Configuration study of large wind parks

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Department of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2003

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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Abstract

In this thesis, layouts of various large-scale wind parks, using both AC as well as DC, are investigated. Loss modelling of the wind park components as well as calculations of the energy capture of the turbines using various electrical systems are performed, and the energy production cost of the various park configurations is determined. The most interesting candidate for a DC transmission based wind park was investigated more in detail, the series DC wind park. Finally, the power quality impact in the PCC (point of common coupling) was studied.

It was found that from an energy capture point of view, the difference in energy production between various wind turbine systems is very small.

Of all the investigated wind park configurations, the wind park with the series connected DC wind turbines seems to have the best potential to give the lowest energy production cost, if the transmission distance is longer then 10-20km. Regarding the series DC wind park it was found that it is the most difficult one to control. However, a control algorithm for the series park and its turbines was derived and successfully tested. Still, several more details regarding the control of the series wind park has to be dealt with.

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Chapter 1

Introduction

1.1 Problem background

Wind energy converters are becoming larger and larger and more and more erected in groups rather than one by one. Today wind farms up to a size of 160 MW are being built and several plans on 1000 MW-parks exist. These larger wind parks are mainly considered to be located out in the sea, preferably at such a distance that they cannot be observed from the shore. The size of the wind parks has led to a problem of finding a suitable grid connection point, which is strong enough to take care of the power from the wind parks. This leads to that in many cases the distance between the grid connection point and the wind park is so long, that a DC-transmission may become more favorable than a conventional AC-transmission. This is due to the well known problem with capacitive current generation of AC-cables, which makes the possible length of an AC-cable limited. This is further stressed by the fact that it is extremely difficult to get permission to build new over-head lines, and therefore it must be taken into consideration that it might be necessary to use DC-cables also for the land transmission.

All of this lead to interesting issues like: When is DC-transmission more feasible than AC-transmission? If DC is used, how far down in the wind park can we have DC? How should DC/DC converters be designed? How should large-scale parks be designed? Is there a risk that wind parks using fix speed wind turbines could create power pulsations (flicker emissions) in the PCC (point of common coupling)?

1.2 Overview of previous work

Wind park design studies have been presented in several papers, for instance [1, 14, 16, 22, 33, 34, 36, 43]. The most detailed study was made by Bauer, Haan, Meyl and Pierik [5]. In [21] some interesting DC solutions for offshore wind parks are presented and especially the proposal of a wind park with wind turbines connected in series, is of great interest. The energy production of various wind parks is calculated in [22, 31, 37], and in [14, 22, 35, 37, 41] the estimated cost of the produced electric energy is presented. In [4] the economics of some offshore wind farms that are build and are planned to be built, are presented.

Of importance when determining the energy capture is to have detailed blade data as well as detailed loss models of components. Relevant blade data is not trivial to obtain, but previous authors have most likely used the same method as here: By not revealing the origin of the blade description, it is possible to obtain such data. Generator loss models has for instance been presented in [11, 35], gear-box losses have been found in [11]. However, available loss models of existing high power DC/DC-converters are very crude.

Cost data is another large problem area. Here the same principle seems to be dominant: Data can be obtained providing that the sources are not revealed. However, in [6, 23, 30, 37, 41] valuable cost information is given which can be utilized.

Energy capture calculations of wind turbine systems and wind farms is a subject in which it is possible to find much information in the literature. However, detailed comparisons between different electric generating systems for wind turbines are not so common. As a part of the present work article [27] was published where a detailed comparison between electric generating systems for wind turbines was studied.

Previously in this Ph.D. project, a detailed evaluation of the energy production cost of various wind parks has been performed and these results can be found in [20]. The chapters in this thesis, that regards the energy production cost of different wind parks, losses in wind park components and the cost of the different wind park components are based on [20]. In [20], a study of the suitability of various DC/DC-converters was made. Three DC/DC-converters, Boost, Full Bridge and Full Bridge Isolated Boost, was found to be interesting candidates as the ”transformer” component in potential DC-based wind parks and accordingly, they are used in this thesis as different DC transformers.

Regarding the power quality impact on the grid by wind turbines there exists a large number of papers. Of special interest are [26, 40] where the impact of X/R is discussed and [38, 40] where there the summary up of power pulsations was investigated.

1.3 Purpose of the report

The purpose of this thesis is to investigate the energy capture and energy loss of different wind park configurations and also to compare the energy production cost of the configurations. Moreover to investigate the series DC wind park and to find a possible control scheme. Finally a goal was to investigate the electrical grid limitations for the installation of fixed speed wind parks.

1.4 Layout of report

In chapter 2 the six different wind park configurations that are investigated in this work are presented. Some of the general boundary conditions are presented in this chapter also.

In chapter 3 the principle of converting kinetic energy of the air flow through the rotor disc to mechanical power on the wind turbine shaft is explained.

In chapter 4 different wind turbine systems are investigated, both AC and DC systems. The energy capture of the different wind turbine systems are compared in order to make the selection of which wind turbine system that shall be used in the study of the wind parks.

In chapter 5 the energy production cost of the six wind park configurations are shown for some different cases. The energy production cost of the configurations are compered and the wind park selection is discussed depending on the transmission distance and the rated power of the wind park.

In chapter 6 the dynamics of and the controllers for the series connected DC wind park are investigated more in detail.

In chapter 7 the conclusions and suggestions for future work are presented.

Appendix A: Publications on power quality impact of fixed speed wind turbines.

Chapter 2

Wind park configuration

In this chapter, the different wind park configurations that are investigated in this work are described. The boundary conditions for the investigation are explained and the different transmission systems are described.

2.1 General wind park layout

Generally, the wind parks investigated in this work can be represented by the sketch presented in figure 2.1. As seen in figure 2.1 the wind park consists of a number of

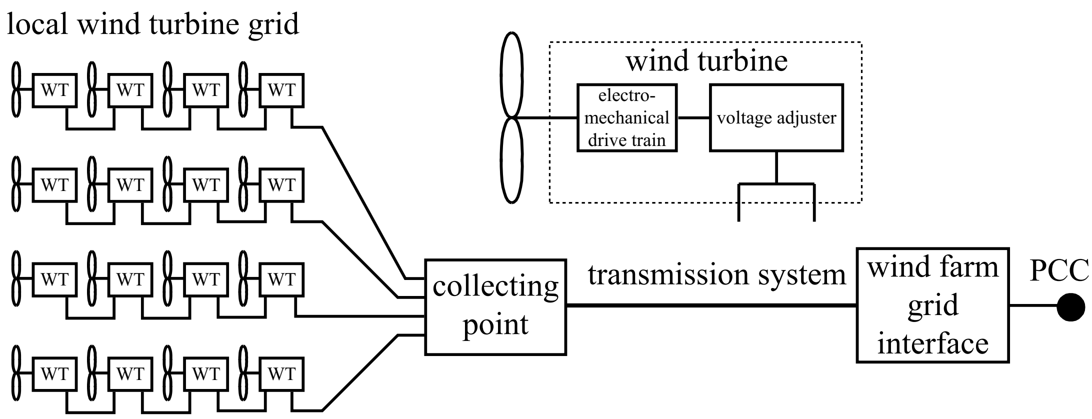

Figure 2.1: General wind park layout.

elements, wind turbines (WT), local wind turbine grid, collecting point, transmission system, wind park interface to the point of common connection (PCC). It shall be noticed that all wind turbines in this work have a voltage adjusting unit (AC or DC transformer) included in the wind turbine unit itself. The local wind turbine grid connects the wind turbine units to the collecting point. The wind turbine units are connected in parallel to radials, unless otherwise is specified in this work. In the collecting point, the voltage is increased to a level suitable for transmission. The energy is then transmitted to the wind park grid interface over the transmission system. The wind park grid interface adapts the voltage, frequency and the reactive power of the transmission system to the voltage level, frequency and reactive power demand of the grid in the PCC.

2.1.1 Rated power of the wind park, Number of turbines

The size of the wind turbines has in this project been selected to 2MW, since these turbines are available for all kinds of wind energy systems today. However, it should be pointed out that the main results of this study would most likely not be very different if another turbine size would have been selected. Almost all wind turbines considered in this work has a rated generator voltage of 690V. Most likely, the generator voltage will be increased when the rated power of the generator is increased in order to decrease the losses. For example NEG Micon has chosen 960V in their 2MW wind turbine [24].

This work focuses on four sizes of wind parks

- 60MW
- 100MW
- 160MW
- 300MW

Although most wind parks today are much smaller then 60MW, 60MW is used as a small wind park here. Horns Ref is one example of a 160MW offshore wind park $14 - 20$km out of the west coast of Denmark [3]. It is today (2003) the largest built sofar. No larger wind parks than 300MW is taken under consideration in this work due to the fact that if a larger wind park is going to be build it will probably be divided into smaller modules, where a maximum module size of 300MW seems appropriate. Two advantages using modular building of wind parks are, that the investment cost of the whole wind park is spread out over a longer period and that part of the production can start before the whole park has been built. Another advantage of this division is that if cross connections between the modules are made, the park will be more fault tolerate.

2.1.2 Distances between the wind turbines

In this work the wind power plants will be placed in a grid with 7 rotor diameters between the turbines in both directions. This seems to be a commonly used distance and at Horns Rev the distance is 7 rotor diameters [3]. The distance between wind turbines in the wind direction can not be too small. This is due to the fact that when the wind passes through the rotor of the wind turbine it gets very turbulent and the wind speed is decreased. This means that if the wind turbines are located to close to each other, the wind will be more and more turbulent after it passes each wind turbine. This would lead to that wind turbines downstream in the wind park, are subjected to aerodynamical stresses, may even have to be shut down due to that the mechanical loading gets to high during difficult conditions. In addition, the energy losses due to the reduced wind speed will be significant if the wind turbines are put to close to each other. The minimum length to avoid this is approximately 5-7 rotor diameters.

Of course, if the wind is mainly coming from one direction, the wind turbines can be placed closer in the direction perpendicular to the prevailing winds. But for the Nordic countries, wind directions from northwest to south are quit normal, which means that the wind turbines should be placed with an equal distance in all directions.

In this work, it is thus assumed that the wind turbines are put in a grid with 7 rotor diameters between. The distance from the column nearest the collecting point to the collecting point is also 7 rotor diameters, see figure 2.1.

Since 7 rotor diameters was used, it was possible to neglect the wake effects. Anyway, if wake effects were taken into account, it would not affect the comparison between different wind park configurations very much. In addition, there is a lack of available, simple and good models for calculating the wake effect in steady-state.

2.2 Electrical system configuration

In this section, the different electrical systems for the wind parks are described. For all systems, the main grid voltage in the PCC is assumed to be constant.

2.2.1 AC/AC

All wind parks that have been build today have an AC electrical system from the wind turbines to the PCC. In this work, two different AC-systems are investigated, referred to as the small and the large AC wind park. Three core cables are used for AC transmission throughout this work.

The first configuration to be discussed is the small AC wind park. The idea with the small AC wind park, is that it should be suitable for small wind parks with a short transmission distance. In the small AC wind park, the local wind park grid is used both for connecting all wind turbines in a radial together and to transmit the generated power to the wind park grid interface, which is shown in figure 2.2. For this system

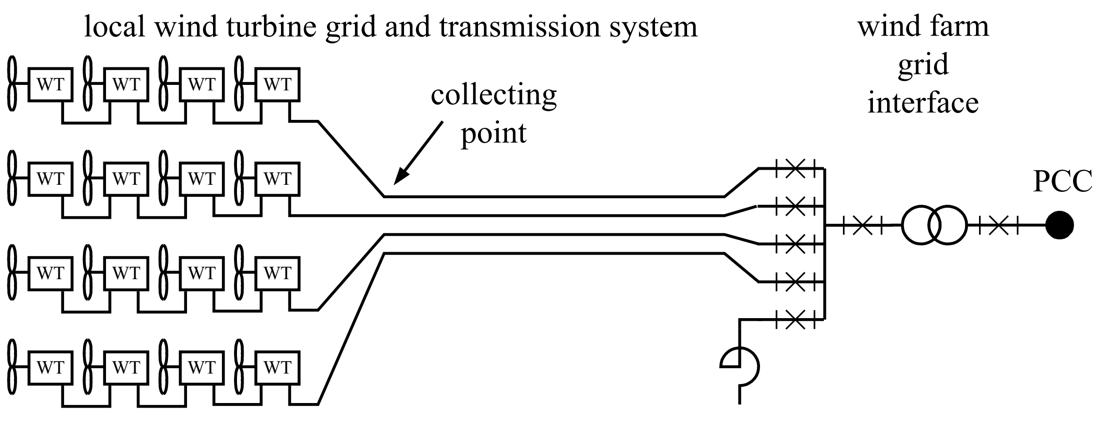

Figure 2.2: The electrical system for the small AC wind park.

the cables in the local wind park grid are assumed to be installed one and one from the wind turbines to the collecting point. From the collecting point to the wind farm grid interface all cables are assumed to be installed together. This means that there is one cable installation cost per cable from the wind turbines to the collecting point and only one cable installation cost for all cables from the collecting point to the wind park grid interface.

Let us now study a slightly different configuration, the large AC wind park. The large AC wind park system is a more traditional system, based on the general system in figure 2.1. This system has a local wind park grid with a lower voltage level (20-30kV) connected to a transformer and a high voltage transmission system. This system requires an offshore platform for the transformer and switch gear, as can be seen in figure 2.3. Horns Rev wind park is build according to this principle. For this system

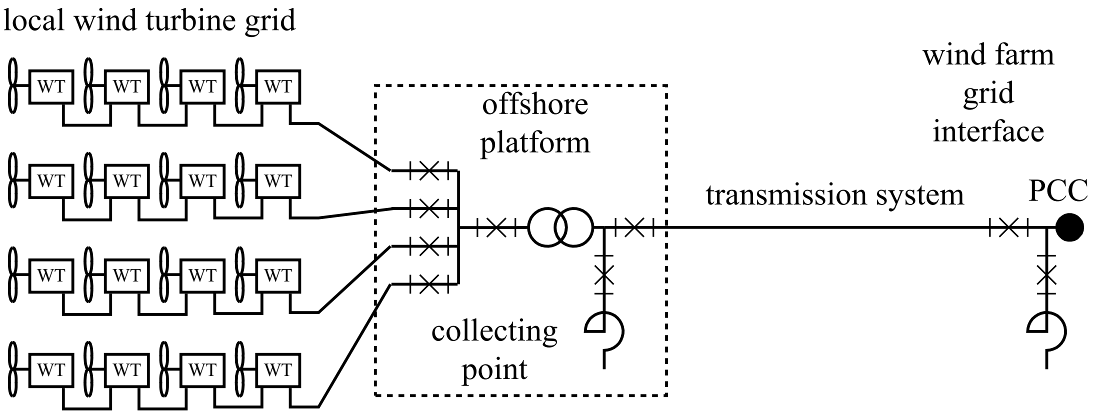

Figure 2.3: The electrical system for the large AC wind park.

there is one cable installation cost per cable, due to the fact that all cables have different routes.

2.2.2 AC/DC

In this system the AC transmission in figure 2.3 has been replaced with a DC transmission, this wind park will be referred to as the AC/DC wind park. This type of system does not exist today but is frequently proposed when the distance to the PCC is long, or if the AC grid that the wind park is connected to is weak. The system is shown in figure 2.4. In this system we have an independent local AC system in which both the voltage and the frequency are fully controllable with the offshore converter station. This can be utilized for a collective variable speed system of all wind turbines in the park. The benefits with this are that the aerodynamic and electrical efficiency can be increased.

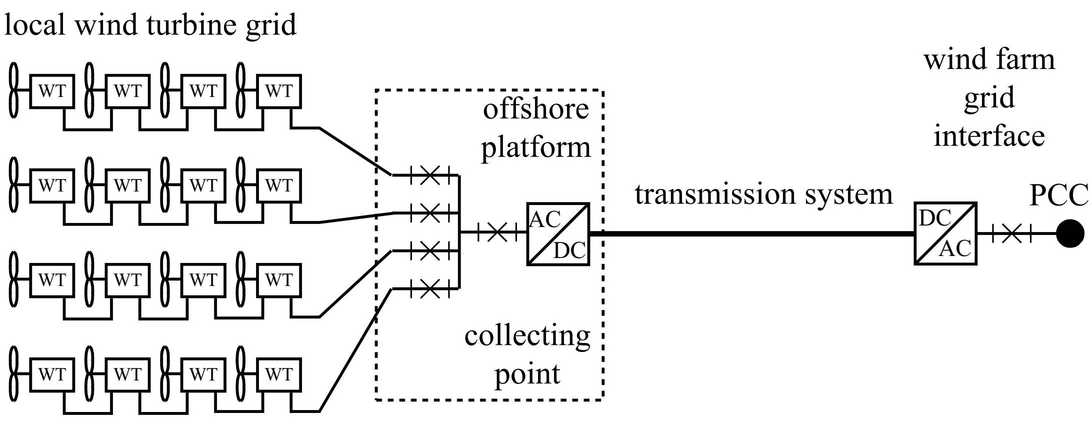

Figure 2.4: The electrical system for the AC/DC wind park.

The installation cost of the cables are the same as for the large AC wind park. The two DC transmission cables, one for the positive pole and one for the negative pole, are assumed to be installed together and therefore there is only one cable installation cost for these two cables.

2.2.3 DC/DC

For the pure DC wind park, three different configurations are investigated. Two that are based on the two layouts of the AC systems, referred to as the small DC wind park and the large DC wind park, and one configuration with the turbines in series, as shown in [21]. In all DC configurations in this work, the two cables, one for the positive pole and one for the negative pole, are assumed to be installed together and are therefore referred to as one cable.

The electrical system for the small DC wind park is shown in figure 2.5. As can be

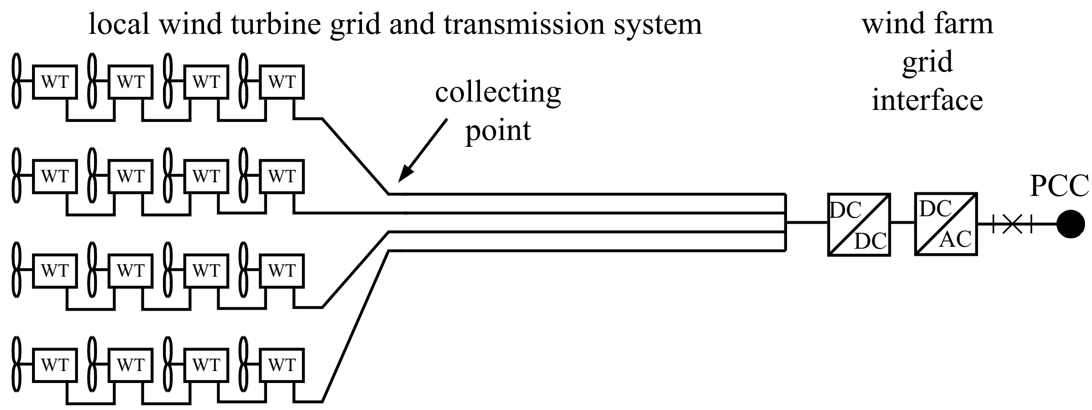

Figure 2.5: The electrical system for the small DC wind park.

noticed, the electrical system for the small DC wind park is identical to the system of the small AC wind park. The only difference is that the transformer in the wind park grid interface is replaced with a DC transformer and an inverter. Of course, a rectifier is needed in each wind turbine. The advantage of the small DC park compered to the large DC park is, as for the small versus large AC park, that it does not require an offshore platform. The installation cost of the cables are assumed to be the same as for the small AC wind park.

The configuration of the electrical system for the large DC wind park can differ somewhat from the configuration of the large AC wind park. The difference is if it requires one or two transformations steps to increase the DC voltage from the wind turbines to a level suitable for transmission. It is assumed that if the DC voltage from the wind turbines is high enough (20-40kV) only one transformation step is required. But if the output voltage of the wind turbine is lower (5kV), two steps are required. In figure 2.6 this system is presented with two DC transformer steps. For the large DC wind farm with two transformation steps, all wind turbines are divided into smaller clusters. All wind turbines within one cluster are connected one by one to the first transformation step. The high-voltage side of the first DC transformer step are then connected to the second step, as can be noticed in figure 2.6. If only one step is used, the wind turbines are connected in radials directly to the second DC transformer step,

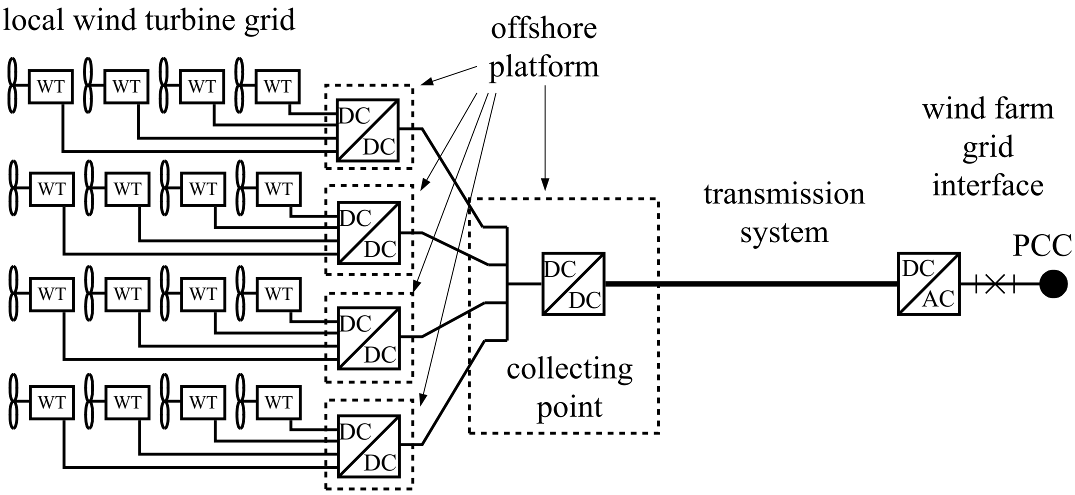

Figure 2.6: The electrical system for the large DC wind park with two DC transformer steps.

similarly as for the large AC wind park in figure 2.3. For this system there is one cable installation cost per cable, due to the fact that all cables have different routes.

In the third DC system shown in figure 2.7 the wind turbines are connected in series, as mention before, in order to obtain a voltage suitable for transmission directly. This system is referred to as the series DC wind park. The benefit of this system is that

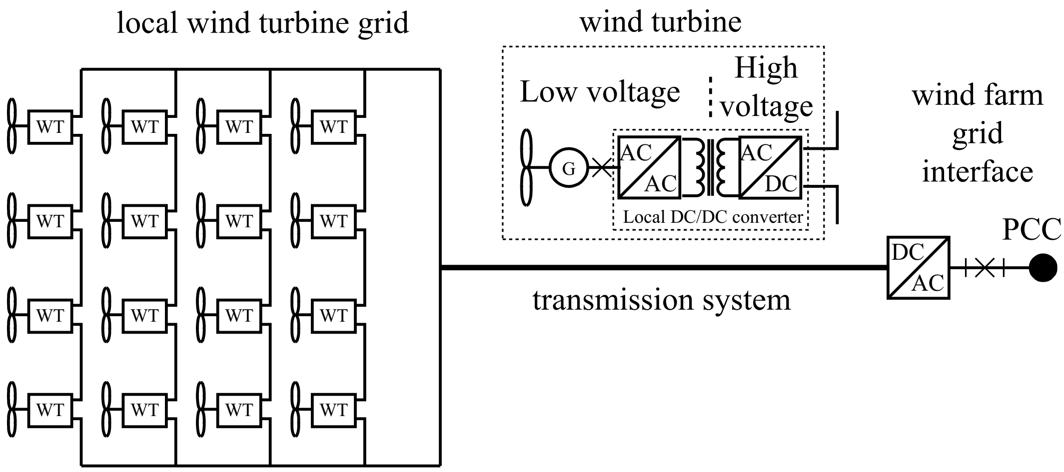

Figure 2.7: DC electrical system with series connected wind turbines.

it, in spite of a relatively large possible size, does not require large DC-transformers and offshore platforms. The voltage insulation in the wind turbines is taken by the transformer in the local DC/DC converter. The drawback with this configuration is that the DC/DC converters in the wind turbines must have the capability to operate towards a very high voltage. This is due to the fact that if one wind turbine does not feed out energy and therefore it fails to hold the output voltage, then the other turbines must compensate for this by increasing their output voltage.

For this system, there is one cable installation cost per cable, due to the fact that all cables have different routes, as can be noticed in figure 2.7.

Chapter 3

Short about aerodynamic energy conversion of wind turbines

3.1 Wind speed distribution

The wind speed can be treated as a continuous random variable. The probability that a given wind speed shall occur can be described with a density function. There are several density functions which can be used to describe how the wind speed is distributed. The two most common are the Weibull and the Rayleigh functions. The Rayleigh distribution, or chi-2 distribution, is a subset of the Weibull distribution. The Weibull distribution is described by [15]

$$f(w_s) = \frac{k}{c}(\frac{w_s}{c})^{k-1}\mathrm{e}^{-(w_s/c)^k} \tag{3.1}$$

Where:

$f(w_s)$	Probability density
w_s	Wind speed > 0 [m/s]
k	Shape parameter > 0
c	Scale parameter > 0

Comparisons with measured wind speeds over the world show that the wind speed can be reasonably well described by the Weibull density function if the time period is not too short. Periods of several weeks to a year or more is usually reasonably well described by the Weibull distribution but for shorter time periods the agrement is not so good [15]. The mean wind speed can be calculated by using the equation for calculating the expectation value of a continuous random variable, which gives

$$w_{s,mean} = \int_0^\infty w_s f(w_s)\mathrm{d}w_s = \frac{c}{k}\Gamma(\frac{1}{k}) \tag{3.2}$$

where Γ is Euler's gamma function

$$\Gamma(z) = \int_0^\infty t^{z-1}\mathrm{e}^{-t}\mathrm{d}t \tag{3.3}$$

If the shape parameter, k, is equal to 2 the Weibull distribution is equal to the Rayleigh distribution. The advantage of the Rayleigh function is that it only depends on the scale parameter, which is dependent only on the mean wind speed. The scale parameter, c, can be calculated by equation 3.4 for a given mean wind speed

$$c = \frac{2}{\sqrt{\pi}} w_{s,mean} \quad \text{for} \quad k = 2, \quad \Gamma(\frac{1}{2}) = \sqrt{\pi} \tag{3.4}$$

In figure 3.1 the Rayleigh distribution function is shown for different mean wind speeds. Mean wind speeds of 5.4m/s and 7.2m/s correspond to a medium and high wind site

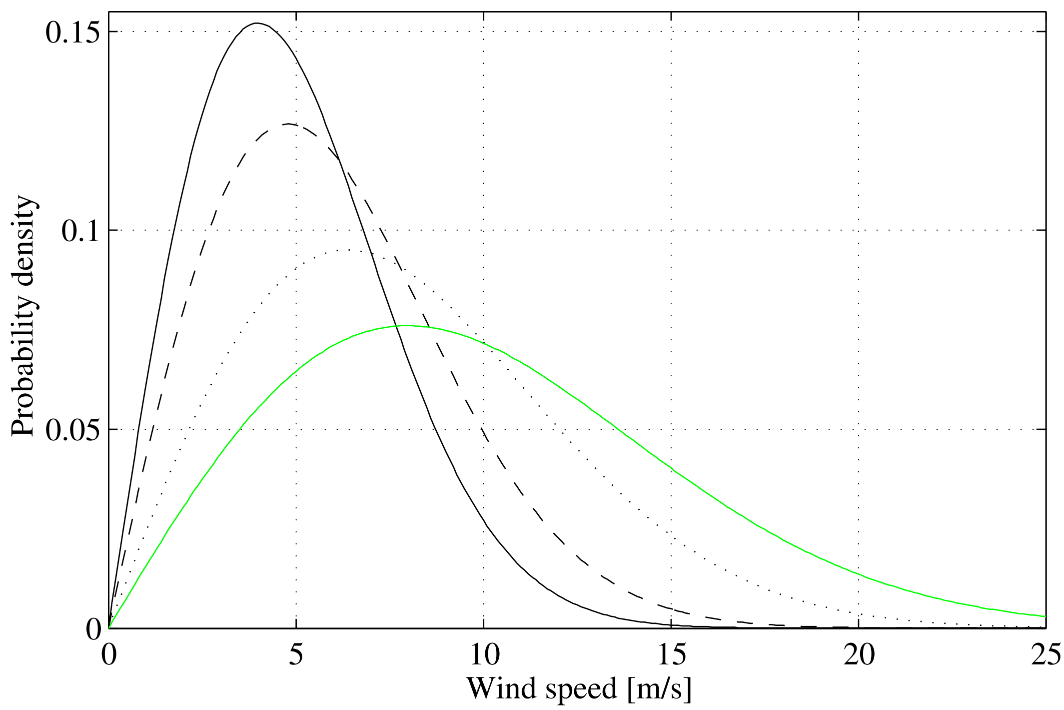

Figure 3.1: Rayleigh distribution function for different mean wind speeds, solid 5m/s, dashed 6m/s, dotted 8m/s and grey 10m/s.

in Sweden respectively, according to [42], and an average wind speed of 9.7m/s is found at Horns Rev [3]. The Rayleigh distribution is used in this work to describe the distribution of the wind speed.

3.2 Operating principle of a wind turbine

A wind turbine consists of a tower, a nacelle and a rotor. The rotor converts wind energy to mechanical energy. In the hub, the drive train is located. In the drive train, the mechanical energy is converted into electrical energy. The drive train consists of one or several shafts, generator and usually a gear-box.

A wind turbine has a specific rating. Sizes year 2003 are up to 4.5MW [9]. The rated power level is reached at a wind speed of 12-15m/s, and the wind speed when the rated power is reached is referred to as rated wind speed. Below rated wind speed the turbine tries to capture as much energy as possible from the wind, a value of the electric output power of about 40% of the available power in the wind is what can be obtained. Below 3-4m/s there is so little energy available in the wind so the turbine stops. At wind speeds above rated, the operation principle is different. The wind turbine rotor must now limit the incoming power to the rated shaft power. This is done by utilizing the blades. Either the blades are turned out of the wind, pitch control, or the blades are designed in such a way that the flow becomes disturbed and the blades loose their efficiency, stall control.

As mention before, the rotor blades convert some of the kinetic energy of the wind to mechanical energy on the rotor shaft. The efficiency of this conversion depends on several factors such as blade profiles, pitch angle, tip speed ratio and air density. The pitch angle, β, is the angle of the blades towards the rotational plane. If the pitch angle is low, the blades are almost perpendicular to the wind and if it is high (near 90 degrees) the blades are almost in parallel with the hub direction. The tip speed ratio, λ, is the ratio between the tip speed of the blades and the wind speed, equation 3.6. The conversion from wind speed to mechanical power can in steady state be described by [15]

$$P_{mec} = \frac{\pi \rho w_s^3 R^2}{2} C_p(\lambda, \beta) \tag{3.5}$$

$$\lambda = \frac{\omega_t R}{w_s}. \tag{3.6}$$

Where:

R	rotor radius [m]
ω_t	rotor speed [rad/s]
ρ	air density = 1.225 [kg/m^3]
w_s	wind speed [m/s]
λ	tip speed ratio
β	pitch angle
$C_p(\lambda, \beta)$	aerodynamic efficiency

In figure 3.2 the mechanical power and the aerodynamic efficiency for the blade profile used in this report is shown for different pitch angles and for a fixed rotor speed.

3.2.1 Stall control

From figure 3.2 it can be noted that if the pitch angle is kept at 0^o the turbine automatically limits the output power to a maximum of 1.2 p.u., for -1^o the power is limited to a maximum of 1.0 pu using the same rotor speed in the whole wind speed interval. As can be noted, the power reaches a maximum around 15 m/s and then decreases for higher wind speeds.

Stall control in combination with fixed speed was the dominating concept for wind turbines earlier. The reason is, of course, that it is cheaper to have blades that do not need a pitching mechanism. Moreover, power electronic equipment was too expensive earlier and therefore induction generators connected to the grid without power electronic equipment were used.

However, for MW size turbines, stall control has been considered to be unfeasible. One important reason is the emergency breaking of the turbine. If the blades can not be turned, the turbine must have a very large brake on the primary shaft. But if turnable blades are used, and in particular if each blade has its own emergency pitching system, this can replace the large main shaft brake. Instead it is sufficient to only have a much smaller parking brake.

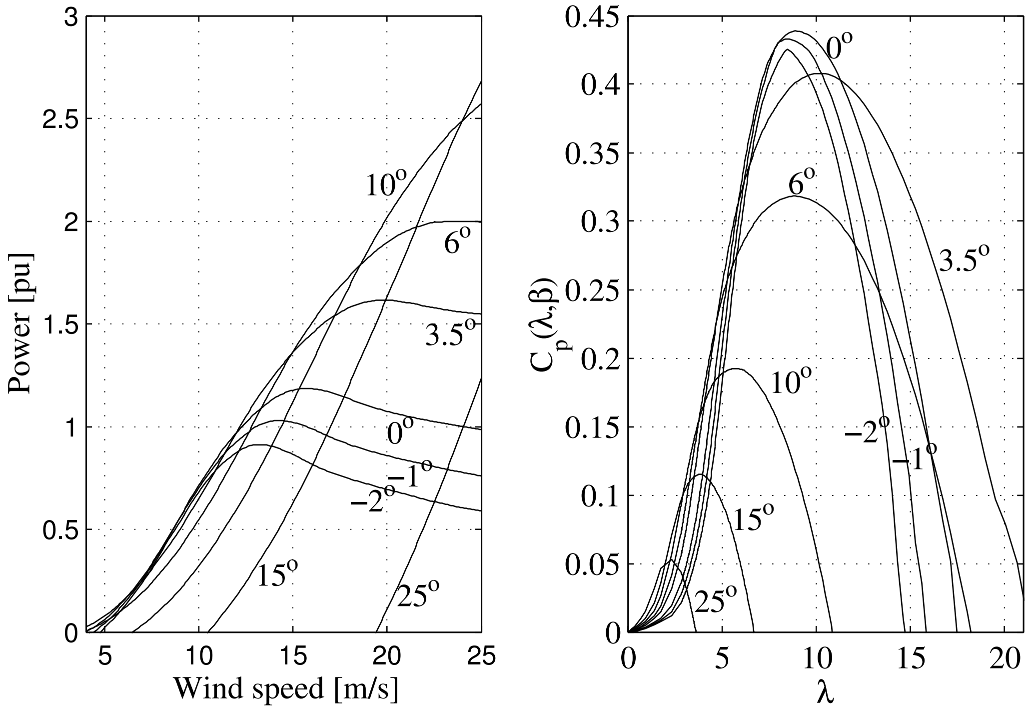

Figure 3.2: The mechanical power as function of wind speed and pitch angle for a fixed rotor speed,left plot, and the aerodynamic efficiency as function of λ and pitch angle, right plot.

3.2.2 Active stall control

If a pitching mechanism is available, a possibility is to slightly modify the pitch angle at high wind speeds also for turbines without a power electronic converter. When the wind speed is 15m/s a pitch angle of -1^o is used, but for 25m/s an angle of 0^o is used instead. In this way, the power level is kept at the rated value in the whole high wind speed region. In addition, the benefits of using a smaller brake and facilitated starting and emergency stopping is obtained.

3.2.3 Pitch control

Another way of obtaining a constant power level at high wind speeds is to turn the blades out of the wind, i.e. to increase the pitch angle. At 12 m/s a pitch angle of 0^o is used, at 17m/s 15^o and at 24 m/s and angle of 25^o is used, according to figure 3.2. The advantage of using pitch control instead of active stall control is that the thrust force (pressure on the turbine disc) is lower.

3.3 Dynamic aspects of aerodynamic power control

If fixed rotor speed is used there is a large drawback with using pitch control, there will be large power variations at high wind speeds. Let us consider the following case: The turbine is operating at 13 m/s with a pitch angle of 6^o. The power is now 1 pu. The wind speed increases rapidly to 15m/s and suddenly the power level is now 1.3 pu. The pitch controller has to increase the pitch angle to 10^o and the power error is eliminated. However, if a new wind speed change occurs a new power pulsation is created. As can be noted from figure 3.2 this situation does not occur when using stall control. If we have a pitch angle of -1^o we can note that wind speed changes in the high wind speed area lead to very small power variations. This has led to that fixed-speed turbines are almost all stall-controlled, either passive or active.

However, if the rotor speed can be varied, pitch control becomes much more favorable. In this case the incoming power fluctuations can instead be taken up by changing the amount of energy stored in the rotor i.e. by adjusting the rotor speed. The wind turbine rotor thus acts as an active low-pass filter for power fluctuations. Variable rotor speed can of course also be used in combination with stall or active stall, but the advantage of using pitch control is, as mentioned, that the thrust force is lowered. This has led to that almost all variable-speed turbines are pitch regulated.

Moreover, it has been fount in appendix A that the power pulsations from fixed speed wind turbines evens out when the number of turbines increases.

3.4 Variable speed wind turbines

As can be noted from figure 3.2, the right one, the maximum efficiency of the investigated turbine occurs at λ equal to 9. For the fixed-speed turbine λ is higher than 9 for lower wind speeds, and accordingly the efficiency of the fixed-speed rotor is lower than optimal at lower wind speeds. For the variable-speed turbine, it is possible to maximize the mechanical power by using a variable rotational speed of the wind turbine. This means that the pitch angle is kept constant at low wind speeds, zero in this case, and the rotational speed of the turbine is adjusted according to the actual wind speed so that λ always equals 9. This means that the turbine will work at the maximum efficiency which gives the maximum mechanical output power of the turbine, in the low wind speed region.

It should be kept in mind that the energy benefit is not the main reason for using variable speed, instead it is the reduced stresses on the turbine that is the main advantage. Also the fact that variable-speed turbines are capable of controlling the reactive power is an important reason for selecting a variable-speed turbine.

The upper rotational speed is limited by the mechanical stresses on the blades and the noise level, high speed results in large stresses on the blades and high noise levels [17]. It [32] it is stated that for a 1.5MW wind turbines the rotor diameter is approximately 64 to 66m and the rotational speed at rated wind speed is approximately 19 to 23.5rpm. Corresponding data for a 2MW wind turbine are: 80m rotor diameter and max rotor speed 19rpm. For the 2MW wind turbines in this work the rotor diameter is set to 80 m and the rotational speed at rated wind speed is set to 19rpm.

Today, two variable speed systems with different electrical generator systems are common: Full variable speed or semi variable speed system. Both systems have the same upper speed limit due to the noise level and mechanical stresses. It should be pointed out that, the upper rotor speed limit is an average limit. Shortly the speed is allowed to be above the average limit in order to reduce the mechanical stresses due to the power fluctuations originating from the wind speed variations. The full variable speed system has no lower speed limit, the rotational speed is controlled so that λ equals 9 also at the lowest wind speeds. The purpose is, as mentioned, to have the highest efficiency of the wind turbine in the low wind speed region. In the semi variable speed case there is a lower average speed limit apart from the upper one. Normally for the semi variable speed systems the speed band is $\pm 30\%$ from synchronous speed [12].

Chapter 4

Energy efficiency comparison of wind turbine systems

In this chapter the different wind turbines used in this work are examined and the energy efficiency is compered in steady state. The energy conversion of the rotor is modelled using equation 3.5 and the rated (maximum) shaft power from the turbine is set equal for all wind turbine systems. This was made in order to make the comparison as comparable and relevant as possible. The losses of the other components in the wind turbine are modelled in [20]. This means, that in this chapter only the results are presented, the loss calculations leading to the results are found in [20].

4.1 AC wind turbines

There exists several different types of wind turbines with an AC interface to the grid. In this work the most common wind turbine types that is produced today for high power applications (above 1MW) is taken under consideration.

4.1.1 Fix speed wind turbine

The fix speed wind turbine has been the most commonly used wind turbine type so far. This depends on that it has a very robust design with few components. The system is presented in figure 4.1. The weakest component is the gearbox which has to take

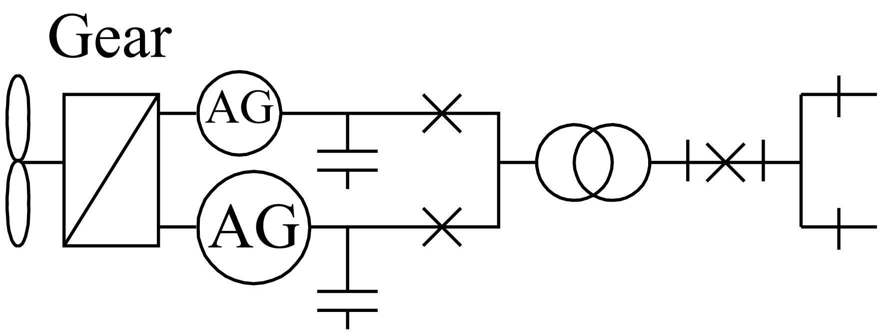

Figure 4.1: Principal scheme of the 2MW fix speed turbine, with two generators.

up a lot of torque pulsations. This is due to the fact that the turbine has an almost fixed speed and can story very little energy from the incoming power pulsations. These pulsations are also seen in the output power from a fix speed wind turbine and they cause fast voltage fluctuations on the grid [2, 19, 28]. For a wind park, these caused voltage pulsations are not a problem from a grid point of view, since they are smothered out when several turbines are connected [18, 25, 39] and appendix A.

The efficiency of the fix speed turbine is increased by having two different generators, one larger and one smaller. The small generator has a lower rotational speed and is used at low wind speeds to increase the aerodynamical as well as the generator efficiency of the turbine (operation close to the ideal λ at low wind speeds and reduced iron losses). At higher wind speeds, the larger generator is used. In figure 4.2 the active and reactive powers for this system are shown, solid and dashed line, respectively. The switch over point between the generators in this work can be noticed in figure 4.2 as the knee of the solid line at 6.7m/s. The dotted line in figure 4.2 shows the output power from the wind turbine if the large generator had been used also for low wind speeds. By comparing the dotted line with the solid line for low wind speeds, the increase in efficiency by having two different generators is clearly seen. Due to this increase in efficiency the two generator system is the only one considered in this work.

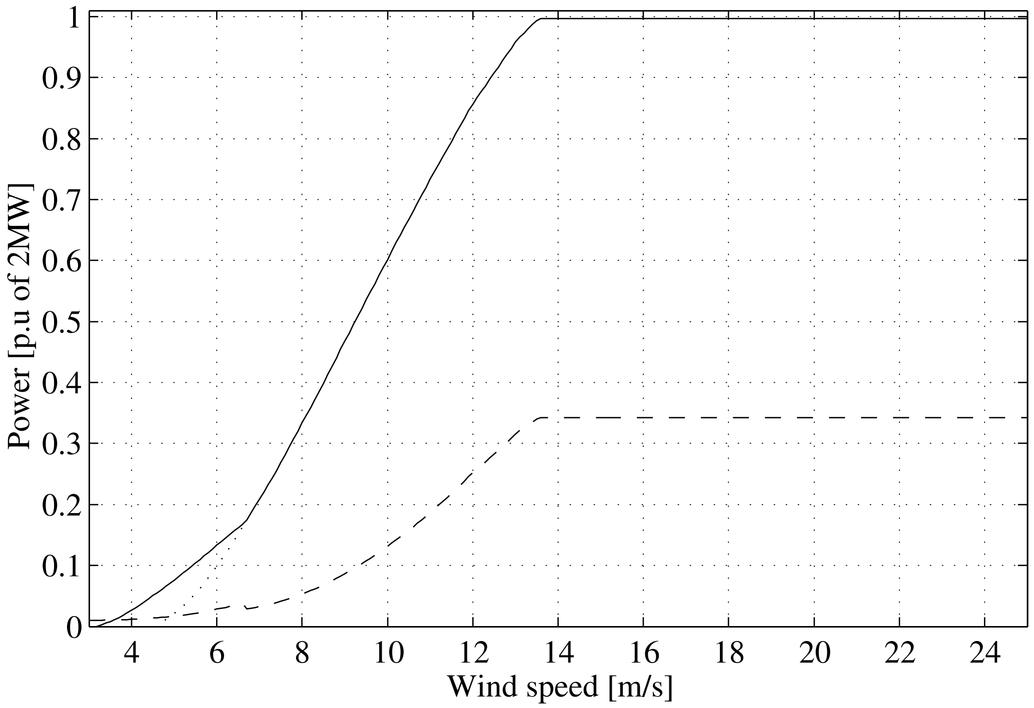

Figure 4.2: The produced active power to the grid is shown (solid) and the reactive power drawn from the grid (dashed) for the 2MW fix speed turbine. Dotted line shows the output power from the wind turbine if the large generator is used for low wind speed also.

A drawback of the fix speed wind turbine system is that the reactive power can not be controlled. The capacitors shown in figure 4.1 are only used to compensate for the no-load reactive power consumption of the generators. This means that the reactive power consumption of the wind turbine will increase when the power production increase, as can be seen in figure 4.2 (dashed line). If the reactive power consumption is to be compensated for more, electronically switched capacitors or an SVC can be used. Due to the fact that if the generator is compensated more then for the no-load consumption of reactive power there is a risk that the generator will be self excited which leads to severe over-voltages.

As mention before, the generator used at low wind speeds has a lower rated power then the generator used for high wind speeds. Due to the lower rated power, the generator no-load losses of the system are lower, and accordingly the total generator losses can be reduced at low wind speeds. This can be noticed in figure 4.3 where the losses of the 2MW fix speed wind turbine is shown. The switch between the different generators can be noticed as the step at 6.7m/s in the losses for the generator (black dashed line). The dashed grey line shows the generator losses of the large generator, if it would have been used for low wind speeds also. By comparing the grey and the black dashed line for low wind speeds it is noticed that an improvement of the generator efficiency by approximately 0.9% at low wind speeds is obtained by having two different generators.

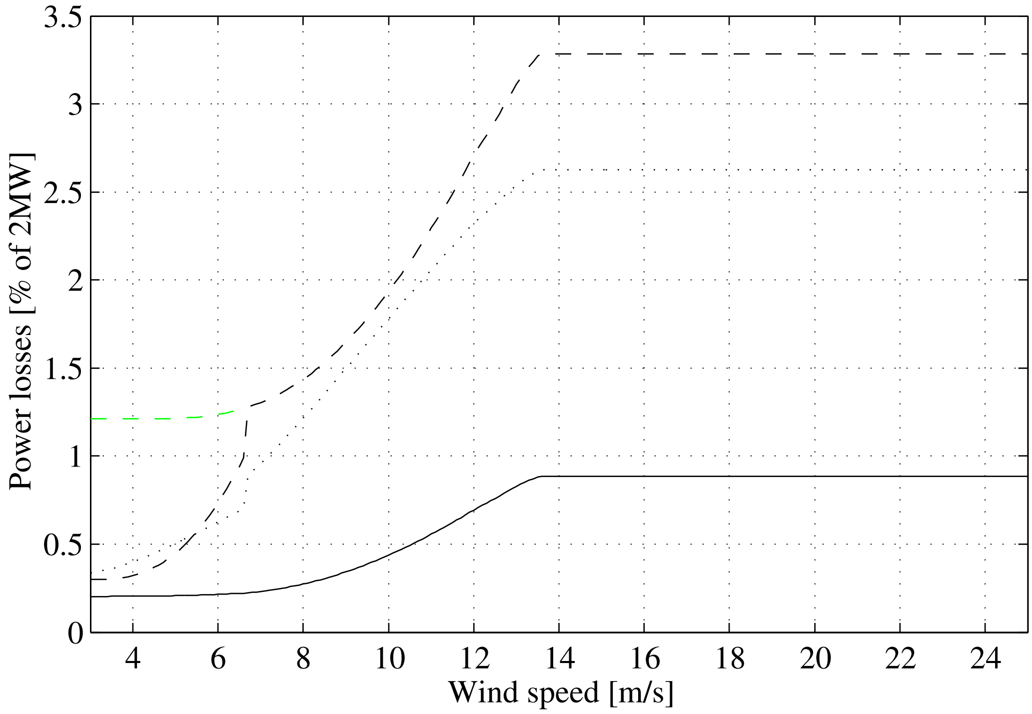

Figure 4.3: The losses for the turbine, solid transformer losses, black dashed generator losses and dotted gearbox losses. Grey dashed line shows the losses of the large generator if it would have been used at low wind speeds also.

4.1.2 Limited speed range wind turbine

There is a trend among the largest manufactures of wind turbines in the MW size towards the semi variable speed wind turbine configuration [12]. The key component in this system is an asynchronous generator with a wound rotor and slip rings, also called Doubly-Feed Induction Generator (DFIG). The converter is connected to the rotor circuit via the slip rings and the stator circuit is connected directly to the transformer, as can be seen in figure 4.4.

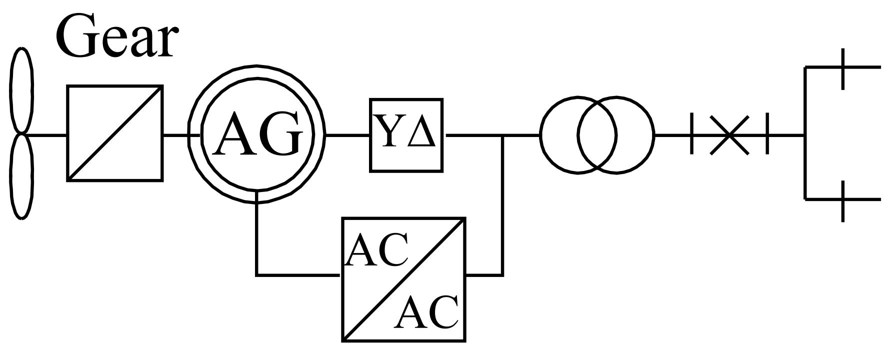

Figure 4.4: Principal scheme of the 2MW semi variable speed wind turbine.

This system can be optimized to produce maximum energy by choosing the speed range and the stator to rotor winding ratio appropriately [27]. The speed range around synchronous speed is approximately equal to the power through the converter. A common speed range is $\pm 30\%$ from synchronous speed, see [12], which gives that the maximum power through the converter is 30% of the rated power [27]. The fact that only a part of the power goes through the converter is the main advantage of this system, which gives a smaller converter (cheaper) and also lower losses.

In [27] it is shown that if the stator of the generator is connected in Y for low wind speeds and in Δ for high wind speeds the energy production can be increased by up to 1.2%. The $Y\Delta$ switch is shown in figure 4.4. This way of increasing the energy production of the DFIG system is used in this work as standard for the DFIG system.

In figure 4.5 the losses of the semi variable speed wind turbine are shown. The switch from Y to Δ connection of the stator is seen at 8.7m/s as a step in the losses of the converter (grey line). If only the efficiency of the generator is studied it can be noticed that the losses of the DFIG is lower at rated power compered to the fix speed system in figure 4.3. This is mainly due to that the losses in the stator winding is lower, due to that 30% of the power is taken out through the rotor and therefore the stator current is approximately 30% lower.

The asynchronous generator can be magnetized through the rotor which gives that if it is desired, it is only the active power that is fed out from the stator. The converter side connected to the transformer, can also be used to generate or consume reactive power. This leads to that the semi variable wind turbine can produce power with a power factor equal to one in the whole wind speed region.

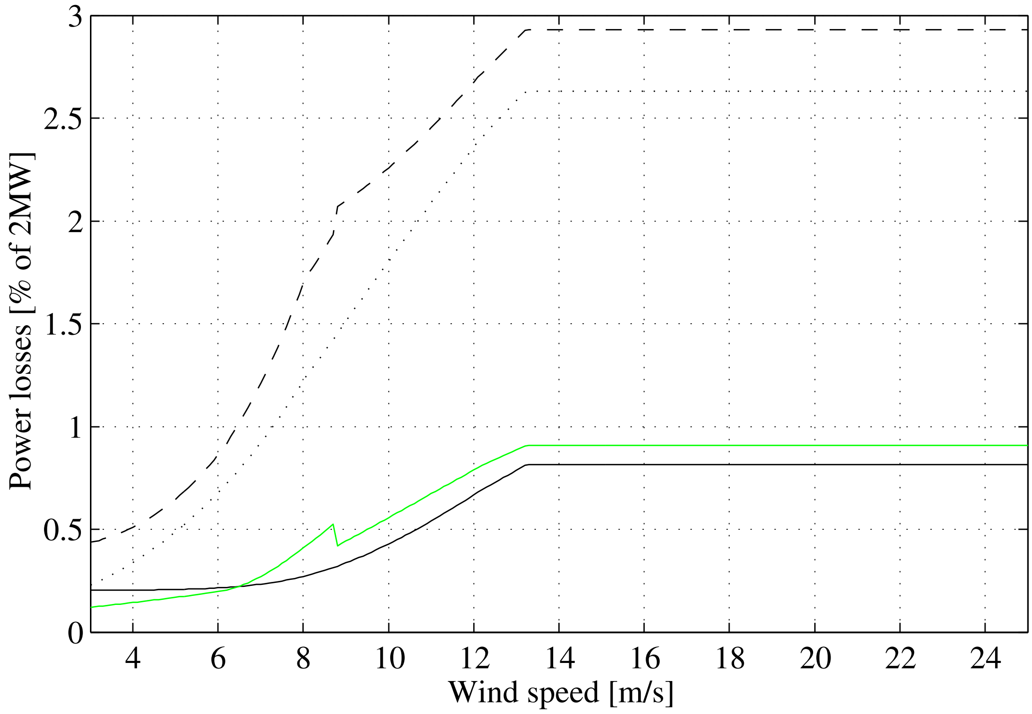

Figure 4.5: The losses of the 2MW semi variable speed wind turbine. Solid transformer losses, dashed generator losses, dotted gearbox losses and grey converter losses.

4.1.3 Full range variable speed wind turbines

The "full variable speed" wind turbines in this work uses a full power converter connected between the stator of the generator and the wind turbine transformer, as shown in figure 4.6. For the full variable speed systems, the reactive power to the grid is fully controllable using the converter.

In this work two types of generators are used, an asynchronous generator and a low speed synchronous generator. Today the system with the low speed synchronous

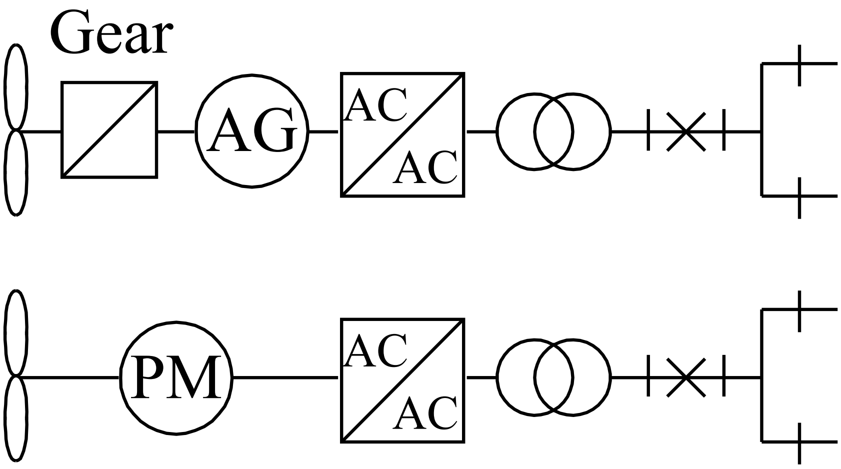

Figure 4.6: Principal schemes of the 2MW full variable speed turbine, top with asynchronous generator and bottom with permanently magnetized generator.

generator is by far the most common one of the two. The reason for this is that this system does not need a gearbox, which is a quite sensitive component as mention before. If a permanently magnetized directly driven machine is used, a drawback is that this generator requires much more reactive power at rated power then the asynchronous generator requires. If an electrically magnetized generator is used, the reactive power is not a problem, since it can be produced internally using the field winding.

But if the generator is permanently magnetized the reactive power needed by the generator at high loads (high wind speeds) must be produced externally in order to have a good utilization of the generator [10]. This gives problems if a diode rectifier is connected to the generator. For this case some kind of reactive power compensation must be used, for example, capacitors on the AC side can be used. In this work it is assumed that the permanently and the electrically magnetized generator performs equally from an energy production point of view, so, only the permanently magnetized generator system is chosen to be investigated in this work.

In figure 4.7 the losses of the variable speed wind turbine with an asynchronous generator are shown. If figure 4.7 and figure 4.3 are compered it is noticed that the generator losses, at low wind speeds, is for the variable speed wind turbine almost the same as for the small generator used in the fix speed turbine. This is due to that in the full variable speed system the voltage and the frequency to the generator is fully controllable by the converter. At low wind speeds, field weakening of the generator is used in order to reduce the no-load losses. This is done by decreasing the voltage to the generator.

In figure 4.8 the losses of the variable speed wind turbine with a permanently

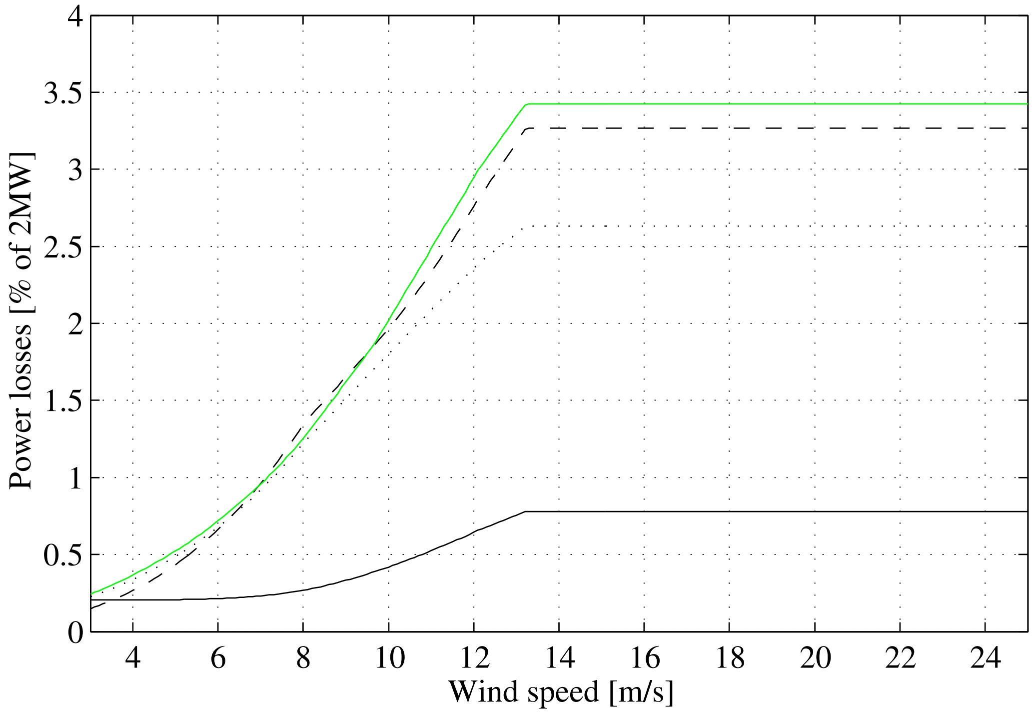

Figure 4.7: The losses of the 2MW full variable speed turbine equipped with a asynchronous generator. Solid transformer losses, dashed generator losses, dotted gearbox losses and grey converter losses.

magnetized generator and a back to back converter between the stator and the wind turbine transformer are shown. From figure 4.8 it is noticed that the losses for the low speed generator is lower then the losses for the system with a gearbox and an asynchronous generator. It shall also be noticed that the converter losses for these two full variable speed systems are much higher then the converter losses in the semi variable system, se figure 4.5.

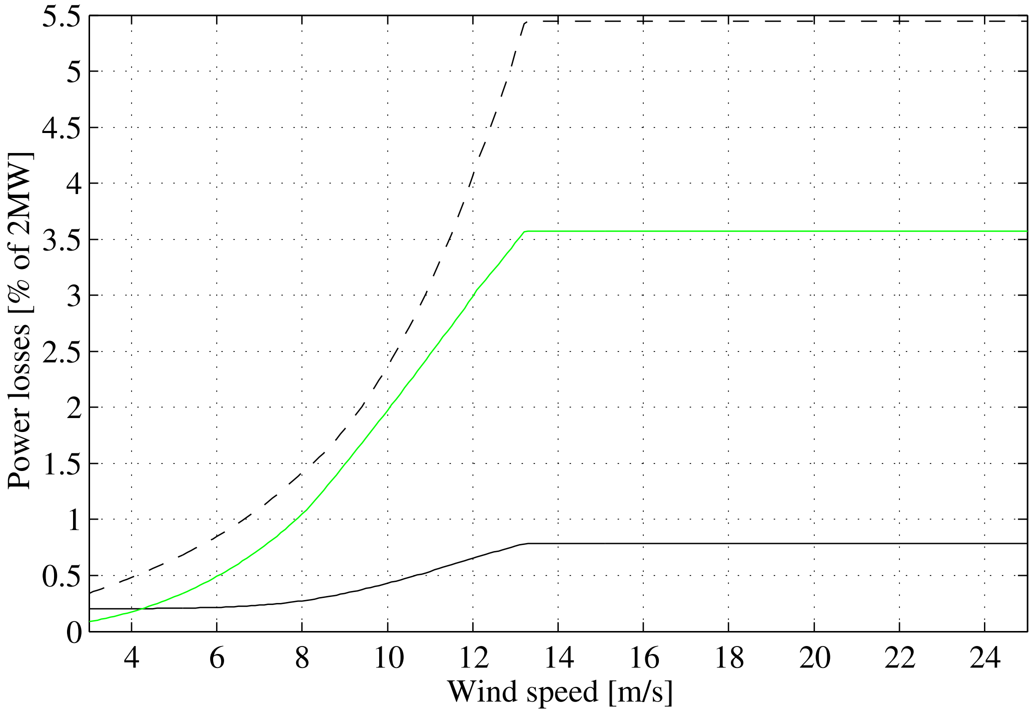

Figure 4.8: The losses of the 2MW full variable speed turbine equipped with a permanent magnetized generator. Solid transformer losses, dashed generator losses and grey converter losses.

4.2 DC wind turbines

In this section some promising layouts of wind turbine units that produces a DC-voltage are examined. For all DC wind turbines, the generator is assumed to be a low speed permanently magnetized generator with a rated voltage of 690V and a rated power of 2MW. Note, that the notation DC wind turbines still means that we have an AC generator. In two cases, a generator with 10kV rated voltage is used, and this generator is realized by using an ideal transformer connected to the 690V generator. In several of the DC systems, the generator is connected to a diode rectifier and the reactive power to the generator is supported by series capacitors, as discusses in [10]. Of course, the capacitors and the main inductance of the generator will form a resonant circuit which must be investigated carefully in order to avoid any resonances which can cause high over-voltages. One DC system with an IGBT rectifier is also investigated. In this system the reactive power to the generator is controlled by the IGBT rectifier.

The main philosophy of the DC-systems is that all wind turbines shall have a fix output voltage regardless of the wind speed in steady-state to simplify the DC-grid, as mention in chapter 2. The exception is in the series DC wind farm, where the sum of the output voltages of the wind turbines in one leg should be held constant.

In figure 4.9 the three DC/DC converter topologies used in this work are shown. The selection of these three DC/DC converters is made in [20]. To the left the boost converter, in the middle the full bridge converter and to the right the full bridge isolated boost converter are shown.

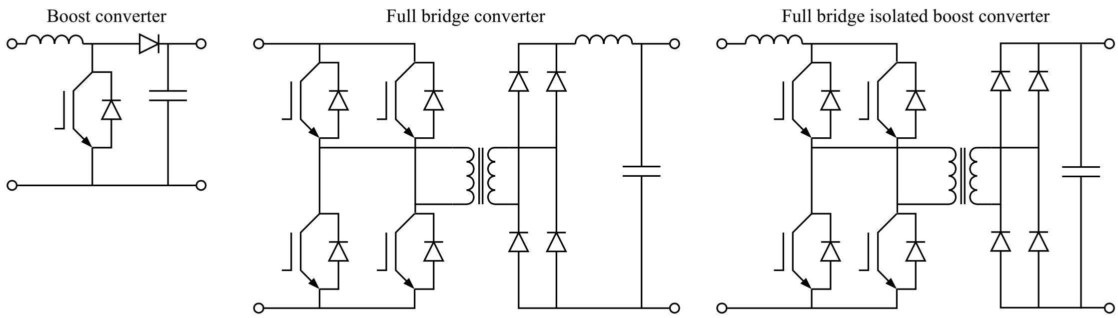

Figure 4.9: Principal scheme of the three most interesting DC/DC converter topologies.

4.2.1 DC-level locked speed wind turbine

In this concept the speed of the turbines are controlled by controlling the DC voltage. The main advantages of this system is that it has very few components and that all of them are passive, as can be seen in figure 4.10. This system is similar to the fix

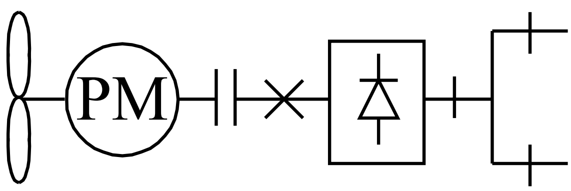

Figure 4.10: Principal scheme of the 2MW DC-level locked speed wind turbine.

speed AC wind turbine system with the only difference that the speed is determined by the DC-voltage at the diode rectifier instead of the frequency of the AC voltage. This means that this systems has the same drawback of fluctuating power production as the fix speed AC wind turbine system. The slip of the conventional AC generator that is governed by the rotor resistance is now determined by the leakage inductance instead.

Since this system in principle is a fixed-speed system with additional complications, it will not be taken into consideration in this report.

4.2.2 Variable speed DC wind turbines

In this sections some different layouts for variable speed DC wind turbines are presented and examined. The speed of the wind turbine is controlled by the DC/DC converter that is connected between the diode rectifier and the DC grid, as shown in figure 4.11. This means that the speed of the turbine is independent of the DC voltage on the grid.

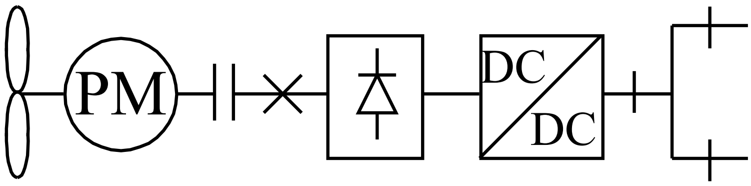

Figure 4.11: Principal scheme of the 2MW DC wind turbine with full variable speed and diode rectifier.

The drawback is that this system requires a DC/DC converter in the MW range, which does not exists today. Another drawback is of course, that the DC/DC converter will have losses.

In figure 4.12 the losses of the variable speed DC wind turbine with a boost converter as DC/DC converter are shown. In this configuration the generator has a rated voltage of 690V and the wind turbine with its DC/DC converter has an output voltage of 5kV. If instead a 10kV generator is used, which is quite possible, the output voltage can be increased to 40kV. The losses of this system are shown in figure 4.13.

In figure 4.14 the power production and the losses of the variable speed DC wind turbine with a full bridge converter as DC/DC converter are shown. In this configuration the generator has a rated voltage of 690V and the wind turbine has a output voltage of 40kV.

By comparing the three figures 4.12, 4.13 and 4.14 it is noticed that the losses for the generator are the same, the only difference is the losses for the diode rectifier and the DC/DC converter. The losses for the diode rectifier and the boost converter in the system with the 10kV generator is lower then for the other system, due to the fact that the current is lower.

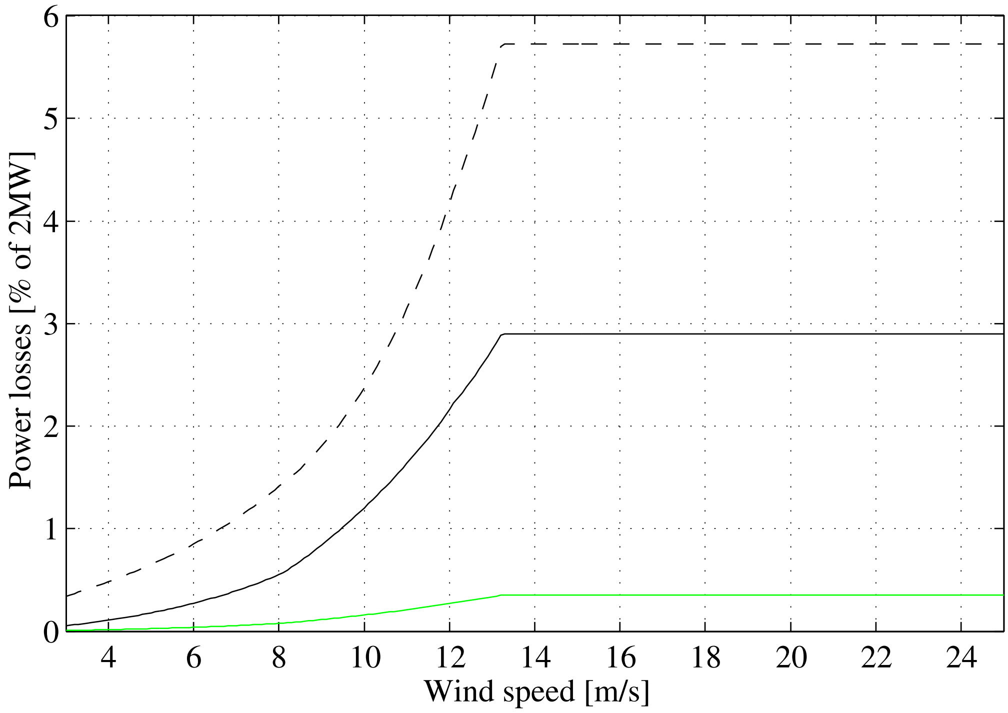

Figure 4.12: The losses of the 2MW wind turbine equipped with a permanent magnetized generator connected to a diode rectifier and a boost converter with 5kV output voltage. Dashed generator losses, solid DC/DC converter losses and grey diode rectifier losses.

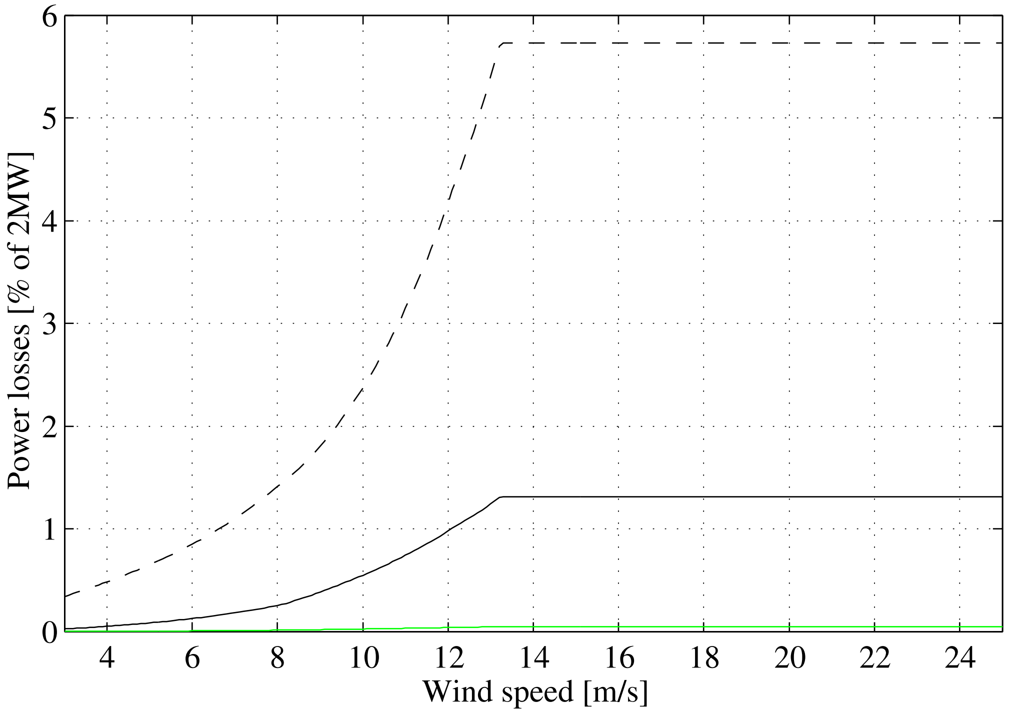

Figure 4.13: The losses of the 2MW turbine equipped with a permanent magnetized generator connected to a diode rectifier and a boost converter with 40kV output voltage. Dashed generator losses, solid DC/DC converter losses and grey diode rectifier losses.

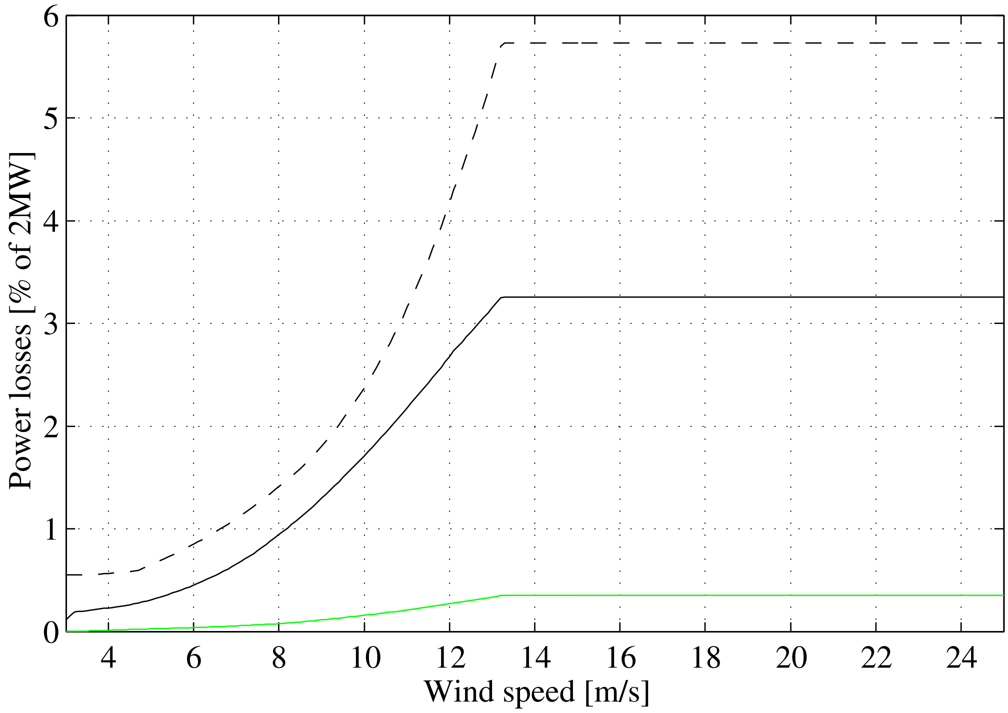

Figure 4.14: The losses of the 2MW turbine equipped with a permanent magnetized generator connected to a diode rectifier and a full bridge converter. Dashed generator losses, solid DC/DC converter losses and grey diode rectifier losses.

4.2.3 Variable speed DC wind turbine with IGBT rectifier

In this DC wind turbine, the diode rectifier and the series capacitors are replaced by an IGBT rectifier, as shown in figure 4.15. The benefit with the IGBT rectifier is that

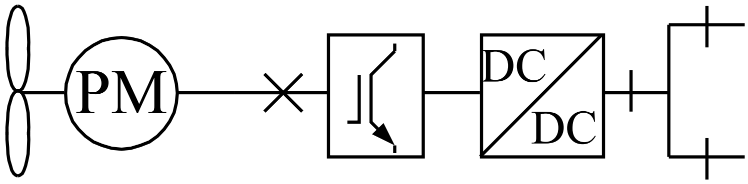

Figure 4.15: Principal scheme of the 2MW DC wind turbine with full variable speed and IGBT rectifier.

the torque of the generator and the reactive power to the generator is easily controlled. Due to the fact that the reactive power can be controlled, any type of generator can be used.

Another benefit of the IGBT rectifier is that it keeps the input voltage to the DC/DC converter constant. This leads to that the DC/DC converter works at a constant transformation ratio in normal operations. This means that the DC/DC converter can be better optimized, it will work as a constant ratio DC transformer.

In figure 4.16 the losses of the variable speed DC wind turbine with an IGBT rectifier and a full bridge converter as DC/DC converter are shown. In this configuration the generator has a rated voltage of 690V and the wind turbine has an output voltage of 40kV. In figure 4.16 it is noticed that the power loss in the generator is lower compered to the cases using a diode rectifier and series capacitors. This is due to the better control of the voltage and reactive power of the generator. It is also noticed that the losses for the full bridge converter is lower in this case compered to the case with a diode rectifier. This is due to that the converter is better utilized when it is operated with constant input and output voltage. The drawback is that the IGBT rectifier has much higher losses then the diode rectifier, which leads to that this wind turbine has a lower rated output power compered to the wind turbine with the 10kV generator, diode rectifier and the boost converter.

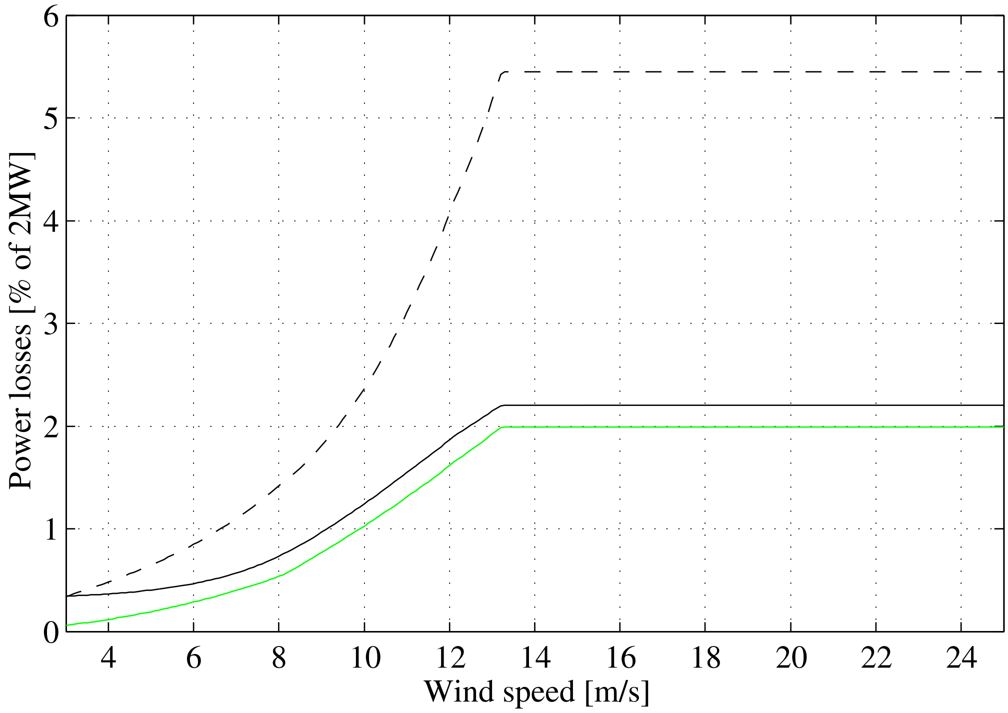

Figure 4.16: The losses of the 2MW wind turbine equipped with a permanent magnetized generator connected to a IGBT rectifier and a full bridge converter. Dashed generator losses, solid DC/DC converter losses and grey IGBT rectifier losses.

4.2.4 Series connected DC wind turbine unit

This type of wind turbine is designed to be connected in series with other wind turbines. The point is that it in this way is possible to get a sufficiently high voltage for transmission directly, without using large centralized DC-transformers. The series connected wind turbine does not differ so much from the variable speed DC wind turbines presented in chapter 4.2.2. The only difference is the type of DC/DC converter that is used, in this case the full bridge isolated boost converter. The series connection however implies that some components in the wind turbine must have a voltage insulation high enough to take up the whole transmission voltage to ground.

In this work, it is the transformer in the DC/DC converter that is the interface between the high transmission voltage and ground. In figure 4.17 the scheme of the series connected DC wind turbine is shown. From this figure it is noticed that the high voltage winding of the transformer in the DC/DC converter is isolated for the transmission voltage to ground. It is also seen that all components on the high voltage

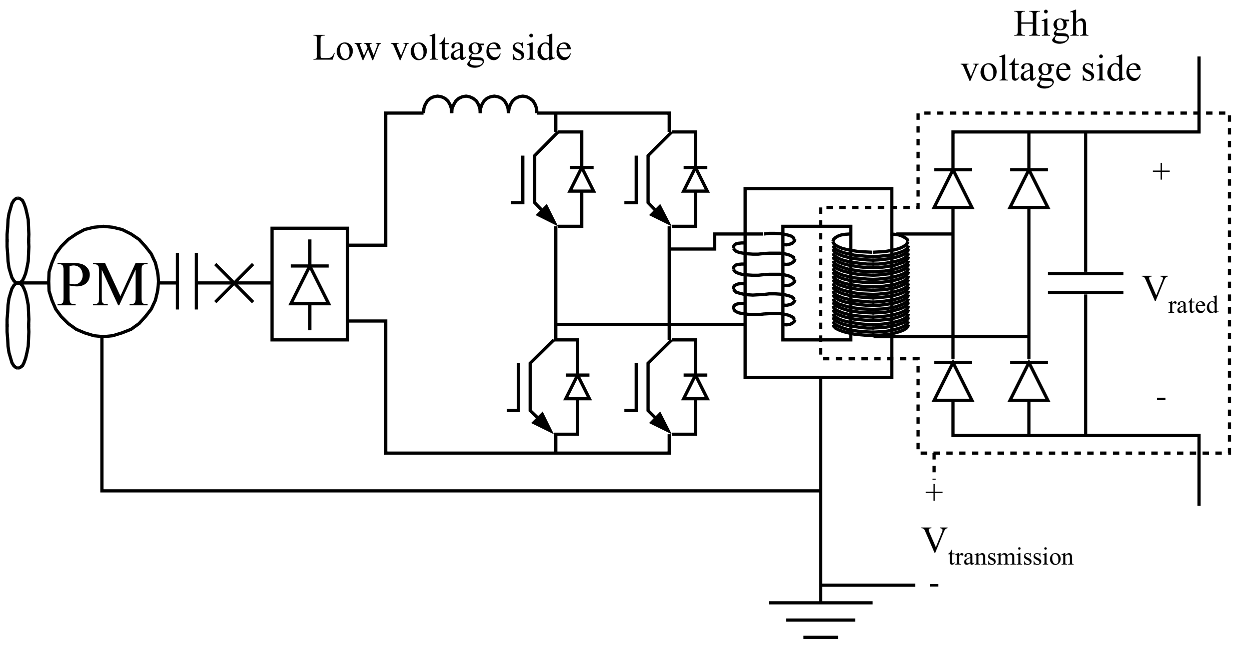

Figure 4.17: Principal scheme of the series connected DC wind turbine.

side in figure 4.17 must be isolated for the transmission voltage to ground. One benefit of the full bridge isolated boost converter is that it has a few numbers of components on the high voltage side of the transformer, the diode rectifier and the output capacitor. This means that it is a few components that must be placed or encapsuled so that they can withstand the transmission voltage to ground. As can be seen in figure 4.17 the voltage rating of the components on the high voltage side is determined by the output voltage rating of the converter and not by the transmission voltage. Another benefit of the full bridge isolated boost converter is that all components on the high voltage side are passive. This means that no control signals or drive circuits for active components is needed on the high voltage side.

In figure 4.18 the losses of the series connected wind turbine are shown. In this configuration the generator has a rated voltage of 690V and the wind turbine has an output voltage of 20kV. As can be noticed from figure 4.18 the series connected wind

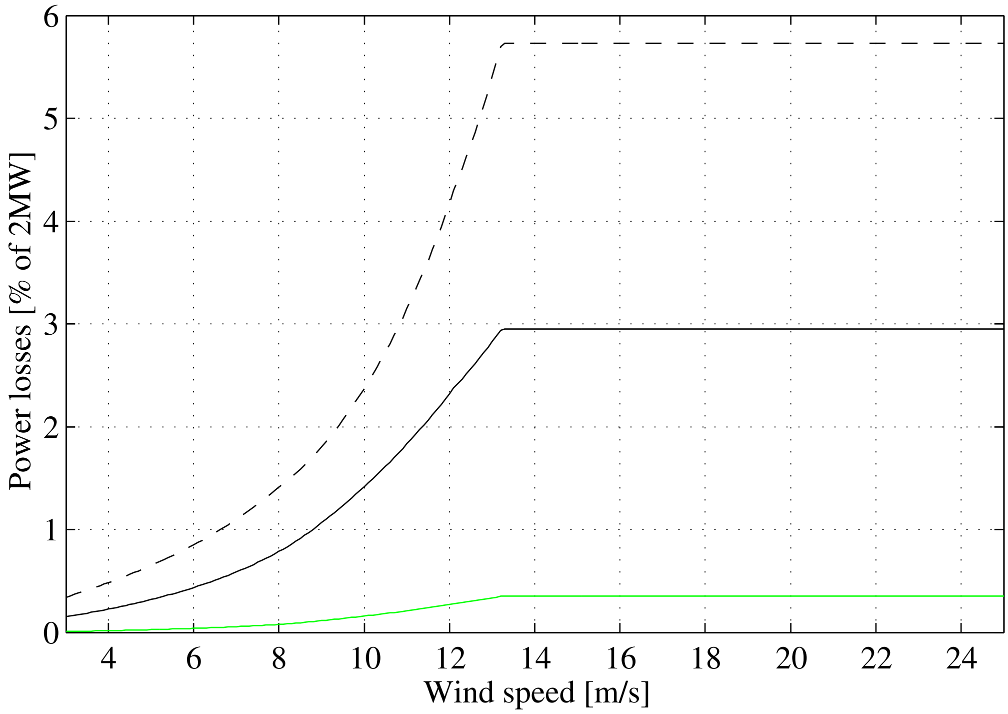

Figure 4.18: The losses of the 2MW series connected wind turbine. Dashed generator losses, solid DC/DC converter losses and grey diode rectifier losses.

turbine has the same generator and rectifier losses as the other DC wind turbines with a diode rectifier to the generator and a 690V generator. It can also be noticed that the DC/DC converter losses are lower for this wind turbine then for the variable speed wind turbine with a full bridge converter and a diode rectifier, se figure 4.14. This is due to that the full bridge isolated boost converter is better utilized in this voltage adjusting application then the full bridge converter.

4.3 Average power production comparison of different wind turbines

In this section the average power production of the wind turbines presented in this chapter will be determined. The average power production is calculated by using the wind speed distribution shown in chapter 3. The average power production is calculated in the same way as the mean wind speed, equation 3.2, ie. the output power is multiplied with the Rayleigh distribution and then integrated from cut in wind speed to cut out wind speed, as can be seen in equation 4.1. In this work the cut out wind speed is selected to 25m/s, this is a normal value for wind turbines. There is no point in using a higher cut out speed since the contribution to the average power production for wind speeds above 25m/s is very low, se figure 3.1 where the Rayleigh distribution has very low values over 25m/s. This means that a further mechanical over-dimension in order to allow operation at these high wind speeds does not pay back. The cut in wind speed is set to 3m/s. The contribution to the average power production from wind speeds lower then 3m/s is quite low due to that the power produced by the wind turbine is low, see figure 4.2, and due to that the distribution decrease rapidly for decreasing wind speeds below 3m/s. The average power production can thus be determined as:

$$P_{out,average} = \int_{cutin}^{cutout} P_{out}(w_s) f(w_s) \mathrm{d}w_s. \tag{4.1}$$

Where:

$P_{out,average}$	Average power production [W]
$cutin$	Cut in wind speed =3 [m/s]
$cutout$	Cut out wind speed =25 [m/s]
$P_{out}(w_s)$	Output power of the wind turbine [W]
$f(w_s)$	Rayleigh distribution

In table 4.1 the average power production of the different wind turbines are shown for some different average wind speeds and the power at cut in wind speed and at rated wind speed in per unit of 2MW. The four first are AC wind turbines and the five last are DC wind turbines. It shall be remembered that all wind turbines has the same

Table 4.1: The output power in p.u. of 2MW for the different wind turbines at cut in wind speed and at rated wind speed and the mean output power in kW for the different wind turbines and for different mean wind speeds.

Type of wind turbine	Power at 3m/s	Rated power	5m/s	6m/s	8m/s	10m/s
AM Fix speed	0	0.997	271	434	769	1037
AM, Rotor converter	0.009	0.992	275	437	771	1038
AM, Stator converter	0.011	0.964	270	428	754	1012
PM, Stator converter	0.013	0.967	281	442	769	1027
PM, Diode, Boost 5kV	0.015	0.975	288	451	781	1040
PM, Diode, Boost 30kV	0.015	0.994	292	457	793	1058
PM, Diode, Full bridge	0.003	0.971	282	444	774	1033
PM, IGBT, Full bridge	0.012	0.968	281	442	770	1028
PM, Diode, FBiB	0.014	0.975	286	448	778	1038

rated shaft power, so the differences in electric power production is only depending on the speed control of the turbine (fix speed, semi variable speed or full variable speed) and the losses in the drive train. From table 4.1 it can be seen that the differences in average power production between the different wind turbines for a given mean wind speed is not large, it is maximum 4-7%. Note, that a possibility is to increase the rotor diameter of the turbine at sites with low average wind speeds and in this way it is possible to adjust the turbine to the mean wind speed of the site. In this work the rotor diameter is the same for all average wind speeds, since the goal here is to compere the energy capture using various electrical systems, so the boundary conditions are set to be as equal as possible in this work.

From table 4.1 it can be noticed that almost all wind turbines with high power at cut in wind speed has the highest average production at low average wind speeds. It can also be noticed from table 4.1 that the wind turbines with high output power at rated wind speed has the highest average output power at high average wind speeds, as can be expected. This is due to the fact that at a low average wind speed the Rayleigh density function has the highest values for low wind speeds, as can be seen from figure 3.1. This gives that a high efficiency at part load gives a higher average output power. Accordingly, for a high average wind speed the Rayleigh density function has the highest values for higher wind speeds and this gives that high efficiency at rated load gives a higher average output power.

This is the explanation why the fix speed AC wind turbine has high average output power at high average wind speeds and low at low average wind speeds. The fix speed AC wind turbine has a lower efficiency at low wind speeds due to the fact that the speed is locked to two specific speeds and due to that the reduction of the no-load losses of the generators is limited (apart from the one archived by using two generators).

The wind turbine with the doubly fed asynchronous generator has a quite good performance for all average wind speeds. This is mainly due to the low losses in the converter and the $Y\Delta$ switch at low wind speeds. As mention before, the DFIG system can only work in a certain speed span and this system thus loose some energy at low wind speeds. But as can be observed from table 4.1, the rotor converter systems has almost the same output power at cut in wind speed as the stator converter system with the asynchronous generator, even though this system operate at full variable speed and can reduce the no-load losses of the generator to a maximum. But the stator converter has much higher losses then the rotor converter so the gain using the full variable speed operation and the reduction of the no-load losses is lost due to the high converter losses. The result is that the stator converter system with an asynchronous generator will not have the highest efficiency.

For the AC wind turbine with the stator converter system and a permanently magnetized generator it can be noticed that it performs well at low average wind speeds compered to the systems with a gearbox and an asynchronous generator. This is due to the fact that the permanently magnetized generator has lower losses at low wind speeds then the system with a gearbox and an asynchronous generator, as can be seen from figure 4.7 and 4.8. For high average wind speeds this system has a lower average output power then the fix speed system and rotor converter system due to the high losses in the converter at high wind speeds.

As it can be noted, the DC wind turbines all performs good for low average wind speeds due to the low losses in the permanently magnetized generator at low wind speeds compered to the system with an asynchronous generator and a gearbox. But for higher average wind speeds they performs somewhat differently depending on the losses in the rectifier and in the DC/DC converter.

From table 4.1 it is found that the best wind turbine is the DC wind turbine with a 10kV generator and a boost converter with an output voltage of 40kV. This is due to that the 10kV generator is made from adding an ideal transformer to the stator of the 690V permanently magnetized generator used in the other wind turbines. This gives that the losses for the 10kV generator are identical to the losses of the 690V generator. But due to the higher voltage, the current is lower and therefore the conduction losses in the diode rectifier and the boost converter are much lower compered with the other DC wind turbines.

For the other DC wind turbines with a 690V generator and a diode rectifier it is noticed that the system with the boost DC/DC converter is the best and that the full bridge isolated boost system comes second and the least efficient is the full bridge system. This is only depending on the DC/DC converter losses, since that the generator is controlled in the same way in all three cases. By comparing the losses for the DC/DC converter in figure 4.12, 4.14 and 4.18 it is seen that the boost converter has the lowest losses.

For the DC wind turbine with an IGBT rectifier it is seen from table 4.1 that it produces the lowest average output power of the DC wind turbines. This is due to the much higher losses in the IGBT rectifier compered to the diode rectifier used in the other DC wind turbines. But it shall be noticed that this DC wind turbine performs quite equal to the AC wind turbine with a permanently magnetized generator and a stator-connected full power converter.

From this comparison of different wind turbine types, the fix speed AC wind turbine and the rotor converter AC wind turbine is chosen to be used in the evaluation of the wind parks with AC wind turbines. For the large DC wind park, the two wind turbine systems with the boost converter are used, the one with 5kV output voltage and the one with the 40kV output voltage. For the small DC wind park only the wind turbine system with the boost converter and 40kV output voltage is used. This due to that 5kV is a too low voltage for transmission over long distances. For the series connected DC wind park, the DC wind turbine with the full bridge isolated boost converter is chosen. This is due to that it has a higher average output power then the full bridge DC wind turbine and due to that the full bridge isolated boost converter has fewer components on the high voltage side of the transformer then what the full bridge converter has.

Chapter 5

Energy Production Cost of Different Wind Parks

In this chapter, the energy production cost for the six different wind park systems based on the wind turbine systems described in chapter 2 are compered with each other. All these six types are individually optimized to give the lowest energy production cost. In the first section the best configuration of these six types are compered with each other. And in the following sections the individual optimization is described for each of the configurations. The input, cost and loss models, for these calculations is taken from [20].

5.1 The energy production cost

The energy production cost is defined as how much it cost to produce and deliver a unit of energy to the grid, i.e to the PCC. This gives that the total investment cost of the wind farm is divided with the total energy delivered to the PCC. The total investment cost is calculated assuming that the whole investment is made in the first year and paid off during the life time of the wind farm. In addition, it is also assumed that some profit shall be made. The total energy that is delivered to the PCC is calculated by multiplying the average power delivered to the PCC with the average number of operational hours during one year multiplied with the lifetime of the wind park. The average power is calculated with equation 4.1. With these assumptions the energy production cost can be calculated as in equation 5.1.

$$E_{prize} = \frac{\text{Invest}}{P_{mean,out}T} \frac{r(1+r)^N}{(1+r)^N - 1} \frac{100}{100 - PR} = K \frac{\text{Invest}}{P_{mean,out}} \tag{5.1}$$

Where:

E_{prize}	Energy production cost [SEK/kWh]
Invest	Investment [SEK]
$P_{mean,out}$	Mean output power [W]
T	Mean operational hour under one year [h]
r	Interest rate [-]
N	Lifetime of the wind farm [years]
PR	Profit in %
K	Constant

The life time of the wind farm is in this work set to 25 years, the interest rate to 4%, the profit to 3% and the average operational hours during one year is set to $365 \cdot 24 = 8760$. This gives that the production cost gets about 65% higher then without profit and interest rate, ie. $K = 7.53 \cdot 10^{-6}$ with interest rate and profit and $K = \frac{1}{TN} = 4.57 \cdot 10^{-6}$ without.

As can be seen from equation 5.1 the losses in the wind farm do not appear explicitly. Indirect they affects the production cost due to that an increase of the losses decreases the average output power. To include the losses more directly in the energy production cost, an input power most be defined. The input power to the wind park is defined as the shaft power of a full variable speed wind turbine, described in chapter 3.4, multiplied with the number of wind turbines in the wind park. The cost of the losses in the wind park is defined as the difference between the energy production cost calculated with equation 5.1 with the average output power and the energy production cost calculated with equation 5.1 with the average input power as P_{mean}. With these definitions the energy production cost can be divided into two parts, as can be seen in equation 5.2.

$$E_{prize} = E_{prize,invest} + E_{prize,loss} = K\frac{\text{Invest}}{P_{mean,in}} + K\frac{\text{Invest}}{P_{mean,in}}\frac{P_{mean,loss}}{P_{mean,out}} \tag{5.2}$$

Where:

E_{prize}	Energy production cost [SEK/kWh]
$E_{prize,invest}$	Energy production cost from the investment [SEK/kWh]
$E_{prize,loss}$	Energy production cost from the losses [SEK/kWh]
K	Constant, defined in equation 5.1
Invest	Investment [SEK]
$P_{mean,in}$	Mean input power [W]
$P_{mean,out}$	Mean output power [W]
$P_{mean,loss}$	Mean losses in the wind park [W]

From equation 5.2 the contribution from each component in the wind park to the energy production cost can be defined. This is due to the fact that the investment, I, is the sum of the costs of all components and the mean power loss is the sum of the average power losses in each component. This gives that the contribution to the energy production cost from one component, $c1$, is defined as in equation 5.3.

$$E_{prize,c1} = E_{prize,invest,c1} + E_{prize,loss,c1} = K\frac{I_{c1}}{P_{mean,in}} + K\frac{\text{Invest}}{P_{mean,in}}\frac{P_{mean,loss,c1}}{P_{mean,out}} \tag{5.3}$$

Where:

$E_{prize,c1}$	Contribution to the energy production cost from component $c1$ [SEK/kWh]
$E_{prize,invest,c1}$	Contribution from the cost of component $c1$ [SEK/kWh]
$E_{prize,loss,c1}$	Contribution from the losses in component $c1$ [SEK/kWh]
K	Constant, defined in equation 5.1
Invest	Investment [SEK]
I_{c1}	Cost of component $c1$ [SEK]
$P_{mean,in}$	Mean input power [W]
$P_{mean,out}$	Mean output power [W]
$P_{mean,loss,c1}$	Mean losses in the component $c1$ [W]

Equation 5.3 will be used in this work, to divide the energy production cost into two components: The contribution from the investment cost of the component and the component losses.

The energy production cost for the six, in this chapter, investigated types of electrical system are normalized by the energy production cost obtained for the Horns Rev wind park. According to [3] Horns Rev has a yearly production of 600 000 000kWh, an average wind speed of 9.7m/s and a project cost of DKK 2 billion. This gives an energy production cost of approximately 0.28SEK/kWh, accordingly to the assumptions in this section.

5.2 Comparison of Energy Production Costs

In this section the best configuration of each of the six wind park types presented in chapter 2 are compered with each other, small AC, large AC, AC/DC, small DC, large DC and series DC. The comparison is made for the for different rated powers presented i chapter 2, 60MW, 100MW, 160MW and 300MW. The presented cases for an average wind speed of 10m/s are shown in figures 5.1 and 5.2.

In figure 5.1 the energy production cost is shown for the six wind park configurations, and as mention in chapter 5.1 it is normalized by the production cost for Horns Rev. If the three wind parks with AC are compered, small AC (solid black), large

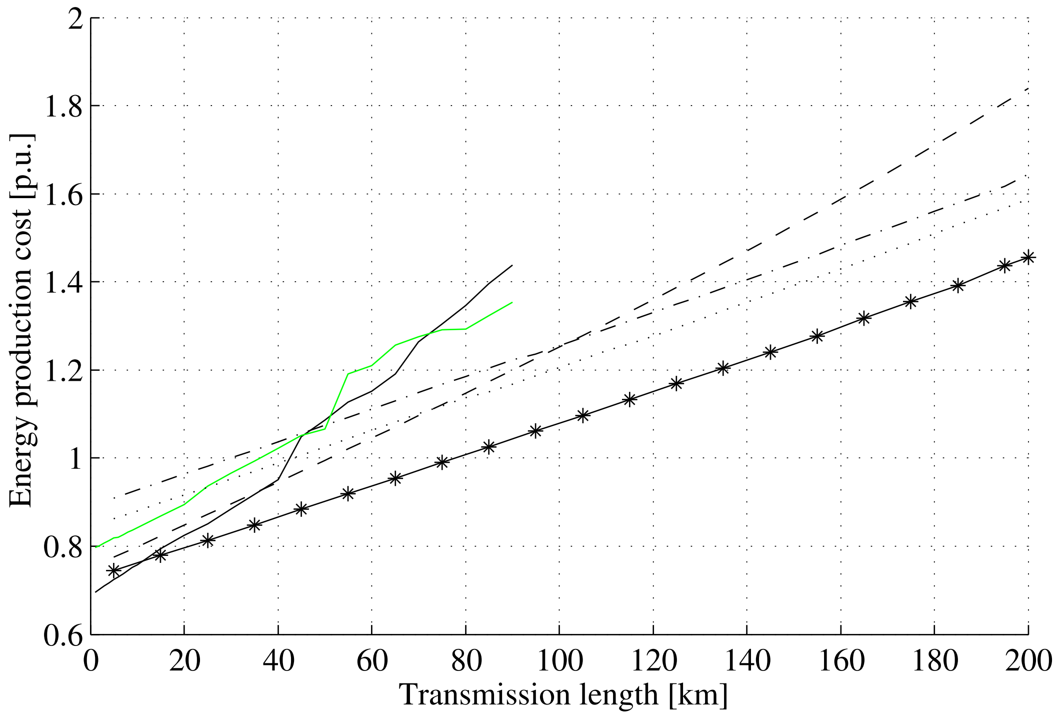

Figure 5.1: The normalized energy production cost of the different 60MW wind parks as function of the transmission distance for an average wind speed of 10m/s. Solid small AC, dashed large AC, dash-dotted AC/DC, grey small DC, dotted large DC and solid with stars series DC.

AC (dashed) and AC/DC (dash-dotted) these results are as expected. The small AC wind park is the best solution for short distances, the AC/DC is best suitable for long distances and the large AC is best in between. The small AC wind park is the best for short distances due to that it does not require an offshore platform. So the additional cost for many low voltage transmission cables is less then the cost for the platform and the high voltage transmission cable for short distances. The cost for the low voltage transmission increases rapidly when the transmission distance increases. The break even point between the small and large AC system is at a transmission distance of 37km. The AC/DC system has, due to the expensive converter stations, a high energy production cost for short distances. Due to the fact that the cost for the transmission cables are less for DC then for AC the AC/DC system gets better then the large AC system for transmission lengths over 100km.

The large DC system is better then the AC/DC system due to that the losses in the DC wind turbine is lower then in the AC wind turbine. Moreover, the cost for the local DC grid is less then the cost for the local AC grid and the losses in the DC transformer are less then the losses in the offshore converter station. These costs are independent of the transmission length, but since the two systems has the same transmission system (DC cables), the large DC wind farm will for any transmission length be better then the AC/DC wind farm (using the assumptions made in this work).

As could be expected, the small DC wind farm is no good solution. This is due to that it still requires a large DC transformer and a converter station. The gain of cheaper cables and somewhat lower losses is not enough to compensate for the expensive DC transformer and converter station. But compered to the large DC system it is better for short distances. The reason is that it does not require an offshore platform.

From figure 5.1 it can be seen that the best wind park solution for a transmission length over 11km is the series DC wind park. This is due to the fact that it does not require an offshore platform, it has a cheaper local wind turbine grid, DC transmission (cheaper then AC) and this system has only one converter station. The uncertainty which is also a great challenge for research in the high voltage field, is how expensive it will be to have the high voltage insulation in each wind turbine.

In figure 5.2 the normalized energy production cost are shown for the six systems for a rated power of the wind park of 160MW. As can be noticed the cost found for the large AC park (The Horns Rev case, totaly 55km transmission length [8]) is 10% lower then the "real" case. However, since real price information is hard to obtain and the fact that Horns Rev was the first large offshore wind park the results are considered to be surprisingly good. It should be stressed that this work focuses on comparing systems rather then obtaining correct total costs, since this was considered to be out of reach without having access to really good cost data. It can be seen if the figures 5.1 and 5.2 are compered that the break even point between the small AC and large AC is decreasing when the wind park size is increased. This is caused by the fact that the contribution to the energy production cost from the transmission system decreases when the wind park size is increased. The decrease is larger for the large AC wind park then for the small AC wind park. Another observation that can be made is that the energy production cost decreases when the rated power of the wind park increases.

In figure 5.3 a curve of how the energy production cost varies with the average wind speed is presented. The curve is normalized by the costs at a average wind speed of 10m/s. As can be noticed from the figure 5.3 the cost increases rapidly if the average wind speed decreases. At a average wind speed of 6.5m/s the energy production cost is twice as high as at 10m/s.

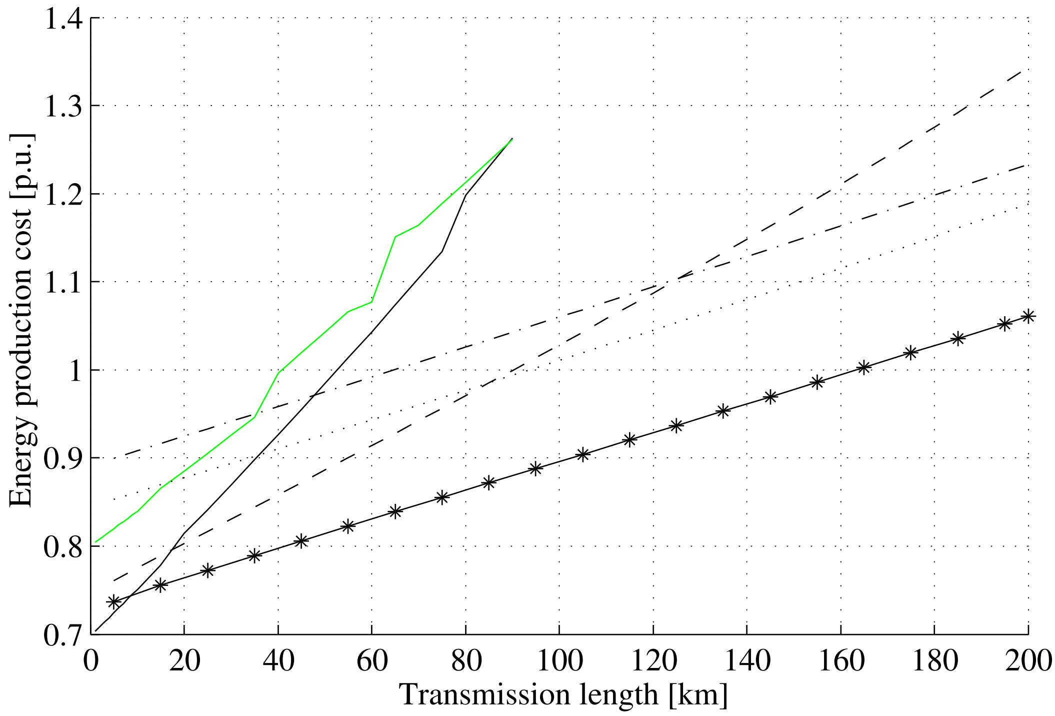

Figure 5.2: The normalized energy production cost of the different 160MW wind parks as function of the transmission distance and at a average wind speed of 10m/s. Solid small AC, dashed large AC, dash-dotted AC/DC, grey small DC, dotted large DC and solid with stars series DC.

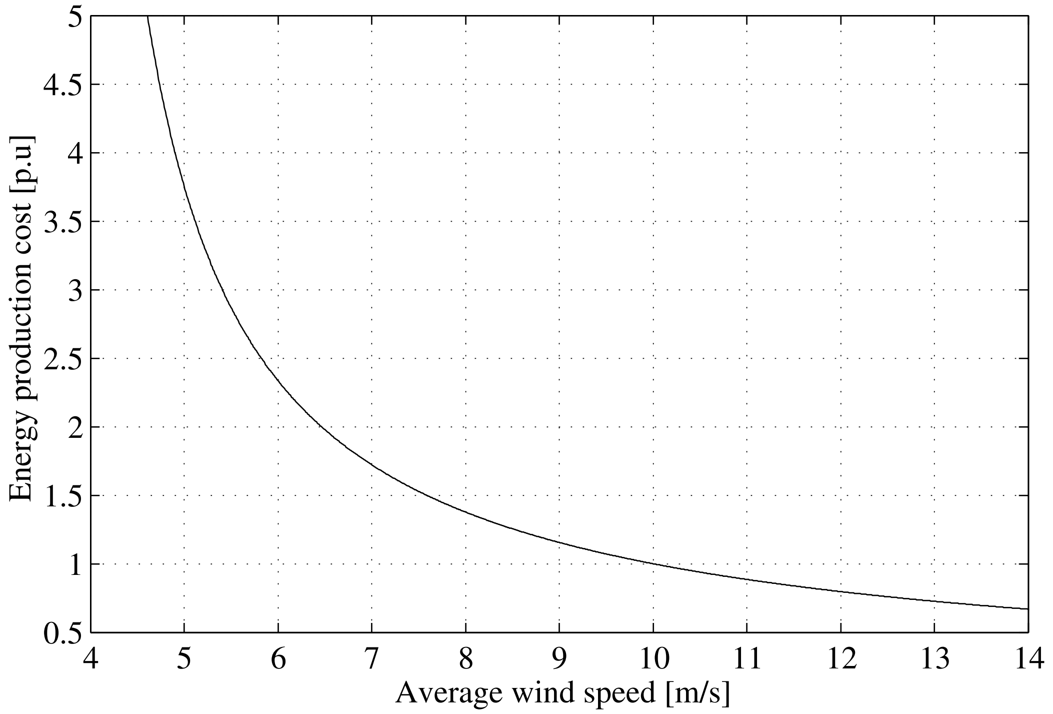

Figure 5.3: Energy production cost as function of the average wind speed, normalized with the prize at a average wind speed of 10m/s.

5.3 Small AC park, local grid for transmission

In this section, the small AC wind park is investigated in detail. First some selections are made to limit the number of cases and then the energy production prize is discussed for the different configurations of the small AC wind park.

5.3.1 Transformer size

The first selection to be made is the transformer size. The reason for investigating this is that it is possible to get lower losses and perhaps lower contribution to the energy production prize, if the transformer size is selected larger then the rating of the wind farm. The reason for this is that in these cases the cost of the losses in the transformer is reduced more then what the cost of the transformer increases. If it is assumed that the investment (Invest) for calculating the contribution to the energy production cost (equation 5.3) from the transformer is described by Invest $= B_I P_{n,wp} + \text{Prize}_{transformer}$, where $P_{n,wp}$ is the rated power of the wind park and B_I is the investment factor for the other components in the wind park. Moreover, it is assumed that the input power to the wind farm as function of wind speed is described by equation 5.4 in per unit of $P_{n,wp}$.

$$\begin{aligned} P &= \frac{w_s^3}{w_{s,P}^3} \text{ for } 0 \leq w_s \leq w_{s,P} \\ &= 1 \text{ for } w_{s,P} \leq w_s \end{aligned} \tag{5.4}$$

Where:

P	Input power [p.u.]
w_s	Wind speed [m/s]
$w_{s,P}$	Wind speed for rated power =11.5m/s

The average input power is calculated with equation 4.1. The output power is calculated according to $P_{out,AVG} = P_{in,AVG} - P_{loss,AVG,transformer} - P_{loss,AVG,other}$. $P_{loss,AVG,other}$ is the average losses of the other components in the wind park and in this case (determination of transformer size) these are set equal to the relative losses of the 2MW wind turbine with the DFIG system. The losses of the transformer are described in [20], as mention before. The input power to the transformer is also assumed to be described by equation 5.4 and the average losses are calculated by equation 4.1. Using these assumptions, the optimum transformer size that minimizes the contribution to the energy production cost, can be calculated. The key results from this calculation are presented in figure 5.4. The main conclusion from figure 5.4 is that it is for high rated powers of the wind park and for high average wind speeds that it is optimal to have a higher rating of the transformer. The fact that it is for high powers, depend on that the derivative of the cost for the transformer is lower for high power levels then it is for lower power levels. In the same way as for electric machines, the load losses is of greater importance for high average wind speeds and the no-load losses for low average wind speeds. The result is that the smallest possible transformer shall almost always be selected. Only in the case of high rated power of the wind park and high average wind speeds, the transformer shall be slightly over-dimensioned. In this work the smallest transformer possible is accordingly always used.

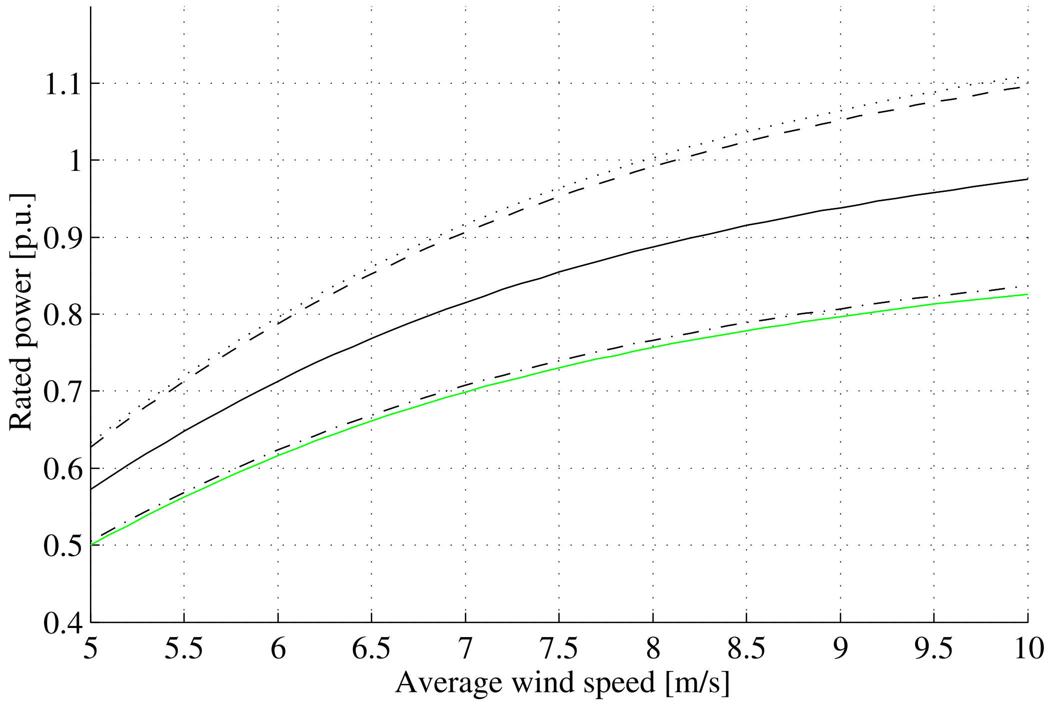

Figure 5.4: Rated power of the transformer in p.u. of the rated power of the wind park as function of the average wind speed for different rated powers of the wind park and different investment factors. Solid 150MW $B_I = 19$, dash-dotted 60MW $B_I = 19$, dotted 300MW $B_I = 19$, grey 150MW $B_I = 14$ and dashed 150MW $B_I = 24$.

5.3.2 Number of wind turbines per radial

With the same technique used to determine the rated power of the transformer, the ideal number of wind turbines per radial can be calculated. For this calculation the wind turbines, the cables between the wind turbines and the transmission cables are treated as the component to be optimized. Otherwise the procedure is similar to the one for the transformer above. In figures 5.5 and 5.6 the results from these calculations are shown for different power levels. The two figures shows the results for the two transmission voltage levels, 22kV and 45kV. The small wind park is also investigated for a voltage level of 33kV, but since the results for this voltage level is in between the ones obtained for the 22kV and 45kV and, moreover, show the same pattern, they are not shown. The black curves in these two figures corresponds to the calculation of the number of wind turbines per radial that gives the lowest contribution to the energy production cost. But since the wind park should have a specific rating, the selection of the number of wind turbines per radial is not free to choice. Due to this fact, the number of wind turbines per radial multiplied by the number of radials multiplied with the rating of the wind turbine should be equal to the rating of the wind park. Therefore the grey curves in the two figures 5.5 and 5.6 shows the discrete number of wind turbines per radial that is used in this investigation. As can be noticed if the grey lines are studied in detail, the rated power of the wind park is allowed to vary somewhat around the desired rated power. This means that for some transmission distances the actual rated power of the wind park is somewhat higher or lower then the desired rated power (60, 100, 160 or 300MW).

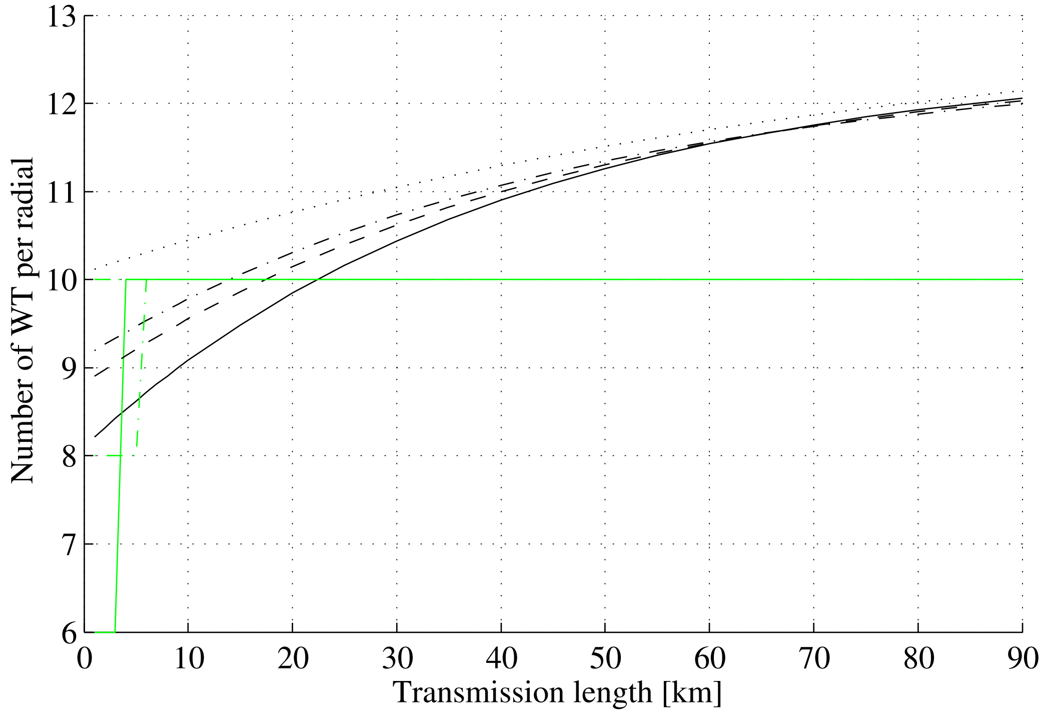

Figure 5.5: Number of wind turbines per radial for 22kV transmission voltage. Black theoretical curves and grey actual curves. Solid 60MW park, dashed 100MW, dash-dotted 160MW and dotted 300MW wind park.

In the calculation of the ideal number of wind turbines per radial, the ideal size of the transmission cables was also calculated. From this calculation it was indicated that the cables should be over-dimensioned if the transmission length is short, shorter then 10km. The desired over-dimension decreased when the transmission length increased. Since the focus in this work is mainly on somewhat longer distances, the smallest conductor area that can be used is chosen here.

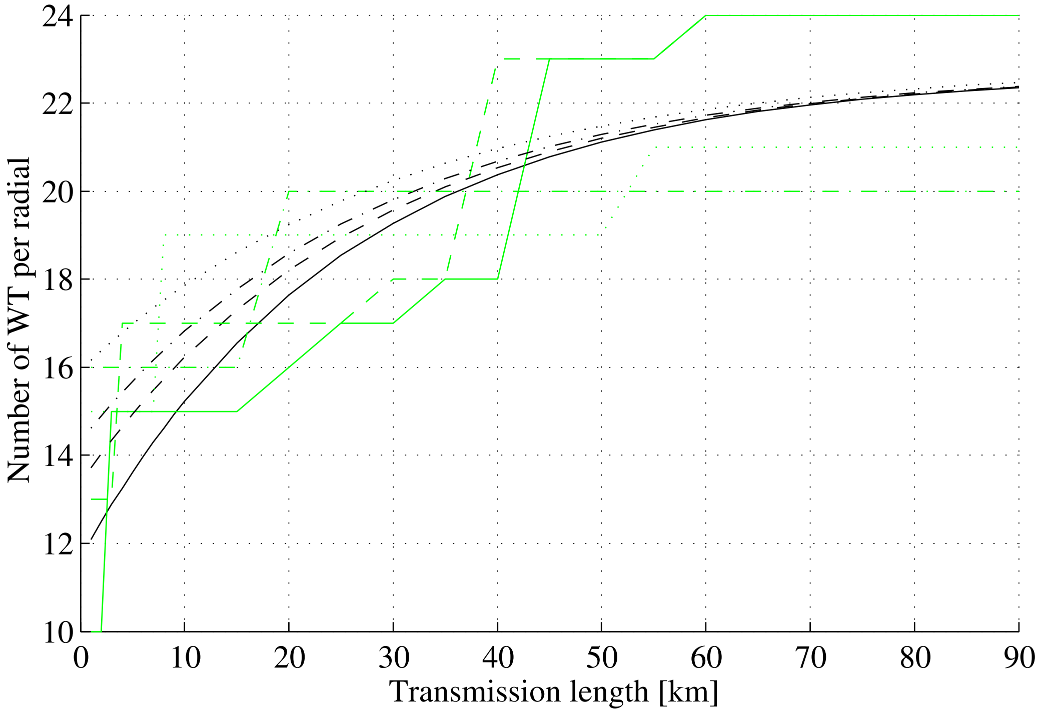

Figure 5.6: Number of wind turbines per radial for 45kV transmission voltage. Black theoretical curves and grey actual curves. Solid 60MW park, dashed 100MW, dash-dotted 160MW and dotted 300MW wind park.

5.3.3 Energy production cost for the different configurations of the small AC wind park

By using the above mentioned selections, the energy production cost of the small AC wind farm can be calculated for different transmission lengths. In figure 5.7 the energy production cost of the 60MW small AC wind farm is shown for different voltage levels, wind turbine types and for an average wind speed of 10m/s. From figure 5.7 it is

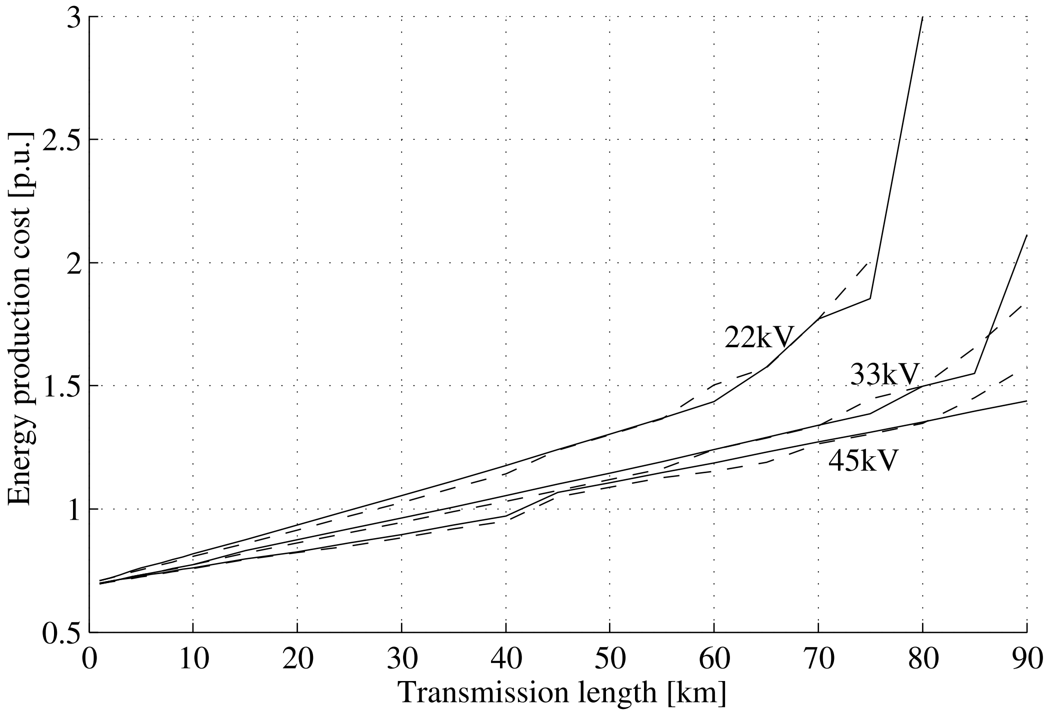

Figure 5.7: The normalized energy production cost for the different configurations of the small AC system. For a 60MW wind park, an average wind sped of 10m/s and for different transmissions lengths. Solid with fix speed wind turbines and dashed wind turbines with the DFIG system.

noticed that 45kV is the best voltage level to use and up to approximate 80km the wind turbine with the DFIG system is to prefer. This result is similar for all the four investigated power levels of the wind park, and can thus be considered as general.

To make the discussion of the dependency of the energy production cost on different parameters more clear, one of the small AC wind park layouts has been selected as a reference and then one parameter at the time has been changed. Table 5.1 shows the selected reference wind park and the parameters that are varied.

In table 5.2 the different contributions to the energy production cost are shown for the different parameter variations from the reference case. The different contributions are presented in % of the total energy production cost of that configuration, i.e the sum of all contributions is always equal to 100%. The explanations of the abbreviations in table 5.2 are found in figure 5.8.

In figure 5.8 the components of the energy production cost are shown for the reference small AC wind park.

Table 5.1: Reference wind park and the variations.

Parameter	Reference			
Transmission length	40	2	40	80
Transmission voltage	45	22	33	45
Power level	60	60	100	160
Wind turbine type	DFIG	DFIG	Fix speed	
Average wind speed	10	5	6	10

Table 5.2: Reference wind park and the variations.

Case type	WT C	WT L	TM C	TM L	LG
Ref case	59.9	7.6	21.6	3.5	7.4
Length = 2	81	7.6	3.2	0.5	7.8
Length = 80	42.6	7.6	38.5	5	6.3
Voltage = 20	49.8	7.6	30.1	6.5	6
Voltage = 30	55.2	7.6	25.7	4.3	7.1
Power = 100	59.8	7.6	20.9	2.9	8.8
Power = 160	61.2	7.6	19.7	3.2	8.3
Fix speed	58.7	7.5	23.6	2.9	7.3
Wind speed = 5	59.2	10.3	21.3	2	7.2
Wind speed = 6	59.6	9.2	21.5	2.5	7.3

Influence of transmission length on the energy production cost

From figure 5.7 it can be noticed that the energy production cost increases when the transmission distance increases. This is, of course, due to the fact that the cost of the transmission system increases when the transmission length increases. This can also be seen in table 5.2 where the components of the energy production cost are shown for the reference wind park and for two different transmission lengths. From table 5.2 it is seen that both the investment cost and the cost of the losses for the transmission system increase when the transmission length increases.

Influence of transmission voltage

From figure 5.7 it can be seen that the energy production cost decreases with increasing transmission voltage. This is due to the fact that the cost of the transmission system is decreasing with an increasing transmission voltage as can be noticed in table 5.2. The decrease of the cost of the transmission system depends on that the number of needed radials decreases when the transmission voltage increases and therefore the number of parallel transmission cables decreases. The reason is that the number of wind turbines per radial increases when the transmission voltage increases, compere figures 5.5 and 5.6. From table 5.2 it can also be noticed that the cost of the local wind turbine grid increases when the transmission voltage increases. This is due to the fact that the VA rating of the cables increases when the voltage increases, due to that the number of wind turbines per radial increases with increasing voltage as noticed before.

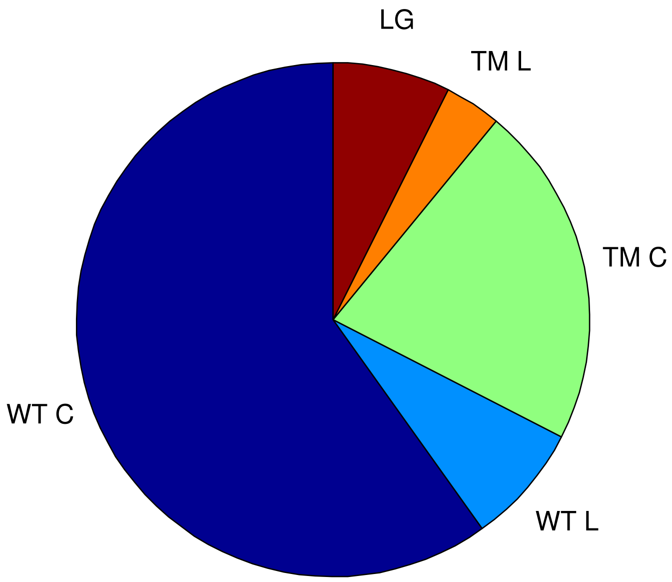

Figure 5.8: The energy production cost divided into components for the small AC wind farm for the reference case.

Where

WT C	Investment cost of the wind turbine
WT L	Cost of the losses in the wind turbine
TM C	Investment cost of the transmission system
TM L	Cost of the losses in the transmission system
LG	Investment and loss cost of the local wind turbine grid

Influence of rated power of the wind park

In table 5.2 the division of the energy production cost into components are also shown for three different power levels. A closer inspection reveals that the different contributions from the parts is almost equal for all power levels. But worth emphasizing again is that the energy production cost decreases when the power of the wind park increases.

Influence of the average wind speed

As was earlier presented, due to the increase in energy production, the energy production cost decreases when the average wind speed increases. From table 5.2 it can be noticed that the cost for the losses in the transmission system increases with an increasing average wind speed and the cost for the losses in the wind turbine decreases. This is mainly due to that the ratio between the load losses and the no-load losses for the transmission system is much larger then the same ratio for the wind turbine.

Influence of wind turbine type

As has been noticed from figure 5.7 the energy production cost for the wind park with wind turbines using the DFIG system is lower up to 80km. This is due to that the fix speed wind turbines require a transmission system that can support them with reactive power from the grid and therefore this system requires a larger conductor area. Therefore the cost of the transmission system is higher for the wind park with fix speed wind turbines, as can be observed in table 5.2.

5.4 Large AC park

In this section, the large AC wind park is investigated in detail.

5.4.1 Configuration selections

In the same way as for the small AC wind park some selections are made to limit the number of parameters. The transformer size is chosen in the same way as for the small AC wind park i.e. the rated power for the transformer is equal to the rated power of the wind park. The voltage for the local wind turbine grid is chosen to 33kV, the voltage level used at the Horns Rev offshore wind park. The number of wind turbines per radial can be calculated in the same way as for the small AC wind park and the result from this calculation can be approximated with the results from figures 5.5 and 5.6 if the transmission distance is put to zero. The selected number of wind turbines per radial and the number of radials are presented in table 5.10 for the different power levels.

Table 5.3: Number of wind turbines per radial and the numbers of radials for the large AC wind park.

Power level	WT/Rad	Rad
60MW	10	3
100MW	10	5
160MW	10	8
300MW	15	10

For the transmission cable it was shown that the cable should be over-dimensioned for short distances. The over-dimensioning decreases with increasing transmission distance and it also decreases with increasing power levels of the wind park. Since the smallest distances are not of such great interest and also to simplify the calculations, the cable with the smallest conductor area that can handle the current is used throughout this work.

5.4.2 Energy production cost for the different configurations of the large AC wind park

By using the above mentioned selections, the energy production cost of the large AC wind farm can be calculated for different transmission lengths. In figure 5.9 the energy production cost of the 100MW large AC wind farm is shown for different voltage levels, wind turbine types and for an average wind speed of 10m/s. From figure 5.9 it can be

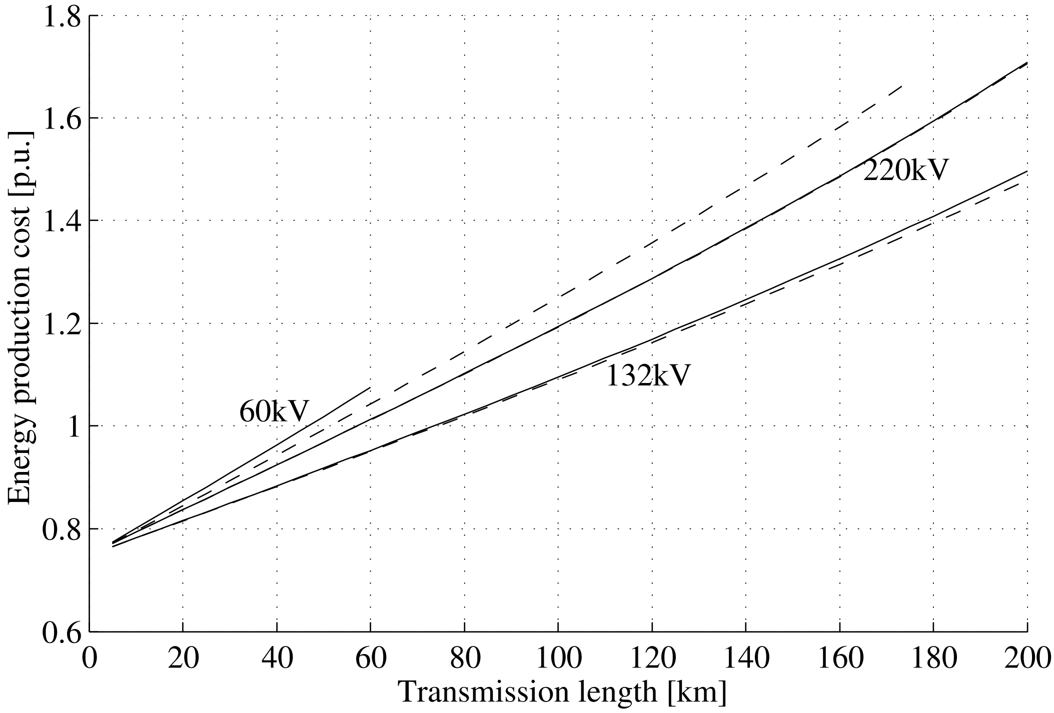

Figure 5.9: The normalized energy production cost for the different configurations of the large AC system. For a 100MW wind park, an average wind sped of 10m/s and for different transmissions lengths. Solid fix speed wind turbines and dashed wind turbines with the DFIG system.

seen that the best wind park configuration of the 100MW large AC wind park is the one with a transmission voltage of 132kV and wind turbines with the DFIG system. For all investigated wind park sizes, the wind turbine with the DFIG system is the best. But the ideal transmission voltage is depending on the power level of the wind park. For the 60MW wind park the 132kV transmission system is the ideal. But for the 160MW and the 300MW wind park the 220kV transmission system is better. For the 160MW wind park the difference between the 220kV system and the 132kV system is small. But for the 300MW park the only system that works is the 220kV system.

To make the discussion of the dependency of the energy production cost on different parameters more clear, one of the large AC wind park layouts has been selected as a reference and then one parameter at the time has been changed. Table 5.4 shows the selected reference wind park and the parameters that are varied.

In table 5.5 the different contributions to the energy production cost are shown for the different parameter variations from the reference case. The different contributions are presented in % of the total energy production cost of that configuration, i.e the sum of all contributions is always equal to 100%. The explanations of the abbreviations in table 5.5 are found in figure 5.10. The cost of the other components, mark with O in table 5.5, the costs of the low and high voltage switch gear is included together with the cost of the cable compensating inductors and the transformer.

In figure 5.10 the components of the energy production cost are shown for the reference large AC wind park.

Table 5.4: Reference wind park and the variations.

Parameter	Reference			
Transmission length	100km	30	100	175
Transmission voltage	132kV	60	132	220
Power level	100MW	60	100	160
Wind turbine type	DFIG	DFIG	Fix speed	
Average wind speed	10m/s	5	6	10

Table 5.5: Reference wind park and the variations.

Case type	WT C	WT L	LG	TM L	TM C	O	PL
Ref case	51.3	7.6	7.5	3.1	25.1	1.4	4
Length = 30	65.9	7.6	9.5	0.9	9.7	1.2	5.2
Length = 175	40.7	7.6	6	6.1	34.9	1.5	3.2
Voltage = 60	44.7	7.6	6.6	4.3	32.2	1.1	3.5
Voltage = 220	46.9	7.6	6.9	1	31.8	2.1	3.7
Power = 60	44.7	7.6	6	3.2	32.9	1.6	4
Power = 160	53.7	7.6	8.2	2.1	23.4	1.2	3.9
Fix speed	51.1	7.5	7.5	3.5	25	1.4	4
Wind speed = 5	50.1	10.2	7.2	2.2	24.6	1.8	3.9
Wind speed = 6	50.7	9.2	7.3	2.4	24.8	1.6	4

Influence of transmission length on the energy production cost

From figure 5.9 it can be noticed, not surprisingly, that the energy production cost increases when the transmission distance increases. This can also be seen in table 5.5, where the components of the energy production cost is shown for the reference wind park and for two different transmission lengths. From table 5.5 it is seen that both the investment cost and the cost of the losses increases when the transmission length increases.

Influence of transmission voltage

From figure 5.9 it has been noticed that the ideal transmission voltage is 132kV for the 100MW large AC wind park. In table 5.5 it is noticed that the 132kV transmission system has the lowest investment contribution to the energy production cost. Another thing that can be noticed is that the cost of the losses in the transmission system decrease with increasing transmission voltage, due to that the current decreases. The contribution of the other components increases with the transmission voltage. This is due to that the cost of the high voltage protections increases with the voltage and that the investment cost and the cost of the losses for the compensating inductance of the cable increase. The fact that the cost of the compensating inductance increase is due to that the reactive power production of the cable increases with the voltage.

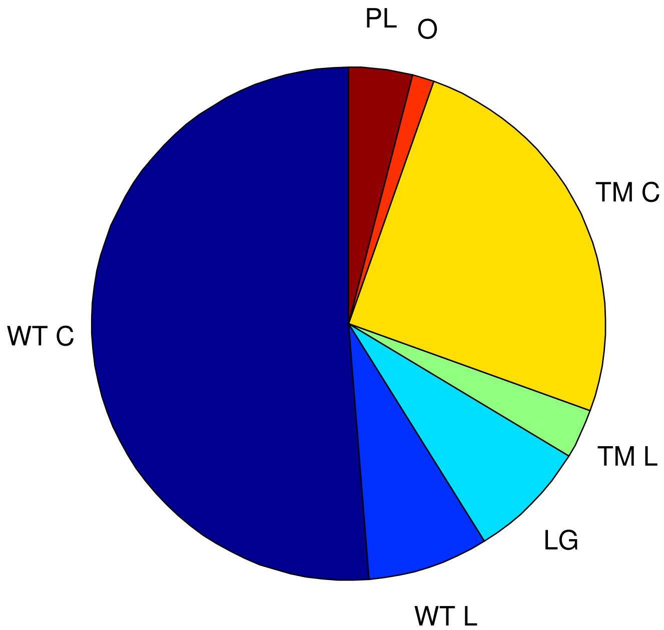

Figure 5.10: The energy production cost divided into components for the large AC wind farm for the reference case.

Where

WT C	Investment cost of the wind turbine
WT L	Cost of the losses in the wind turbine
TM C	Investment cost of the transmission system
TM L	Cost of the losses in the transmission system
LG	Investment and loss cost of the local wind turbine grid
PL	Investment cost of the offshore platform
O	Investment and loss cost of the other components

Influence of rated power of the wind park

The pattern is the same as before, the energy production cost decreases with an increased rated power of the wind park. This can be seen in table 5.5, where the components of the energy production cost is shown for different power levels. The energy production cost decreases due to that the contribution from the transmission system decreases.

Influence of wind turbine type

As can be noticed from figure 5.9 there is no large difference between the fix speed wind turbine and the DFIG wind turbine for the 132kV and 220kV transmission voltage. But for the 66kV transmission voltage there is a large difference, above 60km the fix speed system can not be used. This is due to the reactive power consumption of the fix speed wind turbine. It has been noticed [20] that the cost of the 66kV increases rapidly when the rated power is increased over 100MVA. Due to the reactive power consumption of the fix speed wind turbine, a transmission cable with an higher rating must be used in this case and due to the high derivative of the 66kV cable cost there is a large difference between the fix speed and the DFIG wind turbine for this transmission voltage and for 100MW rating of the wind park. It has also been noticed [20] that the derivative of the cable cost for the 132kV and 220kV cable around 100MVA is low and therefore the increased rated power of the transmission cable for the fix speed wind turbine does not affect the energy production cost much. As can be seen from table 5.5 it is only the losses in the transmission system that is higher for the fix speed wind turbine compered with the DFIG wind turbine.

Influence of average wind speed

In the same way as for the small AC wind park there is a small variation in the cost of the wind turbine losses and the transmission losses for different average wind speeds. As has been noticed before, the cost for the losses in the transmission system increases with an increasing average wind speed and the cost for the losses in the wind turbine decreases. This is, as mentioned before, mainly due to that the ratio between the load losses and the no-load losses for the transmission system is much larger then the ratio for the wind turbine.

5.5 AC/DC Park

In this section, the AC/DC wind park is studied in detail. First some selections are made to limit the number of cases and then the energy production prize is discussed for the different configurations of the AC/DC wind park.

5.5.1 Configuration selections

With the same technique as for the transformer size for the small AC wind park, the ideal size of the converter stations can be calculated. In figure 5.11 the results from these calculation are shown. From figure 5.11 it is noticed that the station should

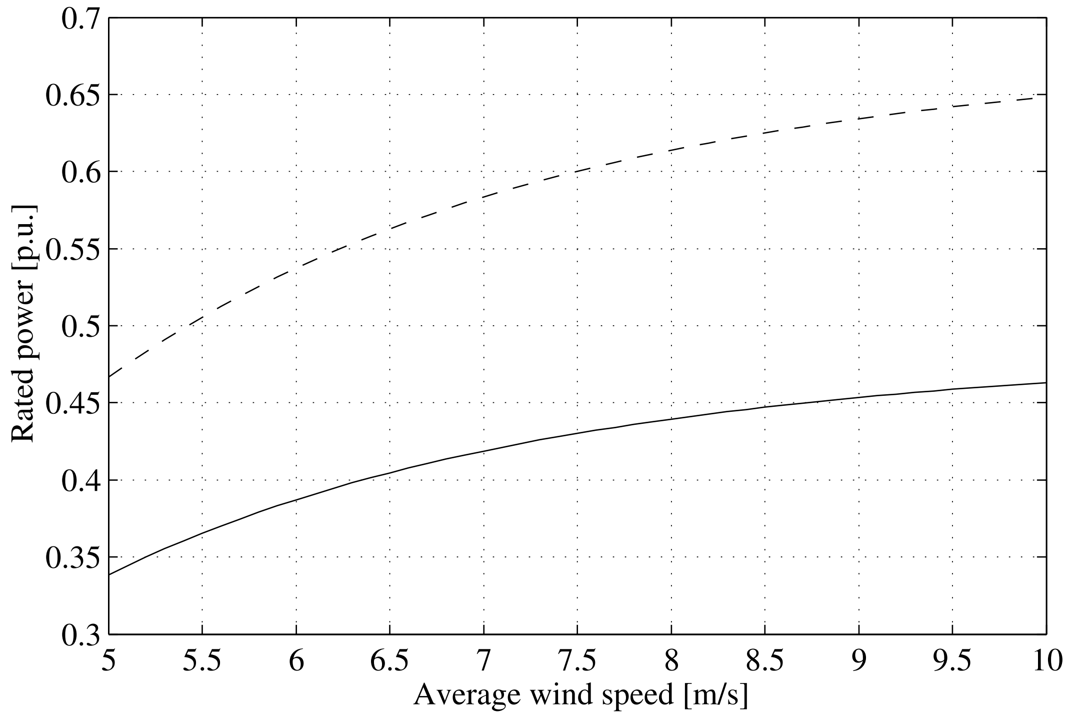

Figure 5.11: Rated power of the HVDC-station in p.u. of the rated power of the wind park as function of the average wind speed for different investment factors. Solid $B_I = 12$ and dashed $B_I = 24$.

ideally have a rated power lower then the rated power of the wind park to be ideal. This is due to the fact that the reduction of cost for the losses is smaller then the increase of the investment cost when the rated power of the converter station is increased. Since this is not possible, the rated power of the converter station is selected equal to the rated power of the wind park.

For the DC cable is was found that it should be over-dimensioned to minimize the contribution to the energy production cost. The over-dimension increased with increasing transmission voltage, increasing transmission length, increasing average wind speed and with decreasing rated power of the wind park. However, since a discrete number of conductor areas are used, the cables will almost in all cases be over-dimensioned and due to the fact that it was found that the losses of the transmission cable has a minor contribution to the energy production cost, the rating of the cable is set as close to the rating of the wind park as possible.

The local wind turbine grid for the large AC wind park is used for the AC/DC wind park also. Which means that the number of wind turbines per radial is presented in table 5.10 and the voltage level is 33kV.

5.5.2 Energy production cost for the different configurations of the AC/DC wind park

With these selections the energy production cost for the different configurations of the AC/DC wind park are calculated. In figure 5.12 the energy production cost of the 300MW AC/DC wind farm is shown for different voltage levels, wind turbine types and for an average wind speed of 10m/s. From figure 5.12 it is noticed that 150kV

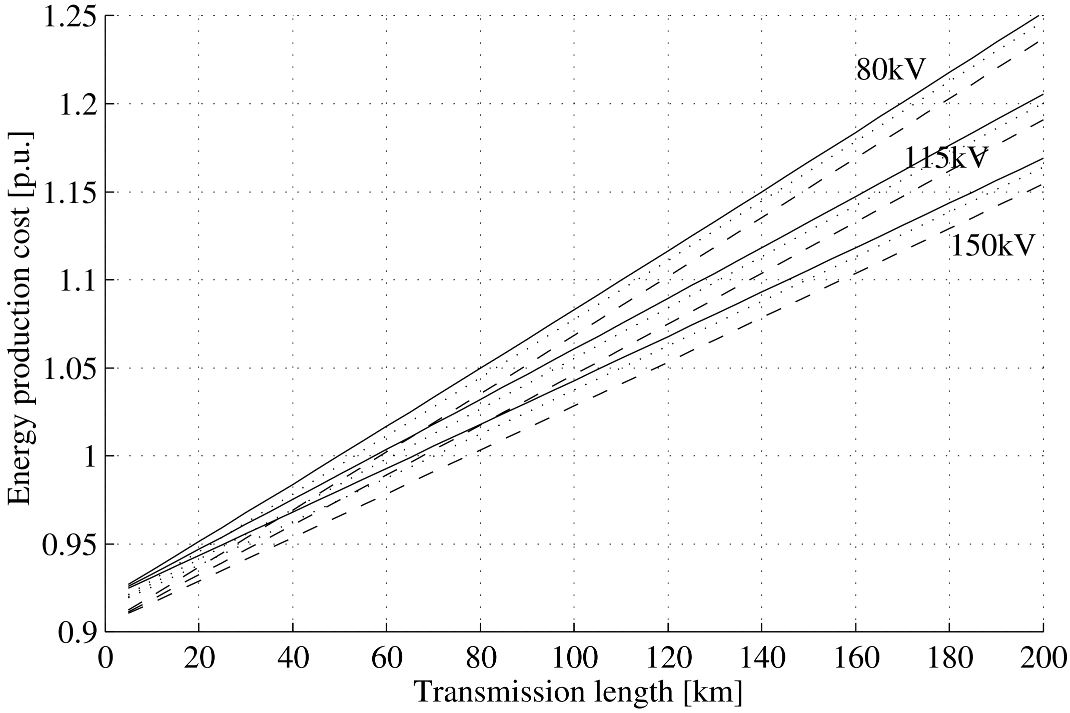

Figure 5.12: The normalized energy production cost for the different configurations of the AC/DC system. For a 300MW wind park, an average wind sped of 10m/s and for different transmissions lengths. Solid fix speed wind turbines, dashed wind turbines with the DFIG system and dotted fix speed wind turbines speed controlled with the offshore converter station.

is the best voltage level to use and the wind turbine using the DFIG system is to prefer. For all power levels, the wind turbine with the DFIG system is to prefer. The ideal voltage level for transmission is depending on the power level. For the 60MW wind park, the 115kV transmission voltage is to prefer and for the 100MW wind park 115kV is to prefer up to a transmission length of 150km. For the 100MW wind park for transmission lengths above 150km and for the 160MW and 300MW wind park the 150kV transmission voltage is to prefer.

To make the discussion of the dependency of the energy production cost on different parameters more clear, one of the AC/DC wind park layouts has been selected as a reference and then one parameter at the time has been changed. Table 5.6 shows the selected reference wind park and the parameters that are varied. The wind turbine

Table 5.6: Reference wind park and the variations.

Parameter	Reference			
Transmission length	100km	30	100	175
Transmission voltage	150kV	80	115	150
Power level	300MW	100	160	300
Wind turbine type	DFIG	DFIG	Fix speed	Fix variable
Average wind speed	10m/s	5	6	10

type Fix variable in table 5.6 is a fix speed wind turbine with only one large generator, with a rated power of 2MW. In this case all wind turbines in the wind park are speed controlled with the offshore converter station, the voltage is also controlled to reduce the iron losses in the generators, in the same way as for the wind turbine with induction generator and a full power converter in section 4.1.3. Using this system, collective variable speed and field weakening can be obtained, still the simple construction of the fix speed wind turbine is utilized [5, 36].

In figure 5.13 the components of the energy production cost are shown for the reference wind park. From figure 5.13 it can be noticed that the contribution to the energy production cost from the transmission system, TM C+TM L, is much lower compered to the large AC wind park. But it shall also be noticed that the converter stations have a significant contribution to the energy production cost. In table 5.7 the different contributions to the energy production cost are shown for the different parameter variations from the reference case. The different contributions are presented in % of the total energy production cost of that configuration, i.e the sum of all contributions is always equal to 100%. The explanations of the abbreviations in table 5.7 are found in figure 5.13.

Table 5.7: Reference wind park and the variations.

Case type	WT C	WT L	LG	TM C	TM L	ST C	ST L	PL
Ref case	54.5	7.6	9.7	9.5	1	9.5	4.6	3.6
Length = 30	59.5	7.6	10.6	3.1	0.3	10.3	4.6	4
Length = 175	49.9	7.6	9	15.3	1.7	8.7	4.6	3.3
Voltage = 80	52.4	7.6	9.4	11.7	1.7	9.1	4.6	3.5
Voltage = 115	53.5	7.6	9.6	10.7	1.1	9.3	4.6	3.6
Power = 100	49.4	7.6	7.2	16.5	2.2	8.6	4.6	3.9
Power = 160	52.9	7.6	8.1	12.1	1.7	9.2	4.6	3.8
Fix	53.7	7.5	10.3	9.4	1	9.9	4.6	3.6
Fix V	54	7.2	9.8	9.4	1	9.9	5	3.6
Wind speed = 5	53.6	10.3	9.3	9.4	0.5	9.3	4.1	3.6
Wind speed = 6	54	9.2	9.5	9.5	0.7	9.4	4.2	3.6

The variations in the contribution to total the energy production cost from the dif-

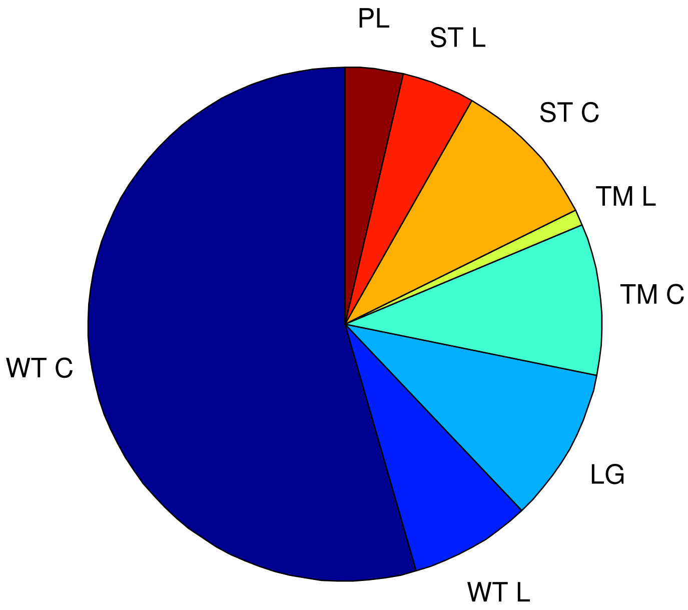

Figure 5.13: The energy production cost divided into components for the AC/DC wind farm for the reference case.

WT C	Investment cost of the wind turbine
WT L	Cost of the losses in the wind turbine
LG	Investment and loss cost of the local wind turbine grid
TM C	Investment cost of the transmission system
TM L	Cost of the losses in the transmission system
ST C	Investment cost of the two converter stations
ST L	Cost of the losses in the two converter stations
PL	Investment cost of the offshore platform

ferent components from variations in the transmission length, the transmission voltage, rated power of the wind park and the average wind speed can be explained in the same way as for the large AC wind park.

As has already been seen in figure 5.12 the wind turbine with the DFIG system is the best suitable. From table 5.7 it is seen that the configuration with the fix speed wind turbine, Fix, the wind turbine losses contributes less to the energy production cost then for the wind turbine with the DFIG system. But the local grid contributes with more for the fix speed system, which is due to the reactive power. For the configuration with the fix speed wind turbines controlled by the offshore station, Fix V, it can be seen that the contribution from the wind turbine losses is reduced compered with the case with wind turbine with the DFIG system. But the gain is lost in an increased contribution from the converter station losses. This is due to the fact that the control of the system is designed to reduce the losses in the wind turbine only. A better, but more complicated way is to use a control that reduces the losses in the whole local grid (wind turbines, cables and offshore converter station).

5.6 Small DC park, local grid for transmission

In this section the small DC wind park is studied in detail. First some selections are made to limit the number of cases and then the energy production prize is discussed for the different configurations of the small DC wind park.

5.6.1 Configuration selections

With the same technique as for the AC transformer size in the small AC wind park the size of the DC transformer can be calculated. The ideal size of the DC transformer is shown in figure 5.14. From figure 5.14 it is noticed that the DC transformer should

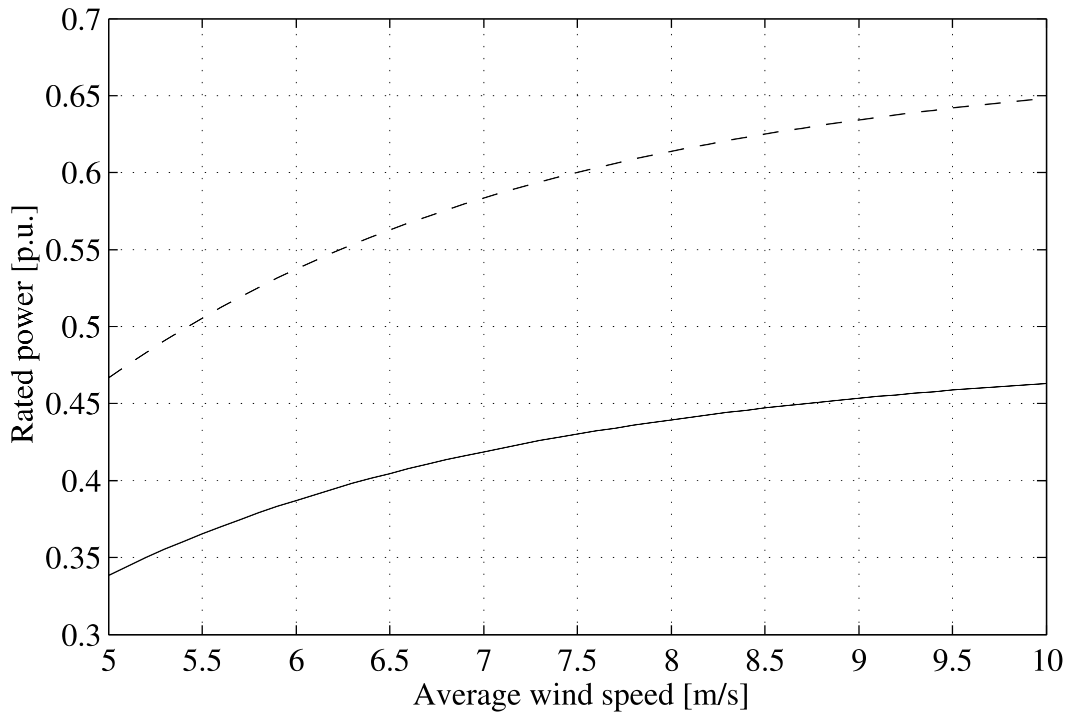

Figure 5.14: Rated power of the DC-transformer in p.u. of the rated power of the wind park as function of the average wind speed for different investment factors. Solid $B_I = 12$ and dashed $B_I = 24$.

ideally have a rated power lower then the rated power of the wind park to be ideal. Since this is not possible, the rated power of the DC transformer is selected equal to the rated power of the wind park. In the same way as for the AC/DC wind park the rated power of the converter station is selected equal to the rated power of the wind park.

In the same way as for the small AC wind park the ideal number of wind turbine per radial can be calculated. The results from this calculation is shown in figure 5.15 for a transmission voltage of 40kV, for different rated powers and for different transmission lengths. Due to the same reasons as for the small AC wind park, the number of wind turbines per radial is not a free choice. Therefore the grey curves in figure 5.15 describe the used number of wind turbines per radial. As can be noticed, the number of wind turbines increases with the transmission length, in order to reduce the number of radials

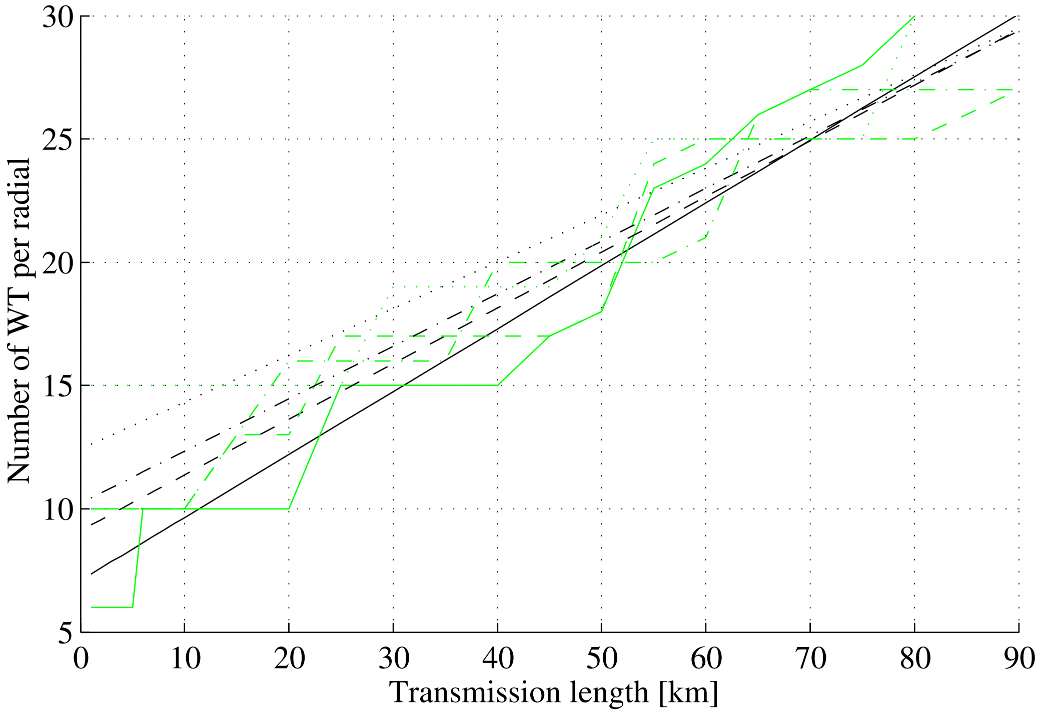

Figure 5.15: Number of wind turbines per radial for 40kV transmission voltage. Black theoretical curve and grey actual curve. Solid 60MW park, dashed 100MW, dash-dotted 160MW and dotted 300MW wind park.

and thereby reduce the number of transmission cables. This is due to the fact that when the transmission length is long, it is expensive to put in an extra transmission cable. In the same way as for the small AC wind park the actual rated power of the wind park is allowed to vary somewhat around the desired rated power when the number of wind turbines per radial and the number of radials are selected.

Again it was found that the transmission cables should be over-dimensioned for short transmission distances in order to minimize the contribution to the energy production cost. But the over-dimensioning decreases with increasing transmission lengths. Therefore the rating of the transmission cables is set equal to the rated power of the radial, as before.

5.6.2 Energy production cost for the different configurations of the small DC wind park

With these selections, the energy production cost for the different configurations of the small DC wind park are calculated. In figures 5.1 and 5.2 the energy production cost of the 60MW and the 160MW small DC wind farm are shown (solid grey line) for an average wind speed of 10m/s.

As in the earlier sections, one of the small DC wind park layouts has been selected as a reference and then one parameter at the time has been changed. Table 5.8 shows the selected reference wind park and the parameters that are varied.

In figure 5.16 the components of the energy production cost are shown for the ref-

Table 5.8: Reference wind park and the variations.

Parameter	Reference			
Transmission length	40km	2	40	80
Transmission voltage	40kV			
Power level	60MW	60	100	160
Wind turbine type	Boost			
Average wind speed	10m/s	5	6	10

erence wind park. From figure 5.16 it can be noticed that the converter station and

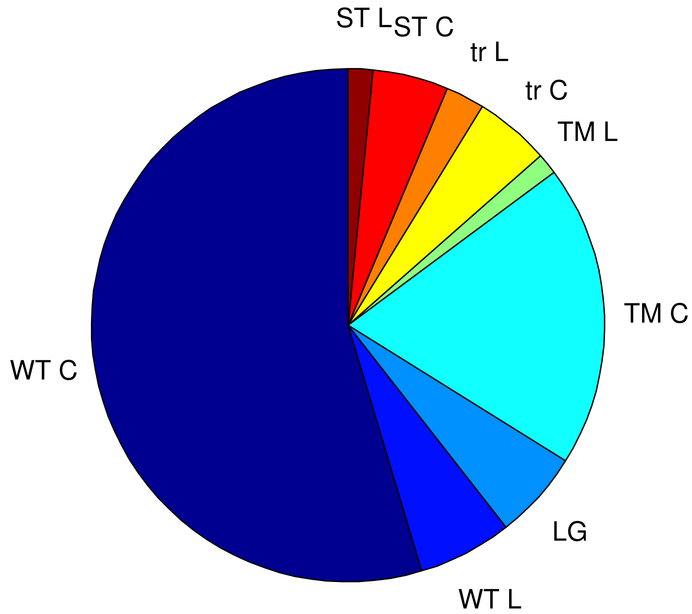

Figure 5.16: The energy production cost divided into components for the small DC wind farm for the reference case.

WT C	Investment cost of the wind turbine
WT L	Cost of the losses in the wind turbine
LG	Investment and loss cost of the local wind turbine grid
TM C	Investment cost of the transmission system
TM L	Cost of the losses in the transmission system
tr C	Investment cost of the DC transformer
tr L	Cost of the losses in the DC transformer
ST C	Investment cost of the converter station
ST L	Cost of the losses in the converter station

the DC transformer has a significant contribution to the energy production cost. In table 5.9 the different contributions to the energy production cost are shown for the different parameter variations from the reference case, see figure 5.16 for the abbreviations in the table. The different contributions are presented in % of the total energy production cost of that configuration.

Table 5.9: Reference wind park and the variations.

Case type	WT C	WT L	LG	TM C	TM L	tr C	tr L	ST C	ST L
Ref case	54.6	5.9	5.6	19	1.3	4.8	2.4	4.8	1.6
Length = 2	69.6	5.9	4.6	3.4	0.2	6.1	2.5	6.1	1.6
Length = 80	43.2	5.9	6.7	30.6	2.1	3.8	2.4	3.8	1.5
Power = 100	55.8	5.9	6.2	17.2	1.2	4.9	2.4	4.9	1.6
Power = 160	56	5.9	7	16.3	1.1	4.9	2.4	4.9	1.6
Wind speed = 5	55.2	5.6	5.6	19.2	0.7	4.8	2.5	4.8	1.6
Wind speed = 6	55.2	5.5	5.6	19.2	0.9	4.8	2.4	4.8	1.6

From table 5.9 it is seen that the contribution from the local wind turbine grid, LG, increases when the transmission length increases, which was expected. This is due to the fact that the number of wind turbines per radial increases when the transmission length increases, see figure 5.15. The increase of number of wind turbines gives that the conductor area must increase and therefore the cost of the cables in the local wind turbine grid increases.

In table 5.9 it is also seen that when the rated power of the wind park increases, the contribution from the local wind turbine grid increases. This is also due to the fact that the number of wind turbines per radial increases when the rated power of the wind park increases. The contribution from the transmission system decreases due to the decrease of the number of radials.

The variations in the energy production cost due to the average wind speed can be explained in the same way as for the small AC wind park.

5.7 Large DC Park

In this section the large DC wind park is studied in detail. As in the previous chapters, first some selections are made to limit the number of cases and then the energy production cost is discussed for the different configurations of the large DC wind park.

5.7.1 Configuration selections

In the same way as before some selections are made to limit the number of parameters. The DC transformer size and the converter station is chosen in the same way as for the small DC wind park i.e. the rated powers for the DC transformer and the converter station are equal to the rated power of the wind park. The number of wind turbines per radial for the large wind park with one DC transformer step can be calculated in the same way as for the small DC wind park and the result from this calculation can be approximated with the results from figure 5.15 if the transmission distance is put to zero. The selected number of wind turbines per radial and the number of radials for the large DC wind park with one DC transformer step is presented in table 5.10 for the different power levels. In table 5.10 the number of turbines per radial, the number of radials per cluster and the number of clusters in the large DC wind park with two DC transformer steps are also shown. The number of radials per cluster is the same as is used in [23] for this type of two step DC wind park.

Table 5.10: Number of wind turbines per radial (WT/Rad) and the numbers of radials (NRad) for the large DC wind park.

Power level	One step WT/Rad	NRad	Two steps WT/Rad	Rad/Cluster	Cluster
60MW	10	3	1	5	6
100MW	10	5	1	5	10
160MW	10	8	1	5	16
300MW	15	10	1	6	25

Due to the same reasons as for the AC/DC wind park, it was found that the transmission cable should be over-dimensioned. The over-dimension increased with increasing transmission voltage, increasing transmission length, increasing average wind speed and with decreasing rated power of the wind park. But as for the other types of wind parks the rating of the cable is set equal to the rating of the wind park.

5.7.2 Energy production cost for the different configurations of the large DC wind park

With these selections the energy production cost for the different configurations of the large DC wind park is calculated. In figure 5.17 the energy production cost of the 300MW large DC wind farm is shown for different voltage levels, wind turbine types and for an average wind speed of 10m/s. From figure 5.17 it is noticed that 150kV is the best voltage level to use and that the wind park configuration with only one DC transformer step is to prefer, for all power levels. The ideal voltage level for transmission is depending on the power level. For the 60MW wind park the 115kV is

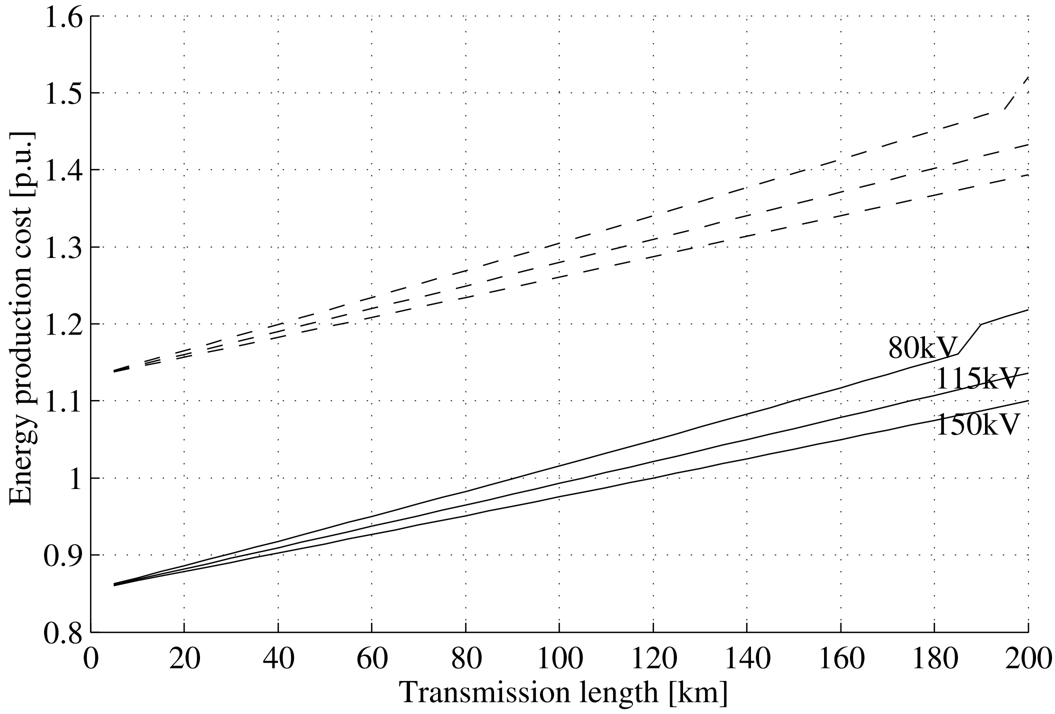

Figure 5.17: The normalized energy production cost for the different configurations of the large DC system. For a 300MW wind park, an average wind sped of 10m/s and for different transmissions lengths.

to prefer and for the 100MW wind park 115kV is to prefer up to a transmission length of 145km. For the 100MW wind park for transmission lengths above 145km and for the 160MW and 300MW wind park the 150kV transmission voltage is to prefer.

To make the discussion of the dependency of the energy production cost on different parameters more clear, one of the large DC wind park layouts has been selected as a reference and then one parameter at the time has been changed. Table 5.11 shows the selected reference wind park and the parameters that are varied.

Table 5.11: Reference wind park and the variations.

Parameter	Reference			
Transmission length	100km	30	100	175
Transmission voltage	150kV	80	115	150
Power level	300MW	100	160	300
Wind park type	One step	One step	Two step	
Average wind speed	10m/s	5	6	10

In figure 5.18 the components of the energy production cost are shown for the reference wind park. If this reference case is compered with the reference case for the large AC wind park, table 5.5, it can be noticed that the DC transmission system has a lower contribution to the energy production cost then the AC transmission system has. From figure 5.18 it can also be noticed that the converter station and the DC transformer has a significant contribution to the energy production cost. In table 5.12

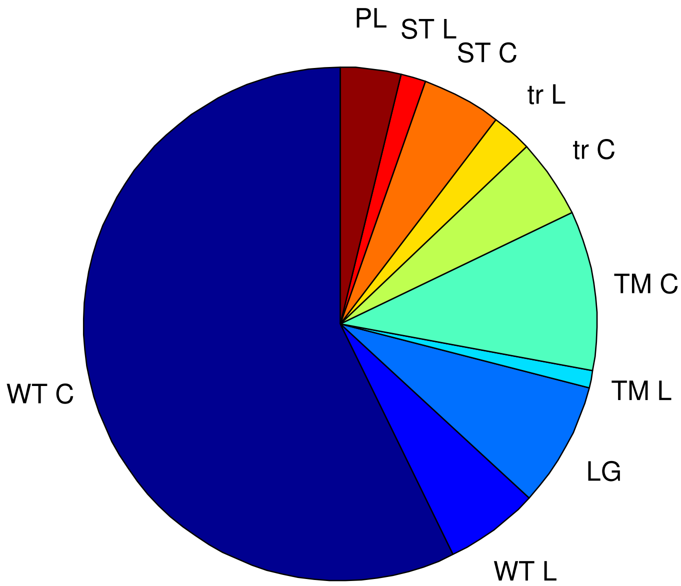

Figure 5.18: The energy production cost divided into components for the large DC wind farm for the reference case.

WT C	Investment cost of the wind turbine
WT L	Cost of the losses in the wind turbine
LG	Investment and loss cost of the local wind turbine grid
TM C	Investment cost of the transmission system
TM L	Cost of the losses in the transmission system
tr C	Investment cost of the DC transformer
tr L	Cost of the losses in the DC transformer
ST C	Investment cost of the converter station
ST L	Cost of the losses in the converter station
PL	Investment cost of the offshore platform

the different contributions to the energy production cost are shown for the different parameter variations from the reference case, se figure 5.18 for explanations for the abbreviations in the table. The different contributions are presented in % of the total energy production cost of that configuration.

The variations in the energy production cost due to the variations in transmission voltage, rated power of the wind park and in the average wind speed can be explained in the same way as for the AC/DC wind park.

One observation that can be made from table 5.12 is that the increase in the contribution from the transmission system is less compered to the large AC wind park. The increase can be explained in the same way as for the AC/DC wind park.

As already has been noticed, the system with two steps of DC transformers has a much higher energy production cost then the system with only one step. This is due to the reason that the contribution from the offshore platforms and DC transformers is higher for the two step, as could have been expected. The rest of the results shows

Table 5.12: Reference wind park and the variations.

Case type	WT C	WT L	LG	TM L	TM C	tr C	tr L	ST C	ST L	PL
Ref case	57.2	5.9	7.8	1.1	10	5	2.5	5	1.6	3.8
Length = 30	62.7	5.9	8.6	0.3	3.3	5.5	2.5	5.5	1.6	4.2
Length = 175	52.3	5.9	7.2	1.9	16.1	4.6	2.5	4.6	1.5	3.5
Voltage = 80	55	5.9	7.5	2	12.3	4.8	2.5	4.8	1.5	3.7
Voltage = 115	56.2	5.9	7.7	1.3	11.3	4.9	2.5	4.9	1.6	3.8
Power = 100	51.6	5.9	5.6	2.6	17.2	4.5	2.6	4.5	1.5	4
Power = 160	55.2	5.9	6.5	2	12.7	4.8	2.5	4.8	1.5	4
Two step	44.2	7.4	9.7	1	7.8	7.7	4.8	3.9	1.5	12.1
Wind speed = 5	57.8	5.5	7.8	0.6	10.1	5	2.6	5	1.6	3.9
Wind speed = 6	57.8	5.4	7.9	0.7	10.1	5	2.5	5	1.6	3.9

the same pattern as presented in previous sections.

5.8 DC Park with series connected wind turbines

In this section the energy production cost of the DC park with series connected wind turbines is studied in detail.

5.8.1 Configuration selections

For the series DC wind park the onshore converter station and the DC transmission cable is selected in the same way as for the large DC wind park i.e the converter station and the DC transmission cable has a rated power equal to the rated power of the wind park.

The ideal number of wind turbines per leg can not be calculated in the same way as for the ideal number of wind turbines per radial. This is due to the fact that in this work there is no difference in the prize of the DC/DC converters when the output voltage is changed. Therefore the efficiency of the wind turbine DC/DC converter is only studied. The efficiency will be dependent on the maximum allowed failure ratio, maximum number of non producing wind turbines divided with the number of producing wind turbines per leg, of the wind turbines in one leg. This is due to the fact that the producing wind turbines in a leg must compensate for the zero output voltage of the non producing wind turbines by increasing their output voltage. This means that the DC/DC converters in the wind turbines must be overrated in the output voltage and this gives a lower efficiency. This can be seen in figure 5.19 where the average efficiency of the wind turbine DC/DC converter is shown for different average wind speeds. In this work a maximum failure ratio of 13 to 20% is used.

In general, the cost of the DC/DC converter in the wind turbine should increase with an increasing rated output voltage. This gives that the number of wind turbines per leg should be as high as possible and the failure ratio as low as possible to keep the output voltage as low as possible. In table 5.13 the used number of wind turbines per leg and the number of legs for the different power levels are shown.

Table 5.13: Number of wind turbines per leg and the numbers of legs for the series DC wind park.

Power level	WT/leg	leg
60MW	30	1
100MW	25	2
160MW	20	4
300MW	30	5

5.8.2 Energy production cost for the different configurations of the series DC wind park

With these selections the energy production cost for the different configurations of the series DC wind park are calculated. In figure 5.20 the energy production cost of the 300MW series DC wind farm is shown for different voltage levels, maximum allowed number of non-working wind turbines and for an average wind speed of 10m/s. From figure 5.20 it can be noticed that the three voltage levels crosses each other. This

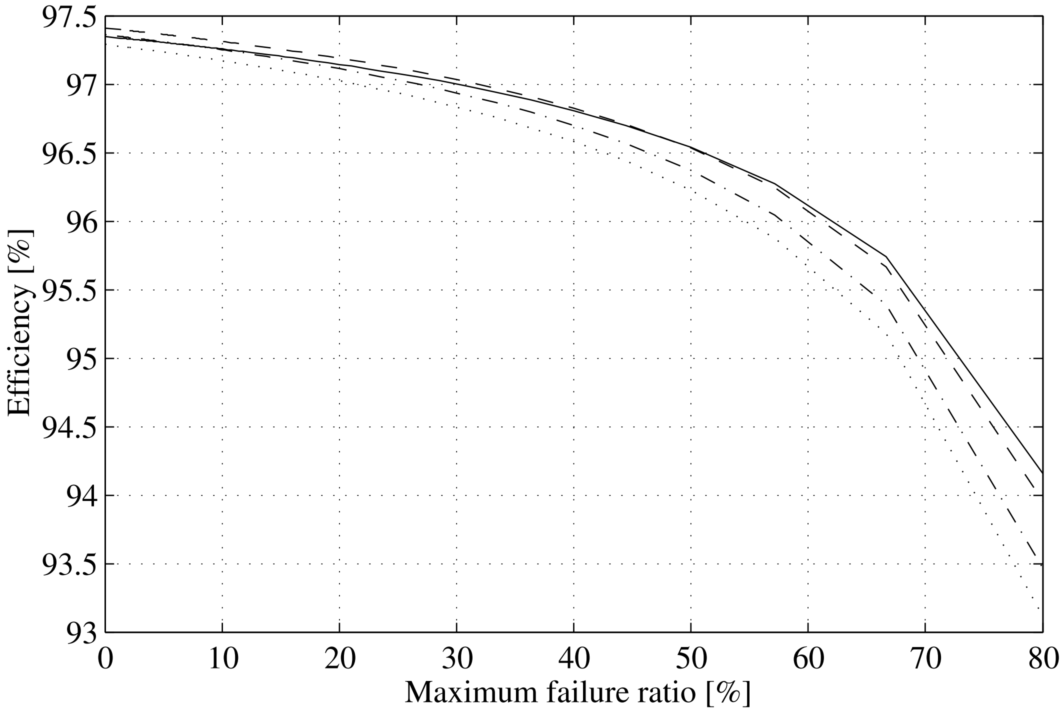

Figure 5.19: The efficiency of the wind turbine DC/DC converter as function of the maximum allowed failure ratio for different average wind speeds. Solid 5m/s, dashed 6m/s, dash-dotted 8m/s and dotted 10m/s.

means that the 80kV transmission is best for short transmission distances, the 150kV transmission voltage is best suitable for long transmission distances and the 115kV for distances in between. When the rated power of the wind park decrease, the crossover point increases. For example, for the 100MW wind park the 80kV is best up to 35km and the 150kV is best above 185km.

To make the discussion of the dependency of the energy production cost on different parameters more clear, one of the series DC wind park layouts has been selected as a reference and then one parameter at the time has been changed. Table 5.14 shows the selected reference wind park and the parameters that are varied.

Table 5.14: Reference series DC wind park and the variations.

Parameter	Reference			
Transmission length	100km	30	100	175
Transmission voltage	150kV	80	115	150
Power level	300MW	100	160	300
Max number of failed WT	4	4	8	
Average wind speed	10m/s	5	6	10

In figure 5.21 the components of the energy production cost are shown for the reference wind park. By comparing figure 5.21 and figure 5.18 it can be noticed that the series wind park has less components that contributes to the energy production cost then the large DC wind park has. Since the number of wind turbines is the same

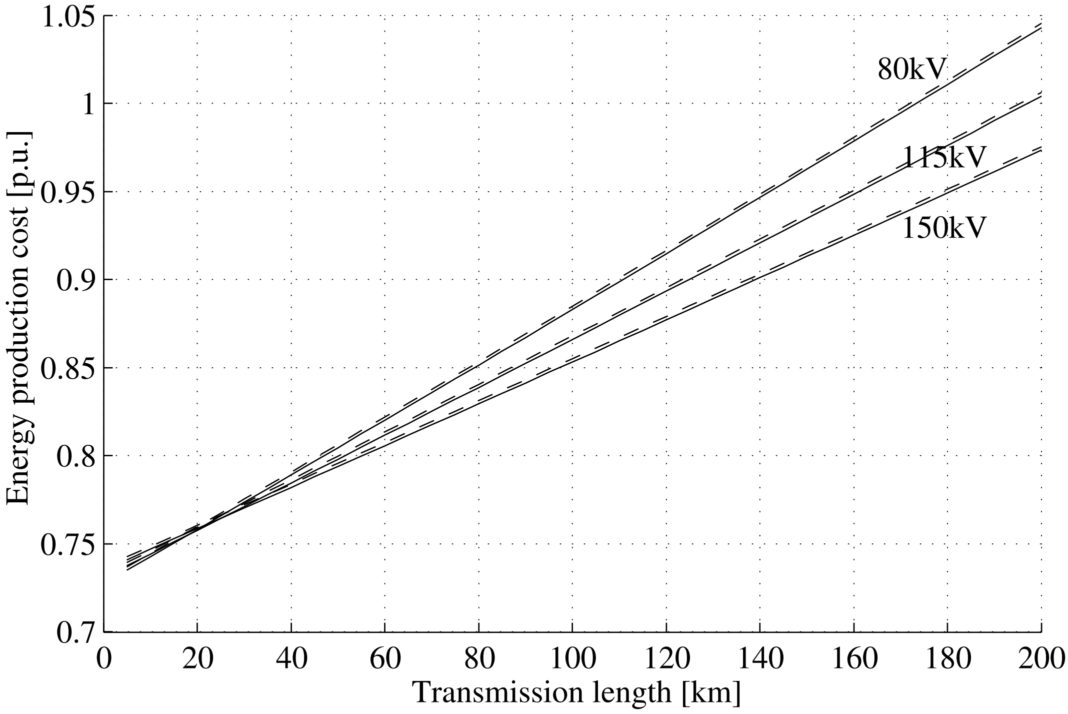

Figure 5.20: The normalized energy production cost for the different configurations of the series DC system. For a $300MW$ wind park, an average wind sped of $10m/s$ and for different transmissions lengths. Solid maximum 4 failed wind turbines per leg, dashed maximum 8 failed wind turbines per leg.

for both configurations and their cost is assumed to be the same it can be noticed that the energy production cost for the series DC wind park must be lower. This is based on the fact that the wind turbines contributes more to the energy production cost in the series wind park compered to the large DC wind park.

In table 5.15 the different contributions to the energy production cost are shown for the different parameter variations from the reference case, se figure 5.21 for explanations for the abbreviations in the table. The different contributions are presented in % of the total energy production cost of that configuration.

The same pattern as for the large DC wind park can be noticed also for the variations in the energy production cost due to variations in transmission length, transmission voltage, rated power of the wind park and in the average wind speed.

For the failure ratio it can be noticed from figure 5.20 that an increasing failure ratio increases the energy production cost. This is due to the fact that the losses in the wind turbine increases, see table 5.15. This increase is caused by the decrease in efficiency in the DC/DC converter as mention before.

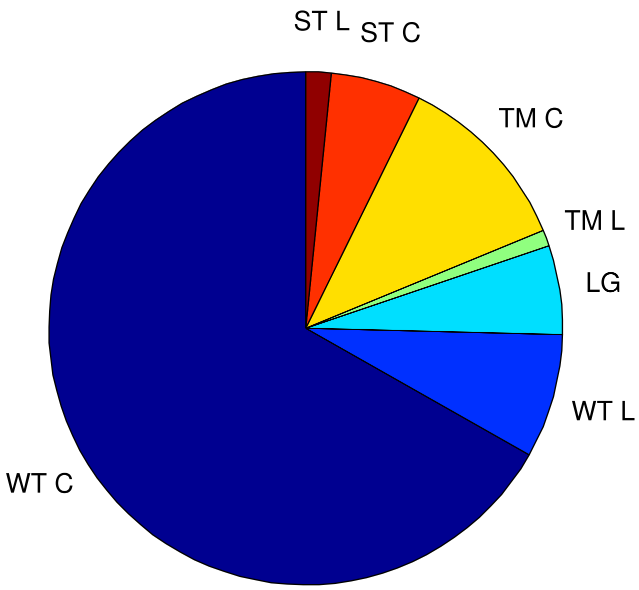

Figure 5.21: The energy production cost divided into components for the series DC wind farm for the reference case.

WT C	Investment cost of the wind turbine
WT L	Cost of the losses in the wind turbine
LG	Investment and loss cost of the local wind turbine grid
TM C	Investment cost of the transmission system
TM L	Cost of the losses in the transmission system
ST C	Investment cost of the converter station
ST L	Cost of the losses in the converter station

Table 5.15: Reference wind park and the variations.

Case type	WT C	WT L	LG	TM L	TM C	ST C	ST L
Ref case	66.8	7.8	5.6	1	11.5	5.7	1.6
Length = 30	74	7.8	6.2	0.3	3.8	6.3	1.6
Length = 175	60.4	7.8	5.1	1.8	18.2	5.2	1.6
Voltage = 80	63.8	7.8	5.4	1.8	14.1	5.5	1.6
Voltage = 115	65.4	7.8	5.5	1.2	12.9	5.6	1.6
Power = 100	59	7.8	4.9	2.3	19.3	5	1.5
Power = 160	63.6	7.9	5.3	1.9	14.3	5.4	1.6
Num fail = 8	66.6	8	5.6	1	11.5	5.7	1.6
Wind speed = 5	67.4	7.6	5.5	0.6	11.6	5.8	1.6
Wind speed = 6	67.4	7.4	5.6	0.7	11.6	5.8	1.6

Chapter 6

Controlling the series connected DC wind park

In this chapter the series DC wind park is described and analyzed more in detail, with the FBIB (Full Bridge Isolated Boost) converter used as wind turbine DC transformer. A control scheme for the DC/DC converter and the wind farm is derived and last in this chapter, start and stop, protections and fault handling are discussed.

6.1 System description in detail

6.1.1 Wind park

As described before, a number of wind turbines in the series connected wind park are connected in series to obtain the desired transmission voltage. One stack of series connected wind turbines are here called a leg in similarity to a phase leg in a converter. To obtain the desired power level of the wind park several legs can be connected in parallel. In figure 6.1 a general layout of a series connected wind park is shown. In this wind park n wind turbines are series connected to a leg and m legs are parallel connected. The number of turbines in each leg is based on the selection of the rated and peak voltage of each wind turbine. In chapter 5.8.1 this theme was discussed from an energy production point of view.

Due to the series connection, the control of the wind park is not trivial. Let us first study the following equations for the voltages in the wind park. These holds if the voltage drop in the cables is neglected

$$V_{WT,x,y} = \frac{P_{out,x,y}}{I_{L,y}} \tag{6.1}$$

$$V_{DC,y} = \sum_{x=1}^{n} V_{WT,x,y}. \tag{6.2}$$

Where:

$x = 1..n$	
$y = 1..m$	
$V_{WT,x,y}$	Voltage over wind turbine x,y [V]
$P_{out,x,y}$	Output power of wind turbine x,y [W]
$I_{L,y}$	Current in leg y [A]
$V_{DC,y}$	Voltage over leg y [V]

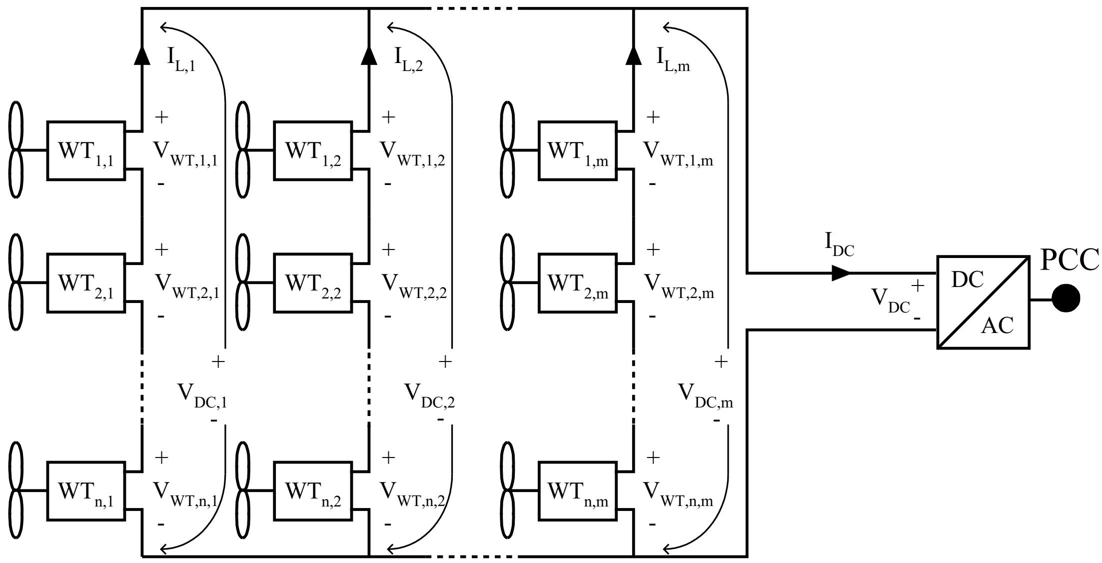

Figure 6.1: The layout of the series connected wind park.

As can be understand from the equations 6.1, 6.2 and by figure 6.1 the voltage over each wind turbine can not be controlled individually by the onshore converter station. The onshore converter station only controls the voltage over the legs by setting the current I_{DC}. The voltage over each wind turbine is thus depending on the output power from each wind turbine in the leg. This means that wind turbines that have a higher output power then the others in the same leg will have a higher output voltage and wind turbines that have lower output power then the others in the same leg have a lower output voltage. This is due to that the output current is the same for all wind turbines in a leg. The current in a leg can be described as

$$I_{L,y} = \frac{P_{out,y}}{V_{DC,y}} \tag{6.3}$$

$$P_{out,y} = \sum_{x=1}^{n} P_{out,x,y}. \tag{6.4}$$

From this equation it can be observed that the current in a leg is fairly independent on the output power from one turbine, if the number of turbines in a leg is large. The leg current is completely dependent on the total power production of the wind turbines in the leg. It shall be remembered that the voltage over the legs are controlled by the onshore converter station.

From equation 6.2 it can also be understand that if a wind turbine fails or stops, which means that the output voltage drops to zero, the other wind turbines in the leg must increase there output voltage to compensate for the failed one, in order to be able to continue their power production. This gives that some overrating of the output voltage must be done in order to prevent that the power production is lost if one or a few wind turbine stop to produce power.

6.1.2 Wind turbine system

The controllers for the wind turbine can be divided into several modules as shown in figure 6.2. The controllers are: optimum power tracker, speed controller, current controller and output voltage controller. The optimum power tracker tries to get the

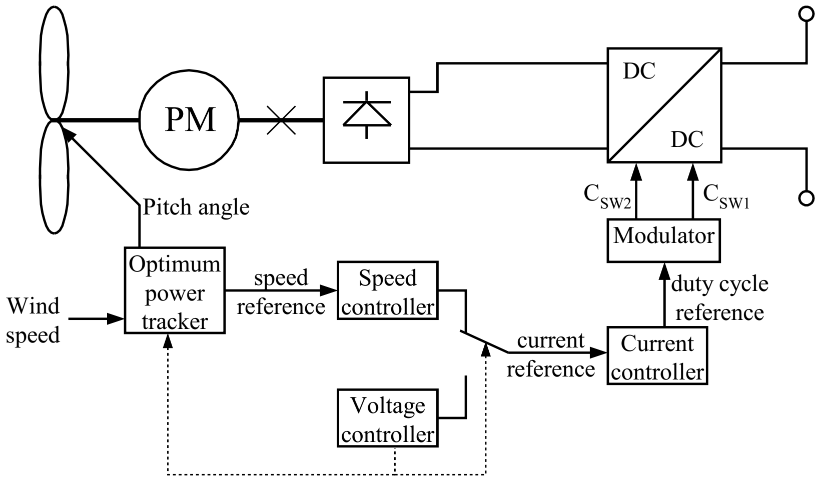

Figure 6.2: The layout of the control system for the series connected wind turbine.

most energy out of the wind. This is achieved by operating the turbine at the best efficiency (best pitch angle and rotational speed for the given wind speed situation). The speed controller controls the rotational speed of the generator by increasing or decreasing the current reference to the current regulator. This is possible since the DC-current from the rectifier is approximatively proportional to the breaking torque of the generator [10]. The current regulator fulfills the current demand from the speed controller by generating the duty cycle reference to the modulator. From the duty cycle reference, the modulator generates the on and off control signals to the valves.

The output voltage regulator is only used when the output voltage exceeds the rated voltage of the converter or when the output voltage gets near the lower limit of the converter. The output voltage controller is accordingly used as a limiter only. As can be seen in figure 6.2 the output voltage controller can take over the input to the current controller from the speed controller, which occurs when the output voltage is outside the limits. This leads, of course, to that when the output voltage regulator is used, the commands from the ordinary optimum power tracker function is no longer followed by the current controller.

6.1.3 Full bridge isolated boost converter

As mention before, the highest output voltage from the wind turbine is limited by the rating of the FBIB (Full Bridge Isolated Boost) converter. The lowest output voltage from the converter is also limited by the input voltage to the converter and by the winding ratio of the transformer [20]. The upper limit for the voltage is desired to be as low as possible to keep the cost down. However, this would lead to a situation where the output voltage controllers of the wind turbines would go into operation often and then reduce the output power of the turbines and accordingly, a lot of energy would be lost. So, due to the fact that it is not desired to lose too much production in one leg due to that one or a few turbines fails or operates at very low or no power, some overrating must be done.

Below an calculation example of the rating of the FBIB converter is presented. The calculations are based on the 160MW series connected wind park in chapter 5.8 with 2MW wind turbines equipped with a permanently magnetized generator connected to a diode rectifier.

$$V_{out,nom} = \frac{V_{DC}}{n} = \frac{300 \cdot 10^3}{20} = 15 \cdot 10^3 [\mathrm{V}] \tag{6.5}$$

$$V_{out,max} = 1.05 \frac{n}{n - N_{fail,WT}} = 1.05 \frac{20}{20-4} = 1.31 [\mathrm{p.u.}] \tag{6.6}$$

Where:

$V_{out,nom}$	Nominal output voltage [V]
V_{DC}	Transmission voltage, pole to pole [V]
n	Number of wind turbines in one leg
$V_{out,max}$	Rated output voltage in p.u. of the nominal
$N_{fail,WT}$	Maximum allowed number of non producing wind turbines
1.05	Factor for variations in the DC voltage

As mentioned above, the lower limit is dependent on the input voltage and the winding ratio of the transformer. Lower winding ratio of the transformer gives a generally lower voltage ratio between the input voltage and the output voltage. But the winding ratio of the transformer can not be too low due to the obvious reason that we want to have a voltage increase. This converter has the possibility to "boost" the voltage regardless of the winding ratio of the transformer, however the boost capability is limited due to losses in the converter. The boost capability of the full bridge isolated boost converter is in this work assumed to be 10. This means that the maximum output voltage is the input voltage multiplied with 10 multiplied with the winding ratio of the transformer. The following equations shows the limits for the winding ratio of the transformer

$$N_{tr} = \frac{V_{out,nom}}{V_{in,nom}} \frac{V_{out,min}}{V_{in,max}} \tag{6.7}$$

$$V_{out,nom} V_{out,max} = 10 N_{tr} V_{in,nom} V_{in,min}. \tag{6.8}$$

Where:

N_{tr}	Winding ratio of the transformer
$V_{in,nom}$	Nominal input voltage [V]
$V_{out,min}$	Lowest output voltage in p.u. of the nominal
$V_{in,max}$	Highest input voltage in p.u. of the nominal
$V_{in,min}$	Lowest input voltage in p.u. of the nominal

These two equations can be combined to the following equation which describe the lowest output voltage of the wind turbine.

$$V_{out,min} = \frac{V_{in,max}}{V_{in,min}} \frac{V_{out,max}}{10} = \frac{1.22}{0.61} \frac{1.31}{10} = 0.26 \tag{6.9}$$

It shall be noticed that the calculations for the lower limit is based on the worst case scenario.

If instead an electrically magnetized generator is used, the field current can be used to control the input voltage to the converter and thereby increase the span of the output voltage. For example, if the lower output voltage limit is reached, the field current can be reduced and thereby the input voltage to the converter is reduced which gives that a lower output voltage can be obtained and, accordingly, the turbine can be kept on-line for a longer time.

6.2 Controllers for the FBIB converter

In this section the input current controller and the output voltage controller of the FBIB converter are derived.

6.2.1 Input current regulator of the FBIB converter

In figure 6.3 the scheme of the full bridge isolated boost converter that is used for the derivation of the input (inductor) current regulator is shown. As can be seen from

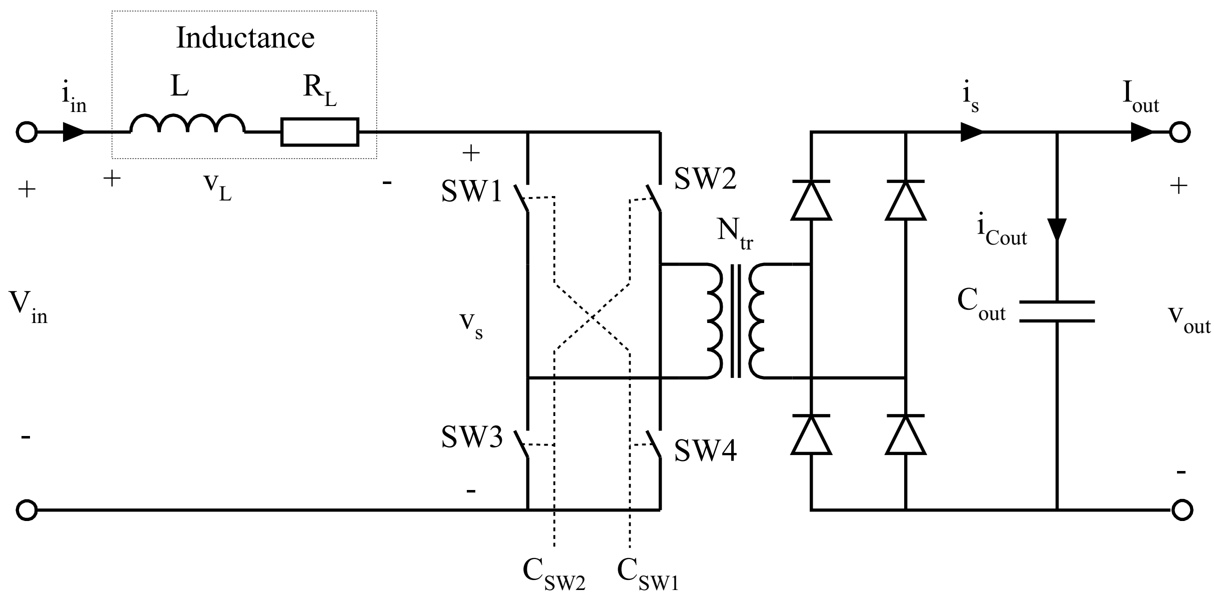

Figure 6.3: The scheme of the full bridge isolated boost converter that is used for derivation of the current controller.

figure 6.3 all components except for the inductor are ideal. The inductor is represented by an ideal inductor in series with a resistance. The differential equation for this RL-circuit can be expressed as

$$L\frac{\mathrm{d}i_{in}}{\mathrm{d}t} = v_L - R_L i_{in}. \tag{6.10}$$

Where:

L	Inductance of the inductor [H]
i_{in}	Inductor current [A]
v_L	Voltage over the non ideal inductor [V]
R_L	Resistance of the inductor [Ω]

The current in this RL-circuit can be sufficiently controlled by a simple proportional integral (PI) controller [13]:

$$F_e(s) = k_p + \frac{k_i}{s}. \tag{6.11}$$

The control parameters can be selected with internal mode control design to [13]

$$k_p = \alpha_e \hat{L} \tag{6.12}$$
$$k_i = \alpha_e \hat{R}_L. \tag{6.13}$$

Where:
α_e The closed-loop (from $i_{in,ref}$ to i_{in}) system bandwidth [rad/s]
$\hat{L}$ Estimate of the inductance value [H]
$\hat{R}_L$ Estimate of the inductor resistance [Ω]

The current controller (equation 6.11) has the reference input current as input and the reference inductor voltage, v_L, as output. But the only two input control signals to the converter are the on/off signals for the switches (C_{SW1} and C_{SW2}). So, additional equations are needed in order to recalculate the reference value of the inductor voltage to the on and off times of the switches (the duty cycle). The inductor voltage can be expressed as

$$v_L = V_{in} - v_s.$$

Where v_s is the average voltage over one switching period, which gives:

$$v_s = 0 \cdot 2D + \frac{v_{out}}{N_{tr}} 2D'.$$

For CCM (continuous current mode) $2D + 2D' = 1$ [20]. By using this information and the above equations, the control law for the input current can be recalculated to have the duty cycle as output. The control law can be written in the time domain as:

$$e = i_{in,ref} - \tilde{i}_{in} \tag{6.14}$$
$$\frac{\mathrm{d}I}{\mathrm{d}t} = e \tag{6.15}$$
$$B = \frac{1}{2} - \frac{\tilde{V}_{in}\tilde{N}_{tr}}{2\tilde{V}_{out}} + [k_p e + k_i I]\frac{\tilde{N}_{tr}}{2\tilde{V}_{out}} \tag{6.16}$$
$$D = s(B) \tag{6.17}$$
$$s(x) = \begin{cases} 0.5 & x > 0.5 \\ x & 0 \le x \le 0.5 \\ 0 & x < 0. \end{cases} \tag{6.18}$$

Where:
e Controller error
I Integral state
B Unlimited duty cycle
D Duty cycle
$\tilde{X}$ Denotes estimate of the quantity X

As can be seen from the equations above, estimates (measurements) of the input and output voltages are needed for this regulator.

Due to the limiter ($s(x)$) in the current controller, the integrator can in some cases cause overshoots due to integrator windup. To prevent integrator windup, the error used to update the integral state is "back-calculated". The "back-calculated" error $\bar{e}$ must fullfill [13]

$$D = \frac{1}{2} - \frac{\tilde{V}_{in}\tilde{N}_{tr}}{2\tilde{V}_{out}} + [k_p\bar{e} + k_i I]\frac{\tilde{N}_{tr}}{2\tilde{V}_{out}}. \tag{6.19}$$

By combining equation 6.16 and equation 6.19 the following relation can be obtained:

$$\bar{e} = e + \frac{2\tilde{V}_{out}}{\tilde{N}_{tr}k_p}(D - B) \tag{6.20}$$

which is used to update the integral state in the controller. This gives the following control law, which is used in the simulations in this chapter

$$e = i_{in,ref} - \tilde{i}_{in} \tag{6.21}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = e + \frac{2\tilde{V}_{out}}{\tilde{N}_{tr}k_p}(D - B) \tag{6.22}$$

$$B = \frac{1}{2} - \frac{\tilde{V}_{in}\tilde{N}_{tr}}{2\tilde{V}_{out}} + [k_p e + k_i I]\frac{\tilde{N}_{tr}}{2\tilde{V}_{out}} \tag{6.23}$$

$$D = s(B) \tag{6.24}$$

To obtain the on and off times for the switches, triangle modulation is used. This means that the duty cycle from the current regulator output is compered with a triangle wave. If the duty cycle is less then the triangle wave then switch 2 and 3 are on, otherwise they are off, and if the negative duty cycle is greater then the triangle wave then switch 1 and 4 are on, otherwise they are off. This is shown in figure 6.4. In figure 6.4 the ideal wave forms of the input current and the output voltage are also shown. By using this, so called symmetrical suboscillation method, an advantage is gained, i.e that as the triangle wave reaches it bottom and peak value, the input current and the output voltage pass there average values [13]. This technique for obtaining the on and off times for the switches and to obtain the average input current and output voltage are used in the simulations presented in this chapter.

For all simulations in this chapter the switching frequency is 1kHz. From figure 6.4 it can be noticed that two samples are taken per switching period. This gives that the sampling frequency in this chapter is 2kHz and accordingly [13], the closed-loop bandwidth for the current regulator can be chosen to maximum 1257rad/s but in this chapter the closed-loop bandwidth is set to 1000rad/s.

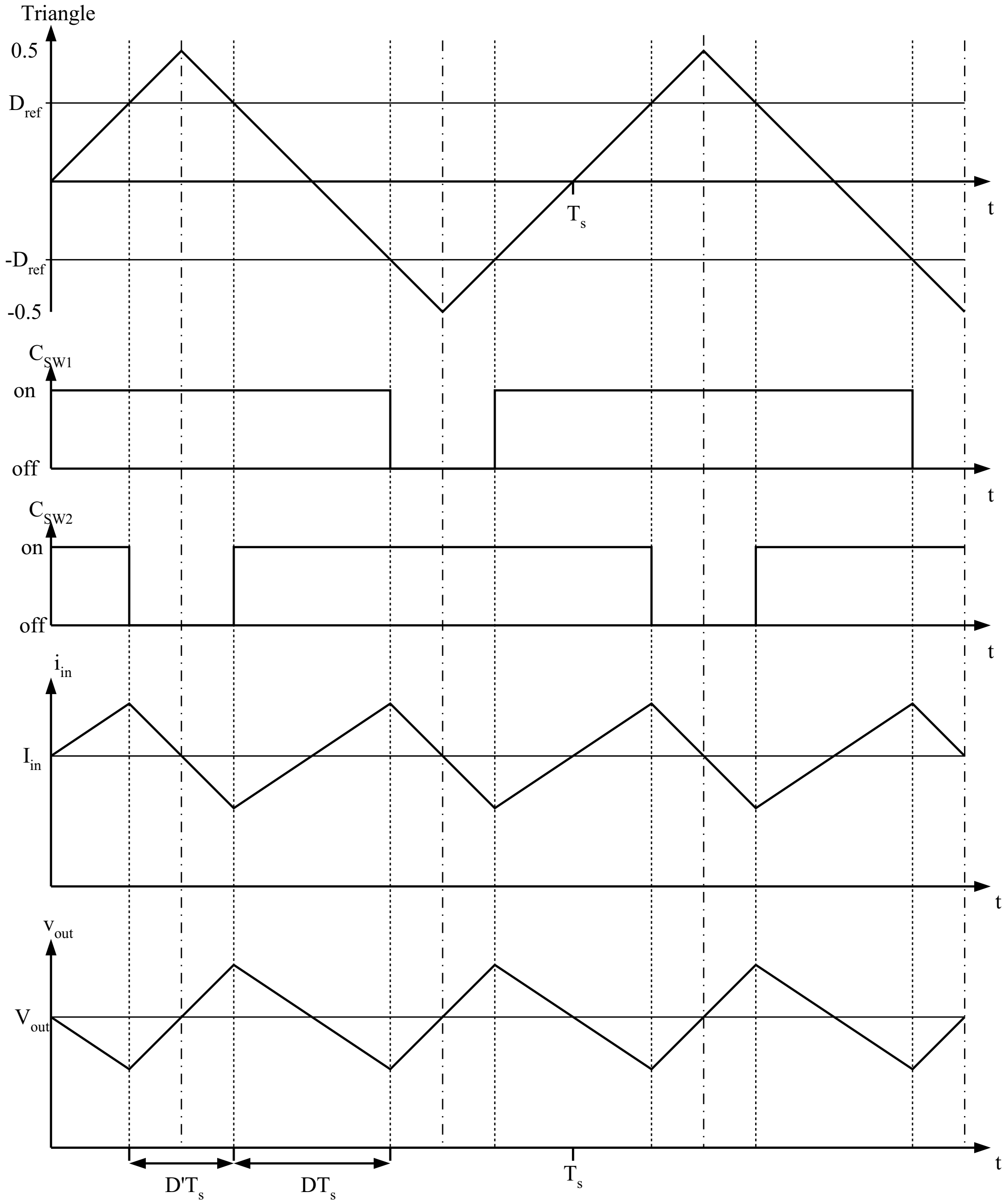

Figure 6.4: Triangle modulation to obtain the on and off times for the switches, and corresponding current and voltage waveforms.

6.2.2 Output voltage regulator of the FBIB converter

As discussed before, the current regulator usually obtain the reference value from the speed controller. The speed reference value is set by the present wind speed. Therefore there is no guarantee whatsoever that the output voltage stays within the limits of the full bridge isolated boost converter. Due to this fact an output voltage regulator that goes into action when the output voltage exceeds the limits is suggested in this work. As shown in figure 6.2 this regulator takes over the input current reference to the current regulator when the output voltage exceeds the limits and holds the output voltage fixed at the output voltage reference value.

The control law for the output voltage regulator is obtained by looking on the change of energy in the full bridge isolated converter. By assuming a lossless converter and that the energy stored in the transformer does not change, the following expression for the change of energy can be derived

$$\frac{1}{2}C_{out}\frac{\mathrm{d}v_{out}^2}{\mathrm{d}t} = V_{in}i_{in} - v_{out}I_{out} - \frac{1}{2}L\frac{\mathrm{d}i_{in}^2}{\mathrm{d}t}. \tag{6.25}$$

Which can be rewritten to

$$C_{out}v_{out}\frac{\mathrm{d}v_{out}}{\mathrm{d}t} = V_{in}i_{in} - v_{out}I_{out} - Li_{in}\frac{\mathrm{d}i_{in}}{\mathrm{d}t}. \tag{6.26}$$

Since the output voltage regulator is an outer loop seen from the input current regulator this regulator must be approximately 10 times slower then the input current regulator. This is due to the fact that the current dynamics are neglected when the output voltage controller is designed [29]. This means that the change (derivative) of the input current is neglected. The system then becomes

$$C_{out}\frac{\mathrm{d}v_{out}}{\mathrm{d}t} = \frac{V_{in}}{v_{out}}i_{in} - I_{out} = i_C. \tag{6.27}$$

For this system a proportional (P) regulator can be designed with IMC to

$$\begin{aligned} K_{pV} &= \alpha_{eV}\hat{C}_{out} && (6.28)\\ i_C &= K_{pV}(V_{out,ref} - \tilde{v}_{out}) \Rightarrow \\ i_{in} &= \frac{\tilde{v}_{out}}{\tilde{V}_{in}}(\tilde{I}_{out} + K_{pV}(V_{out,ref} - \tilde{v}_{out})). && (6.29)\end{aligned}$$

Where:

K_{pV}	Controller parameter
α_{eV}	The closed-loop (from $V_{out,ref}$ to v_{out}) system bandwidth [rad/s]
$\hat{C}_{out}$	Estimate of the output capacitor [F]
$V_{out,ref}$	Reference value of the output voltage [V]
$\tilde{v}_{out}$	Estimate (measured) of the output voltage [V]
$\tilde{I}_{out}$	Estimate (measured) of the output current [A]
$\tilde{V}_{in}$	Estimate (measured) of the input voltage [V]

The controller in equation 6.29 is used to control the output voltage when it reaches the over- or under-voltage limit. If the overvoltage limit is reached, then the output voltage controller holds the output voltage to a few percent below the rated output voltage. The output voltage regulator is used until the current reference from the speed regulator is less then the current reference from the output voltage regulator. This is done in order to prevent that the output voltage increases immediately after the switch over. As can be noticed from equation 6.27, if $\frac{V_{in}}{v_{out}}i_{in}$ is less then I_{out} then the output voltage will decrease. If the undervoltage limit is reached, the output voltage controller holds the output voltage to a few percent over the minimum output voltage, until the wind turbine stops. If the energy returns (the wind speed increases) before the turbine stops, the output voltage regulator is used until the current reference from the speed regulator is greater then the current reference from the output voltage regulator. This is done to prevent the output voltage from decreasing immediately after the switch over. If the wind does not return quickly, the turbine must however be shut down due to lack of incoming energy.

6.3 Simulations

In this section the performance of the series connected wind turbine is evaluated by simulations made in EMTDC©. In appendix B a printout over the full bridge isolated boost converter implemented in EMTDC© is shown and also the fortran code for the input current and output voltage regulator that are used for the simulations in this work.

6.3.1 One wind turbine in normal operation

In this section the performance of the current regulator for the full bridge isolated boost converter is evaluated. The test scheme for this evaluation is shown in figure 6.5. For

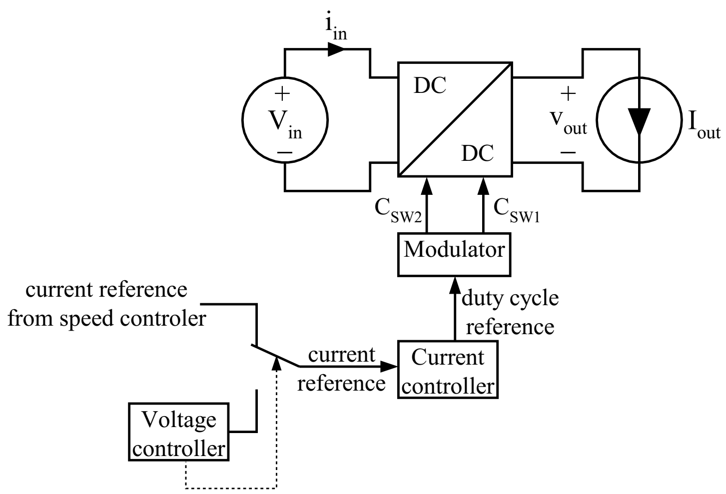

Figure 6.5: The test scheme for evaluation of the performance of one full bridge isolated boost converter.

the sake of simplicity, the input to the converter is connected to an ideal voltage source and the output is connected to an ideal current source. The usage of the current source is quite natural because as shown before, the output current for the series connected wind turbines is only dependent on the total output power from all wind turbines in the leg. Therefore the output current will be quite independent of the output power from one wind turbine in the leg.

In figure 6.6 the current response to steps in the reference current is demonstrated. In the figure the input current, top plot, and output voltage, bottom plot, are shown when the input voltage and the output current are constant. As mention before, the

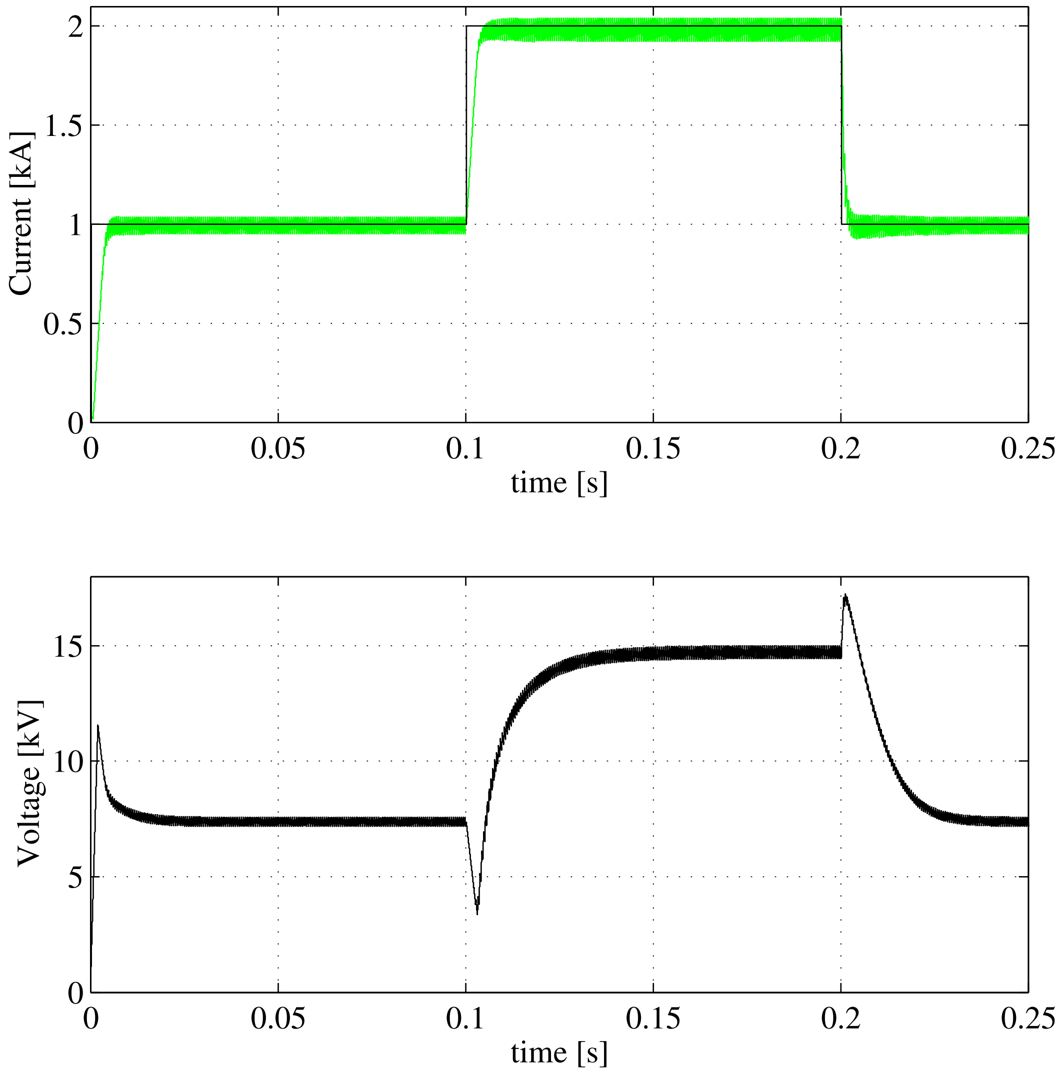

Figure 6.6: In the top plot the input current reference, black line, and the input current, grey line, are shown. In the bottom plot the output voltage is shown.

full bridge isolated converter can not operate when the output voltage is to low. Due to this fact, the current source connecter to the output is used to charge the output capacitor in the beginning of the simulation. This is the reason for the fast increase of the output voltage in the beginning of the simulation. After this charge pulse, the current source takes a constant positive current from the converter. As can be seen from figure 6.6 the current regulator performs excellently, there are no overshoots and no remaining error.

The initial decrease in the output voltage when the input current increases can be explained from equation 6.26. When the input current increases, from steady state, initially the input current and the output voltage are approximately the same, but the derivative of the input current is positive which gives that the derivative of the output voltage becomes negative. Due to this fact, the output voltage decrease initially when the input current increases. Another way to explain it is: When the current increases in an inductor, the stored energy in it increases. Therefore, in order to increase the inductor current quickly, all the input energy is used to increase the energy in the inductor and therefore the capacitor has to deliver all energy to the output. When the output capacitor delivers energy to the output it discharges and the output voltage decreases. The opposite happens when the input current decrease.

6.3.2 One wind turbine hitting the output voltage limit

In figure 6.6 the output voltage was within the allowed limits for the output voltage during the whole simulation. In figure 6.8 the results from a simulation when the output voltage regulator goes into action are shown. The nominal voltage is 11kV for this simulation and the maximum is 18kV and the minimum is 4kV. These selections was made in order to clearly demonstrate the effects of the limitations. The setup for this simulation is the following. For the investigated wind turbine, the input voltage to the FBIB converter and the input current reference from the speed regulator is kept constant. This means that the incoming wind power, which is the power the wind turbine wants to deliver to the grid, is constant, see figure 6.7. For the other turbines

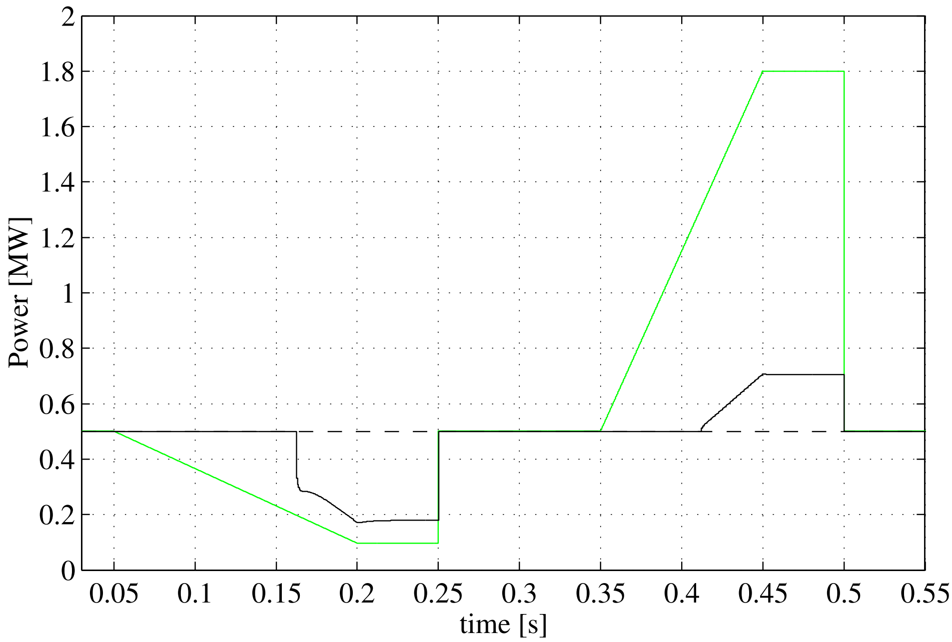

Figure 6.7: The grey line shows the average power production of the wind turbines in the leg, the black solid line shows the actual output power of the investigated wind turbine and the black dashed line shows the desired turbine output power.

in the same leg as the investigated one, they first slowly looses power, which means that the total power production in the leg decreases, as can be noticed in figure 6.7. This leads to that the grid inverter reduces the total current demand in order to keep the DC-voltage constant, see the top plot in figure 6.8. Between 0.2s and 0.25s a new steady-state situation is reached. At 0.25s the other turbines experience a rapid increase in the wind speed to the same value as in the beginning of the simulation, leading to that the grid converter increases the total current demand rapidly to 0.047kA again. At 0.35s the opposite happens, then the other wind turbines experience a "slow" increase of the wind speed, which of course leads to an increased average power production in the leg and an increased current. Between 0.45s and 0.5s a new steady state is reached, followed by a rapid decrease at 0.5s in the wind speed, to the initial value.

As can be seen from the middle plot of figure 6.8 the output voltage increases in the time interval 0.05s to 0.16s, when the output current decreases due to that the other wind turbines in the leg looses power. This is quite natural due to the fact that the output power is constant, see figure 6.7 and therefore, in order to maintain the output power, the output voltage has to increase when the output current decreases. Observe that input current and voltage means current and voltage on the wind turbine side of the DC/DC converter, while output current and voltage means the leg current and the output voltage of the wind turbine.

From the middle plot of figure 6.8 it can be noticed that at 0.16s the output voltage regulator goes into action, due to overvoltage (the 18kV limit is reached). From the bottom plot it is observed that the output voltage regulator decreases the input current reference (black solid line) and the input current follows (grey), it can also be observed that the current reference from the speed regulator is constant (black dashed line). It can be seen that the output voltage regulator performers quite good, there is some remaining error and the overshoot at 0.16s in the output voltage is due to the phenomena discussed previously (discharging of the inductor). It shall be noticed that when the output voltage regulator goes into action due to overvoltage, it limits the output power, as can be noticed in figure 6.7. This means that the blades has to be pitched in order to reduce the input power to the turbine in order to prevent overspeed of the rotor.

When the output current increases rapidly at 0.25s the output voltage also decreases rapidly, due to the power balance. From the middle plot of figure 6.8 it can be seen that the output voltage regulator is disconnected immediately when this happens, the output voltage reference disappears (black line). This is due to, as mention before, that the current reference from the output voltage regulator gets greater then the reference from the wind turbine speed regulator. When the output voltage regulator is disconnected the current reference is taken from the speed regulator and the wind turbine is back to normal operation again.

At 0.35s when the output current starts to slowly increase, it can be noticed that the output voltage starts to slowly decrease, due to the constant output power. At approximately 0.41s the output voltage regulator goes into action due to undervoltage, middle plot of figure 6.8. From the bottom plot it is observed that the output voltage regulator increases the input current reference (black solid line) and the input current follows (grey). It can be seen that the output voltage regulator perform quite good, even though there is some remaining error. It shall be noticed that when the output voltage regulator goes into action due to undervoltage, it increases the output power, as can be noticed in figure 6.7. This will most certainly lead to that the rotational speed of the turbine starts to decrease, due to lack of power. This lack of power is due to that the power tracker always tries to gain the most power from the wind, unless

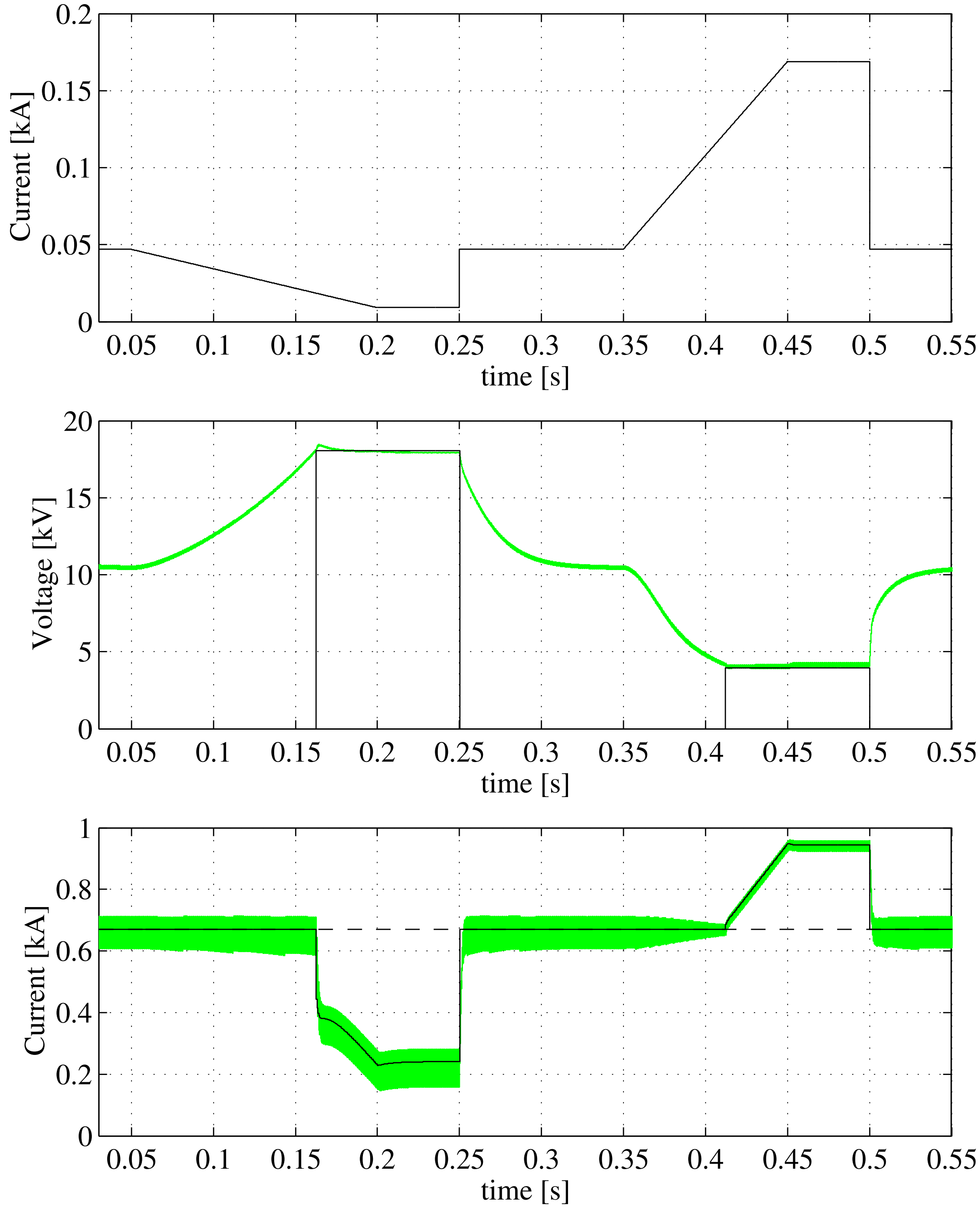

Figure 6.8: The currents and voltages of the investigated wind turbine. In the top plot the output current is shown. In the middle plot the output voltage (grey line) and the output voltage reference (black line) when the output voltage regulator is active are shown. In the bottom plot the input current reference (black solid line), the input current (grey line) and the input current reference from the speed regulator (black dashed line) are shown.

rated power is produced, then the output power is limited by the rating. So this means that there is no extra power available when the output voltage regulator increases the input current. The benefit from this decrease of the rotational speed is that the input voltage decreases, which leads to that a lower output voltage can be allowed. The drawback is that when the rotational speed decreases, the turbine will not operate at the optimum tip-speed ratio and this leads to that the converted power from the wind decreases.

At 0.5s when the output current decreases rapidly due to the decrease of power from the other wind turbines in the leg, and the output voltage regulator is again disconnected and the wind turbine is back to normal operation.

6.3.3 Three wind turbines

In this section, the performance of a small wind park consisting of three series connected wind turbines is evaluated. This low number of wind turbines is chosen to make the result analysis clearer, but the results should be representative also for a larger park. The test scheme for this evaluation is shown in figure 6.9. As can be noticed

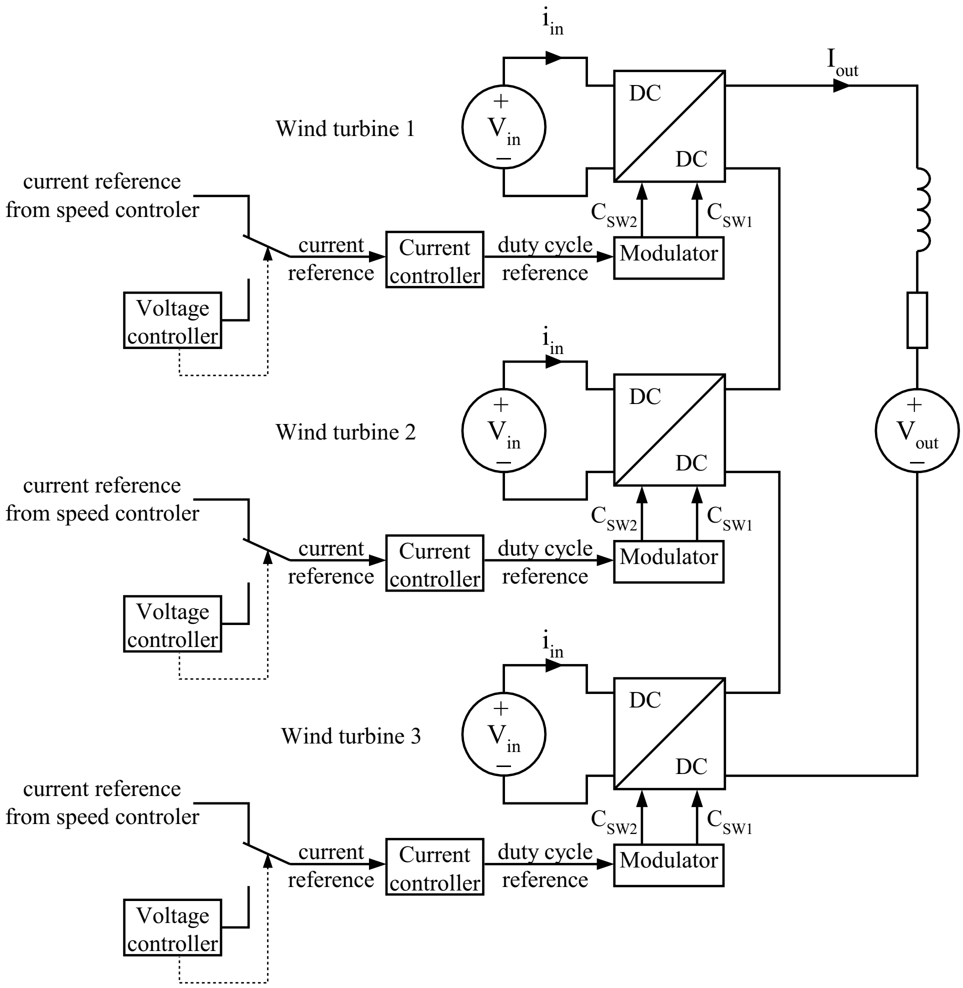

Figure 6.9: The test scheme for evaluation of the performance of three series connected full bridge isolated boost converter.

from figure 6.9 the output of the three series connected converters are connected to a transmission wire and a ideal voltage source. Otherwise the circuit are the same as for the case with one converter previously.

The setup for this simulation is the following. The nominal voltage is 11kV, the maximum is 18kV and the minimum is 4kV, same as in chapter 6.3.2. The wind speeds to the three wind turbines are varied individually in order to study the behavior of the series connection. The used variations are unrealistic, as shall be noticed later on, they are only used to really test the performance of the wind turbines. At the beginning the three wind turbines are operating in steady state, experiencing the same wind speed, as can be seen in figure 6.10. Then at 0.1s the wind speed increases for the first turbine which leads to an increased input power for the DC/DC converter of turbine 1 and

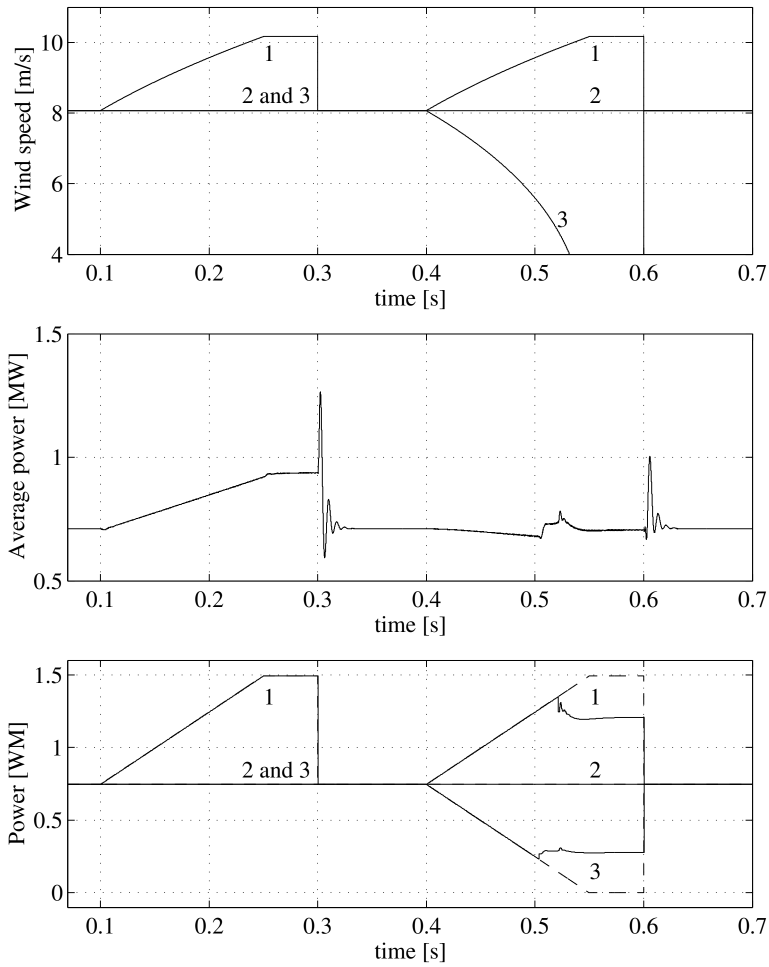

Figure 6.10: The input to the simulations of the three series connected converters, the different inputs to the three wind turbines are numerated 1 to 3. In the top plot the wind speeds for the wind turbines are shown. In the middle plot the average output power and in the bottom plot the optimal turbine power (black dashed lines), actual turbine power (solid black line) are shown.

also for the whole leg, bottom plot of figure 6.10. At 0.25s to 0.3s a new steady-state is reached, where all turbines still operate at their optimal points. At 0.3s the wind speed drops to the value before the increase and still all turbines are operating at maximum efficiency. Then at 0.4s the first wind turbine experience an increased wind speed and the third wind turbine experiences a decreased wind speed, which leads to an increased and decreased current reference. And finally at 0.6s the wind speeds for the wind turbines 1 and 3 returns rapidly to the steady-state values they had before, at 0.35s.

In figure 6.11 the results from this simulation are shown. As can be seen at 0.1s in figure 6.11 when the first converter starts to increase the input current, due to the increased wind speed, the output voltage of the first converter increases and the output voltage of the other decreases. This is due to the fact that the power production increases for the first converter and the power production are constant for the two other. This leads to a total increasing power production of the leg, which results in an increasing output current, see equation 6.3 and the top plot in figure 6.11. Since the power production of the two other wind turbines are constant, this increasing current must lead to a decreasing output voltage for the other two turbines. From the top plot it is seen that the output current increases quite much in opposite to what has been said earlier. This large increase is due to that it is only three wind turbines that are series connected, if it would have been more wind turbines in series, then the increase would have been more moderate. At 0.25s to 0.3s a new steady-state is reached for the wind park.

At 0.3s the wind speed for the first wind turbine drops back to the value it had before the increase and the three wind turbines returns to the same steady-state power production as they had before the increase. It shall be noticed that the changes in wind speeds up to the time 0.4s, did not cause the output voltage regulators in the wind turbines to go into action.

At the time 0.4s, the third converter starts to decreasing the input current and the first starts to increasing the input current, due to a decreasing and increasing wind speed, for the different wind turbines. After a time this leads to, as can be seen in the middle plot in figure 6.11, that the output voltage regulator goes into action for undervoltage for converter 3 and overvoltage for converter 1. Worth noting is that the voltage for converter 3 stabilizes at the lower limit (solid line) and the voltage for converter 1 stabilizes at the higher limit, as they should. The overshoot and undershoot in the output voltage for converter 1 and 3 comes from the discharging and charging of the inductor as mention before.

From figure 6.11 it can be noticed that at 0.6s the wind speed for wind turbine 1 drops to the value it had before the increase and the wind speed for the third wind turbine jumps up to the value it had before the decrease. This leads to that the output voltage regulators for wind turbines 1 and 3 are disconnected and all three wind turbines are back in normal operation and returns to the same steady-state point as in the beginning of this simulation.

The oscillations in the output current at 0.3s and 0.6s comes from that the inductance in the line swings together with the FBIB converters.

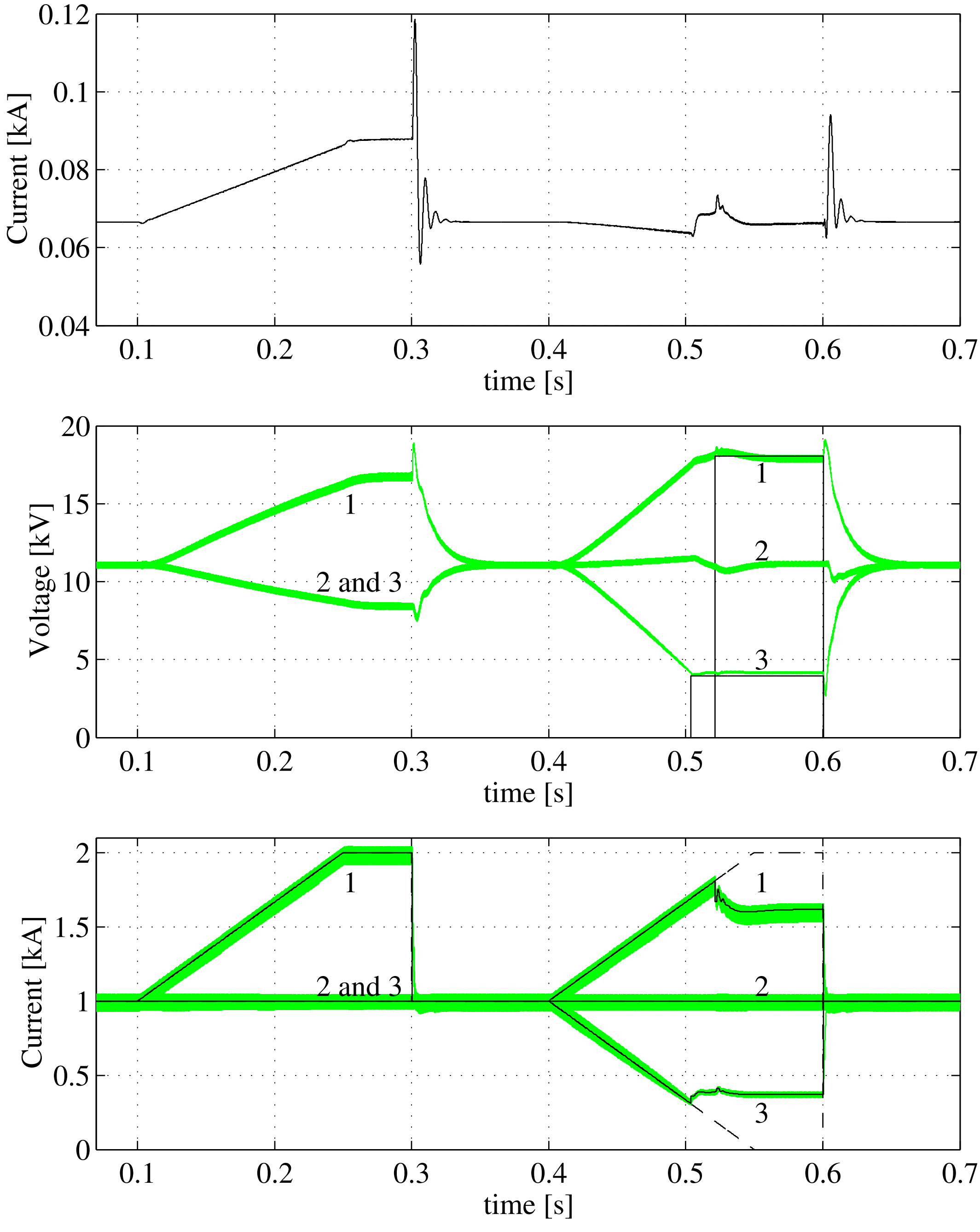

Figure 6.11: The results from simulations of the three series connected converters, the results are numerated 1 to 3 for the different converters. In the top plot the current that goes through the leg, I_{out}, is shown. In the middle plot the output voltage for the three converters are shown and in the bottom plot the input current (grey lines), input current reference (solid black line) and the input current reference from the speed regulator (dashed black lines) are shown.

6.4 Startup, stop, faults handling and protections

The main problem with series connection is the voltage division between the components and especially overvoltages. As already has been discussed overvoltages are devastating for the FBIB converter and undervoltages are problematic. But it has already been shown that overvoltages can be controlled if the output current is positive by decreasing the input current and undervoltages can be controlled, at least for a short time, by increasing the input current, at least until the rotor speed and the local wind turbine DC voltage has been lowered enough or that the converter can be safely shut-down, se section 6.2.2 and figure 6.11.

If there is not enough energy available at undervoltages, first the kinetic energy in the turbine will be used to keep the voltage up and then the magnetic energy in the inductor in the full bridge isolated boost converter will be discharged. When the current through the inductance is zero the valves will be turned off and last the output capacitor is discharged. When the output voltage reaches zero the diodes in the diode rectifier will start to conduct and clamp the output voltage to about zero. This is an example of how undervoltages can be handled by the full bridge isolated converter scheme in figure 6.3.

If the output current in figure 6.3 reaches zero or negative values, then the output voltage can not be controlled by decreasing the input current. This is due to that the input current can not be negative. If the output current gets equal to zero then the output voltage will increase (if the input current is greater then zero) to the point where the output voltage regulator goes in action. The output voltage regulator will discharge the inductor (decrease the input current) and the energy stored in it will be transferred to the output capacitor, which increases the output voltage even more. When the input current is zero, the converter can be blocked and the output voltage will stay high. If the output current becomes negative, then the output voltage will increase independently of the input current. This can happen at faults on the cables between the wind turbines. To avoid serious damages at these types of faults, the negative current must be lead beside the converter. This can be done using a thyristor in parallel with the capacitor, as shown in figure 6.12. When an event that will lead to an uncontrolled overvoltage is detected, then the thyristor is turned on which leads to that the output voltage rapidly is decreased to zero. The energy in the inductor has to be taken care of in a snubber circuit on the low voltage side in this case, in order to avoid overvoltages and overcurrents on the low voltage side.

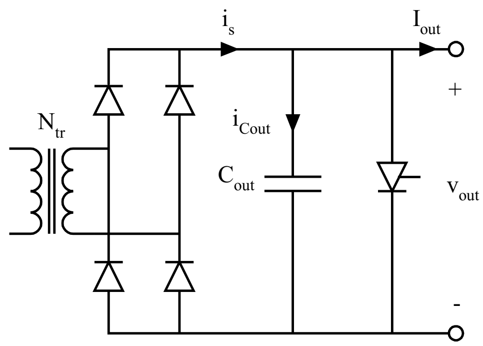

Figure 6.12: Protection for the series connected wind turbine.

In figure 6.13 a leg is shown with the assumption that an even number of turbines are series connected and that the center point is grounded. Assume that a ground fault

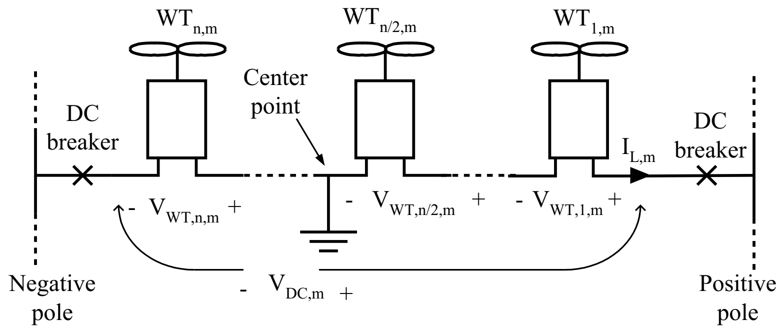

Figure 6.13: Series connected wind park.

happens on the cable between wind turbines $WT_{n/2,m}$ and $WT_{n/2-1,m}$ in figure 6.13. This will lead to that wind turbine $WT_{n/2,m}$ will be shut down due to overload (it is short circuited) and wind turbines $WT_{1,m}$ to $WT_{n/2-1,m}$ will have an increased output voltage. But they will not be damaged due to that they are designed to be able to operate with some wind turbines out of service. If the ground fault happens closer to the first wind turbine in the leg, then all wind turbines between the fault and the first wind turbine will sense an overvoltage and short circuit their outputs. This leads to that the positive pole will be connected through some conducting thyristors to the ground fault. This will give some time for the onshore station to disconnect from the AC grid in order to break the fault current. This must be made assuming that there is no DC breaker to disconnect the faulted leg from the poles.

If there is no DC-breaker for each leg, then a ground fault may lead to that the production of the whole wind park is lost. This is most likely not acceptable for large production sites. For lower voltages, standard AC breakers can be used with a reduced rating as DC-breaker but for higher voltages this is not today possible. Often today when DC-breakers are discussed, there is some sort of semiconductor solution that is discussed, IGBT:s or diodes. Due to the fact that the wind park only delivers power, the normal current direction is fixed and therefore a DC-breaker made of diodes should be sufficient. This is correct if the startup charging current for the output capacitors is neglected. This can be solved by connecting a resistance in parallel with the diode. This resistance limits the charging current and fault current. The current through the resistance must be limited to a level that can be disconnected with a standard AC breaker or disconnecter. This gives the layout shown in figure 6.14 of the DC-breaker that should be able to prevent faults in one leg to affect the rest of the wind park. The main drawback of this DC breaker is the same as for all semiconductor breakers, the losses. Due to the forward voltage drop over the diodes when they conduct, there will be some power loss in them. This power loss most be taken into account when the energy production cost of the wind park is evaluated.

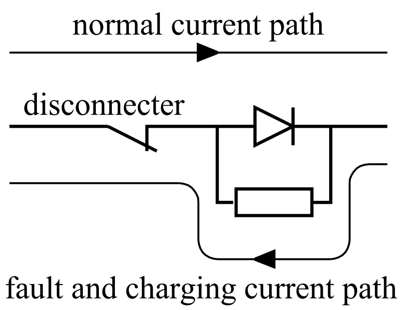

Figure 6.14: Scheme of the DC-breaker.

Chapter 7

Conclusions

Some different configurations of the drive train for wind turbines were investigated for the energy capture of wind turbines. In this investigation it was found that the difference between the investigated systems was quite small. For the AC wind turbines, the fix speed system and the doubly feed induction generator system were selected. For the DC wind turbines, the system with a low speed permanently magnetized generator and a boost converter is used. In the series connected DC wind park, a system with a low speed permanently magnetized generator and a full bridge isolated boost converter is used. The result found was that given a specific rotor diameter, the energy capture is almost the same regardless of the system used. The selection of the system to be used thus depend on other factors.

Six different types of electrical configurations of wind parks has been investigated for the energy production cost. The investigate types are

Small AC	Where the local wind turbine grid is used for transmission
Large AC	Which has a low voltage grid between the wind turbines and has a central transformer on an offshore platform for increasing the voltage level to a level suitable for transmission to the PCC
AC/DC	Similar to the Large AC wind park but with the difference that the transmission is made using DC instead of AC
Small DC	Similar to the Small AC wind park but with the difference that the wind turbine has a DC voltage output
Large DC	Similar to the Large AC wind park but with the difference that the wind turbine has a DC voltage output
Series DC	Uses series connected wind turbines with a DC voltage output

The investigation is done for different rated wind park powers, different transmission lengths and different average wind speeds.

The results regarding the energy production cost for the AC wind parks was as expected. The small AC wind park was best for short transmission distances (up to approximately 20km) and the AC/DC wind park was best for long distances (above approximately 130km). The large AC wind park is best in between the small AC and the AC/DC wind park.

For the DC wind parks the results was somewhat surprising, except for the small DC wind park, where it was found that it is not a good solution, due to the high costs of the converter station and DC transformers. For the large DC wind park it was found that it is better then the AC/DC wind park. This is due to that the DC cables are cheaper then the AC cables. But the reduction in the energy production cost is not so large, which gives that the large AC wind park is still better for shorter transmission distances. The most surprising results was for the series DC wind park. This configuration shows very promising performance. The energy production cost for the series DC wind park was the lowest for all the six investigated wind park configurations for transmission lengths over 10km. For example, for a wind park with a rated power of 160MW, a transmission length of 80km and a average wind speed of 10m/s it was found that the series DC wind park has a energy production cost of 0.86p.u. The large AC has an energy production cost of 0.97p.u, the AC/DC 0.98p.u and the small AC and DC approximately 1.2p.u. The message can also be expressed as: An increased investment cost of 13% can be allowed for the series DC park before it gets a production cost equal to the large AC park, using the input data that was available in this work

As expected, the energy production cost was strongly dependent on the average wind speed. As an example, the energy production cost at an average wind speed of 6.5m/s was twice as high as the cost for an average wind speed of 10m/s. It was also found that the energy production cost decreases when the power of the wind park increases.

By comparing the contribution to the energy production cost from the fix speed wind turbine system with the wind turbine system using the DFIG system it was found that for the configuration with the fix speed wind turbines, the wind turbine losses contributes less to the energy production cost then for wind turbines using the DFIG system. But the local grid contributes with more for the fix speed system, due to the reactive power flow.

This work has presented necessary steps to determine the energy production cost. It should be stressed that the cost results, of course, depend strongly on the cost input parameters. The aim here has been to present a determination strategy that can be of value for further wind park design and cost studies. Although, the series DC park is complicated to control, it was shown here that it is possible. Normal operation is fairly straightforward, while startup and uneven power production is difficult to handle. It was also found that it could be an advantage to use an electrically magnetized generator in the series DC wind park due to the possibility to reduce the voltage using the field winding.

A investigation of how much wind power that can be connected to different grids without encounter problems with the power quality at the nearest consumer, has also been performed in this work. The result depends, of course, on the acceptable limits. Here, the limits stated by the Swedish requirements, AMP [7], are used.

It was found that the flicker contribution can only be a problem if less than three stall-regulated fixed-speed wind turbines are connected to a weak grid. If more than three turbines are connected to the same point or if variable-speed turbines are used it is the line capacity or voltage limitations that sets the limits. The goal of an installation to a weak grid is to reach the line capacity limit, and the key to reach this limit is the possibility to control the reactive power once the flicker emission is not a problem.

7.1 Future Work

Since the series DC wind park shows very promising results, this configuration is interesting to investigate more in detail. More efforts must be put into investigating the dynamic performance of the wind park, for example the voltage division between the wind turbines, sensitiveness against different faults, startup and undervoltage problems, etc. Also the trade-off between energy loss and voltage over-rating of the converters must be studied. Another interesting area is what types of protections that are necessary to guarantee safe operation of the series DC wind park. Are DC breakers necessary or is it sufficient just to use the converter to block the power transfer, is an example of an aspect that should be investigated.

There are some question marks about a MW DC/DC converter in the wind turbine, apart from the fact that none has been built so far. How shall the non-ideal characteristics of the components be treated. For the high frequency transformer there are uncertainties about how it shall be designed, what type of material shall be used for the core, etc. There is also some interesting challenges in the high voltage field regarding the insulation of the high voltage winding.

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Appendix A

List of publications

A.1 Publication 1

Flicker contribution from wind turbine installations

Thiringer, T., Petru, T., Lundberg, S.

accepted for publication in *IEEE transactions on Energy conversion*

Flicker contribution from wind turbine installations

Torbjörn Thiringer, Tomas Petru, Stefan Lundberg

Abstract— **In this paper the flicker emission from a wind park connected to a grid with a high wind energy penetration is evaluated. The influence of wind speed, turbulence intensity, grid voltage quality, grid types and number of turbines operating in the same group is measured and analyzed. The investigated wind turbines are of constant-speed stall-regulated type. It is found that the voltage quality of the grid to which the turbines are connected strongly influences the flicker emission of the turbines. Moreover, it is found that the formula used in IEC-61400-21 for determining the flicker contribution from a whole wind park gives too low total flicker value.**

Keywords— **wind power generation, power quality, voltage fluctuations, flicker emission, measurement**

I. Introduction

There is a focus on the power quality impact by wind turbines. A frequently discussed power quality issue but difficult to predict is the flicker emission from wind turbines. Due to a few events where power quality problems have occurred that have not been reported in written form but only reported orally, utilities in deregulated markets can be reluctant to permit wind turbines to be installed in their grid. Once a turbine has been installed it is for instance in Sweden the responsibility of the utility to maintain a good power quality. Due to this reason it is very important to clearly demonstrate in advance how much wind turbines affect the power quality.

As the grid strength (ratio between grid short-circuit capacity and rating of wind turbine) increases, the flicker emission from wind turbines is reduced [1], [2]. The grid impedance angle, also called X/R-ratio, is also an important factor for the flicker emission [3]. An X/R-ratio of 1 corresponds thus to a grid impedance angle of 45 degrees, and accordingly, an X/R-ratio of 0.6 corresponds to a grid impedance angle of 30 degrees. In [1] it is reported that the flicker emission for an X/R-ratio of 0.5 is 10 times higher compared to an X/R-ratio of 2 while in [2] a ratio of 4 is reported. According to [1], [3], [4] the flicker emission increases with increasing wind speed. The X/R-ratios in these papers were 0.6-1. A different observation was made in [2] where the flicker emission value at 20 m/s was only one sixth compared to the value obtained at 10 m/s for an X/R-ratio of 1.

Another factor that influences the flicker emission is the turbulence intensity. In [5] it is reported that the flicker emission at 16 % turbulence intensity is twice as high compared to a turbulence intensity of 8 % and similar results were found in [1], [2].

An interesting topic is how the flicker from a single wind turbine is to be summed up to be valid for a wind park. In [1], [3] it was found that the summing up should be performed as the square root of the sum of the squared flicker values from the individual turbines. This means, when considering the same type of wind turbines on the same grid strength, that the total flicker contribution increases with the square root of the number of turbines. This conclusion also means that N small wind turbines of the same total rating as one big turbine will produce $\sqrt{N}$ times lower flicker impact.

The main document stating how the flicker evaluation of a wind turbine installation is to be performed is the IEC-61400-21 [6]. A determination of the flicker impact by a single wind turbine is described as well as how these results shall be used to determine the total flicker impact of a wind farm installation. [6] allows the turbulence intensity to be anything between 0.08-0.16 when the flicker determination is performed. Moreover it is stated that since other sources of flicker are always present in the grid, the flicker emission should not be measured using the voltages at the turbines directly, but instead the active and reactive power from the wind turbine should be used to determine a fictitious voltage.

It has been found that the flicker emission from variable speed turbines are low [7]. This means that it is only of interest to study the flicker emission from constant-speed turbines, and almost all of these are stall-regulated.

The purpose of this paper is to evaluate and analyze the flicker impact from the individual wind turbines as well as the flicker impact from the whole wind park. Various wind conditions (speed and turbulence), various X/R-ratios of the grid and the impact of the connected grid voltage are aspects that are to be treated.

II. Power Quality aspects of Wind Turbine installations

At wind turbine installations there are four power quality aspects that are mainly discussed: steady state voltage impact, impact by dynamic voltage fluctuations (flicker impact), injection of harmonic currents and finally voltage transients due to switching actions.

A. Steady state voltage level

A change of steady state voltage level is an inherent consequence of injecting a current into the grid. The voltage level as a function of produced active and exchanged reactive power can approximately be determined using Equation 1.

The financial support provided by Sydkraft AB, Energimyndigheten and ABB Power Systems is gratefully acknowledged. Moreover the authors would like to thank Göran Olsson at Vattenfall AB for invaluable help with the operation of the measurement system and with the experiments.

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$$U = R\frac{p}{U_n} - X\frac{q}{U_n} + U_n \tag{1}$$

Where:

U_n	nominal voltage of the grid
U	voltage at connection point
p	active power produced
q	reactive power consumed
R	grid resistance
X	grid reactance

The voltage level impact of the systems with induction generators directly connected to the grid (fixed-speed systems) depends to a smaller extent on the induction generator characteristics but mainly on the grid X/R-ratio. A ratio of around 2-3 usually gives a very low impact. This holds provided that the system is equipped with a capacitor bank designed typically to compensate for no-load reactive power consumption of the induction generator. It is also possible to have a system, in which the capacitor bank is connected in several steps in order to gradually compensate for a reactive power demand required for an actual active power production.

Wind turbine systems with power electronic converters connected to the grid automatically provide reactive power control. They can principally control the system according to any required criteria, e.g. to keep the power factor to one, or if desired, control the voltage level at the turbine [8]. An advantage compared to the system with a switched capacitor bank is a smooth control of the reactive power without switching transients.

B. Dynamic voltage fluctuations (Flicker emission)

In the same way as the average wind speed affects the voltage level in a long time scale (in order of minutes and upwards), the voltage level is also affected by the wind turbine installation in a short time scale (in order of tens of seconds down to tenth of a second). The turbulence in the wind together with the wind turbine itself create power variations in the region of 0.01 - 10 Hz.

A standardized method to evaluate the dynamic voltage fluctuations, which is the one used in this paper, is described in [9]. It is based on the fact that people are irritated by flickering of the light. A light bulb connected to a fluctuating voltage is taken as a source of the flickering. A dimensionless quantity that classifies this level of irritation over a 10 minutes period is the short time flicker severity index, P_{st}. The P_{st} is most sensitive to a voltage fluctuation in the frequency region about 9 Hz where a fluctuation with the amplitude of 0.25 % will cause $P_{st} = 1$, which in turn means that the majority of people is likely to be irritated. National installation standards prescribe maximum allowed values of P_{st}, for instance in Sweden this value is given by [10] and it is $P_{stmax} = 0.35$.

The use of power electronic converters in wind turbine systems provides a possibility to reduce the dynamic voltage fluctuations. It is so because the incoming power fluctuations can be taken up by changing of the turbine rotor speed slightly, i.e. variable-speed operation. Furthermore, the reactive power can be controlled to minimize the voltage fluctuations caused by varying active power [11] instead of keeping it to zero, if so desired.

C. Influence by switching actions

The influence of a wind turbine on the connected grid by switching actions is classified for two distinct cases. The first considered aspect is an impact on steady state voltage level during connecting the turbine generator. High currents drawn by the turbine generator cause a voltage dip. This is an important factor that limits the installation of a wind turbine to a specific grid. In Sweden, [10] prescribes the maximum allowed voltage change due to turbine connecting to be below 4 %.

The other switching related disturbance is due to a capacitor switching. The switching is followed by a high-frequency inrush current and a corresponding voltage transient in the connected grid. This can only be a problem if sensitive equipment is connected to the same low-voltage bus bar as the wind turbine [12].

Both switching related problems give rise to high flicker values. The flicker impact due to switching actions has different limits compared to the flicker impact originating from continuous turbine operation, however, it is limited. Due to this limitation, switched capacitor banks cannot be used for a dynamic reactive power control, which would be a theoretical option for minimizing the continuous flicker impact of fixed-speed wind turbine systems.

D. Harmonics current injection

Injection of current harmonics has been measured and reported in the literature. A common conclusion in these observations is that the harmonic current emission is below the recommended values. However, in a case where thyristor inverters were used, the emission of current harmonics was reported to be above the recommended values [13].

E. Limiting factors for wind turbine installations from the grid point of view

An important factor that also determines the amount of wind power that can be connected to an existing grid, is the line capacity. If it is the line capacity that sets the limit for the installation instead of any power quality restriction, the same case is reached as with conventional power production, and no further installations can be done unless the grid is reinforced. For variable-speed turbines the line capacity is the limiting factor while the limiting factor varies for installations with fixed-speed turbines. Of course, distinct borders between the limiting factors vary on details, but roughly the following holds:

In the case of a single fixed-speed turbine it is usually the voltage change requirement during the period of connecting the turbine to the grid that sets the limit. For a few turbines it is the flicker emission [14]. The limiting factor when more than 5-10 turbines are installed is the steady-state voltage restriction for a mainly resistive grid, and it is the line capacity restriction for a mainly inductive grid.

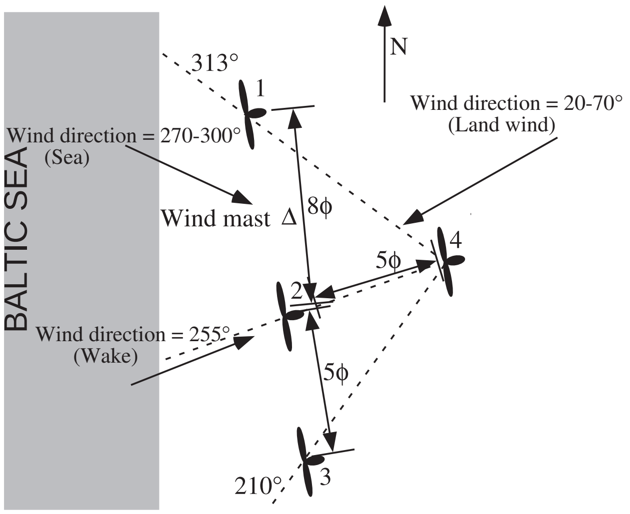

Fig. 1. The Alsvik wind park.

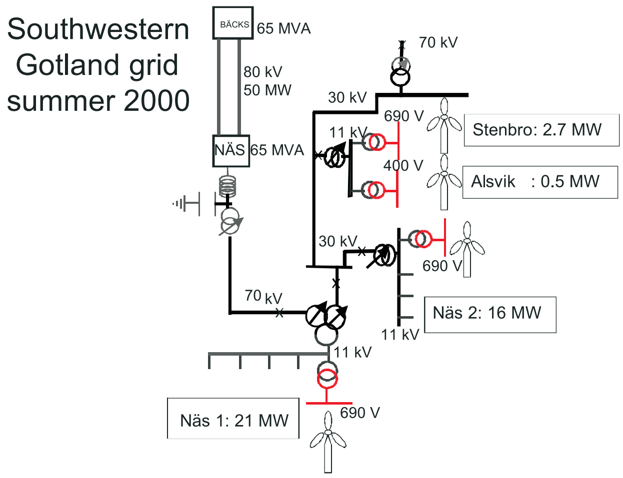

Fig. 2. Schematic sketch of the Näsudden grid.

III. The measurement arrangement

A. The wind park

The wind park is located at Alsvik on the west coast of the island of Gotland in the Baltic sea. It consists of four stall regulated three-bladed 180 kW wind turbines. However, during the whole measurement period, turbine number one was out of operation due to a gear box malfunction and during most of the time turbine two was also out of order. There is also a wind measuring mast available with wind speed sensors at three levels: at the hub height, at the bottom level of the wind turbine rotor and at the top level of the wind turbine rotor. The wind park is presented in Fig. 1. Details of the wind park can be found in [15]. The short-circuit capacity on the high-voltage side of the local 10/0.4 kV transformer is 11 MVA. All flicker emission calculations are done for a grid strength of 7 MVA, which corresponds to the short-circuit capacity on the low-voltage side of this transformer. The wind park is connected to the Näsudden grid on Gotland, which has around 100 wind turbines and has recently been reinforced by a HVDC-Light transmission. Fig. 2 presents the Näsudden grid with the HVDC-Light installation.

B. Data acquisition system

The voltages at the low-voltage side of the local 10/0.4 kV transformer are measured using isolation amplifiers, AD 210 BN and the currents are measured using LEM-modules. These signals are together with the 3 wind speeds and the wind direction collected by a data acquisition system. The signals are prefiltered before being acquired by the data acquisition system. In accordance with [6], the voltage fed into the flicker algorithm is determined for various fictitious grids from the measured active and reactive powers using Equation 1.

In addition, a Siemens Oscillostore P513 is used to verify the flicker calculations performed with the data acquisition system. The flicker algorithm used in Siemens Oscillostore P513 is the one stated in [9].

[6] states that the bandwidth of a data acquisition system, when flicker calculations are to be performed, should be 400 Hz. This means that the sampling speed should be minimum 1000 Hz. Sampling frequencies of 256 Hz and 2048 Hz were mainly used during the performed data acquisition. There was no detectable difference between using 2048 Hz and 256 Hz sampling frequency when determining the flicker emission from a turbine or when evaluating the flicker level on the grid. Thus, the decision was made to use the sampling frequency of 256 Hz. The flicker values determined using the data acquisition system (and, of course the flicker algorithm from [9]) are compared with the results using the Siemens Oscillostore P513 in order to investigate the accuracy. As is shown in Fig. 3 and Fig. 4 the agreement is very good. The reason for the slight differences, especially in the case of the very high flicker values, is that the Oscillostore and the data acquisition system do not run synchronously. In average, however, the discrepancy was very low with about 5 % higher values for the Oscillostore P513 compared to the data acquisition system.

IV. Flicker contribution from a single wind turbines

[6] states that the wind turbine should be connected to a grid with a short-circuit capacity of 50 times the rating of the turbine in order to perform the flicker emission evaluation of the turbine. This would have been fulfilled if one of the investigated turbines had been operating with the other two turbines shut off. The grid-short-circuit power is as mentioned 11 MVA which is 61 times the rating of one of the investigated turbines. Since it was not possible to do this for the measurement period of six months, it was first investigated how much the turbines disturbed each other. During this test, turbine two and three were shut down simultaneously and started simultaneously in intervals of about 15 minutes while turbine four was continuously operating. In Fig. 5 the flicker contribution from turbine four is presented during the test period of three hours and it can be observed that there is no detectable

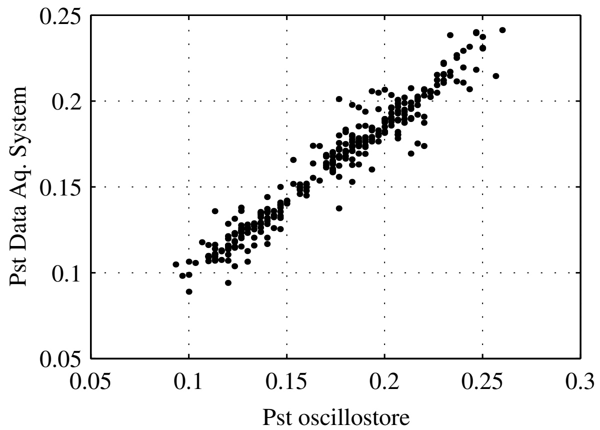

Fig. 3. P_{st} level on the local 400 V grid determined using Oscillostore and from data aquisition system, during three hours of operation with low flicker levels. One minute P_{st} values.

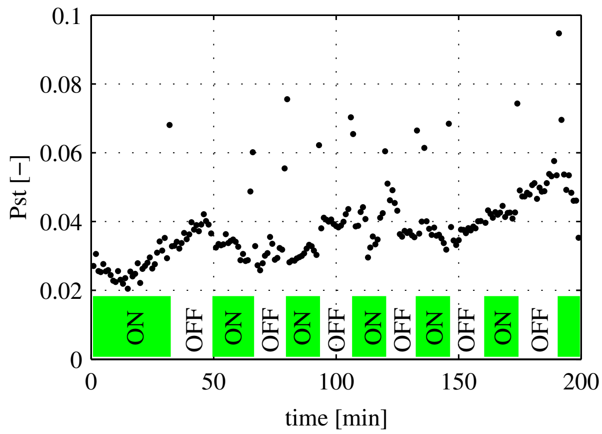

Fig. 5. P_{st} contribution (flicker emission) from turbine four with the other wind turbines on (gray patch intervals) and off. One minute P_{st} values.

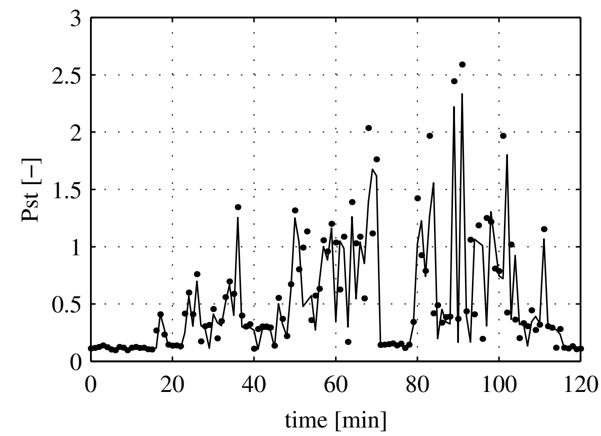

Fig. 4. P_{st} level on the local 400 V grid determined using Siemens Oscillostore P513 (dots) and from data acquisition system (solid line), operation at high flicker levels.

difference between the flicker emission from turbine four when the other turbines are operating or not. Of course, at the times when the turbines are started and switched off there are peaks with higher flicker levels, due to the switching actions. Turbine four responds to the grid voltage disturbances that are caused by the switching operations of the other two turbines. The conclusion is that the flicker emission of turbine four is not affected by the operation of the other turbines.

In Fig. 6, Fig. 7, Fig. 8 and Fig. 9 the flicker contribution from turbine four is presented when the turbine is operating with the wind from the sea, land and when it is in wake operation of turbine two, see Fig. 1. Only turbines three and four were operating when the data presented in this section were acquired. The various wind directions imply that the investigated turbine is exposed to winds with different turbulence intensities. The four presented figures show the results determined for four different values of the grid X/R-ratio, since the flicker impact varies substantially depending on the grid type.

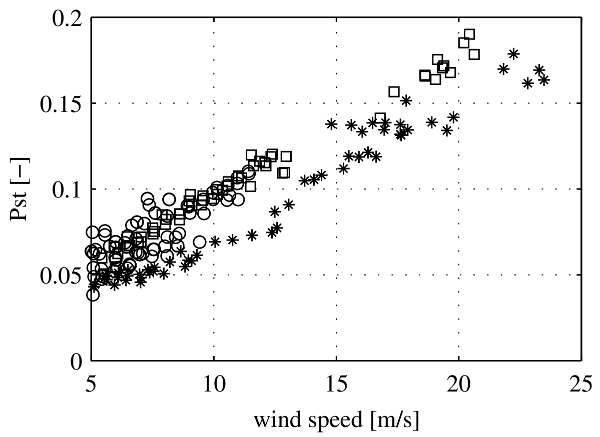

Fig. 6. P_{st} contribution as function of wind speed, X/R=0.5. * sea wind, circles forest wind and squares wake operation (255 degrees). Ten minute P_{st} values.

It is observed that the flicker emission is lower for an X/R-ratio of 2 compared to the other grids. The reason for this is the active power versus reactive power relation of the generator. The active power produced by the generator causes a voltage increase due to the grid resistance. The reactive power consumed by the generator causes a voltage drop over the grid reactance. For an X/R-ratio of about 2 these two voltages approximately have the same size. Another way of analyzing this result is to study the derivative of the ratio of active and reactive power for an induction machine at its nominal operating point and using Equation 1. Since this ratio is about 2-3 W/VAr this means that the resulting voltage change due to an active power change (and the caused reactive power change) will be very small when the X/R is around 2-3. Of course, the

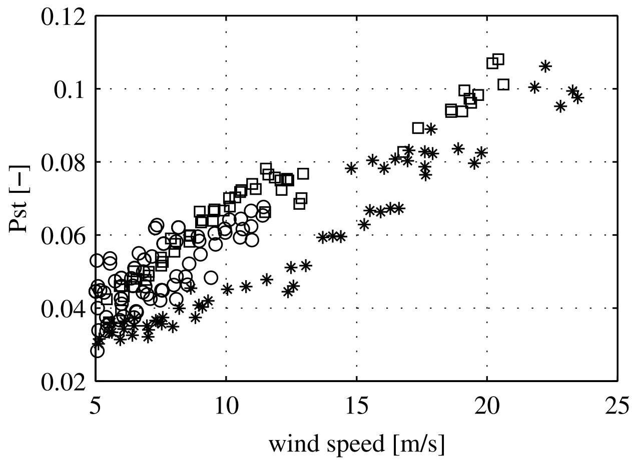

Fig. 7. P_{st} contribution as function of wind speed, X/R=1, legend as in Fig 6.

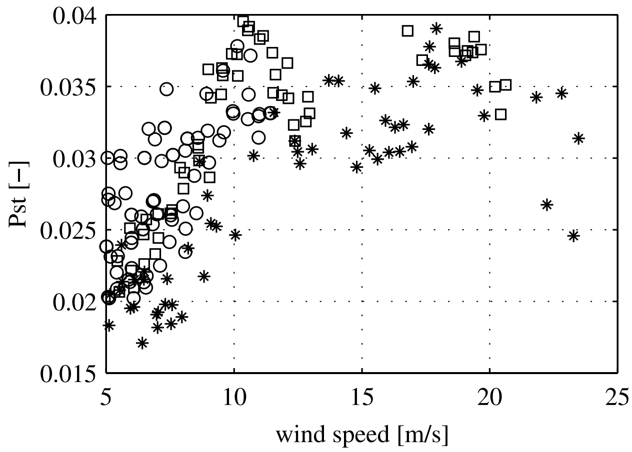

Fig. 8. P_{st} contribution as function of wind speed, X/R=2, legend as in Fig 6.

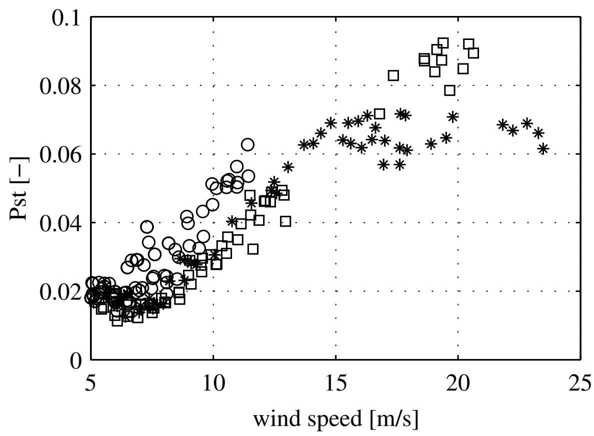

Fig. 9. P_{st} contribution as function of wind speed, X/R=5, legend as in Fig 6.

minimum point depends slightly on the characteristics of the specific induction generator used.

The observation made in [1], [3], [4], that the flicker increases with increasing wind speed for low X/R-ratios, was also observed in this work (see Fig. 6 and Fig. 7). The results presented in Fig. 7 are the opposite to the strong decrease in the flicker emission levels at higher wind speeds for an X/R-ratio of 1 that was reported in [2].

The flicker emission is higher when the turbulence intensity is higher, as for land wind and wake operation, especially for the X/R-ratio of 0.5 and 1. For the X/R-ratio of 2 the turbulence of the wind plays a less dominant role. The importance of the turbulence intensity can be further observed in Fig. 10 which presents the influence of the turbulence intensity on the P_{st} value for an X/R-ratio of 1 (wind speed between 12 and 13 m/s). It is observed that there is about 20 % higher flicker level for turbulence intensities of 0.16 compared to 0.08, which are the upper and lower limits allowed by [6]. The difference in the determined P_{st} values for these two turbulence intensity values found in this work are, in fact, lower compared to the results reported in [1], [2], [5]. Even the smaller difference found in this work is important according to the authors. Some utilities rigorously follow the national recommendations, for instance [10], and a 20 % higher flicker level could lead to that a specific turbine type can not be connected to a given grid.

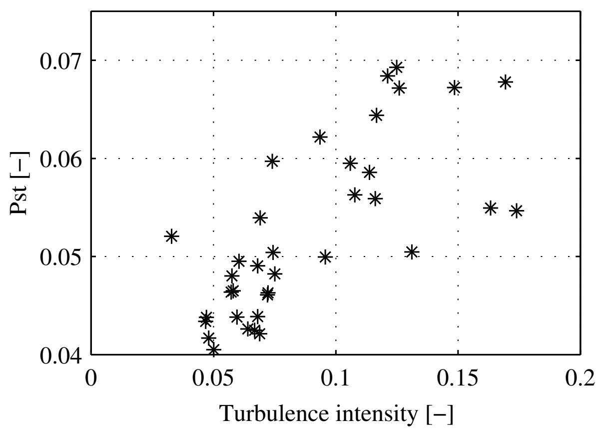

Fig. 10. P_{st} contribution as function of turbulence intensity, for wind speeds between 12 and 13 m/s. X/R=1, one minute P_{st} values.

V. Flicker emission from a no-loaded wind turbine generator

It is not only changes in the wind and the wind turbine that create the flicker emission, it is also the connected grid that affects the wind turbine flicker emission. When the grid voltage contains fluctuations, the connected turbine produces an output power that contains fluctuations in the same frequency region. Especially severe is the case when the grid voltage fluctuations are in the frequency range where the flicker algorithm is as most sensitive (1 - 10 Hz).

The impact of this kind of voltage fluctuations was investigated as follows.

The flicker impact from turbine number two and three were evaluated during 24 hours of operation where the wind varied between 6 and 15 m/s. In turbine two, the generator was disconnected from the gear-box and the wind turbine rotor was parked. This means that the generator of turbine two is spinning as a motor at no-load. In Fig. 11 and Fig. 12 the flicker emissions from turbines two and three are compared. Turbine three experienced undisturbed winds during this test. Turbine four is not involved in this comparison since it has a newer generator with a lower slip which would give a higher flicker emission. For the 70 degrees grid there is in fact almost no difference in the flicker emission from turbine two and three which indicates that the flicker impact from these turbines originates mainly from the present grid voltage fluctuations. For the more resistive grid, turbine three gives a higher flicker emission than turbine two for higher wind speeds. This is in line with the observation that can be made when comparing Fig. 6 and Fig. 8, i.e. that for an X/R ratio other than around 2 the flicker emission increases with increasing power production, but since turbine two is no-loaded there will be no increase of the power with increased wind speed. The results presented in this section indicate very clearly: In order to certify the flicker emission from a certain type of turbine, it is important to use a grid with low voltage fluctuations.

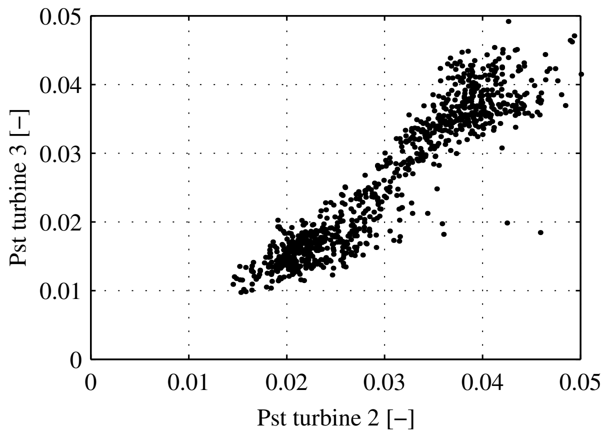

Fig. 11. Flicker emission from the no-loaded generator compared to flicker emission from turbine 3, 70 degrees grid angle. One minute P_{st} values.

VI. Flicker contribution from the whole park

In [6] it is stated that the total flicker contribution from a wind park is determined from the flicker emission of one turbine using the following expression

$$P_{st,tot} = \sqrt{\sum_{i=1}^{N} P_{st,ind}^2} \tag{2}$$

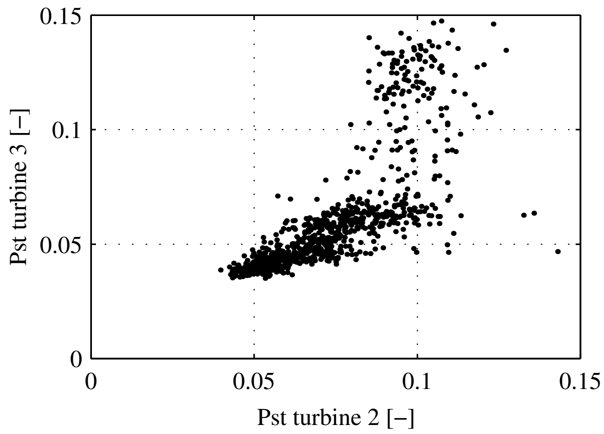

Fig. 12. Flicker emission from the no-loaded generator compared to flicker emission from turbine 3, 30 degrees grid angle. One minute P_{st} values.

where N = number of turbines, $P_{st,tot}$ is the total flicker contribution from the wind park and $P_{st,ind}$ is the flicker contribution from one individual turbine.

If all turbines are of the same type, Equation 2 can be simplified to

$$P_{st,tot} = \sqrt{N} P_{st,ind} \tag{3}$$

Fig. 13 presents the discrepancy between two different P_{st} evaluating approaches. The first approach makes use of the flicker values determined from the total active and reactive powers of the wind park. The second approach uses the P_{st} values obtained using the individual P_{st} values and Equation 2.

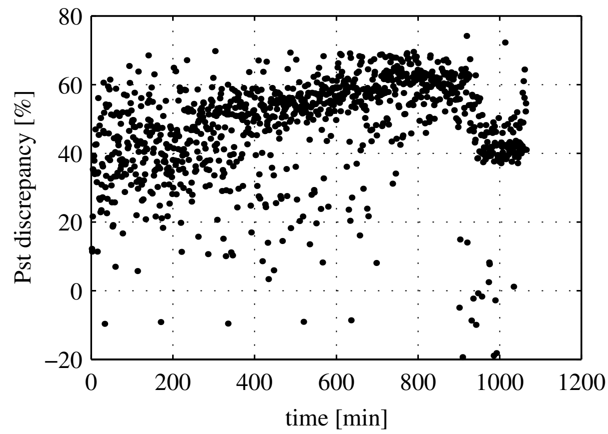

Fig. 13. Discrepancy between the actual flicker emission and the formula from IEC-61400-21, 70 degrees grid impedance angle.

As can be noted from Fig. 13, the flicker levels are usually much higher when the total active and reactive powers from the wind park are used. For the 70 degree grid this method on average gave 48 % higher results, and for a 30 degree grid 20 % higher. In [1], [3] the results found were that there was no detectable differences between these two methods. The reason for the higher flicker values reported here is most likely the voltage fluctuations originating from the grid. This influences all the turbines in the same way, giving rise to fluctuations in the active and reactive powers that are similar from all the turbines, i.e. the sum of the contributions from the wind turbines, not the square root sum. So the result is a mix of these two components. The conclusion that can be made is that when the voltage quality is not very good, caution must be taken when Equations 2 and 3 are used to determine the flicker emission from a whole wind park.

VII. Response of a wind turbines to a grid disturbance

In Fig. 14 a recording of the P_{st} levels at Alsvik is presented as a function of wind speed during two weeks in September 2000.

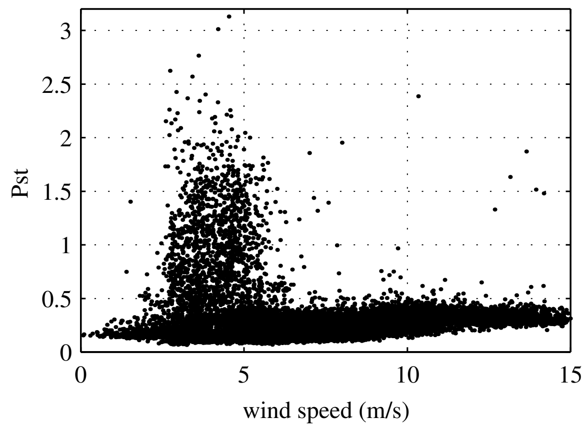

Fig. 14. P_{st} contribution as function of wind speed at Alsvik. One minute P_{st} values.

As can be noted, there are very high flicker levels at low wind speeds, which led to complaints from customers. A closer look at the files containing high flicker levels revealed a large number of voltage dips. These were varying in duration and level and the origin of these is not completely clear. A probable cause could be the connecting of nearby turbines. On the Näsudden grid there are about 100 turbines connected. In Fig. 15 such an occasion is presented. The wind speed is low, around 4 m/s and turbine four is producing only a small percentage of the rated power, as can be noted from Fig. 15. The voltage goes down shortly with a maximum dip of 10 %. The grid angle variation shows that even the grid frequency is temporarily affected. The grid angle was determined by comparing the instantaneous grid frequency (identified from measured voltages) against a constant frequency value. After 0.7 seconds the frequency is stable again, but at a slightly lower value. The power of the turbine goes from 0 to 75 % of the rated one in a fraction of a second as the grid disturbance occurs and a damped oscillation takes place with a frequency of 8 Hz. The 8 Hz oscillation occurs since this is the dominating eigenfrequency of the induction generator [16]. Apart from the voltage dip, this power oscillation also contributes strongly to the flicker value. The flicker algorithm is as most sensitive to 9 Hz voltage fluctuations.

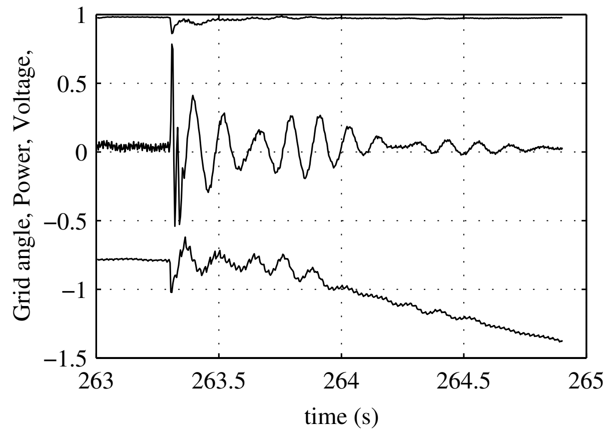

Fig. 15. Voltage (pu, upper line) and grid angle (no relevant scale, lower line) dip causing a power oscillation (pu, medium line).

VIII. Conclusions

In this work it is found that the voltage quality on the supplying grid is important when determining the flicker emission from wind turbines. It is found that the flicker emission increases with increasing wind turbulence intensity, however, not as much as previous authors reported [1], [2]. Moreover it is found that the highest flicker contribution actually occurs at low wind situations probably due to connections of nearby wind turbines. Finally it is found that the formula used in [6] for the summation of flicker from individual wind turbines gives too low total flicker value unless the voltage quality of the supplying grid is extremely good.

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Torbjörn Thiringer received his Ph.D. in 1996 from Chalmers University of Technology. Currently, he is an Associate Professor at the Department of Electric Power Engineering at Chalmers University of Technology. His area of interest is control and modelling of induction machines, especially for wind turbine applications.

Tomas Petru recieved his M.Sc. from the University of West Bohemia in Pilsen, Czech Republic in 1997. He is now working towards his Ph.D. at the Department of Electric Power Engineering at Chalmers University of Technology. His area of study is modelling wind turbines for power system studies.

Stefan Lundberg was born in Göteborg, Sweden in 1976. He received his M.Sc. in 2000 from Chalmers University of Technology. He is now working towards his Ph. D at the same department. His area of interest is the control and modelling of wind turbine parks.

A.2 Publication 2

Electrical Limiting Factors for Wind Energy Installations in Weak Grids

Lundberg, S., Petru, T., Thiringer, T.

International Journal of Renewable Energy Engineering, vol. 3, no. 2, August 2001, p. 305-310

Electrical limiting factors for wind energy installations in weak grids

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Abstract

In this paper the electrical limiting factors for installation of wind turbines have been used to determine which types of power quality problems that will dominate when wind turbines are installed in weak grids. The main limiting factors are static voltage level influence, the flicker emission, and of course, the capacity of the line. The investigation is based on field measurements on a fixed-speed wind turbine and on a semi-variable-speed wind park. It is found that the limiting factor from the power quality point of view is the flicker emissions if one fixed-speed wind turbine is installed. If three or more turbines are installed it is the static voltage variations or the line capacity that sets the limit. It is found that the X/R-ratio of the grid plays a significant influence on the installation possibility, and a ratio of 1.3-2.8 is the most favourable, depending on the short circuit ratio. For variable-speed wind turbines it is the static voltage change and the line capacity that are the limiting factors.

I. INTRODUCTION

Today, when people talk about wind energy installations, they frequently talk about large, often sea-based wind parks. In these cases the connection of the park to a strong grid point is a natural part of the wind energy installation. However, a large part of the installations that takes place today are done in sites, where it is totally impossible to consider anything else but to connect to the closest distribution line. This gives rise to quite different requirements for connection of wind turbines. The turbines must contribute with a minimum power quality impact, or preferable, they should even improve the power quality on the grid to which they are connected.

The financial support provided by Energimyndigheten (Swedish Energy agency), Sydkraft AB and ABB Power Systems is gratefully acknowledged.

There is a great advantage in installing wind turbines at the end of weak lines: The energy produced by the wind turbines is consumed locally, which means a loss reduction since less energy must be distributed from far away to this line. Thus, we have an extra value of locally produced small-scale energy.

Especially in deregulated energy markets, utilities are somewhat reluctant to allow wind turbines to be connected, unless they are absolutely sure that no power quality problems will arise. In order to be on the safe side they demand a connection fee that can be up to 20% of the total investment cost. To reduce the connection fee, it must be shown that the power quality impact will be acceptable.

It has been noted that the grid short circuit power and the X/R-ratio of the grid have a great influence on the power quality impact from wind turbines [1]. It has been shown that the power quality impact from wind turbines is inversely proportional towards the short circuit ratio [2, 3, 4]. A minimum for the power quality impact occurs for XR-ratios between 1.7 and 2.7 [3, 4].

The purpose with this work is to investigate which kind of power quality problems that limits a wind turbine installation. Both fixed-speed as well as variable-speed turbines are treated.

II. THEORY

In the case of a large-scale wind integration, the grid has to be adjusted to the wind installation. However, the work presented here focuses on the situation where one or a few turbines is to be connected to an existing grid without doing any reinforcements. The reason is that often it will be too expensive to reinforce the grid, thus the existing grid must be used. There are mainly three aspects that has to be considered: The lines/cables must not be overloaded, the steady-state voltage variations are to be kept within a stated limit and the flicker emission should not exceed a certain level.

There are basically two wind turbine systems marketed today. There are the fixed-speed stall-regulated ones with a generator connected directly to the grid and there are turbines using power electronic converters and thus variable rotor speeed.

A. Network model

In order to determine the steady-state voltage and flicker impact on an electrical grid the grid model presented in Fig. 1 is used.

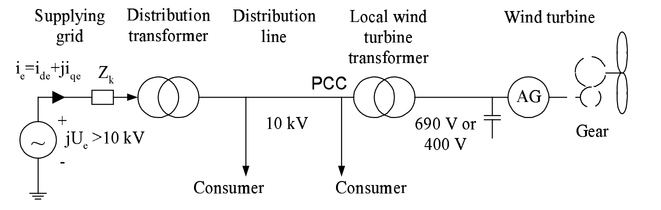

Figure 1. Model of the wind turbine and electrical grid.

To determine the electric impact of the wind turbines, the measured active and reactive current are fed into the network so the voltage level impact and flicker emission can be determined.

It is assumed that there exists a strong grid far away, with a network impedance Z_k. The smaller Z_k is, the higher short-circuit capacity the grid has. Another important quantity of a grid is the grid short-circuit impedance angle ratio, the X/R-ratio. A cable grid can have an X/R ratio as low as 0.33 while an overhead-line grid close to a transformer can have a ratio of up to 5-20. Usual values in Sweden are around 1-3 where a few turbines are to be installed. In principle, any type of combination can exist [5].

B. Steady-state voltage variations

Variations in the long-term voltage level are caused by variations in the power production, and the reactive power flow. In the case of the traditional system with fixed-speed turbines and phase-compensating capacitors the reactive power flow can not be controlled. According to the Swedish regulations, AMP, [6] wind turbines should not cause voltage variations of the RMS voltage that exceed 2.5% in the Point of Common Connection (PCC) if other consumers are connected close to this point.

C. Flicker emission

Voltage magnitude variations can be sufficient in duration and frequency to allow visual observations of a change in the intensity of electric light source. These light intensity variations are called flicker. Humans are especially sensitive to luminance fluctuations around 8.8 Hz. The IEC (International Electromechanical Commission) has published a norm for a flicker meter, IEC 61000-4-15 [7] which is used in this paper. According to the Swedish regulations [6] a wind installation may contribute with a maximum P_{st}-value of 0.25 if other consumers are connected to the same line. If the total flicker level on the grid is 0.7-1, customers will begin to be disturbed by “flickering” lamps.

D. Line Capacity

If the limit for our wind turbine installation is the line capacity it of course means that we are using the existing grid as much as possible. Unless something can be done with the reactive power control, it is not possible to install more wind turbines to this line without performing grid reinforcements.

III. MEASURING SITES

Measurements were made on a stall-regulated wind turbine which has a generator directly connected to the grid and on a wind park which operates both at variable and at fixed speed.

A. Alsvik

The stall-regulated wind turbine studied is a part of a group of 4 turbines located on the west shoreline of the island of Gotland in the Baltic Sea. The wind turbines are three-bladed with a rated power of 180 kW each. The details of this wind energy installation can be found in [8]. Of course, various turbines produce different power fluctuations, but the power pulsation from constant-speed stall-regulated turbines are fairly similar, therefore the results here is most likely valid also for other constant speed stall-regulated turbines. The wind turbines are equipped with phase-compensating capacitors which compensate for the no-load current of the generator.

B. Bockstigen

The semi-variable speed wind park investigated consists of 5 500 kW wind turbines and is located outside the west coast of Gotland. At low wind speeds the wind turbines operate at variable speed through the converters. At medium and high wind speeds they operate with the generators directly connected to the grid and the converters now operate as controlled reactive power sources in order to support the grid voltage. A sketch of the Bockstigen electrical system is presented in Fig. 2. The wind park is located 5 km out in the sea. More information about the electrical system of the wind park can be found in [9].

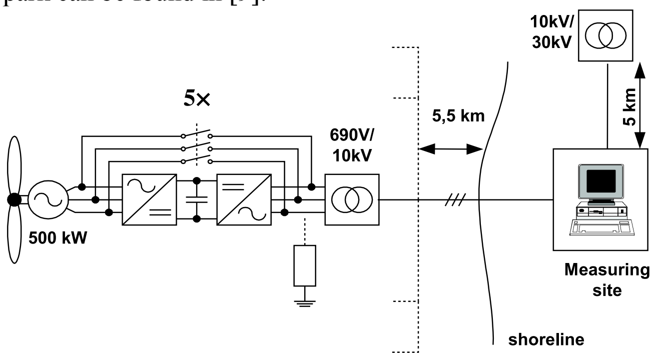

Figure 2. The electrical system of the Bockstigen wind park.

IV. ANALYSIS OF GRID IMPACT BY FIXED-SPEED TURBINES

A. Steady-state voltage level

In Fig. 3 the voltage level change as a function of produced power is presented for some different grids together with the 2.5 % voltage level change limit. It is observed that an X/R-ratio of 0.5 leads to a very strong voltage increase, while a ratio of around 2-3 gives a very small voltage change. Although, these result is obtained using a specific induction generator, the results are fairly similar for other induction generators.

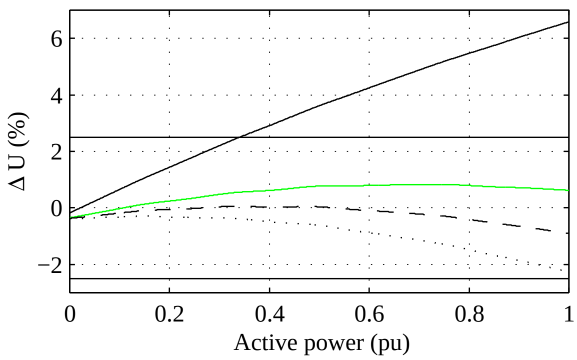

Figure 3. Voltage change as a function of produced power for various X/R-ratios. The grid strength is 10 times the rating of the turbine. Solid XR=0.5, Grey XR=2 , Dashed XR=3, Dotted XR=5. The 2.5 % limits are marked with solid lines.

In Fig. 4 the voltage as function of the X/R-ratio and short-circuit capacity ratio is presented. Here a very interesting observation can be done. In the case of a low X/R-ratio, i.e. a cable grid, the short-circuit capacity of the grid must be rather high, while an X/R-ratio of 2 makes it possible to have an extremely low short-circuit capacity of the grid which is a common situation in countries with many over-head line grids.

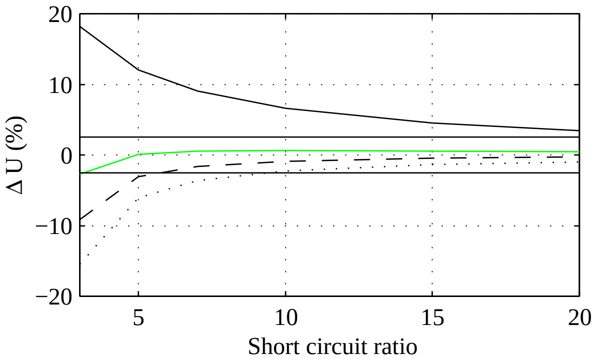

Figure 4. Steady-state voltage as function of short circuit ratio for different XR-ratios. Lines as in Fig. 3.

Once the grid parameters are known, it is in fact possible to select an induction generator that suits the grid in the best way. Depending on the X/R-ratio of the grid a generator which consumes less or more reactive power can be chosen. In Fig. 5 the reactive power consumption and the resulting voltage change as a function of power on a specific grid using two different induction generators are presented. Observe that the no-load reactive power consumption of the generator has been compensated for.

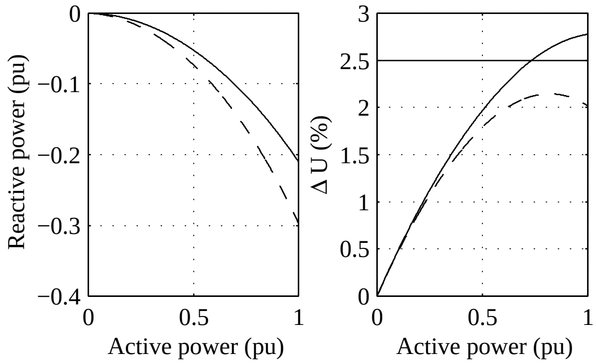

Figure 5. Reactive power consumption for two different induction generators, X/R=1.7.

B. Flicker emission

In Fig. 6 the flicker impact on a grid with a short-circuit impedance ratio of 10 is presented. It can again be noted that the flicker impact varies strongly with the X/R-ratio. Again it can be noted that a ratio of 2 is the most favourable.

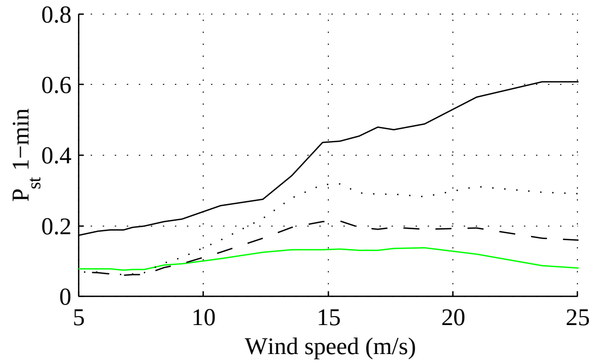

Figure 6. One minute flicker value and for the fixed-speed stall-regulated turbine using different XR-ratios. Short circuit ratio is equal to 10. Lines as in Fig. 3.

In Fig. 7 the limitations from a flicker and steady-state voltage point of view are presented for an installation of one and three stall-regulated turbines. The installations have the same total power rating. To be on the safe side one has to be above the limiting curves. In the case of a wind park the total flicker level from the whole wind park increases with the square-root of the number of turbines [6]. It can be observed that if one turbine is installed it is the flicker emission that sets the limit, while if three or more turbines are installed it is the steady-state voltage change that limits the installation.

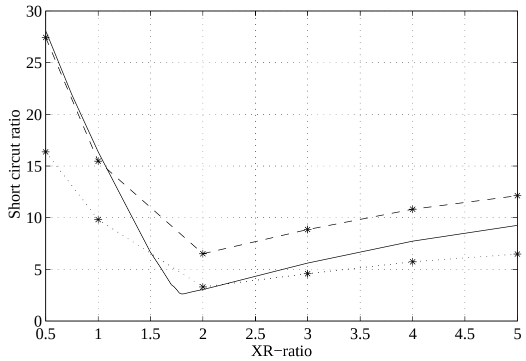

Figure 7. Limiting curves for the stall-regulated turbines. The solid curve is for the 2.5 % static voltage level change limit, the dashed curve is for flicker contribution of 0.25 with one turbine and the dotted curve is for flicker contribution of 0.25 with a wind farm consisting of 3 wind turbines.

V. GRID IMPACT BY VARIABLE-SPEED WIND TURBINES

In this paper only self-commutated transistor converters (or IGCT-converters) are treated. Thyristor-based line-commutated converters are not considered here.

Unless the variable rotor speed wind turbine is erroneously tuned, the flicker and harmonic current contribution will be low and will not be a problem. Assuming that these problems do not exist, leaves the electrical limitations of voltage level and line capacity. From the voltage level point of view it is the reactive power flow that is the key question.

Standard wind turbines with an asynchronous generator connected directly to the grid consumes reactive power from the grid according to a function of the active power. Capacitors located at the wind turbines compensate for the no-load consumption of reactive power. Once the installation is done the reactive power and thus the voltage level can not be controlled. This leads to a predestined steady-state voltage level impact on the grid as presented in Fig. 3 and discussed in Section II. However, using variable speed wind turbines or a set-up as in the Bockstigen wind park, converters are available to control the reactive power and in this way the voltage level and the grid losses can be influenced. There are of course numerous control strategies to control the reactive power flow. A standard choice could be the one used at the Bockstigen wind park. The reactive power is kept to zero as long as there are no over-voltage problems. In the case that the grid voltage is too high, the wind park starts to consume reactive power until a maximum reactive power limit is reached. At Bockstigen, the over-voltage limit is set to 11.05 kV in the PCC, and it is the responsibility of the wind park to maintain the voltage level below this value.

The ratio between installed wind power and short-circuit ratio of the grid in Bockstigen wind park is 7 and the X/R-ratio is 1.1. To install an additional wind turbine is not possible since this would lead to overheating of the supply lines. The desired limiting factor has thus been reached.

In figures 8-10 the steady-state impact on three different grids is presented. Fig. 8 presents the voltage level influence, Fig. 9 the reactive power demand and Fig. 10 the supply line losses between the wind turbines and the 30/10 kV transformer.

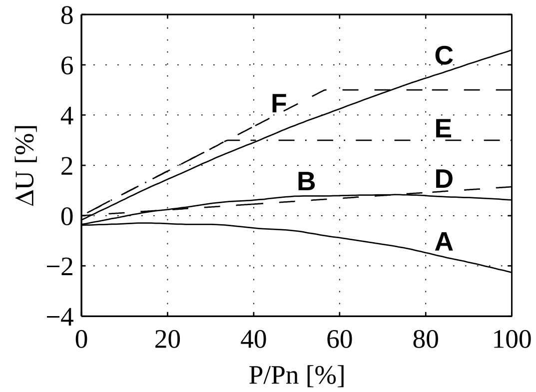

Fig. 8. Voltage level influence by different WECS. A-C Fixed-speed system, D-F variable-speed system. A & D: X/R=5, B: X/R=2, C: X/R=1.1, E: X/R=1.1 over voltage limit 3% and, F: X/R=1.1 over voltage limit 5%.

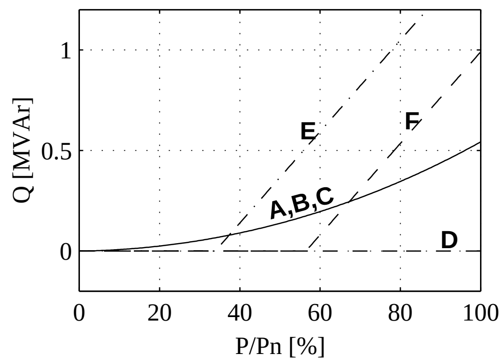

Fig. 9. Reactive power demand of different WECS. Notation as in Fig. 8.

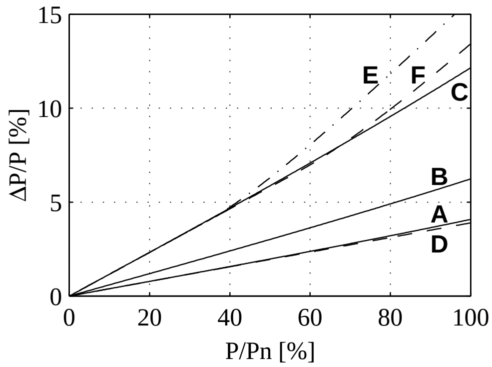

Fig. 10 - Supply line losses by different WECS. Notation as in Fig. 8.

From Figs. 8 and 10 it can be noted that the grid voltage influence and also the losses in the supply lines are worse when we have a mainly resistive grid (lower X/R ratio, C, E,F), as in the case with the Bockstigen wind park. This low ratio is due to the fact that the utility grid between Bockstigen and the 30 kV transformer consists of large portion of cables. It can be noted that with the 2.5 % voltage change limit the possible wind turbine production is only 40% of the desired one, case C, if fixed-speed wind turbines with standard phase-compensating equipment were used. For a higher power production, wind turbines has to be shut down in this case. However, with a high X/R ratio we will have no steady-state voltage variation problems at all with or without additional converters.

In the Bockstigen case a somewhat higher steady-state voltage variation is allowed, about 5 % which would have made it possible to produce about 70 % of the desired wind power with ordinary electrical systems for wind turbines (for given grid parameters). Here we can produce about 100 % of the desired power production by using the converters. During the first year of operation it was discovered that the park could only produce 85 % of the desired power due to the voltage limitation of 11.05 kV. This was caused by the fact that the 10/30 kV transformer also supply other lines where no wind turbines are connected. In order to keep the voltage high enough on these lines, the tap-changer could not lower the voltage enough. This problem has now almost been solved by changing the settings of the 10/30 kV transformer. In Figs. 11-13 an operation period close to the voltage limit is presented. The wind speed is above rated during this time series. The consumption by the other lines from the 30/10 kV transformer is also high which means that the tap-changer position must be high in order to give the customers at the end of these line a voltage that is high enough. Unfortunately this means that the receiving end from the Bockstigen 10 kV line also has a voltage higher than desired, leading to problems to keep the voltage down at the point of common connection. In Fig. 11 the active power is presented and Figs. 12 and 13 present the voltage level and reactive power respectively.

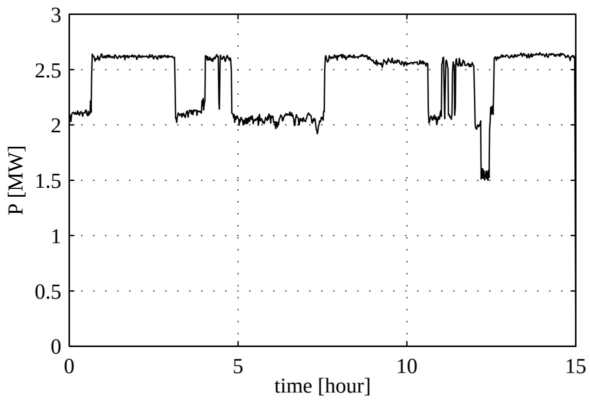

Fig. 11. Active power from Bockstigen during a high wind speed and high load condition.

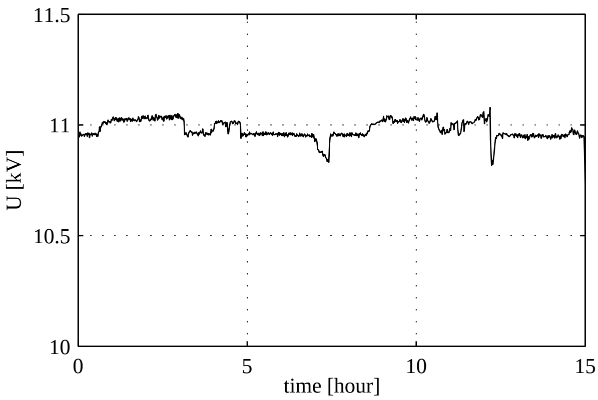

Fig. 12. Voltage level at Bockstigen during a high wind speed and high load condition.

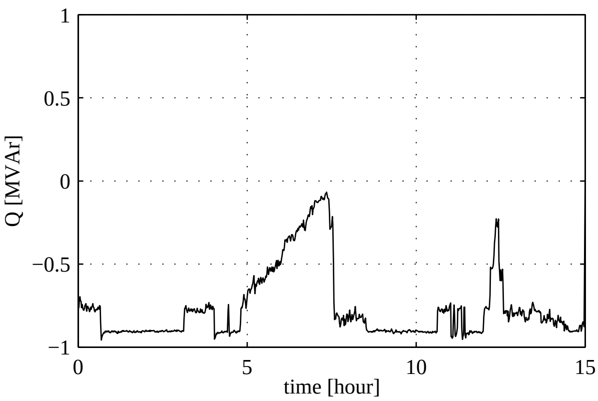

Fig. 13. Reactive power from Bockstigen during a high wind speed and high load condition.

From the figures it is observed that the voltage regulation works excellent. Sometimes the control system even has to shut down wind turbines due to the high voltage situation. This always occur when maximum reactive power is consumed. When there is no problem with the voltage level as between the 5th and 7th hour, the control system reduced the reactive power as much as possible without violating the voltage limit.

VI. CONVERTER TOPOLOGIES FOR WIND ENERGY CONVERTERS CONNECTED TO WEAK GRIDS.

In the wind turbines using electrical converters, it is the conventional 6-pulse converter that exclusively is used today. However, it would also be possible to use some other converter topologies, especially if the wind turbines are connected to a very weak, unbalanced grid. Either a 6-puls converter with an additional phase-leg for the neutral could be used or the "Neutral Point Clamped Converter", NPC-converter. Lundberg [10] presents very good experimental results are presented where the NPC-converter is used to balance one- or two-phase loads.

VII. CONCLUSIONS

This work investigates how much wind power that can be connected to different grids without encounter problems with the power quality at the nearest consumer. The result depends, of course, on the acceptable limits. Here, the limits stated by the Swedish requirements, AMP [6], are used.

It was found that the flicker contribution can only be a problem if less than three stall-regulated fixed-speed wind turbines are connected to a weak grid. If more than three turbines are connected to the same point or if variable-speed turbines are used it is the line capacity or voltage limitations that sets the limits. The goal of an installation to a weak grid is to reach the line capacity limit, and the key to reach this limit is the possibility to control the reactive power.

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IX. BIOGRAPHIES

Stefan Lundberg was born in Göteborg, Sweden in 1976. He received his M.Sc. in 2000 from Chalmers University of Technology. He is now working towards his Ph. D at the same department. His area of interest is the control and modelling of wind turbine parks.

Tomas Petru received his M.Sc. from the University of West Bohemia in Pilsen, Czech Republic in 1997. He is now working towards his Ph. D. at the Department of Electric Power Engineering at Chalmers University of Technology. His area of study is modelling wind turbines for power system studies.

Torbjörn Thiringer was born in Göteborg, Sweden in 1966. He received his Ph.D. in 1996 from Chalmers University of Technology. He is now working at the Department of Electric Power Engineering at Chalmers University of Technology. His area of interest is the control and modelling of induction machines, especially for wind turbine applications.

Appendix B

EMTDC© code

B.1 EMTDC© diagram

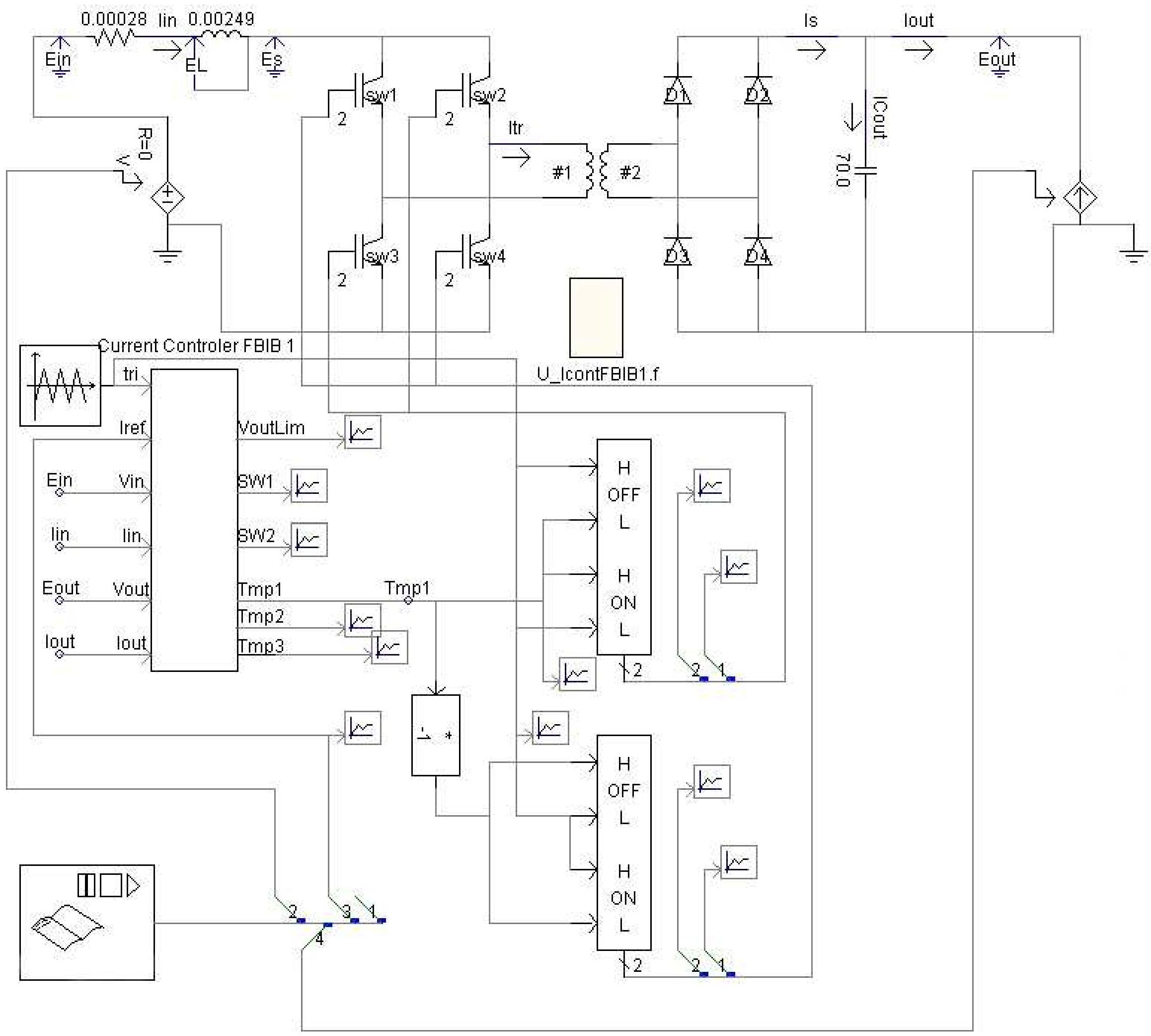

Figure B.1: Printout over the full bridge isolated boost converter implemented in EMTDC©

B.2 Fortran code for the current and voltage regulator

```
!
      SUBROUTINE U_IcontFBIB1(Triangel,Iref,Vin,Iin,Vout,VoutLim,Iout,SW1,
      SW2,Vrated,Ntr,fstilde,KpI,KiI,KpV,KiV,alfaVbeg,YaV,Tmp1,Tmp2,Tmp3)
!
! Purpose  - Controler for the FBIB converter
! Language - Fortran 77/90
! Date     - 2003-08-12
! Author   - Stefan Lundberg
!
! Include Files
! -------------
      INCLUDE 'nd.h'
      INCLUDE 's1.h'
      INCLUDE 'emtstor.h'
      IMPLICIT NONE
!
! Variable Declarations
! ---------------------
      REAL    Triangel,Iref,Vin,Iin,Vout,Iout,Vrated,Ntr,fstilde,KpI,KiI,
      KpV,KiV,alfaVbeg,YaV,Tmp1,Tmp2,Tmp3
      INTEGER SW1,SW2,VoutLim
      INTEGER ISTORF
      INTEGER Samplat,UtVreg,OverVoltage
      REAL    Tri2Sampl,Bref,Dref,Dmax,VoutMarg,Iinref,IntIreg,IntVreg,
      IntIregOLD,IntVregOLD,IinVreg,IinMaxVreg,IrefVreg,VoutT,KVsys
!
! Program begins
! --------------
      ISTORF = NSTORF
      NSTORF = NSTORF + 6
! it is good to assign NSTORF to ISTORF and
! have all the user assigned STORx locations at the
! top, then you can even use the other functions
! available in EMTDC in your code without worrying
! about which STORx locations are used by them
      Samplat  = STORF(ISTORF)      ! Visar om jag redan har samplat
      UtVreg = STORF(ISTORF+1)      ! Bestämmer moden för regulatorn
      OverVoltage = STORF(ISTORF+2) ! Överspännings begränsning
      Dref = STORF(ISTORF+3)        ! Värdet för D i denna halv perioden
      IntIregOLD = STORF(ISTORF+4)  ! Integraldelen för strömregleringen
      IntVregOLD = STORF(ISTORF+5)  ! Integraldelen för utspänningsregleringen
! here NSTORF points to the first STORF location
! used in the routine, in the old method in V2, NEXC
! pointed to the last STOR location in the previously
```

```
! called subroutine/function.

     !*********************************
     ! Här sätter jag alla konstanter
     Dmax = 0.4999       ! Maximala duty ration, = 0.5 går inte för då
      triggas inte switcharna
     Tri2Sampl = 0.48    ! Vad triangelvågen skall vara större än för att
      man skall sampla
     VoutMarg = 0.05     ! Säkerhetsmarginal för utspänningen i p.u. av
     märkspänningen
     IinMaxVreg = 3      ! Strömbegränsning för utspänningsregulatorn [kA]

! At time zero
     IF (TIMEZERO) THEN
    Samplat = 1      ! Kan inte sampla då t=0 för alla signaler har
     inte kommit upp än
    Dref = Dmax
    UtVreg = 0
    OverVoltage = 0
    IntIreg = 0
    IntIregOLD = 0
    IntVreg = 0
    IntVregOLD = 0
    VoutLim = 0
    IrefVreg = 0
     ENDIF

     IF (((Triangel .GE. Tri2Sampl) .OR. (Triangel .LE. -Tri2Sampl)) .AND.
      (Samplat .EQ. 0)) THEN
        ! Har inte samplat ännu. Beräknar regulator utvärdet
        Samplat = 1
        !**************************************************************
        ! Output Voltage Limiter Controler
        !
        ! Funktionen:
        ! Om utspänningen är förhög så beräknar jag ett nytt referensvärde
        för inströmen
        ! när detta är gjort jämför jag detta med den begärda inströmen
        från WT regulatorn
        ! och tar det minsta värdet.
        ! Om utspänningen är för låg beräknar jag ett nytt referensvärde
        för inströmen, när
        ! detta är gjort jämför jag detta med den begärda inströmen från
        WT regulatorn och
        ! tar det största värdet

        IF (((UtVreg .EQ. 1) .AND. (OverVoltage .EQ. 0)) .OR.
```

```
(Vout .LT. (Ntr*Vin+VoutMarg*Vrated))) THEN
   ! Utspänningsreglering används för underspänning
   ! Utspänningsreg enbart Preg

   ! Kan inte använda förstärkningen Vout/Vin ty ripplet i Vout
   gör att referensvärder
   ! börjar att ocilera. Därför använder jag börvärdet för att
   beräkna förstärkningen.
   KVsys = (Ntr*Vin+VoutMarg*Vrated)/Vin
   IrefVreg = KVsys*(Iout+(Ntr*Vin+VoutMarg*Vrated-Vout)*KpV)

   IF (Iref .GE. IrefVreg) THEN
      ! Strömreferensen från WT regulatorn är större än
       referensvärdet
      ! från utspäningsregleringen alltså väljer jag att använda
       WT reg
      ! referensen
      UtVreg = 0
      OverVoltage = 0
      VoutLim = 0
      Iinref = Iref
   ELSE
      ! Jag väljer strömreferensen från utspänningsregleringen
      UtVreg = 1
      OverVoltage = 0
  VoutLim = 1

  ! Inför en övre begränsning, ty Iin bör inte vara större än
   märkströmen
  IF (IrefVreg .GE. IinMaxVreg) THEN
     Iinref = IinMaxVreg
  ELSE
     Iinref = IrefVreg
  ENDIF
   ENDIF
   ! Här skall integraldelar för utspänningsregleringen uppdateras

ELSEIF (((UtVreg .EQ. 1) .AND. (OverVoltage .EQ. 1)) .OR.
 (Vout .GT. Vrated*(1-VoutMarg))) THEN
   ! Utspänningsreglering används för överspänning
   ! Utspänningsreg enbart Preg
   !KVsys = Vrated*(1-VoutMarg)/Vin
   KVsys = Vout/Vin
   IrefVreg = KVsys*(Iout+(Vrated*(1-VoutMarg)-Vout)*KpV)

   IF (Iref .LE. IrefVreg) THEN
      ! Strömreferensen från WT regulatorn är mindre än
```

```
        referensvärdet
       ! från utspäningsregleringen alltså väljer jag att använda
        WT reg
       ! referensen
       UtVreg = 0
       OverVoltage = 1
       VoutLim = 0
       Iinref = Iref
    ELSE
       ! Jag väljer strömreferensen från utspänningsregleringen
       UtVreg = 1
       OverVoltage = 1
   VoutLim = 1

   ! Inför en nedre begränsning, ty Iin kan alldrig vara
   negativ
   IF (IrefVreg .LE. 0) THEN
      Iinref = 0
   ELSE
      Iinref = IrefVreg
   ENDIF
    ENDIF
    ! Här skall integraldelar för utspänningsregleringen uppdateras

 ELSE
    ! Utspännings reglering skall ej användas
UtVreg = 0
VoutLim = 0
IntVreg = 0
Iinref = Iref
    IrefVreg = 0
 ENDIF

 !***********************
 ! Input Current Controler
 ! Bref är signalen D innan begränsningen
 ! För att strömregleringen inte skall hänga sig när utspänningen
 blir
 ! noll gör jag denna fix, ty utspänningen skall inte vara mindre än
 Ntr*Vin
 IF (Vout .LE. Vin*Ntr) THEN
    VoutT = Vin*Ntr
 ELSE
    VoutT = Vout
 ENDIF
 Bref = 0.5-Vin*Ntr/(2*VoutT)+Ntr/(2*VoutT)*
 ((Iinref-Iin)*KpI+KiI*IntIregOLD)
```

```
        Tmp2 = Iinref
        Dref = Bref
        IF (Dref .LE. 0) THEN
           Dref = 0
        ELSEIF (Dref .GE. Dmax) THEN
           Dref = Dmax
        ENDIF
        Tmp1 = Dref
        ! Uppdatering av integraltermen med anti wind upp
        IntIreg = IntIregOLD + (Iinref-Iin+2*Vout/(Ntr*KpI)*(Dref-Bref))/
        fstilde

     ELSEIF (((Triangel .GE. Tri2Sampl) .OR. (Triangel .LE. -Tri2Sampl))
      .AND. (Samplat .EQ. 1)) THEN
        ! Har samplat -> Skall inte göra något
     ELSE
        Samplat = 0
     ENDIF
     Tmp3 = Samplat

!********************
! Skapar modulationen
     IF (Triangel .LE. Dref) THEN
        SW2 = 1
     ELSE
        SW2 = 0
     ENDIF

     IF (Triangel .GE. -Dref) THEN
        SW1 = 1
     ELSE
        SW1 = 0
     ENDIF

!********************************
! save the data for next time step
     STORF(ISTORF) = Samplat
     STORF(ISTORF+1) = UtVreg
     STORF(ISTORF+2) = OverVoltage
     STORF(ISTORF+3) = Dref
     STORF(ISTORF+4) = IntIreg
     STORF(ISTORF+5) = IntVreg
!
     RETURN
     END
```