power system dynamics simulations and more specifically in order to use them in large scale power system simulations, where the modelling of each and every wind turbine individually would increase the computational burden and the data requirements without adding significantly to the accuracy of the results.
First, a wind speed model is incorporated in order to allow the simulation of wind speed sequences with various characteristics without having to take measurements in advance. Then, a general variable speed wind turbine model is developed, based on the notion that in the time frame of interest, the behaviour of the two types of variable speed wind turbines is mainly governed by their rotor speed controllers, which are identical. The main difference between the two types are the generator and the converter, but the resulting differences are characterized by very short time constants and hence these do not lie in the time frame of interest. Finally, aggregated wind park models are developed for wind parks with constant speed turbines and for wind parks with variable speed turbines.

In chapters 5 and 6, the derived models are used to draw conclusions with respect to transient and small signal stability, respectively. In chapter 5, the impact on the transient behaviour of power systems is investigated. First, the behaviour of the different wind turbine types and DC connections is described qualitatively. Then, the impact of various parameters on the fault response is illustrated quantitatively for both constant and variable speed wind turbines using simulations. The qualitative conclusions are illustrated further by simulation results obtained with a widely used dynamics test system and with a model of a real power system.
In chapter 6, a similar approach is applied to the investigation of the impact of wind power on small signal stability. Again, first the behaviour of the different wind turbine types is investigated and related to the physical origin of power system oscillations in order to draw general conclusions with respect to the impact of wind power on the small signal stability of power systems. Then, the qualitative conclusions are illustrated with simulation results obtained with small test systems that were developed specifically for this study.

In chapter 7, the conclusions from the research project are summarized and topics for further research are indicated.

# Power Generation with Wind Turbines

## 2.1 INTRODUCTION

This chapter gives an introduction to the working principles of electrical power systems and to power generation with wind turbines. First, the general structure of electrical power systems is discussed and electrical power generation, transmission and distribution and consumption are introduced. The differences between conventional and renewable power generation are also touched upon.

The main part of the chapter is devoted to wind power generation. First, the basics of wind power generation and the various generating systems used in wind turbines are described. Then, the relation between wind speed and generated power, as given by a wind turbine's power curve, is commented upon and the control principles of variable speed wind turbines are discussed.

Finally, the impact of wind power on power systems is analysed. A distinction is made between local impacts, i.e. impacts whose origin can be located and that are observed in the vicinity of a wind turbine on the one hand and system wide impacts, i.e. impacts whose origin can not be located and that are observed on the system level, on the other. It is also pointed out that although some aspects of the interaction of wind turbines with the power system are mainly related to the use of the wind as the primary energy source, and hence apply to all wind turbines, there are a few other aspects that reflect the differences between the various types of wind turbines.

## 2.2 ELECTRICAL POWER SYSTEMS

### 2.2.1 Function and Structure of Electrical Power Systems

The overall purpose of an electrical power system is to deliver electrical energy to the loads, i.e. the customers, in a safe, economic, and reliable way. Before it can be consumed at the loads, electrical power is first generated and then transported. Two different levels of electric power transport are generally distinguished: transmission and distribution. The generation, transmission and distribution of electrical power are therefore the three main tasks, or primary functions, of a power system. Apart from these three primary functions, there are secondary functions, such as metering, protection, etc. These functions are fulfilled by secondary systems, whereas the primary functions are fulfilled by primary systems. In figure 2.1, a schematic representation of the primary structure of an electrical power system is depicted.

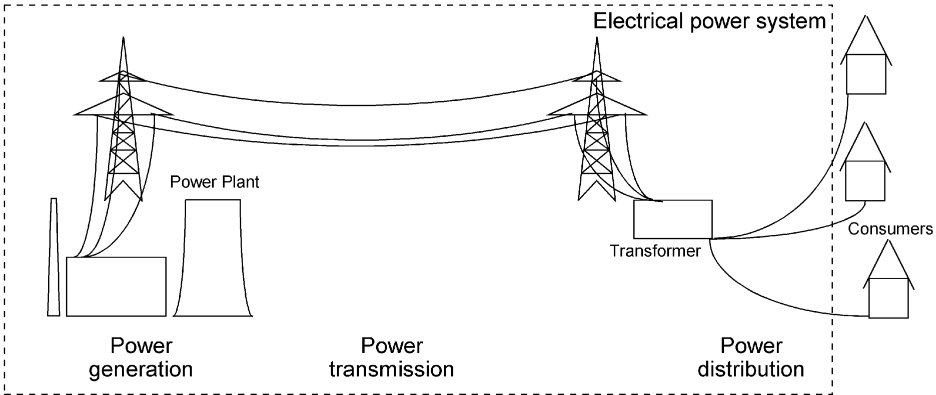


*Figure 2.1 Schematic representation of primary structure of an electrical power system.*

In reality, power systems are much more complicated than the schematic representation in the figure above, because they consist of a grid of meshed transmission lines that spans a certain region and to which a large number of power plants and loads is connected. The advantages of having a transmission network are [17]:

- economies of scale in electrical power generation
- a strong reduction of the required reserve margins on the level of the individual plant, because the outage of one unit can be compensated for by all other plants connected to the system, which hence only have to supply a relatively small amount of extra power
- a flattening of the load curve, enabling a more effective use of the generation equipment
- a reduction of the chance of occurrence and the consequences of *common cause* failures, because both generation and network equipment of various manufacturers and ages are used
- the possibility to minimize the cost of electrical power by shifting generation between units using different prime movers (such as oil, coal and gas), dependent on the prices of these primary energy sources

Together, these factors provide the economic justification for the use of relatively large power plants combined with a transmission and distribution system to deliver the generated power to the loads, rather than constructing small, decentralized generators and possibly also electricity storage at all loads, although the latter option would at least partly cancel the need for an extended transmission and distribution network.

### 2.2.2 Power Generation

To generate electrical power, a source of primary energy is required. In fossil fuel fired power plants, fossil fuels such as oil, gas, and coal are burnt and the resulting thermal energy is converted into electrical power by means of a steam cycle. In nuclear power plants, nuclear fission is used to release the energy contained in atom nuclei. This energy is then used to create high pressure steam that is used to drive a turbine and a generator. Both in case of fossil fuel fired and nuclear power generation, a synchronous generator is used to convert the mechanical torque into electrical power. This electrical power is supplied to the grid and transmitted to the loads. In figure 2.2, a schematic diagram of fossil fuel fired and nuclear power generation is depicted.

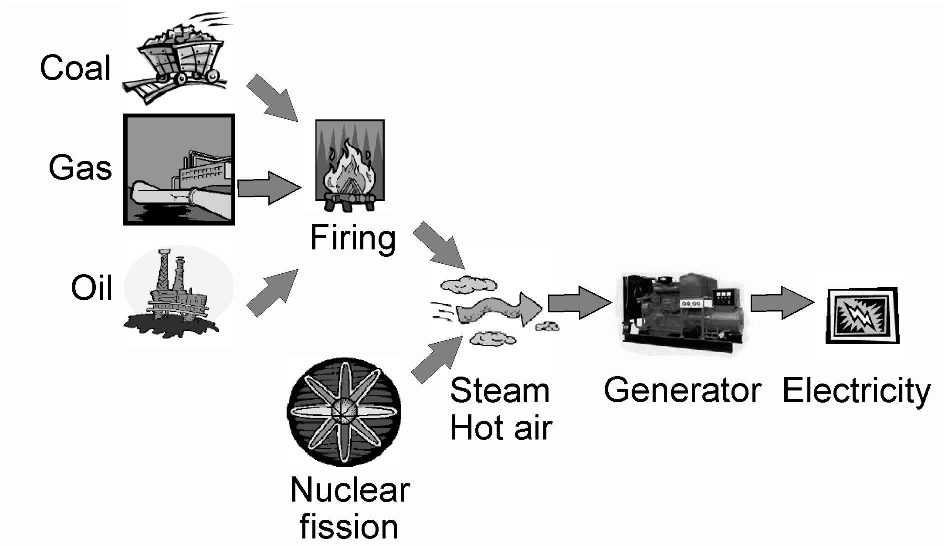


*Figure 2.2 Conventional power generation.*

All technologies depicted in figure 2.2 consume natural resources that are in principle finite. Further, they have adverse environmental impacts, such as the greenhouse effect and the problem of nuclear waste disposal. Renewable power generation technologies, however, use infinitely available natural resources as a primary energy source for the generation of electrical power. Examples are wind power, hydro power, wave and tidal power, biomass and solar power. In figure 2.3, a schematic diagram of renewable power generation is depicted.

Like nearly all conventional power plants, the most common types of renewable power generation plants use a synchronous generator for converting mechanical energy into electrical. Biomass is fired in plants that are very similar to conventional power plants. Geothermal energy, i.e. heat, is converted into electrical power by a synchronous generator. Further, also in hydro power plants, in most cases a synchronous generator is used, although doubly fed induction generators are also applied.

On the other hand, other types of renewable power generation plants use different types of generators. In wind turbines, asynchronous squirrel cage generators, doubly fed induction generators and direct drive synchronous generators that are coupled to the grid by a power electronics converter are applied, as will be discussed below. In wave power plants, rare designs like permanent magnet linear machines are used, and in solar panels, the sunlight is directly converted into electricity using semiconductors; there is no mechanical energy in between.

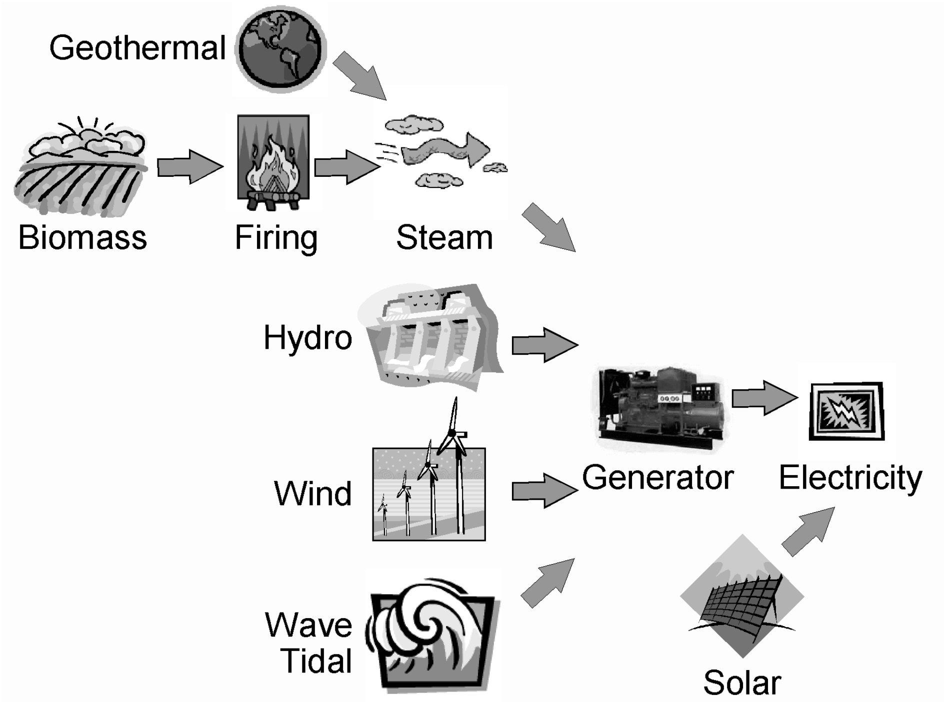


*Figure 2.3 Renewable power generation.*

### 2.2.3 Power Transmission and Distribution

The transmission of electrical power is carried out at high voltages and often over long distances, whereas the distribution is carried out at lower voltages and usually over short distances. This difference is caused by the fact that the amount of power transmitted is dependent on both voltage and current, whereas the losses are mainly dependent on the current and the distance to be covered. Hence, the power losses for a certain distance and the amount of power to be transmitted can be minimized by reducing the current and increasing the voltage. On the other hand, the higher the voltage, the more expensive and bulky the components. As a result, loss minimization also comes at a price. Therefore, there exists an optimal voltage at which the overall cost, made up by the capital expenditure for the equipment and the operational expenditure caused by the losses, is minimized for a particular distance and a specific amount of power to be transmitted.

For practical reasons, voltages cannot be chosen completely arbitrarily. Equipment for various voltage classes can be bought and hence one of these classes should be chosen. Nominal voltages that are used in practice are for instance 750 kV/433 kV, 380 kV/219 kV, and 220 kV/127 kV for transmission and of 50 kV/29 kV, 10 kV/5.8 kV, and 400 V/230 V for distribution. In all of these cases, the first figure is the line to line voltage, which equals the RMS (Root-Mean-Square) value of the voltage between two phases, and the second figure is the phase to ground voltage, which equals the RMS value of the voltage of one of the three phases to earth. In practice, the actual value of the voltage can deviate from the nominal value within a margin of a few percent.

## 2.3 WIND POWER GENERATION

### 2.3.1 Wind Turbine Generating Systems

The working principle of a wind turbine encompasses two conversion processes, which are carried out by its main components: the rotor, which extracts kinetic energy from the wind and converts it into a mechanical torque, and the generating system, which converts this torque into electricity. This general working principle is depicted in figure 2.4. Although this sounds rather straightforward, a wind turbine is a complex system in which knowledge from the areas of aerodynamics, mechanical, civil, electrical and control engineering comes together.

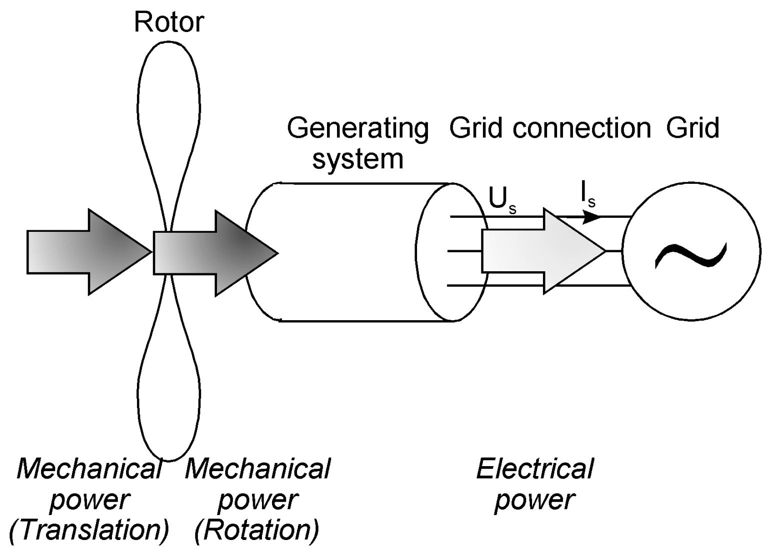


*Figure 2.4 General working principle of wind power generation.*

Currently, three main wind turbine types are on the market. The main differences between the three concepts are the generating system and the way in which the aerodynamic efficiency of the rotor is limited during high wind speeds (for reasons that will be discussed later on).

As for the generating system, nearly all wind turbines installed at present use either one of the following systems, depicted in figure 2.5, from the left:

- Squirrel cage induction generator
- Doubly fed (wound rotor) induction generator
- Direct drive synchronous generator

The first generating system is the oldest one. It consists of a conventional, directly grid coupled squirrel cage induction generator. The slip, and hence the rotor speed of a squirrel cage induction generator varies with the amount of power generated. These rotor speed variations are, however, very small, approximately 1 to 2 per cent. Therefore, this wind turbine type is normally referred to as a *constant speed* or *fixed speed* turbine. It should be mentioned that squirrel cage induction generators used in wind turbines can often run at two different (but constant) speeds by changing the number of pole pairs of the stator winding.

A squirrel cage induction generator always consumes reactive power. In most cases, this is undesirable, particularly in case of large turbines and weak grids. Therefore, the reactive power consumption of the squirrel cage induction generator is nearly always partly or fully compensated by capacitors in order to achieve a power factor close to one.

The other two generating systems depicted in figure 2.5 are variable speed systems. These are used in *variable speed* turbines. To allow variable speed operation, the mechanical rotor speed and the electrical frequency of the grid must be decoupled. To this end, power electronics are used. In the doubly fed induction generator, a back-to-back voltage source converter feeds the three phase rotor winding. In this way, the mechanical and electrical rotor frequency are decoupled and the electrical stator and rotor frequency can be matched, independently of the mechanical rotor speed. In the direct drive synchronous generator, the generator is completely decoupled from the grid by a power electronics converter. The grid side of this converter is a voltage source converter, i.e. an IGBT (Insulated Gate Bipolar Transistor) bridge. The generator side can either be a voltage source converter or a diode rectifier. The generator is excited using either an excitation winding or permanent magnets.

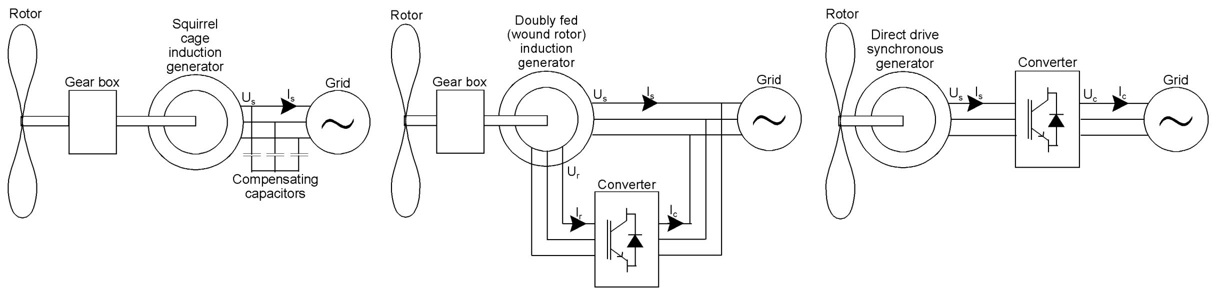


*Figure 2.5. Generating systems used in wind turbines: squirrel cage induction generator, doubly fed (wound rotor) induction generator and direct drive synchronous generator (from the left).*

In addition to these three mainstream generating systems, there are some varieties. One that must be mentioned here is the semi-variable speed system. In a semi-variable speed turbine, a squirrel cage induction generator of which the rotor resistance can be changed by means of power electronics is used. By changing the rotor resistance, the torque/speed characteristic of the generator is shifted and transient rotor speed increases of 10% of the nominal rotor speed are possible. In this generating system, a limited variable speed capability is thus achieved at relatively low cost. Other variations are a squirrel cage induction generator or a conventional high speed synchronous generator that is connected to the turbine's rotor through a gear box and to the grid by a power electronics converter of the full rating of the generator.

Directly grid coupled synchronous generators, which are used in the majority of conventional power stations, are not applied in wind turbines. Although wind turbines with directly grid coupled synchronous generators have been built in the past, this generator type is not applied any longer. Its unfavourable dynamic characteristics when used in combination with a fluctuating prime mover cause high structural loads. Further, wind turbines rather frequently connect to and disconnect from the grid and a synchronous generator must be synchronized before connecting. This is complicated when an uncontrollable prime mover is used.

### 2.3.2 Comparison of Wind Turbine Generating Systems

Each of the three main generating systems has its own benefits and drawbacks. The advantage of a constant speed system is that it is relatively simple. Therefore, the list price of constant speed turbines tends to be lower than that of variable speed turbines. However, constant speed turbines must be more mechanically robust than variable speed turbines. Since the rotor speed cannot be varied, fluctuations in wind speed translate directly into drive train torque fluctuations, causing higher structural loads than with variable speed operation. This partly cancels the cost reduction achieved by using a relatively cheap generating system. Further, noise can be a problem, because the noise level is strongly connected to the blade tip speed and hence to the rotational speed of the rotor, which of course cannot be changed in constant speed turbines. This problem is, however, alleviated by using a generator whose number of pole pairs can be changed, allowing the turbine to run at lower rotational speed when wind speed is low.

The main advantage of variable speed operation is that more energy can be generated for a specific wind speed regime. Although the electrical efficiency decreases, due to the losses in the power electronics that are essential for variable speed operation, there is also a gain in aerodynamic efficiency due to variable speed operation (as will be discussed later on). The aerodynamic efficiency gain exceeds the electrical efficiency loss, overall resulting in a higher energy yield [18, 19]. There is also less mechanical stress, because the rotor acts as a flywheel (storing energy temporarily as a buffer), reducing the drive train torque variations. Noise problems are reduced as well, because the turbine runs at low speed when there is little wind.
The main drawback of variable speed generating systems is that they are more expensive. However, using a variable speed generating system can also give major savings in other subsystems of the turbine, such as lighter foundations in offshore applications, limiting the overall cost increase. Further, the price of power electronic components is dropping steadily.
When comparing the two variable speed designs, it can be concluded that the advantages of the concept based on the doubly fed induction generator are that a more or less standard generator and a smaller and hence cheaper power electronics converter can be used. A drawback of the concept with the doubly fed induction generator when compared with direct drive variable speed turbines is that they still need a rather maintenance-intensive and potentially unreliable gearbox.
The drawbacks of the direct drive design are the large, heavy and complex ring generator and the larger power electronic converter, through which all of the generated power has to pass, compared with about 1/3 of the power in the case of the doubly fed induction generator based

wind turbine. The benefits and drawbacks of the different generating systems are summarized in table 2.1.

*Table 2.1. Benefits and drawbacks of wind turbine generating systems.*

| | **Constant speed** | **Doubly fed** | **Direct drive** |
|---|---|---|---|
| **Strengths** | Simple and robust | Less mechanical stress | Less mechanical stress |
| | Less expensive | Less noisy | Less noisy |
| | Electrically efficient | Aerodynamically efficient | Aerodynamically efficient |
| | Standard generator | Standard generator | No gearbox |
| | | Small converter suffices | |
| **Weaknesses** | Aerodynamically less efficient | Electrically less efficient | Electrically less efficient |
| | Gearbox included | Gearbox included | Large converter necessary |
| | Mechanical stress | Expensive | Expensive |
| | Noisy | | Heavy and large generator |
| | | | Complex generator |

### 2.3.3 The Power Curve

Given the working principle of wind turbines, which is depicted in figure 2.4, the power generated by a wind turbine is inherently dependent on the wind speed. The dependence of the power extracted from the airflow on the wind speed is given by the following equation

$$P_w = \frac{\rho}{2} c_p(\lambda,\theta) A_r v_w^3 \tag{2.1}$$

in which $P_w$ is the mechanical power extracted from the airflow [W], ρ the air density [kg/m$^3$], $c_p$ the performance coefficient or power coefficient, λ the tip speed ratio $v_t/v_{w,}$, the ratio between the blade tip speed $v_t$ and the wind speed upstream the rotor $v_w$ [m/s], θ the blade pitch angle [deg], and $A_r$ the area swept by the rotor [m$^2$].

At low wind speeds, a wind turbine does not generate any power at all, because the airflow contains too little energy. Between the *cut-in wind speed* (in the order of 3-5 m/s) and the *nominal wind speed* or *rated wind speed*, the generated power is directly dependent on the wind speed. It is, however, not proportional to it; the power that can be extracted from the wind increases with the cubic of the wind speed, as can be concluded from (2.1). The nominal wind speed, i.e. the wind speed at which the nominal power of the turbine is reached, is somewhere between 11 m/s and 16 m/s, but the precise value depends on the combination of the rotor diameter and the nominal power of the generating system. For this reason this design variable can be optimised for various wind speed regimes.

When the wind speed increases to levels above the nominal wind speed, the generated power cannot be increased further, because this would lead to overloading of the generator and/or, if present, the converter. Therefore, the aerodynamic efficiency of the rotor must be reduced, in order to limit the power extracted from the wind to the nominal power of the generating system. This corresponds to a reduction of the performance coefficient $c_p$ in (2.1) and can be achieved in two ways.

The first way is to design the rotor blades in such a way that their efficiency inherently decreases when the wind speed increases to values above nominal. This approach is called *stall power limitation* or *stall control*. In this case, no active control systems are applied and the value of $c_p$ is not dependent on the pitch angle $\theta$ in (2.1) in case of stall control. The second possibility to reduce the aerodynamic efficiency of the rotor is to turn the blades out of the wind using hydraulic mechanisms or electric motors. This approach is called *pitch control*. In contrast to stall control, pitch control requires active control systems to turn the blades. In general, nowadays stall control is mainly used in constant speed turbines, whereas pitch control is used in variable speed turbines.

A combination of the two approaches is *active stall control*, which is sometimes used in large constant speed turbines. With this approach, the blades are turned in the opposite direction as with pitch control. This causes the so called deep stall effect. The angle of rotation is less than in case of pitch control and the blades are turned in a number of discrete steps, rather than controlling the blade angle continuously as with pitch control.

When the wind speed becomes very high, the energy contained in the airflow and the structural loads on the turbine become too high and the turbine is taken out of operation. Depending on whether the wind turbine is optimised for low or high wind speeds, the *cut-out wind speed* is somewhere between 17 and 30 m/s.

The relation between wind speed and generated power is given by the power curve of the wind turbine. In figure 2.6, typical power curves of a constant speed stall controlled and a variable speed pitch controlled wind turbine are depicted. As can be seen in the figure, there are two differences between constant and variable speed turbines:

- variable speed turbines tend to generate slightly more power at a given wind speed between cut-in and nominal, which also results in a lower nominal wind speed
- at wind speeds above nominal, variable speed turbines have a flat power curve, which does not apply to constant speed, stall controlled turbines

The first difference is caused by the fact that the aerodynamic efficiency of the rotor depends on the tip speed ratio, which equals the blade tip speed divided by the wind speed. The value of the tip speed ratio at which maximum aerodynamic efficiency is achieved, normally lies between 6 and 8. In constant speed turbines, the blade tip speed cannot be changed. The maximum aerodynamic efficiency is hence only achieved at one, or in case of a dual speed generator, at two wind speeds. At other wind speeds, the aerodynamic efficiency is less. In variable speed turbines, however, the rotor speed, and thus the blade tip speed, can be changed. Therefore, maximum aerodynamic rotor efficiency can be achieved at a whole range of wind speeds, which leads to increased power generation.

The second difference is caused by the fact that in practice, it is impossible to design a blade profile that both achieves optimal aerodynamic efficiency at wind speeds between cut-in and nominal and limits the power extracted from the wind to exactly the nominal value at wind speeds above nominal. The power curve of a stall controlled wind turbine reflects the resulting design compromise: at wind speeds slightly above nominal, more than nominal power is generated, whereas at wind speeds much higher than nominal, less than nominal power is generated. In variable speed turbines, in contrast, the generated power can be very accurately tuned by using the degrees of freedom offered by the power electronics and the pitch control system.

Note the different design (and in variable speed turbines also controller) goals for wind speeds between cut-in and nominal on one the hand and between nominal and cut-out wind speeds on the other. At wind speeds between cut-in and nominal, the goal is to extract as much power from the airflow as possible by maximising the aerodynamic rotor efficiency. At wind speeds between nominal and cut-out, the goal is no longer to extract power from the airflow efficiently, but to reduce the extracted power to the nominal power of the generating system. To this end, the aerodynamic rotor efficiency must be reduced, rather than maximised.

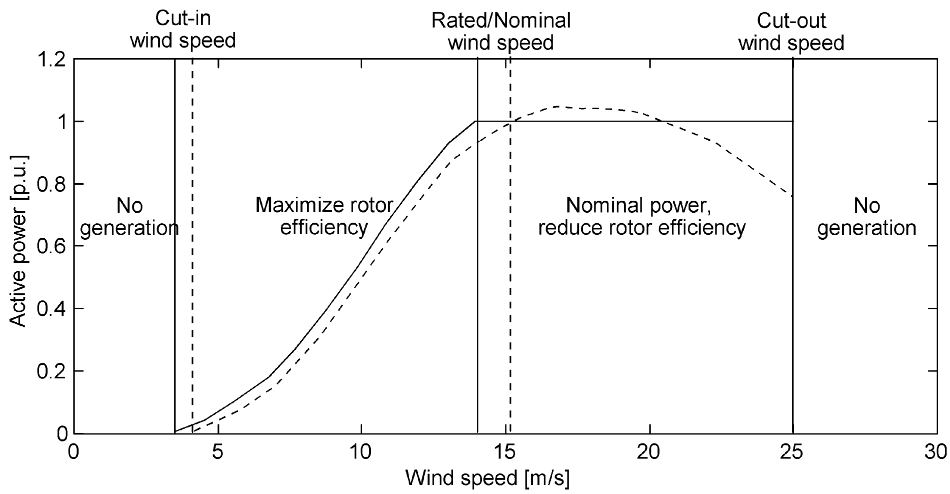


*Figure 2.6. Typical power curves for a constant speed, stall controlled (dashed) and variable speed pitch controlled (solid) wind turbine.*

### 2.3.4 Wind Power Generation versus Conventional Power Generation

As can be concluded from the above, there are principal differences between wind power on the one hand and conventional generation on the other:

- In wind turbines, generating systems different from the synchronous generator used in conventional power plants are applied.
- The prime mover of wind turbines, i.e. the wind, cannot be controlled, and fluctuates randomly. Up to this moment, the generated power of wind turbines is completely determined by the wind speed and not controlled any further.

An additional difference is that the typical size of wind turbines is much lower than that of a conventional power plant. These differences between conventional and wind power generation are reflected in a different interaction with the power system, the topic discussed now.

In the analysis in the next section, a distinction is made between local and system wide impacts of wind power. Local impacts of wind power are impacts that occur in the (electrical) vicinity of a wind turbine or wind park that can be attributed to a specific turbine or park, i.e. of which the cause can be localized. These effects occur at each turbine or park, independently of the overall wind power penetration level in the system as a whole. When the wind power penetration level in the whole system is increased, the local effects occur in the vicinity of each turbine or park, but when the (electrical) distance is large enough, adding wind power on one location does not affect the local impacts of wind power elsewhere. Only adding turbines locally increases the local impacts. Further, the local impacts differ for the three main wind turbine types.

System wide impacts, on the other hand, are impacts of which the cause can not be localized. They are a consequence of the application of wind power that can, however, not be attributed to individual turbines or parks. Nevertheless, they are strongly related to the penetration level in the system as a whole. However, in opposition to the local effects, the level of geographical spreading of the wind turbines and the applied wind turbine type are less important.

## 2.4 LOCAL IMPACTS OF WIND POWER

Wind power locally has an impact on the following aspects of a power system:

- branch flows and node voltages
- protection schemes, fault currents and switchgear ratings
- harmonics
- flicker

The first two topics must always be investigated when connecting new generation capacity to a power system. This applies independently of the prime mover of the generator and the grid coupling, and these issues are therefore not specific for wind power but apply to all cases where a generator is connected to a grid. The third topic is particularly of interest when generators that are grid coupled through a power electronic converter are used. For wind power, it does therefore mainly apply to variable speed turbines. Further, it applies to other converter connected generation equipment, such as photovoltaics and small scale CHP (combined heat and power) systems that often use high speed synchronous generators grid interfaced with power electronics. The last topic is specific for wind turbines, particularly for constant speed turbines, as will be argued below.

The way in which wind turbines affect the voltages at nearby nodes depends on whether they are constant speed or variable speed turbines. The squirrel cage induction generator in constant speed turbines has a fixed relation between rotor speed, active power, reactive power and terminal voltage. Therefore, it cannot effect its terminal voltage by changing the reactive power exchange with the grid. Additional equipment such as capacitor banks, SVCs (Static Var Compensators) or STATCOMs (STATic COMpensators) is hence necessary for voltage control.

On the other hand, variable speed turbines have, at least in theory, the capability of varying the reactive power at a given active power, rotor speed and terminal voltage. However, the range over which the reactive power can be controlled depends on the size of the power electronic converter. Direct drive variable speed turbines often have an advantage here. They already have a large converter and some extra capacity to allow reactive power control can be added at marginal cost. Doubly fed induction generator based turbines in general have the advantage that a small converter can be used. Adding converter capacity to allow reactive power control tends to cancel this advantage of course.

The contribution of wind turbines to the fault current is also different for the three main wind turbine types. Constant speed turbines are equipped with a directly grid coupled squirrel cage induction generator. They therefore contribute to the fault current and rely on conventional protection schemes (overcurrent, overspeed, over- and undervoltage, over- and underfrequency).

Turbines based on the doubly fed induction generator also contribute to the fault current. However, the control system of the power electronics converter that controls the rotor current measures the grid voltage at a very high sampling rate (several kHz). A fault is therefore detected very quickly. Due to the sensitivity of power electronics to overcurrents, this wind turbine type is at present quickly disconnected when a fault occurs. Thus, although a doubly fed induction generator based wind turbine contributes to the fault current, the duration of its contribution is rather short.

Wind turbines with a direct drive generator hardly contribute to the fault current at all, because the power electronic converter through which such a turbine is connected to the grid cannot carry a fault current. It is therefore normal practice that these turbines are also quickly disconnected in case of a fault.

The third topic, harmonics, is mainly an issue in the case of variable speed turbines, because these are equipped with power electronics, the main source of harmonics. However, in case of modern power electronics converters with their high switching frequencies and advanced control algorithms and filtering techniques, the harmonics issue should not be a major problem. Well-designed synchronous and asynchronous generators hardly emit any harmonics. Harmonics are therefore no issue for constant speed wind turbines that use directly grid coupled squirrel cage induction generators.

The flicker problem is typical for wind turbines. Wind is a quite rapidly fluctuating prime mover. In constant speed turbines, prime mover fluctuations are directly translated into output power fluctuations, because there is no energy buffer between mechanical input and electrical output. Depending on the strength of the grid connection, the resulting power fluctuations can result in grid voltage fluctuations, which can cause unwanted and annoying fluctuations in bulb brightness. This problem is referred to as *flicker*.
In general, no flicker problems occur with variable speed turbines, because in these turbines wind speed fluctuations are not directly translated into output power fluctuations. The controller of the power electronics in these wind turbines derives a set point for active power from the rotor speed. Hence, only if the rotor speed varies, the active power is changed. Due to the rotor inertia, the rotor acts as an energy buffer or low pass filter. Rapid wind speed fluctuations hardly effect the rotor speed and are therefore hardly observed in the output power. The local impacts of the various wind turbine types are summarized in table 2.2.

*Table 2.2 Summary of local grid impacts for main wind turbine types.*

| **Local impact** | **Constant speed** | **Doubly Fed** | **Direct Drive** |
|---|---|---|---|
| **Changes in node voltages** | Yes, compensation only possible with additional equipment, e.g. capacitor banks, SVCs or STATCOMs | Yes, compensation theoretically possible, but dependent on converter rating | Yes, compensation theoretically possible, but dependent on converter rating |
| **Harmonics** | Hardly of interest | In theory of interest, but should not be a major problem | In theory of interest, but should not be a major problem |
| **Flicker** | Important, particularly in weak grids | Unimportant because the rotor acts as an energy buffer | Unimportant because the rotor acts as an energy buffer |
| **Contribution to fault currents** | Yes | Yes; but turbine is normally quickly disconnected | No; converter not capable of carrying fault current; turbine is quickly disconnected |

## 2.5 SYSTEM WIDE IMPACTS OF WIND POWER

Apart from the local impacts, wind power also has a number of system wide impacts, because it affects:

- dynamics and stability
- reactive power generation/voltage control possibilities
- system balancing: frequency control and dispatch of the remaining conventional units

The impact on the dynamics and stability of a power system is mainly due to the fact that wind turbine generating systems are not based on a conventional synchronous generator. The different working principles of the generating systems used in wind turbines are reflected in how they respond to changes in their terminal voltage and frequency. In order to investigate the impact of wind power on power system dynamics and stability, adequate wind turbine models are essential. As the development of these models and their application to investigate the impact of wind power on power system dynamics is the topic of this thesis, it will be treated in depth in the next chapters.

Wind power affects the reactive power generation and voltage control possibilities in the system for various reasons. Firstly, not all wind turbines are capable of varying their reactive power output, as stated above when discussing the local impacts. This is, however, only one aspect of the impact of wind power on voltage control in a power system. Apart from this, there are two other issues that determine this impact. Wind power plants cannot be very flexibly located compared to conventional power plants. As mentioned above, wind turbines affect the scenery and hence can only be constructed at locations at which this is not considered a major problem. Further, it must be erected at locations with a good wind resource.

The locations that meet these two conditions are not necessarily locations that are favourable from the perspective of grid voltage control. When it comes to choosing a location for a conventional power plant, it is generally easier to take into account the voltage control aspect, because these plants are more flexible in location. The last factor that plays a role in the impact of wind power on voltage control is that wind turbines are relatively weakly coupled to the system because their output voltage is rather low and because they are often erected at distant sites. This further reduces their contribution towards voltage control.

When the output of conventional synchronous generators is replaced by that of wind turbines at remote sites on a large scale, the voltage control aspect must be taken into account explicitly. Voltage is a local quantity, which can only be affected at or in the direct vicinity of a node. It can therefore even be necessary to install additional equipment for voltage control at or near the locations of the synchronous generators whose output is being replaced by wind power, in order to be able to control the node voltages everywhere in the system.

This is, however, primarily caused by the geographical displacement of generating capacity that accompanies the replacement of conventional generation by wind turbines, rather than by the fact that the output of conventional generators is replaced by that of wind turbines as such. Hence, other developments that lead to a geographical shift of generation, such as market liberalization, can also give rise to the necessity to take measures to maintain enough possibilities for reactive power generation and voltage control throughout the system. Further, the cause of the necessity for these measures can not be localized, so that this is an example of a system wide impact.

The impact of wind power on system balancing, i.e. frequency control and the dispatch of the remaining conventional units, is caused by the fact that the prime mover of wind power can not be controlled. Therefore, in general the power generation of wind turbines is uncontrolled as well and wind power does not contribute to primary frequency regulation. Although this would be technically possible, the drawback is a reduction in energy yield and thus in income for the wind turbine operator. Therefore, as long as exceptions from connection requirements referring to the controllability of the generated power are granted to wind turbines and/or as long as there are cheaper means available to keep the system balanced, wind turbines will probably not contribute to system balancing.

Further, the variability of the wind on the longer term (from 15 mins. till hours) tends to complicate the dispatch of the remaining conventional units used to supply the load, because it causes the demand curve to be matched by these units (which is equal to the system load minus the wind power generation) to be far less smooth than would be the case without wind power. This heavily affects the dispatch of the conventional units and the required reserve margins.

Note that the aggregated short term (< 1 min.) output power fluctuations of a large number of wind turbines are smoothed to a large extent and are in general not considered problematic. These fluctuations are induced by turbulence, which is a stochastic quantity that evens out with many turbines. An exception to this is formed by storm induced outages that occur when the wind speed exceeds the cut-out value. These are not induced by turbulence but by storm fronts and can therefore affect a large number of turbines simultaneously.

All these effects become more severe at high wind power penetrations. The higher the wind power penetration, the larger the impact of wind power on the demand curve faced by the remaining conventional units and the less of these units remain. Thus, the stricter the requirements on the ramping capabilities of these units must be in order to both match the remaining demand curve and to keep the fluctuations of the system's frequency, caused by unbalances between generation and load, within acceptable limits. It is, however, impossible to quantify the wind power penetration level at which system wide effects start to occur, because of the differences in e.g. conventional generation portfolio, wind regime, demand curve and network topology between various power systems.

## 2.6 CONCLUSIONS

In this chapter, an overview of the topic of wind power generation was given. First, the general structure of the electrical power system was discussed, as well as the basic principles of electrical power generation and the main difference between conventional and renewable power generation. Then, the general working principle of wind power generation was described, which consists of two main conversion steps, namely:

- extraction of mechanical power from the wind
- conversion of this mechanical power into electricity

The three main wind turbine generating systems and their advantages and disadvantages have been described and the concept of the power curve, which depicts the dependence of the generated power on the wind speed, was analysed and discussed. The strongly related topic of the control of the rotor speed of variable speed wind turbines was also highlighted.

In the second part of this chapter, the grid impacts of wind power generation were discussed. It was indicated that the applied generator system and the controllability of the prime mover are the two main differences between wind power and conventional generation. It was also shown that due to these differences, wind power has both local and system wide impacts on power systems. Some of these impacts depend on the applied generating system, due to the profound differences between the generating systems used in wind turbines.

Locally, wind power affects the following aspects of the power system:

- branch flows and node voltages
- protection schemes, fault currents and switchgear ratings
- harmonics
- flicker

whereas on a system level, consequences can be observed in the following areas:

- dynamics and stability
- reactive power generation/voltage control
- system balancing: frequency control and dispatch of the remaining conventional units

This thesis focuses on the first item of this list: the impact of wind power on the dynamics and stability of an electrical power system.

# Wind Turbine Modelling

## 3.1 INTRODUCTION

In this chapter, models of each of the three wind turbine concepts that were described in section 2.3.1 are derived. When developing a model, one must take into account its intended application. The model should neither become too complex, as this would make the calculations cumbersome and time consuming, nor too simple; this would render the model inapplicable for its original goal or give unreliable results.

In order to clearly define the application area of the models presented, this chapter first shortly describes various phenomena that occur in power systems and the corresponding time scales, pointing out for which time scale and simulation approach the models derived in this chapter have been developed. This specific simulation approach will be further referred to as power system dynamics simulation.

Subsequently, earlier work on the topic of wind turbine modelling is discussed. From a survey of the literature on the topic of wind turbine modelling, it is concluded that the models found in the literature cannot be used for power system dynamics simulations for several reasons. The models presented in this chapter fill this need. The chapter primarily describes the various subsystems of each of the wind turbine types and the corresponding equations. Finally, simulation results obtained with the models are compared to measurements and it is investigated which impact the turbines have on the grid voltage and whether they are able to contribute to voltage control.

From a qualitative comparison of the measurements and the simulations it is concluded that the models are reasonably accurate and can hence be used for representing wind turbines in power system dynamics simulations. From the investigation of the impact of each of the turbines on grid voltage it is concluded that the output power fluctuations are the largest and most rapid for the constant speed turbine, which thus affects the grid voltage most. The impact of the two variable speed turbine types is smaller, even when they are operated in unity power factor mode, because the rotor acts as an energy buffer. Their impact on the grid voltage can be further reduced by equipping variable speed turbines with a terminal voltage controller that uses the measured terminal voltage to adapt the reactive power accordingly.

The contribution of this chapter is twofold. First, equations that can be used to model a constant speed wind turbine in power system dynamics simulations have been collected from the literature and combined into a model of a constant speed wind turbine for use in power system dynamics simulations. Second, equations to model the most common types of variable speed wind turbines including their controllers have been derived and combined into models of these turbines for use in power system dynamics simulations.

### 3.2 POWER SYSTEM DYNAMICS SIMULATION

An electrical power system can be described by the following general equation

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},t) \\ \boldsymbol{y} &= \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u}) \end{aligned} \tag{3.1}$$

where
**f** is a vector containing *n* first-order non-linear differential equations
**x** is a vector containing *n* state variables
**u** is a vector containing *r* input variables
**g** is a vector containing *m* non-linear algebraic equations
**y** is a vector containing *m* output variables
and t is time. By assuming that the system in equation (3.1) is time invariant, i.e. the time derivatives of the state variables are not explicit functions of time, t can be excluded from equation (3.1)
Differential equations can be handled in various ways. One can apply a mathematics software package capable of symbolic calculations to obtain a closed form solution or a mathematics software package that contains numerical integration routines. However, in the specific case of power systems, these approaches are not straightforward.

A power system consists of a large number of components: overhead lines and underground cables, transformers, generators and loads. The behaviour of most of these components is described by differential equations. Thus, in case of a large power system, the vector **f** in equation (3.1) can easily contain hundreds or thousands of differential equations. A system of coupled differential equations of this size cannot be solved analytically, for which reason numerical integration remains as the only practical possibility to analyse the behaviour of a power system.
A second difficulty in the analysis of power systems is posed by the vast difference in time scales or frequency bands in which the various phenomena of interest occur. On one side of the time spectrum, there are phenomena that take micro to milliseconds, such as lightning induced transients, switching transients, switching semiconductors in power electronic converters and the interruption of fault currents [20, 21]. On the other side of the time spectrum, there are phenomena that take several minutes or hours. Examples are substantial changes in the active power output of thermal power plants that can only occur at a limited

rate in order to prevent unallowable mechanical stress, and changes in the output of wind turbines as a result of travelling weather systems [22]. Figure 3.1 gives an overview of the various areas of consideration and their characteristic time scales or frequency bands [23].

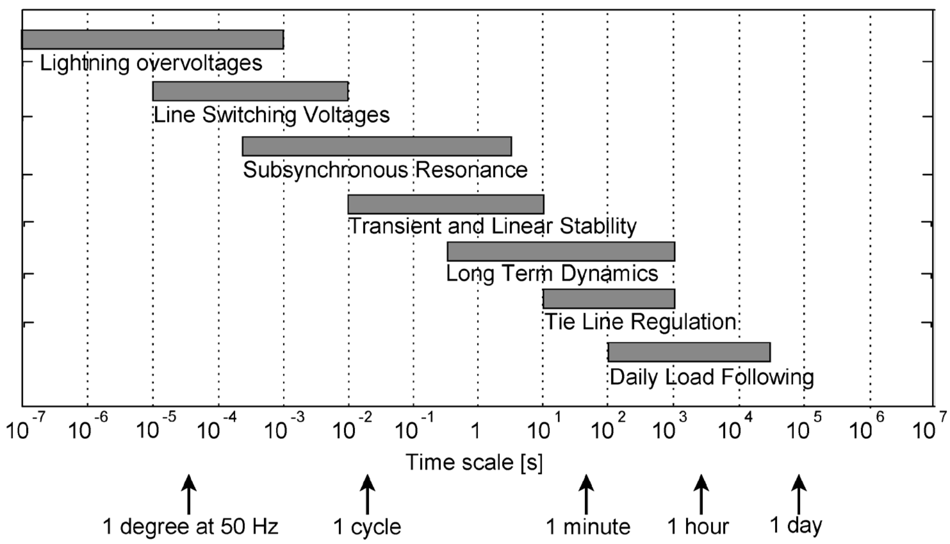


*Figure 3.1 Frequency bands and time scales of various dynamic phenomena in power systems [23].*

Using a complete model of the power system for studying each of the areas depicted in figure 3.1 would have the following drawbacks:

- Data requirements become excessive, because for each study all parameters of the various components of the power system must be specified.
- When the phenomenon of interest is characterized by relatively long time constants, i.e. low frequencies, a simulation run of a certain duration is necessary. However, when high frequency phenomena are included in the model of the power system, such a simulation run would be very time consuming, because a small time step would be necessary.

To avoid these drawbacks, normally a model of the power system and its components that is tailored to the phenomena under study is used. Such a model is based on the following assumptions:

- Phenomena with a frequency above the bandwidth of interest can be neglected when it is assumed that they die out before they affect the investigated phenomenon.
- Phenomena with a frequency below the bandwidth of interest can be neglected because they are so slow that the value of the associated state variables does not change during the simulation run.

An example of this approach is the modelling of a circuit breaker as an ideal switch when studying the angle stability of a synchronous or asynchronous machine [20]. In this situation, it is assumed that the switching arc does not affect the rotor speed of the machine. The arc is therefore neglected. Thus, the short time constants that would be present when a detailed arc representation would be used are cancelled and both the complexity of the modelling task and the computation time are reduced.

One way to simulate power systems is formed by what will be further referred to as power system dynamics simulations. This approach is used to study phenomena occurring in a frequency range of 0.1 Hz to 10 Hz, or with typical time constants between 10 s and 100 ms. The typical problems that can be analysed with this approach are voltage and rotor angle stability. The quantities of interest are node voltages, rotor speeds and angles as well as the behaviour of the exciters of synchronous generators. The approach is also known as fundamental frequency simulation or electromechanical transient simulation.

The main characteristic of this simulation approach is that it neglects network transients, by assuming that they are characterised by very short time constants and die out before they affect the quantities of interest in power system dynamics simulations. The network can therefore be represented with an impedance matrix, like in load flow calculations. As a result of this simplification, only the fundamental frequency component of voltages and currents is considered and higher harmonics are neglected. The assumption also implies that at the terminals of generators and loads only the fundamental frequency component should be present, in order to have a consistent representation of the whole system.

The power system dynamics simulation approach has the following advantages [24]:

- It reduces the number of differential equations, because no differential equations are associated with the network and less with the generators and in some cases also with the controllers.
- It allows the use of a larger time step, because short time constants have been eliminated. The typical time step in PSS/E™ equals half a cycle, i.e. 10 ms in a 50 Hz system.
- Due to the network representation, the associated equations can be solved using conventional load flow solution algorithms, which also increases the computation speed.

The accuracy of the simulation results obtained when using the power system dynamics simulation approach has been studied extensively during the late seventies, but is still subject of discussion [25-29]. There are two main reasons for this. First, the similarity of the simulation results obtained with different models of the same power system depends heavily on the system's characteristics and on the phenomenon under investigation, so that it is difficult to draw generic conclusions with respect to the impact of the applied simplifications on the accuracy of the results. Second, conclusions with respect to the degree of similarity are by nature partly subjective and can hence always be disputed.

There exist other types of power system simulations. A first example is formed by what is called instantaneous value or electromagnetic transient simulation, where the network is represented by differential equations and the time step is in the order of microseconds or shorter. In this type of simulations, short time constants are incorporated so that high frequency phenomena can be studied. A second example are simulations for load following and dispatch, where the emphasis lies on the load pattern and the characteristics of the primary energy conversion system and where the typical time step is in the order of several seconds to minutes. In terms of figure 3.1, these simulation types cover time scales to the left and to the right of power system dynamics simulation respectively.

For this thesis, v25.4 of the power system dynamics simulation software package PSS/E™ (Power System Simulator for Engineering) from PTI (Power Technologies, Inc.) has been used. This program incorporates the assumptions applied in power system dynamics simulations and according to the manual, it can therefore be used to study phenomena that occur in bandwidths up to about 10 Hz [30]. Although this is not mentioned in the manual, often a lower bandwidth limit of around 0.1 Hz is also allowed for, because the simulation of lower frequencies requires detailed models of the primary conversion system and its rather long time constants, which are, however, not incorporated in the PSS/E™. The program uses a fixed time step forward Euler method for the numerical integration of the differential equations describing the power system.
PSS/E™ is not the only program that applies the power system dynamics simulation approach to investigate low frequency phenomena in large power systems. Other software packages for power system dynamics simulations, such as NETOMAC® from Siemens, Eurostag from Tractebel and EDF, PowerFactory from DIgSILENT and Simpow® from ABB are based on it as well. However, some of these programs also offer an instantaneous value simulation mode and may even able to switch automatically or manually between the fundamental frequency mode and the instantaneous value mode.

## 3.3 EARLIER WORK AND CONTRIBUTION OF THIS THESIS

### 3.3.1 Overview of Literature on Wind Turbine Modelling

The modelling of wind turbines has been a research topic since the development era of modern wind turbines started with the oil crisis, now about three decades ago. In this section, an overview of the developments in wind turbine modelling will be given. It is of course not feasible to cover thirty years of research in a few pages. Therefore, the indicated references are only for illustrative purposes and the bibliography of this section is limited to journal papers and in no way exhaustive. Further, only the development of large wind turbines (several hundreds of kWs to MWs) is addressed. The development of small scale wind turbines for the built environment and for small scale island systems is a different topic which is not covered here.
The first wind turbines were based on a direct grid coupled synchronous generator with pitch controlled rotor blades to limit the mechanical power in high wind speeds. Therefore, the first modelling efforts were devoted to this wind turbine concept [31, 32]. Nowadays, wind turbines with a directly grid coupled synchronous generator have completely disappeared from

the scene. It has proven to be very difficult to design cost effective and reliable wind turbines with directly grid coupled synchronous generators. Because the rotor speed of a grid coupled synchronous generator is constant, wind speed variations are completely translated into variations in mechanical power and torque, resulting in considerable mechanical loads. Further, a direct grid coupled synchronous generator must be synchronized before it can be connected to the grid, which is quite complicated when an uncontrollable prime mover is used. For these reasons, other generator types such as the squirrel cage induction generator and the more modern variable speed schemes that were described in chapter 2, have replaced the directly grid coupled synchronous generator as the electromechanical conversion system used in wind turbines.

The directly grid coupled synchronous generator was followed by the directly grid coupled asynchronous squirrel cage induction generator. This generator type has a more favourable torque versus speed characteristic than the synchronous generator, thus reducing the mechanical loads and is also cheaper. This concept is still applied nowadays by some manufacturers. To limit the power extracted from the wind at high wind speeds, either pitch control or stall control can be applied. Many papers on the modelling of a wind turbine with a directly grid coupled squirrel cage induction generator can be found in the literature, both in combination with pitch control and with stall control of the mechanical power, e.g. [28, 33, 34].

It should, however, be noted here that the concept of a wind turbine with a directly grid coupled squirrel cage induction generator and pitch control does no longer appear in the product portfolio of any manufacturer. This is a result from problems with the design of the pitch controller. It has appeared to be rather difficult to limit the output power to the nominal value by controlling the pitch of the rotor blades. Thus, although models and analyses of a wind turbine with a directly grid coupled squirrel cage induction generator still appear in journals and conference proceedings now and then, the value of these is rather limited [33, 80].

For a number of years, many established wind turbine manufacturers have been abandoning the conventional constant speed wind turbine with a directly grid coupled squirrel cage induction generator in favour of the more modern variable speed wind turbine with a doubly fed induction generator. Also, manufacturers have started to apply a direct drive synchronous generator grid coupled through a power electronic converter of the full generator rating. Therefore, modelling efforts have been devoted to these wind turbine concepts as well.

Variable speed wind turbines are complicated systems, as discussed in chapter 2. Therefore, most papers addressing their modelling only cover one subsystem, such as the drive train, the electromechanical conversion system, the control of the generator currents and the DC link voltage or the rotor speed controller, see e.g. [35-40]. Full models representing all subsystems could, however, not be found in the literature.

Apart from these wind turbine concepts, other wind turbine concepts have been designed and built, such as wind turbines with a gearbox and a conventional high speed synchronous or squirrel cage induction generator grid coupled through a full scale power electronic converter and wind turbines with a doubly fed induction generator with a thyristor based current source converter that feeds the rotor winding (a so-called static Kraemer cascade). Although models of these concepts have been developed and published as well, these concepts are not considered here, because they are not commonly applied and are therefore of limited interest.

### 3.3.2 Characteristics of Models Developed in this Thesis

As pointed out in the last section, many models of wind turbines have been presented by various authors. However, these models cannot be applied in the power system dynamics simulations carried out in this research project nor can they be incorporated into PSS/E™ or other programs that use this simulation approach for one or more of the following reasons:

- they focus on one subsystem of the wind turbine, such as the generator, the drive train and mechanical structure or the controllers, while neglecting the other subsystems, whereas for investigation of the impacts of wind power on power system dynamics full models are necessary [34, 35, 38, 39]
- they are not fully documented, i.e. either not all equations are given or the value of some of the parameters is not specified [28]
- they contain time constants which are too short to be taken into account in power system dynamics simulations [33, 36, 37, 40]

On the contrary, the models derived in this chapter can be used for representing wind turbines in power system dynamics simulations that cover phenomena in a band width of 0.1 to 10 Hz, because they:

- match the assumptions made in the power system dynamics simulation approach, i.e. they contain no time constants shorter than $\approx$100 ms and there are only fundamental frequency currents and voltages present at the terminals
- contain models of those subsystems that affect the interaction between the wind turbine and the grid
- are fully documented, which means that all equations and parameters of the relevant subsystems are given

The models presented in this chapter comprise a useful addition to the current state of knowledge on wind turbine modelling because they enable the incorporation of wind turbine models in power system dynamics simulations and facilitate studies of their impact on power system dynamics.

## 3.4 MODELLING CONTEMPORARY TYPES OF WIND TURBINES

### 3.4.1 Contemporary Types of Wind Turbines

Section 2.3 described the three most important contemporary wind turbine types: the constant speed wind turbine with the squirrel cage induction generator and the variable speed wind turbine with a doubly fed (wound rotor) induction generator or a direct drive synchronous generator. For a more elaborate treatment of their working principles and advantages and disadvantages, the reader is referred to section 2.3. The three wind turbine types are depicted in figure 3.2.

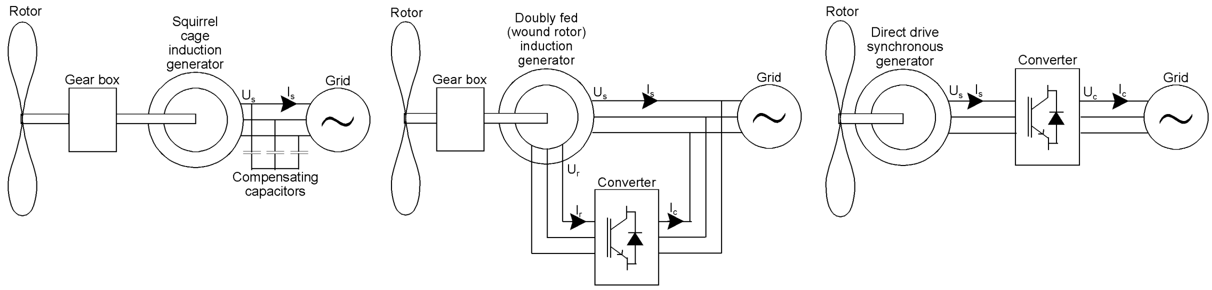


*Figure 3.2 Most frequently occurring actual wind turbine types. From the left: constant speed wind turbine with squirrel cage induction generator, variable speed wind turbine with doubly fed (wound rotor) induction generator and variable speed wind turbine with direct drive synchronous generator.*

### 3.4.2 Assumptions for Rotor and Generator Modelling

A state of the art rotor model to calculate the mechanical generator torque exercised by the wind would be based on the blade element impulse method [7]. However, using the blade element impulse method has a number of drawbacks, namely:

- It requires more knowledge of aerodynamics than most electrical engineers possess, making the models difficult to use for the intended audience.
- It requires the simulation of a wind speed field including the spatial correlation between its individual elements, rather than the simulation of a single point wind speed. It does not allow the use of a measured wind speed sequence either.
- It requires detailed knowledge of the wind turbine blade geometry, which is often not available, which is particularly true at the initial planning stages in which power system studies are carried out.

Therefore, in the wind turbine models presented below, a quasistatic rotor model is used, which assumes an algebraic relationship between the wind speed and the mechanical power extracted from the wind. The disadvantages of using a quasistatic approach are a reduced accuracy and a neglect of the dynamic nature of the conversion of wind speed to mechanical torque. Nevertheless, given the objective of the research, we consider the advantages of the quasistatic approach stronger than its disadvantages.

The models of the generators in each of the wind turbine concepts are derived assuming the following:

- Magnetic saturation is neglected.
- Flux distribution is sinusoidal.
- All losses are neglected, except for copper losses.
- The sum of the stator currents equals zero.

Depending on the wind turbine concept, other assumptions may apply as well. This will be indicated when appropriate.

### 3.4.3 Constant Speed Wind Turbine Model

As discussed in section 2.3.1, the main subsystems of a constant speed wind turbine are a rotor and a squirrel cage induction generator. It has, however, repeatedly been argued in the literature that a representation of the low speed wind turbine shaft, which connects the wind turbine rotor to the gearbox, should be included in the model, particularly for transient stability studies [28, 41, 42].

The shaft of conventional synchronous generators is normally neglected in power system dynamics simulations, because the torsional resonance frequencies tend to lie above 10 Hz, the upper limit of the investigated frequency band [23]. However, this is not true for constant speed wind turbines. Due to the softness of the low speed shaft between the turbine rotor and the gearbox, its resonance frequency is in the order of 2 Hz and thus well within the bandwidth of interest. Therefore, the shaft is also represented in the constant speed wind turbine model presented here. The resonance frequencies of the gearbox and the high speed shaft are well above 10 Hz [35]. These are therefore neglected.

The general structure of the constant speed wind turbine model is depicted in figure 3.3. From the left, first a wind speed model is depicted of which the output is a wind speed sequence. The wind speed sequence is converted into mechanical power by the rotor model. This mechanical power serves as an input for the model of the shaft or the drive train, of which the second input is the rotational speed of the generator. The outputs of the shaft model are the wind turbine rotor speed and the mechanical generator power. The inputs of the generator model are the mechanical power from the rotor model and the grid voltage and frequency. Its outputs are the active and reactive power supplied to the grid.

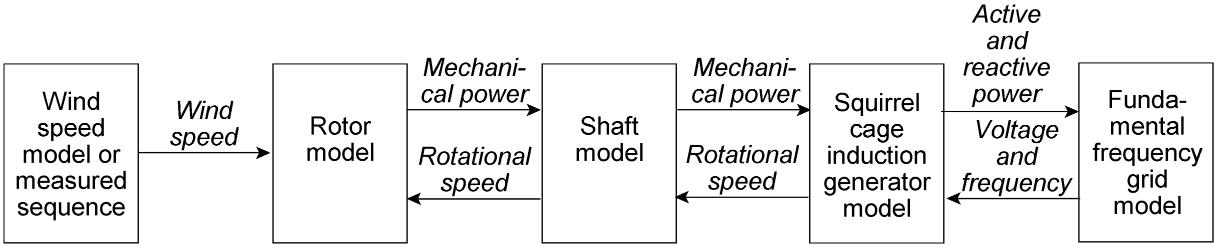


*Figure 3.3 General structure of constant speed wind turbine model.*

For each of the blocks depicted in figure 3.3, models will be presented below, apart from the wind speed model and the fundamental frequency grid model. The wind speed model is excluded, because the simulations in this chapter are carried out using a measured wind speed sequence, making a wind speed model unnecessary. The grid model, which consists of an impedance matrix, is excluded because it is already available in the simulation program, so there is no need to include it in the model. A description of fundamental frequency grid models can be found in the manual of PSS/E™ and in text books covering load flow calculations [30, 81].

***Rotor Model***

The mechanical power extracted from the wind is calculated from the following equation

$$P_w = \frac{\rho}{2} c_p(\lambda) A_r v_w^3 \tag{3.2}$$

in which $P_w$ is the mechanical power extracted from the airflow [W], ρ the air density [kg/m$^3$], $c_p$ the performance coefficient or power coefficient, λ the tip speed ratio $v_t/v_{w,}$, the ratio between the blade tip speed $v_t$ and the wind speed upstream the rotor $v_w$ [m/s], and $A_r$ the area swept by the rotor [m$^2$].

In this thesis, only stall controlled constant speed wind turbines are considered, because pitch controlled ones are not very common, for reasons discussed in section 3.3.1. Therefore, the performance coefficient depends only on the tip speed ratio and not on the pitch angle, as was the case in equation (2.1); the pitch angle is constant and is therefore not included as a variable in equation (3.2). A numerical approximation of the $c_p(\lambda)$ curve is obtained in the following way:

1. The $c_p(\lambda)$ curves of two commercially available wind turbines are calculated from the power curve as given in the manufacturer's documentation. By assuming the rotor speed constant, the tip speed ratio can be calculated for each wind speed.
2. The obtained $c_p(\lambda)$ curves are averaged.
3. The Matlab routine `fminsearch` is used to determine the coefficients in the equation for the numerical approximation of the $c_p(\lambda)$ curve in such a way that the sum of squares of the error between the numerical approximation and the average $c_p(\lambda)$ curve obtained at step 2 is minimized.

The following equation was used to approximate the $c_p(\lambda)$ curve

$$c_p(\lambda) = 0.44\left(\frac{125}{\lambda_i} - 6.94\right) e^{\frac{16.5}{\lambda_i}} \tag{3.3}$$

with

$$\lambda_i = \frac{1}{\frac{1}{\lambda} + 0.002} \tag{3.4}$$

The structure of this equation is obtained from [7]. However, only coefficients for the approximation of the $c_p(\lambda,\theta)$ curve of pitch controlled wind turbines are given here. Therefore, it was necessary to calculate the value of the coefficients for a rotor model of a stall controlled constant speed wind turbine. To this end, the pitch angle $\theta$ was removed from (3.3).

Figure 3.4 depicts the power curve that results when the numerical approximation of equations (3.3) and (3.4) is applied, together with the power curve of the two commercially available wind turbines from which the approximation was derived. Note that it is assumed that equations (3.3) and (3.4) can be used to represent all constant speed wind turbines, i.e. small differences between various wind turbines of different manufacturers are neglected.

High-frequency wind speed variations are very local and are therefore smoothed over the rotor surface, particularly in the case of the present, large wind turbines. To approximate this effect, a low pass filter is included in the rotor model. It is depicted in figure 3.5. The value of $\tau$ depends on the rotor diameter and also on the turbulence intensity of the wind and the average wind speed [43]. In the simulations in this chapter, $\tau$ equals 4.0 s. A periodic torque pulsation is also added to the torque calculated from the wind speed to represent the *tower shadow*; the term for the periodic decreases in mechanical torque that occur when one of the rotor blades passes the tower. The frequency of this pulsation depends on the number of blades and the rotor speed of the wind turbine. Its amplitude is assumed to equal 0.1 p.u., which results in output power fluctuations with an amplitude of about 0.025 p.u. This value is in agreement with measurements presented in the literature [28].

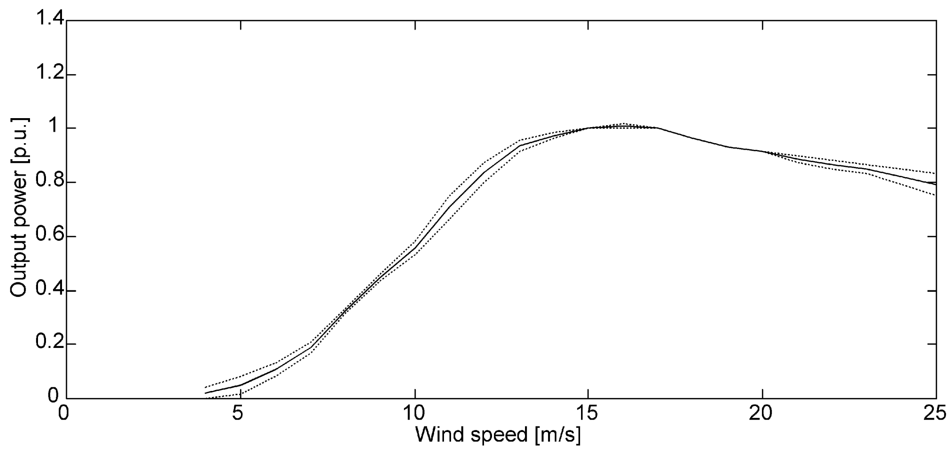


*Figure 3.4 Comparison of numerical approximation of the power curve of a stall controlled wind turbine according to equations (3.3) and (3.4) (solid) with the power curves of two commercially available stall controlled wind turbines (dotted).*

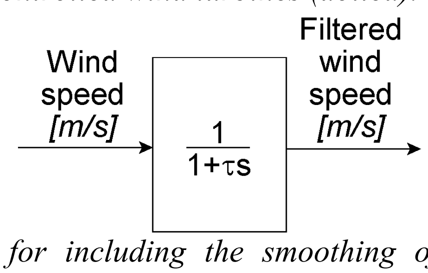


*Figure 3.5 Low pass filter for including the smoothing of high-frequency wind speed variations over the rotor surface.*

***Shaft Model***

Figure 3.6 shows a two mass representation of the rotating part a wind turbine. The reason that a two mass representation is used, is that the only the low speed shaft of the turbine needs to be included, as mentioned above. Its resonance frequency is about 2 Hz and hence well within the bandwidth of interest, 0.1-10 Hz. The resonance frequencies of the gearbox and the high speed shaft are much higher and therefore these are assumed to be infinitely stiff [35]. When the shaft damping is neglected, the shaft is described by the following equations:

$$\frac{d\omega_{wr}}{dt} = \frac{T_{wr} - K_s\gamma}{2H_{wr}}$$
$$\frac{d\omega_m}{dt} = \frac{K_s\gamma - T_e}{2H_m} \qquad (3.5)$$
$$\frac{d\gamma}{dt} = 2\pi f(\omega_{wr} - \omega_m)$$

where f is the nominal grid frequency [Hz], T is torque [p.u.], $\gamma$ is the angular displacement between the two ends of the shaft [electrical radians], $\omega$ is rotational speed [p.u.], H is the inertia constant [s] and $K_s$ is the shaft stiffness [p.u. torque/electrical radians]. The indices wr, m and e mean wind turbine rotor, generator mechanical and generator electrical respectively.

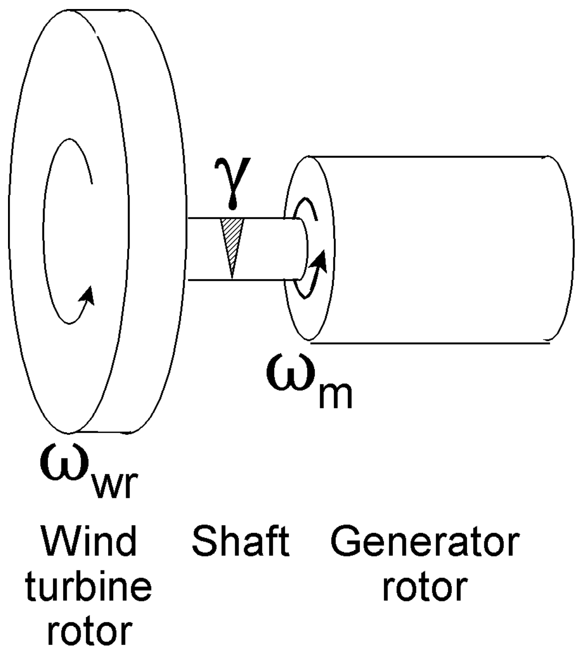


*Figure 3.6 Two mass representation of the rotating part of a wind turbine.*

***Generator Model***

The following equations describe a squirrel cage induction generator in the d-q reference frame [24]. The generator convention is applied, which means that rotor and stator currents are positive when they are outputs

$$
\begin{aligned}
v_{ds} &= -R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \\
v_{qs} &= -R_s i_{qs} + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \\
v_{dr} &= 0 = -R_r i_{dr} - s\omega_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \\
v_{qr} &= 0 = -R_r i_{qr} + s\omega_s \psi_{dr} + \frac{d\psi_{qr}}{dt}
\end{aligned}
\tag{3.6}
$$

with v the voltage, R the resistance, i the current, $\omega_s$ the stator electrical frequency, $\psi$ the flux linkage and s the rotor slip. All quantities are in per unit. In (3.6) the indices d and q indicate the direct and quadrature axis components and s and r indicate stator and rotor quantities. Apart from the generator resistance, all quantities in (3.6) chapter are functions of time. Also, in all other equations in this chapter, all quantities except generator and controller parameters are functions of time.

The d-q reference frame is rotating at the synchronous speed with the q-axis leading the d-axis by 90°. The position of the d-axis coincides with the maximum of the stator flux, which means that $v_{qs}$ equals the terminal voltage $e_t$ and $v_{ds}$ equals zero. The flux linkages in (3.6) can be calculated using the following set of equations with all quantities in per unit [24]

$$
\begin{aligned}
\psi_{ds} &= -(L_{s\sigma} + L_m) i_{ds} - L_m i_{dr} \\
\psi_{qs} &= -(L_{s\sigma} + L_m) i_{qs} - L_m i_{qr} \\
\psi_{dr} &= -(L_{r\sigma} + L_m) i_{dr} - L_m i_{ds} \\
\psi_{qr} &= -(L_{r\sigma} + L_m) i_{qr} - L_m i_{qs}
\end{aligned}
\tag{3.7}
$$

with $L_m$ the mutual inductance and $L_{s\sigma}$ and $L_{r\sigma}$ the stator and rotor leakage inductance respectively. In (3.7) the generator convention is used again. The rotor slip s is defined as [24]

$$
s = \frac{\omega_s - \frac{p}{2}\omega_m}{\omega_s} \tag{3.8}
$$

in which p is the number of poles and $\omega_m$ is the mechanical frequency of the generator [rad/s].

From (3.6) and (3.7) the voltage current relationships of the squirrel cage induction generator can be derived. When doing this, the stator transients, represented by the last terms in the upper two equations of (3.6) must be neglected because of the simplifications in power system dynamics simulations, as described in section 3.1.1. The following voltage current relationship results in per unit quantities

$$
\begin{aligned}
v_{ds} &= -R_s i_{ds} + \omega_s((L_{s\sigma} + L_m)i_{qs} + L_m i_{qr}) \\
v_{qs} &= -R_s i_{qs} - \omega_s((L_{s\sigma} + L_m)i_{ds} + L_m i_{dr}) \\
v_{dr} = 0 &= -R_r i_{dr} + s\omega_s((L_{r\sigma} + L_m)i_{qr} + L_m i_{qs}) + \frac{d\psi_{dr}}{dt} \\
v_{qr} = 0 &= -R_r i_{qr} - s\omega_s((L_{r\sigma} + L_m)i_{dr} + L_m i_{ds}) + \frac{d\psi_{qr}}{dt}
\end{aligned}
\tag{3.9}
$$

The equations for the active power P and reactive power Q generated or consumed by a squirrel cage induction generator are the following

$$
\begin{aligned}
P_s &= v_{ds} i_{ds} + v_{qs} i_{qs} \\
Q_s &= v_{qs} i_{ds} - v_{ds} i_{qs}
\end{aligned}
\tag{3.10}
$$

From this equation, it can once more be concluded that only the stator winding is connected to the grid. Using equation (3.10), the active and reactive power fed into or drawn from the grid can be calculated and used in the load flow solution algorithm of the simulation program.
Equations (3.9) and (3.10) describe the electrical part of a squirrel cage induction generator. However, also the mechanical part must be taken into account in a dynamic model for use in power system dynamics simulations. The following equation gives the electro mechanical torque developed by a squirrel cage induction generator

$$
T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} \tag{3.11}
$$

The changes in generator speed that result from a difference in electrical and mechanical torque can be calculated using the generator equation of motion

$$
\frac{d\omega_m}{dt} = \frac{1}{2H_m}(T_m - T_e) \tag{3.12}
$$

in which $H_m$ is the inertia constant of the generator rotor [s] and $T_m$ is the mechanical torque [p.u.]. Equation (3.12) is identical to the middle equation of (3.5). The equation of motion of the generator couples the mechanical and electrical system and in this case, the mechanical torque of the generator depends on the angular displacement between the shaft ends.
Equations (3.2) to (3.5) and (3.8) to (3.12) form a model of a constant speed wind turbine that can be used in power system dynamics simulations. In its present form, the model contains five states and the equations describe a generator equipped with a single cage rotor winding. If necessary, equation (3.9) can be modified in order to represent a rotor with multiple rotor windings [24].

### 3.4.4 Model of Wind Turbine with Doubly Fed Induction Generator

In figure 3.7, the structure of a variable speed wind turbine with a doubly fed induction generator is depicted. The model consists of a block whose output is a wind speed sequence. Like for the constant speed turbine, this block can either contain a wind speed model or a measured wind speed sequence. In this chapter, the latter is the case. Then, again a rotor model, a generator model and a grid model follow. Their inputs are the wind speed, mechanical rotor speed and pitch angle, the torque exerted by the rotor and the current from the converter and the active and reactive power, respectively.

However, because a doubly fed induction generator is more complex, there are a number of additional blocks in figure 3.7 compared to figure 3.3, namely:

- A pitch angle controller, which controls the blade pitch angle based on the actual value of the rotor speed, which is therefore an input to the controller.
- A rotor speed controller, which determines a set point for active power based on the actual value of the rotor speed, which is therefore an input to this controller as well.
- The model of the converter and the protection system, which controls the rotor current of the doubly fed induction generator based on the set point of the rotor speed controller, the voltage controller and the actual value of the terminal voltage, which are hence all inputs to this subsystem.

For each of the indicated blocks, models are presented below, except for the wind speed model and the fundamental frequency grid model, for reasons explained at the start of section 3.2.2.

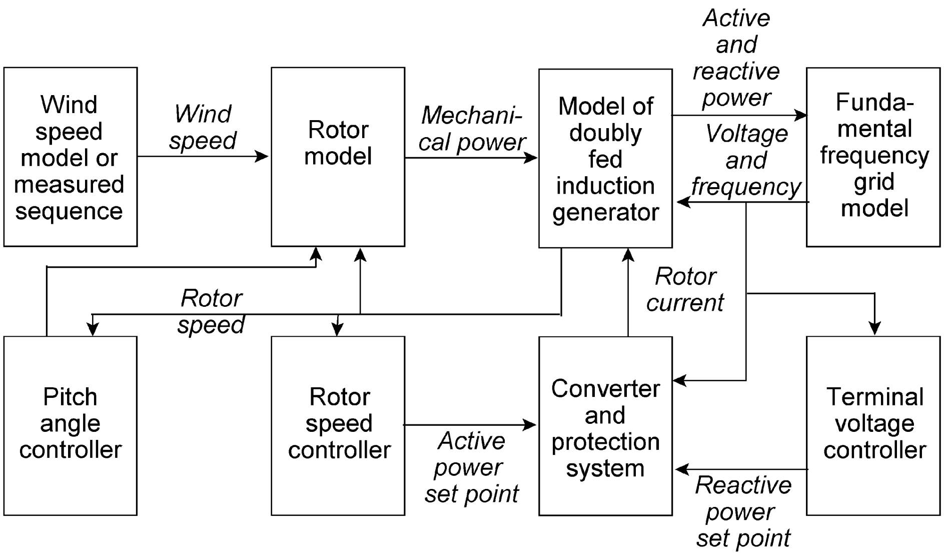


*Figure 3.7 General structure of a model of a variable speed wind turbine with a doubly fed induction generator.*

Note that there is no shaft representation included in the mode of the doubly fed induction generator. Variable speed wind turbines include advanced controllers, in order to minimize any effects from the shaft. If a shaft model were to be included, these controllers would have to be included as well, but this topic is considered beyond the scope of this thesis. As the goal of these controllers is to minimize the impact of the shaft, it can as well be assumed that these controllers are perfect, which is equivalent to neglecting the shaft. Therefore, the electrical and mechanical behaviour of variable speed wind turbines are for a large part decoupled. It is therefore not necessary to include a shaft model if the main topic of interest is the impact of the wind turbine on power system dynamics, like in this thesis. Measurements supporting this assumption can be found in the literature [44, 45].

***Rotor Model***

The mechanical power that the rotor extracts from the wind is calculated using equation (2.1), which is repeated here for convenience:

$$P_w = \frac{\rho}{2} c_p(\lambda,\theta) A_r v_w^3 \tag{3.13}$$

Notice that the performance coefficient $c_p$ is not only dependent on the tip speed ratio $\lambda$, as ws the case in equation (3.2), but also on the pitch angle $\theta$ [deg]. This is caused by the fact that variable speed wind turbines are assumed to be equipped with a pitch angle controller, as is normally the case.

A numerical approximation of the $c_p(\lambda,\theta)$ curve was obtained in the same way as for the constant speed wind turbine. Again, the general structure of the equation is identical to the one given in [7]. However, although the coefficients given therein refer to the rotor of a pitch controlled wind turbine, their value has been changed in order to obtain better correspondence between the numerical approximation and the curves found in manufacturer's documentation.

A factor that complicates the usage of the approach for numerically approximating the $c_p(\lambda)$ curve of a constant speed wind turbine as given in section 3.2.1 to develop an approximation for the $c_p(\lambda,\theta)$ curve of variable speed wind turbines is that the steady state rotor speed at a certain amount of generated power is not given in manufacturer's documentation. This was solved by assuming that the rotor speed is equal to its minimum value at zero power and to its nominal value at nominal power. As will be discussed when deriving a model of the rotor speed controller, the values of the rotor speed between minimum and maximum can then be calculated when it is assumed that the rotor speed is controlled such that an optimal energy yield is obtained.

The following equation was used to approximate the $c_p(\lambda,\theta)$ curve:

$$c_p(\lambda,\theta) = 0.73\left(\frac{151}{\lambda_i} - 0.58\theta - 0.002\theta^{2.14} - 13.2\right)e^{\frac{18.4}{\lambda_i}} \tag{3.14}$$

with

$$\lambda_i = \frac{1}{\dfrac{1}{\lambda - 0.02\theta} + \dfrac{0.003}{\theta^3 + 1}} \tag{3.15}$$

The upper graph of figure 3.8 shows the power curve that results when the numerical approximation of equations (3.14) and (3.15) is applied, together with the power curve of the two commercially available wind turbines from which the approximation was derived. These curves can be found in product descriptions of wind turbines and are publicly available. In the

lower graph, the approximation for the pitch angle is depicted. Only one example could be found in the consulted product descriptions of various manufacturers.
Again, a low pass filter is included in the rotor model, although this is less important than in case of the constant speed wind turbine model, because in variable speed wind turbines the rotor itself acts as a low pass filter. The tower shadow was not incorporated in the rotor model of this wind turbine concept, because it can be concluded from measurements that it is hardly reflected in the generated power [44, 45].

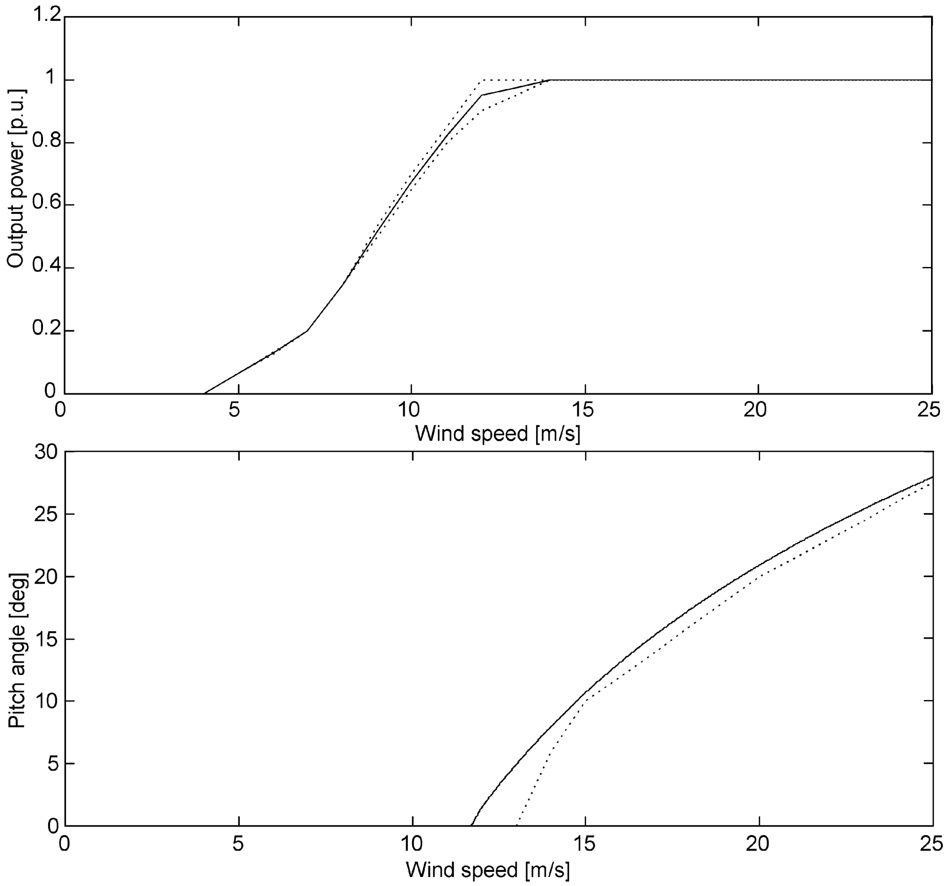


*Figure 3.8 Upper graph: comparison of numerical approximation of the power curve of a pitch controlled wind turbine (solid) with the power curves of two existing pitch controlled wind turbines as found in manufacturer's documentation (dotted). Lower graph: pitch angle deviation above nominal wind speed based on numerical approximation (solid) and manufacturer's documentation (dotted).*

***Generator Model***

A model of a doubly fed induction generator is similar to that of a squirrel cage induction generator. The first difference is that the rotor windings are not shorted, thus the rotor voltage does not equal zero. Equation (3.6) therefore becomes

$$
\begin{aligned}
v_{ds} &= -R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \\
v_{qs} &= -R_s i_{qs} + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \\
v_{dr} &= -R_r i_{dr} - s\omega_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \\
v_{qr} &= -R_r i_{qr} + s\omega_s \psi_{dr} + \frac{d\psi_{qr}}{dt}
\end{aligned} \tag{3.16}
$$

The flux linkage equations of a doubly fed induction generator are identical to that of the squirrel cage induction generator, as given in (3.7). Note that it is assumed that the sum of the rotor currents of the doubly fed induction generator is equal to zero.

To obtain the voltage current relationship, the stator transients must again be neglected in order to make the generator compatible with the assumptions used in power system dynamics simulations. However, this time the rotor transients must be neglected as well [46]. Taking them into account would necessitate detailed modelling of the converter including the semiconductor switches and the current control loops. The reason for this is that when the rotor transients are included, instantaneous flux changes would be impossible and the power electronic converters could not be modelled as current sources, but would have to be modelled as current controlled voltage sources. This would result in time constants well below 100 ms, the typical minimum value of the time constant studied in power system dynamics simulations. The resulting model would also be much more complex and therefore difficult to use and more parameters would be required, which are often difficult to obtain in practice. With this approach, the following voltage current relationships result in per unit quantities

$$
\begin{aligned}
v_{ds} &= -R_s i_{ds} + \omega_s((L_{s\sigma} + L_m)i_{qs} + L_m i_{qr}) \\
v_{qs} &= -R_s i_{qs} - \omega_s((L_{s\sigma} + L_m)i_{ds} + L_m i_{dr}) \\
v_{dr} &= -R_r i_{dr} + s\omega_s((L_{r\sigma} + L_m)i_{qr} + L_m i_{qs}) \\
v_{qr} &= -R_r i_{qr} - s\omega_s((L_{r\sigma} + L_m)i_{dr} + L_m i_{ds})
\end{aligned} \tag{3.17}
$$

In [47], it is proposed to include the $d\psi/dt$ terms of the rotor voltage equations in the model and to model the rotor side of the power electronic converter that feeds the rotor winding as a fundamental frequency voltage source with current control loops, instead of as a current source. The value of various model parameters is not supplied and no simulation results are presented. It is therefore doubted whether this models can be used for power system dynamics simulations.

The equations for active power P and reactive power Q generated or consumed by a doubly fed induction generator are similar to that of the squirrel cage induction generator. However, in the doubly fed induction generator, the rotor winding can also be accessed, leading to terms that refer to the rotor winding in the equations for P and Q

$$\begin{aligned} P &= v_{ds} i_{ds} + v_{qs} i_{qs} + v_{dr} i_{dr} + v_{qr} i_{qr} \\ Q &= v_{qs} i_{ds} - v_{ds} i_{qs} + v_{qr} i_{dr} - v_{dr} i_{qr} \end{aligned} \tag{3.18}$$

It should be noted that the reactive power Q in equation (3.18) is not necessarily equal to the generated reactive power fed into the grid, which is the quantity that must be used for the load flow. This quantity depends on the control strategy for the grid side of the power electronic converter that feeds the rotor winding. The active power P in equation (3.18) is equal to the active power fed into the grid, because although the converter can generate or consume reactive power, it cannot generate, consume or store active power, at least not on the time frame studied in power system dynamics simulations.
The equation for electromechanical torque and the equation of motion of a doubly fed induction generator are equal to that of a squirrel cage induction generator, as given in equations (3.11) and (3.12).

***Model of Converter and Protection System***

The converter is modelled as a current source that supplies a sinusoidal current at the electrical rotor frequency, as mentioned above. This assumption is only true if the current control loops of the power electronic converter connected to the rotor winding are able to quickly reach a new set point for the rotor current. With modern power electronic converters with high switching frequencies and advanced controllers, this is generally the case provided that the converter operates within the design limits.
The latter is, however, not true during a voltage drop caused by a grid fault. Nevertheless, this is not considered a problem, because the response of the power electronic converter to a voltage drop is characterized by very high frequency phenomena that do not affect the quantities investigated with power system dynamics simulations. Therefore, a low frequency representation of the behaviour of the converter during faults must be incorporated in the model, like is done for HVDC converters [30]. The appropriateness of this approach requires further research, and is beyond the scope of this thesis.
The current set points are derived from the active and reactive power set points. The active power set point is generated by the rotor speed controller, based on the actual rotor speed value. The reactive power set point is generated by the terminal voltage or power factor controller, based on the actual value of the terminal voltage or the power factor.
If the stator resistance is neglected and it is assumed that the d-axis coincides with the maximum of the stator flux, which implies that $v_{ds}$ equals zero and $v_{qs}$ equals the terminal voltage, the electrical torque is dependent on the quadrature component of the rotor current [7]. The following relation between electrical torque and $i_{qr}$ can be derived from equations (3.7), (3.9) and (3.11)

$$T_e = -\frac{L_m v_t i_{qr}}{\omega_s (L_{s\sigma} + L_m)} \tag{3.19}$$

in which $v_t$ is the terminal voltage. Using the actual value of the rotor speed, a set point for the electrical torque can be derived from the active power set point generated by the rotor speed controller. Equation (3.19) can then be used to calculate the set point for $i_{qr}$.
The reactive power is dependent on the direct component of the rotor current. Using equations (3.7), (3.9) and (3.10), and again neglecting the stator resistance and assuming that the d-axis coincides with the maximum of the stator flux, it can be shown that

$$Q_s = -\frac{L_m v_t i_{dr}}{L_{s\sigma} + L_m} - \frac{v_t^2}{\omega_s(L_{s\sigma} + L_m)} \tag{3.20}$$

Using this equation, a set point for $i_{dr}$ can be derived from the active power set point generated by the terminal voltage/power factor controller.
The grid side of the converter is described by the following equations

$$\begin{aligned} P_c &= v_{dc} i_{dc} + v_{qc} i_{qc} \\ Q_c &= v_{qc} i_{dc} - v_{dc} i_{qc} \end{aligned} \tag{3.21}$$

in which the index c means converter. In this equation $P_c$ is equal to the rotor power of the doubly fed induction generator and can be multiplied with the converter efficiency if the converter losses are to be included. $Q_c$ depends on the control strategy and the converter rating, but normally equals zero.

The model of the protection system consists of three parts:

- a converter current limiter
- a part that switches off the wind turbine when the terminal voltage deviates more than a specified amount from its nominal value during a specified time interval
- a part that switches off the wind turbine when the grid frequency deviates more than a specified amount from its nominal value during a specified time interval

The converter current must be limited to protect the semiconductor switches in the power electronic converter. The limiter's boundaries are specified by giving the maximum amount of reactive power the wind turbine can generate in per unit. From this value and the nominal active power, the nominal current is calculated for nominal terminal voltage. This way of specifying the current limits is more user friendly than specifying the current limits directly. It is also possible to specify an overloading percentage and a time during which the converter can be overloaded, because power electronic converters may have a limited overloading capability, depending on the design [48].
The parts of the protection system reacting to voltage and frequency are characterized by the upper and lower voltage and frequency boundary values that can be tolerated and by the time interval during which these values are allowed to be exceeded. If voltage and frequency return to within these boundary values after having exceeded them, the timer is reset and starts again if the boundary values are exceeded once more. When voltage and frequency do not return to values within the allowable range during the specified time interval, the wind turbine is

disconnected. It is reconnected when the terminal voltage and/or frequency have returned to within their allowable limits again, after which active and reactive power are ramped up to their initial values. All protection system parameters can be adjusted. Boolean logic is used for the implementation of the protection system, which is based on `if..then..` constructions.

***Rotor Speed Controller***

The speed controller of the wind turbine model operates as follows:

- With a sample frequency $f_{ss}$ [Hz], the actual rotor speed is measured. The sample frequency is in the order of 20 Hz.
- From this value a set point for the generated power is derived using the control characteristic.
- Taking into account the actual generator speed, a torque set point is derived from the power set point.
- A current set point is derived from the torque set point, using equation (3.19).
- As a result of the generator and converter modelling approach described above, this current set point is reached immediately. In practice, the current set point would be used as an input to the current control loops and it would take some time to achieve the desired value of the current. However, the time necessary to arrive at the new current is well below the bandwidth of 10 Hz.

To acquire a set point for generated real power, a rotor speed versus generator power characteristic is used. In most cases, the rotor speed is controlled in such a way that optimal energy capture is achieved, although sometimes other goals, particularly noise minimization, are pursued.

The solid line in figure 3.9 depicts the rotor speed versus power characteristic that leads to optimal energy capture, while reducing the thrust at the nominal wind speed. At low wind speeds, the rotor speed is kept at its minimum by adjusting the generator torque. At medium wind speeds, the rotor speed varies proportionally to the wind speed in order to keep the tip speed ratio $\lambda$ at its optimal value. When the rotor speed reaches its nominal value, the generator power is kept at its nominal value as well [44, 49, 50].

However, controlling the power according to the rotor speed versus power characteristic that leads to optimal energy capture causes some problems:

- The desired power is not defined uniquely at nominal and minimal rotor speed.
- If the rotor speed decreases from slightly above nominal speed to slightly below nominal speed or from slightly above minimal speed to slightly below minimal speed, the change in generated power is very large.

To solve these problems, a control characteristic similar to the one that leads to optimal energy capture is used here. This control characteristic is depicted by the dashed line in figure

3.9. The problem is sometimes also solved by applying more advanced controller types, such as integral controllers or hysteresis loops [50, 51].
The points at which the implemented control characteristic deviates from the control characteristic leading to optimal energy capture can be adjusted in the model. If these points are close to the minimal and the nominal rotor speed, the maximum amount of energy is extracted from the wind over a wide range of wind speeds, but for changes in the rotor speed near the minimum and nominal rotor speed result in large power fluctuations. If these points lie further away from the minimal and nominal rotor speed, the wind speed range in which energy capture is maximal is narrowed, but the power fluctuations near minimal and nominal rotor speed are smaller.

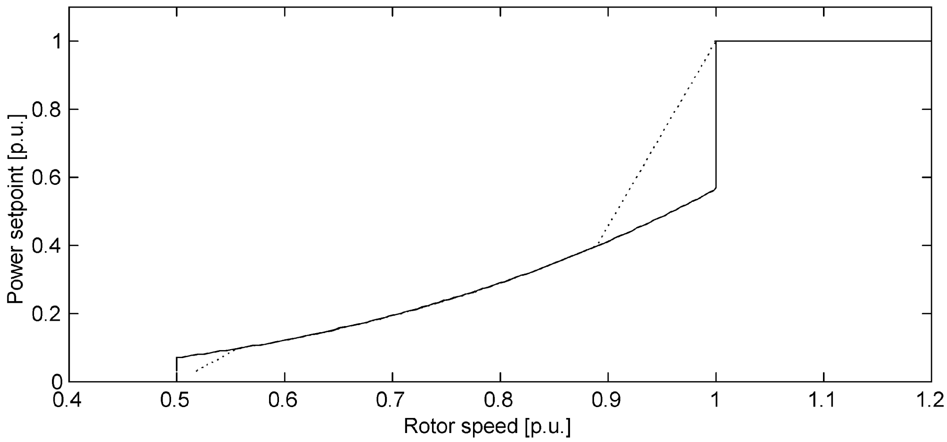


*Figure 3.9 Optimal (solid) and implemented (dotted) rotor speed versus power characteristic of an example variable speed wind turbine.*

Finally, it should be mentioned that purely theoretically the solid line in figure 3.9 only leads to optimal energy capture when the *mechanical power extracted by the rotor*, rather than the *generated electrical power* is controlled accordingly. The difference between these two quantities is made up by the generator losses. However, the maximum of the $c_p(\lambda,\theta)$ characteristic is rather flat [7]. Therefore, it is assumed that in practice the decrease in energy yield introduced by neglecting the generator losses, which are difficult to calculate in advance and depend on the generator operating point, is negligible and the generator power is controlled according to the dashed characteristic depicted in figure 3.9.

***Pitch Angle Controller***
The pitch angle controller is only active in high wind speeds. In those circumstances, the rotor speed can no longer be controlled by increasing the generated power, as this would overload the generator and/or the converter. To prevent the rotor speed from becoming too high, which would result in mechanical damage, the blade pitch angle is adjusted in order to limit the aerodynamic efficiency of the rotor. The optimal pitch angle is approximately zero below the nominal wind speed and from the nominal wind speed on, it increases steadily with the wind speed, as can be seen in figure 3.8. With equations (3.14.) and (3.15) the impact of the pitch

angle on the performance coefficient can be calculated and the resulting value can be substituted in equation (3.13) to calculate the mechanical power from the wind.

It should be taken into account that the pitch angle cannot change immediately, but only at a finite rate. The rate of change may be quite low due to the size of the rotor blades of modern wind turbines and the desire to save money on the blade drives. The maximum rate of change of the pitch angle is in the order from 3 to 10 deg/s, depending on the size of the wind turbine. Because the blade pitch angle can only change slowly, the pitch angle controller works with a sample frequency $f_{ps}$ which is in the order of 1 to 3 Hz. In figure 3.10 the pitch angle controller is depicted. The model offers the possibility to specify all parameters shown in this figure.

Note that using this controller type, the rotor speed is allowed to exceed its nominal value by up to 20%, depending on the value of $K_{pa}$. However, a proportional controller is used, because:

- a slight overspeeding of the rotor above its nominal value can be allowed and poses no problems for the wind turbine construction
- the system is never in steady state due to the varying wind speed, so that the advantage of an integral controller, which can achieve zero steady state error, is not applicable

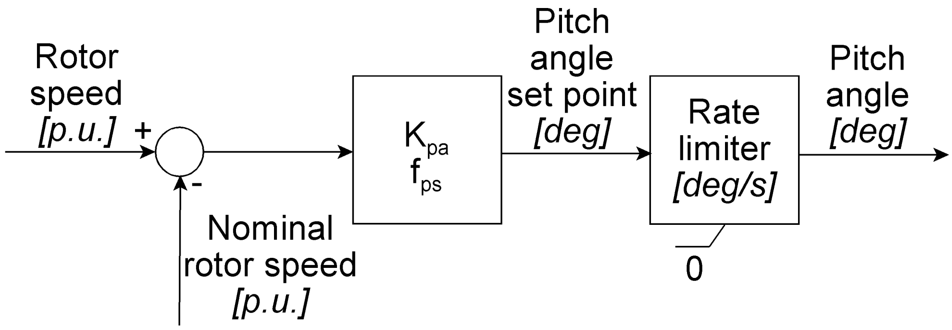


*Figure 3.10 Pitch angle controller model.*

***Terminal voltage controller***

A variable speed wind turbine with a doubly fed induction generator is theoretically able to vary its reactive power output and thus to take part in terminal voltage control. As can be concluded from equation (3.20), the reactive power exchanged with the grid can be controlled, provided that the current rating of the power electronic converter is sufficient to circulate reactive current even at nominal active current.

The first term in equation (3.20) determines the net reactive power exchange with the grid, which can be controlled by changing $i_{dr}$. The second term represents the magnetization of the stator. By rewriting equation (3.20) in the following way

$$Q = -\frac{L_m v_t (i_{dr,magn} + i_{dr,gen})}{L_{s\sigma} + L_m} - \frac{v_t^2}{\omega_s (L_{s\sigma} + L_m)} \tag{3.22}$$

it can be seen that $i_{dr,magn}$, the rotor current required to magnetize the stator, equals

$$i_{dr,magn} = -\frac{v_t}{\omega_s L_m} \tag{3.23}$$

The nett reactive power exchange with the grid then equals

$$Q = -\frac{L_m v_t i_{dr,gen}}{L_{s\sigma} + L_m} \tag{3.24}$$

A terminal voltage controller for a doubly fed induction generator is depicted in figure 3.11. When the value of $K_v$ is changed to zero, a controller keeping the power factor equal to one results. This is the dominating mode of operation nowadays.

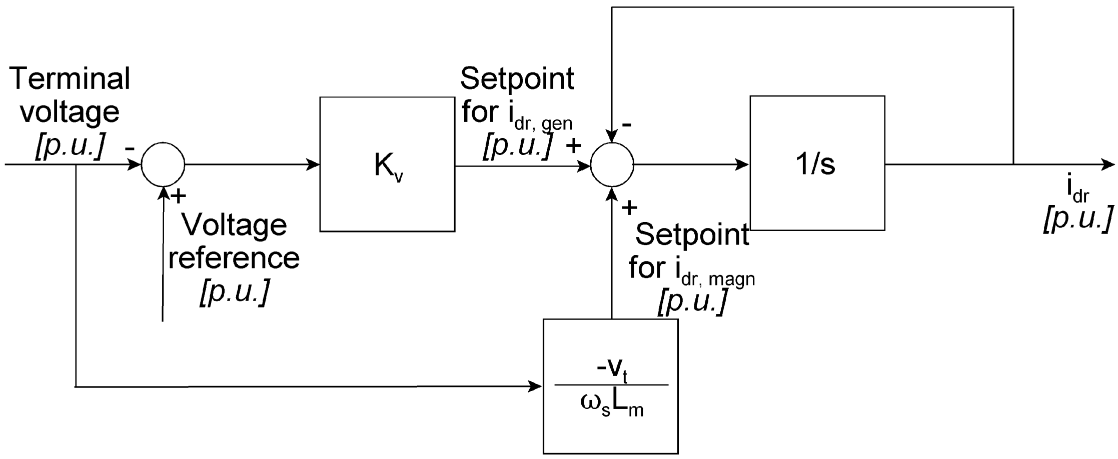


*Figure 3.11. Terminal voltage controller for variable speed wind turbine with doubly fed induction generator.*

It should be noted that practical terminal voltage controllers might differ from the one depicted in figure 3.11. However, the same applies to other components of a power system: it is a general problem in power system dynamics simulations that the structure and parameters of the models of the components are not available. Standard governor and exciter models for synchronous generators have for instance been developed to represent controllers whose exact structure and parameters are not known in simulations [30]. This problem is also alleviated by the fact that the results of power system dynamics simulations depend only to a limited extent on the exact structure and the parameters of the individual controllers. Therefore, in many cases, a proportional voltage controller will probably even suffice.

### 3.4.5 Model of Wind Turbine with Direct Drive Synchronous Generator

The general structure of a model of a wind turbine with a direct drive synchronous generator is depicted in figure 3.12. The model of a variable speed wind turbine with a direct drive synchronous generator is similar to that of a variable speed wind turbine with a doubly fed induction generator. The rotor model, the rotor speed and pitch angle controllers and the converter and protection system model are identical. There are, however, differences in the generator model, because a different generator type is applied and there are differences in the voltage controller model, because the reactive power generation or consumption of a wind turbine with a direct drive synchronous generator is not governed by the generator, but by the grid side of the converter. Therefore, only the generator model and the terminal voltage controller will be treated below.

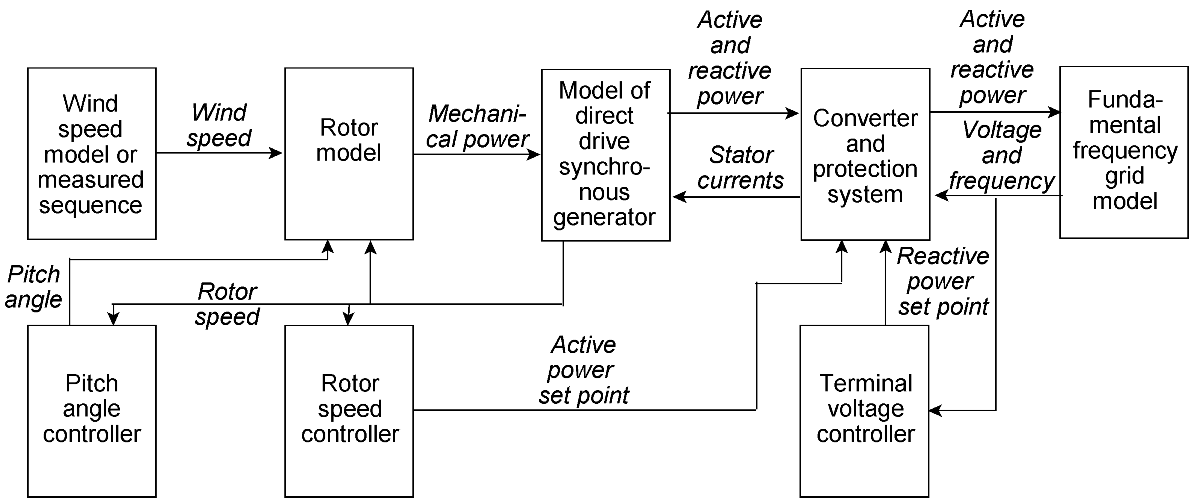


*Figure 3.12. General structure of a model of a variable speed wind turbine with a direct drive synchronous generator.*

***Generator Model***

In wind turbines, both synchronous generators with a wound rotor and synchronous generators with a permanent magnet rotor are used. For a wound rotor synchronous generator, the flux equations in a d-q reference frame are the following, assuming the generator convention for the stator windings [24]

$$\begin{aligned}\psi_{ds} &= -(L_{s\sigma} + L_{dm})i_{ds} + L_{dm}i_{fd}\\ \psi_{qs} &= -(L_{s\sigma} + L_{qm})i_{qs}\\ \psi_{fd} &= L_{fd}i_{fd}\end{aligned} \tag{3.25}$$

in which the index fd stands for field winding quantities. Damper windings are neglected, because they hardly effect the grid interaction in power system dynamics simulations, due to the decoupling effect of the power electronic converter. In case of a permanent magnet rotor, the last equation of (3.25) disappears and the first one becomes

$$\psi_{ds} = -(L_{s\sigma} + L_{dm})i_{ds} + \psi_p \tag{3.26}$$

in which $\psi_p$ equals the amount of flux of the rotor mounted permanent magnets linked by the stator winding.

The voltage equations are

$$\begin{aligned} v_{ds} &= -R_s i_{ds} - \omega_m \psi_{qs} + \frac{d\psi_{ds}}{dt} \\ v_{qs} &= -R_s i_{qs} + \omega_m \psi_{ds} + \frac{d\psi_{qs}}{dt} \\ v_{fd} &= R_{fd} i_{fd} + \frac{d\psi_{fd}}{dt} \end{aligned} \tag{3.27}$$

The d$\psi$/dt terms in the stator equations are neglected, to eliminate the short time constants associated with these terms and to allow a simplified representation of the power electronic converter. The active and reactive power are given by equation (3.10) and the torque equation is equal to that of the asynchronous machine, given in (3.11). The control strategy of the generator depends on whether a generator with a wound rotor or a permanent magnet rotor is used and on whether a diode rectifier or a back-to-back voltage source converter is applied.

When a diode rectifier is used, the generator power factor equals unity when commutation is neglected. In the upper equation of (3.25) the term $L_{ds}i_{fd}$ or in (3.26) the term $\psi_p$ is known. The excitation current $i_{fd}$ follows from the excitation voltage, which depends on the control strategy. Excitation control can e.g. be aimed at minimizing the generator losses. In a permanent magnet generator, the flux linkage of the permanent magnets $\psi_p$ is determined by the generator design. Further, the desired active power P is known, because it is derived from the actual value of the rotor speed $\omega_m$, according to the control characteristic depicted in figure 3.9. Thus, the following four equations with four unknowns result for a synchronous generator with a wound rotor

$$\begin{aligned} v_{ds} &= -R_s i_{ds} + \omega_m (L_{s\sigma} + L_{qm}) i_{qs} \\ v_{qs} &= -R_s i_{qs} - \omega_m ((L_{s\sigma} + L_{dm}) i_{ds} - L_{dm} i_{fd}) \\ P_s &= v_{ds} i_{ds} + v_{qs} i_{qs} \\ Q_s &= v_{qs} i_{ds} - v_{ds} i_{qs} = 0 \end{aligned} \tag{3.28}$$

For a synchronous generator with permanent magnets, the second equation becomes

$$v_{qs} = -R_s i_{qs} - \omega_m ((L_{s\sigma} + L_{dm}) i_{ds} - \psi_p) \tag{3.29}$$

Equation (3.28), if applicable combined with (3.29), can be solved, after which the d and q components of stator voltage and current are known. By controlling the stator voltage of the generator accordingly, the desired operating point can be reached.

When instead of a diode rectifier, a back-to-back voltage source converter is applied, the user can not only determine the active power P but also the reactive power Q. The last equation of (3.28) changes to

$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} \tag{3.30}$$

The other equations remain unchanged and again a system with four equations and four unknowns is obtained.

It must be emphasized that $Q_s$ in equations (3.28) and (3.30) is not equal to the reactive power exchanged with the grid. The reactive power value to be used in the load flow is determined by the control of the grid side of the power electronic converter and is fully decoupled from the reactive power of the generator itself, which is exchanged with the generator side of the converter, and not with the grid.

***Terminal Voltage Controller Model***

The voltage controller as applied in a direct drive wind turbine is different from that in a wind turbine with a doubly fed induction generator, because the generator is fully decoupled from the grid. It is hence not the generator that generates active power and controls the terminal voltage, but the converter. The generated reactive power is given by the lower equation of (3.21). Assuming that the terminal voltage $v_t$ is equal to $v_{qc}$ in equation (3.21), the model of the voltage controller is depicted in figure 3.13. If wind turbines operating with a power factor equal to one are to be simulated, the voltage controller can be removed.

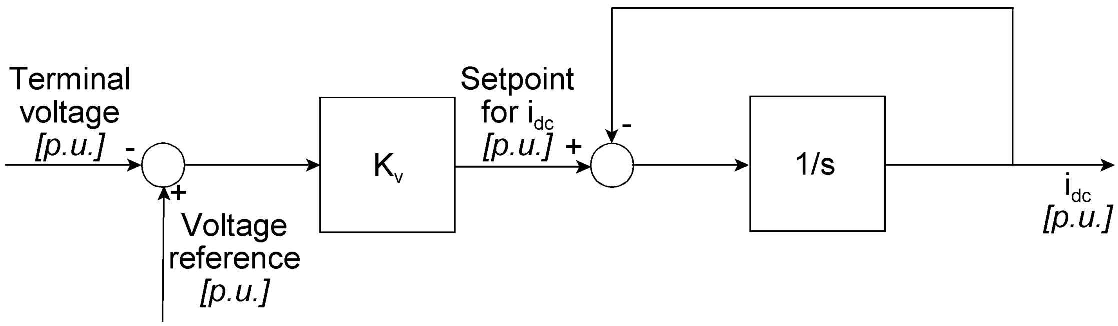


*Figure 3.13 Terminal voltage controller for variable speed wind turbine with direct drive synchronous generator.*

## 3.5 COMPARISON OF SIMULATION RESULTS AND MEASUREMENTS

In this section, the responses of the models to a particular measured wind speed sequence is investigated and compared to actual measurements. The measurements have been obtained from wind turbine manufacturers under a confidentiality agreement. Therefore, the wind turbine types are not given and all values except the wind speed and pitch angle are in per unit without indicating their base values. The simulation results presented here were obtained with MATLAB®.

In the upper graph of figure 3.14, a measured wind speed sequence is depicted. Subsequently, the simulated rotor speed, the pitch angle if applicable and the output power are depicted for each of the wind turbine types. In the upper graph of figure 3.15, three measured wind speed sequences are shown. Then, the measured rotor speed and pitch angle of both a variable speed wind turbine with doubly fed induction generator and with a direct drive synchronous generator are shown. In the lower graph, the measured output power of all three turbine types is depicted. The rotor speed of the constant speed wind turbine was not measured, because the small variations of the rotor speed are hard to measure; therefore, this quantity is not depicted. In both figures, the meaning of each of the curves is indicated in the graphs. The characteristics of the wind turbine are given in table 3.1. The generator parameters of the induction generator used in the constant speed wind turbine and the variable speed wind turbine with a doubly fed induction generator are given in table 3.2; the parameters of the direct drive synchronous generator are given in table 3.3.

*Table 3.1. Characteristics of simulated wind turbine.*

| **Wind turbine characteristic** | **Value** |
|---|---|
| Rotor speed (constant speed) | 17 RPM |
| Minimum rotor speed (variable speed) | 9 RPM |
| Nominal rotor speed (variable speed) | 18 RPM |
| Rotor diameter | 75 m |
| Rotor swept area $A_r$ | 4418 $m^2$ |
| Nominal power | 2 MW |
| Nominal wind speed (constant speed) | 15 m/s |
| Nominal wind speed (variable speed) | 14 m/s |
| Gear box ratio (constant speed) | 1:89 |
| Gear box ratio (doubly fed) | 1:100 |
| Inertia constant H | 2.5 s |
| Shaft stiffness (constant speed) $K_s$ | 0.3 p.u./el. rad. |

*Table 3.2. Induction generator parameters.*

| **Generator characteristic** | **Value** |
|---|---|
| Number of poles p | 4 |
| Generator speed (constant speed) | 1517 RPM |
| Generator speed (doubly fed) | 900-1900 RPM |
| Mutual inductance $L_m$ | 3.0 p.u. |
| Stator leakage inductance $L_{s\sigma}$ | 0.10 p.u. |
| Rotor leakage inductance $L_{r\sigma}$ | 0.08 p.u. |
| Stator resistance $R_s$ | 0.01 p.u. |
| Rotor resistance $R_r$ | 0.01 p.u. |
| Compensating capacitor (constant speed) | 0.5 p.u. |
| Inertia constant H | 0.5 s |

*Table 3.3. Direct drive synchronous generator parameters.*

| **Generator characteristic** | **Value** |
|---|---|
| Number of poles p | 80 |
| Generator speed | 9-19 RPM |
| Mutual inductance in d axis $L_{dm}$ | 1.21 p.u. |
| Mutual inductance in q axis $L_{qm}$ | 0.606 p.u. |
| Stator leakage inductance $L_{s\sigma}$ | 0.121 p.u. |
| Field inductance $L_{fd}$ | 1.33 p.u. |
| Stator resistance $R_s$ | 0.06 p.u. |
| Field resistance $R_{fd}$ | 0.0086 p.u. |
| Inertia constant H | 1.0 p.u. |

The available measurements cannot be used for a quantitative validation of the models for two reasons. Firstly, the wind speed is measured with a single anemometer, whereas the rotor has a large surface. Secondly, the measured wind speed is severely disturbed by the rotor wake, because the anemometer is located on the nacelle. Therefore, the wind speed as measured with a single anemometer is not an adequate measure of the wind speed acting on the rotor as a whole and it is not possible to feed a measured wind speed sequence into the model in order to compare measured and simulated response of the turbine.

The discrepancy between the wind speed measured with a single anemometer and the aggregated wind speed acting on the rotor is clearly illustrated by the behaviour of the variable speed wind turbine with doubly fed induction generator from about 18 to 23 seconds. The wind speed decreases from about 12 to 10 m/s. However, rotor speed, pitch angle and generated power increase. If the wind speed as measured by the anemometer were a good indicator for the wind speed acting on the rotor as a whole, the observed behaviour would of course be impossible.

Thus, although it would be possible to use the wind speed sequence measured by the anemometer as the model's input, it is not possible to validate the model by comparing the measured and simulated response to that wind speed sequence quantitatively. Therefore, only a qualitative comparison was carried out.

The comparison of the simulation results and the measurements is based on a time sequence and not on a frequency domain analysis, i.e. on the Fourier transformed time series. The main reason for this is that not all dynamic modes are included in the constant speed wind turbine model. The two most important modes, the tower shadow and the low speed shaft torsional resonance are included and an analysis of the Fourier transform of the simulated time series has shown that they can indeed be observed in the Fourier transform. However, other modes, such as the torsional resonance of the coupling of the blade to the shaft have not been included. Their impact on the value of the output power, which is our main interest, is very limited. Nevertheless, they are observed in the Fourier transform if the measurements and could hence raise unjustified doubts with respect to the validity of the model. In case of a variable speed wind turbine, Fourier transformed signals do not give much useful information, because the mechanical properties of the generator are not reflected in the output.

***Conclusions from the Comparison***

From the simulation results depicted in figure 3.14, it can be concluded that:

- Particularly short term (seconds) output power fluctuations are more severe for a constant speed wind turbine than for both types of variable speed wind turbines. This is because in variable speed wind turbines the rotor acts as an energy buffer. As a result, rapid wind speed changes and the tower shadow are not reflected in the rotor speed nor in the power supplied to the grid.
- The response of the variable speed wind turbine types is similar, because their behaviour is for the largest part determined by the controllers, which are identical.

These findings also apply to the measurements depicted in figure 3.15.

When the simulated and measured responses are compared, it can be seen that:

- The ranges of the measured and simulated rotor speed fluctuations of the variable speed turbines are similar (they fluctuate within a band of about 0.1 p.u. width).
- Measured and simulated pitch angle behaviour are similar with respect to the rate of change (≈3-5 deg/s) and the minimum (≈0 deg) and maximum value (≈6 deg).
- The ranges of the measured and simulated output power fluctuations of the constant speed wind turbine and that of the wind turbine with doubly fed induction generator are similar (they fluctuate within a band of ≈0.3-0.4 p.u. width).
- The rates of change of the measured and of the simulated output power fluctuations of the constant wind turbine show differences. However, it can be observed that there is a rather poor correlation between the measured wind speed and output power in case of the constant speed wind turbine. The observed discrepancies between measurement and simulation are therefore probably caused by inaccuracies in the measurements, rather than by the model.
- The ranges of the measured (≈0.2 p.u.) and simulated (≈0.4 p.u.) output power fluctuations of the wind turbine with direct drive synchronous generator are different, which is, however, probably caused by the fact that the direct drive wind turbine was only exposed to rather high wind speeds in the measurements, whereas in the simulation, also lower wind speeds occurred.

Although a quantitative validation of the models is not possible with the available measurements, this qualitative comparison of measured and simulated responses gives confidence about the accuracy and applicability of the derived models and shows that the consequences of the assumptions and simplifications applied in modelling the rotor, the generator and the controllers are rather limited. Probably, the consequences of the

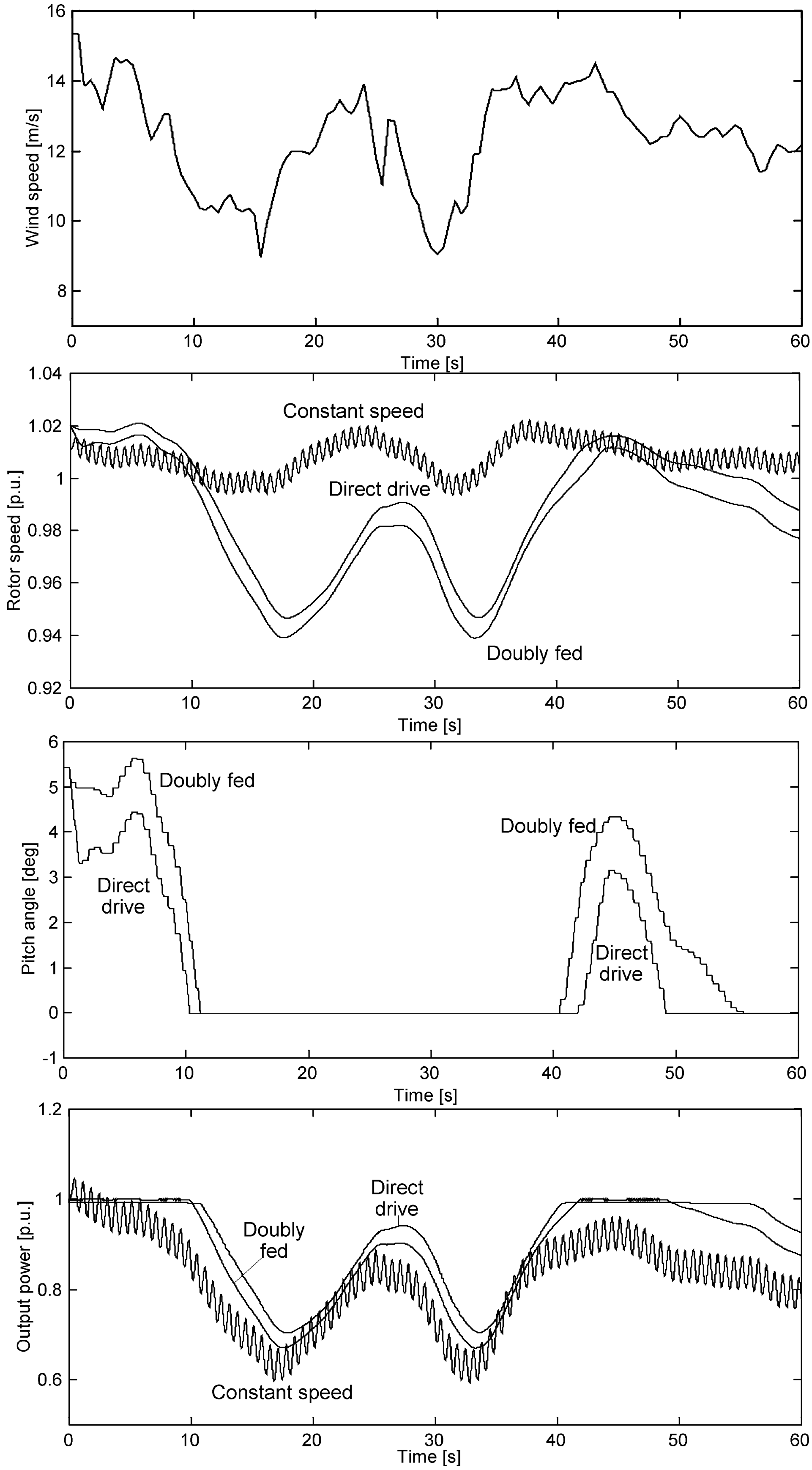


*Figure 3.14 Simulated responses of each of the investigated wind turbine types. Starting from above: measured wind speed and simulated rotor speed, pitch angle and output power.*

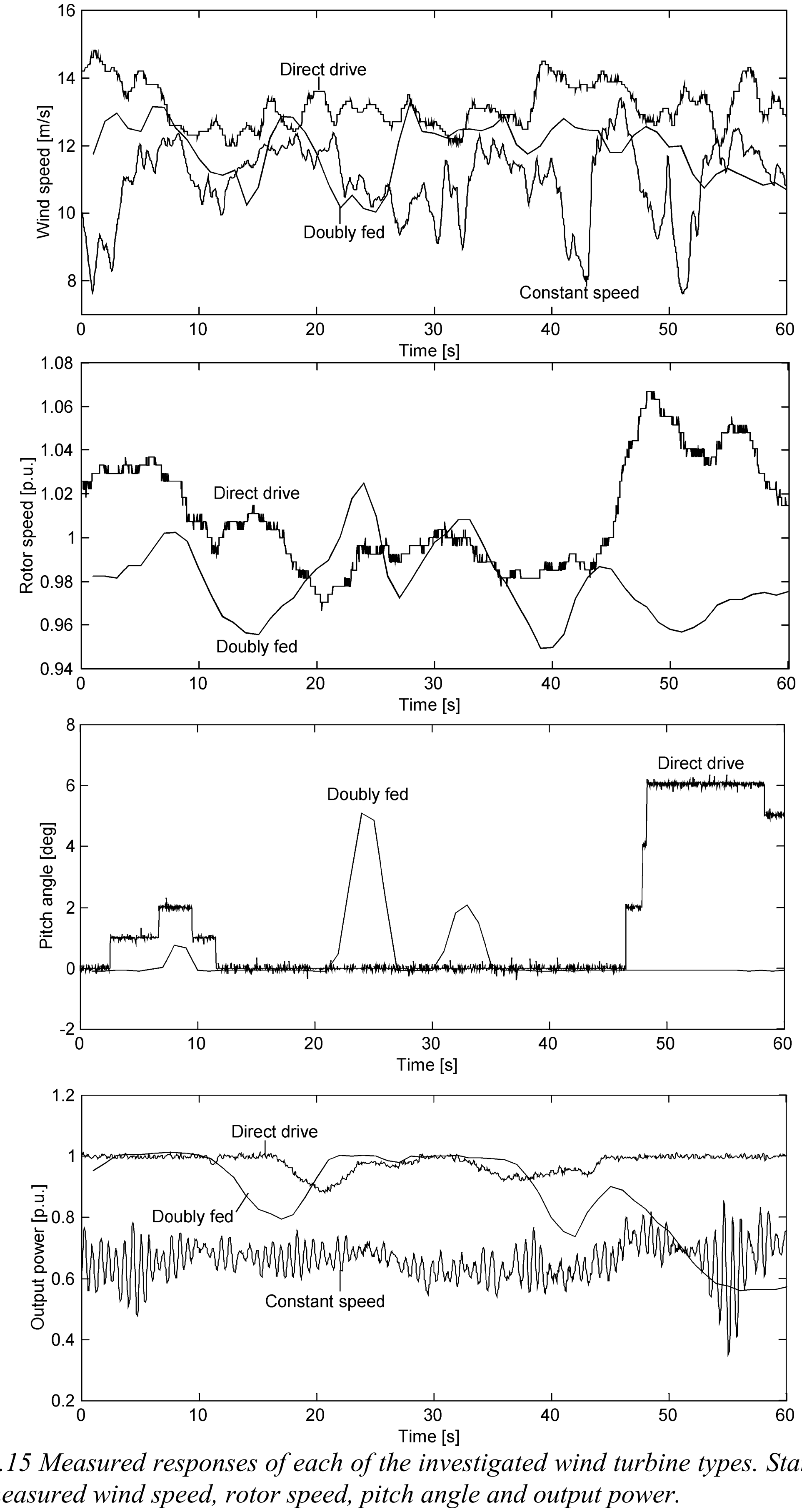


*Figure 3.15 Measured responses of each of the investigated wind turbine types. Starting from above: measured wind speed, rotor speed, pitch angle and output power.*

simplifications for the simulation results are smaller than that of other sources of uncertainty, such as generator and controller parameters and the topology of the investigated power system.

## 3.6 ILLUSTRATION OF TERMINAL VOLTAGE CONTROLLER FUNCTIONING

In this section, the functioning of the terminal voltage controller will be illustrated by means of simulation results. The simulations that are carried out are identical to those on which figure 3.14 is based. The wind turbine was connected to an infinite bus by an impedance of 0.01+0.1j per unit on a 2 MVA base. After 30 seconds, the value of the voltage of the infinite bus dropped by 0.025 p.u. In practice, such a voltage drop could be caused by switching on a large reactive load or by tripping of a nearby generator or transmission line. The resulting terminal voltage is depicted in figure 3.16.

From this figure, the following can be concluded:

- The frequency of the voltage variations is highest in the case of a constant speed wind turbine. This is caused by the constant rotational speed of the rotor, because the generator is directly grid coupled. Therefore, the rotating mass cannot act as an energy buffer, as is the case for both types of variable speed wind turbines. Changes in wind speed as well as the tower shadow are directly transferred into changes in active power. Because the reactive power consumed by the generator depends on the active power, this in turn influences both the generated reactive power and the terminal voltage.
- The terminal voltage variations are relatively high in case of a constant speed wind turbine and a variable speed wind turbine in unity power factor mode. This is caused by the relatively high impedance of the grid connection and cannot be attributed to be a general characteristic of the constant speed turbine or of variable speed wind turbines operated at unity power factor.
- The response of the variable speed wind turbine types is similar, which is because their behaviour is for the largest part determined by the controllers, which are identical.
- The terminal voltage is smoothest in the case of the variable speed wind turbines in voltage control mode. This can of course be expected, because it is obvious that a wind turbine with terminal voltage controller should perform better than one without terminal voltage controller.
- Although their voltage controllers work in a different way, the performance of both types of variable speed wind turbines is similar. If the controllers are well designed, both types of variable speed wind turbines perform with respect to terminal voltage control equally well.
- Finally, it is clear that only in the case of variable speed wind turbines in voltage control mode, the grid voltage drop is compensated and the wind turbine terminal voltage is kept close to its reference value. Only variable speed wind turbines in voltage control

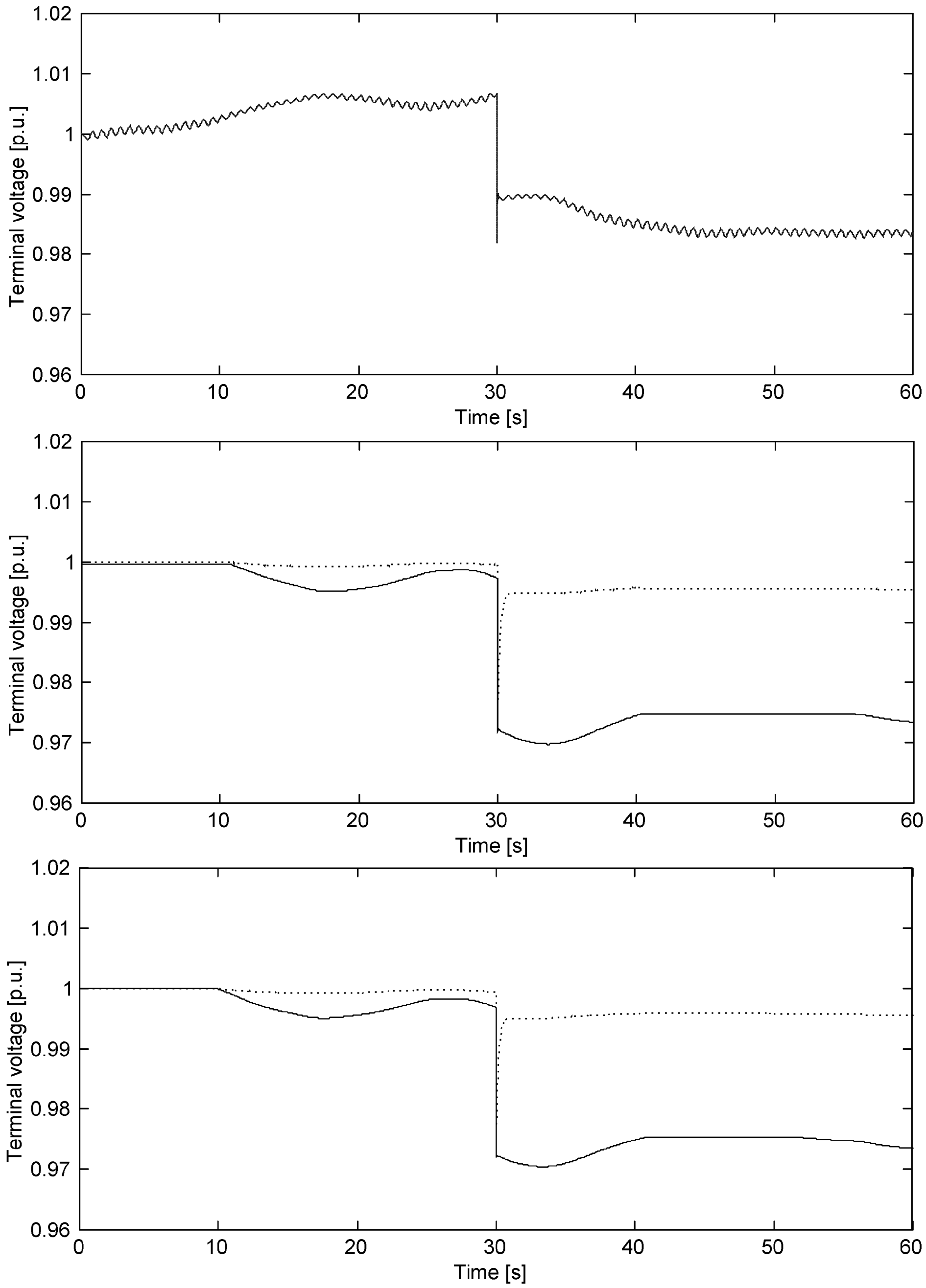


*Figure 3.16. Terminal voltage when the simulated wind turbines are connected to an infinite bus by an impedance of 0.01+0.1j p.u. on a 2 MVA base. Starting from above: constant speed wind turbine, variable speed wind turbine with doubly fed induction generator, variable speed wind turbine with direct drive generator. In the middle and lower figure, the solid lines correspond to wind turbines operating at unity power factor, the dotted lines to wind turbines operating in voltage control mode.*

mode are capable of terminal voltage control independent of the grid voltage, as long as their operating limits are not exceeded.

The first three findings also apply to the measurements depicted in figure 3.15.

## 3.7 CONCLUSIONS

The topic covered in this chapter was the development of models of the most important current wind turbine types for power system dynamics simulations. First, the power system dynamics simulation approach was introduced, the assumptions on which it is based were discussed and the software package used for the research was described. Then, an overview over the area of wind turbine modelling and simulation was given and the contribution of the models presented in this chapter was indicated: they are particularly developed for use in power system dynamics simulations and contain all subsystems that are of importance in these simulations and only those time constants that are within the band width of interest.

The main part of the chapter consists of a description of models of the constant speed wind turbine with a squirrel cage induction generator and the variable speed wind turbine with a doubly fed induction generator and the one with a direct drive synchronous generator. The structure of the model of each of these turbine types was depicted, after which equations for each of the subsystems were given. The implications of the assumptions on which the power system dynamics simulation approach is based, were explicitly taken into account in the simplification of these equations.

Finally, the models were used in simulations in order to compare the simulation results with measurements and to investigate the impact of the turbines on the grid voltage and the effect of the terminal voltage controller on both variable speed types. It was explained that it is not possible to use the measurements for a quantitative validation of the models and therefore only a qualitative comparison was carried out. This comparison showed that the models are reasonably accurate and can be used in power system dynamics simulations. The investigation of the impact of the wind turbines on the grid voltage showed that the grid voltage is effected mostly by constant speed wind turbines. With variable speed wind turbines, the impact is already less when they operate in unity power factor mode, as the rotor functions as an energy buffer. Equipping variable speed wind turbines with a terminal voltage controller that adapts the reactive power exchange with the grid based on the actual value of the voltage further reduces their impact on the grid voltage and can even help to compensate for voltage drops.

# Turbine Model Adaptation and Aggregation

## 4.1 INTRODUCTION

Chapter 3 introduced models of the most important contemporary wind turbine concepts that meet the assumptions and principles applied in power system dynamics simulations. This chapter continues with the development of models for representing wind turbines and wind parks in power system dynamics simulations. First, the developed wind turbine models are further tailored for use in power system dynamics simulations by incorporating a wind speed model. The advantage of a wind speed model in comparison to a measured wind speed sequence is that the characteristics of the wind speed sequence to be simulated can be freely specified by the user.

Next, a general variable speed wind turbine model is derived that can be used to represent both variable speed wind turbine concepts discussed in the preceding chapter. The idea behind this model is that the main difference between the two variable speed wind turbine concepts - where one has a doubly fed induction generator and the other a direct drive synchronous generator- is in the generator and the controller of the power electronic converter. The resulting differences in the behaviour of the turbines are outside the frequency bandwidth that is of interest in power system dynamics simulations. It is therefore allowed to represent both types of variable speed wind turbines in power system dynamics simulations with the same model. Both the use of the wind speed model and the use of the general variable speed wind turbine model are illustrated with simulations, carried out for normal operating conditions and for a grid disturbance.

Finally, aggregated wind park models, which represent a whole wind park instead of only a single wind turbine, are discussed. The aggregation approach to be used for both constant and variable speed wind turbines is commented upon and the consequences of the aggregation are investigated by comparing the simulation response of a detailed and an aggregated wind park model for various circumstances. It is concluded that both during normal operating conditions, in which only wind speed changes occur, as well as during faults, the simulation results of the detailed and the aggregated model are rather close.

The contribution of this chapter is twofold. First, a general variable speed wind turbine model is presented for the first time. Such a model facilitates the investigation of the impact of variable speed wind turbines on power system dynamics by reducing the number of simulations to be carried out: both types of variable speed wind turbines can be investigated with a single model. Further, no aggregated models of wind parks with variable speed wind turbines have been presented so far.

## 4.2 WIND TURBINE MODEL ADAPTATIONS

### 4.2.1 Incorporation of a Wind Speed Model

The wind turbine models in chapter 3 were simulated with a measured wind speed sequence. This approach is, however, not very suitable for simulations with large numbers of wind turbines connected to an electrical power system, because every wind speed range and turbulence intensity must be measured before it can be simulated, which makes it necessary to acquire and store a large amount of wind speed data and to develop ways to select a wind speed sequence with specific properties from the available ones.

The advantages of incorporating a wind speed model are:

- When a number of wind turbines is connected to a power system, it is not realistic to assume that exactly the same wind speed acts on all of them. Therefore, some difference should be present. When measured wind speed sequences are used, this could be done by using different sequences for the individual wind turbines, but it is easier to somehow randomize a simulated wind speed sequence generated by a wind speed model.
- The flexibility of a wind speed model; it is desirable to be able to simulate wind speed sequences with varying speed range and turbulence intensity. When measured wind speed sequences are used as the model's input, wind speed sequences with values within the desired wind speed range and with the desired turbulence intensity must have been measured beforehand and either have been stored on the computer or incorporated in the wind turbine model. This would render the wind turbine model relatively inflexible and inconvenient to use, which is an additional argument for using a wind speed model rather than a measured wind speed sequence.

***Wind Speed Model***

The wind speed model used in this thesis has a structure that is similar to that proposed in [31, 32]. It is assumed that the wind speed consists of the sum of four components, namely:

- the initial average value of the wind speed $v_{wa}$
- a ramp component $v_{wr}$
- a gust component $v_{wg}$
- turbulence $v_{wt}$

The wind speed model is of course independent of the characteristics of the wind turbine itself and can therefore be applied in combination with all three wind turbine models of chapter 3. The wind speed $v_w$ to be used in equations (3.2) and (3.13) is thus given by the following equation:

$$v_w(t) = v_{wa} + v_{wr}(t) + v_{wg}(t) + v_{wt}(t) \tag{4.1}$$

Apart from the initial average value of the wind speed $v_{wa}$, all components of (4.1) are time dependent.

The initial average value of the wind speed $v_{wa}$ can be calculated from the active power generated by the wind turbine in the load flow case and does not change during the simulation. For constant speed wind turbines, there exists a nearly unique relation between wind speed and active power, as can be seen in figure 3.4. The fact that a certain range of values for the generated power (between approximately 0.8 and 1.05 p.u.) occurs at two wind speeds can be easily solved by assuming that the wind speed is either below or above the value at which the maximum power generation occurs.

For variable speed wind turbines, a unique relation between wind speed and generated power only exists below the nominal wind speed. Above the nominal wind speed, the active power is always equal to the nominal value. Therefore, either the initial pitch angle or the initial average wind speed must be specified in order to initialize the wind turbine model if it generates nominal power in the load flow case.

Note that during the initialization of the dynamic model of the power system under investigation, the wind turbine models presented in the last chapter are calculated through from the 'output' (active and possibly reactive power generation) to the 'input' (wind speed). This is done for all generator models during the initialization, because at this stage only load flow data, i.e. generated active and reactive power and terminal voltage, are available and the value of internal model variables has to be deduced from these, taking into account the model's structure [30].

The ramp component is specified by its amplitude and its starting and stopping time. The actual value is calculated using the following equation

$$\begin{aligned} t<T_{sr}:&\ v_{wr}(t) = 0 \\ T_{sr}<t<T_{er}:&\ v_{wr}(t) = A_{wr}\frac{(t-T_{sr})}{(T_{er}-T_{sr})} \\ T_{er}<t:&\ v_{wr}(t) = A_{wr} \end{aligned} \tag{4.2}$$

in which T is a specific point of time and A is amplitude. The indices wr, sr and er indicate wind speed ramp, start of ramp and end of ramp, respectively.

The gust component is also specified by its amplitude and starting and stopping time. It is represented by the following equation

$$\begin{aligned} t<T_{sg}&: \; v_{wg}(t)=0 \\ T_{sg}<t<T_{eg}&: \; v_{wg}(t)=\frac{A_{wg}}{2}\left(1-\cos\left(2\pi\left(\frac{t-T_{sg}}{T_{eg}-T_{sg}}\right)\right)\right) \\ T_{eg}<t&: \; v_{wg}(t)=0 \end{aligned} \tag{4.3}$$

The indices wg, sg and eg indicate wind speed gust, start of gust and end of gust, respectively.

The last component of the wind speed model represents the wind speed turbulence. Turbulence is described by a power spectral density. In this thesis, the following spectral density is used [52]

$$S_{wt}(f)=\frac{\frac{1}{(\ln(h/z_0))^2}\cdot l\cdot v_{wa}}{\left(1+1.5\frac{f\cdot l}{v_{wa}}\right)^{\frac{5}{3}}} \tag{4.4}$$

where f is frequency [Hz], h is the height at which the wind speed signal is occurs, which is equal to the wind turbine hub height [m], $z_0$ is the roughness length and l is the turbulence length scale [m], which equals 20·h if h is below 30 m and 600 when h is above 30 m. The parameter $z_0$ is used to characterise the landscape type around the turbine, as it reflects the impact of the structure of the wind turbine surroundings on the turbulence intensity. Table 4.1 gives the roughness length for various landscape types [53, 54].

*Table 4.1 Roughness length $z_0$ for various landscape types [53, 54].*

| **Landscape type** | **Roughness length $z_0$ [m]** |
|---|---|
| Open sea, Sand | 1e-4-1e-3 |
| Snow surface | 1e-3-5e-3 |
| Mown grass, Steppe | 1e-3-1e-2 |
| Long grass, Rocky ground | 0.04-0.1 |
| Forests, Cities, Hilly areas | 1-5 |

The final step is to derive a time series of wind speed values with a power spectral density according to equation (4.4) to be applied in the simulation. A method to generate a time series from a given power spectral density is necessary to this end. Here, the method described in [55] is used, which is also applied in [31, 32]. This method is based on the summation of a great number of sine functions with different frequencies, of which the amplitude is determined by the given power spectral density, from which the time series is to be derived.
A power spectral density only contains information on the amplitude of the various frequency components of the signal, but no information on the phase angle. In the time domain,

however, both the amplitude and the phase angle of the sine components of a signal must be known. Therefore, to derive a time series from a given power spectral density, the phase angle of each of the frequency components must be established. In the applied method, this is done by randomizing the initial phase angle of each of the frequency components that are included in the time series in the interval from 0 to 2π. Thus, an infinite amount of random time series corresponds to a single power spectral density.

The following equation applies to the turbulence component of the wind speed sequence

$$v_{wt}(t) = \sum_{i=1}^{n} \sqrt{S_{wt}(f_i)\Delta f} \cos(2\pi f_i t + \phi_i + \Delta\phi) \tag{4.5}$$

where $f_i$ and $\phi_i$ are the frequency and the initial phase of the $i^{th}$ frequency component. According to [32], Δf should be chosen between 0.1 Hz and 0.3 Hz and n equal to 50. The term Δϕ in equation (4.5) is not present in [31] and [32]. It is a small random phase component that is added at each time step in order to avoid periodicity of the turbulence. Mathematically, this term turns the stationary process described by equation (4.5) into a quasi stationary process [56].

### 4.2.2 General Variable Speed Wind Turbine Model

When one compares the simulated response of both types of variable speed wind turbines to the same measured wind speed sequence, as depicted in figure 3.14, one observes a high degree of similarity. This is because the behaviour of a variable speed wind turbine in the frequency bandwidth studied in power system dynamics simulations is mainly governed by the rotor speed controller and by the pitch angle controller. When those are identical, as was the case in chapter 3, the behaviour of the turbines is very similar. The main origin of the remaining differences between the two variable speed concepts in the simulation results presented in chapter 3 is the difference in inertia constant, which was chosen 0.5 s higher for the direct drive wind turbine than for the wind turbine with doubly fed induction generator.

It seems therefore possible to represent both variable speed wind turbines with one general variable speed wind turbine model in power system dynamics simulations, which would greatly facilitate dynamics studies. In deriving such a model, the focus must be on the generators. When the differences between the models of the generators in both types of variable speed wind turbines that were presented in chapter 3 could be eliminated somehow, they can indeed be represented with the same model.

As discussed in chapter 3, the generator currents in both types of variable speed wind turbines are controlled by the power electronic converters and therefore the active and reactive power can be adjusted very quickly. It was argued that therefore the dψ/dt terms in the rotor equations of the doubly fed induction generator and in the stator equations of the direct drive synchronous generator can be neglected.

As a result of these simplifications, an algebraic relation results between the q-component of the rotor current in the doubly fed induction generator and the stator currents of the direct drive generator on the one hand and the electro mechanical torque on the other. This means that generator torque set points can be reached instantaneously by injecting the appropriate rotor or stator currents. In this situation, it is not necessary to include the equations describing the two generator types. Instead, the combination of the generator and the converter can be modelled as a torque source, which immediately generates an amount of torque equal to the set point generated by the rotor speed controller. The resulting active power, calculated from the torque and the actual rotor speed, is injected directly into the grid.

The only remaining differential equation for the generator and the converter after this simplification is the equation of motion (see equation (3.12)). It is identical for both variable speed wind turbine concepts. Therefore, they can be represented with a single model, which will be further referred to as the general variable speed wind turbine model.

The overall structure of the general variable speed wind turbine model is depicted in figure 4.1. The main differences when compared with figures 3.7 and 3.12, in which the structure of models of the two variable speed wind turbine concepts is shown, is that the generator, the converter and the protection system are combined into one block. This reflects the assumptions discussed earlier. The protection system has the features that were described earlier in section 3.4.4. If it is desirable to account for the generator and converter losses, this can be done by multiplying the mechanical power drawn from the rotor by the assumed efficiency of the generator and the converter, before injecting it into the grid. The terminal voltage controller is identical to that of the direct drive wind turbine from figure 3.13.

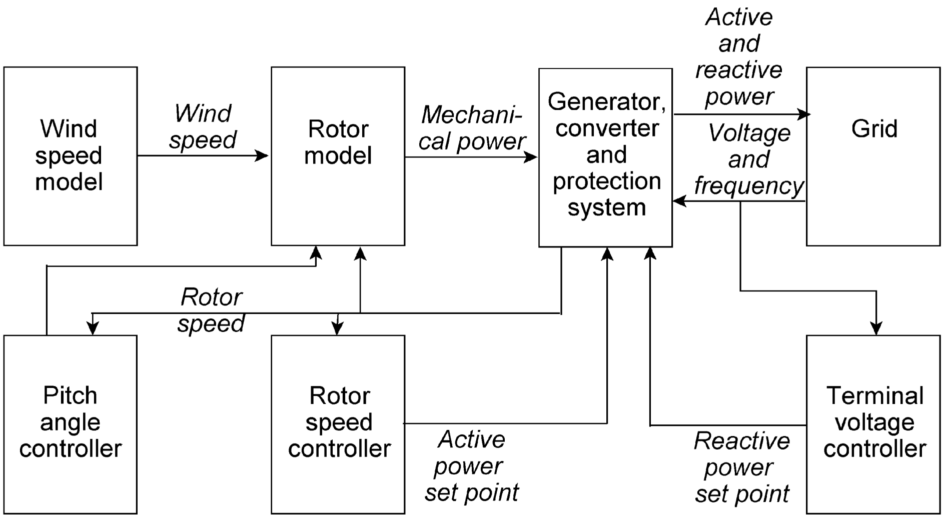


*Figure 4.1 Structure of the general variable speed wind turbine model.*

It should be emphasized once more that this approach and the resulting general variable speed wind turbine model are only valid for power system dynamics simulations. Although the behaviour of the two types of variable speed wind turbines types is similar in the bandwidth of 0.1-10 Hz, it is very different when the frequencies of interest are higher, because of the differences in the generators and in the current controllers of the power electronic converters. Models of both types of generators in which high frequency phenomena are included can be found in the literature (see chapter 3).

***Importance of Wind Turbine Nominal Power***

Many parameters that characterize a variable speed wind turbine are linked. Examples are:

- the combination of the $c_p(\lambda,\theta)$ curve, the nominal rotor speed and the rotor diameter determines the nominal wind speed of a wind turbine of given nominal power
- the allowable amount of rotor overspeeding determines the parameters of the pitch angle controller in figure 4.1
- the minimum rotor speed is related to the cut-in wind speed, because the lower the minimum rotor speed, the more efficient the energy extraction at low wind speeds and thus the lower the cut-in wind speed

Because of these interdependencies, it is essential to use a consistent set of parameters for the general wind turbine model presented above, because otherwise it is most likely that incorrect results will be obtained.

To facilitate the application of the general variable speed wind turbine model for easy modelling and simulation of wind turbines of various ratings, table 4.2 gives parameters for wind turbines of varying nominal power that can be used together with the numerical approximation of the $c_p(\lambda,\theta)$ given in (3.14) and (3.15). The entries in the table have been calculated taking into account that:

- the maximum value of the performance coefficient $c_p$ is not affected by changing the rating of the wind turbine, so that the required rotor diameter to generate a certain amount of power at a certain wind speed can be calculated using equation (2.1).
- the value of the tip speed ratio $\lambda$ at which the maximum value of $c_p$ occurs is not affected, so that the value of the tip speed should not change and the minimum and nominal rotor speed can be calculated when the rotor diameter is known.

The parameters not given in table 4.2, e.g. the constants of the pitch angle and voltage controllers and the rotor speed versus power characteristic in per unit, can be set independently from the wind turbine rating.

If it is considered necessary to change the parameters in equations (3.14) and (3.15) in order to represent a specific wind turbine type, the data below might not be adequate and the data of the specific wind turbine to be simulated should be used. However, care should be taken that a consistent set of parameters results.

*Table 4.2. Values of some model parameters for simulating wind turbines of various ratings.*

| Nominal Power [MW] | Rotor Diameter [m] | Minimum Rotor Speed [RPM] | Nominal Rotor Speed [RPM] |
|---|---|---|---|
| 0.75 | 46 | 15 | 30 |
| 1.0 | 53 | 12.5 | 25 |
| 1.25 | 60 | 11.5 | 23 |
| 1.5 | 65 | 10.5 | 21 |
| 1.75 | 70 | 9.5 | 19 |
| 2.0 | 75 | 9 | 18 |
| 2.5 | 84 | 8 | 16 |

### 4.2.3 Simulation Results

The simulations in this section illustrate the application of the wind speed model and the use of both the constant speed wind turbine model and the general variable speed wind turbine model in power system dynamics simulations. The response of the turbine models to grid disturbances, or faults, is analysed. The general variable speed model is based on the models that were derived and validated in chapter 3. The controllers which govern the behaviour of the turbine in the bandwidth of interest are identical. A validation of the general variable speed wind turbine model against measurements will therefore not yield any new insights.

In chapter 3, only simulations under normal operating conditions were carried out, which means that grid voltage and frequency were close to their nominal values. The reason for this is that the simulations carried out in chapter 3 mainly focus on comparing simulation results with measurements. Only measurements under normal operating conditions were available. Thus, given the goal of the simulations, the simulation of faults was of no use. For practical application, it should not only be possible to use wind turbine models for power system dynamics simulations to study normal operating conditions, but also to investigate the consequences of faults. In this section not only a wind speed change is simulated, but also a fault.

The simulations are carried out with PSS/E™. The constant speed wind turbine model and the general variable speed wind turbine model were incorporated in PSS/E™ as user models [30]. A 2 MW wind turbine is simulated with the parameters given in table 3.3. The settings of the protection system of the general variable speed wind turbine are give in table 4.3. The wind turbine is connected to an infinite bus by an impedance of 0.01+0.1j p.u. on a 2 MVA base.

*Table 4.3 Protection system settings of the general variable speed wind turbine model.*

| Protection System Parameter | Value |
|---|---|
| Current overload capability | 0.25 p.u. |
| Maximum overloading duration | 1 s |
| Allowable voltage deviation | +0.1 p.u./-0.2 p.u. |
| Response time for voltage deviation | 10 ms |
| Allowed frequency deviation | 0.01 p.u. |
| Response time for frequency deviation | 1 s |
| Reconnection time after restoration of voltage and/or frequency | 10 ms |
| Ramping time after reconnection | 0.5 s |

***Normal Operating Conditions***

The simulation run carried out to illustrate the application of the model to investigate wind turbines operating under normal conditions lasted 60 seconds. Three cases were studied, namely a constant speed wind turbine, and a variable speed wind turbine without and a variable speed wind turbine with voltage control. The applied wind speed signal consists of all four terms given in equation 4.1. The ramp start and stop time are 30 s and 50 s respectively, the gust start and stop time 10 s and 20 s. The ramp and gust amplitude both equal 4 m/s. The roughness length $z_0$ is equal to 0.01 m, corresponding to a wind turbine erected in a meadow, according to table 4.1.

The simulation results are depicted in figure 4.2. Starting from above, first the wind speed is depicted. Then, the rotor speed, the pitch angle of the variable speed wind turbine, the active and reactive power, and the terminal voltage are shown. Because the only difference between the wind speed signals applied to the wind turbine models is the random component representing the wind turbulence, some of the simulated signals are rather similar. For reasons of clarity, not all signals are therefore depicted in each of the graphs. Only one wind speed and pitch angle trace are shown. In the case of rotor speed and active power, only the constant speed wind turbine and one of the variable speed wind turbine traces are drawn. The reactive power and terminal voltage are depicted for each of the simulations separately, because they are different for each of the three cases, as can be seen from the figure.

In figure 4.2, the observations that have already been made in section 3.3 are confirmed once more. The short term output power fluctuations are most severe in case of the constant speed wind turbine. This is due to the effect of the tower shadow and because of the constant rotor speed, which has as a result that the rotating mass of the rotor can not act as an energy buffer, which is the case for both types of variable speed wind turbines.

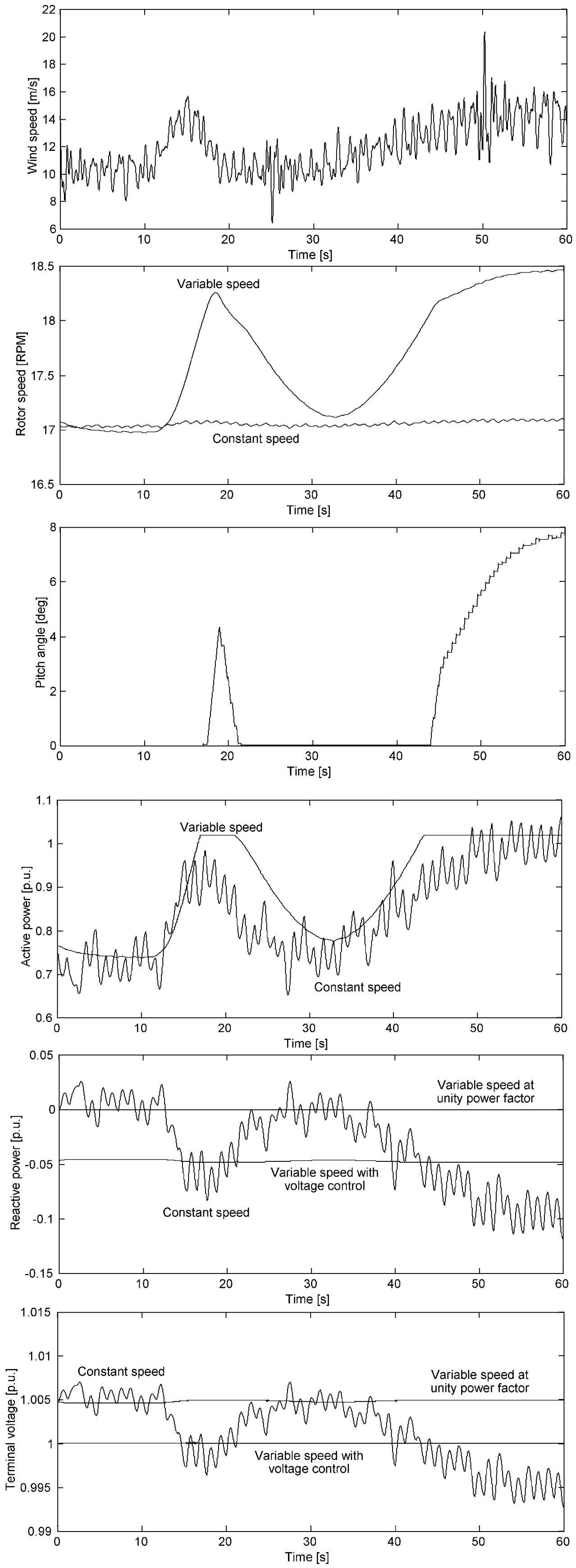


*Figure 4.2 Simulation results, starting from above: wind speed, rotor speed, pitch angle, active and reactive power and terminal voltage.*

Further, a variable speed wind turbine with voltage control can keep the terminal voltage better close to the nominal value than one without voltage controller. Although the differences between the two types of variable speed wind turbines in unity power factor operating mode and with voltage control are rather small in these simulations, nevertheless the following qualitative differences can be observed:

- In case of a variable speed wind turbine in unity power factor operating mode, the initial value of the terminal voltage deviates more from the nominal one than that of a turbine equipped with a voltage controller. In the case of a wind turbine without voltage controller, the terminal voltage is determined by the active power generation, the voltage at the point of grid connection and the impedance of the connection between the turbine and the grid. Normally it does not equal the nominal value, whereas in case of a wind turbine with voltage controller, the reactive power is manipulated in order to keep the terminal voltage equal to or at least near its nominal value.
- In case of a variable speed wind turbine in unity power factor mode, the reactive power output is constant and equal to zero and the terminal voltage shows small variations, whereas in case of a wind turbine with voltage controller, the reactive power is not equal to zero and varies, but the terminal voltage is constant.

The quantitative effect of equipping a variable speed wind turbine with a voltage controller depends on the grid impedance and the ratio of the resistance and the reactance (R/X-ratio) of the grid connection [57].

***Fault Response***

For this simulation run, the first ten seconds of the simulation carried out above were repeated. After 1 second, a fault with a duration of 150 ms was applied to the terminals of the wind turbine to illustrate the model's use for investigating disturbances. The simulation results are shown in figure 4.3. The meaning of the graphs is identical to the ones of figure 4.2.

From the simulation results, it can be seen that in case of a fault, the rotor speed increases due to the unbalance between mechanical and electrical generator power. The fact that the increase in rotor speed of a constant speed wind turbine is more than that of a variable speed wind turbine is caused by the relaxation of the shaft of the constant speed turbine during the fault. The energy stored in the shaft is released and then stored in the rotating mass.

It can also be seen that in case of the constant speed wind turbine, large excursions of active and reactive power and of the rotor speed take place at the instant of fault clearance and the restoration of the voltage, whereas in case of the variable speed wind turbine, the wind turbine returns to normal operation rather smoothly. This is caused by the decoupling effect of the power electronics converter. For the constant speed wind turbine, the rotor must be decelerated and pulled back to the normal operating point by the grid, which results in large fluctuations in both active and reactive power.

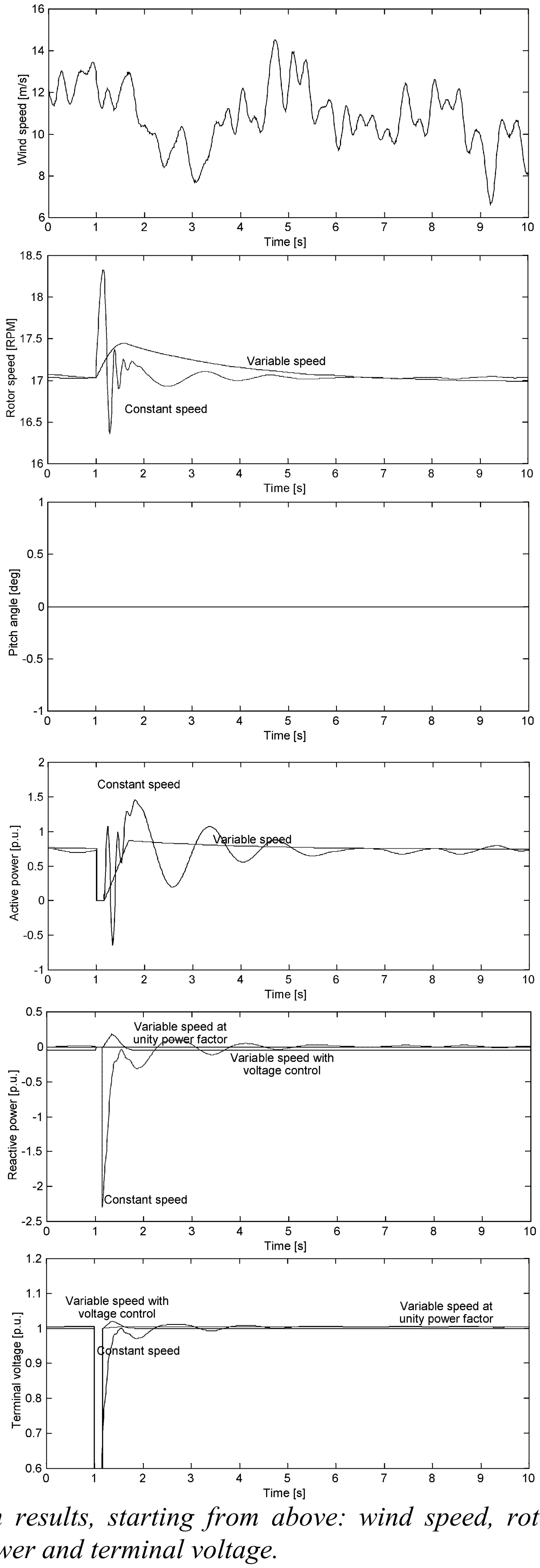


*Figure 4.3 Simulation results, starting from above: wind speed, rotor speed, pitch angle, active and reactive power and terminal voltage.*

In case of the variable speed wind turbine, the rotor speed is not coupled to the grid frequency and the rotor is therefore not directly affected by the restoration of the grid voltage. Instead, the power electronic converter picks up the rotor at the higher post fault speed and restarts to draw power from the generator according to the control characteristic depicted in figure 3.9. Due to the higher rotor speed after the fault, more power is generated than before the occurrence of the fault. However, the wind speed has not increased. Therefore, more electrical power is withdrawn from the generator than the mechanical power supplied by the wind and the rotor speed returns to its pre fault value. This topic will be discussed in more detail in the next chapter, which discusses the impact of wind turbines on power system dynamics and their characteristic response to various types of disturbances in the grid.

### 4.2.4 Conclusions

In this section, the wind turbine models derived in the last chapter were adapted in order to make them more convenient for use in power system dynamics simulations. The first adaptation was the incorporation of a wind speed model, which enhances the flexibility of the wind turbine models, because it enables the user to freely specify the properties of the wind speed sequence to be simulated, whereas when measured wind speed sequences are used, only those that have been measured in advance can be simulated and therefore large amounts of wind speed data have to be stored.

The second adaptation was the development of a general constant speed wind turbine model for use in power system dynamics simulations, to which the second part of this section was devoted. The main difference between the two types of variable speed wind turbines are found in the generator and the converter. The resulting differences are only observed for phenomena containing high characteristic frequencies, such as the control of the power electronics converter and the details of the response to grid disturbances. In the bandwidth of interest, the behaviour of the wind turbines is governed by other subsystems, such as the rotor speed controller and the terminal voltage controller. The conclusion is that both types of variable speed wind turbines can be represented with the same model in power system dynamics simulations and a general variable speed wind turbine model was derived starting from the validated turbine models introduced in chapter 3.

Finally, the incorporation of the wind speed model and the use of the general variable speed wind turbine model was illustrated with simulations for normal operating conditions and for a fault.

## 4.3 AGGREGATED WIND PARK MODELLING

### 4.3.1 Reasons and Requirements for Aggregated Models

Till now, the main focus was on the modelling of individual wind turbines. Models of individual wind turbines are useful to study the impact of single wind turbines or small groups of turbines and to investigate the behaviour of a wind park and its response to faults in the internal park grid. However, our goal here is to study the impact of high penetration levels of wind power on the dynamic behaviour of large power systems. This is complicated by the fact that even the largest wind turbines have a scale which is small compared to that of conventional thermal and hydro power stations with several tens to hundreds of MW generation capacity. Therefore, if the effects of a high wind power penetration have to be studied using models of single wind turbines, hundreds or even thousands of wind turbine models as well as their interconnections would have to be included in the model of the investigated power system, which is not realistic.
To solve this problem, aggregated wind park models have been proposed. Aggregated wind park models make it possible to represent a whole wind park by a single model. This reduces the size of the power system model, the data requirements and the computation time. In this section, aggregated models of wind parks with either constant speed or variable speed wind turbines will be presented.

***Model Requirements***
The requirements for an aggregated wind park model are that:

- They must adequately represent the behaviour of the wind park during normal operation, characterized by small deviations of the grid quantities from the nominal values and the occurrence of wind speed changes.
- They must adequately represent the behaviour of the wind park during disturbances, like voltage drops and frequency deviations.

The behaviour of the wind park meant here consists of the active and reactive power exchanged with the power system at the *point of common coupling* (PCC). The aggregated model is considered to represent a wind park adequately if there is a sufficient degree of correspondence between the active and reactive power exchange at the PCC.

### 4.3.2 Aggregated Wind Speed Modelling

As described in section 4.2.1, the wind speed in this thesis is considered to consist of four terms: the initial average value, a ramp component, a gust component and turbulence. In deriving the wind speed signal for the aggregated wind park model, the wind speed is divided into a deterministic and a stochastic part. The stochastic part consists of the turbulence term in equation (4.1). In the aggregated park model, this term is neglected, because in a wind park the effect of turbulence on the aggregated output power is reduced due to the smoothing effect of the large number of wind turbines, which is supported by measurements carried out at existing wind parks [58]. A further advantage of neglecting the turbulence is that it accelerates the computations, as calculating the turbulence for each wind turbine at each time step using the method described in section 4.2.1 comprises a substantial computational burden.

The deterministic part consists of the average value of the initial average wind speed and, if present, the gust and ramp component. The pattern is assumed to be the same for each wind turbine, but it may be shifted in time, depending on the layout of the park and the wind speed and angle of attack. The initial average value can be assumed to be the same throughout the park. The gust and ramp components travel through the park and the time instant at which they arrive at the individual turbines depends on the average wind speed, the angle of attack and the wind park layout. The start and stop times of the gust and the ramp at each individual wind turbine can thus be calculated from a single wind speed signal applied to the aggregated wind park model as a whole, taking the wind direction and the park layout into account. The wind speed signal is specified by entering the start and stop times of the gust and the ramp relative to the centre of the wind park as well as the wind direction. Note that this implies that wake effects are neglected.

The following steps are taken in order to calculate the wind speed at the individual turbines from the wind speed acting on the aggregated wind park model

***Step 1. Construct Line Parallel to Wind Speed Front through Park's Centre***

First, a coordinate system with its origin at the lower left corner of the wind park is assumed. Then, an equation describing a line parallel to the wind speed front within this coordinate system and running through the park's centre with the coordinates (w/2, h/2) is derived. The equation that describes this line is the following:

$$\begin{gathered} a_1 = \tan\ \alpha \\ b_1 = \frac{l}{2} - a_1\frac{w}{2} \\ y = a_1 x + b_1 \end{gathered} \tag{4.6}$$

in which α is the angle of attack of the wind speed front, w and l are the width and length of the wind park respectively and a and b are coefficients.

***Step 2. Calculate Distance of Turbines to Line Parallel to Wind Speed Front***

Second, the distance of the individual turbines to the line parallel to the wind speed front is calculated. Tho this end, for each turbine an equation for a line perpendicular to the line constructed in step 1 and crossing through the turbine's location is derived:

$$a_2 = -\frac{1}{\tan\alpha}$$
$$b_2 = y_i - a_2 x_i \tag{4.7}$$
$$y = a_2 x + b_2$$

in which $x_i$ and $y_i$ are the coordinates of the $i$th turbine in the coordinate system defined in step 1.

Then, the point of intersection ($x_{is}$,$y_{is}$) of both lines is calculated

$$y_{is} = a_1 x_{is} + b_1 = a_2 x_{is} + b_2$$
$$x_{is} = \frac{b_2 - b_1}{a_1 - a_2} \tag{4.8}$$
$$y_{is} = a_1 \frac{b_2 - b_1}{a_1 - a_2} + b_1 = a_2 \frac{b_2 - b_1}{a_1 - a_2} + b_2$$

Finally, the length between the point of intersection of the line through the park's centre and the line from step 1 on the one hand and the location of the $i$th wind turbine on the other is calculated.

$$D_i = \sqrt{(x_i - x_{is})^2 + (y_i - y_{is})^2} \tag{4.9}$$

***Step 3. Calculate Ramp and Gust Arrival Times***

The last step is to calculate the ramp and gust arrival times at the individual wind turbines. To this end, the distance between the $i$th turbine and the line from step 1 divided by the initial average wind speed $v_{wa}$, is added to or subtracted from the arrival times at the park's centre.

$$T_{sr,i} = T_{sr} \pm \frac{D_i}{v_{wa}}$$
$$T_{er,i} = T_{er} \pm \frac{D_i}{v_{wa}}$$
$$T_{sg,i} = T_{sg} \pm \frac{D_i}{v_{wa}} \tag{4.10}$$
$$T_{eg,i} = T_{eg} \pm \frac{D_i}{v_{wa}}$$

Whether the amount is added or subtracted depends on the angle of attack α of the wind speed and on the location of the turbines. If a negative start and end time result from (4.10), this means that the corresponding wind speed component has passed the turbine already. If only the start time is negative, the wind speed component is currently passing the turbine. The ramp and gust amplitude are of course not affected.

### 4.3.3 Wind Turbine Aggregation

***Aggregation of Constant Speed Wind Turbines***

The simplified and aggregated modelling of constant speed wind turbines has been a research topic for a number of years [59-61]. Reference [59] applies a singular perturbation approach to reduce the order of the wind park model but in fact only the order of the model of the individual turbine is reduced. No aggregation of wind turbines is applied. Reading the article learns that the authors only apply the simplifications that are common in power system dynamics simulations (see section 3.2) to the individual turbines in their wind park model. In references [60] and [61] the individual wind turbines are aggregated and represented by a lower number of wind turbines by combining the individual wind turbines into larger aggregated wind turbine models. To this end, the MVA ratings of the individual generators are added. In [60], the compensating capacitors are also added and it is assumed that the same wind speed acts on all wind turbines being aggregated into one equivalent. In [61], the aggregation of the wind speed or mechanical power and of the compensating capacitors is not treated explicitly.

The aggregation approach applied in this thesis is mathematically formulated as:

$$\begin{aligned} S_{eq} &= \sum_{i=1}^{n} S_i \\ C_{eq} &= \sum_{i=1}^{n} C_i \\ P_{m,eq} &= \sum_{i=1}^{n} P_{m,i} \end{aligned} \tag{4.11}$$

in which S is the MVA rating, C is the compensating capacitor and P is power. the indexes m and eq refer to mechanical and aggregated equivalent wind turbine respectively. The difference between (4.11) and the equations given in [60], is that in [60] the wind speeds are aggregated instead of the mechanical power, which makes it impossible to aggregate wind turbines experiencing different wind speeds. Compared to [61], the difference is that mechanical power and compensating capacitors are treated explicitly.

The resulting aggregated wind park model is shown schematically in figure 4.4. From the left to the right, first the wind speed model is depicted, which generates a wind speed sequence with properties determined by the user. Then, the wind speed at the individual turbines is calculated, using the overall wind speed and the wind park layout. The individual wind speeds are used to calculate the mechanical power at the individual turbines, using the rotor characteristics. The mechanical power of the individual turbines is added and fed into the equivalent generator that represents all generators and is connected to the power system.

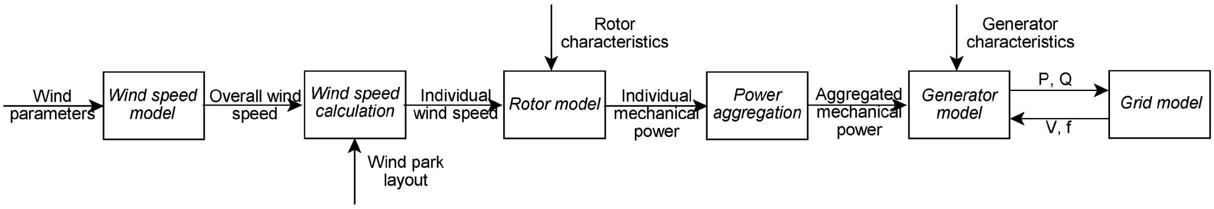


*Figure 4.4 Structure of an aggregated model of a wind park with constant speed wind turbines.*

In the literature, it is not mentioned explicitly how the internal park grid that connects the individual wind turbines to the PCC is represented in the aggregated model. In this thesis, the only components of the internal wind park infrastructure that are included in the aggregated model are the transformers at the wind turbine's generator terminals and, if applicable, the transformer at the PCC. Transformers have a relatively high impedance, whereas the cables within the park are rather short and therefore have a low impedance when compared to the transformer impedances. The cable impedances are therefore neglected.

***Aggregation of Variable Speed Wind Turbines***

Our literature search revealed that the aggregation of variable speed wind turbines has not been treated in the literature, so we had to start from scratch. It is not possible to apply the aggregation approach for constant speed wind turbines, given in equation (4.11), to variable speed wind turbines. The reason for this is that for constant speed wind turbines, the relation between the wind speed acting on the rotor and the generated power is mainly algebraic, because there is no energy buffer present. However, for variable speed wind turbines this is not true: the rotor acts as an energy buffer. Therefore, a relation between rotor speed and generated power exists, rather than between the wind speed and generated power. Thus, in an aggregated model, the rotor speed of the individual wind turbines must be tracked.

The aggregated model of a wind park with variable speed wind turbines is based on the general variable speed wind turbine model described earlier. However, two additional steps are taken in the aggregation:

- the general variable speed wind turbine model is simplified
- the power generated by each of the wind turbines in the wind park, represented by this simplified model, is added and fed into the grid

The structure of the aggregated model is shown in figure 4.5. From the left to the right, first the wind speed model is depicted, which generates a wind speed sequence with properties determined by the user. Then, the wind speed for the individual turbines is computed, using the overall wind speed and the wind park layout. The resulting individual wind speeds are used to calculate the electrical power of the individual wind turbines using the simplified wind turbine model in figure 4.7, which are added and fed into the system. Thus, different from what is done for constant speed turbines, the electrical power of the individual turbines is added, and not the mechanical power. The following equations apply

$$S_{eq} = \sum_{i=1}^{n} S_i$$
$$P_{eq} = \sum_{i=1}^{n} P_i \tag{4.12}$$

If the wind park is equipped with a voltage controller, one voltage controller is incorporated in the model as well.

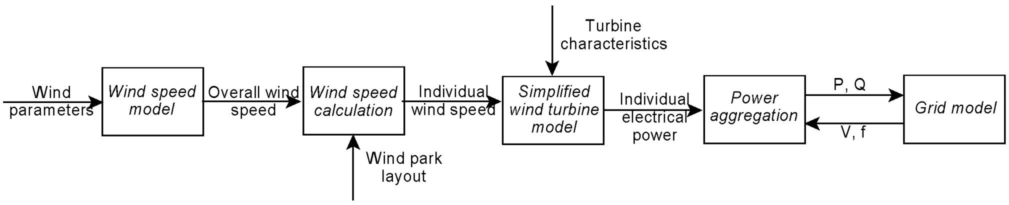


*Figure 4.5. Structure of an aggregated model of a wind park with variable speed wind turbines.*

***General Variable Speed Wind Turbine Model Simplification***

Section 4.2.2 implies that if the variable speed wind turbines in the wind park must be represented in detail, this would require a quite complex model. However, it is possible to simplify the variable speed wind turbine model used in the aggregated wind park model when:

- It is assumed that the performance coefficient $c_p(\lambda,\theta)$ is always equal to its maximum value, because then the complicated $c_p(\lambda,\theta)$ characteristic can be omitted from the model and be replaced by a constant equal to the maximum value of $c_p$. Only a minor error results from this simplification, because the rotor speed versus power control characteristic is such that $c_p$ is kept at its maximum as much as possible. In other words, a perfect rotor speed controller is assumed.
- The implemented rotor speed versus control characteristic is replaced by a first order approximation (see figure 4.6).
- The upper value of the integrator where the rotor speed is stored is limited to the maximum allowable rotor speed, e.g. to a value of 1.1 p.u., because then the pitch angle controller can be omitted from the model, as it is no longer needed for limiting the rotor speed.

The simplified variable speed wind turbine model that results is applied to represent each of the turbines in the aggregated park model and is depicted in figure 4.7.

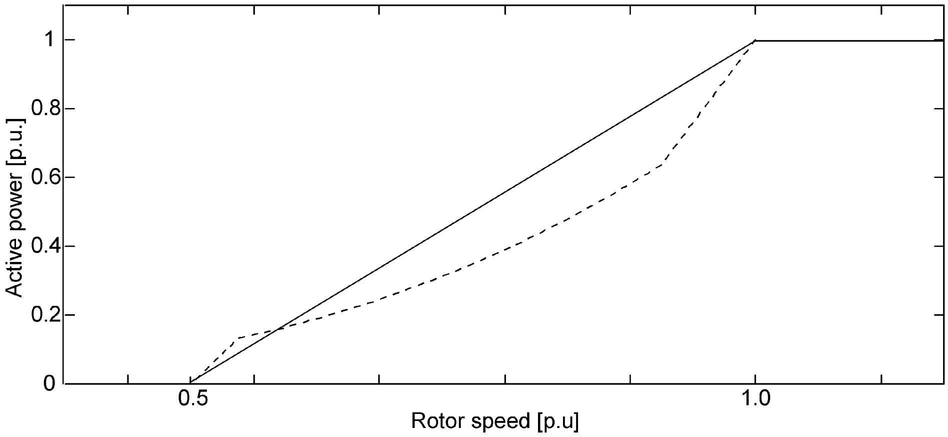


*Figure 4.6 Implemented rotor speed versus power control characteristic (dashed) and its first order approximation (solid).*

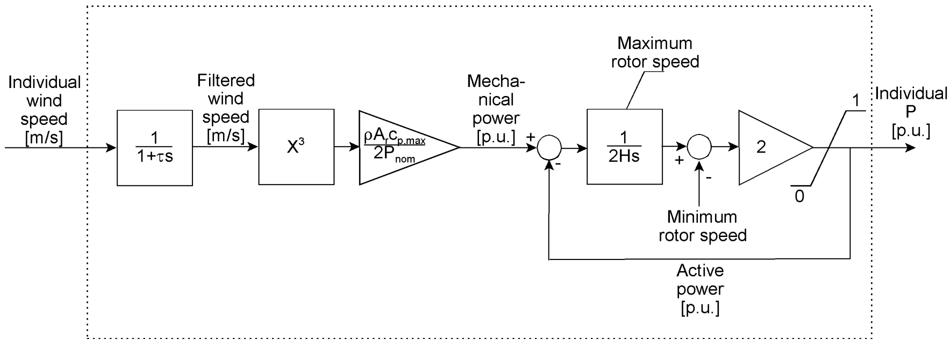


*Figure 4.7 Simplified variable speed wind turbine model used in the aggregated model of a wind park with variable speed wind turbines, as indicated in figure 4.5.*

From left to right, figure 4.7 starts with a wind speed signal, which is the *individual wind speed*, the output of the block *wind speed calculation* in figure 4.5. The structure of the simplified model resembles that of the general variable speed wind turbine model shown in figure 4.1. The third power of the wind speed is calculated and by using equation (3.2), the mechanical power is calculated while assuming that the performance coefficient $c_p$ equals the maximum value. The mechanical power and electrical power are used to calculate the rotor speed, which is the only remaining state variable in the simplified model. The upper limit represents the effect of the pitch angle controller, and the rotor speed versus power controller is represented by a gain, because a linear approximation of the control characteristic is used (see figure 4.6). From the rotor speed, the electrical power is derived, which is then added for all wind turbines in the park and fed into the grid.

### 4.3.4 Aggregated Wind Park Model Simulation Results

In this section, the simulation results obtained with the aggregated wind park model are compared with the results from a detailed wind park model in which each wind turbine is represented separately. Because the aggregated wind park model should adequately represent a detailed wind park model during normal operation as well as during disturbances, both situations will be analysed.

***Simulated Cases***

In order to obtain a broad picture of the validity of the proposed aggregated wind park model, a variety of situations has been investigated:

- Two wind park layouts are studied, namely a star connect layout and a string connected layout. These are depicted in figure 4.8.
- For each wind park layout and turbine concept, the same wind speed signal is simulated for two different wind directions.
- For each wind park layout and turbine concept, the fault response is studied.

This gives a total of twelve simulation runs. Of these, only four will be analysed in this chapter: one for normal operation of each of the turbine concepts and wind park layouts, as well as the fault response of a string connected park with constant speed wind turbines and of a park with variable speed wind turbines. For a more elaborate validation, the reader is referred to publications that resulted from the research project.

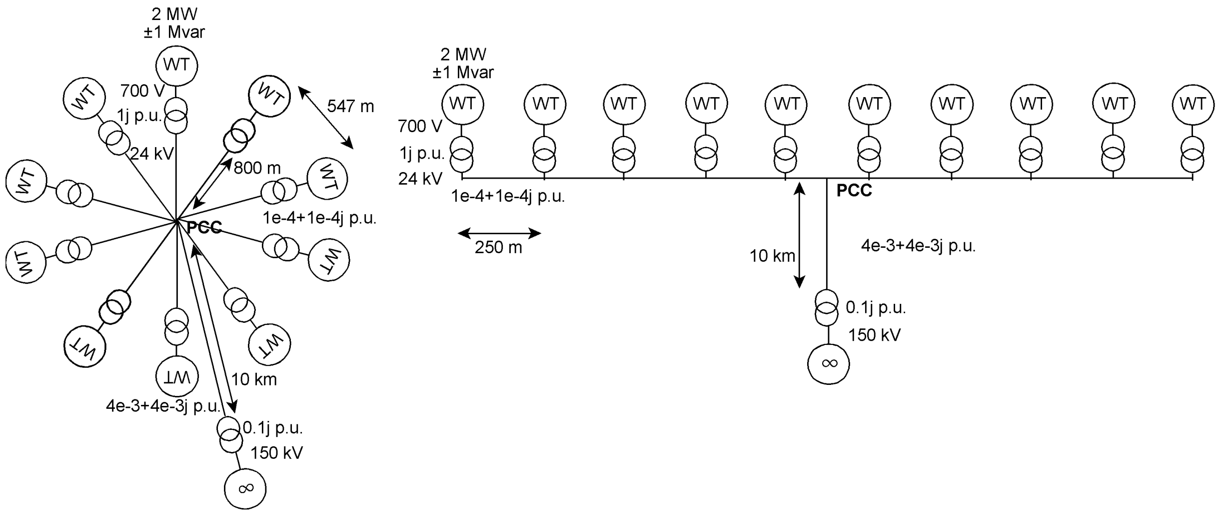


*Figure 4.8. Investigated wind park layouts. The values of the impedances are on a 20 MVA basis.*

The detailed and aggregated wind park models will be compared on the basis of the voltage at the point of common coupling (PCC) and the active and reactive power flowing from the PCC to the power system, because the PCC is the point that is closest to the wind park and is present in both the detailed and the aggregated park model. The point of common coupling of the wind park layouts is indicated in figure 4.8. No internal wind park signals could be compared, as these are not present in the aggregated model.

The aggregated wind park model of the two wind park layouts both for a park with constant and variable speed wind turbines is depicted in figure 4.9. In this picture, the aggregated wind turbine model, indicated with *WT*, contains the structure shown in figure 4.4 or that shown in figure 4.5, depending on whether constant or variable speed turbines are represented.

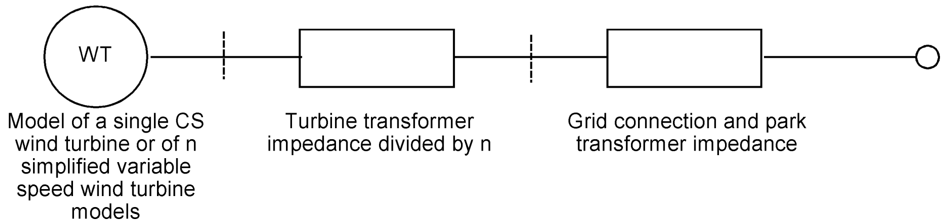


*Figure 4.9 Aggregated wind park model for constant and variable speed wind turbines.*

***Simulation Results***

Figures 4.10 to 4.13 show the simulation results. As mentioned earlier, in power system dynamics simulations, the main point of interest is the interaction of the wind park with the power system. Therefore, the aggregated and the detailed model are compared on the basis of the PCC voltage and the active and reactive power exchange between the wind park and the system. In each of the figures, starting from above the active and reactive power and the terminal voltage are given. The solid lines correspond to the detailed model and the dotted lines to the aggregated model. Figures 4.10 and 4.11 show a park with constant speed turbines and figures 4.12 and 4.13 a park with variable speed turbines.

### 4.3.5 Analysis of Simulation Results

In this section, we analyse the simulation results presented in section 4.3.4. As can be seen from figures 4.10 to 4.13 there is in general a very close match between the responses of the aggregated and detailed wind park model, although small differences remain. As will be argued, all observed differences can be attributed to the simplifications made in the development of the aggregated model, as described in sections 4.3.2 and 4.3.3.

***Normal Operating Conditions***

A first difference that can be seen between the detailed and the aggregated model of the wind park with constant speed turbines is the absence of turbulence induced output power fluctuations in the aggregated model. This is due to the assumption that turbulence can be neglected in the aggregated model, because it is a completely stochastic phenomenon that is smoothed over the wind turbines in the park. Therefore, the larger the number of turbines, the less the turbulence should be reflected in the output power. From the simulation results depicted in figures 4.2 and 4.10, it can be seen that this is indeed true. The peak-peak value of the turbulence induced output power fluctuations of one constant speed wind turbine is about 0.15 MW (0.075 p.u. on a 2 MVA base), as can be seen in figure 4.2. In the detailed wind park model, the peak-peak value is about 0.5 MW (0.025 p.u. on a 20 MVA base), see figure 4.10. Thus, the turbulence induced output power fluctuations reduce with the square root of the number of turbines, in this case ten.

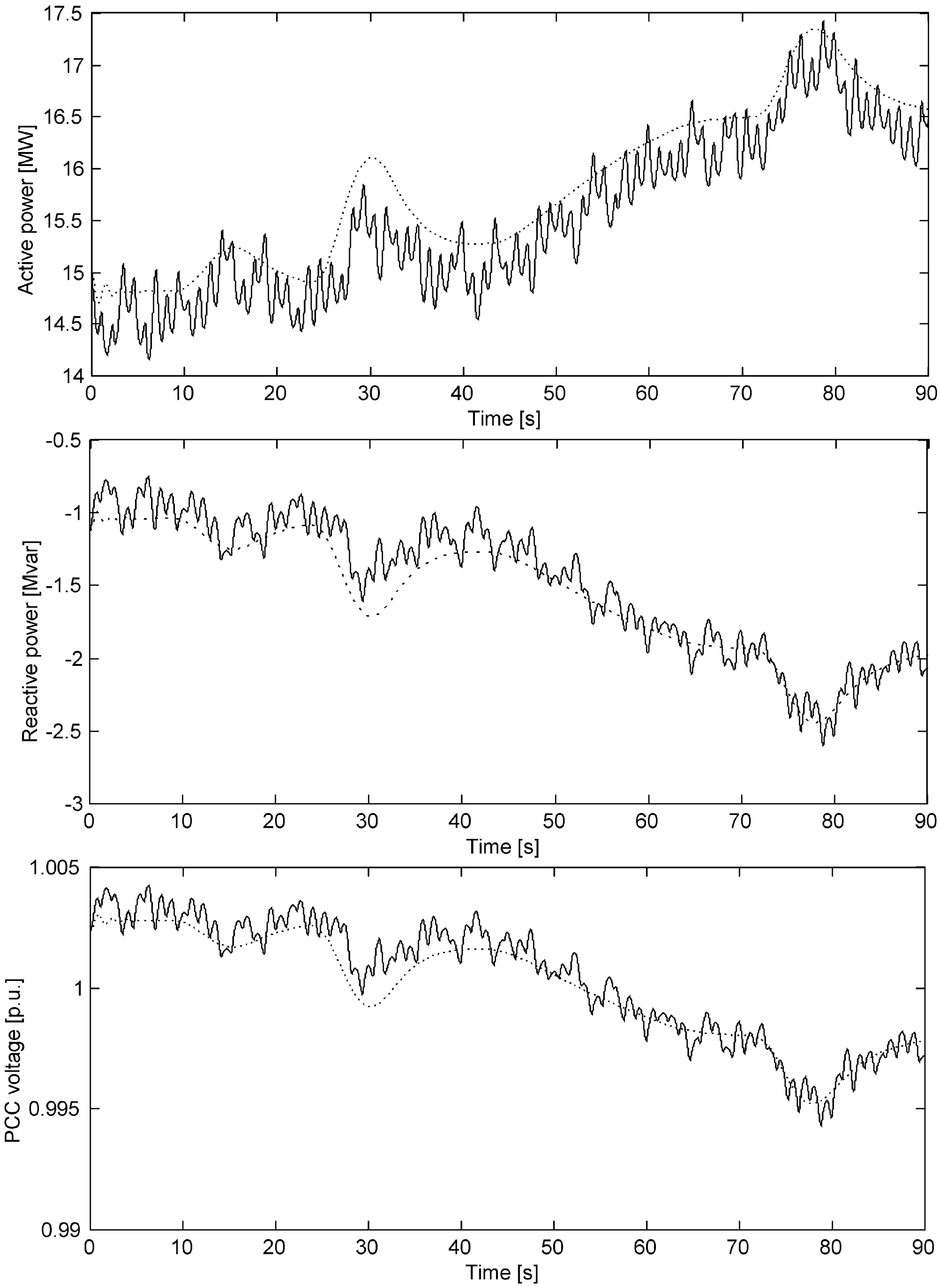


*Figure 4.10 Simulation of the normal operation of a wind park with constant speed wind turbines. Starting from above the active and reactive power flowing from the point of common coupling and the PCC voltage are depicted. The solid lines correspond to the detailed model and the dashed lines to the aggregated model.*

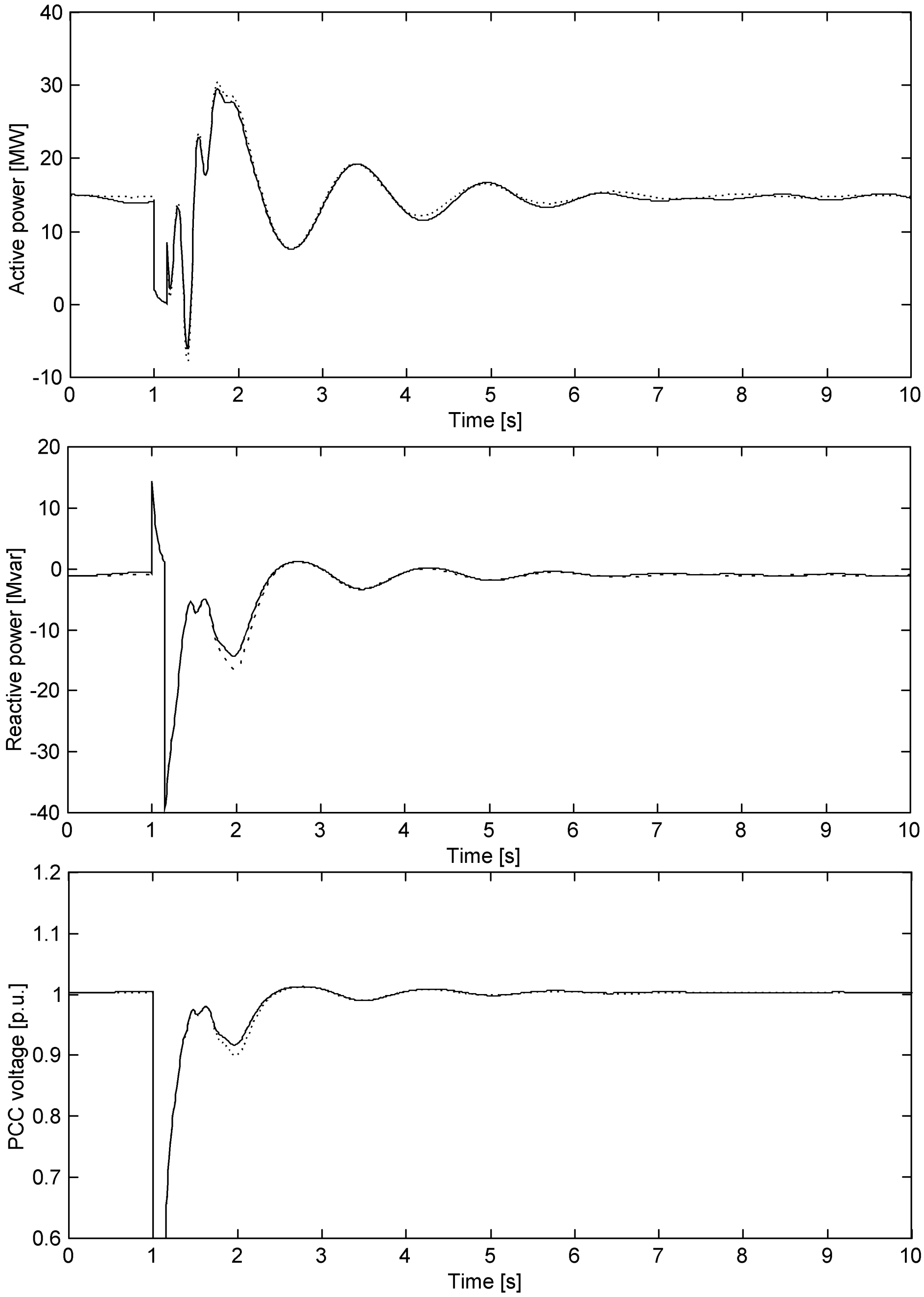


*Figure 4.11 Simulation of the fault response of a wind park with constant speed wind turbines. Starting from above the active and reactive power flowing from the point of common coupling and the PCC voltage are depicted. The solid lines correspond to the detailed model and the dashed lines to the aggregated model.*

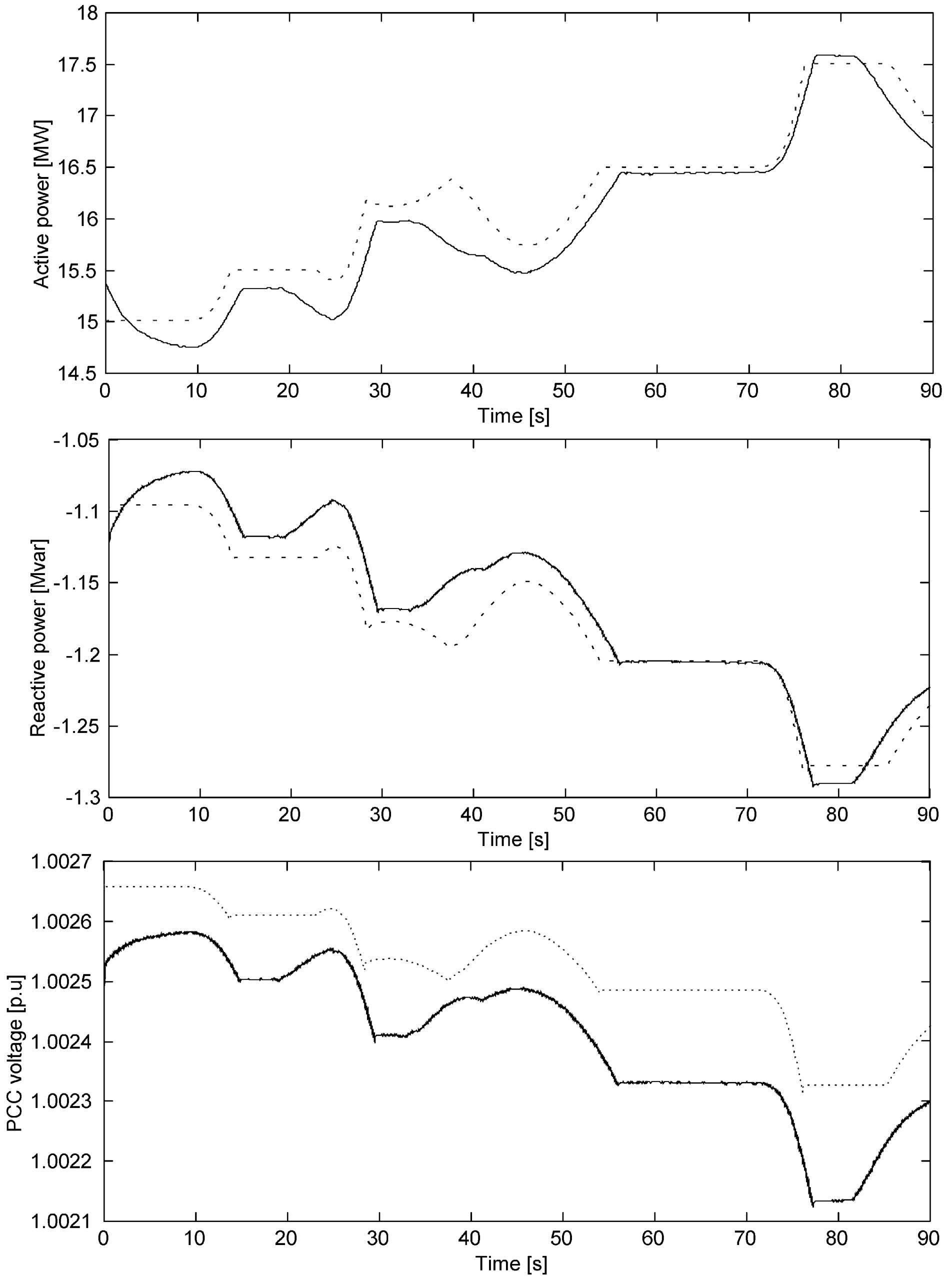


*Figure 4.12 Simulation of the normal operation of a wind park with variable speed wind turbines. Starting from above, the active and reactive power flowing from the point of common coupling and the PCC voltage are depicted. The solid lines correspond to the detailed model and the dashed lines to the aggregated model.*

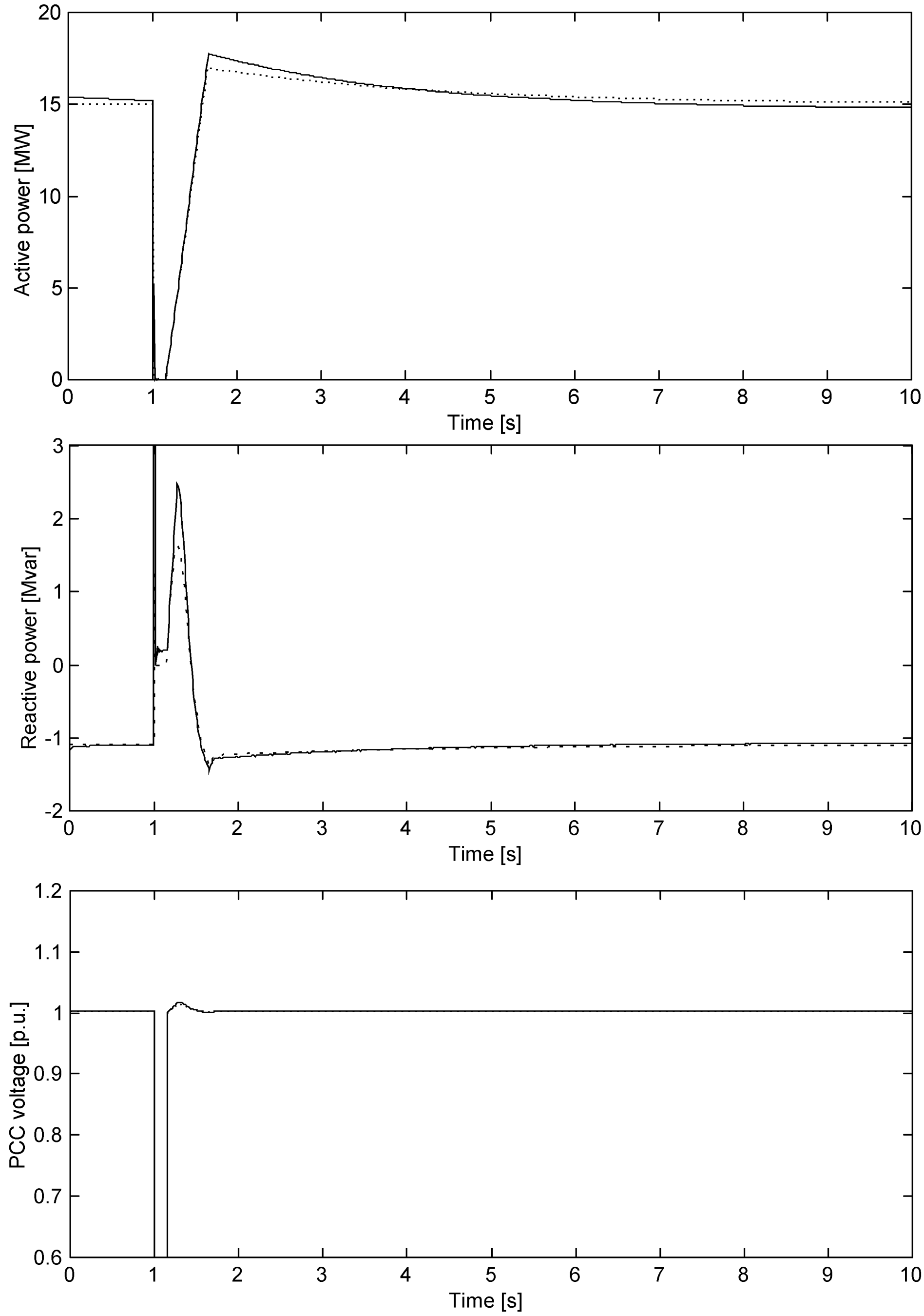


*Figure 4.13 Simulation of the fault response of a wind park with variable speed wind turbines. Starting from above, the active and reactive power flowing from the point of common coupling and the PCC voltage are depicted. The solid lines correspond to the detailed model and the dashed lines to the aggregated model.*

The turbulence induced output power fluctuations have not fully disappeared in a wind park with ten constant speed wind turbines. Thus, the neglect of the turbulence in the aggregated model of the park with constant speed turbines is not completely justified. However, it must be taken into account that in many cases much larger wind parks, consisting of several tens to hundreds of turbines will be modelled. This will lead to a further damping of the short term output power fluctuations. It was therefore not considered useful to spend additional efforts on including turbulence in an aggregated model of a wind park with constant speed wind turbines.
In the case of the variable speed wind turbines, hardly any turbulence can be seen neither in the detailed wind park model nor in the aggregated wind park model. This can be explained by the combined effect of the averaging of the turbulence over the turbines in the park and of the rotor that acts as an energy buffer, which already nearly completely damps the turbulence for one wind turbine, as can be concluded from figure 4.2. Therefore, in a wind park with several variable speed turbines, turbulence completely disappears in the output power.

A second difference which can be observed both in the park with constant speed wind turbines and the park with variable speed wind turbines is that the active power output of the detailed model tends to be slightly lower than that of the aggregated model. This is because the losses in the park's internal grid are neglected in the aggregated model, because the internal grid is not taken into account. If the difference is considered significant, the internal park losses could be taken into account by multiplying the output of the aggregated model by a loss factor lower than 1.

A third difference, which only applies to the park with the variable speed wind turbines, is that the response of the active power output to wind speed changes is not identical for the detailed and the aggregated model. The shape of the curves slightly differs, as can be particularly seen in figure 4.12 around 35 seconds and 85 seconds This difference originates from the simplifications implemented in the wind turbine model used in the aggregated wind park model (figure 4.7). The relation between rotor speed and active power is assumed to be linear, the performance coefficient $c_p$ is always kept equal to its maximum value and the pitch controller can be neglected if the state variable representing the rotor speed is limited. Therefore, the response of the wind turbine's active power output to wind speed changes differs between the detailed and the aggregated model.

The last difference, which also mainly applies to the park with the variable speed wind turbines, is that the reactive power of the detailed and the aggregated model are not similar. This can either be caused by the difference in active power, which leads to a different voltage profile and subsequently to different voltage controller actions, or by the neglect of the internal park network. The fact that the observed difference is much larger than in case of the constant speed turbines leads to the conclusion that the neglect of the internal park network has a limited impact and that the observed differences must for the largest part be attributed to the differences in the active power output. This conclusion is supported by the observation that the reactance of the cables between the wind turbines is much lower than that of the transformers, for which reason the neglect of the reactance of the cables in the aggregated model is of minor importance, as mentioned before.

***Fault Response***

The fault responses of the detailed and the aggregated wind park model are very similar as can be seen from figures 4.11 and 4.13. The high level of correspondence that is partly caused by the fact that the investigated quantities vary much more than during normal operation. The slight differences that occur during normal operation, which can be seen in figures 4.10 and 4.12, cannot be observed in figures 4.11 and 4.13 due to the different scaling. However, during disturbances, the small differences in figures 4.11 and 4.13 are unimportant. Therefore, figures 4.11 and 4.13 should be used to assess the usability of the aggregated model during disturbances, rather than figures 4.10 and 4.12, and the conclusion that the level of correspondence is also high during disturbances, is justified.

### 4.3.6 Conclusions

In this section, aggregated models of wind parks were presented. The use of aggregated models reduces the modelling effort for the user and the amount of data to be entered, because it does not require a detailed model of the wind park infrastructure and of the individual turbines. It also eliminates the necessity to specify the wind speed for each individual wind turbine in the park.

It is concluded that the aggregation approach that must be used differs for constant and variable speed wind turbines. In the first case, there is an approximately algebraic relation between mechanical power and electrical power, whereas in the second case, the generated electrical power is determined by the rotor speed, rather than by the actual value of the wind speed.

The response of the aggregated model was compared with that of a detailed model, and it was concluded that notwithstanding the applied simplifications, the agreement between the responses of the aggregated and detailed wind park models is rather close, both constant speed and variable speed wind turbines and both for a wind speed change and a fault.

The final decision whether to use an aggregated or a detailed model should be taken carefully and be based on the task at hand. For dynamics simulations, the accuracy achieved with an aggregated model will in most cases be sufficient. If one wants to study the behaviour of the individual turbines in the wind park, a detailed model of the wind park with its individual turbines is of course required.

# Impact of Wind Turbines and Wind Parks on Transient Stability

## 5.1 INTRODUCTION

Chapters 3 and 4 describe the development of models of the different types of constant and variable speed wind turbines, a general variable speed wind turbine model, as well as aggregated models of wind parks with constant and variable speed wind turbines. In this chapter, these models will be applied to investigate the impact of wind power on power system transient stability. First, the concept of transient stability is defined and explained. Next, the way the various types of wind turbines and wind parks respond to several kinds of disturbances that occur in power systems is analysed.
In this analysis, the working principles and inherent characteristics of the different types of wind turbines and wind parks are taken into account. It is concluded that there exist fundamental differences between the response of constant wind speed wind turbines and that of variable speed wind turbines. These differences are mainly caused by the power electronics converter, which decouples the mechanical and electrical quantities of the generator in case of variable speed wind turbines. Further, the considerations playing a role in the design and tuning of the wind turbine's protection system are discussed. As will be pointed out, an important aspect is to find a balance between the risk of what is called *islanding* on the one hand, and a severe disruption of the power balance due to a fault on the other.

In the second part of the chapter, simulation results are presented. We explore what effect the characteristics of a constant speed wind turbine and the protection system parameters of variable speed wind turbines have on the fault response. The effects of wind power on the transient stability of a power system are illustrated using simulation results obtained with a dynamic model of a widely used power system dynamics test system and with a model of a real power system, to which the wind turbine and wind park models developed in chapters 3 and 4 are connected. The simulation results support and illustrate the conclusions from the qualitative analysis in the first part of this chapter. With constant speed wind turbines, the characteristics of the wind turbine are of great importance. With variable speed wind turbines, the protection system parameters are the factor that determines the fault response.

In this chapter, the response of the various types of wind turbines to different types of disturbances and their impact on power system transient stability is discussed in a structured way for the first time. An analysis like this one has not been presented in the literature yet.

## 5.2 TRANSIENT STABILITY

Transient stability is defined as

*The capability of a power system to return to a stable operating point after the occurrence of a disturbance that changes its topology.*

Examples of changes of the topology of a power system are:

- the tripping of a generator or a line
- the sudden change of a load, including a load trip, which is equivalent to the change of a load to zero
- the occurrence of a fault, i.e. a short circuit, which is equivalent to switching on an impedance of very low value

If one of the above disturbances occurs, the system is no longer in steady state. Various quantities in the system, such as rotor speeds and node voltages, start to change and to deviate from their steady state values. If the fluctuations of the system's quantities damp out and the system settles at a stable operating point, it is considered stable, whereas when the deviation of the various quantities becomes ever larger, the system is unstable and will eventually collapse, leading to a blackout.

In the majority of cases, however, this will be prevented by the action of protection devices. The goal of protection devices is to prevent damage to components in the power system, e.g. due to fault currents, overvoltages or overspeed. Protection devices operate if certain quantities exceed a threshold value, which has been established in advance and is stored in the device. The operation of protection devices changes the topology of the power system, e.g. by disconnecting a generator, a load or a line or cable. In many cases, the resulting change in the system's topology will also restore the stability of the power system, because the faulted component, which threatens the stability, is removed from the system.

The stable operating point that is reached after a disturbance leading to a transient phenomenon, i.e. a change in the system's topology, can be different from the initial steady state. This applies particularly if either the disturbance itself, or the actions of protection devices occurring during the transient phenomenon, cause a sustained change in the topology of the power system. Examples of such disturbances are a generator or line trip and a load change. A fault that is cleared without tripping any components, however, does not lead to a

sustained change in the topology of the power system. In this case, the steady state after the event is normally identical to that before its occurrence.
The above definition of transient stability specifies that the system's *electrical topology* must change. This point is the main distinction between transient stability and small signal stability. The latter refers to the response to disturbances that do not change the system's topology, but only the values of the *state variables*, like generator load angle, rotor speed and exciter voltage and the state variables of generator controllers. The impact of wind power on the small signal stability of power systems is the topic of the next chapter. For a more elaborate discussion of the concepts of transient and small signal stability and their differences, excellent literature is available [24, 62].

## 5.3 RESPONSE OF WIND TURBINES TO DISTURBANCES

As discussed earlier, there are various types of wind turbines. The differences in working principle and in the inherent characteristics between the wind turbine types are reflected in differences in the response to a disturbance of the terminal quantities of the turbine. In this section, the transient behaviour of the different types of wind turbines is related to their working principles. A thorough understanding of the transient behaviour of wind turbines is essential for evaluating the transient stability of solitary turbines and wind parks and for investigating the causes of any instability that may be observed.

### 5.3.1 Constant Speed Wind Turbine

As pointed out earlier, in a constant speed wind turbine, a directly grid coupled squirrel cage induction generator is used for the conversion of mechanical power into electrical power. The behaviour of a constant speed wind turbine is determined by the intrinsic relations between active power, reactive power, terminal voltage and rotor speed of a squirrel cage induction generator. These can be studied using the network equivalent, depicted in figure 5.1 [24]. In this figure, U is the voltage, I is the current, s the slip, R resistance and L reactance. The indices σ, s, m and r stand for leakage, stator, mutual and rotor, respectively. The values of the generator parameters are given in table 5.1 in per unit values.

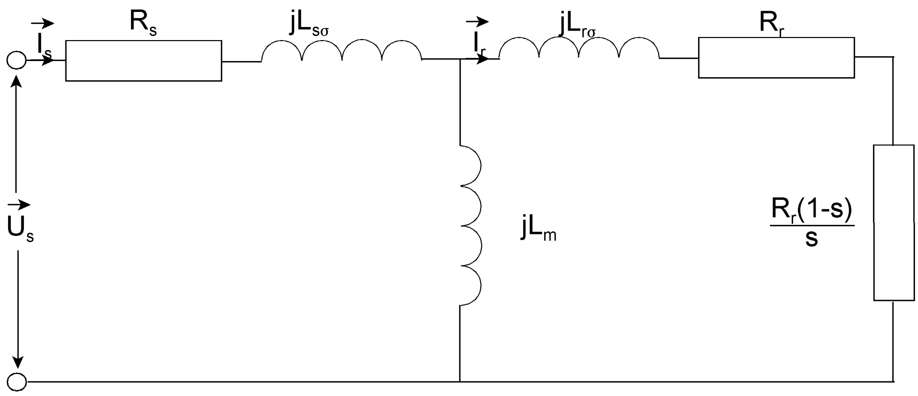


*Figure 5.1 Network equivalent of the squirrel cage induction generator.*

*Table 5.1 Value of the parameters of the squirrel cage induction generator.*

| **Quantity** | **Value** |
|---|---|
| Mutual reactance $L_m$ | 3.0 p.u. |
| Stator leakage reactance $L_{s\sigma}$ | 0.10 p.u. |
| Rotor leakage reactance $L_{r\sigma}$ | 0.08 p.u. |
| Stator resistance $R_s$ | 0.01 p.u. |
| Rotor resistance $R_r$ | 0.01 p.u. |

In figure 5.2, the relation between active power output and rotor slip and the relation between reactive power consumption and rotor slip are drawn, with the terminal voltage as a parameter. From this figure, it can be seen that only one value of reactive power corresponds to a certain amount of generated active power and a particular value of the terminal voltage. This supports the earlier conclusion that a constant speed wind turbine does not allow voltage control: the reactive power consumption is determined by active power generation, terminal voltage and the generator parameters. Reactive power generation is even completely impossible. Controlling bus voltages when using constant speed wind turbines therefore requires additional technology for controllable reactive power generation, such as switched capacitors, STATCOMs (STATic COMpensators) or SVCs (static var compensators).

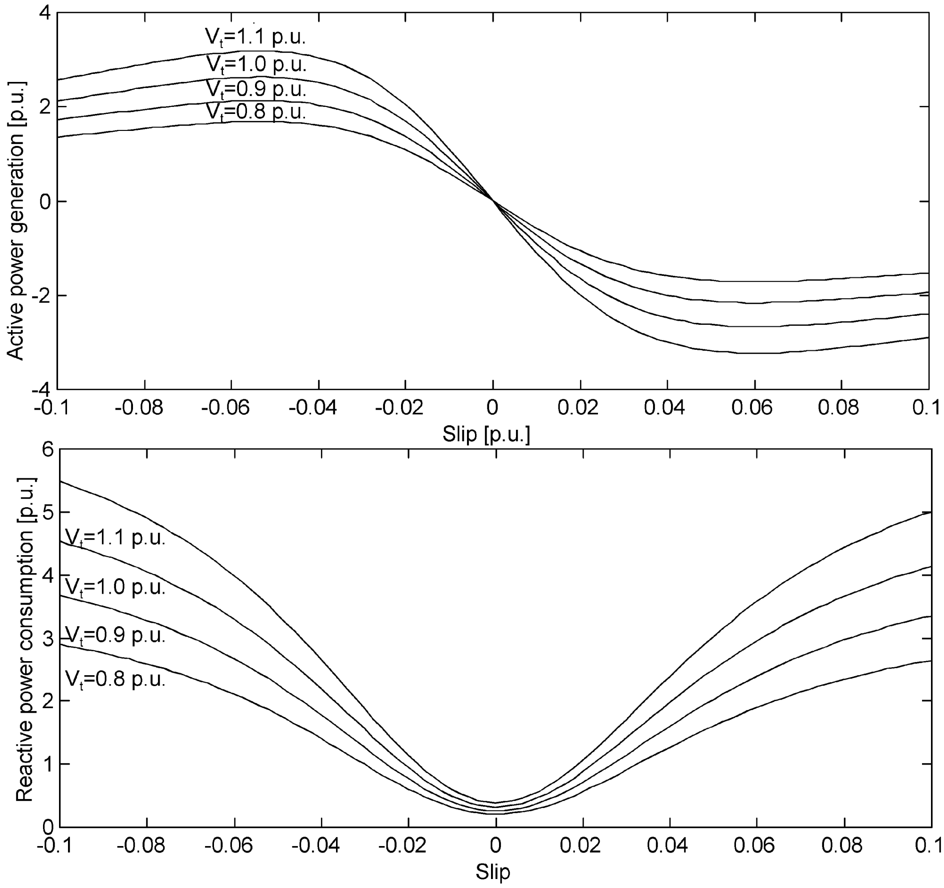


*Figure 5.2. Active (above) and reactive (below) power of a squirrel cage induction generator dependent on rotor slip with the terminal voltage as a parameter.*

***Mechanism Causing Instability***

Squirrel cage induction generators can also become easily unstable [63]. This can be seen as follows. From figure 5.2, it can be concluded that:

- The lower the terminal voltage, the larger the absolute value of the rotor slip that corresponds to a certain amount of active power generation.
- The larger the rotor slip, the larger the reactive power consumption.

When a fault occurs in the network, the generator terminal voltage drops. The generated electrical power is proportional to the terminal voltage. Therefore, at low terminal voltage, only a small amount of electrical power can be fed into the grid. However, mechanical power continues to be supplied by the wind. Due to the resulting unbalance between supplied mechanical power and generated electrical power, the generator speeds up, corresponding to a more negative slip in figure 5.2. When the fault is cleared, the squirrel cage induction generator draws a large amount of reactive power from the grid because of its high rotational speed, as can be seen in the lower graph of figure 5.2.

However, when the generator terminal voltage is low, the electrical power generated at a given slip is lower than that at nominal terminal voltage, as can be seen in the upper graph of figure 5.2. If the rotor accelerates more quickly than the terminal voltage restores, the reactive power consumption increases ever more, leading to a decrease in the terminal voltage and thus to a further disturbance of the balance between mechanical and electrical power and to a further acceleration of the rotor. Eventually, the voltage at the wind turbine terminals will collapse towards zero and it may be necessary to disconnect the turbine from the grid to allow restoration of the grid voltage.

The wind turbine itself will be either disconnected by its undervoltage protection or it will accelerate further and be disconnected by its overspeed protection, depending on the design and settings of its protection system. The turbine can only be reconnected after restoration of the grid voltage in the affected parts of the network, which may take several minutes, particularly if other protection systems were also activated during the disturbance. In this case, the power system with the wind turbine connected is not transiently stable: it does not return to a stable operating point after the disturbance. Instead, protection devices that change the topology of the system by disconnecting the wind turbine restore the stability of the system as a side effect.

The observed instability is an example of combined rotor speed instability and voltage instability, which is typical for squirrel cage induction generators. The exact quantitative behaviour of the terminal voltage and the required restoration time depend on the actual wind speed, wind turbine characteristics, network topology and protection system settings.

Wherever possible, it should be ensured that a fault is removed from the system to avoid the mechanism pointed out above, which leads to instability of the wind turbines. A fault should therefore be cleared quickly to limit the amount of overspeed and therewith the reactive power consumption when the voltage is restored. The time available to clear the fault before it leads to instability is called the *critical clearing time* [42].

Note that constant speed wind turbines cannot become unstable only after a fault. The above sequence of events may also be initiated by a relatively small drop in terminal voltage, resulting from, for instance, the tripping of a nearby synchronous generator or the switching in of a highly inductive load. When the wind turbine delivers its nominal power and the terminal voltage drops slightly, the rotor speed will increase, because a larger slip is required to deliver nominal power at a terminal voltage below nominal. This leads to an increase in the reactive power consumption, which in turn leads to a further lowering of the terminal voltage. This mechanism can lead to a voltage collapse that is not preceded by a short circuit and forms an example of voltage instability.

***Countermeasures***

A number of countermeasures to prevent instability of constant speed wind turbines have been proposed in the literature [64]:

- Constant speed wind turbines, which are usually stall controlled, can be equipped with pitch drives that quickly increase the pitch angle when acceleration of the rotor is detected. This reduces the mechanical power and thus limits the rotor speed and the reactive power consumption after the fault and in this way the risk of instability.
- The wind turbines can be equipped with a controllable source of reactive power, e.g. a STATCOM or SVC, to deliver the reactive power required to accelerate the voltage restoration.
- Mechanical and/or electrical parameters of the wind turbine and the generator can be changed in order to make the turbine more stable. This, however, often has the disadvantages of increased cost, reduced electrical efficiency and a more complicated mechanical construction.

Although these measures alleviate the problem, they do not fully solve it, because it originates from the working principle of an induction generator, which is not affected by the above measures. This topic will be treated more elaborately in section 5.5.2.

### 5.3.2 Variable Speed Wind Turbine with Doubly Fed Induction Generator

In contrast to a constant speed wind turbine, a variable speed wind turbine with doubly fed induction generator does not have a unique relationship between active power, reactive power, terminal voltage and rotor speed. Instead it has an operating range, within which it can operate at any desired point. This is because the back-to-back voltage source converter decouples the electrical and mechanical behaviour of the generator from the grid voltage and frequency. From equations (3.19) and (3.24) it can be concluded that the generator torque is directly dependent on the quadrature component of the rotor current and the reactive power on the direct component of the rotor current [7]. The converter and its controllers thus govern the behaviour of the generator.

In figure 5.3, the operating range of a wind turbine with a doubly fed induction generator is displayed, assuming nominal terminal voltage and generator parameters as given in table 5.1. The two depicted surfaces are the limits of the operating range. When the terminal voltage deviates from nominal, the location and shape of the surfaces in the coordinate system depicted in figure 5.3 changes. Motor operation has not been taken into account. The exact quantitative value of the operating limits mainly depends on:

- The voltage and current rating of the power electronic converter
- The presence of a star/delta switch at the rotor winding or a tap changing transformer between the rotor winding and the power electronic converter, which is applied in order to better utilize the converter at low wind speeds

Figure 5.3 reemphasizes the observation that a variable speed wind turbine with doubly fed induction generator allows reactive power/terminal voltage control, because a range of reactive power values corresponds to a given value of active power and rotor speed.

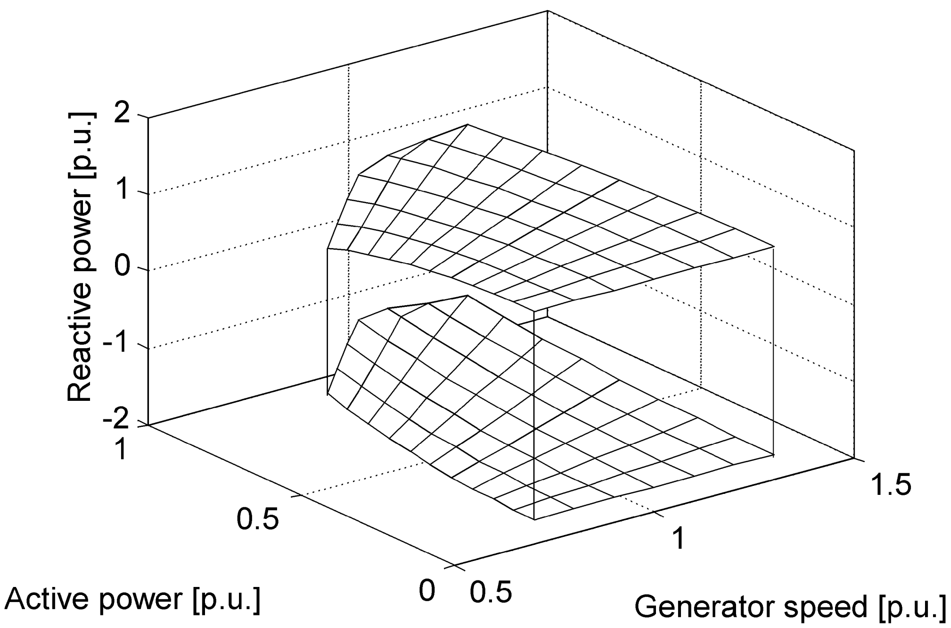


*Figure 5.3 Operating range of a doubly fed induction generator at a terminal voltage of 1 p.u.*

When a fault occurs in the network, the resulting voltage drop and current increase are noticed very quickly by the power electronic converter. Commonly, this leads to immediate disconnection of the wind turbine in order to protect the power electronics. The grid side of the converter feeding the rotor winding is blocked and the rotor side shorted. At the same time, the switchgear between the wind turbine and the grid is activated to disconnect the wind turbine. Due to the presence of a rather vulnerable power electronic converter with short thermal time constants, a variable speed wind turbine with doubly fed induction generator is much more sensitive to voltage drops than a constant speed wind turbine.

If the wind turbine should stay connected during a voltage drop or reconnect immediately after clearance of the fault, modification would be required of the controller of the power electronic converter and/or of the converter itself. This is already prescribed by some network operators for large scale projects connected to high and medium voltage grids, for reasons which will be explained in the section 5.3.4 [65].

As discussed in section 2.3.1, the mechanical rotor speed and the grid frequency are decoupled by the power electronic converter. This results in a second difference between a conventional synchronous generator or a constant speed wind turbine on the one hand and a variable speed wind turbine with doubly fed induction generator on the other. If the grid frequency drops due to a mismatch between generation and load, the mechanical frequency of the doubly fed induction generator does not change, and no energy stored in the rotating mass is supplied to the grid, as would happen in case of a directly grid coupled generator. Thus, a variable speed wind turbine with a doubly fed induction generator does not intrinsically contribute to frequency stabilization.

### 5.3.3 Variable Speed Wind Turbine with Direct Drive Synchronous Generator

As with a wind turbine with a doubly fed induction generator, and in contrast to a constant speed wind turbine, a wind turbine with a direct drive synchronous generator has no unique relationship between active power, reactive power, terminal voltage and rotor speed. Instead, it has an operating range, within which it can operate at each point. In a wind turbine with a direct drive synchronous generator, the generator is fully decoupled from the grid and the operating range is fully determined by the converter parameters, rather than by the combination of the characteristics of both the generator and the power electronics, as is the case for a wind turbine with a doubly fed induction generator.
In figure 5.4, the operating range of a variable speed wind turbine with a direct drive synchronous generator is given with the terminal voltage as a parameter. The rotor speed is not taken into account, because it hardly affects the grid interaction due to the decoupling of the generator and the grid. It is assumed that at nominal voltage and power, the wind turbine can operate with a power factor between 0.9 leading and 0.9 lagging. From figure 5.4, it can once more be concluded that a variable speed wind turbine with a direct drive synchronous generator allows reactive power/terminal voltage control.

Normally, a wind turbine of this type disconnects when a fault is detected by the power electronic converter, as does a wind turbine with a doubly fed induction generator. However, it is possible to keep it connected during a fault, provided that the controllers of the power electronic converter are adapted. This enables supplying the nominal current, or even more than the nominal current if the power electronic converter is overdimensioned. This current could activate conventional overcurrent protection schemes. When the fault is cleared, the wind turbine can quickly resume normal operation and even support voltage restoration by temporarily reducing the active power generation in order to generate extra reactive power. Examples of controllers allowing this approach have been discussed in the literature [66].

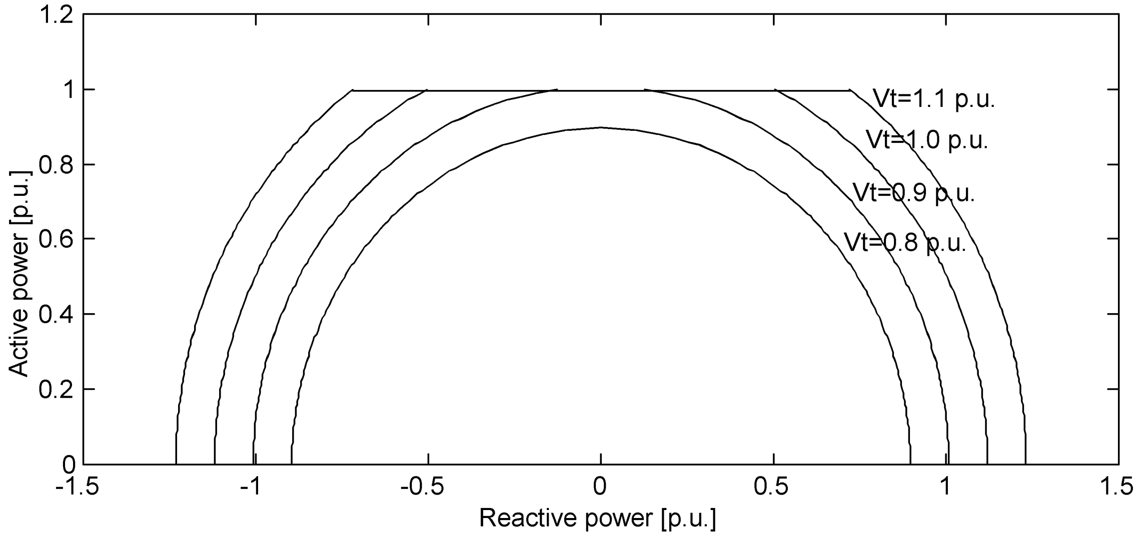


*Figure 5.4 Operating range of a wind turbine with direct drive synchronous generator with the terminal voltage as a parameter.*

Due to the decoupling between the generator and the grid, the wind turbine with direct drive synchronous generator also has the characteristic that a change in grid frequency will not result in a change in the mechanical rotor speed. Thus, no energy will be released from the rotating mass of this wind turbine in case of a frequency drop so that the variable speed wind turbine with direct drive generator does not intrinsically contribute to frequency stabilization.

### 5.3.4 Wind Turbine Protection and the Islanding Phenomenon

***The Islanding Phenomenon***

At this point, it should be mentioned that the normal procedure is that wind turbines are disconnected when a fault occurs and are reconnected somewhere from several minutes to up to a quarter of an hour after the voltage has recovered. In the case of variable speed wind turbines, this is done to protect the power electronic equipment, which is very sensitive to overcurrents. However, nowadays this practice is also applied to constant speed wind turbines, although this is not necessary to protect the wind turbine: constant speed wind turbines can withstand fault currents for some time, due to the relatively long thermal time constants of the generator.

The reason why at present all wind turbines are quickly disconnected in case of a fault, independent of the wind turbine type and its intrinsic capability to withstand a fault current, is to prevent *islanding*. Islanding refers to a situation in which a relatively small grid starts to operate independently of the power system after being disconnected due to a disturbance, such as a fault leading to the tripping of a line or transformer previously connecting that grid to the main power system. The independently operating grid is referred to as an (electrical) island.

Islanding is highly undesirable, because in the islanded grid the voltages and frequency are no longer controlled by the conventional large scale power plants. This could lead to large deviations from the nominal values of voltage and frequency, endangering both the components of the grid itself and customer equipment. The occurrence of islanding also threatens the personal safety of the workers, because the assumption that any part of the system that is disconnected from the main grid is no longer energized is not true anymore.

Note that wind turbines are by far not the only generation technology that can lead to islanding. Islanding can occur in any situation where generators are connected to low and medium voltage grids, independent of the prime mover of these generators. Such generators are commonly referred to as embedded, distributed or dispersed generators [67]. Besides wind power, examples are solar power and small scale combined heat and power (CHP) generators.

***Wind Power Penetration Level and Wind Turbine Protection***

Initially, wind turbines were erected solitarily or in small groups and were connected to low and medium voltage grids. They were therefore equipped with anti-islanding protection. As long as the penetration of wind turbines and other types of distributed generation in the system as a whole was modest, it was considered appropriate to have quite strong criteria in anti-islanding protection schemes. This means that the quantities used for detecting an island, such as terminal voltage and frequency, were allowed to deviate only slightly from their nominal values before tripping the generator. This could of course easily lead to unnecessary tripping, referred to as *nuisance tripping*. However, islanding was considered risky, whereas nuisance tripping had hardly any consequences and was thus readily accepted.

After a trip by the islanding protection system, the wind turbines were disconnected and reconnected some time after the voltage and/or the frequency had recovered. The resulting loss in energy production incurred during the period of disconnection was not significant. It can thus be concluded that in most cases not the physical properties and working principles of wind turbines determine their fault response, but other factors, particularly the perceived risk of islanding.

If this traditional approach were to be kept in the future, it would not make much sense to investigate the impact of wind turbines on a power system's transient stability. Instead, the wind turbines could be disconnected in the simulation as soon as the islanding criteria were violated and it could be assumed that they were not reconnected during the simulation run, which normally lasts no longer than a minute. However, due to the increasing penetration of wind turbines, accompanied by an increasing penetration of other types of distributed generation, such as solar panels and small scale combined heat and power (CHP) plants, it is no longer possible to support the traditional point of view that islanding should be prevented at all costs whereas nuisance tripping can be readily accepted.

This can be seen as follows. When the penetration of distributed generation is high and the anti-islanding criteria are strong, an event affecting a larger part of the system, such as a fault in a transmission line that leads to a voltage drop in a large geographic area, can cause the loss of a substantial amount of distributed generation, because this distributed generation is disconnected by its anti-islanding protection [68]. Depending on a number of factors, such as the total amount of generation, the type of generation and the grid topology, maintaining the power balance with the remaining generators may be quite complicated or even impossible, which could lead to load shedding and even to major blackouts.
In any case, as the penetration of distributed generation increases, the consequences of nuisance tripping become much more severe than they were at a low penetration of distributed generation. As a result, the trade off between the two failure modes of anti-islanding protection (letting an island go by undetected and nuisance tripping) will be quite different between systems with a low distributed generation penetration and systems with a high distributed generation penetration. This in turn affects the settings of the anti-islanding protection schemes.

Further, specifically for wind turbines a tendency can be observed to erect them in large scale wind parks, particularly offshore, instead of solitarily or in small groups. These wind parks are connected at high voltage levels. For high voltage networks, the islanding problem does not really exist. The safety problem is less pronounced, because components of high voltage networks are continuously monitored and equipped with remote control and high voltage networks are highly meshed and the chance of splitting up in different parts is therefore rather low. Moreover, nearly all generators connected at high voltage levels are equipped with voltage and frequency controllers. Large voltage and frequency fluctuations should be prevented by these controllers, even when an interconnected system splits in a number of parts.

Because of these developments, anti-islanding protection is not only unnecessary for wind parks connected to high voltage networks, but could even have severe consequences for the power balance. Large wind parks should therefore stay connected during faults. As a result, the intrinsic behaviour and physical limits of the wind turbine itself and the topology of the power system to which it is connected determine the wind turbine's impact on the dynamics of the power system, rather than the somewhat arbitrary criteria embedded in anti-islanding protection systems.
As can be concluded from the connection requirements of those network companies that already have dedicated connection requirements for wind parks, these indeed are such that wind turbines and wind parks connected to high voltage grids must stay connected during a fault in the network. They also require that large scale wind parks are equipped with voltage and frequency controllers similar to those of synchronous generators, in order to allow them to contribute to grid voltage and frequency control [65, 69].

## 5.4 RESPONSE OF WIND PARKS TO DISTURBANCES

Increasing attention is given to the erection of large scale (offshore) wind parks (also called wind farms) that are connected to the high voltage grid. Various configurations for these parks have been proposed [6]. Some characteristics of the interaction between the wind park and the grid are similar for all configurations, because they are inherently associated with using wind turbines for power generation. Examples of such characteristics are a fluctuating output power and a poor controllability and predictability of generated power. Other aspects of the interaction of the wind park, especially the controllability of the reactive power output and the behaviour during faults, strongly depend on wind park's configuration. The reactive power capabilities and the response to a terminal voltage or grid frequency drop will therefore be discussed for different wind park configurations separately.

When both the infrastructure within the wind park and the grid connection are implemented using conventional AC links and transformers, the response of the wind park to disturbances is determined by the wind turbines themselves. The park's infrastructure consists of passive elements. In this case, both the reactive power capabilities and the fault response depends on the wind turbine type used. When constant speed wind turbines are used, reactive power control is only possible by using additional components for generating reactive power.
When variable speed wind turbines are used, controllable reactive power generation is possible at the turbine terminals. However, the value of this for controlling node voltages in the system to which the wind park is connected may be rather limited. The individual wind turbines are relatively weakly coupled to the power system, because:

- the individual turbines have a rather low terminal voltage, therefore there are normally at least two transformers between the turbines and the point of grid connection
- in many cases, there will be a cable of substantial length between the point of common coupling (PCC) and the point of grid connection

Because of this, measures to allow voltage control at the grid connection or even elsewhere in the system will be necessary when the output of conventional power plants is replaced by wind parks on a substantial scale. However, the exact measures that are necessary to enable grid voltage control throughout the whole system with high penetrations of wind power depend strongly on the location and characteristics of the wind park, the topology of the network and the location and capabilities of the remaining synchronous generators.

When a HVDC system is used to connect the wind park to the grid, the wind turbines are electrically decoupled from the investigated system and the reactive power capabilities and fault response of the wind park are governed by the technology used for implementing the DC connection, rather than by the applied wind turbine concept. In figure 5.5, some examples of various wind park schemes with a DC grid connection are depicted.

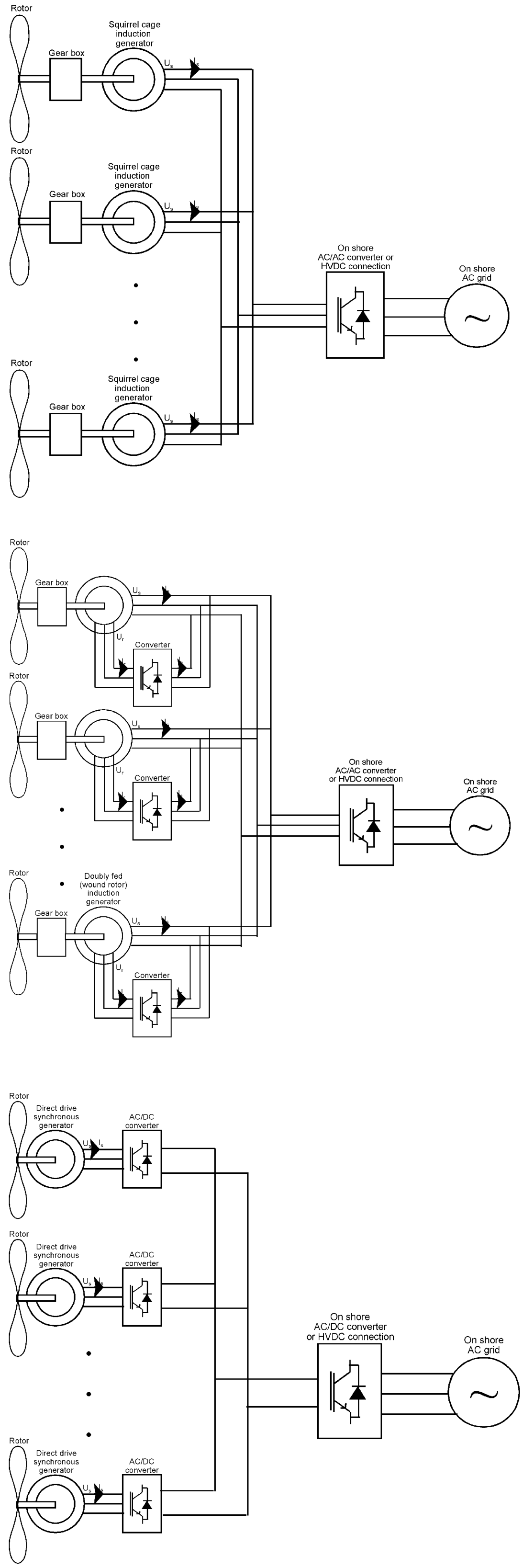


*Figure 5.5 Examples of Wind park schemes with a DC grid connection. From above: wind turbines with squirrel cage induction generators and variable frequency AC grid; wind turbines with doubly fed induction generator with limited converter rating and variable frequency AC grid; wind turbines with a direct drive synchronous generator and DC grid.*

When a HVDC system connects a wind park to a grid, the power flow will predominantly be from the park towards the power system. Nevertheless, faults on the output side seriously affect a DC connected wind park, because they cause the grid voltage to deviate substantially from its nominal value, for which the HVDC system has been designed. Frequency deviations are normally not a problem for HVDC systems.

The fault response of HVDC systems to disturbances depends on the applied technology. The response of a current source HVDC system to voltage drop caused by a fault somewhere in the power system can be summarized as follows [24]. During a voltage drop, even in case of small dips, commutation failures can easily occur, which means that the current does not transfer from one semiconductor switch to another. When the voltage stays below nominal, but increases sufficiently to clear the commutation failure, the system may continue to operate at a lower DC voltage, thus transferring less power. When the voltage stays low and commutation failures continue to occur, the inverter is bypassed by shorting its input and blocking its output. When the voltage comes back, the inverter is reconnected. The time of recovery is in the range of 100 ms to several seconds, depending on the control strategy and the characteristics of the grid to which the inverter is connected.

In a voltage source type of HVDC system, IGBT (Insulated Gate Bipolar Transistor), IGCT (Integrated Gate Commutated Thyristor) or power MOSFET (Metal Oxide Semiconductor Field Effect Transistor) semiconductor switches are used. Such technology is often referred to as ‘HVDC Light™’ or ‘HVDC PLUS’, depending on the manufacturer. The interaction of a voltage source HVDC connection with the grid is similar to that of a variable speed wind turbine with direct drive generator, which was described before, because the technology is essentially identical. This means that reactive power control is possible within the limitations of the converter and that it should in principle be possible to limit the converter current to its nominal value during faults, so that it can stay connected to the grid, by controlling the semiconductors accordingly.

## 5.5 SIMULATION RESULTS

### 5.5.1 Test System Preparation

***Test System Topologies***

In this section, two test systems and a model of a practical power system are used. The first test system consists of a wind turbine connected to an impedance through an infinite bus. This system is only used to illustrate the transient behaviour of the constant and variable speed wind turbines as discussed qualitatively before, and to illustrate the impact of the various characteristics of the turbines. It is depicted in figure 5.6.

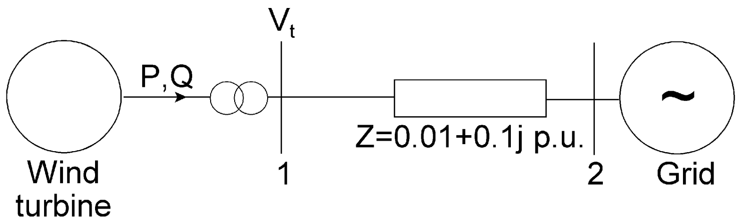


*Figure 5.6 Two bus test system.*

The second test system is a widely used dynamics test system: the New England Test System [70]. This system does not exist in reality, but is an artificial test system that is used in many publications on various aspects of power system dynamics. General reasons for using a test system rather than a model of a practical system are the following:

- Models of practical power systems are not very well documented and the data is partly confidential. This easily leads to a shift in focus from using the model to investigating certain phenomena towards improving the model itself. Most parameters of test systems are, however, given in the literature, which makes them convenient to use.
- Models of practical power systems tend to be very large, which makes the development and calculation of numerous scenarios cumbersome and time consuming and complicates the identification of general trends.
- The results obtained with models of practical systems are less generic than those obtained with general purpose test systems and can be validated more easily by and compared with results of other investigations given the availability of the system data.

Some of the characteristics of the New England Test System are given in table 5.2. The system is depicted in figure 5.7. The load flow data of the system are given in [70].

*Table 5.2 Characteristics of the New England Test System.*

| **System characteristic** | **Value** |
|---|---|
| # of buses | 39 |
| # of generators | 10 |
| # of loads | 19 |
| # of transmission lines | 46 |
| Total generation | 6140.7 MW / 1264.3 Mvar |
| Total load | 6097.1 MW / 1408.7 Mvar |

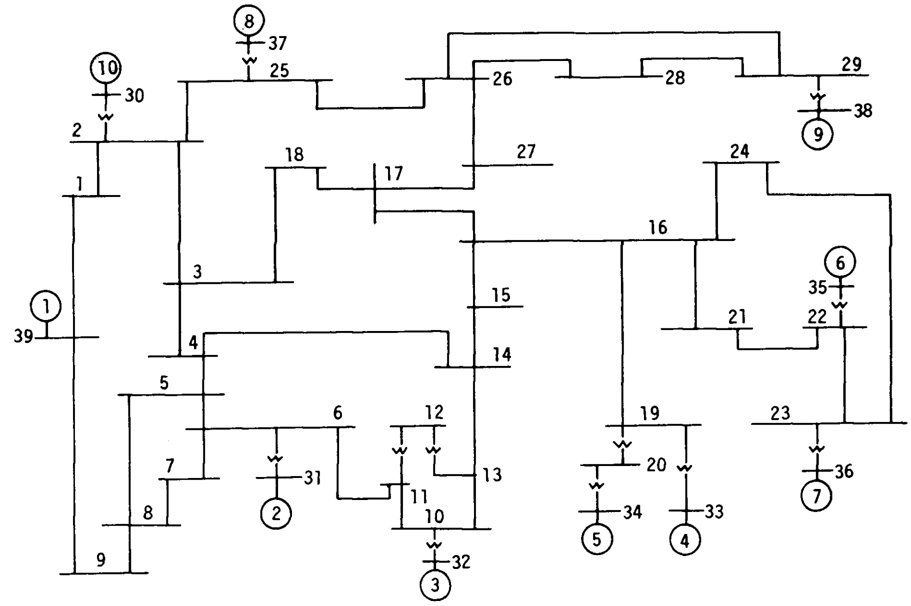


*Figure 5.7 One line diagram of the New England Test System [70]. The systems contains 10 generators and 39 buses.*

***Topology of the Practical System***

The practical power system used in this research project consists of a detailed model of the Dutch grid and a simplified model of the surrounding UCTE system. Some of its characteristics are given in table 5.3. The Dutch power system is depicted schematically in figure 5.8 [71].

*Table 5.3 Characteristics of the model of the Dutch system and the UCTE network.*

| **System characteristic** | **Value** |
|---|---|
| # of buses | 1262 |
| # of generators | 262 |
| # of loads | 934 |
| # of transmission lines | 2674 |
| Total generation | 137158.2 MW/19525.4 Mvar |
| Total load | 126714.8 MW/27856.8 Mvar |

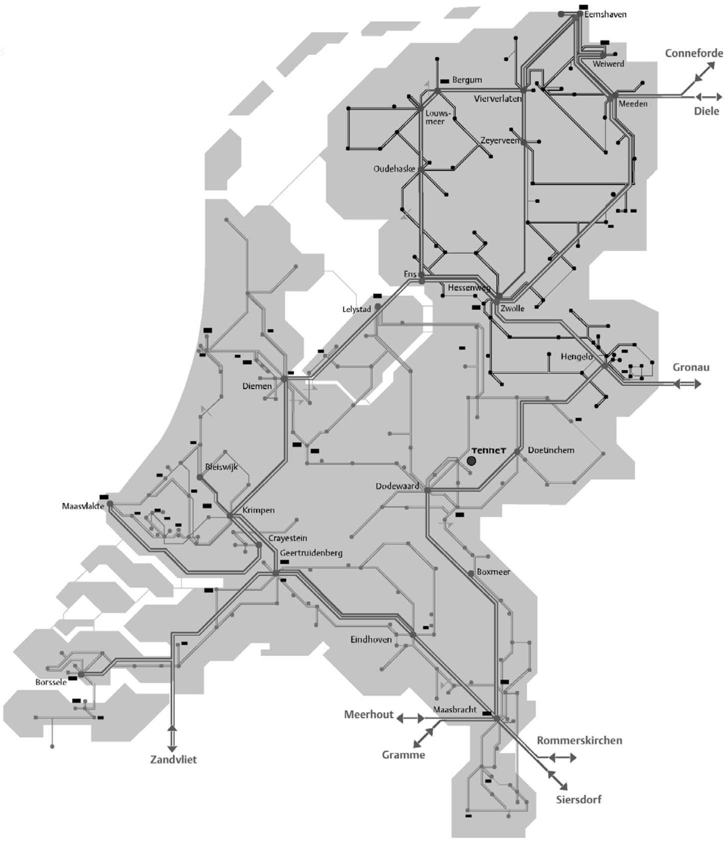


*Figure 5.8 Schematic depiction of the Dutch power system [71].*

***Dynamic Modelling***

For dynamic simulations, a dynamic model of a power system is necessary and load flow data are not sufficient. In order to obtain a dynamic model of the test system from figure 5.6, we connect dynamic models of a generator, governor and exciter to each of the generators in the system. The block diagrams of these models, including the values of the parameters for the New England Test System, are given in figures 5.9 to 5.11 and tables 5.4 to 5.6 respectively. Note that in PSS/E, the index l is used for leakage, rather than the index σ, like in this thesis.

For obtaining a dynamic model of the Dutch grid, models of the governors and exciters of the large power plants in The Netherlands were incorporated as user models in PSS/E™. For the smaller generators and the generators outside the Netherlands, standard models were used as in the case of the New England Test System. The parameters of the generators in the Dutch power system that are represented by dedicated models are based on measurements or manufacturer documentation and hence vary.

To represent the wind turbines in the dynamic simulations, the wind turbine and aggregated wind park models developed in chapters 3 and 4 were used. The model of the constant speed wind turbine has been described in section 3.4.3, the model of the general variable speed wind turbine has been described in section 4.2.2 and the aggregation of the models into aggregated wind park models can be found in section 4.3.3.

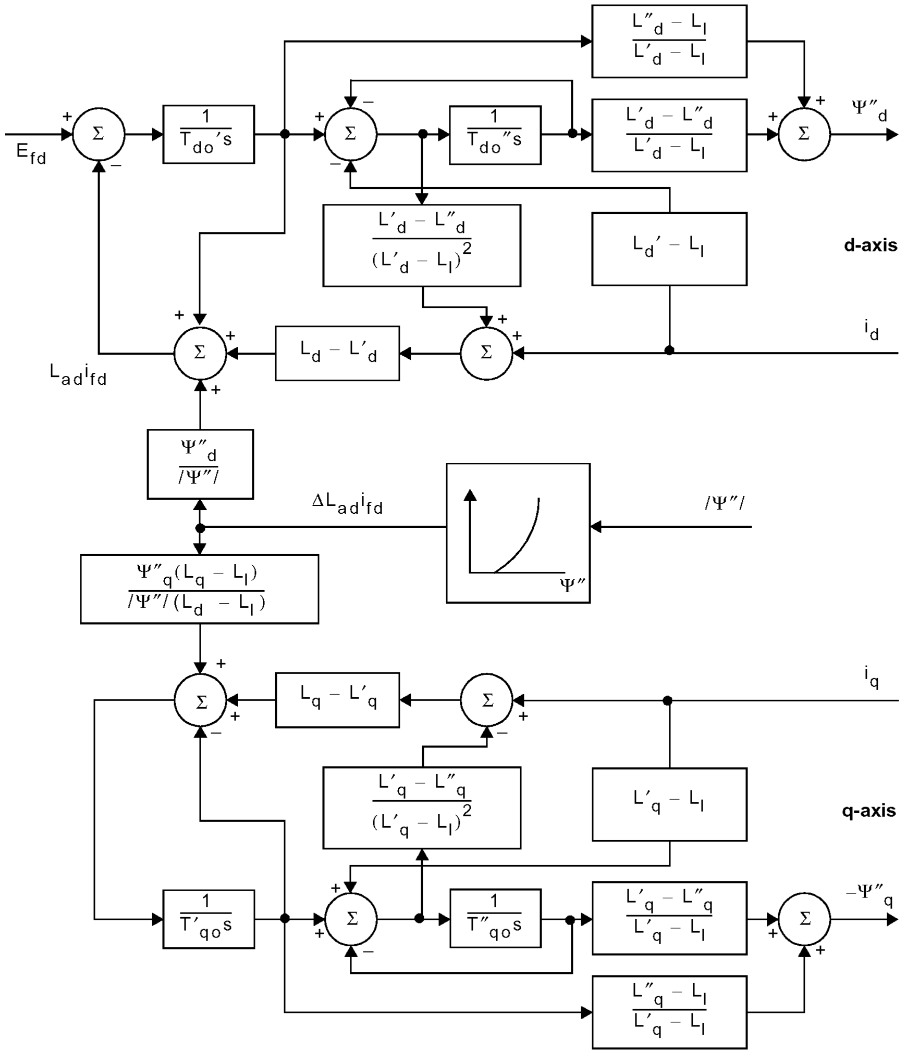


*Figure 5.9 Generator model block diagram [30].*

*Table 5.4 Generator model parameters for the generators in the New England Test System.*

| **Parameter** | **Value** | **Parameter** | **Value** |
|---|---|---|---|
| $T'_{do}$ | 5.0 s | $L_q$ | 1.65 p.u. |
| $T''_{do}$ | 0.05 s | L'd | 0.30 p.u. |
| $T'_{qo}$ | 1.0 s | $L'_q$ | 0.75 p.u. |
| $T''_{qo}$ | 0.04 s | $L''_d$=$L''_q$* | 0.20 p.u. |
| H | 4 s | $L_l$ | 0.175 p.u. |
| D | 0 | S(1.0) | 0.2 p.u. |
| $L_d$ | 1.75 p.u. | S(1.2) | 0.4 p.u. |

* $L''_d$ equals $L''_q$ due to the PSS/E synchronous generator model structure

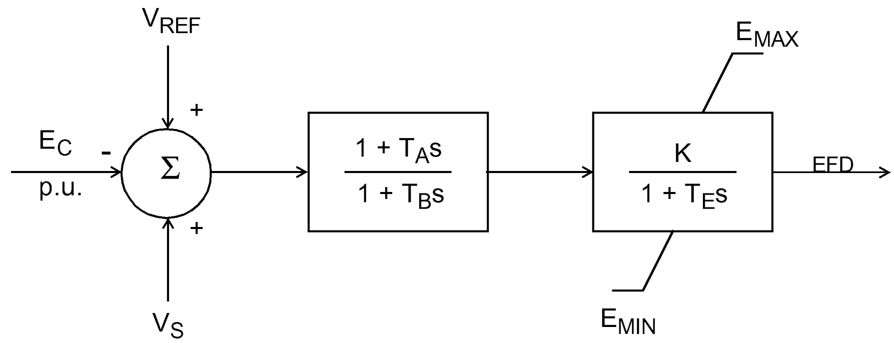


*Figure 5.10 Exciter model block diagram [30].*

*Table 5.4 Exciter model parameters for the generators in the New England Test System and for those generators in the Dutch power system for which no dedicated model was available.*

| **Parameter** | $T_A/T_B$ | $T_B$ | K | $T_E$ | $E_{MIN}$ | $E_{MAX}$ |
|---|---|---|---|---|---|---|
| **Value** | 0.1 | 10 | 300 | 0.05 | 0 | 5 |

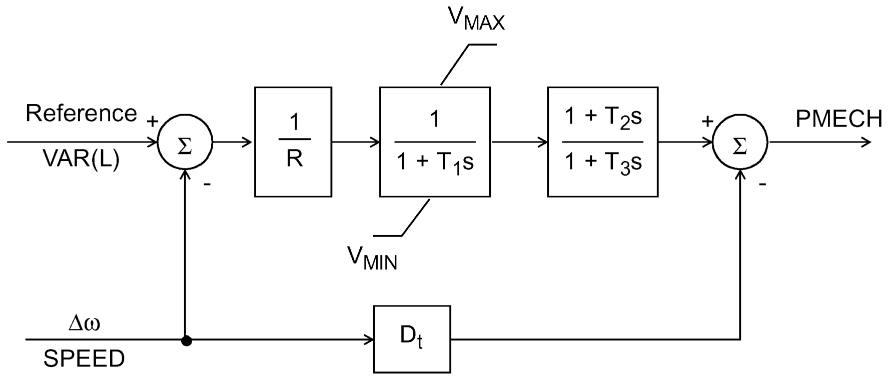


*Figure 5.11 Governor model block diagram [30].*

*Table 5.6 Governor model parameters for the generators in the New England Test System and for those generators in the Dutch power system for which no dedicated model was available.*

| **Parameter** | R | $T_1$ | $V_{max}$ | $V_{min}$ | $T_2$ | $T_3$ | $D_t$ |
|---|---|---|---|---|---|---|---|
| **Value** | 0.05 | 0.05 | 0.91 | 0 | 2.1 | 7 | 0 |

It should be observed at this point that the time period needed for reconnecting the general variable speed wind turbine model after a fault is reduced to below to what it is in practice (several tens of seconds to a quarter of an hour). In this way, it is implicitly assumed that the manufacturers of variable speed wind turbines have solved the problems associated with the fault response, as described before.

In theory, the problem can be solved either by keeping the wind turbine connected during the fault or by reconnecting it quickly (within about 25 ms) after the fault [72]. Although the problem does not seem to be solved completely in practice at this moment yet, it must be before variable speed wind turbines can be connected in such quantities that the penetration levels that are studied in this chapter are reached. Simulating a system with a high penetration of variable speed wind turbines that all disconnect when a relatively small voltage drop occurs does not make sense, because it can be predicted in advance that such a system is not stable. Moreover, such a system will never be allowed to exist in practice. This will be prevented by grid connection requirements, as can already be observed from the grid connection requirements of transmission system operators (TSOs) in areas with a high wind power penetration level, such as the Danish Eltra and the German E-On Netz [65, 69]. Therefore, when simulating the New England Test System and the Dutch power system, it will be assumed that the fault behaviour of both variable speed wind turbines is controllable, although this is presently not completely true.

### 5.5.2 Results for a Wind Turbine Connected to an Infinite Bus

***Constant Speed Wind Turbine***

The fault response of a constant speed wind turbine was already simulated in section 4.2.3. However, the goal there was to compare the fault responses of constant and variable speed wind turbines and to illustrate the use of the models. The focus here is to investigate the impact of various variables on the fault response, namely:

- fault clearing time
- impedance of the grid connection, i.e. the strength of the grid coupling
- moment of inertia of the wind turbine
- shaft stiffness

The analysis is similar to the one presented in [64], but is repeated here in order to allow a comparison of the results of a constant speed wind turbine with those of a variable speed wind turbine, which is carried out at the end of this section.

In figure 5.12, the impact of the fault clearing time is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 100 ms, 150 ms and 250 ms respectively. The resulting wind turbine rotor speed, generator rotor speed, active and reactive power and terminal voltage are depicted in figure 5.12. The dotted, dashed and solid lines correspond to an increasing fault duration.

In figure 5.13, the impact of the impedance of the grid coupling is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 150 ms. The impedance between buses 1 and 2 in figure 5.6 was then multiplied by a factor 2 and a factor 3, making it equal to 0.02+0.2j p.u. and 0.03+0.3j p.u. The resulting wind turbine rotor speed, generator rotor speed, active and reactive power and terminal voltage are depicted in figure 5.13. The dotted, dashed and solid lines correspond to an increasing impedance value.

In figure 5.14, the impact of the moment of inertia is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 150 ms. The inertia constant H of the wind turbine rotor and the generator rotor were then multiplied by 2/3 and 4/3 respectively, resulting in a total moment of inertia of 2.0 s and 4.0 s. The resulting wind turbine rotor speed, generator rotor speed, active and reactive power and terminal voltage are depicted in figure 5.14. The dotted, dashed and solid lines correspond to an increasing moment of inertia.

In figure 5.15, the impact of the shaft stiffness is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 150 ms. The initial value of the shaft stiffness, which equals 0.3 p.u. torque/el.rad, was then reduced to 0.1 el.rad/p.u. torque and increased to 0.5 p.u. torque/el.rad respectively. The resulting wind turbine rotor speed, generator rotor speed, active and reactive power and terminal voltage are depicted in figure 5.15. The dotted, dashed and solid lines correspond to an increasing shaft stiffness.

***Analysis of Constant Speed Wind Turbine Simulation Results***
The first conclusion that can be drawn from the simulations is that there is a strong relation between active and reactive power, terminal voltage and rotor speed, as shown earlier in a different way in figure 5.2. A disturbance of the terminal voltage affects the active and reactive power and rotor speed, whereas mechanical oscillations after the fault are reflected in the active and reactive power and thus in the terminal voltage. Note that the quick oscillations in the generator rotor speed directly after the fault reflect the effect of the rotor time constants.
Further, it can be concluded that a short fault duration, a strong grid coupling, a higher moment of inertia and a stiff shaft contribute to voltage restoration. A short fault duration and a high moment of inertia reduces the amount of overspeeding during the fault and thus the reactive power consumed after the fault. A strong grid coupling does not affect the amount of overspeeding and reactive power consumed after the fault very much, but it reduces the impact of the reactive power consumption of the generator on the restoration of the voltage.

The impact of the shaft stiffness on the voltage restoration is less straightforward. It can be concluded from the simulation results that a stiff shaft contributes to a quick voltage restoration, which has also been pointed out in the literature [42, 64]. However, a stiff shaft hardly affects the amount of overspeeding of the rotor of the wind turbine, nor the relation between reactive power consumption and terminal voltage, as was the case with fault duration, moment of inertia and strength of the grid coupling respectively.
However, as can be seen in the simulations, the shaft stiffness strongly affects the amount of overspeeding of the generator rotor. This is caused by the potential energy accumulated in the shaft. This energy is released at a fault, when the (average) electrical generator torque becomes equal to zero and accelerates the generator rotor, which has a much lower inertia than the wind turbine rotor. The softer the shaft, the more potential energy is accumulated in the shaft. Thus, the more the rotor is accelerated, the higher the reactive power consumption after the fault and the slower the voltage recovery.

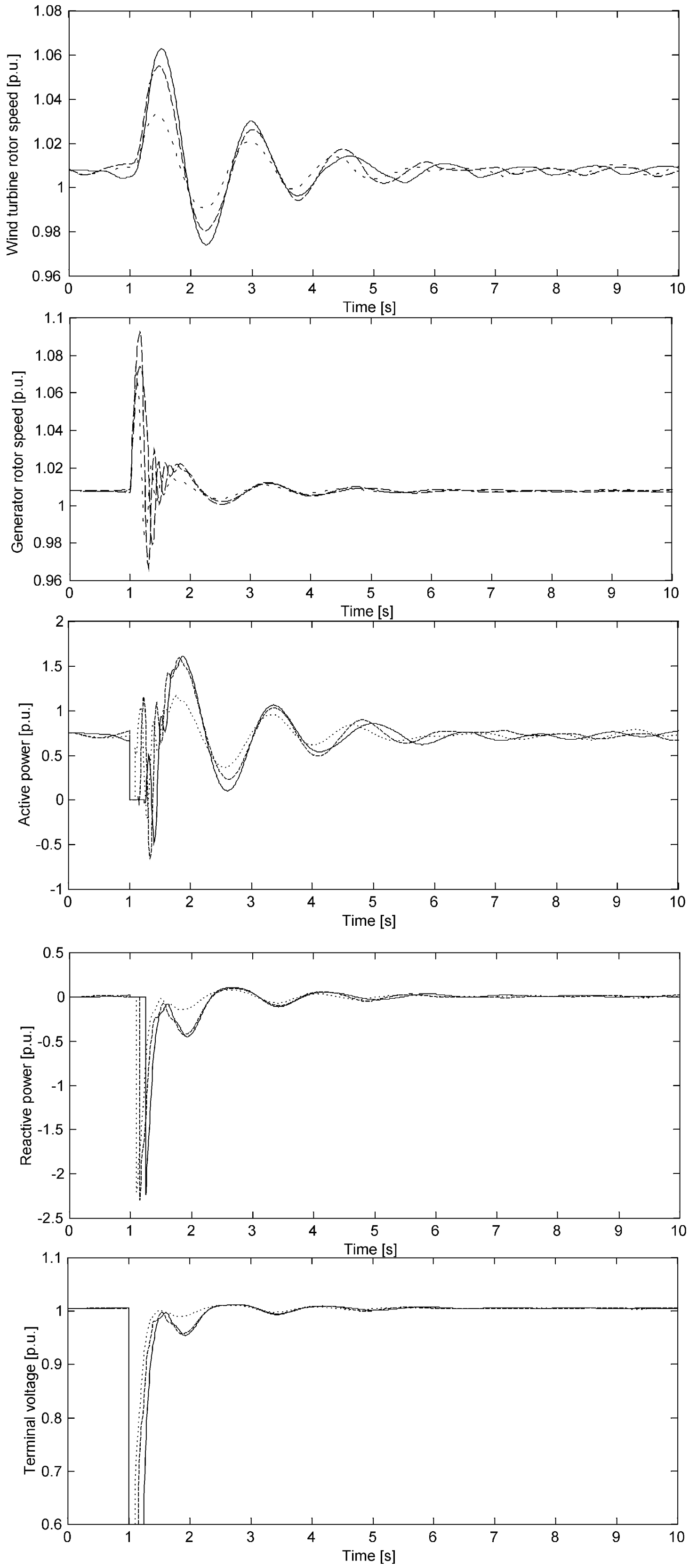


*Figure 5.12 Impact of fault clearing time on wind turbine fault response. From above: wind turbine rotor speed, generator rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a fault clearing time of 100 ms, 150 ms and 250 ms respectively.*

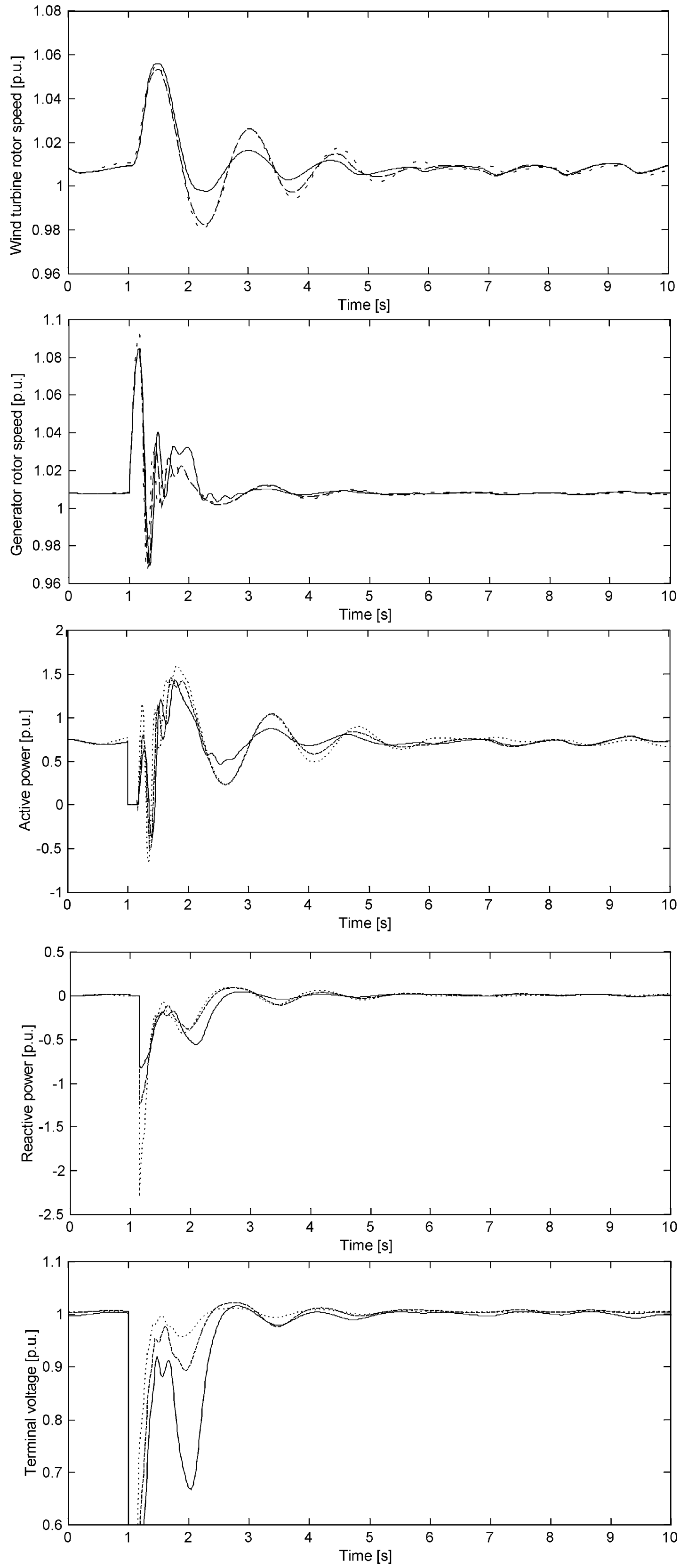


*Figure 5.13 Impact of strength of grid coupling on wind turbine fault response. From above: rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a grid coupling impedance of 0.01+0.1j, 0.02+0.2j and 0.03+0.3j p.u. respectively.*

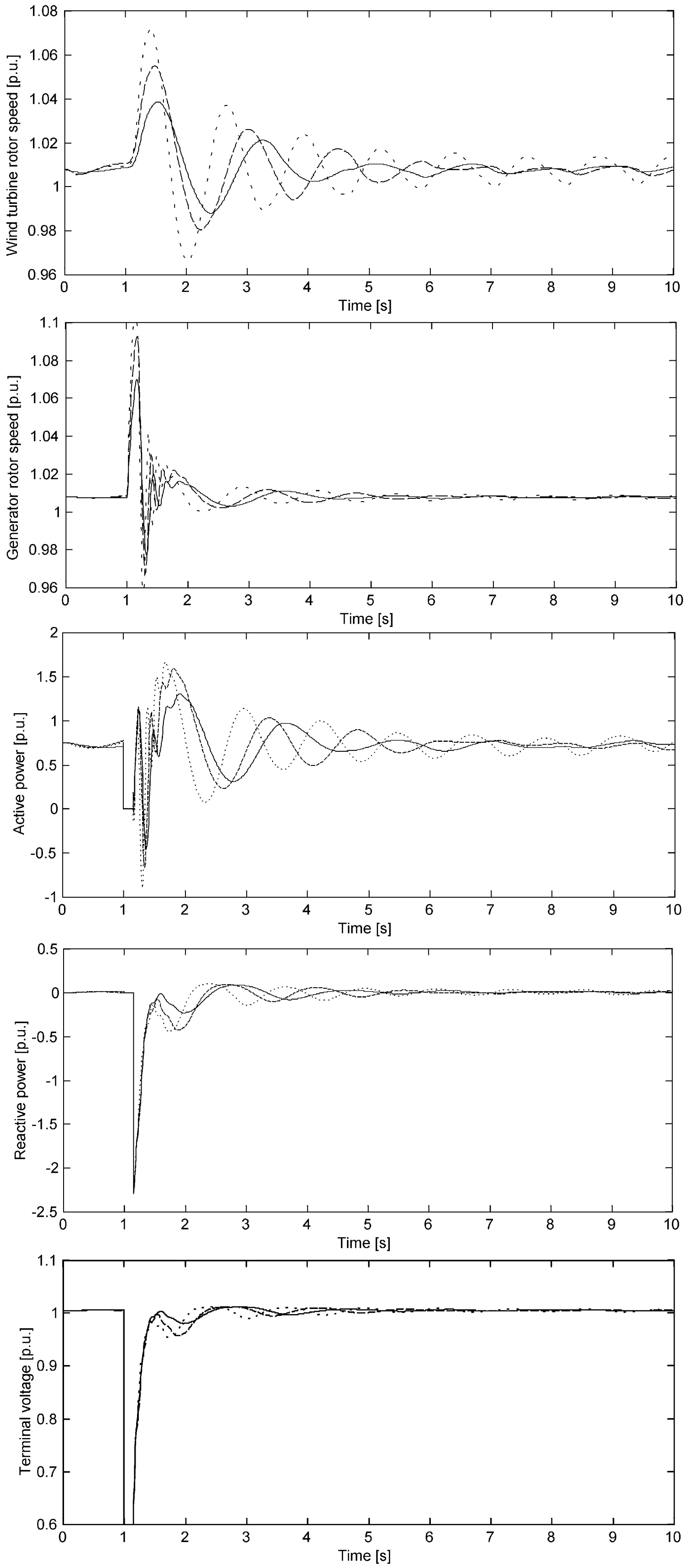


*Figure 5.14 Impact of moment of inertia on wind turbine fault response. From above: wind turbine rotor speed, generator rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a total moment of inertia of 2.0 s, 3.0 s and 4.0 s respectively.*

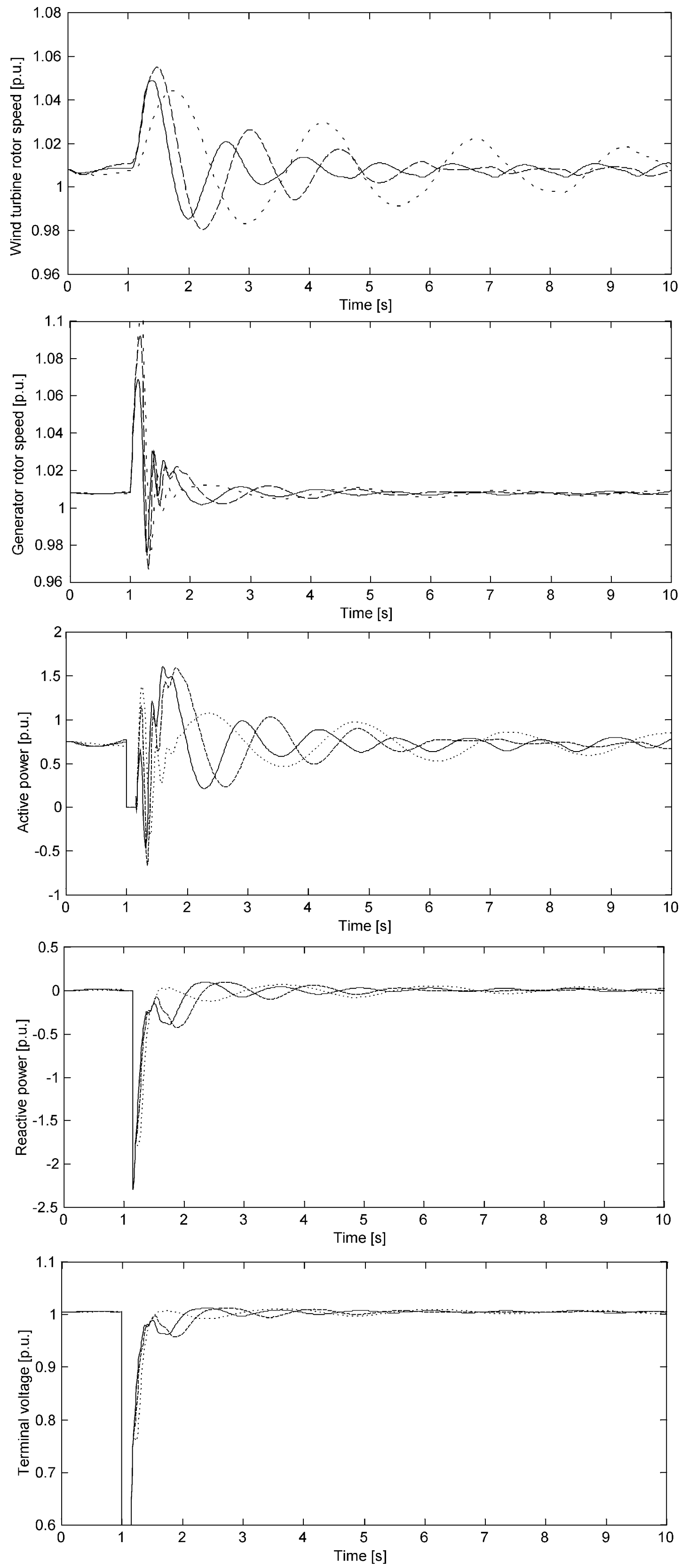


*Figure 5.15 Impact of shaft stiffness on wind turbine fault response. From above: wind turbine rotor speed, generator rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a shaft stiffness of 0.1, 0.3 and 0.5 p.u. torque/el.rad respectively.*

Apart from the factors listed above, other factors affect the fault response of constant speed wind turbines, such as the presence of a blade pitch controller to limit the speed increase during the fault or the presence of a source of reactive power to support voltage restoration after clearance of the fault, such as switched capacitors or an SVC or STATCOM [64, 73]. This kind of measures, however, leads to either substantial modifications to the stall controlled constant speed wind turbines available on the market or to modifications to the power system itself. A quantitative investigation of modifications to the wind turbine's design and/or the power system's topology in order to improve the transient stability of wind power based on constant speed wind turbines has been presented in the literature and is outside the scope of the research reported in this thesis.

The principles on which these approaches are based can, however, be understood intuitively when considering the fault response of the constant speed wind turbine as described in section 5.3.1 and the above simulation results. The post fault behaviour is governed by the reactive power consumption and the terminal voltage restoration, which are interdependent. If the amount of overspeeding during the fault is reduced by pitching the blades and thus by reducing the mechanical power supplied to the generator, the reactive power consumed after the fault will decrease as well, resulting in an improved voltage restoration. If a source of reactive power is added to the wind turbine or wind park, the turbine's reactive power consumption after the fault will not be affected, but (part of) the required reactive power will be supplied by the additional source, which also results in an improved voltage restoration.

***Variable Speed Wind Turbines***

The fault response of a variable speed wind turbine was already simulated in section 4.2.3. However, the goal there was to compare the fault responses of constant and variable speed wind turbines and to illustrate the use of the models. In this section, the impact of a number of parameters will be investigated, namely:

- fault clearing time
- impedance of grid connection, i.e. strength of grid coupling
- moment of inertia of the wind turbine
- the protection system parameters reconnection time and ramping time after reconnection

In the first three investigations, the values of the protection system parameters were equal to those given in table 4.3. In the last investigation, the protection system parameters were changed in order to investigate their impact.

In figure 5.16, the impact of the fault clearing time is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 100 ms, 150 ms and 250 ms respectively. The resulting rotor speed, active and reactive power and terminal voltage are depicted in figure 5.16. The dotted, dashed and solid lines correspond to an increasing fault duration.

In figure 5.17, the impact of the impedance of the grid coupling is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 150 ms. The impedance between buses 1 and 2 in figure 5.6, was then multiplied by a factor 2 and a factor 3, making it equal to 0.02+0.2j p.u. and 0.03+0.3j p.u. The resulting rotor speed, active and reactive power and terminal voltage are depicted in figure 5.17. The dotted, dashed and solid lines correspond to an increasing impedance value.

In figure 5.18, the impact of the moment of inertia is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 150 ms. The inertia constant H of the rotating mass was then multiplied by 2/3 and 4/3 respectively, resulting in a moment of inertia of 2.0 s and 4.0 s. The resulting wind turbine rotor speed, generator rotor speed, active and reactive power and terminal voltage are depicted in figure 5.18. The dotted, dashed and solid lines correspond to an increasing moment of inertia.

In figure 5.19, the impact of the protection system parameters reconnection time and ramping time after reconnection is shown. After 1 s, a fault was applied at bus 1 of the system depicted in figure 5.6. The fault was cleared after 150 ms. Then, the reconnection time and ramping time after reconnection were changed from 10 ms and 0.5 s to 0.5 s and 1 s and 1 s and 5 s respectively. The resulting wind turbine rotor speed, generator rotor speed, active and reactive power and terminal voltage are depicted in figure 5.19. The dotted, dashed and solid lines correspond to an increasing reconnection time and ramping time after reconnection.

***Analysis of Variable Speed Wind Turbine Simulation Results***

The fact that the behaviour of a variable speed wind turbine is fundamentally different from that of a constant speed wind turbine is clearly illustrated by these simulations. The fault duration, the strength of the grid coupling and the moment of inertia do not greatly affect the fault response of a variable speed wind turbine. In all cases, the voltage restored very quickly after the fault, the active and reactive power exchange with the grid were by far not as much affected as in case of a constant speed wind turbine. No tendency towards instability could be observed, as was the case for the constant speed wind turbine with increasing fault duration and decreasing coupling strength, moment of inertia and shaft stiffness. Further, the post fault value of the rotor speed was reduced by controlling the electrical power based on the actual value of the rotor speed. This has a braking effect, caused by the fact that the generated electrical power is greater than the mechanical power supplied by the wind. Thus, the rotor is not decelerated by the grid, but by the power electronic converter.

Instead, the behaviour of the variable speed wind turbines is governed by the protection system parameters reconnection time and ramping time after reconnection. The reconnection time is the time that the wind turbine needs before reconnecting after a disconnection induced by a terminal voltage or frequency deviation. The ramping time refers to the time it takes before the wind turbine has returned to its normal operating regime, of which the most

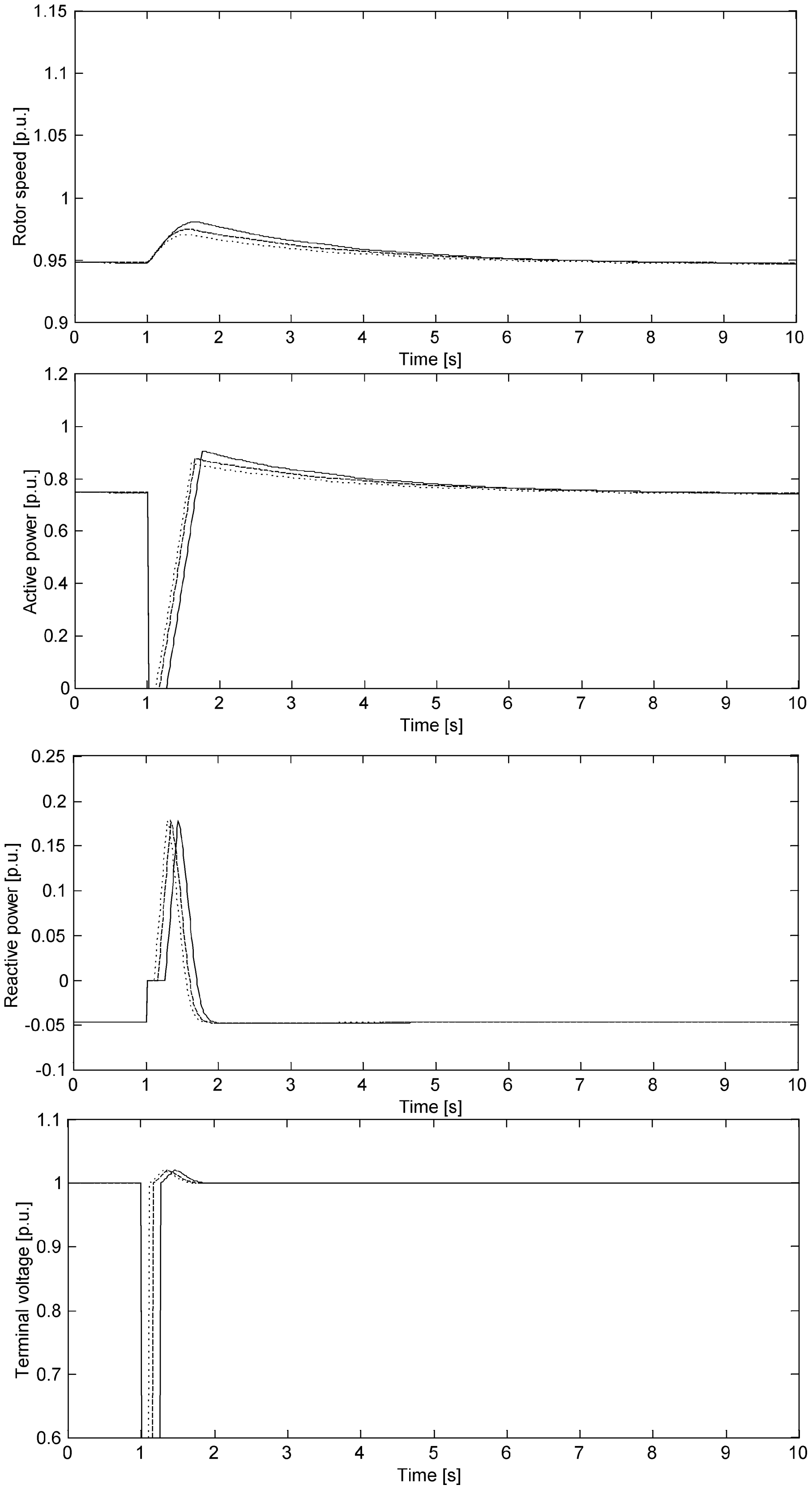


*Figure 5.16 Impact of fault clearing time on wind turbine fault response. From above: rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a fault clearing time of 100 ms, 150 ms and 250 ms respectively.*

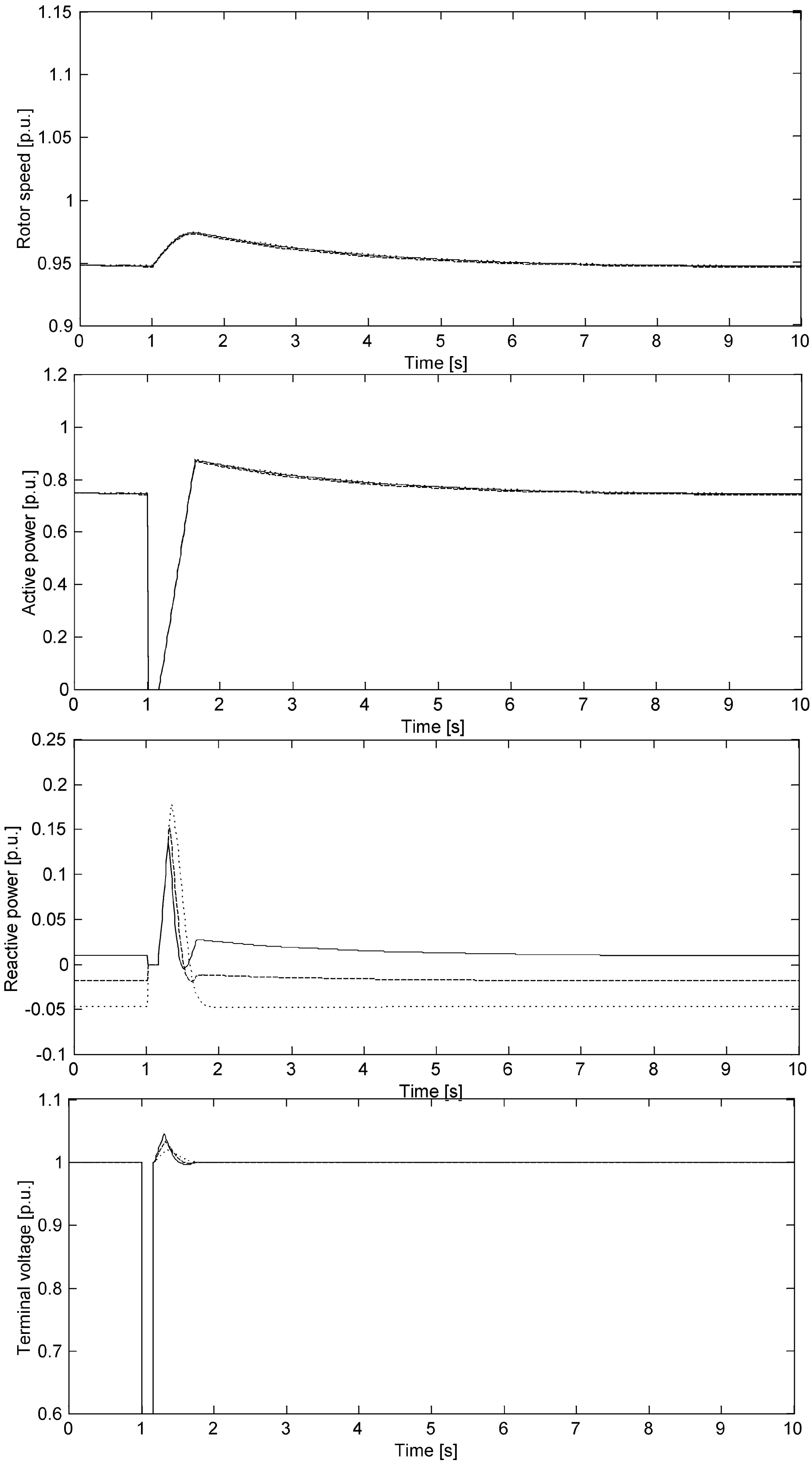


*Figure 5.17 Impact of strength of grid coupling on wind turbine fault response. From above: rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a grid coupling impedance of 0.01+0.1j, 0.02+0.2j and 0.03+0.3j p.u. respectively.*

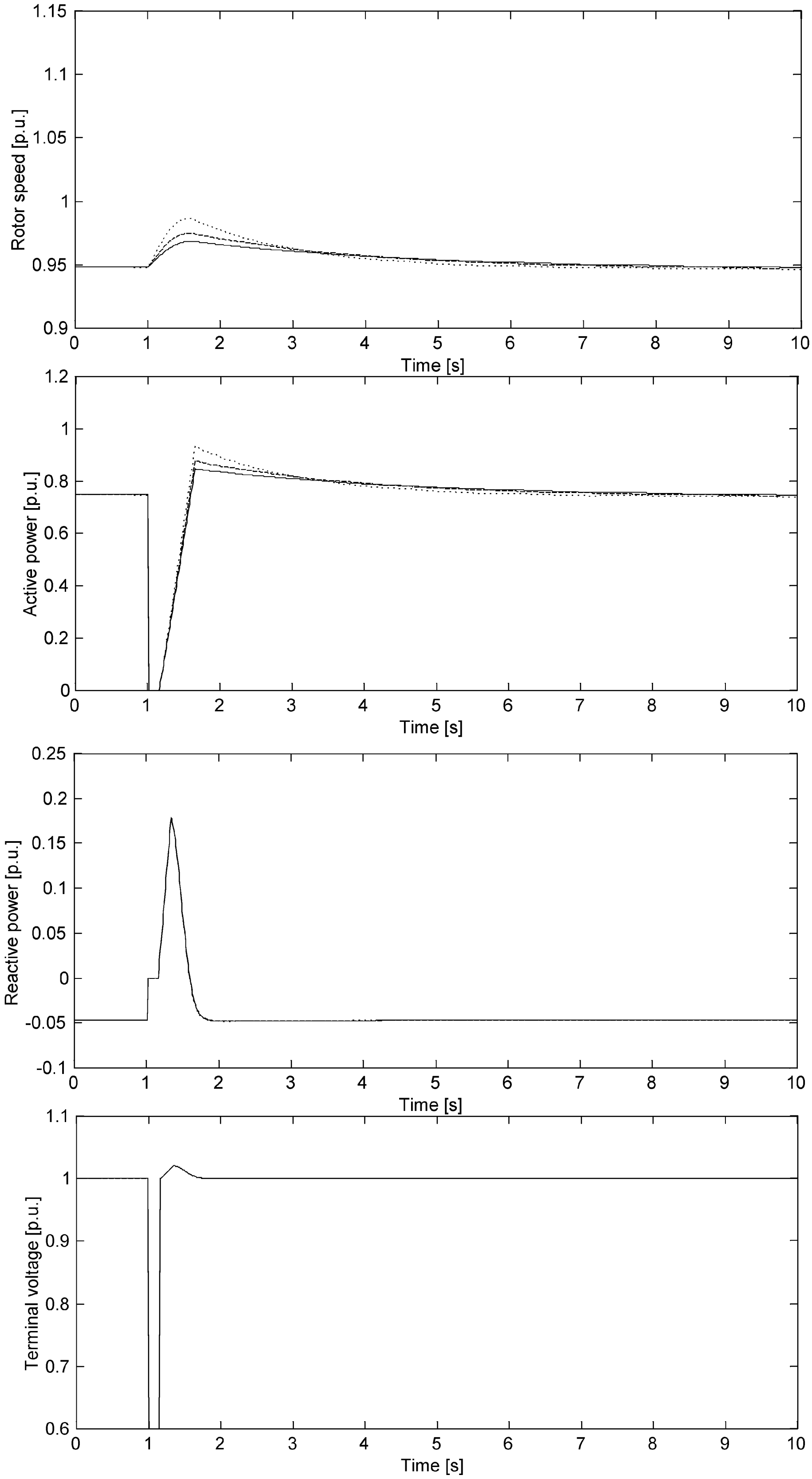


*Figure 5.18 Impact of moment of inertia on wind turbine fault response. From above: wind turbine rotor speed, generator rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a total moment of inertia of 2.0 s, 3.0 s and 4.0 s respectively.*

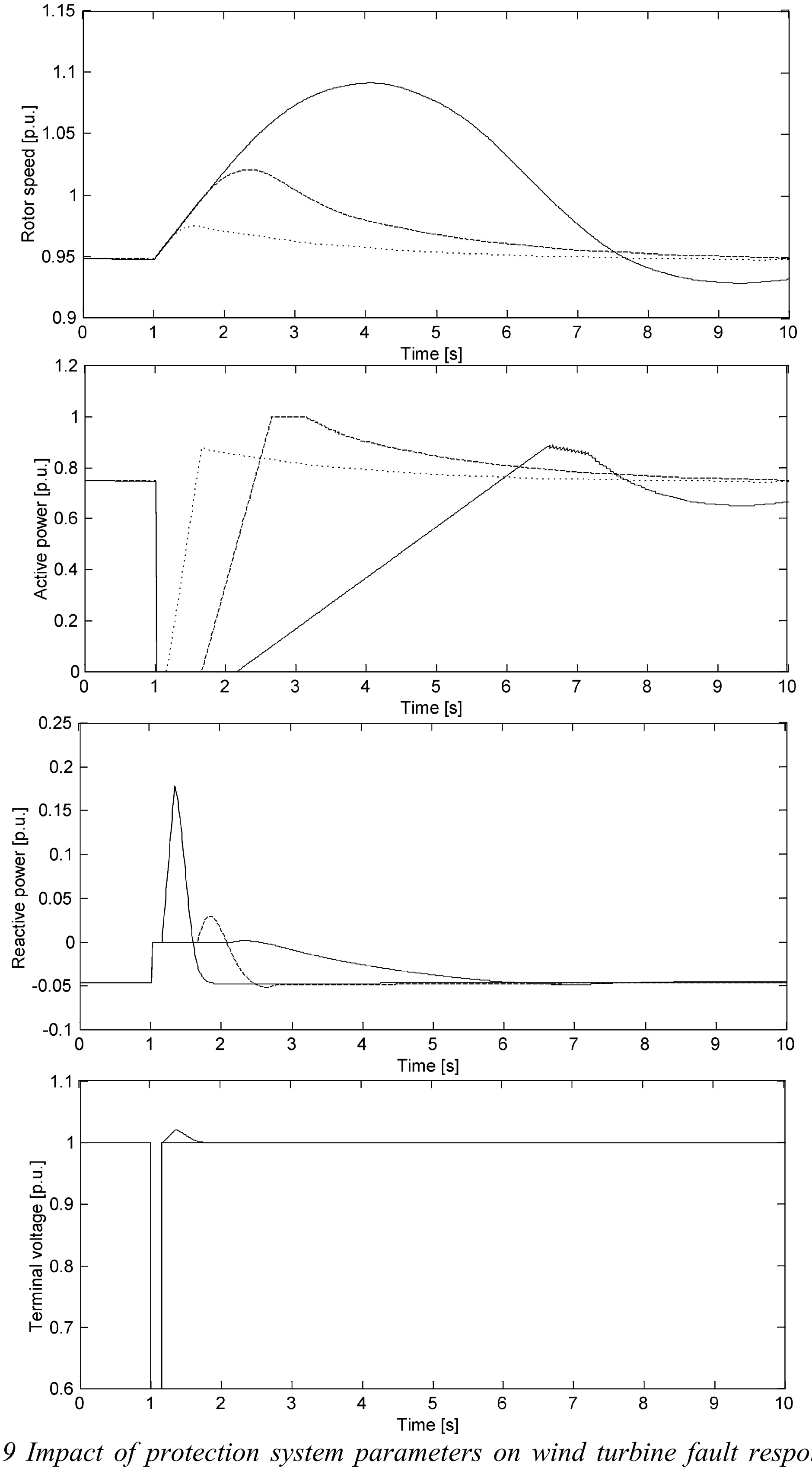


*Figure 5.19 Impact of protection system parameters on wind turbine fault response. From above: rotor speed, active power, reactive power and terminal voltage. The dotted, dashed and solid lines correspond to a reconnection time of 10 ms, 0.5 s and 1 s and a ramping time after reconnection of 0.5 s, 1.0 s and 5.0 s respectively.*

important characteristic is that the generated amount of electrical power is determined by the actual rotor speed, rather than by the protection system. In other words, the protection system does no longer overrule the functioning of the rotor speed controller.

Note that if the reconnection time and/or the ramping time after reconnection are very long, the pitch controller can become active, even when the wind speed is lower than the nominal value. This can explained by observing that the input of the pitch controller is the actual rotor speed, not the wind speed, as can be seen in figure 3.10. The wind turbine does not generate any active power before being reconnected, whereas during ramping up, the generated electrical power is lower than the amount that would be generated if the rotor speed controller was operating normally. However, the mechanical power extracted from the wind is hardly reduced and thus an unbalance between mechanical and electrical torque results, both before reconnection as well as during ramping up. The resulting rotor speed increase can exceed the nominal rotor speed and thus activate of the rotor pitch controller, even at wind speeds below nominal.

### 5.5.3 Results for the New England Test System

In this section, the impact of wind power on the transient stability is further illustrated, based on simulation results for the New England Test System. Some of the synchronous generators in this test system are replaced by an aggregated model of a wind park with either constant speed or variable speed wind turbines, which is described in section 4.3.3. Simulation results are given and if applicable, the results of the base case and the modified system are compared. Note that this approach implies that the change in spinning reserve requirements caused by the incorporation of wind power in the system is neglected.

***Response to Fault and Generator Trip***

In this section, the mechanisms that lead to voltage and rotor speed instability are investigated. First, the synchronous generator at bus 32 of the New England test system depicted in figure 5.7 was replaced by a wind park with constant speed wind turbines and a 150 ms fault occurred at bus 11. The voltage at bus 32 and the rotor speed of the constant speed wind turbines are depicted in the upper two graphs of figure 5.20.

From the figure, it can be concluded that the voltage does not return to its pre disturbance value. Instead, the voltage oscillates. The oscillation is caused by the relatively soft shaft of the wind turbine. As pointed out earlier, the shaft softness causes a large angular displacement between the two shaft ends and a significant energy storage in the shaft. When the fault occurs, this energy is released and rotor speed increases quickly. When the voltage restores, the shaft causes an oscillation that can be seen in the figure. The results shown in figure 5.17 correspond with those presented in the last section and in other literature [41, 42].

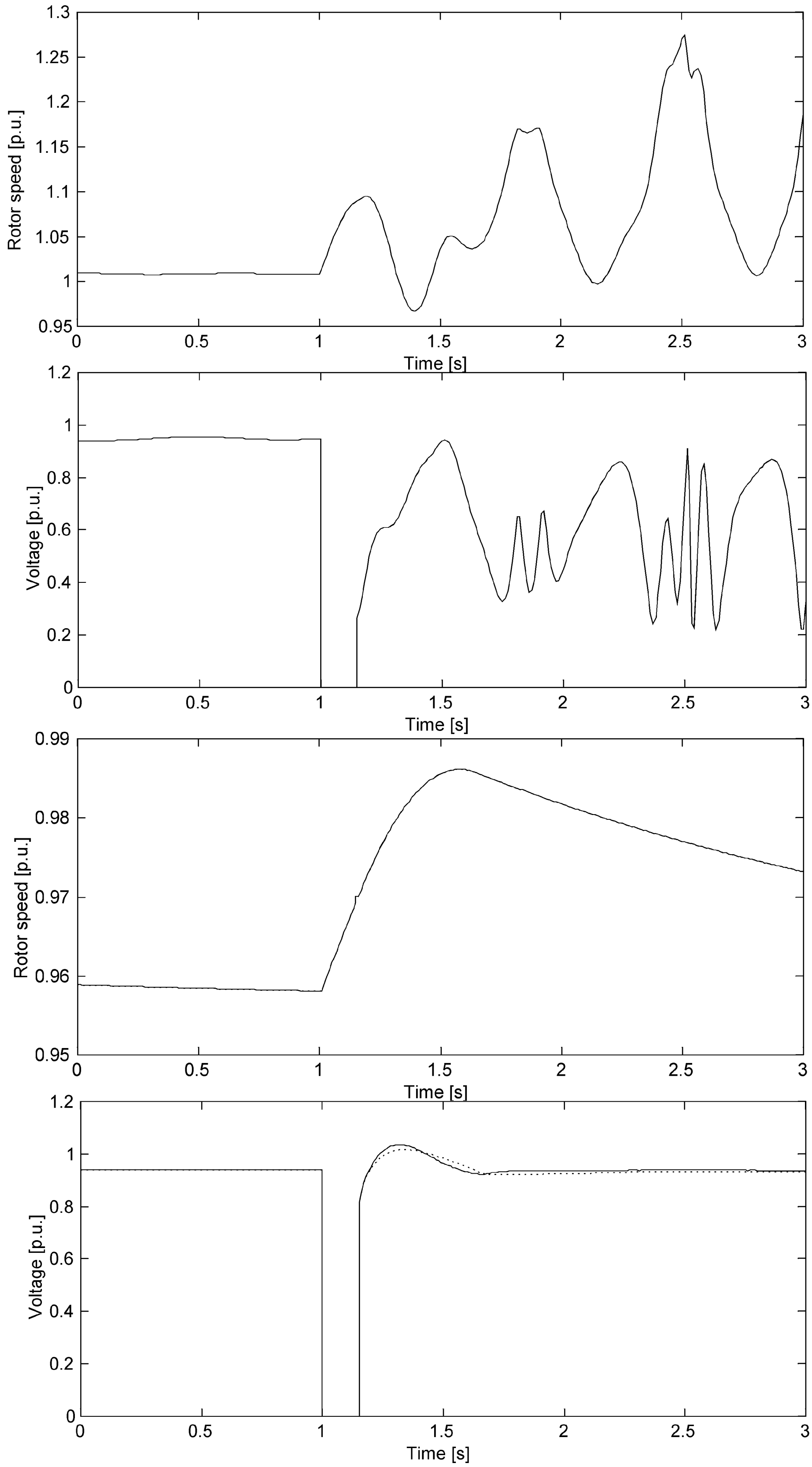


*Figure 5.20 Rotor speed and voltage at bus 32 for constant speed wind turbines (upper graphs) and for variable speed wind turbines (lower graphs) after a 150 ms fault at bus 32. In the lowest graph, the dotted and solid lines correspond to variable speed wind turbines operating at unity power factor or in terminal voltage control mode, respectively.*

Thereafter, the synchronous generator at bus 32 was replaced by a wind park with variable speed wind turbines either without (dotted line) or with (solid line) terminal voltage/reactive power control and the same fault was applied. The results are depicted in the two lower graphs in figure 5.20. It can be seen that the variable speed wind turbines are transiently stable.

As already mentioned, voltage and rotor speed instability can occur independently of a fault. Instability can also be caused by the voltage drop that results after the tripping of a synchronous generator from the grid. In the upper graphs of figure 5.21, the rotor speed of a wind park with constant speed turbines and the voltage at bus 32 are depicted when the synchronous generator at bus 31 trips. In the lower graphs, the rotor speed of variable speed turbines and the voltage at bus 32 are depicted when variable speed turbines either without (dotted line) or with (solid line) terminal voltage/reactive power control are applied.
It can be concluded from figure 5.21 that constant wind turbines can become unstable due to a bus voltage decrease and hence have to be disconnected, whereas variable speed wind turbines can stay connected. Further, it can be seen that wind turbines with terminal voltage control behave more favourably than wind turbines without voltage control, because they attempt to bring the voltage back to its pre disturbance value.

***Response to Frequency Disturbance***
As discussed in section 5.2, the mechanical and electrical behaviour of variable speed wind turbines are decoupled by the power electronic converters. As a result, mechanical quantities, such as rotor speed and mechanical power are largely independent of electrical quantities, such as active and reactive power and generator terminal voltage and frequency. Therefore, the energy stored in the rotating mass of variable speed wind turbines is not released when the grid frequency drops.
To illustrate this effect, the generators at buses 32, 36 and 37, generating 1750 MW, were replaced by wind parks. Given that the total generation in the system equals 6140 MW, this corresponds to a wind power penetration level of 28.5 %. If synchronous generators are replaced by wind turbines on such a large scale, it is not possible to replace only the active power from the synchronous generators by power from wind turbines. Also the reactive power generation/voltage control task of the synchronous generators that are replaced must be fulfilled by the wind turbines that replace them. Therefore, only constant speed wind turbines with SVCs and variable speed wind turbines with terminal voltage controllers are studied when investigating the impact of wind power on frequency stability. Constant speed wind turbines without controllable reactive power source and variable speed wind turbines running at unity power factor were not taken into account.

In figure 5.22, the simulation results are shown when the synchronous generator at bus 30, delivering 250 MW, was tripped. This corresponded to a loss of 4% of the generation in the system, and thus to a severe disturbance of the power balance. The solid line corresponds to

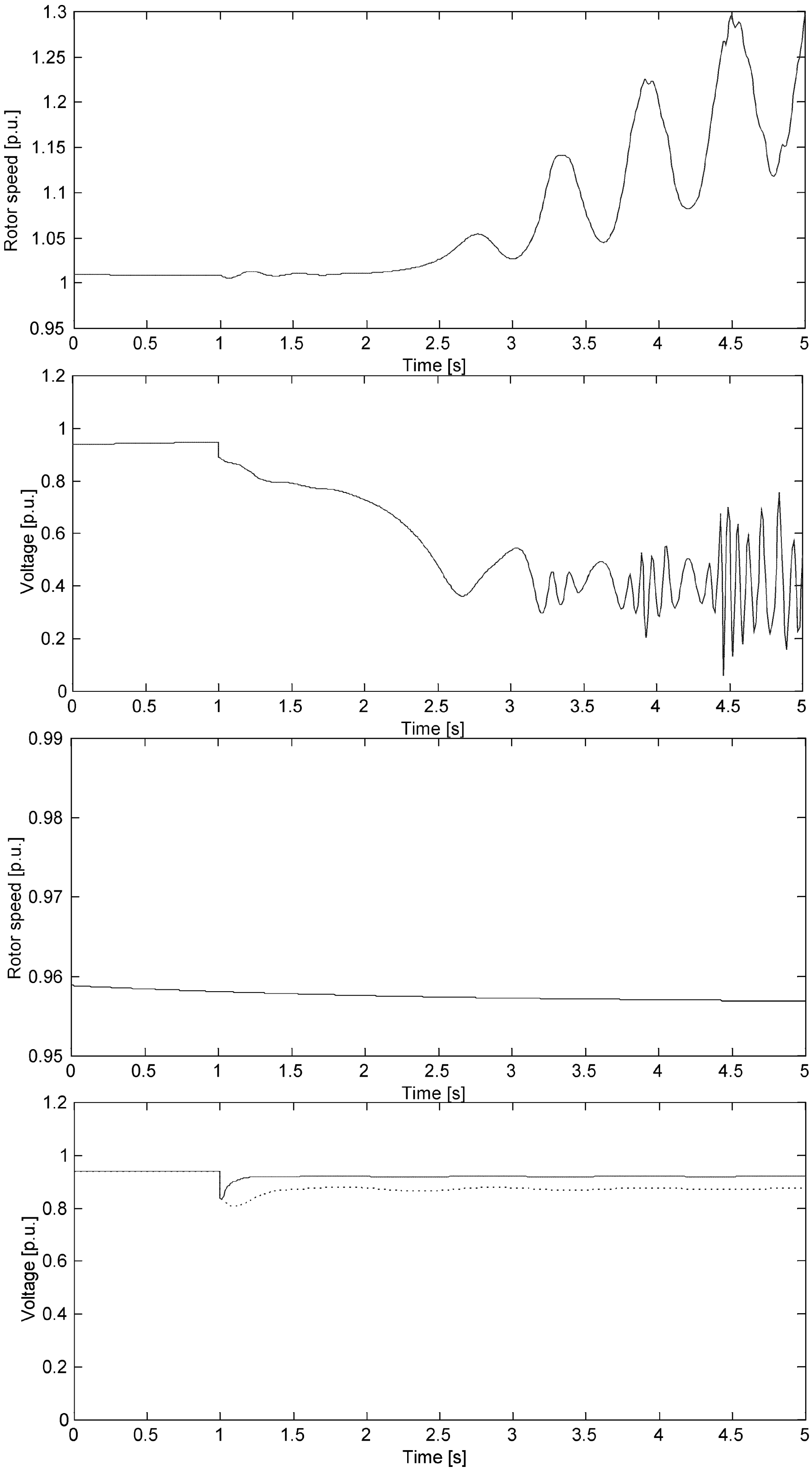


*Figure 5.21. Rotor speed and voltage at bus 32 for constant speed wind turbines (upper graphs) and for variable speed wind turbines (lower graphs) after the tripping of the synchronous generator at bus 31. In the lowest graph, the dotted and solid lines correspond to variable speed wind turbines operating at unity power factor or in terminal voltage control mode, respectively.*

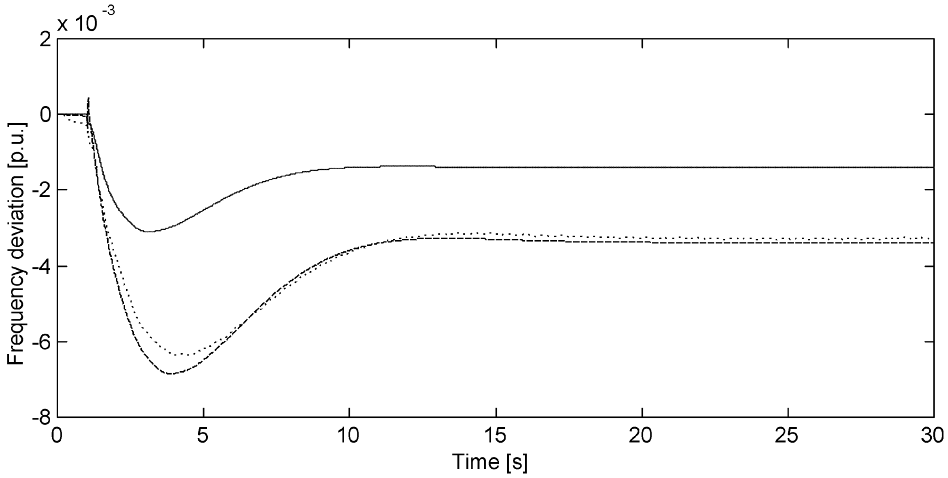


*Figure 5.22 Frequency drop after the tripping of the synchronous generator at bus 30: base case (solid line) compared with wind parks with variable speed wind turbines (dashed line) and constant speed wind turbines (dotted line) at buses 32, 36 and 37, corresponding to a wind power penetration level of 28.5 %.*

the base case, the dashed line to the case with variable speed wind turbines and the dotted line to the case with constant speed wind turbines.

From the figure, it can be concluded that the frequency drop is both deeper and lasts longer when wind turbines are connected instead of synchronous generators. This result can be explained by noticing that the wind turbines are not equipped with governors. As a result, less synchronous generators remain to compensate for the loss of generation and a larger frequency deviation occurs before the balance is restored. Equipping wind turbines with governors would mean that not all primary energy could be used, because there must remain room to increase generated power. This could lead to a substantial reduction in energy yield.

It can also be concluded that the frequency drop is deepest for variable speed wind turbines, which is caused by the decoupling of electrical and mechanical quantities. Although the prime mover power of constant speed wind turbines does not increase when the frequency drops, they nevertheless supply some extra power. The rotor speed is reduced and in this way, some of the energy stored in the rotating mass is supplied to the system, counteracting the frequency drop. This effect does not occur in case of variable speed wind turbines, where the mechanical rotor speed and grid frequency are decoupled. This explains why the frequency drop is slightly deeper with variable speed wind turbines than with constant speed wind turbines.

***Impact on Rotor Speed Oscillations of Synchronous Generators***

The third effect of an increasing wind turbine penetration in electrical power systems to be studied here is the possible change in the damping of the rotor speed oscillations of the remaining synchronous generators that occur after a fault. Again, only constant speed wind turbines with SVCs and variable speed wind turbines with terminal voltage controllers were studied, because a high wind energy penetration was assumed.

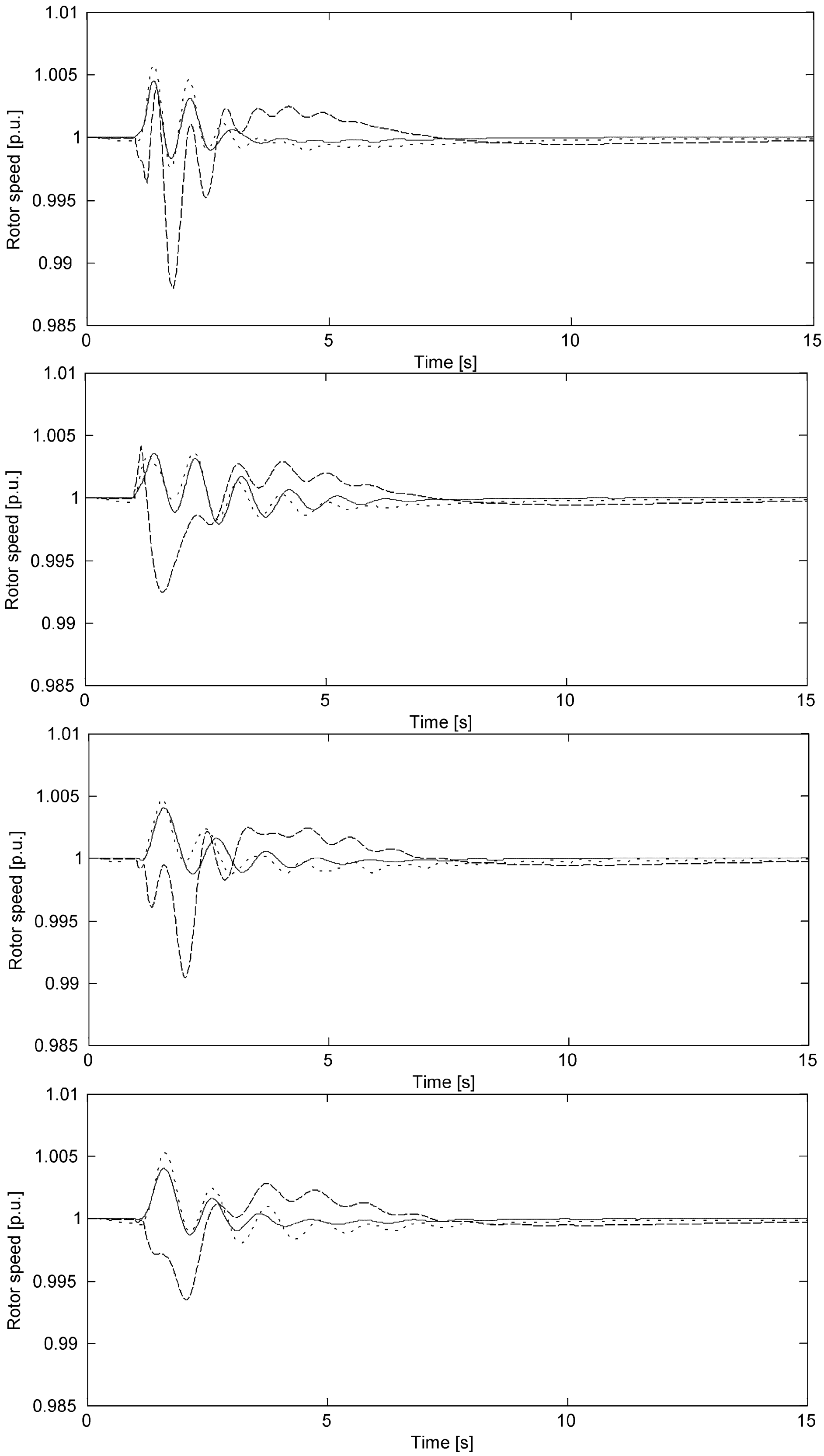


*Figure 5.23 Rotor speed oscillations of the synchronous generators at buses 30, 31, 35 and 38 (from above) at a wind power penetration level of 28.5 %. The solid line corresponds to the base case, the dotted line to constant speed wind turbines and the dashed line to variable speed wind turbines.*

A 150 ms fault was applied to bus 39. In figure 5.23, the rotor speed of the synchronous generators at buses 30, 31, 35 and 38 (from above) are depicted to illustrate the results. The solid line corresponds to the base case, the dotted line to constant speed wind turbines and the dashed line to the variable speed wind turbines. From the figure, it can be concluded that the time constant of the damping of the oscillations that occur after the fault is not significantly influenced by the presence of the wind turbines. Although the shapes of the oscillations are quite different, the system remains stable and returns to steady state in less than 10 s in all cases. Further, the following can be seen:

- The shape of the oscillations is slightly changed if constant speed wind turbines are connected. This is caused by the different behaviour of squirrel cage induction and synchronous generators and by the shaft of the wind turbines. As already pointed out, the shaft is relatively soft, resulting in a large angular displacement between the shaft ends and in a significant amount of energy being stored in the shaft. When the fault occurs, this energy is released and rotor speed increases quickly. When the voltage restores, the shaft causes an oscillation that can be seen in the figure.
- With variable speed wind turbines, the rotor speed of some of the generators drops when a remote fault occurs. This is caused by the fact that the variable speed wind turbines do not generate power during the fault and take some time to reconnect and increase their power back to the prefault value after restoration of the terminal voltage.
- With variable speed wind turbines, the rotor speed of the generators increases after clearance of the fault. This can be explained as follows. Due to the rotor speed decrease of some of the synchronous generators during the fault, that is caused by the generation deficit during the fault, the mechanical power of these generators is increased by their governors. After clearance of the fault, the power generated by the wind turbines returns to a value that is slightly higher than the pre fault value, due to the rotor speed increase of the wind turbine during the fault. In combination, these two effects lead to a generation surplus after the fault, which is converted to rotational energy and causes an increase of the rotor speed of the synchronous generators.

### 5.5.4 Results for the Dutch power system

This section illustrates the application of the models for the investigation of the impact of wind turbines on the dynamics of a practical power system. The case that is studied is the connection of 1500 MW of offshore wind power to the Dutch grid. This amount of wind power is the official goal of the Dutch government for the year 2010 for offshore wind.

In the study, the wind power was assumed to be geographically concentrated and connected to a new 380 kV substation in the west of the Netherlands (Beverwijk), which does not exist yet. This substation was connected to the Dutch high voltage grid with one double circuit overhead line. Although the chosen solution is not the most favourable from the perspective of reliability and the smoothing of output power fluctuations, it is the most interesting case for studying the impact of a large amount of wind power on the power system. If the wind power is spread over more substations, its impact on system dynamics becomes less. Connection to one substation can hence also be considered as the worst case scenario. If this does not lead to instability, the chance that connection of the same amount of wind power to a number of different substations will nevertheless lead to instability can be assumed to be very low.

Four technologies were studied in the simulations, namely:

- a wind park with constant speed wind turbines, connected to the system through an AC cable
- a wind park with variable speed wind turbines without voltage control, connected to the system through an AC cable
- a wind park with variable speed wind turbines with voltage control, connected to the system through an AC cable
- a wind park connected to the system through a voltage source converter based HVDC link, where the on shore converter is equipped with voltage control

Further, a reference scenario without wind power was included as well, resulting in five different system topologies.

In the simulations, the aggregated wind park models described in section 4.3 were used to represent the wind park. The wind park connected through a DC cable was represented by an aggregated model of a wind park with variable speed wind turbines with voltage control, which was directly connected to the 380 kV substation Beverwijk, rather than through an impedance, as was the case with the other three technologies. The impedance used to connect the wind park to the grid in the other cases represents a sea cable and two transformers: one at the turbine's terminals and one at the PCC.

***Fault in the High Voltage Network***

Firstly, the occurrence of a fault in the high voltage network was simulated. In order to investigate the robustness of the results for variations in fault duration and network topology, four different cases were investigated, namely:

- a 150 ms fault at substation Beverwijk
- a 200 ms fault at substation Beverwijk
- a 200 ms fault at substation Beverwijk with one of the two 380 kV lines between Beverwijk and Diemen out of service
- a 200 ms fault at substation Beverwijk with all conventional generators in the vicinity out of service

In all four cases, the fault was cleared without disconnecting any network components. The results are depicted in figures 5.24 and 5.25. In figure 5.24, the voltage at substation Beverwijk is shown, whereas in figure 5.25, the rotor speed of the wind turbines is depicted.

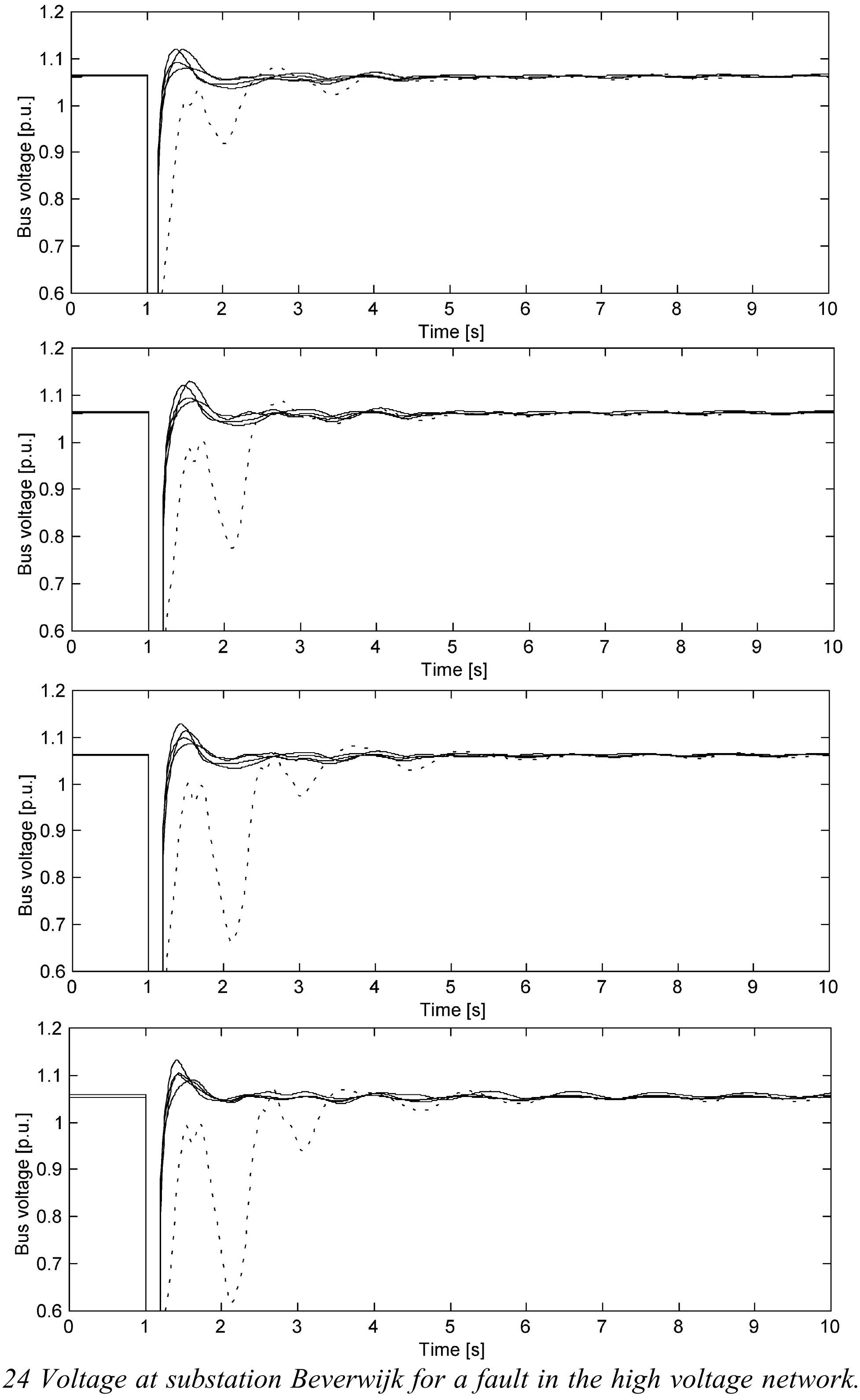


*Figure 5.24 Voltage at substation Beverwijk for a fault in the high voltage network. Starting from above: 150 ms fault at substation Beverwijk, 200 ms fault at substation Beverwijk. 200 ms fault at substation Beverwijk with one of the two 380 kV lines between Beverwijk and Diemen out of service and 200 ms fault at substation Beverwijk while all conventional generators in the vicinity are out of service. The dotted line corresponds to a wind park with constant speed wind turbines, the solid lines to a wind park with variable speed wind turbines with and without voltage control, a DC connected wind park and the reference scenario.*

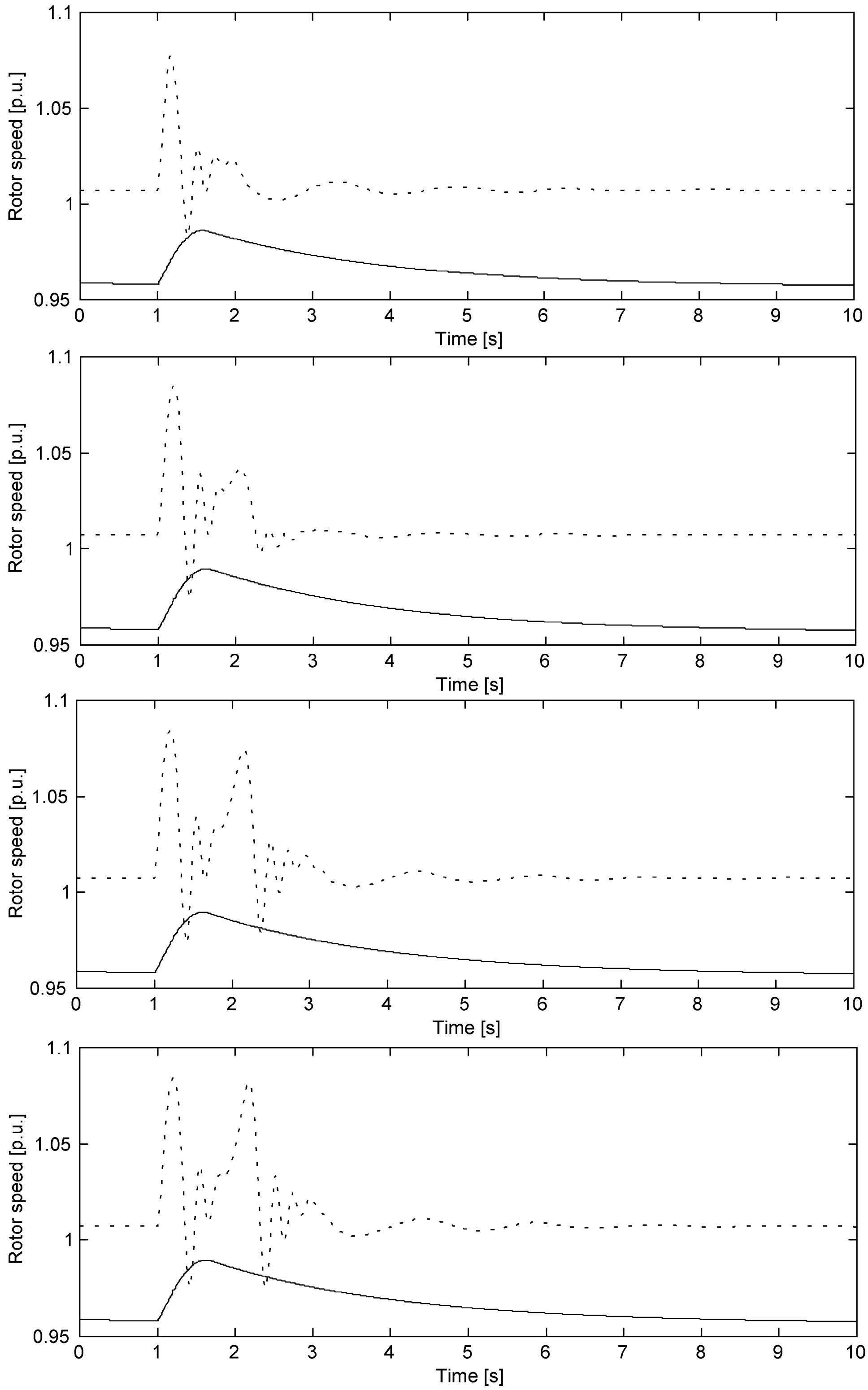


*Figure 5.25 Rotor speed of wind turbines for a fault in the high voltage network. Starting from above: 150 ms fault at substation Beverwijk, 200 ms fault at substation Beverwijk. 200 ms fault at substation Beverwijk with one of the two 380 kV lines between Beverwijk and Diemen out of service and 200 ms fault at substation Beverwijk while all conventional generators in the vicinity are out of service. The dotted line corresponds to a wind park with constant speed wind turbines, the solid line to a wind park with variable speed wind turbines and a DC connected wind park.*

From the simulation results, it can first of all be concluded that the power system remains stable in all cases that were examined. The instability observed in the New England Test System does not occur in this practical case. The first reason for this is that although a 1500 MW wind park is as such substantial, the corresponding wind power penetration in the UCTE network is still very low, as can be seen when comparing the 1500 MW with the total amount of generated power, given in table 5.3. Further, the Dutch power system is quite compact because of the high load density in The Netherlands. As a result, the wind park is connected to a stronger system than was the case with the New England Test System and the instability that was observed in case of the New England Test System can therefore not be found in the Dutch power system for the examined cases.

From figure 5.24, it can further be concluded that four of the five traces are very similar, whereas one deviates significantly from the other four. This one is also much more affected by changes in fault duration and grid topology. Based on the discussions and simulation results presented earlier in this chapter, it can easily be concluded that this trace corresponds to a wind park with constant speed wind turbines, whereas the other four correspond to the AC connected wind park with variable speed wind turbines, either without or with voltage controller, the DC connected wind park and the reference scenario. Constant speed wind turbines are much more affected by the strength of the grid coupling and the amount of overspeed, which is dependent on the fault duration, than variable speed wind turbines. This can also be seen in figure 5.22, where it can be observed that the rotor speed of the constant speed turbines is affected by changes in fault duration, grid topology and commitment of the nearby conventional generators, whereas this does hardly apply to the variable speed wind turbines. Figure 5.22 thus once more illustrates the decoupling effect of a power electronics converter.

The reasons that there is not much difference between the four other cases, namely an AC connected wind park with variable speed wind turbines without or with voltage control, a DC connected wind park and the reference scenario, are:

- If an AC connection is used, the wind turbines are relatively weakly coupled to the power system because there are two transformers and a cable between the wind turbine terminals and the point of grid connection. The influence that the wind turbines exert on the voltage at the Beverwijk substation is therefore limited.
- During and immediately after the fault, the output of the variable speed wind turbines and that of the onshore AC/DC converter is limited due to the action of the protection system. It takes 500 ms until the wind turbines or the converter are back at their normal operating point and in this period, they hardly contribute to voltage restoration.

For these two reasons, in all these cases the voltage restoration is mainly determined by the characteristics of other components of the power system, such as conventional generators.

Therefore, the differences between the three technological options that require power electronics and the case without wind power generation are small.

***Tripping of a Nearby Unit***

Secondly, the response of the wind park to the tripping of a nearby conventional unit, which was equipped with a directly grid coupled synchronous generator, was simulated. The simulation results are given in figure 5.26. In the upper graph, the reactive power flowing from the PCC to the Dutch power system is depicted; in the lower graph the voltage at substation Beverwijk. The meaning of the curves is indicated in the graphs.

From the simulations results, it can again be concluded that the system is stable and that the instability that occurs in the New England Test System after the tripping of a unit close to a wind park with constant speed wind turbines, is not observed in the Dutch power system. Further, in all cases the voltage at substation Beverwijk stays well within the allowable limits, independently of the applied wind turbine technology. The reason for this is that the Dutch power system is relatively compact and strong, as pointed out before.

However, in contrast to what applies to the fault response, which was studied above, in this case there are differences between the various technologies used for the wind park. The main reason for this is that the technologies with power electronics do not disconnect when a unit trips, as was the case with a fault, but stay connected and respond to the disturbance. It can be concluded that the DC connected wind park and the wind park with variable speed wind turbines with voltage control contribute to node voltage control. For these technologies, the voltage at substation Beverwijk settles close to the initial value. Further, these technologies respond to the change in terminal voltage caused by the tripping of the nearby conventional unit by changing their reactive power output, as can be seen in the lower graph. The fact that the DC connected wind park contributes more to maintaining node voltages than the AC connected wind park with variable speed wind turbines with voltage control is caused by the stronger grid coupling of the DC connected park.

The response for the wind park with variable speed wind turbines without voltage control and that with constant speed wind turbines is very similar. In both cases, the reactive power exchange between the wind park and the system is hardly or not affected and the voltage settles about 0.02 p.u. below the initial value.

The observation that in the reference scenario the voltage recovers most quickly and settles near the initial value can be explained as follows. In the reference scenario, more conventional power plants in that part of the network where the wind park is connected are in operation than is the case when the wind park is disconnected, in order to compensate for the power generated by the wind park. These conventional units contribute to node voltage control as well.

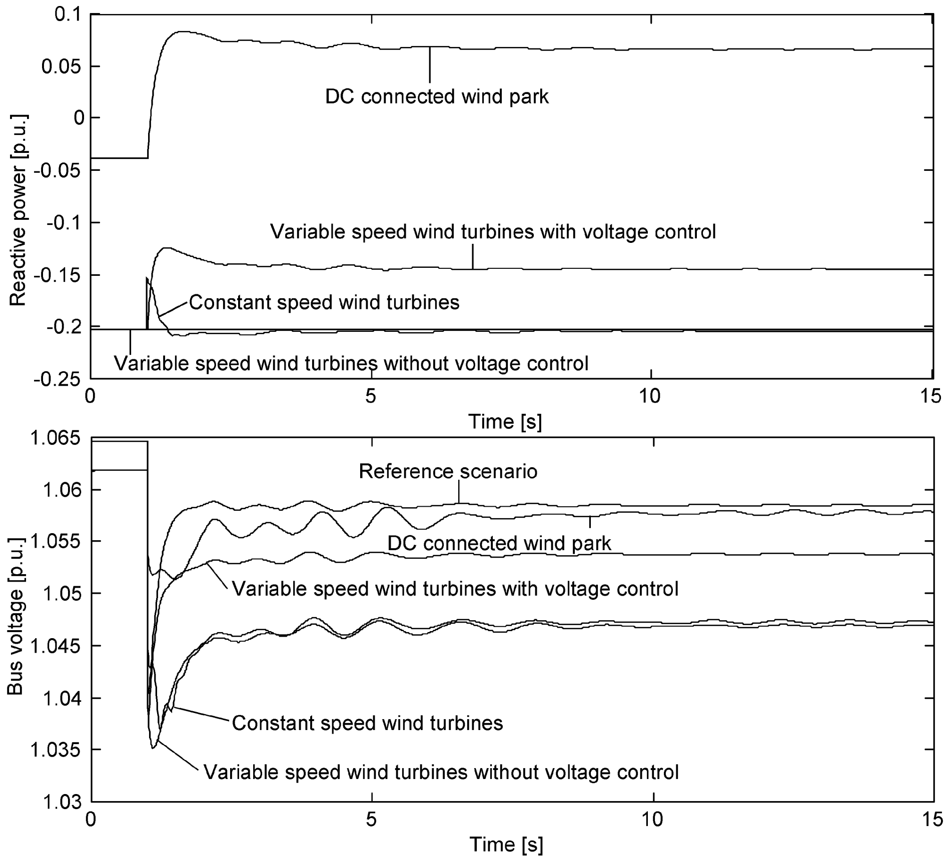


*Figure 5.26 Reactive power exchange (upper graph) and voltage at substation Beverwijk (lower graph) when a unit close to the offshore wind park trips.*

## 5.6 CONCLUSIONS

### 5.6.1 Behaviour of Wind Turbines and Parks

In this chapter, first the response of each wind turbine concept to disturbances was discussed. It was shown that the impact of constant speed wind turbines and that of variable speed wind turbines on power system transient stability is fundamentally different. This is mainly caused by the fact that:

- Constant speed wind turbines are equipped with stall control, whereas variable speed wind turbines are equipped with pitch control. Therefore, in case of variable speed wind turbines, the mechanical power extracted from the wind can be reduced to limit the amount of overspeed during the fault, whereas this is normally not possible in case of constant speed wind turbines.
- Constant speed wind turbines are based on a directly grid coupled asynchronous squirrel cage induction generator, which must be decelerated and pulled back to its normal operating point by the grid after a fault. In case of a squirrel cage induction generator, this leads to a large demand for reactive power, which impedes the voltage restoration and can lead to voltage instability. The generator in variable speed wind turbines is grid coupled by power electronics. As a result, grid frequency and mechanical rotor

frequency are decoupled. The rotor of variable speed wind turbines is therefore not affected by the restoration of the voltage after a fault. Rather, the rotor is picked up by the converter at the actual rotor speed and then driven back to the normal operating point.

- The power electronics in variable speed wind turbines tends to be very sensitive to overcurrents and therefore to voltage drops. A relatively small voltage drop can lead to the disconnection of a variable speed wind turbine in order to protect the power electronics. The squirrel cage induction generator in a constant speed wind turbine is less sensitive to overcurrents, because thermal time constants are longer and can thus better withstand voltage drops.

It was also pointed out that the decoupling of mechanical rotor speed and grid frequency in variable speed wind turbines means that the rotor speed of variable speed wind turbines is not affected by the grid frequency. Thus, no rotational energy is released from or stored in the rotor inertia at changes in the grid frequency, as is the case with generators that are coupled directly to the grid.

Then, the behaviour of wind parks was analysed. It was concluded that if the park's internal infrastructure and the grid coupling are implemented using conventional AC technology, the park's behaviour is governed by the wind turbine type used, as the infrastructure is passive. However, if a DC link is used to connect the wind park to the grid, the wind turbines are electrically decoupled from the investigated system and the reactive power capabilities and fault response of the wind park are governed by the technology used for implementing the DC connection, rather than by the applied wind turbine concept. The DC connection can be of a current source type or of a voltage source type. These technologies show differences in reactive power controllability and fault response.

Further, the topic of wind turbine protection was discussed. It was pointed out that the protection systems of wind turbines can either be tuned in order to optimize the grid interaction, or to prevent the turbine from becoming damaged. Anti-islanding protection is an example of the first approach. In this protection system, the perceived risk of islanding determines the setting of the protection system parameters, rather than the physical limits of the turbine's generator, converter or mechanical structure. The main goal of the protection system is to prevent islanding, not to protect the turbine. The disconnection of variable speed wind turbines at voltage drops, on the other hand, is an example of a protection system preventing turbine damage, which is tuned according to the physical limits of the power electronics converter without taking into account the interaction with the grid.

It was argued that if the wind power penetration level increases, it becomes more and more important to keep wind turbines connected during faults, in order to prevent the loss of a significant amount of generation that would cause large disturbances of the power balance. As a result, with an increasing wind power penetration level the goal of the protection system shifts away from optimizing the interaction with the power system (because the optimum interaction with the power system is to stay connected to the grid under nearly all circumstances) and shifts towards protecting the turbine itself.

It may even be necessary to change the turbine's design in order to improve the fault response and the capability to withstand voltage drops at high wind power penetration levels. Grid requirements established by a number of transmission system operators and grid companies, who are responsible for the stability of the system, contain the requirement that a wind turbine must stay connected during a fault of a certain duration and with a certain residual voltage. This makes profound design changes to the generating system of variable speed wind turbines inevitable and could even lead to a general shift towards different types of generating systems amongst manufacturers.

### 5.6.2 Impact of Wind Power on Transient Stability of Power Systems

The second half of this chapter was devoted to a quantitative investigation of the impact of wind power on the transient dynamics of power systems, based on simulations. First, the impact of various quantities on the fault response of both constant and variable speed wind turbines was investigated. It was concluded that in case of constant wind turbines the fault response is dependent on many factors, such as the fault duration, the strength of the grid coupling and on mechanical properties of the turbine, such as the shaft stiffness and the moment of inertia. In case of variable speed wind turbines, the fault response is for the largest part determined by the settings of the protection system. The fault duration, strength of grid coupling and mechanical properties only play a minor role. These results are directly linked to the differences in the working principles between constant and variable speed turbines that were treated in the more qualitative analysis of the response of each of the types of wind turbines to disturbances.

Then, dynamic models of a widely used test system, the New England Test System, and a practical power system, the Dutch power system, were developed and used to investigate the impact of wind power on the dynamics of a larger power system. In the test systems, conventional synchronous generators were replaced by aggregated wind park models and various events were simulated.

From the results obtained with the New England Test System, it could be concluded that the impact on the dynamics of a power system differs between constant and variable speed wind turbines, due to their different working principles. Constant speed wind turbines can easily cause voltage and rotor speed instability, initiated by a fault or by the tripping of a nearby synchronous generator. This risk hardly exists in case of variable speed wind turbines.

It was also concluded that the frequency drop occurring after the tripping of a generator becomes higher when the wind energy penetration in the system increases. This observation can be explained in the following way:

- Because the prime mover of wind turbines cannot be controlled, the power generated by the wind turbines does not increase when the frequency decreases, as is the case with conventional power plants due to governor action
- In variable speed wind turbines, the mechanical rotor frequency is decoupled from the grid frequency and the energy stored in the rotating mass is not released, resulting in a frequency drop that is larger than that for constant speed wind turbines.

Finally, the rotor speed oscillations of the synchronous generators that occur after a fault were studied. It was concluded that the shape of the oscillation changed due to the connection of the wind turbines. The time constant of the damping of the oscillations, however, was hardly affected and the system returned to a stable operating point in all cases.

The results of the simulations with the practical system, a model of the Dutch power system and the surrounding UCTE network to which an offshore wind park of 1500 MW was connected, further supported the qualitative analysis of the first part of the chapter. The differences between constant and variable speed turbines were reemphasized. However, in the practical power system, no instability occurred, as was the case with the New England Test System. The reasons for this are that the wind power penetration in the practical power system was much lower than that in the test system and the fact that the practical power system was more strongly coupled due to the high load density in the Netherlands.

# Impact of Wind Turbines and Wind Parks on Small Signal Stability

## 6.1 INTRODUCTION

In chapters 3 and 4, models of individual wind turbines and aggregated wind park models were developed. In chapter 5, these models were applied to investigate the impact of wind power on power system transient stability. In this chapter, the models are used to investigate the impact of wind power on the small signal stability of a power system.
First, the concept of small signal stability is defined and explained. The linearization of the equations describing an electrical power system is discussed and the correspondence between the eigenvalues of the state matrix, which is part of the linearized representation of the system, and its time domain response is pointed out. Then, the physical origin of power system oscillations, which are related to the physical working principles of synchronous generators, is treated and the different types of power system oscillations, namely oscillations of a (group of) generator(s) against a strong system, intra-area oscillations and inter-area oscillations, are commented upon.
The software package PSS/E™ was used for the calculations that were carried out to investigate the small signal stability. Before using this program to investigate the impact of wind power on power system small signal stability, its eigenvalue calculation capabilities were investigated and validated by comparing the obtained results with results yielded by another power system analysis software package and with results given in the literature.
Then, the impact of wind power on the small signal stability of a power system is studied. First, it is analysed whether the generator systems used in wind turbines are prone to power system oscillations, as applies to synchronous generators. It is concluded that this is not the case, because both in the squirrel cage induction generator used in constant speed wind turbines as well as in variable speed generating systems, rotor speed oscillations are much better damped.
This conclusion is then illustrated with calculation results. To this end, first two test systems were developed. The three different kinds of power system oscillations that exist occur in these test systems. In the base case, all power consumed by the loads in the test systems is

generated by synchronous generators. Various cases were investigated in which some of these generators were either partly or fully replaced by wind power. The impact of wind power on the small signal stability is then investigated by depicting the trajectory of the system's eigenvalues in the complex plane while varying the wind power penetration level and its location.

The conclusion that wind turbines themselves do not lead to power system oscillations is confirmed by the results of the calculations. Further, these results show that wind turbines affect oscillations of a (group of) generator(s) against a strong system and inter-area oscillations, whereas the impact on intra-area oscillations is rather limited. In this chapter, the impact of wind turbines on the small signal stability of a power system is investigated for the first time. This topic has not been treated before in the literature.

## 6.2 SMALL SIGNAL STABILITY

### 6.2.1 Definition of Small Signal Stability

Small signal stability is defined as

*The capability to return to a stable operating point after the occurrence of a disturbance that leads to an incremental change in one or more of the state variables of the power system.*

This definition is similar to the definition of transient stability in section 5.2. The difference is, however, that the definition of transient stability refers to the system's response to a change in its *topology*, that may cause unbalances between load and generation, whereas the definition of small signal stability refers to the system's response to a small change in one or more of its *state variables*.

Examples of state variables of a power system are:

- synchronous and asynchronous machine rotor speeds
- synchronous machine load angles
- magnetic flux linkages
- controller state variables

If a disturbance causes a change in the value of one or more of these state variables, the system is driven from the equilibrium. If thereafter the system returns to its steady state, it is stable, whereas if the initial deviation from the steady state becomes ever larger, it is unstable. A further difference between transient stability and small signal stability is that if a steady state is reached after a disturbance leading to a transient phenomenon, i.e. a change in the system's topology, the new steady state can be different from the initial one. In contrast, if a system returns to a steady state after an incremental change in a state variable, this steady state is identical to the initial steady state, because no change in the network's topology has occurred.

### 6.2.2 Eigenvalues and Small Signal Stability

The aim of this section is to point out the correspondence between the eigenvalues of an electrical power system and its dynamic behaviour. To this end, first the linearization of the state equations of the power system is discussed. Thereafter, the correspondence between the eigenvalues of the *state matrix*, which is part of the linearized description, and the time domain will be pointed out.

***Linearization of State Equations***

The behaviour of a dynamic system, of which an electrical power system is one example, can be described with equation (3.1), which is repeated here for convenience

$$\begin{aligned}\dot{\boldsymbol{x}} &= \boldsymbol{f}(\boldsymbol{x},\boldsymbol{u},t)\\ \boldsymbol{y} &= \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u})\end{aligned} \tag{6.1}$$

where

**f** is a vector containing $n$ first-order non-linear differential equations
**x** is a vector containing $n$ state variables
**u** is a vector containing $r$ input variables
**g** is a vector containing $m$ non-linear algebraic equations
**y** is a vector containing $m$ output variables
and t is time. By assuming that the system in (6.1) is time invariant, i.e. the time derivatives of the state variables are not explicit functions of the time, t can be excluded from equation (6.1). Equation (6.1) can be linearized and the resulting linearized description of the system can be used to investigate its response to small variations in the input or state variables, starting at an equilibrium point [24, 74]. To this end, equation (6.1) is first expressed in terms of its Taylor's series expansion. With second and higher orders of the partial derivatives of **f** to the state variables omitted and only taking into account first-order terms, this gives the following for the *i*th component of vector **x**

$$\begin{aligned}\dot{x}_i = \dot{x}_{i0} + \Delta\dot{x}_i &= f_i[\boldsymbol{x_0} + \Delta\boldsymbol{x}, \boldsymbol{u_0} + \Delta\boldsymbol{u}]\\ &= f_i(\boldsymbol{x_0},\boldsymbol{u_0}) + \frac{\partial f_i}{\partial x_1}\Delta x_1 + \dots + \frac{\partial f_i}{\partial x_n}\Delta x_n\\ &\quad + \frac{\partial f_i}{\partial u_1}\Delta u_1 + \dots + \frac{\partial f_i}{\partial u_r}\Delta u_r\end{aligned} \tag{6.2}$$

From (6.1) it follows that

$$\dot{x}_{i0} = f_i(\boldsymbol{x_0},\boldsymbol{u_0}) \tag{6.3}$$

and therefore (6.2) can be written as

$$\Delta\dot{x}_i = \frac{\partial f_i}{\partial x_1}\Delta x_1 + \dots + \frac{\partial f_i}{\partial x_n}\Delta x_n + \frac{\partial f_i}{\partial u_1}\Delta u_1 + \dots + \frac{\partial f_i}{\partial u_r}\Delta u_r \tag{6.4}$$

The same can be done for the *j*th component of **y**

$$\Delta y_j = \frac{\partial g_j}{\partial x_1}\Delta x_1 + \ldots + \frac{\partial g_j}{\partial x_n}\Delta x_n + \frac{\partial g_j}{\partial u_1}\Delta u_1 + \ldots + \frac{\partial g_j}{\partial u_r}\Delta u_r \qquad (6.5)$$

Doing this for all components of the vectors **x** and **y** gives the following linearized set of equations

$$\begin{aligned} \Delta\dot{\boldsymbol{x}} &= \boldsymbol{A}\Delta\boldsymbol{x} + \boldsymbol{B}\Delta\boldsymbol{u} \\ \Delta\boldsymbol{y} &= \boldsymbol{C}\Delta\boldsymbol{x} + \boldsymbol{D}\Delta\boldsymbol{u} \end{aligned} \qquad (6.6)$$

with

$$\boldsymbol{A} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \ldots & \frac{\partial f_1}{\partial x_n} \\ \ldots & \ldots & \ldots \\ \frac{\partial f_n}{\partial x_1} & \ldots & \frac{\partial f_n}{\partial x_n} \end{bmatrix} \quad \boldsymbol{B} = \begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \ldots & \frac{\partial f_1}{\partial u_r} \\ \ldots & \ldots & \ldots \\ \frac{\partial f_n}{\partial u_1} & \ldots & \frac{\partial f_n}{\partial u_r} \end{bmatrix}$$

$$\boldsymbol{C} = \begin{bmatrix} \frac{\partial g_1}{\partial x_1} & \ldots & \frac{\partial g_1}{\partial x_n} \\ \ldots & \ldots & \ldots \\ \frac{\partial g_m}{\partial x_1} & \ldots & \frac{\partial g_m}{\partial x_n} \end{bmatrix} \quad \boldsymbol{D} = \begin{bmatrix} \frac{\partial g_1}{\partial u_1} & \ldots & \frac{\partial g_1}{\partial u_r} \\ \ldots & \ldots & \ldots \\ \frac{\partial g_m}{\partial u_1} & \ldots & \frac{\partial g_m}{\partial u_r} \end{bmatrix} \qquad (6.7)$$

Thus, the matrices **A**, **B**, **C** and **D** contain the partial derivatives of the functions in **f** and **g** to the state variables **x** and the input variables **u**. Matrix **A** is the *state matrix* of the system.

Equation (6.6) can be Laplace transformed to obtain the state equations in the frequency domain

$$\begin{aligned} s\Delta\boldsymbol{x}(s) - \Delta\boldsymbol{x}(0) &= \boldsymbol{A}\Delta\boldsymbol{x}(s) + \boldsymbol{B}\Delta\boldsymbol{u}(s) \\ \Delta\boldsymbol{y}(s) &= \boldsymbol{C}\Delta\boldsymbol{x}(s) + \boldsymbol{D}\Delta\boldsymbol{u}(s) \end{aligned} \qquad (6.8)$$

A solution to the state equations can be obtained by rearranging the upper equation of (6.8) as follows

$$(s\boldsymbol{I} - \boldsymbol{A})\Delta\boldsymbol{x}(s) = \Delta\boldsymbol{x}(0) + \boldsymbol{B}\Delta\boldsymbol{u}(s) \qquad (6.9)$$

The values of s which satisfy

$$\det(s\boldsymbol{I} - \boldsymbol{A}) = 0 \qquad (6.10)$$

are known as the eigenvalues of matrix **A** and equation (6.10) is defined as the characteristic equation of matrix **A**.

***Correspondence between Eigenvalues and Time Domain Response***

As will be shown now, the eigenvalues of the state matrix **A** determine the time domain response of the system to small perturbations and therefore contain important information on the dynamics of the power system under study. It can be shown that for any eigenvalue λ, a left and right eigenvector ψ and ϕ can be calculated, such that

$$\begin{aligned} \boldsymbol{A}\phi &= \lambda\phi \\ \psi\boldsymbol{A} &= \lambda\psi \end{aligned} \tag{6.11}$$

ϕ is a vector with $n$ rows and ψ is a vector with $n$ columns. According to the upper equation of (6.6), if no inputs are applied, the system is described by

$$\Delta\dot{\boldsymbol{x}} = \boldsymbol{A}\Delta\boldsymbol{x} \tag{6.12}$$

In this equation, the states are coupled, which means that they influence each other. It is hence difficult to draw conclusions with respect to the system behaviour. Therefore, the eigenvalues are put onto the diagonal of a matrix **Λ**, the transposed right eigenvectors are turned into the columns of a matrix **Ψ**, and the left eigenvectors are turned into the columns of a matrix **Φ**, after which the following transformation is applied

$$\Delta\boldsymbol{x} = \boldsymbol{\Phi}\boldsymbol{z} \tag{6.13}$$

Substituting this into equation (6.12) gives

$$\boldsymbol{\Phi}\dot{\boldsymbol{z}} = \boldsymbol{A}\boldsymbol{\Phi}\boldsymbol{z} \tag{6.14}$$

When the individual eigenvalues in the upper equation of (6.11) are replaced by the diagonal matrix **Λ** and both sides of the equations are multiplied the inverse of **Φ**, the following is true

$$\begin{aligned} \boldsymbol{A}\boldsymbol{\Phi} &= \boldsymbol{\Phi}\boldsymbol{\Lambda} \\ \boldsymbol{\Phi}^{-1}\boldsymbol{A}\boldsymbol{\Phi} &= \boldsymbol{\Lambda} \end{aligned} \tag{6.15}$$

Using the second equation together with (6.14), it can be seen that

$$\dot{\boldsymbol{z}} = \boldsymbol{\Lambda}\boldsymbol{z} \tag{6.16}$$

Because the matrix **Λ** is diagonal, it represents $n$ uncoupled algebraic equations of the form

$$\dot{z}_i = \lambda_i z_i \tag{6.17}$$

An equation of this form can be easily transformed back to the time domain, yielding

$$z_i(t) = z_i(o)e^{\lambda_i t} \tag{6.18}$$

Again using the transformation in equation (6.13) results in

$$\Delta\boldsymbol{x}(t) = \boldsymbol{\Phi}\boldsymbol{z}(t) \tag{6.19}$$

in which z contains the $n$ equations as given in (6.18).
This can be written as

$$\Delta\boldsymbol{x}(t) = \sum_{i=1}^{n} \phi_i z_i(0)e^{\lambda_i t} \tag{6.20}$$

It can be shown that the inverse of the matrix **Φ**, containing the left eigenvectors as columns, is the matrix **Ψ**, containing the transposed right eigenvectors as columns. Thus, using equation (6.19)

$$\boldsymbol{z}(t) = \boldsymbol{\Psi}\Delta\boldsymbol{x}(t) \tag{6.21}$$

and with t=0,

$$\boldsymbol{z}(0) = \boldsymbol{\Psi}\Delta\boldsymbol{x}(0) \tag{6.22}$$

The scalar product of $\psi_i$ and $\Delta\boldsymbol{x}(0)$ can be replaced by $c_i$. With equation (6.22), this results in

$$\Delta \boldsymbol{x}(t) = \sum_{i=1}^{n} \phi_i c_i e^{\lambda_i t} \tag{6.23}$$

Thus, the time response of the ith state variable is given by

$$\Delta x_i(t) = \phi_{i1} c_1 e^{\lambda_1 t} + \ldots + \phi_{in} c_n e^{\lambda_n t} \tag{6.24}$$

and it has been shown that the eigenvalues of the linearized system matrix determine the time domain response of the system to a perturbation, as was the aim of this discussion. If the eigenvalues are complex, in the case of real physical systems they always occur in pairs that are complex conjugates. Therefore, the imaginary parts cancel each other and equation (6.24) is real.

Equation (6.24) clearly illustrates the well known fact that the real part of an eigenvalue has to be negative for a system to be stable. An eigenvalue with a positive real part would cause the value of the corresponding state variable to increase over time and would thus cause instability. In practical situations, however, it has to be kept in mind that the eigenvalues of a linearized set of equations have been calculated. In non-linear systems, the eigenvalues depend on the system state and the eigenvalues change as the system state evolves. Therefore, a set of eigenvalues only characterizes the actual state of the system and not necessarily other states, and particularly eigenvalues near the imaginary axis must be treated with care.

### 6.2.3 Power System Oscillations

As can be concluded from equation (6.24), real eigenvalues of the matrix **A** translate into damped exponential terms in the equations describing the time domain response of an electrical power system. On the other hand, a complex eigenvalue of matrix **A** translates to sine and cosine terms in the time domain equations. A complex eigenvalue hence corresponds to an oscillation in the time domain. If oscillatory terms in the equations describing the behaviour of the mechanical quantities of synchronous generators, i.e. the rotor speed and the load angle, appear, the resulting oscillation is called a power system oscillation.

In general, three kinds of generator power system oscillations are distinguished, namely [24, 75]:

- Oscillations of one generator or a group of coherent generators against a strong system.
- Intra-area oscillations, i.e. oscillations of (groups of coherent) generators in a certain area of the network against each other. However, these affect the rest of the generators in the network hardly or not at all.
- Inter-area oscillations, i.e. oscillations of (groups of coherent) generators in a certain area of the network against (groups of coherent) generators in another area of the network, also hardly or not affecting the rest of the generators in the network.

The various oscillation types can be distinguished on the basis of their mode shape. The shape of a mode that corresponds to a certain eigenvalue can be investigated using participation factors and eigenvectors. A participation factor indicates the relative contribution of each state variable to a certain mode. The elements in the right eigenvector belonging to a mode indicate the phase angle of the contribution of each of the state variables to that mode. High participation factors and phase angle differences in the order of 180° indicate (groups of coherent) generators oscillating against each other. The location of these generators in the system determines the oscillation type. A group of generators that oscillates coherently will be further referred to as a swing node [76].

In general, the oscillation frequency becomes lower, starting from above in the list of oscillation types. Oscillations of the first type normally have a frequency above 1.0 Hz, those of the second type between 0.4 and 0.7 Hz and those of the third type between 0.1 and 0.3 Hz, depending on the size of the system. However, in a large system with many oscillatory modes, this order does not always hold. Therefore, the oscillation type should in this case not be determined only on the basis of the calculated oscillation frequency, but the mode shape, i.e. the location of the generators involved in the oscillation, should be taken into account as well.

### 6.2.4 Physical Origin of Power System Oscillations

In synchronous generators, the electrical torque is mainly dependent on the angle between rotor and stator flux. This angle is the integral of the difference in rotational speed between these two fluxes, which is in turn dependent on the difference between electrical and mechanical torque. This makes the mechanical part of the synchronous machine a second order system that intrinsically shows oscillatory behaviour. Further, small changes in rotor speed do hardly affect the electrical torque developed by the machine, as they hardly change the rotor angle.

Therefore, the mechanical part of a synchronous system is intrinsically prone to weakly damped oscillations and the damping of these oscillations must come from other sources, such as damper windings, the machine's controllers and the rest of the power system. However, the lower the frequency, the less damping is provided by the damper windings. Because power system oscillations have frequencies in the order of a few Hz and lower and a rather small amplitude, hardly any damping is provided by the damper windings, leaving the controllers and the rest of the power system as the main contributors to the damping of the rotor speed oscillations.

The factors contributing to the risk of weakly damped or undamped oscillations identified in the literature are relatively weak links and large concentrations of synchronous generators [76, 77]. This can be explained by noticing that if a synchronous generator is large compared to the scale of the system as a whole and/or if it is weakly coupled, the rest of the system will contribute less to the damping torque and thus damps an oscillation less. Further, the oscillation of a generator that is large compared to the system will also affect other generators, thus spreading the oscillation through the system and causing inter and intra-area oscillations in which a number of generators takes part that oscillate against each other.

## 6.3 EIGENVALUE CALCULATION IN PRACTICE

### 6.3.1 Eigenvalue Calculation with PSS/E™

In order to investigate the small signal stability of a power system by studying its eigenvalues, one needs the state matrix **A**. For large power systems, the number of states in equation (6.1) can amount to several hundreds or even thousands. In that case, it is impossible to linearize equation (6.1) by hand in order to calculate the matrix **A**. Therefore, computers are used to this end. Because for eigenvalue calculations the same information is needed as for time domain simulations, most power system dynamics simulation software packages cannot only be used for time domain simulations of power system dynamics like those carried out in chapter 5, but also to calculate the eigenvalues of a power system. This also applies to PSS/E™, the software package used for the research project reported in this thesis.

Even with a computer, it is quite complicated to construct the matrix **A** in equation (6.6) analytically, because this requires symbolic mathematics capabilities, particularly symbolic differentiation. Therefore, in PSS/E™, a method is implemented to construct the matrix **A** numerically, after which its eigenvalues can be calculated. Nevertheless, there exist power system dynamics simulation software packages that can calculate the matrix **A** analytically by means of symbolic differentiation of the right hand part of equation (6.1).
In PSS/E™, the matrix **A** is constructed in the following way. Starting from a valid equilibrium condition $\mathbf{x}_0$, a second state vector is created, $\mathbf{x}_i$, in which the *i*th component of $\mathbf{x}_0$ is perturbed. This means that a small amount is added to the *i*th component. The value of the other components of $\mathbf{x}_i$ is equal to that of the components of $\mathbf{x}_0$. Substituting $\mathbf{x}_i$ in equation 6.1 and evaluating the first-order differential equations in **f** for $\mathbf{x}_i$ gives

$$\dot{\boldsymbol{x}}_i = \boldsymbol{f}(\boldsymbol{x}_i, \boldsymbol{u}, t) = \boldsymbol{f}(\boldsymbol{x}_0 + \Delta\boldsymbol{x}_i, \boldsymbol{u}, t) \tag{6.25}$$

In (6.25), the vector $\Delta\mathbf{x}_i$ contains the applied perturbation as the *i*th component and zeros for the rest. According to equations (6.2) and (6.3),

$$\Delta\dot{\boldsymbol{x}}_i = \boldsymbol{f}(\boldsymbol{x}_i, \boldsymbol{u}, t) - \boldsymbol{f}(\boldsymbol{x}_0, \boldsymbol{u}, t) \tag{6.26}$$

However, if no inputs are applied, the following holds as well, according to equation (6.12)

$$\Delta\dot{\boldsymbol{x}}_i = \boldsymbol{A}\Delta\boldsymbol{x}_i \tag{6.27}$$

In (6.27), $\Delta\mathbf{x}_i$ is known because it is the vector with the applied perturbation and $\Delta d\mathbf{x}_i/dt$ is known from equation (6.25). The only unknown in (6.26) is therefore the matrix **A**. However, because all entries of $\Delta\mathbf{x}_i$ except the *i*th one contain zeros, most entries of the matrix **A** cannot be calculated using equation (6.27), as this would lead to an unallowed division by zero.
By defining a matrix $\mathbf{A}_i$, which is a matrix with the same dimensions of **A**, but containing only the *i*th column of the matrix **A** and zeros for the rest, equation (6.27) is turned into

$$\Delta\dot{\boldsymbol{x}}_i = \boldsymbol{A}_i\Delta\boldsymbol{x}_i \tag{6.28}$$

Equation (6.28) can be solved by calculating the entries of the *i*th column of $\mathbf{A_i}$, which are equal to the entries of $\Delta d\mathbf{x}_i/dt$ divided by the perturbation size. By sequentially perturbing all entries of the vector $\mathbf{x}_0$ to get different vectors $\mathbf{x}_i$ and $\Delta\mathbf{x}_i$, different matrices $\mathbf{A_i}$ result and all columns of the matrix **A** can be computed subsequently. When the matrix **A** has been constructed, its eigenvalues are calculated using numerical eigenvalue calculation routines [30].

The following remark must be made regarding this approach. The entries of the matrix **A** will be affected by the size of the applied perturbation. The larger the perturbation, the more inaccurate the resulting approximation of **A**. A perturbation as small as possible therefore seems preferable. However, when the perturbation is too small, numerical inaccuracies in calculating $\mathbf{x}_0$ and $\mathbf{x}_i$ will lead to inaccuracies in the approximation of **A** as well [78]. Therefore, if an eigenvalue with a very small real part is observed, it should be investigated how robust the approximation of **A** is to changes in the perturbation size, and it is advised to treat the results carefully if it is concluded that they are very sensitive to such changes.

### 6.3.2 Validation of PSS/E™ Eigenvalue Calculation Capabilities

Eigenvalue analysis does not have a history as long as transient stability analysis because of its computational requirements. Further, the results are often difficult to verify experimentally since this requires parallel, synchronous measurements at different locations in a power system for which a Wide Area Measurement System (WAMS) would be necessary. Therefore, it is important to assure that the results delivered by any software package used to calculate the eigenvalues of a power system are indeed correct, before applying the software to practical problems.

In order to validate the eigenvalue calculation capabilities of PSS/E™, we compared the results yielded by the analysis of some example systems to those found in the literature and those yielded by Simpow®, the power system dynamics simulation software package from ABB. The first test system that was used consists of a generator connected to an infinite bus, as depicted in figure 6.1. The generator is modelled with the classical model, consisting of a transient impedance behind an infinite bus. There are only two state variables: the load angle and the rotor speed deviation from 1 p.u.. The moment of inertia H equals 3.5 s and $L'_d$ equals 0.3 p.u., both on a 2220 MVA base. The system is described in [24], p. 732. In case of this rather simple system, it is possible to verify the eigenvalue calculation analytically. In table 6.1, the results yielded by PSS/E™, an analytical calculation and Simpow® are given, together with the results from [24].

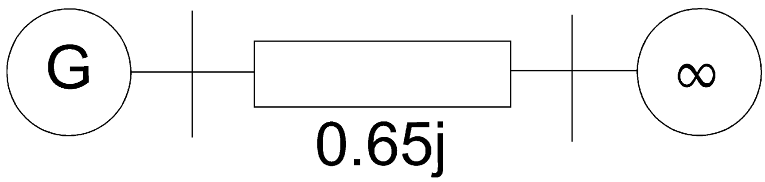


*Figure 6.1 Test system consisting of a generator connected to an infinite bus.*

*Table 6.1 Eigenvalues of a synchronous generator connected to an infinite bus when the generator is modelled with the classical model.*

| **PSS/E™** | **Analytical calculation** | **Simpow®** | **Ref. [24]** |
|---|---|---|---|
| +6.366j | +6.3847j | +6.3847j | +6.39j |
| -6.366j | -6.3847j | -6.3847j | -6.39j |

In the second case, again a synchronous generator connected to the infinite bus was studied, but this time, the generator was modelled with a sixth-order model. The state variables were the field winding flux and one damper winding flux in the d-axis, two damper winding fluxes in the q-axis, rotor speed speed deviation from 1 p.u. and load angle. The generator's governor and exciter were not modelled, the stator resistance $R_a$ equalled 0 and the stator transients, represented by the $d\psi/dt$ terms in equation (3.27), were neglected as is normally done in power system dynamics simulations for the reasons discussed in section 3.2. The generator parameters are given in table 6.2; the results in table 6.3. The difference between the columns marked Simpow® 1 and Simpow® 2 is that in the Simpow® 1 column mechanical power is an input to the synchronous generators, like in PSS/E™, whereas in the Simpow® 2 column, the input is the mechanical torque, like in [24].

*Table 6.2 Sixth-order synchronous generator model parameters.*

| **Quantity** | **Value** | **Quantity** | **Value** |
|---|---|---|---|
| $T'_{do}$ | 8.0 s | $L_q$ | 1.76 p.u. |
| $T''_{do}$ | 0.03 s | $L'_d$ | 0.30 p.u. |
| $T'_{qo}$ | 1.0 s | $L'_q$ | 0.65 p.u. |
| $T''_{qo}$ | 0.07 s | $L''_d$* | 0.25 p.u. |
| H | 3.5 s | $L_l$ | 0.16 p.u. |
| D | 0 | S(1.0)** | 0.124 p.u. |
| $L_d$ | 1.81 p.u. | S(1.2)** | 0.431 p.u. |

* $L''_d$ equals $L''_q$ due to the PSS/E™ synchronous generator model structure
** Equals 0 when magnetic saturation is neglected

*Table 6.3 Eigenvalues of a synchronous generator connected to an infinite bus when the generator is modelled with a sixth-order model.*

| **PSS/E™** | **Simpow® 1** | **Simpow® 2** | **Ref. [24]** |
|---|---|---|---|
| -0.262+6.34j | -0.225+6.41j | -0.160+6.41j | -0.171+6.47j |
| -0.262-6.34j | -0.225-6.41j | -0.160-6.41j | -0.171-6.47j |
| -0.185 | -0.114 | -0.114 | -0.2 |
| -2.227 | -2.148 | -2.148 | -2.045 |
| -21.396 | -22.08 | -22.08 | -25.01 |
| -35.425 | -35.88 | -35.88 | -37.85 |

As can be concluded from tables 6.1 and 6.3, the results yielded by PSS/E™ and Simpow® are similar when the input variables are identical. On the other hand, the results obtained with Simpow® agree closely with the results given in the literature when the input variables are again identical. Thus, the differences observed in table 6.3 can be attributed to the different selection of the variable for the mechanical input and to a different treatment of the rotor speed term in the stator voltage equations. They should therefore not raise doubts with respect to the reliability of the results. Further, given the rather large differences that result from differences in the selection of input variables and in the treatment of the rotor speed term in the stator voltage equations, the results yielded by eigenvalue analysis should be treated with care anyway.

The eigenvalue calculation capabilities of PSS/E™ were validated further by means of performing calculations with a larger test system with four generators and by investigating the impact of controller parameters on the eigenvalues in both PSS/E™ and Simpow®. In all cases, the level of correspondence between the results obtained with the two programs and, if available, the results given in reference [24] was very high. It was therefore concluded that the results yielded by eigenvalue calculations in PSS/E™ are trustworthy, so that the program can be used to investigate the impact of wind power on the small signal stability of power systems.

## 6.4 ANALYSIS OF WIND TURBINE CHARACTERISTICS

In section 6.3, the physical origin of power system oscillations was discussed. It was concluded that power system oscillations are caused by the working principle of a synchronous generator, in which the coupling between rotor speed and electrical torque forms a weakly damped second order system.

However, this does not apply to the generator types normally used in wind turbines. The squirrel cage induction generator used in constant speed wind turbines shows a relation between rotor slip, i.e. the rotor speed, and electrical torque, instead of between rotor angle and electrical torque. Its mechanical part is therefore of first order and does not show oscillatory behaviour, in opposition with that of a synchronous generator. Although an oscillation can be noticed when the rotor transients are included in the model, because this increases the model order, the amplitude of this oscillation is still small and it is well damped. Thus, squirrel cage induction generators are intrinsically better damped and rely on the power system to provide damping less than synchronous generators. Thus they do not lead to power system oscillations.

The generator types used in variable speed wind turbines are decoupled from the power system by power electronic converters that control the rotor speed and electrical power and that damp any rotor speed oscillations that may occur. Thus, variable speed wind turbines do not react to any oscillations that occur in the power system, because the generator does not notice them as they are not transferred through the converter. Therefore, they do not lead to power system oscillations either.

From this analysis, the following can be concluded. If it is assumed that wind power replaces the power generated by synchronous generators, the contribution of synchronous generators to the overall demand for power becomes less. The topology of the system stays unchanged, however. Thus, the synchronous generators become smaller relative to the impedances of the grid. This strengthens the mutual coupling, which in most cases improves the damping of any oscillations that occur between the synchronous generators. Hence, the expectation is that replacement of synchronous generators by wind turbines will improve the damping of power system oscillations.

## 6.5 TEST SYSTEMS AND CALCULATION RESULTS

### 6.5.1 Test System Topologies and Development of Cases

To further investigate the impact of wind power on power system oscillations, we developed two test systems particularly for this study. The first system is depicted in figure 6.2. It consists of two areas, one with a large, strongly coupled system represented by an infinite bus and the other consisting of two synchronous generators. The impedances are in per unit on a 2500 MVA base and the loads are modelled as constant MVA. This test system shows two types of oscillations: an oscillation of a group of generators and an intra-area oscillation. The generators at buses 3 and 4 oscillate against the strong system and also against each other. The shapes of these oscillatory modes are also depicted in figure 6.2. Note that the generators in the test system do not represent one single generator, but a group of strongly coupled, coherent generators.

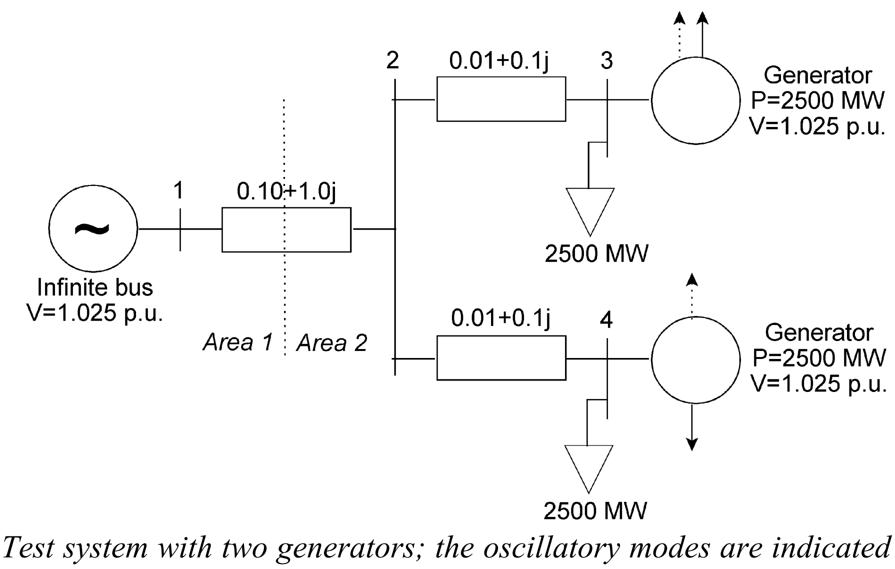


*Figure 6.2 Test system with two generators; the oscillatory modes are indicated with arrows: oscillation of a group of generators (dotted) and intra-area oscillation (solid).*

The second test system is depicted in figure 6.3. The impedances are again in per unit on a 2500 MVA base and the loads are modelled as constant MVA. In this test system, the strongly coupled large system in area 1 of the first test system is replaced by a system identical to that in area 2. Thus, no infinite bus is present in this test system. The test system shows oscillations of the second and third type: intra-area oscillations between buses 1 and 2 and between buses 5 and 6 and an inter-area oscillation between buses 1 and 2 and 5 and 6. The shapes of these oscillatory modes are also depicted in figure 6.3. Note that the generators in the test system do again not represent one single generator, but a group of strongly coupled, coherent generators.

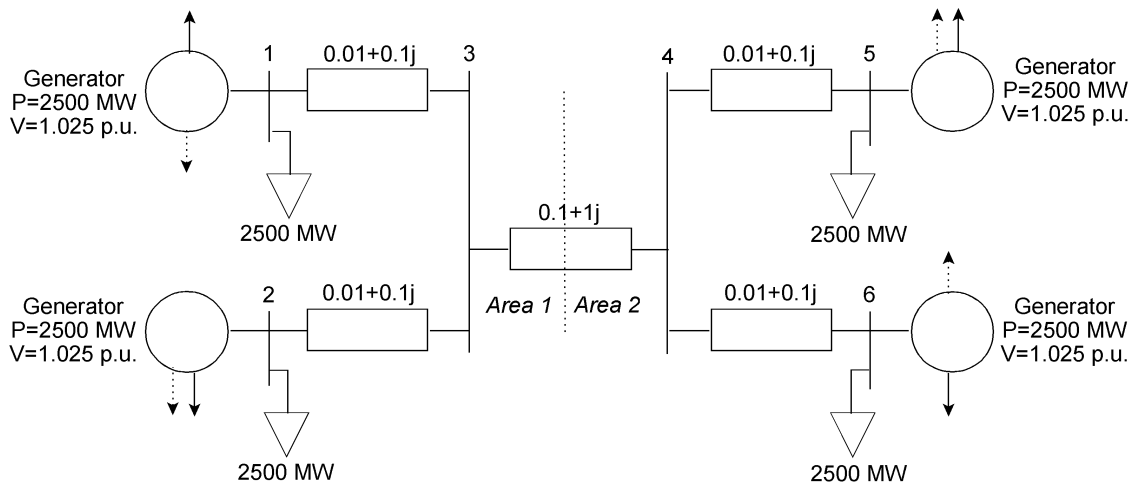


*Figure 6.3 Two area test system with four generators; the oscillatory modes are indicated with arrows: intra-area oscillation (solid) and inter-area oscillation (dotted).*

To investigate whether the obtained results depend on the loading of the tie line between the two areas, we introduced a power transfer between the two areas was introduced in both systems, by increasing each of the loads in area 2 of the systems with 500 MW (=20%) and by reducing both loads in area 1 of the second system, depicted in figure 6.3, with 500 MW. The mode shape, that can be determined using participation factors as mentioned in section 6.2.3, was used to identify the relevant eigenvalues.

***Dynamic Models***

To create dynamic models of the network topologies depicted in figures 6.2 and 6.3, a dynamic generator model must be attached to the generators in the load flow cases. In this study, a sixth order model of a round rotor generator with exponential modelling of magnetic saturation was used [30]. The generator model parameters can be found in table 6.4, the block diagram of the generator model is depicted in figure 5.9. In order to limit the number of states, to reduce the complexity of the problem and to improve the usability of the results, we did not equip the synchronous generators with governors and exciters. If accurate quantitative results from a real power system are pursued, a detailed representation of the governors and exciters of the generators is of course very important. In the cases with wind power, the wind turbines were not modelled individually, but with the aggregated wind park models described in section 4.3.3. The parameters of the aggregated model for the wind park with the constant speed wind turbines are given in table 6.5.

*Table 6.4 Sixth-order synchronous generator model parameters, MVAbase equals 1.25 × active power.*

| Quantity | Value | Quantity | Value |
|---|---|---|---|
| $T'_{do}$ | 5.0 s | $L_q$ | 1.65 p.u. |
| $T''_{do}$ | 0.05 s | L'd | 0.30 p.u. |
| $T'_{qo}$ | 1.0 s | $L'_q$ | 0.75 p.u. |
| $T''_{qo}$ | 0.4 s | $L''_d$* | 0.20 p.u. |
| H | 4 s | $L_l$ | 0.175 p.u. |
| D | 0 | S(1.0) | 0.2 p.u. |
| $L_d$ | 1.75 p.u. | S(1.2) | 0.4 p.u. |

* $L''_d$ equals $L''_q$ due to the PSS/E™ synchronous generator model structure

*Table 6.5 Asynchronous generator model parameters, MVAbase equals 1.25 × active power.*

| Quantity | Value | Quantity | Value |
|---|---|---|---|
| T' | 5.0 s | L | 3.1 p.u. |
| T'' | 0.05 s | L' | 0.178 p.u. |
| $H_{gen}$ | 4 s | $L_l$ | 0.10 p.u. |
| $H_{turbine}$ | 0 | S(1.0)* | 0.0 p.u. |
| Shaft stiffness | 1.75 p.u. | S(1.2)* | 0.0 p.u. |

*Magnetic saturation is neglected

***Development of Cases***

Using the test systems depicted in figures 6.2 and 6.3, the cases used to investigate the three oscillation types are developed in the following way:

- One or more buses were selected to which a synchronous generator involved in the oscillatory mode to be studied is connected. The buses were selected according to the case being investigated. We investigated both cases in which generators in one of the two swing nodes are gradually replaced by wind power, as well as cases in which generators in both swing nodes are gradually replaced by wind power. This would clarify the impact of the division of the wind power over the swing nodes that are involved in a certain oscillation.
- An aggregated model of a wind park with either constant or variable speed wind turbines was connected to the selected buses.

- The active power, reactive power capability and rating of the selected synchronous generator(s) were gradually reduced. The reduction in active power was compensated by increasing the power generated by the wind park, whose rating was increased accordingly. The reduction in reactive power generation, if any, was not compensated. The impedance between the wind park and the grid was also changed according to the rating of the wind park, because it is constant on the wind park's MVA base, but not on the network's MVA base.

The above sequence of activities was carried out both for the cases without and with an inter-area power transfer and for each of the two test systems. This resulted in a total of 164 cases.

In order to calculate the eigenvalues for each of the cases, the load flow was solved and dynamic models of the synchronous generators and the wind park(s) were attached. The resulting dynamic model of the investigated case was then linearized and the eigenvalues of the state matrix were calculated as described above. In this way, the trajectory of the eigenvalues in the complex plane with changing wind power penetration can be depicted, which gives information on the oscillatory behaviour.

### 6.5.2 Calculation Results

***Oscillation Against a Strong System***

The oscillation of the generators at buses 3 and 4 in the system depicted in figure 6.2 against the infinite bus, is taken as an example of an oscillation of a group of generators against a strong system. The wind power penetration level was changed stepwise from zero in the base case to 50% eventually. First, it was changed in ten steps of 250 MW at bus 3 until the synchronous generator was fully replaced by the wind park. Then, it was changed in ten steps of 125 MW at buses 3 and 4 until half of the power of each of the synchronous generators (=1250 MW) was replaced by wind power.

In this way, we investigated whether the effect of the wind power on the oscillation depended on the way in which the wind power is spread over the swing node, which here consists of the generators at buses 3 and 4. This was done for both constant and variable speed wind turbines and for cases without and with an inter-area power transfer. In total, 82 eigenvalues were obtained, namely the base case either without and with inter-area power transfer and then ten values for the cases with different wind power penetrations, different wind turbine technologies and different wind park locations.

The results are depicted in figure 6.4. The damping ratio is indicated on the horizontal and the oscillation frequency on the vertical axis. The upper figure depicts the eigenvalues that correspond to one wind park, at bus 3, the lower figure the eigenvalues that correspond to two wind parks, at buses 3 and 4. The meaning of the symbols is given the figure's legend. The direction that corresponds to an increasing wind power penetration is indicated with an arrow.

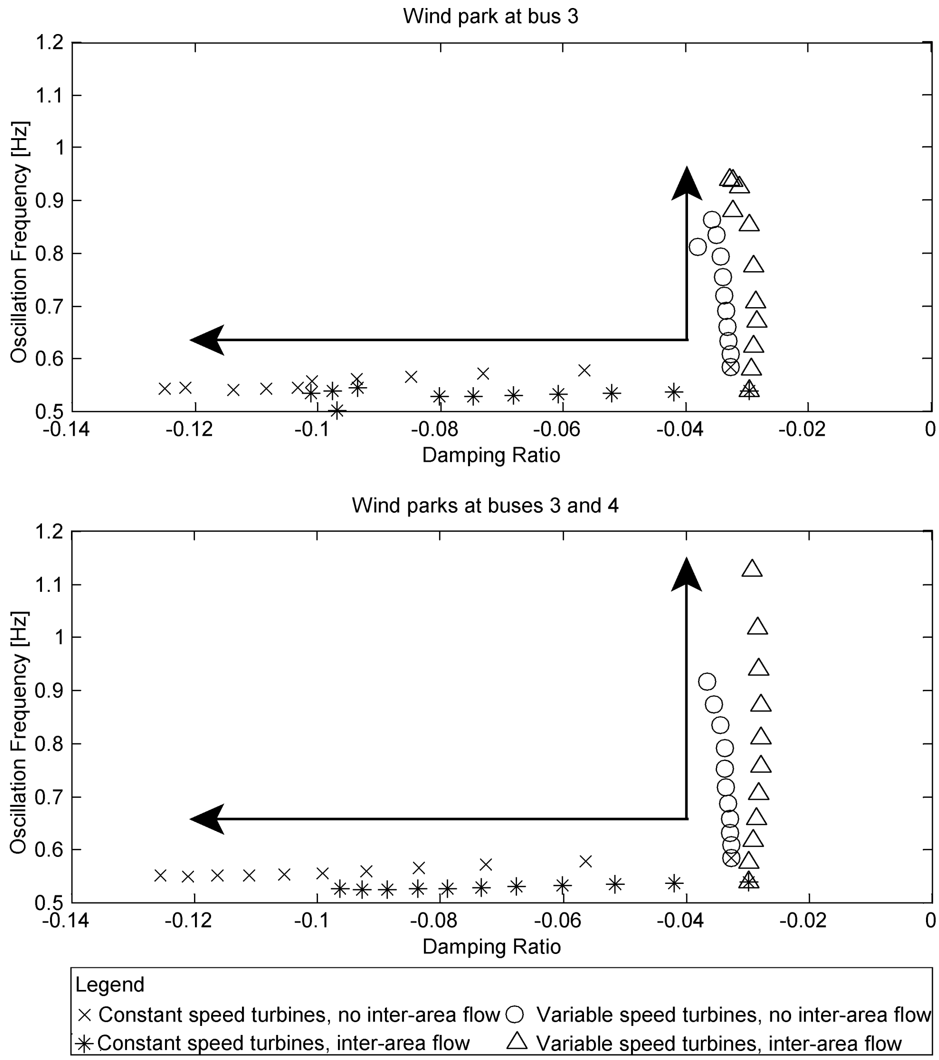


*Figure 6.4. Impact of increasing wind power penetration on the oscillation of the generators at buses 3 and 4 against the infinite bus. The upper figure depicts the eigenvalues with a wind park at bus 3; the lower figure the eigenvalues with two wind parks, at buses 3 and 4. The meaning of the symbols is indicated in the legend. The direction of the arrow indicates increasing wind power penetration.*

### *Intra and inter-area oscillations*

The system depicted in figure 6.2 shows an intra-area oscillation between buses 3 and 4. Again, the amount of wind power was changed until the penetration was 50%, first in ten 250 MW steps at bus 3 and then in ten 125 MW steps at buses 3 and 4, both for the system without and with an inter-area flow. This corresponds to erecting wind power at one or both of the swing nodes involved in the oscillation respectively. The results are depicted in figure 6.5. Note that the oscillation frequency is higher than in figure 6.4, because a different type of oscillation is studied.

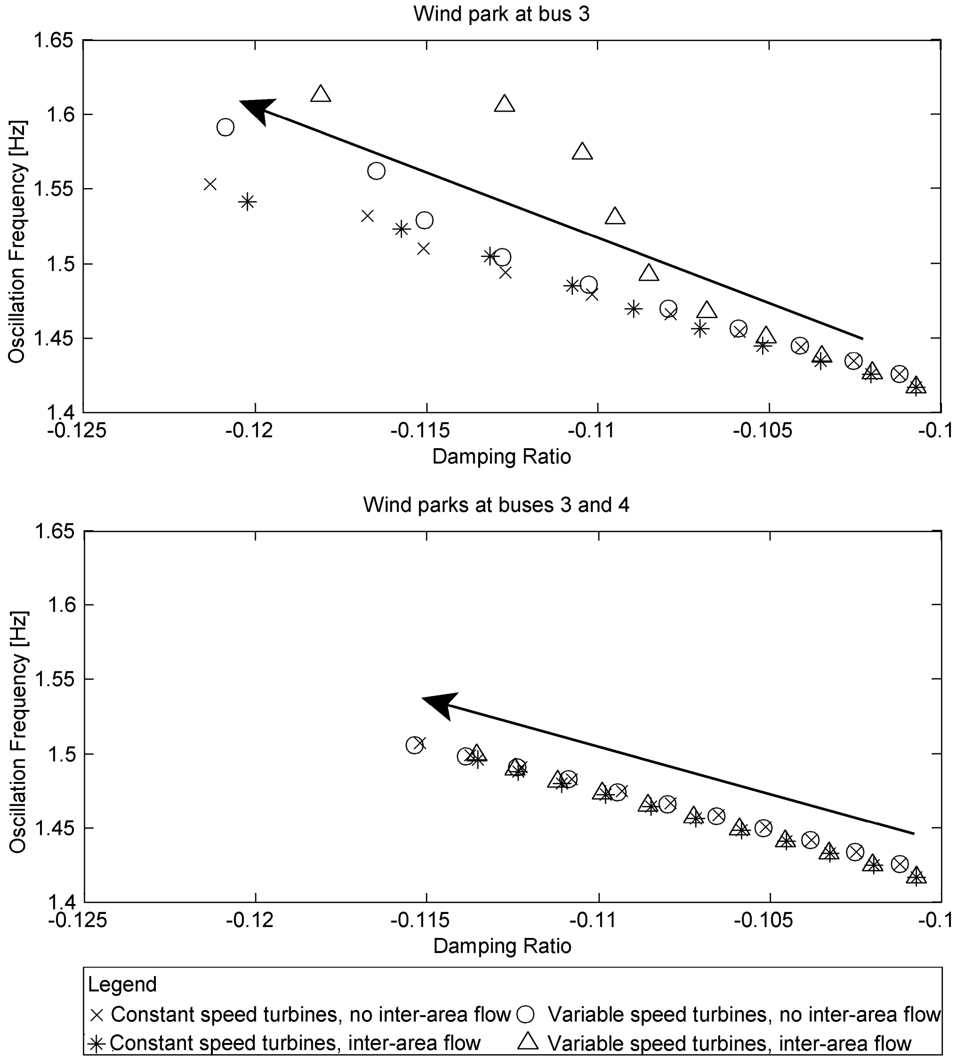


*Figure 6.5 Impact of increasing wind power penetration on the intra-area oscillation of the generators at buses 3 and 4 against each other. The upper figure depicts the eigenvalues with a wind park at bus 3; the lower figure the eigenvalues with two wind parks, at buses 3 and 4. The meaning of the symbols is indicated in the legend. The direction of the arrow indicates increasing wind power penetration.*

The system in figure 6.3 shows both an intra-area and an inter-area oscillation. These oscillations were analysed by changing the wind power penetration at buses 1 and 2 and at buses 1, 2, 5 and 6 in ten steps of 250 MW and ten steps of 125 MW respectively until the synchronous generators at buses 1 and 2 were completely replaced, or all synchronous generators were replaced for 50% (=1250 MW).

From the topology of the system, it can be concluded that in the first case, both swing nodes of one of the two intra-area oscillations were affected and the swing nodes involved in the other intra-area-area oscillation were not affected. In the second case both swing nodes of each of the two intra-area oscillations were affected. With respect to the inter-area oscillation, in the first case only one swing node was affected, whereas in the second case both swing nodes were affected.

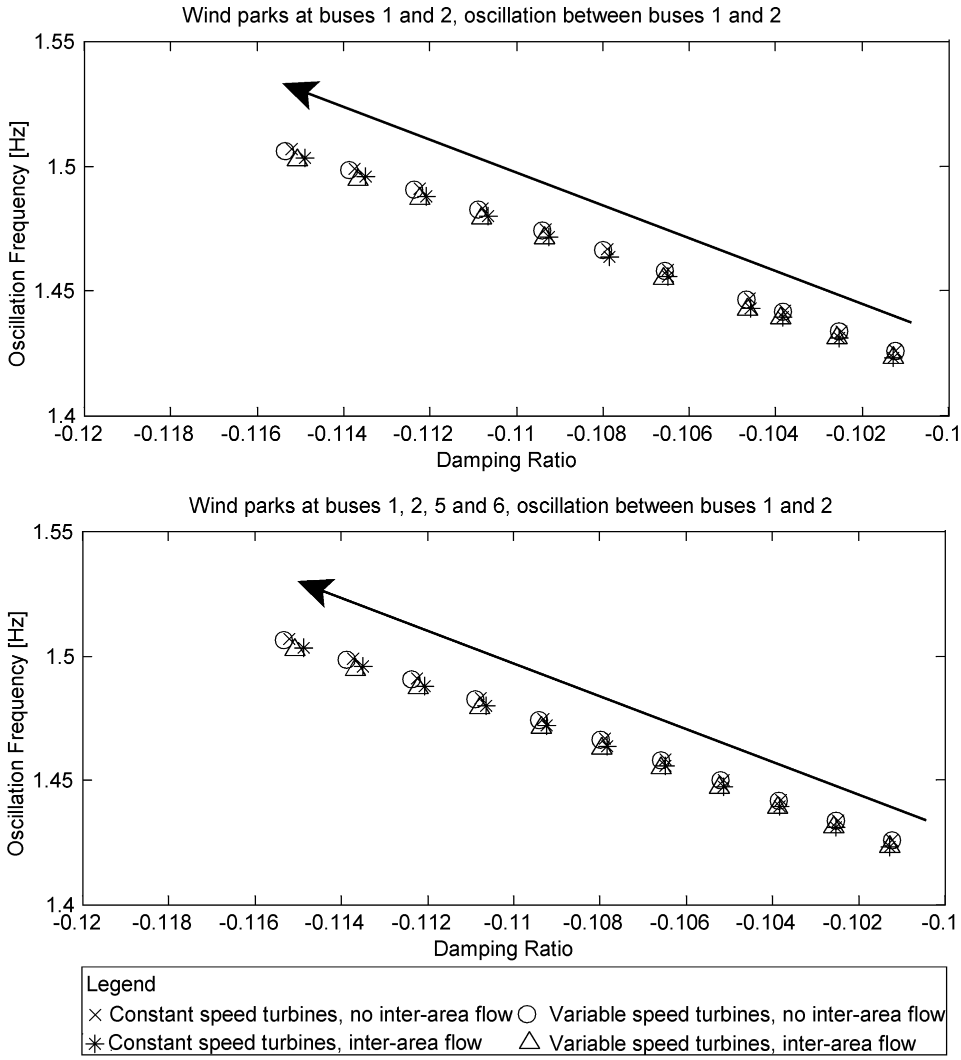


*Figure 6.6 Impact of increasing wind power penetration on the intra-area oscillation of the generators at buses 1 and 2 against each other. The upper figure depicts the eigenvalues with two wind parks, at bus 1 and 2; the lower figure the eigenvalues with four wind parks, at buses 1, 2, 5 and 6. The meaning of the symbols is indicated in the legend. The direction of the arrow indicates increasing wind power penetration.*

In figures 6.6 and 6.7, the results for the two intra-area oscillations that are present in the system depicted in figure 6.3 are shown. In figure 6.8, the results for the inter-area oscillation are shown. Results are given for the system without and with an inter-area power flow.

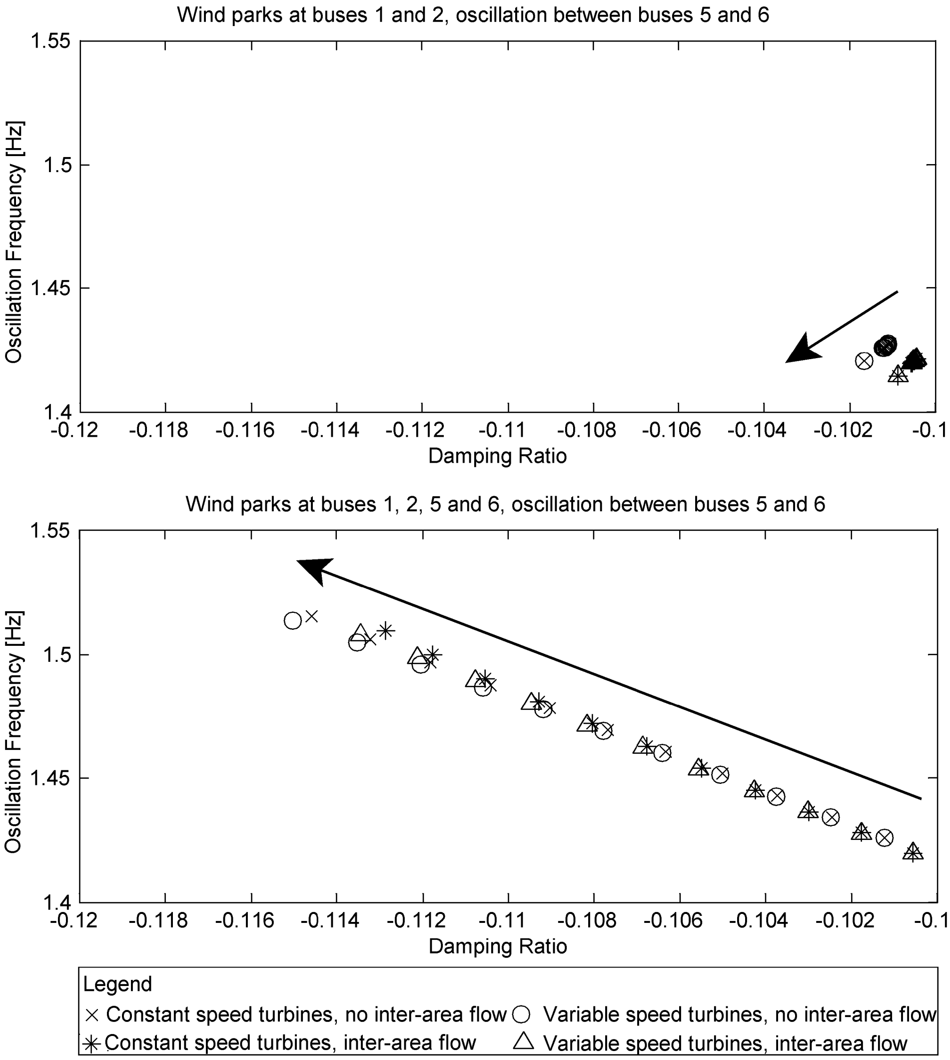


*Figure 6.7 Impact of increasing wind power penetration on the intra-area oscillation of the generators at buses 5 and 6 against each other. The upper figure depicts the eigenvalues with two wind parks, at bus 1 and 2; the lower figure the eigenvalues with four wind parks, at buses 1, 2, 5 and 6. The meaning of the symbols is indicated in the legend. The direction of the arrow indicates increasing wind power penetration.*

### 6.5.3 Analysis of Results

From the results depicted in figures 6.4 to 6.8, the following general conclusions can be drawn:

- In general, replacing synchronous generators by wind turbines mainly influences oscillations of a (group of coherent) generator(s) against a strong system (see figure 6.4) but to a lesser extent also inter-area oscillations (see figure 6.8), whereas the impact on intra-area oscillations is not significant (see figures 6.5 to 6.7).
- Constant speed wind turbines increase the damping of power system oscillations, whereas their impact on the frequency varies, depending on the type of oscillation.

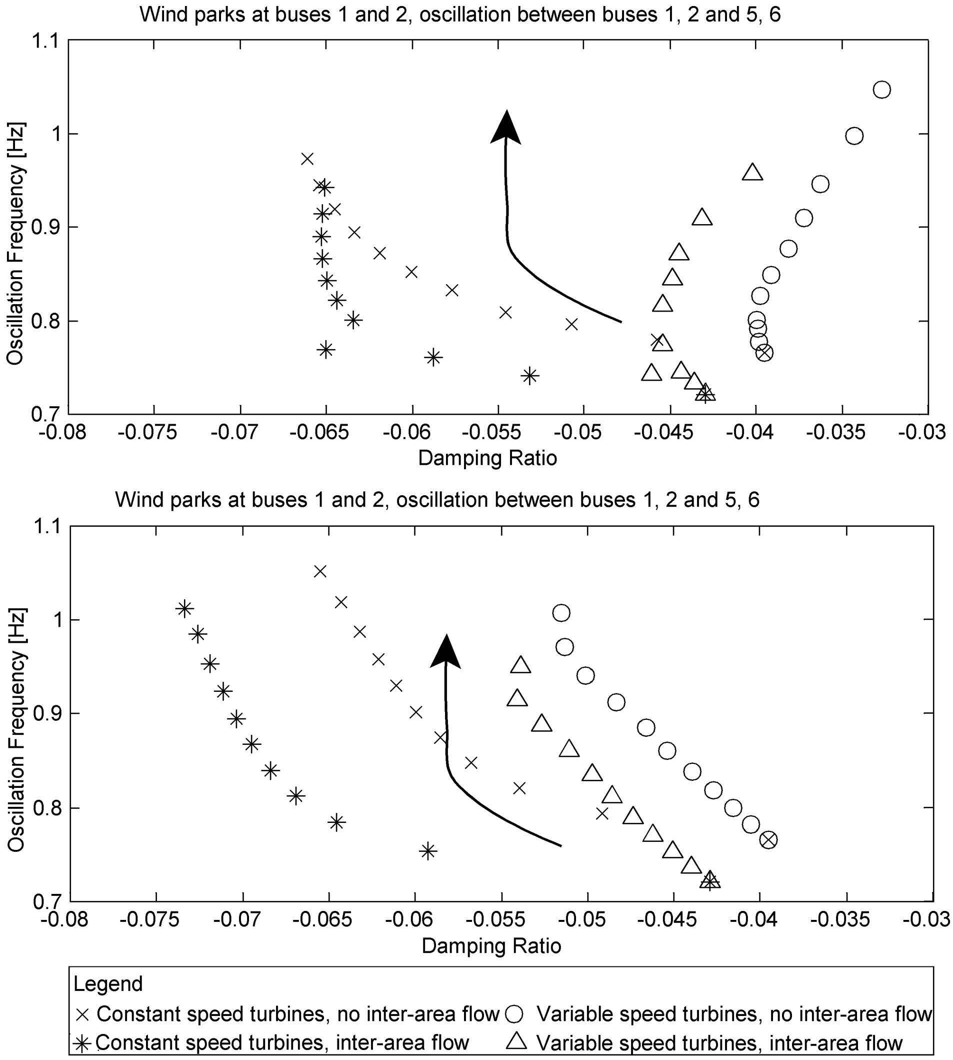


*Figure 6.8 Impact of increasing wind power penetration on the inter-area oscillation of the generators at buses 1 and 2 and 5 and 6 against each other. The upper figure depicts two wind parks, at buses 1 and 2; the lower figure four wind parks, at buses 1, 2, 5 and 6. The meaning of the symbols is indicated in the legend. The direction of the arrow indicates increasing wind power penetration.*

- Variable speed wind turbines increase the frequency of power system oscillations, whereas their impact on the damping is rather limited and varies, depending on the type of oscillation.
- Replacement of synchronous generators by wind turbines does not significantly affect oscillations whose swing nodes are not influenced by the substitution of synchronous generation by wind turbines (see first graph of figure 6.7).
- Although the impact of wind turbines on power system oscillations is affected by the loading of tie lines in a quantitative sense, the above conclusions do not change when tie line loadings are varied.

These findings can, as already observed, for the largest part be explained by considering the physical origin of power system oscillations. In synchronous generators, the electrical torque is mainly dependent on the angle between rotor and stator flux. This angle is the integral of the rotational speed difference between these two fluxes, which is in turn dependent on the difference between electrical and mechanical torque. This makes the mechanical part of the synchronous machine a second order system that intrinsically shows oscillatory behaviour. This does not apply to the generator types used in wind turbines, which hence do not lead to power system oscillations.

Further, in the above investigations, it was assumed that wind power replaces the power generated by synchronous generators. Thus, the share of synchronous generators in the power being supplied, becomes less. The topology of the system, however, stays unchanged. Thus, the synchronous generators become smaller relatively to the impedances of the grid. This strengthens the mutual coupling, which in most cases improves the damping of any oscillations that occur between the synchronous generators. On the other hand, the generator types used in wind turbines do not cause power system oscillations.

The differences between the impact of constant and variable speed wind turbines that were observed can also be explained from the difference in working principles between the two concepts. A squirrel cage induction generator tends to damp power system oscillations [79]. This is due to the fact that an increase in synchronous generator speed would lead to a slight voltage increase. This shifts the rotor speed versus power curve of the squirrel cage induction generator, which has a damping effect on the power system oscillation. This effect does not occur in case of variable speed wind turbines, in which the generator is decoupled from the grid by the power electronic converter. This explains why constant speed wind turbines affect the damping of power system oscillations more than variable speed wind turbines.

It was also observed that when the synchronous generating capacity at one of the swing nodes involved in an oscillation is replaced by wind power to a large extent, the impact of wind power becomes ambiguous, particularly in the case of inter-area oscillations (see upper graphs of figures 6.5 and 6.9). This is probably caused by the fact that in this situation, the nature of the oscillation changes. The change of the nature of the oscillation was observed when studying the mode shape using the eigenvectors corresponding to the relevant eigenvalue. By reducing the rating of the synchronous generators in one of the swing nodes of the oscillation, one makes it smaller when compared to the generator(s) in the other swing node. This results in a change in mode shape and in some cases also of oscillation type, namely from an inter-area oscillation into an oscillation of a generator against a strong system.

However, the presented results also pose some questions, of which the most important are:

- Why are oscillations of a (group of coherent) generator(s) against a strong system and inter-area oscillations much more effected than intra-area oscillations?
- Why is the impact of constant and variable speed wind turbines similar in case of an intra-area oscillation, whereas it is quite different in case of oscillations of a (group of coherent) generator(s) against a strong system?

These questions can not be answered from the theoretical insights and simulation results presented in this chapter. Further research into the topic of the impact of wind power on power system oscillations is therefore necessary.

## 6.6 CONCLUSIONS

In this chapter, the impact of wind power on power system oscillations was investigated. This was done by observing the behaviour of the eigenvalues while changing the wind power penetration in two test systems. The test systems show all three distinct types of power system oscillations, namely oscillations of a (group of) generator(s) against a strong system and intra- and inter-area oscillations. To investigate the impact of the tie line loading, cases with an unloaded as well as a loaded tie line were investigated.

It can be concluded that wind turbines tend to improve the damping of oscillations of a (group of coherent) generator(s) against a strong system and of inter-area oscillations, particularly if constant speed wind turbines are used. The effect on intra-area oscillations is not significant. The fact that in the calculations presented here the impact of wind turbines on power system oscillations depends on the studied oscillation type could, however, not be clarified.

The damping effect of wind turbines can be explained by noticing that the remaining synchronous generators are smaller whereas the system's impedances do not change. Thus, the synchronous generators become relatively more strongly coupled. On the other hand, wind turbines themselves do not induce new oscillatory modes, because the generator types used in wind turbines do not cause power system oscillations: oscillations in a squirrel cage induction generator, which is used in constant speed wind turbines, are intrinsically better damped and the generators of variable speed wind turbines are decoupled from the power system by a power electronic converter, which controls the power flow and prevents them from causing power system oscillations.

When a considerable part of the synchronous generation capacity in a swing node is replaced by wind power, the results become ambiguous, which is probably caused by the fact that the mode shape changes, which can also change the oscillation type.

This chapter forms a first exploration of the topic of the impact of wind power on power system oscillations. Many of the observations could be explained by noticing that in wind turbines no directly grid coupled synchronous generators are used, whereas particularly this generator type causes power system oscillations. Nevertheless, some questions are still unanswered and the conclusions should be treated with care. No other studies covering the impact of wind turbines on power system small signal stability are available and further research on this topic is therefore necessary.

# Conclusions and Future Work

## 7.1 CONCLUSIONS

### 7.1.1 Wind Power in Power Systems

Chapters 1 and 2 contain a general introduction to the thesis and to wind power technology. It was concluded that in some countries, as a result of legislation, governmental financial support and tax benefits to promote renewable energy sources, wind power has grown rapidly. It was also concluded that wind power fundamentally differs from conventional generation technologies, because the primary energy source is not controllable and because generating systems are used that differ from the conventional directly grid coupled synchronous generator.

Because of these differences between conventional power generation technologies and wind power, the use of wind power affects a power system in several ways. A distinction can be made between local impacts on the one hand and system wide impacts on the other. Local impacts are observed in the direct vicinity of the wind turbine or wind park. Only increasing the amount of installed wind power locally increases the local impacts, but installing wind power elsewhere in the system does not affect the local impacts of a wind turbine or park at a different location. Further, the local impacts differ for the various types of wind turbines, particularly for constant and variable speed turbines. The most important local impacts are changes in node voltages and branch flows, harmonic distortion, flicker and contribution to fault currents.

System wide impacts are impacts that affect the behaviour of the power system as a whole. They mainly result from the use of the wind as the primary source of energy and the extent to which they occur is strongly related to the wind power penetration level in the power system as a whole. However, in contrast to what applies to the local impacts, the geographic distribution of the turbines and the wind turbine type are only of limited importance.

One of the system wide impacts of wind power is the influence on the dynamics and stability of a power system. This effect of wind power on the behaviour of a power system is treated in this thesis. Other system wide impacts of wind power comprise a change in the reactive power/voltage control possibilities and an increase in the complexity of maintaining the system frequency and the power balance.

### 7.1.2 Wind Turbine Modelling

To investigate the impact of wind power on power system dynamics and stability, a special simulation approach is applied, which in this thesis is referred to as power system dynamics simulation. From our literature search we concluded that there models matching the assumptions on which the power system dynamics simulation approach is based and meeting the requirements posed by this approach did not exist yet. The models found in the literature either did not include all subsystems that are relevant in power system dynamics simulations, were not completely documented, or contained time constants too short to be taken into account. Therefore, chapter 3 presented models for the three most important actual types of wind turbines for power system dynamics simulations, which are used to study phenomena in the frequency range of about 0.1 tot 10 Hz. These models match the assumptions on which the power system dynamics simulation approach is based.

The level of correspondence between simulations with the developed models and measurements proved to be satisfactory. It was therefore decided to use the models for this research project, i.e. to use them to investigate the impact of wind power on power system dynamics and stability, rather than to spend efforts to further improve them. This decision was also inspired by the fact that it is rather complicated to carry out a true validation of wind turbine models by feeding a measured wind speed sequence into a model and then comparing measured and simulated quantities such as the rotor speed, the pitch angle and the active and reactive power, because the wind speed as measured with a single anemometer is not an adequate measure of the wind speed acting on the rotor as a whole.

The first part of chapter 4 was devoted to the adaptation of the developed models in order to further improve their usability for power system dynamics simulations. To this end, first a wind speed model was developed and incorporated in the wind turbine models. This increased the flexibility of the models by allowing the simulation of wind speed sequences with various characteristics, instead of only wind speed sequences that have been measured in advance.

Second, a general variable speed wind turbine model was developed. From the simulation results and measurements shown in chapter 3, it was concluded that both types of variable speed wind turbines can be represented with the same model. The physical explanation for this observation is that the differences between these two wind turbine types fall outside the time scale that is studied in power system dynamics simulations. The main difference between the two types of variable speed wind turbines are the generator and the converter. The interaction between the generator and the converter is, however, a high frequency phenomenon, well above the bandwidth studied in power system dynamics simulations. In the bandwidth of 0.1 to 10 Hz, the behaviour of the turbine is mainly determined by the rotor speed and voltage controllers and the protection system, which are very similar for both turbine types, so that they can be represented with the same general variable speed wind turbine model.

The second part of chapter 4 is devoted to the aggregated modelling of wind parks. Wind parks can consist of tens to hundreds of turbines and are connected to the transmission grid. It is of course inconvenient to model all these turbines as well as their interconnections individually in power system dynamics simulations, particularly when high wind power penetration levels, i.e. large numbers of turbines, are involved. An aggregated wind park model was developed in order to avoid this.
The aggregated wind park model was validated by comparing simulation results obtained with a detailed and an aggregated wind park model. The comparison was based on the exchange of active and reactive power and voltage at the *point of common coupling* (PCC). A high degree of correspondence was observed, justifying the conclusion that the aggregated models can be used to represent wind parks in power system dynamics simulations.

### 7.1.3 Impact on Power System Dynamics

***Transient Stability***
Chapters 5 and 6 are devoted to investigations of the impacts of wind power on power system dynamics and stability. The models developed in chapters 3 and 4 were used to carry out these investigations. In chapter 5, the impact of wind power on the transient dynamics and stability of power systems was investigated. First, the response of the three main wind turbine types to voltage and frequency disturbances was treated qualitatively. It was concluded that due to the intrinsic relationship between active and reactive power, terminal voltage and rotor speed, a squirrel cage induction generator used in constant speed wind turbines impedes voltage restoration after a fault and can therefore cause voltage instability. Although this risk depends on many factors, such as the wind turbine parameters and controllers, the grid coupling strength and the actual wind speed, it is an inherent property of the squirrel cage induction generator used in constant speed wind turbines.
Further, constant speed wind turbines tend to have a slight damping effect on frequency deviations because a directly grid coupled generator is used that withdraws energy from the grid at frequency increases and supplies energy to the grid at frequency decreases, where the rotor acts as a buffer. Due to the lack of a governor, the damping by constant speed wind turbines is less than that by the synchronous generators used in conventional power plants.

The behaviour of variable speed wind turbines is fundamentally different from that of constant speed wind turbines. In response to a voltage disturbance, they tend to disconnect quickly in order to protect the power electronic converter, which is very sensitive to overcurrents. However, it was argued that continuing this practice at high wind power penetration levels could make it difficult to maintain the system balance, because a fault in the transmission grid could lead to the disconnection of large numbers of wind turbines, resulting in a large generation deficit. Therefore, some grid companies are starting to prohibit disconnection at voltage drops and manufacturers are working on solutions to reduce the sensitivity of variable speed wind turbines for voltage drops.

Variable speed wind turbines do not intrinsically respond to frequency disturbances, due to the decoupling of the mechanical rotor frequency and the grid frequency and therefore they do not provide any damping on frequency deviations. However, they can be made to respond to changes in the grid frequency by using appropriate control approaches. The consequence is, however, a reduced energy yield.

It was also argued that when wind turbines are grouped in wind parks, the interaction of the park with the grid is only determined by the wind turbine type if the park's infrastructure and the grid coupling are implemented using conventional AC connections. From a qualitative analysis, it was concluded that if DC connections are used for either the grid connection or the internal park infrastructure, the interaction of the wind park with the grid is mainly determined by the type and the control approach of the power electronic converters of the DC connection, rather than by the wind turbine type; the wind turbines are electrically decoupled from the grid by the DC connection. Further, it was pointed out that there are differences between conventional HVDC connections of a current source type and the more modern voltage source type of HVDC connections with respect to reactive power/voltage control capabilities and fault response.

The qualitative analysis was illustrated with simulations from a widely used dynamics test system, the New England test system, and a model of a practical power system, the Dutch power system with the surrounding UCTE network. From the simulation results obtained with the New England Test System, it was concluded that voltage disturbances, caused by a fault or the tripping of a nearby synchronous generator, can cause instability of constant speed wind turbines. As for the variable speed wind turbines, it was assumed that they comply with the grid connection requirements that have recently been issued by grid companies facing large amounts of wind. This implies that they resume operation quickly after a fault, rather than being disconnected, as is often the case nowadays. Under this assumption, variable speed wind turbines did not cause any instability after a fault. Further, variable speed wind turbines are hardly affected by the tripping of a nearby generator. When equipped with voltage control, they can even reduce the resulting voltage drop.

Further, it was shown that high wind power penetration levels result in an increase of the frequency deviations caused by a disturbance of the power balance in the system. This effect is due to the fact that wind turbines are not equipped with governors. In case of variable speed wind turbines, the effect is most pronounced, due to the decoupling of grid frequency and generator speed. Finally, it was shown that although wind turbines affect the shape of the rotor

speed oscillations that occur after a fault, they hardly affect the damping. The time for the oscillations to die out was very similar for the case without wind turbines, for that with constant speed wind turbines, and for that with variable speed wind turbines.
In case of the Dutch power system, to which an offshore wind park of 1500 MW was connected in the study, no instability was observed. This can be explained by noticing that although a 1500 MW wind park is substantial, the corresponding wind power penetration in the UCTE network is still very low. Further, the Dutch power system is quite compact. Hence, the wind power is connected to a stronger grid than was the case with the New England Test System. These two observations explain that the instability that was observed for the constant speed wind turbines in case of the New England Test System does not occur in the Dutch power system.

***Small Signal Stability***
In chapter 6, the impact of wind power on power system small-signal stability was discussed. First, a mathematical treatment of the linearization of the non-linear equations describing a power system and of the relation between the eigenvalues and the time domain was given. Then, the eigenvalue analysis capabilities of PSS/E™ were validated by comparing the results yielded by some test systems with the results given in the literature and with those yielded by another software package. It was concluded that the eigenvalue analysis capabilities of PSS/E™ were adequate, so that the package could be used to investigate the impact of wind power on power system small signal stability.

A qualitative analysis was carried out on the origin of power system oscillations and the impact of wind power on oscillations. It was concluded that a replacement of the output of synchronous generators by wind power could be expected to lead to an improvement in the damping of oscillations. The generator concepts used in wind turbines do not take part in power system oscillations and due to the reduction of the size of the synchronous generators, they become relatively more strongly coupled: the impedances of the grid do not change, but the size of the synchronous generators decreases. This generally improves the damping of power system oscillations.

The qualitative analysis was illustrated and verified with calculations using two test systems that have been developed particularly for this study and that show the three main types of power system oscillations: oscillation of a (group of coherent) generator(s) against a strong system and intra and inter-area oscillations. From the calculation results, it could be concluded that wind power tends to improve the damping of oscillations of a (group of coherent) generator(s) against a strong system and of inter-area oscillations, particularly if constant speed wind turbines are used. The effect on intra-area oscillations is not significant.
If a very large part of the synchronous generation capacity in a swing node is replaced by wind power, the results become ambiguous, which is probably caused by the fact that the mode

shape changes, which can also change the oscillation type. Further, it is not clear why the impact of wind turbines on an oscillation differs for the various oscillation types.

Although only two small test systems were investigated in this research project, many of the obtained results can be explained on the basis of the physical origin of power system oscillations and the differences between synchronous generators used in conventional power plants and the generator concepts used in wind turbines. It can therefore be expected that investigations on other power systems will yield similar results. However, some questions are still unanswered and the conclusions should be treated with care.

## 7.2 FUTURE WORK

***Model Validation***

The wind turbine models developed in this research project have been qualitatively compared with measurements. No quantitative validation was carried out because the available measurements were not suitable for this purpose. Further, no measurements of the behaviour of the wind turbines during voltage and frequency disturbances were available. Therefore, the first topic that must be paid more attention to is the validation of the wind turbine models presented in this thesis.

Validation of wind turbine models is a comprehensive and difficult task. For a complete model validation, measurements must be carried out during normal operation and during disturbances. However, disturbances occur rather infrequently, and in order to obtain useful measurements, they must occur when the wind turbine is in operation; not during calms. Further, because models of three different wind turbine types have been developed, each of the turbine types must be measured separately. In practice, carrying out measurements is further complicated by the fact that both terminal quantities, namely voltage and current, and quantities in the wind turbine itself, such as rotor speed and pitch angle, must be measured. Therefore, cooperation with both the owner of the wind turbine and the grid company responsible for the network to which the turbine is connected is essential.

Finally, the behaviour of variable speed wind turbines depends for a large part on the controllers of the power electronic converter. Information on this topic is therefore also important, in order to be able to equip the models with controllers that are identical to that of the real system. By doing so, one ensures that differences between measurements and simulations that may be observed are not caused by using a wrong controller model, but that they indeed give information that can be used to improve the wind turbine model. However, information on the control approach can only be provided by the manufacturer and is often confidential.

An easier approach to validate the models derived in this thesis would be to compare their response with that of higher order models of the generators as found in the literature or supplied by the manufacturer. Although this does not yield a complete picture, it could at least give more insight in the consequences of the simplifications used in power system dynamics simulations for the accuracy of the models.

***Small Signal Stability***

Until now, the topic of the impact of wind power on power system small signal stability has not received much attention in the literature and this thesis appears to be the first publication in which it is covered. However, it only makes up one part of this thesis and not all questions could be answered. Therefore, this subject should be investigated more elaborately. Other power system topologies should be investigated in order to confirm the results presented in this thesis. In case these are found to be inaccurate, the explanation of the results presented in chapter 6 does not give the complete picture and the question which (other) factors determine the impact of wind power on power system oscillations becomes paramount.

Further, it should be investigated whether variable speed wind turbines can actively contribute to the damping of power system oscillations by appropriately controlling the power electronics converter. Other power electronics based components, such as HVDC connections and energy storage systems, are capable of contributing to the damping of power system oscillations by adjusting their output power. The difference between HVDC connections and storage systems on the one hand and variable speed wind turbines on the other is that the latter use an uncontrollable primary energy source. It would, however, be interesting to verify whether they still can contribute to the damping of power system oscillations or not.

***Reduction of Power System Inertia***

If wind turbines are used to generate electrical power, the contribution of conventional directly grid coupled synchronous generators decreases: the wind turbines replace that of synchronous generators. Particularly during situations with high wind speeds and a low load, the wind power penetration level can become significant, even though the contribution to overall electricity consumption may still be modest.

As mentioned in chapter 2, wind turbine manufacturers are increasingly applying variable speed generating systems in wind turbines. In variable speed wind turbines, the electrical and mechanical quantities are decoupled by the power electronic converter, as pointed out in section 5.3. Thus, the increasing use of variable speed wind turbines leads to a lowering of the inertia of a power system. This development is enlarged by the growing use of other generation technologies that do not use directly grid coupled synchronous generators to generate electricity, such as photovoltaics and small scale combined-heat-and-power (CHP) generation.

At this stage, it is not clear to which extent the reduction of the inertia in a power system that results from replacing conventional, directly grid coupled generators by generation technologies in which the generator is grid coupled through a power electronic converter or in which no mechanical energy stage is present is feasible. It is clear that if no additional measures are taken, this leads to a decrease in frequency stability. However, the question at which penetration level of the new generation technologies these negative consequences will occur and which measures can be taken to mitigate these is a topic that should be studied more elaborately.

***Impact of Wind Power on Power Balance***

As indicated in chapter 2, the specific characteristics of wind power compared to those of conventional generation do not only affect the dynamics of a power system, as shown in this thesis, but also the power balance and the dispatch of the remaining conventional units. The main reason for this is that the prime mover of wind power is hardly controllable and that the power generated by wind turbines therefore fluctuates and is uncertain. As a result, the load curve faced by the conventional units (equal to the original load curve minus the wind power generation) is less smooth and more uncertain than the original load curve without wind power. This affects the dispatch and the operation of the conventional units that remain.

Although some attention has been paid to this subject in the literature, the number of thorough, quantitative analyses is limited. Further, the impact of wind power on the operation of conventional units is not only dependent on the wind speed pattern and the load curve. There are various other factors that determine the impact of wind power on the power balance and the dispatch and thus the cost associated with incorporating a high wind power penetration in a system. Examples of such factors are the technical characteristics of the existing generation portfolio, the operation and control of the wind park, the correlation between wind speed and demand on various time frames, the treatment of wind power in liberalized markets and the arrangements used to provide spinning reserve. In hardly any of the publications covering the impact of wind power on conventional units the impact of these factors is investigated, and in most cases the assumptions with respect to these are not even mentioned explicitly.

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# List of Symbols

***Symbols***

A amplitude of wind speed component [m/s]
$A_r$ area swept by wind turbine rotor [$m^2$]
C capacitance [p.u.]
$c_p$ performance coefficient
D distance [m]
f frequency [Hz]
h hub height [m]
H inertia constant [s]
i current [p.u.]
$K_s$ shaft stiffness [p.u. torque/electrical radians]
K controller constant
l turbulence length scale [m], wind park width [m]
L inductance [p.u.]
p number of poles
P active power [W, p.u.]
Q reactive power [var, p.u.]
R resistance [p.u.]
s rotor slip
$S_{wt}$ power spectral density of turbulence [$Hz^{-1}$]
S apparent power [p.u.]
t time (variable) [s]
T torque [p.u], time (instant)[s]
v voltage [p.u.]
w wind park width [m]
$v_t$ blade tip speed [m/s]
$v_w$ wind speed [m/s]
$z_0$ roughness length [m]
α angle of attack of wind speed in aggregated park models [deg]
γ angular displacement between shaft ends [electrical radians]

| | |
|---|---|
| $\theta$ | pitch angle |
| $\lambda$ | tip speed ratio |
| $\lambda_i$ | intermediate result in calculation of $c_p$ |
| $\rho$ | air density [kg/m$^3$] |
| $\tau$ | low pass filter time constant [s] |
| $\phi$ | angle between terminal voltage and current, phase angle of sine components [rad] |
| $\psi$ | flux linkage [p.u.] |
| $\omega$ | rotational speed or frequency [p.u.] |

***Indices***

| | |
|---|---|
| c | power electronic converter |
| d | direct component |
| e | generator electrical |
| eg | end of gust |
| er | end of ramp |
| eq | wind park equivalent |
| fd | field winding |
| is | intersection |
| m | generator mechanical |
| l, σ | leakage |
| p | permanent magnet |
| pa | pitch angle |
| ps | pitch angle sampling |
| q | quadrature component |
| r | rotor |
| s | stator |
| sg | start of gust |
| sr | start of ramp |
| ss | speed sampling |
| t | terminal |
| v | voltage |
| w | wind |
| wa | wind speed initial average value |
| wg | wind gust |
| wr | wind ramp |
| wt | wind turbulence |
| wr | wind turbine rotor |

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6. J.G. Slootweg, W.L. Kling, "Is the answer blowing in the wind? The current status of wind as a renewable energy source and its power system integration issues", scheduled for publication in the November/December 2003 issue of the IEEE Power & Energy Magazine.
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# Summary

The availability of electricity is an important precondition for economic activity and societal development. That the present way of generating electrical power has negative environmental consequences and consumes finite natural resources causes increasing concern. To overcome the disadvantages of conventional electrical power generation, electricity must be generated from renewable sources. This can be done by extracting energy from infinitely available natural resources, such as sunlight, wind and flowing water and converting this energy into electricity.
Wind turbines are one technology that can be used for generating renewable electricity. They can be applied nearly everywhere and the electricity generated with wind turbines tends to be less expensive than that from other sources of renewable energy. Governmental support for renewable energy sources by a number of national governments has therefore resulted in a strong growth of the installed wind power in those countries.
In Denmark and Germany, two countries in which wind power was strongly supported, 2.880 MW and 12.001 MW was installed by the end of 2002 respectively. The installed wind power in the Netherlands amounted to 688 MW at that time. The share of wind power in the overall electricity consumption of 2002 in these three countries was 14 %, 4,5 % and 1,6 % respectively. In the near future, a further growth of wind power is expected, not only in these three countries, but also in many other countries, such as Spain, the United Kingdom, France, Greece and the United States.

There exist two fundamental differences between wind turbines on the one hand and technologies for conventional electrical power generation on the other:

- the primary energy source of wind turbines, the wind, cannot be controlled, while that of conventional power generation, fossil fuels or nuclear fission, can.
- in wind turbines, generator types are applied that differ from the directly grid coupled synchronous generator; the type of generator used in nearly all conventional power plants.

Due to these two differences, wind turbines affect the behaviour of electrical power systems both locally and system wide.

In this thesis, one of the system wide impacts of wind power is treated, namely the impact of wind power on the dynamic stability of a power system. The concept of dynamic stability of

power systems refers to the extent to which a system is able to find a new stable equilibrium after a disturbance. One of the properties of such an equilibrium is that all electrical quantities must be within the allowable limits.
There exist two types of disturbances, namely changes in the network topology and changes in the value of the state variables of generators. Examples of topological changes are a short circuit (often referred to as a fault), the disconnection of cables or overhead lines, changes in generation due to unit trips and changes in or disconnection of loads. State variables of generators are for instance rotor speed and flux linkages. Their value can change due to variations in the supply of primary energy or exciter voltage. The quantities of interest when investigating dynamic stability are mainly generator rotor speeds and node voltages.

For this research project covering the impact of wind turbines on the dynamic stability of power systems, the software package PSS/E™ was used. This simulation program is used by utilities, research institutes and engineering consultants worldwide. PSS/E™ is based on a specific approach for simulating electrical power systems. This approach is applied in order to increase the simulation speed.
Up to this moment, no wind turbine models are included in the standard model library of PSS/E™. Furthermore, at the start of the research project, it turned out that wind turbine models fulfilling the requirements posed by the simulation approach used in PSS/E™ were even not described in the scientific literature yet. Because the availability of these models was essential to reach the goal of the research project, it was necessary to develop them.

In order to develop wind turbine models that could be incorporated into PSS/E™, first the working principles of the different types of wind turbines were investigated and mathematical equations governing their behaviour were derived. Then, the equations were simplified in such a way that the resulting model met the requirements posed by the simulation approach used in PSS/E™.
The effect of the simplifications on the accuracy of the derived models was investigated by comparing simulation results with measurements obtained from various wind turbine manufacturers. The level of correspondence between the measurements and the simulations proved to be acceptable. The developed models were therefore incorporated into PSS/E™.

It proved cumbersome to model each wind turbine separately in the simulations. This is caused by the difference between the typical capacity of a wind turbine and of a conventional power plant. The typical capacity of a conventional power plant is about 50 to 250 times higher than that of an average wind turbine. When a conventional power plant is replaced by a wind park, this means that several tens or even hundreds of wind turbines must be incorporated into the model of the investigated power system. This is impractical and involves much computation time.

Therefore, aggregated wind park models were developed. This type of models represents a complete wind park, rather than an individual turbine. The input parameters for such a model are the parameters of the applied wind turbine, the location of the individual turbines in the park and characteristics of the wind speed. It proved necessary to develop separate models for wind parks with constant speed turbines and those with variable speed turbines. The aggregated wind park models were validated by comparing their response to that of a detailed wind park model, in which all turbines were modelled individually. The results showed a high level of correspondence.

Using the developed tools, simulations were carried out to investigate the impact of wind turbines on the dynamic stability of a power system. For the simulations, models of electrical power systems were used, in which conventional generators that were directly coupled to the grid were gradually replaced by wind turbines. For the various wind power penetration levels, the same event was applied and the responses of the system were compared. In this way, knowledge on the impact of wind power on the dynamic stability of the investigated power system was gathered. A test system that is described in the international literature, as well as a model of the Dutch power system have been used for the investigations.

Firstly, the impact of wind turbines on the dynamic stability of a power system responding to the occurrence of a topological change was investigated, the so-called transient stability. From the simulation results, it was concluded that there are fundamental differences between the impact of the various types of wind turbines, particularly between constant and variable speed wind turbines. Constant speed wind turbines can lead to voltage instability after a fault or after the trip of a nearby generator. They consume a large amount of reactive power if the rotor speed deviates from the nominal value, which impedes voltage restoration. Solutions to prevent voltage instability after connecting constant speed wind turbines to the grid have been discussed in the literature. These solutions have not been paid any further attention to in this research project.

In case of variable speed wind turbines, there hardly exists a risk on voltage instability, because the electrical and mechanical behaviour of variable speed wind turbines are decoupled by the power electronic converter. Therefore, they do not have to resynchronize after a fault and they do not consume reactive power. A drawback of the present generation of variable speed wind turbines is, however, that they disconnect immediately when a fault occurs. The power electronic converter is very sensitive to overcurrents. The main reason to disconnect variable speed wind turbines at a fault is hence to protect the power electronic converter.

In this research project, it was assumed that variable speed wind turbines disconnect during a fault and that they quickly reconnect after clearing of the fault. There are two reasons for this assumption. First, if the present approach (immediate disconnection at a fault) is continued, it is clear beforehand that this will cause problems when the wind power penetration level is high. Second, grid companies facing large amounts of wind power are currently adapting their connection requirements, in order to prevent large scale disconnection of variable speed wind turbines. With the assumed behaviour of variable speed wind turbines, no negative impact on power system transient stability was observed.

Secondly, the impact of wind turbines on the dynamic stability of a power system responding to the occurrence of a change in the value of a state variable was investigated, the so-called small signal stability. It was concluded that wind turbines do not affect small signal stability negatively: the damping of the system's eigenvalues does not decrease. Constant speed wind turbines even have a favourable impact on the small signal stability in certain cases. Variable speed wind turbines seem hardly to affect power system small signal stability.
Although these observations can be explained by noticing that in wind turbines no synchronous generators that are directly coupled to the grid are used, whereas particularly this generator type causes power system oscillations, the conclusions should nevertheless be treated with care. No other studies covering the impact of wind turbines on power system small signal stability are available and further research is therefore necessary.

The results of this research project are important for two reasons. Firstly, we have developed wind turbine models that can be used to carry out dynamics studies and to investigate the impact of wind power on the dynamic stability of a power system. The models can be used by e.g. grid companies, designers and consultants and can be applied for investigating the transient stability, which concerns the response of a power system to a topological change, and for investigating the small signal stability, which concerns the response of the power system to a change in the value of a state variable. Secondly, the research has yielded knowledge on the topic of the impact of wind turbines on power system dynamic stability. This knowledge is essential to determine whether goals concerning a certain contribution of wind power are indeed feasible and to decide which type of studies must be carried out to investigate this.
The second aspect also explains why the research was carried out as a part of the AIRE (*Accelerated Implementation of a Renewable Electricity supply in the Netherlands*) project. This project is financially supported within the framework of the Energy Research Stimulation Programme set up by the Netherlands Organization for Scientific Research (NWO) and the Netherlands Agency for Energy and the Environment (Novem). Participants in the AIRE project are the universities of Utrecht, Maastricht and Delft, and the Energy Research Centre of The Netherlands (ECN). The purpose of the project is to accelerate the implementation of renewable energy in the Netherlands, taking an integral approach towards technical, legal and financial barriers impeding implementation. In this research project, the emphasis was on the technical barriers.

This thesis covers only some aspects of the impact of wind power on power systems. Further research on this topic is hence necessary. Firstly, a more elaborate validation of the wind turbine models developed in this research project must be carried out. Further, the impact of wind power on the small signal stability of power systems must be investigated further, as well as maintaining the power balance at high wind power penetration levels and the consequences of the reduction of the system's inertia caused by the application of variable speed wind turbines.

# Samenvatting

De beschikbaarheid van elektrische energie vormt een belangrijke randvoorwaarde voor economische activiteit en maatschappelijke ontwikkeling. Het feit dat de opwekking van elektriciteit een aantal negatieve consequenties heeft voor het milieu en dat er eindige natuurlijke hulpbronnen bij worden verbruikt, is een punt van toenemende zorg. Om deze nadelen van de zogenaamde conventionele elektriciteitsopwekking te ondervangen, moet elektriciteit meer duurzaam worden opgewekt. Bijvoorbeeld door energie te onttrekken aan oneindig beschikbare natuurlijke hulpbronnen, zoals zonlicht, wind of stromend water en deze energie om te zetten in elektriciteit.
Windturbines vormen één van de mogelijke technologieën die gebruikt kunnen worden voor het duurzaam opwekken van elektriciteit. Ze kunnen vrijwel overal worden toegepast en elektriciteit opgewekt door windturbines is minder duur dan elektriciteit opgewekt door de meeste andere technologieën voor duurzame elektriciteitsopwekking. De stimulering van duurzame elektriciteitsopwekking door een aantal nationale overheden heeft dan ook geleid tot een sterke groei van het geïnstalleerde windvermogen in de betreffende landen.
Zo was in Denemarken en Duitsland, twee landen waarin windenergie sterk wordt gestimuleerd, eind 2002 respectievelijk 2.880 MW en 12.001 MW aan windvermogen opgesteld. Het opgesteld vermogen in Nederland bedroeg op dat moment 688 MW. De bijdrage aan het totale elektriciteitsverbruik bedroeg in het jaar 2002 voor deze drie landen respectievelijk 14 %, 4,5 % en 1,6 %. In de komende jaren wordt een verdere groei van windenergie verwacht en dat niet alleen in deze drie landen, maar ook in een groot aantal andere landen, waaronder Spanje, het Verenigd Koninkrijk, Frankrijk, Griekenland en de Verenigde Staten.

Er zijn twee fundamentele verschillen tussen windturbines enerzijds en middelen voor conventionele elektriciteitsopwekking anderzijds:

- de primaire energiebron van windturbines, de wind, is niet stuurbaar, terwijl dit wel zo is in het geval van conventionele elektriciteitsopwekking met fossiele brandstoffen of kernsplijting.
- in windturbines worden andere typen generatoren toegepast dan de direct aan het net gekoppelde synchrone generator waarmee vrijwel alle installaties voor conventionele elektriciteitsopwekking zijn uitgerust.

Als gevolg van deze twee verschillen beïnvloeden windturbines het gedrag van het elektriciteitsnet zowel lokaal als op systeemniveau.

In dit proefschrift staat één aspect van de invloed van windturbines op het gedrag op systeemniveau centraal, namelijk de invloed van windenergie op de korte termijn stabiliteit van het elektriciteitsnet. De korte termijn stabiliteit van een elektriciteitsnet behelst de mate waarin een systeem in staat is om na een verstoring opnieuw een stabiele evenwichtstoestand te bereiken, waarvoor geldt dat alle elektrotechnische grootheden zich binnen de toegestane grenzen bevinden.
Verstoringen zijn enerzijds veranderingen in de topologie van het net en anderzijds variaties in de toestandsvariabelen van generatoren. Voorbeelden van topologische veranderingen zijn een kortsluiting (ofwel een fout), de afschakeling van verbindingen, veranderingen in de opwekking door afschakeling van generatoren en veranderingen in of afschakeling van belastingen. Toestandsvariabelen van generatoren zijn onder andere het rotortoerental en de magnetische fluxen. De waarde hiervan kan veranderen door variaties in de toevoer van de primaire energie of in de bekrachtigingsspanning. De grootheden die van belang zijn bij de korte termijn stabiliteit zijn voornamelijk de spanningen op de knooppunten in het net en de toerentallen van de aangesloten generatoren.

Bij dit onderzoek naar de invloed van windturbines op de korte termijn stabiliteit van een elektriciteitsnet is gebruik gemaakt van het programma PSS/E™. Dit simulatieprogramma wordt wereldwijd door elektriciteitsbedrijven, onderzoeksinstituten en ingenieursbureaus toegepast. PSS/E™ is gebaseerd op een specifieke aanpak om elektriciteitsnetten relatief snel te kunnen simuleren.
Tot op heden zijn er in de bij PSS/E™ behorende bibliotheek met standaardmodellen geen simulatiemodellen van windturbines aanwezig. Bovendien bleek bij aanvang van dit onderzoek dat er in de wetenschappelijke literatuur nog geen modellen van windturbines beschreven waren die compatibel waren met de in PSS/E™ toegepaste benadering. Omdat de beschikbaarheid van dergelijke modellen voor dit onderzoek essentieel was, was het noodzakelijk om deze modellen zelf te ontwikkelen.

Voor het ontwikkelen van windturbinemodellen die in PSS/E™ geïntegreerd konden worden, zijn eerst de werkingsprincipes van de verschillende typen windturbines bestudeerd en zijn wiskundige vergelijkingen opgesteld die hun gedrag beschrijven. Daarna zijn deze vergelijkingen vereenvoudigd op een dusdanige wijze dat het resulterende model consistent was met de simulatieaanpak zoals die in PSS/E™ wordt toegepast.
De invloed van de toegepaste vereenvoudigingen op de nauwkeurigheid van de modellen is onderzocht door simulatieresultaten te vergelijken met metingen die door enkele turbinefabrikanten beschikbaar zijn gesteld. De mate van overeenkomst tussen metingen en

simulatieresultaten bleek bevredigend. De ontwikkelde modellen zijn daarom vervolgens in PSS/E™ geïntegreerd.

Het apart modelleren van elke windturbine in de uit te voeren simulaties bleek enigszins omslachtig te zijn. De oorzaak hiervan is het verschil in schaalgrootte tussen windturbines en conventionele installaties voor elektriciteitsopwekking. Een typische conventionele elektriciteitscentrale heeft een capaciteit die een factor 50 tot 250 hoger ligt dan die van een gemiddelde windturbine. Wanneer bij het onderzoek een conventionele centrale vervangen wordt door een windpark, betekent dit dus dat er enkele tientallen tot zelfs honderden windturbines in het simulatiemodel van het bestudeerde elektriciteitsnet moeten worden opgenomen.
Omdat dit niet erg praktisch is en tevens tot gevolg heeft dat de simulaties erg lang duren, zijn geaggregeerde windparkmodellen ontwikkeld. Met deze modellen kan in één keer een compleet windpark worden gerepresenteerd. De invoergegevens voor een dergelijk model bestaan uit de parameters van de in het park gebruikte windturbine, de locatie van de individuele turbines waaruit het park is opgebouwd en de karakteristieken van de windsnelheid. Het bleek noodzakelijk om aparte modellen te ontwikkelen voor windparken met constant toerental turbines en met variabel toerental turbines. De ontwikkelde modellen zijn gevalideerd door de responsies te vergelijken met die van een gedetailleerd model van een windpark waarin alle turbines afzonderlijk gerepresenteerd werden. De simulatieresultaten vertoonden een zeer grote mate van overeenkomst.

Met deze gereedschappen zijn vervolgens simulaties uitgevoerd om de invloed van windturbines op de korte termijn stabiliteit van het elektriciteitsnet te onderzoeken. Bij deze simulaties is gebruik gemaakt van modellen van elektriciteitsvoorzieningsystemen, waarin conventionele, direct aan het net gekoppelde synchrone generatoren stapsgewijs zijn vervangen door windturbines. Door vervolgens steeds dezelfde gebeurtenis te laten optreden en de responsies van het systeem met verschillende bijdragen van windenergie onderling te vergelijken, is inzicht verkregen in de invloed van windturbines op de korte termijn stabiliteit van elektriciteitsnetten. Er zijn analyses uitgevoerd met een testsysteem beschreven in de internationale wetenschappelijke literatuur en met een model van het Nederlandse hoogspanningsnet.

Allereerst is onderzocht welke invloed windturbines hebben op de korte termijn stabiliteit van het systeem bij het optreden van verstoringen die leiden tot een topologische verandering: de zogenaamde transiënte stabiliteit. Uit de resultaten van de simulaties kon worden geconcludeerd dat er grote verschillen zijn tussen de invloed van de verschillende typen windturbines, voornamelijk tussen turbines met constant en variabel toerental. Constant toerental turbines veroorzaken in bepaalde situaties spanningsinstabiliteit na een kortsluiting of na de afschakeling van een nabije generator. De oorzaak hiervan is dat deze windturbines

wanneer hun toerental afwijkt van de nominale waarde een grote hoeveelheid blindvermogen uit het net opnemen, wat het herstel van de netspanning belemmert. In de literatuur worden oplossingen aangedragen om het optreden van spanningsinstabiliteit na aankoppeling van constant toerental turbines te voorkomen. Deze oplossingen zijn in dit onderzoek niet verder onderzocht.
In geval van variabel toerental turbines is er nauwelijks een risico op spanningsinstabiliteit. Dit komt doordat bij deze turbines het mechanisch en elektrisch gedrag zijn ontkoppeld door de vermogenselektronische omzetter. Zij hoeven daardoor na een fout niet te resynchroniseren en onttrekken geen blindvermogen aan het net. Een problematisch aspect van het gedrag van de huidige generatie variabel toerental turbines is echter wel dat deze bij een spanningsdaling onmiddellijk afschakelen. De reden hiervoor is dat de vermogenselektronische omzetter erg gevoelig is voor te hoge stromen. Afschakeling vindt dan ook voornamelijk plaats om de vermogenselektronica hiertegen te beschermen.
In dit onderzoek is ten aanzien van het gedrag van variabel toerentalturbines aangenomen dat deze gedurende een spanningsdaling weliswaar afschakelen, maar daarna weer snel inschakelen. De redenen voor deze aanname zijn de volgende. Enerzijds is wanneer de huidige praktijk wordt gehandhaafd (de windturbines schakelen bij een spanningsdaling onmiddellijk af) op voorhand duidelijk dat dit bij een grote bijdrage van windenergie tot problemen leidt. Anderzijds passen de beheerders van netten waarin veel windenergie hun aansluitvoorwaarden op dit moment aan om grootschalige afschakeling te voorkomen. Onder deze aanname kon in het geval van variabel toerentalturbines geen negatieve invloed op de transiënte stabiliteit worden vastgesteld.

Vervolgens is onderzocht welke invloed windturbines hebben op de korte termijn stabiliteit van het systeem bij het optreden van verstoringen die leiden tot een verandering in de waarde van de toestandsvariabelen: de zogenaamde klein-signaal stabiliteit. Er is vastgesteld dat windturbines de klein-signaal stabiliteit niet negatief beïnvloeden: de demping van de eigenwaarden van het systeem verslechtert niet. Constant toerental turbines lijken in een aantal gevallen zelfs een gunstige uitwerking op de klein-signaal stabiliteit van een systeem te hebben. Variabel toerental turbines hebben nauwelijks invloed op de klein-signaal stabiliteit.
Hoewel deze observaties kunnen worden verklaard door het feit dat er in windturbines geen direct aan het net gekoppelde synchrone generatoren worden toegepast, terwijl juist dit generatortype aanleiding geeft tot het optreden van oscillaties, dienen ze met enige voorzichtigheid te worden betracht. Er zijn namelijk nog geen andere studies naar de invloed van windturbines op de klein-signaal stabiliteit van elektriciteitsvoorzieningsystemen, zodat aanvullend onderzoek noodzakelijk is.

Het belang van dit onderzoek is tweeledig. Ten eerste zijn er modellen van windturbines ontwikkeld die door netbeheerders, ontwerpers van windparken, adviseurs en andere belanghebbenden gebruikt kunnen worden om dynamische studies uit te voeren en de invloed van windturbines op de korte termijn stabiliteit van een elektriciteitsnet te onderzoeken. De modellen zijn geschikt voor het onderzoek van de transiënte stabiliteit, die betrekking heeft op de reactie van het systeem op een verstoring als gevolg van een topologische verandering, en voor het onderzoek naar de klein-signaal stabiliteit, die betrekking heeft op de reactie van het systeem op een verstoring als gevolg van een verandering in de waarde van een toestandsvariabele. Ten tweede heeft het onderzoek geleid tot meer inzicht in de invloed van windturbines op de korte termijn stabiliteit van elektriciteitsnetten. Dit inzicht is essentieel bij het bepalen van de haalbaarheid van doelstellingen ten aanzien van windenergie en om vast te stellen welke studies daartoe moeten worden uitgevoerd.

Dit laatste aspect verklaart tevens waarom dit onderzoek plaatsgevonden heeft in het kader van het AIRE (*Accelerated Implementation of a Renewable Electricity supply in the Netherlands*)-project. Dit project is financieel ondersteund in het kader van het Stimuleringsprogramma Energieonderzoek, dat is opgezet door de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) en de Nederlandse Organisatie voor Energie en Milieu (Novem). In het AIRE-project werken de universiteiten van Utrecht, Maastricht en Delft samen met Energieonderzoek Centrum Nederland (ECN). Het doel van het onderzoek is het versnellen van de implementatie van duurzame energie in Nederland. De technische, juridische en economische barrières die de implementatie van duurzame energie belemmeren, worden daartoe in samenhang bestudeerd. Bij dit onderzoek waren voornamelijk de technische barrières onderwerp van studie.

In dit proefschrift komen slechts enkele aspecten van de invloed van windenergie op een elektriciteitsvoorzieningsysteem aan de orde. Verder onderzoek naar dit onderwerp is dan ook noodzakelijk. Ten eerste dient een uitgebreidere validatie van de in dit onderzoek ontwikkelde modellen plaats te vinden. Verder dient aanvullend onderzoek naar de invloed op de klein-signaal stabiliteit te worden verricht en dient meer aandacht te worden besteed aan de handhaving van de vermogensbalans bij een grote bijdrage van windenergie en aan de gevolgen van het reduceren van de massatraagheid van het systeem, als gevolg van de toepassing van variabel toerental windturbines.

# Curriculum Vitae

Johannes Gerlof (Han) Slootweg was born on February 29th, 1976 in De Bilt. He attended secondary school at the Van Lodensteincollege in Amersfoort from 1988 to 1994. After obtaining his Gymnasium-ß degree in June 1994, he started to study Electrical Engineering at Delft University of Technology in September that same year.
From October 1997 till March 1998, Han Slootweg stayed in Berlin for six months. He took courses at the Technical University of Berlin in Electrical Machines and Drives, Power Electronics and High Voltage Technology. He also did an internship at the Dynamowerk of Siemens AG, which was financially supported by Siemens Nederland N.V., The Hague, within the framework of the Siemens Future World Scholarship.
From April until August 1998, Han Slootweg carried out his M.Sc. project at the Power Electronics and Electrical Machines (now Electrical Power Processing) group under supervision of dr. ir. M.J. Hoeijmakers and dr. ir. H. Polinder, in cooperation with Philips CFT, Eindhoven. The title of his M.Sc. thesis was *Calculation of the Force Generated by a Linear Permanent Magnet Machine Including Magnetic Saturation*. The thesis was awarded the mark 9 and in September 1998, Han obtained his M.Sc. (ir.) degree cum laude.

After graduating, Han Slootweg started to work with the Delft Interfaculty Research Centre *Design and Management of Infrastructures*. After a year, he returned to the faculty of Electrical Engineering, Mathematics and Computer Science, this time to the Electrical Power Systems Laboratory, to carry out Ph.D. research under supervision of prof. ir. W.L. Kling. The topic of the research project was the impact of wind power on power system dynamics. The project formed one of the three Ph.D. projects that are part of the AIRE project, funded by Netherlands Organization for Scientific Research (NWO) and the Netherlands Agency for Energy and the Environment (Novem) and managed by the Utrecht Centre for Energy Research.

From February 2000 till June 2003, Han also completed a part time M.Sc. (drs.) in Management Science at the Open University of The Netherlands, Heerlen. The title of his M.Sc. thesis was *Monitoring Long Term Reliability of Electricity Networks*. Currently, he is a staff engineer with Essent Netwerk Noord bv, Zwolle. Han is married to Hanneke Slootweg-van de Craats and has a daughter, Lidewij, who was born on October 22nd, 2002.