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The Power Quality of Wind Turbines

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Abstract

The power quality of wind turbines is dealt with in this dissertation. The thesis consists of four parts. The first part describes the electrical systems used in wind turbines. The second part presents the results of measurements of different types of wind turbines connected to different types of grids. The measurements include voltage and frequency variations, flicker, transients and harmonics. The third part deals with future standards for measuring and testing wind turbine power quality. In the last part, regulatory requirements concerning the power quality of wind turbines are discussed. Special emphasis has been given to flicker and flicker calculations according to new recommendations for the grid connection of wind turbines.

The operation of wind turbines has an impact on the power quality of the connected grid. Depending on the grid configuration and the type of wind turbine used, different power quality problems may arise. All wind turbines have an uneven power production following the natural variations of the wind. If the wind turbine is operating at fixed-speed, the tower shadow and wind speed gradients will result in fluctuating power. The power fluctuations caused by the turbine may cause flicker disturbances. In order to evaluate the significance of flicker, measurements and subsequent flicker calculations must be performed. In the case of variable-speed wind turbines, one drawback is the injection of harmonic currents into the grid. Depending on the type of inverter used, different orders of harmonics are produced.

The new recommendations provide tools for predicting the interaction between wind turbines and the grid. Wind turbines which, in combination with the grid, are likely to cause power quality problems can at an early stage of planning be rejected and replaced by a more proper type of wind turbine.

Keywords: Power quality, wind turbines, measurements, flicker, frequency variations

List of Publications

This thesis is based on the work contained in the following journal and conference papers:

Paper 1A: Å. Larsson, O. Carlson, G. Sidén, ”Electrical Generating Systems in Wind Turbine Applications”. *Stockholm Power Tech*, Stockholm, Sweden, 18-22 June 1995, Proceedings, Vol. Electrical Machines and Drives, p. 205 - 210.

Paper 1B: Å. Larsson, ”Power Quality of Wind Turbine Generating Systems and their Interaction with the Grid”, Technical Report No. 4R, Department of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden, 1997.

Paper 2A: Å. Larsson, T. Thiringer, ”Measurements on and Modelling of Capacitor-Connecting Transients on a Low-Voltage Grid Equipped with Two Wind Turbines”. *International Conference on Power System Transients* (IPST '95), Lisbon, Portugal, 3-7 September 1995, Proceedings, p. 184 - 188.

Paper 2B: Å. Larsson, ”Voltage and Frequency Variations on Autonomous Grids: A Comparison of Two Different Wind-Diesel Systems”. *European Union Wind Energy Conference* (EUWEC '96), Göteborg, Sweden, 20-24 May 1996, Proceedings, p. 317 - 320.

Paper 2C: Å. Larsson, ”Flicker and Slow Voltage Variations from Wind Turbines”. *International Conference on Harmonics and Quality of Power* (ICHQP '96), Las Vegas, USA, 16 - 18 October 1996, Proceedings, p. 270 - 275.

Paper 2D: Å. Larsson, P Sørensen, F. Santjer, “Grid Impact of Variable-Speed Wind Turbines”, *European Wind Energy Conference* (EWEC '99), Nice, France, 1-5 Mars 1999, Proceedings, p. 786 - 789.

Paper 3A: P Sørensen, G. Gerdes, R. Klosse, F. Santjer, N. Robertson, W. Davy, M. Koulouvari, E. Morfiadakis, Å. Larsson, “Standards for Measurements and Testing of Wind Turbine Power Quality", *European Wind Energy Conference* (EWEC '99), Nice, France, 1-5 Mars 1999, Proceedings, p. 721 - 724.

Paper 4A: Å. Larsson, "Guidelines for Grid Connection of Wind Turbines", *15th International Conference on Electricity Distribution* (CIRED ´99), Nice, France, 1-4 June, 1999.

Paper 4B: Å. Larsson, "Flicker Emission of Wind Turbines During Continuos Operations", *submitted to IEEE Transactions on Energy Conversion*, 2000.

Paper 4C: Å. Larsson, "Flicker Emission of Wind Turbines Caused by Switching Operations", *submitted to IEEE Transactions on Energy Conversion*, 2000.

Preface

The work involved in this thesis has been carried out at the Department of Electric Power Engineering of Chalmers University of Technology. The research has been funded through the EU-Joule II program and by Elforsk AB. The financial support given is gratefully acknowleged.

I would like to thank Dr Ola Carlson who initiated this research project and my examiner Professor Jaap Daalder for valuable comments, fruitful discussions and for persistently revising the manuscript. I also wish to thank Poul Sørensen for his support and encouraging guidance during my three month guest research-work at Risø National Laboratory.

The work presented is partly based on field measurements. I would like to thank the wind turbine manufacturers who have supported me with data; the owners of wind turbines who have given me the opportunity to perform measurements on their wind turbines; and Göteborg Energi AB, Varberg Energi AB and Gotland Energi AB for their cooperation in performing field measurements in their grid.

Finally, I would like to thank all the colleagues at the Department of Electric Power Engineering for a pleasant working atmosphere.

Contents

Abstract

Preface

1 Introduction

Wind power has developed dramatically. In 1999, more than 10 000 MW of wind power capacity was installed worldwide, during this year the world has installed more new wind power capacity than nuclear capacity. The global perspectives for wind power seem to be quite good. In 1999, the U.S. Department of Energy announced the ”Wind Powering America” initiative which sets a goal of 80 000 MW of wind power by the year 2020. Such an amount of wind power corresponds to approximately 5% of the U.S. electricity consumption. The European Commission’s white paper ”Energy for the Future - Renewable Energy Sources” presented in late 1997, targets 40 000 MW of wind power by 2010. At the end of 1999, Germany had almost 4 500 MW of wind power installed of which 1 500 MW was installed during that year. In Denmark, wind power is expected to cover 13% of the electricity consumption in 2000 if it turns out to be an average wind year. A Danish energy plan says that 15 to 16% of the Danish electricity consumption should come from wind power by the end of 2002. By 2030, 50% of the Danish electricity consumption should come from renewable, in particular, 4 000 MW of offshore wind power.

As a result of the growth of installed capacity, the wind power industry is one of the fastest expanding industries. New statistics from the Danish Wind Turbine Manufacturers Association show that production has increased six-fold in the course of the last five years, corresponding to an annual growth rate of 44% per year. German wind turbine export has also showed a clearly positive trend in 1999 with a growth rate of 42% as compared with 1998. Andersen [1] concludes; (i) that wind power over the last 20 years has become a competitive technology for clean energy production, (ii) that wind power will provide two digit percentages in many countries’ electricity supply and (iii) there is no reason why wind power should not become as important to the world’s future energy supply as nuclear power is today.

The question that needs to be raised is how wind power will affect both the distribution network and the whole grid. The role of the distribution networks is mainly confined to the interconnection between generation and transmission systems on one side and load centers on the other side. Consequently, such networks are described as “passive” networks. However, the integration of wind power into distribution networks will transform them from being passive to active networks. Various published work is related to this subject; [2 – 10] have shown that generators embedded into distribution networks can affect operation in such networks in a number of ways. These studies have shown that embedded generators; (i) can increase the fault levels to a degree that makes reinforcement mandatory, (ii) require new protection practices in order to provide protection to the network against abnormal conditions including faults and islanding conditions, (iii) affect the losses of distribution networks, (iv) introduce stability problems and (v) cause power quality problems.

Power quality relates to factors which describe the variability of the voltage level, as well as the distortion of voltage and current waveforms. The various power quality parameters fall into different categories, according to the time scale of the phenomena examined. A great number of works related to power quality have been published. Van Vyk [11] gives a brief historical introduction of power quality which includes a selected biography of 300 literature references. When it comes to the power quality of embedded generators, in general, and wind turbines, in particular, only some specific power quality problems are relevant. Some examples of published works covering this field are; the power quality improvements of wind farms [12], power quality improvements of wind parks using advanced static var compensators [13] and power quality and grid connection of wind turbines [14]. The power quality of wind turbines can be subdivided into different phenomena. Examples of published works dealing with different power quality phenomena are; load flow calculations [15], flicker [16], harmonics [17], lightning protection and over voltages [18]. There has also been work published concerning international standards for the power quality of wind turbines [19] and measurement systems for power quality measurements of wind turbines [20].

This thesis focuses on the power quality of wind turbines. The work has been performed in two different projects. The first project was financed by the European Union and the aim of the project, Power Quality of Wind Turbine Generation Systems and Their Interaction with the Grid, was to increase the general understanding of the interaction between wind turbines and the grid. The three principal objectives of the project were;

(i) the identification of current knowledge and clarification of regulatory requirements, (ii) the definition of appropriate power quality measures in the context of wind turbines and the development of related measurement procedures, (iii) the measurement and analysis of power quality at a limited range of sites of varying grid stiffness. The project concentrated mainly on steady-state measurements.

The objective of the second project was to study dynamic and transient phenomena of wind turbines and to contribute to the development of a new Swedish recommendation for the grid connection of wind turbines. In the project, dynamic and transient measurements were performed on four different types of wind turbines. The measurements and subsequent calculations have been used to verify the power quality caused by the turbines.

This thesis consists of a summarizing part followed by the appended journal and conference papers which constitute the main part of the thesis. The first summarizing part contains a short discussion of wind turbine concepts, such as wind turbine performance, design and electrical systems used in wind turbines operating at fixed-speed and variable-speed. The first summarizing part also includes a discussion of the power quality of wind turbines. Comments are made on the included papers and some conclusions are drawn.

The second part of the report consists of ten papers which are divided into four sections. The first section is an introduction to electrical systems and the power quality of wind turbines. The second section presents measurements of different types of wind turbines connected to different types of grids. The measurements include voltage and frequency variations, flicker, transients and harmonics. The third section deals with standards for measuring and testing wind turbine power quality. In the last section, regulatory requirements concerning the power quality of wind turbines are discussed. Special emphasis is given to flicker and flicker calculations according to Danish and Swedish recommendations for the grid connection of wind turbines and the draft of IEC 61400-21.

2 Wind Turbine Performance and Design

The wind has been used to power sailing ships for many centuries. On land, wind turbines date back to the middle of the seventh century A.D. The earliest recorded English wind turbine dates from A.D. 1191. The first corn-grinding wind turbine was built in The Netherlands in 1439. Denmark was the first country to use wind turbines for the generation of electricity. In 1890, a wind turbine with a diameter of 23 meters was used for that purpose. By 1910, several hundred units with a capacity of 5 to 25 kW were in operation in Denmark [21].

A strong interest in renewable energy sources started in the mid 1970s when concerns about the environmental effects of fossil energy sources coincided with the OPEC oil embargoes. Wind turbine technology has matured during the last 25 years and is today an accepted technology.

2.1 Turbine

Wind turbines generate power by converting the kinetic energy in the air into rotating mechanical power. The most common wind turbine is of the horizontal-axis propeller type with two or three blades mounted on the top of a tower. The number of blades on a wind turbine is not an easy design choice. Two blades cost less than three blades, but two-bladed wind turbines must operate at higher rotational speeds than three-bladed wind turbines. As a result, the individual blades in a two bladed wind turbine need to be lighter and stiffer and are therefore more expensive [22].

The power of the wind in an area, *A,* perpendicular to the wind direction is given by the formula [21]:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \tag{1}$$

where P is the power, ρ is the air density and v is the wind speed. The fraction of the wind captured by a wind turbine is given by a factor, Cp, called the power coefficient. The value of the power coefficient has a theoretical Betz limit of 59.3%.

The design of wind turbines is governed by the need to withstand mechanical loads. Most wind power sites experience high wind speeds only during a few hours per year and some form of power regulation is necessary if a design is to be economical. The aerodynamic design can be regulated either by designing the blades to go into an aerodynamic stall above a certain wind speed or by designing the blades as feathered in order to spill the unwanted power. The first method is called stall-regulation; the second method is called pitch-control. One advantage of stall-regulation is the simplified mechanical design which allows the blades to be attached rigidly to the hub. In addition, stall-regulation will not permit power excursions from gusty winds to pass through the drive train. The disadvantages are the technical difficulties of aerodynamic stall design, the need for a rotor brake, motor driven start and more aerodynamic noise [23].

Fig. 2.1 shows a design wind speed-power curve which reflects both the aerodynamic power and the regulated power from the wind turbine. At low wind speeds, the generated power is too low to be exploited. Normally, wind turbines are started when the wind speed exceeds 3-4 m/s. This wind speed is denoted as the cut-in wind speed. As can be seen in Fig. 2.1, a wind turbine is started at cut-in wind speed and the power increases with the cube of the wind speed until the rated wind speed is reached.

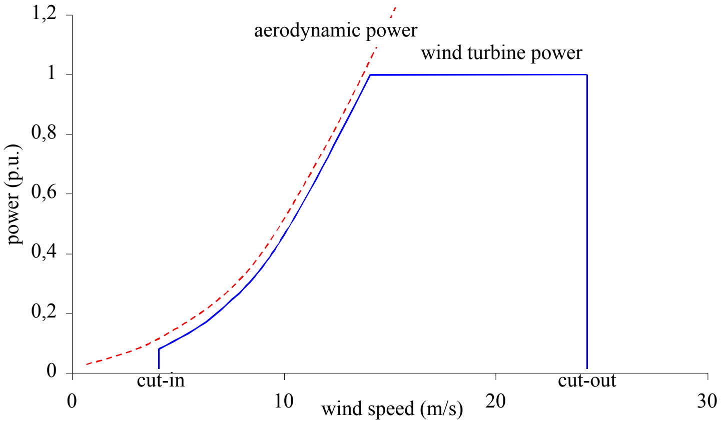

Fig. 2.1: Power curve of a wind turbine. 1 p.u. corresponds to the rated power of a wind turbine.

At wind speeds from 12 m/s to 25 m/s the power is limited to the rated power of the wind turbine by means of stall-regulation or pitch-control. At wind speeds over 20-25 m/s wind turbines are normally stopped to avoid high mechanical loads. The wind speed at which wind turbines are stopped is called the cut-out wind speed.

2.2 Fixed-speed Wind Turbines

The generator in fixed-speed wind turbines is of the induction type connected directly to the grid. Synchronous generators have been used in some early prototypes but the induction machine has been more widely adopted because of lower cost, improved environmental durability and a superior mechanical compatibility with rapid wind variations. The generator together with a gearbox are placed in a nacelle on the top of the tower. The function of the gearbox is to change the low rotational speed of the turbine to a high rotational speed on the generator side. The rotational speed of an induction generator is typically 1000 or 1500 rpm [24]. The turbine speed is dependent on the rotor diameter, for example a 200 kW turbine has a rotational speed of approximately 50 rpm, while the rotational speed of a 1 000 kW turbine is approximately 30 rpm. Figure 2.2 illustrates the major components in a fixed-speed wind turbine.

A fixed-speed wind turbine is designed to obtain maximum efficiency at one wind speed that will give the optimum tip speed to wind speed ratio for the rotor airfoil. In order to capture more energy, some fixed-speed wind turbines have two different rotational speeds. This can be achieved either by two generators or by one generator with two windings.

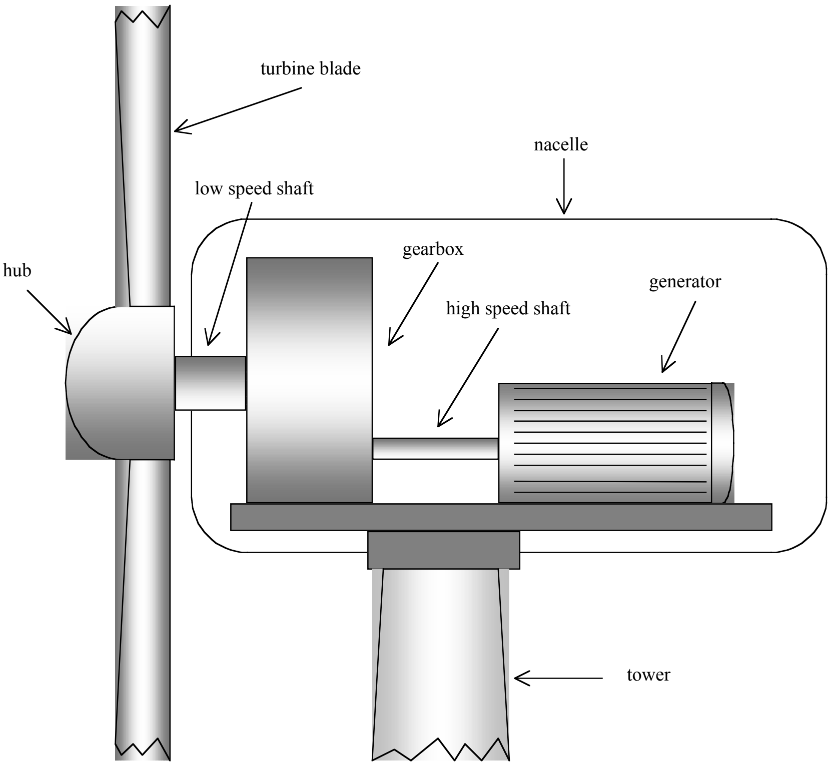

Fig. 2.2: Schematic figure of a typical fixed-speed wind turbine illustrating the major components.

2.3 Variable-speed Wind Turbines

The construction and the major components in wind turbines operating within a narrow variable-speed range are similar to fixed-speed wind turbines. Wind turbines operating within a narrow speed range normally have a double-fed induction generator with a converter connected to the rotor circuit. Since the rotational speed of the generator varies around 1000 or 1500 rpm a gearbox is required.

Wind turbines operating within a broad variable-speed range are equipped with a frequency converter. The use of a frequency converter makes it possible to use a direct-driven generator. A direct-driven generator with a large diameter can operate at a very low speed and does not need a gearbox. The use of a direct-driven generator makes it possible to simplify the nacelle design. In a conventional fixed-speed wind turbine, the gear and the generator must be mounted on a stiff bed plate and aligned precisely. A direct-driven generator can be integrated with the nacelle so that the generator housing and support structure are also the main parts of the nacelle [25]. Figure 2.3 illustrates the major components in a broad variable-speed range wind turbine equipped with a large diameter direct-driven generator.

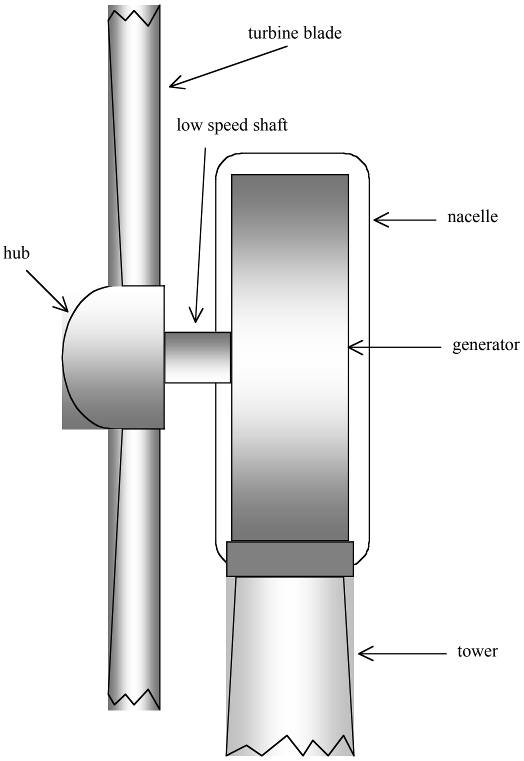

Fig. 2.3: Schematic figure of a typical variable-speed wind turbine illustrating the major components.

3 Electrical Systems in Wind Turbine Generator Systems

Electrical systems in wind turbine generator systems can be divided into two main groups, i.e., fixed speed and variable speed. Fixed-speed wind turbines, equipped with a generator connected directly to the grid, are the most common type. The major advantage of the fixed-speed turbine is the simplicity and the low price of the electrical system used.

Variable-speed wind turbines are today not as common as fixed-speed wind turbines, although in the future they will most likely be the dominating type. The advantages of using variable-speed turbines are increased power quality, noise reduction and reduced mechanical stress on the wind turbine. Variable-speed wind turbines are equipped with a converter, which allows the generator frequency to differ from the grid frequency.

3.1 Fixed Speed

Almost all manufacturers of fixed-speed turbines use induction generators connected directly to the grid. Since the frequency of the grid is fixed, the speed of the turbine is settled by the ratio of the gearbox and by the number of poles in the generator. In order to increase the power production, some fixed-speed turbines are equipped with a two speed generator and thereby can operate at two different speeds. In order to avoid a large inrush current, a soft starter for the limitation of the current during the start sequence is used [26]. In Fig. 3.1, a schematic figure of the electric system of a fixed-speed wind turbine is shown.

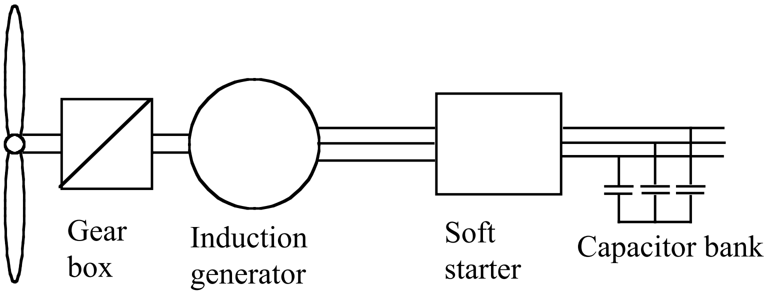

Fig. 3.1: Schematic figure of the electric system of a fixed-speed wind turbine.

The induction generator has several advantages, such as a robust design, no need for maintenance, well enclosed and produced in large series. It also has a low price and can withstand overloads. The major disadvantage is the uncontrollable reactive power consumption of the induction generator. In order to compensate for the reactive power consumption, shunt capacitor banks are used. Fig. 3.2 shows the measured reactive power consumption *Q* of an induction generator as a function of the active power *P*. The generator in the figure is equipped with shunt capacitors which compensate for the reactive power consumption of the induction generator at no-load [27].

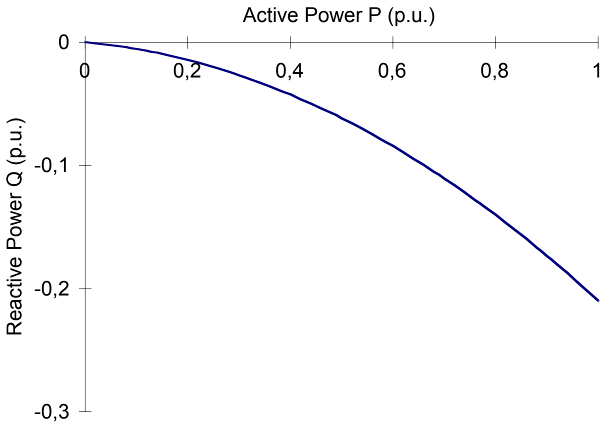

Fig. 3.2: Reactive power as a function of active power. 1 p.u. corresponds to the rated active power.

3.2 Variable Speed

Today, several manufacturers are using variable-speed wind turbines. The electrical system becomes more complicated when it comes to variable-speed operation. The variable-speed operation of a wind turbine can be obtained in many different ways, and several different electrical systems are used for a broad or a narrow speed range. The difference between broad and narrow speed ranges is mainly the energy production and the capability of noise reduction. A broad speed range increases the power production and reduces the noise further when compared with a narrow speed range. Controlled in a proper way, all kinds of variable speed systems can reduce power fluctuations emanating from the tower shadow.

3.2.1 Narrow Speed Range

For a narrow speed range, a double-fed induction generator with a converter connected to the rotor circuit can be used [28]. This type of variable-speed system is used by several large manufacturers. A schematic figure of the system is shown in Fig. 3.3.

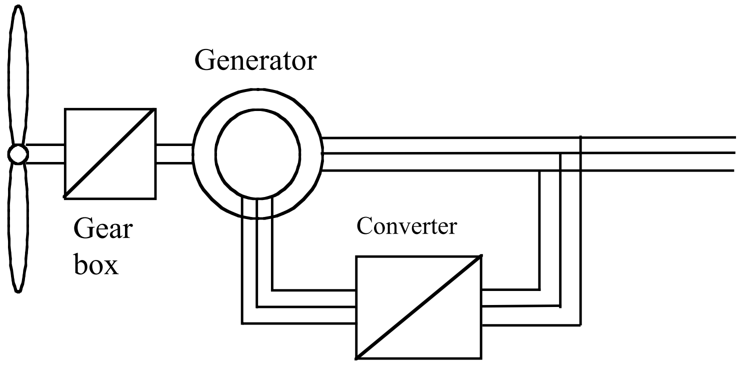

Fig. 3.3: Schematic figure of the electrical system of a variable-speed wind turbine equipped with a double-fed induction generator with a converter connected to the rotor circuit.

Another possible arrangement is to use controllable rotor resistances. A Danish manufacturer is producing a wind turbine in which the slip of the induction generator, and thereby the speed of the rotor, can vary by 1-10%. The system uses an optically controlled converter by which the resistance of the rotor in the generator can be varied [29]. In Fig. 3.4, a schematic figure of the electrical system of a wind turbine equipped with controllable rotor resistances is shown.

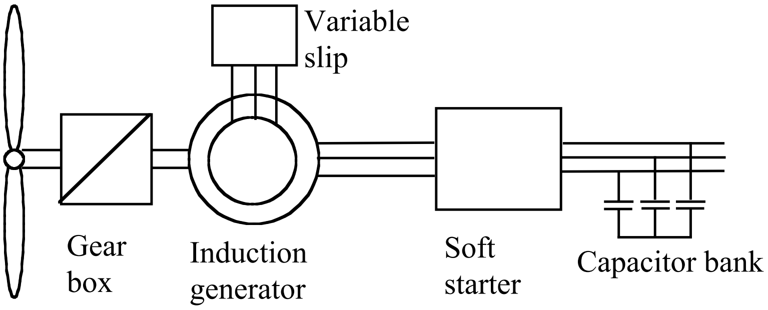

Fig. 3.4: Schematic figure of the electrical system of a wind turbine equipped with controllable rotor resistances.

3.2.2 Broad Speed Range

Broad-range variable-speed systems are equipped with a frequency converter. In such a system, the alternating current from the generator first needs to be rectified and then inverted into alternating current before being fed into the grid. The electrical system must, therefore, consist of three main parts: generator, rectifier and inverter. The choice of these three main parts can be subdivided into two almost independent choices. The generator and rectifier must be chosen as a combination and the inverter can be chosen almost independently of the generator and rectifier used. Some broad-range, variable-speed systems have no gearbox. Systems without a gearbox normally have a direct-driven multipole generator with a large diameter. The generator can be an electrically excited or permanent magnet excited synchronous type. A German manufacturer uses a large diameter generator that is an electrically excited synchronous type.

When it comes to power quality aspects, only the inverter is of interest. In Fig. 3.5, a schematic figure of a variable-speed wind turbine equipped with a converter is shown. The converter includes a rectifier and an inverter.

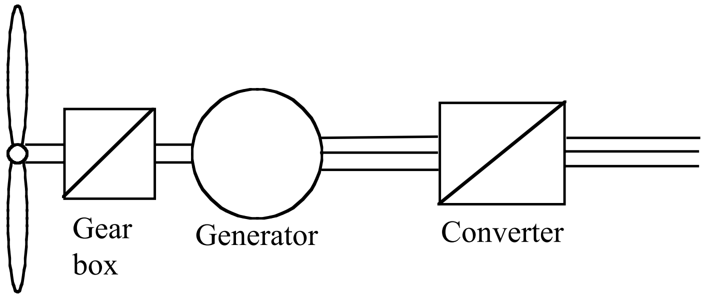

Fig. 3.5: Schematic figure of the electric system of a variable-speed wind turbine equipped with a converter.

The two most common types of inverters used are the line-commutated and the forced-commutated ones. These two types of inverters produce harmonics of different orders and hence need different types of filters. The line-commutated inverter is equipped with thyristors which must be connected to the grid in order to operate. Moreover, the power factor of the line-commutated inverter varies and is at most 0.9. The line-commutated inverter produces not only fundamental current but also harmonic current, which will cause voltage harmonics in the grid. A six-pulse line-commutated inverter produces odd harmonics which are not multiples of 3. If the RMS value of the fundamental current is $I_{(1)}$=1 p.u., the relative RMS values of the harmonics become $I_{(n)}$=1/n p.u. where n=5, 7, 11, 13, 17, 19, ... [30]. A large grid filter must be used to eliminate these harmonics. A positive effect of a grid filter is that the filter produces reactive power. This production of reactive power increases the power factor of the wind turbine generator system.

In a forced-commutated inverter it is possible to freely choose when to turn on and when to turn off the valves. This possibility means that the forced-commutated inverter can create its own three-phase voltage system. If the inverter is connected to the grid, the inverter can freely choose which power factor to use. Fig. 3.6 shows the measured reactive power of a variable-speed wind turbine equipped with a forced-commutated inverter. In the figure, the reactive power consumption *Q* is plotted as a function of the active power *P*. The power factor of this particular wind turbine is 0.98.

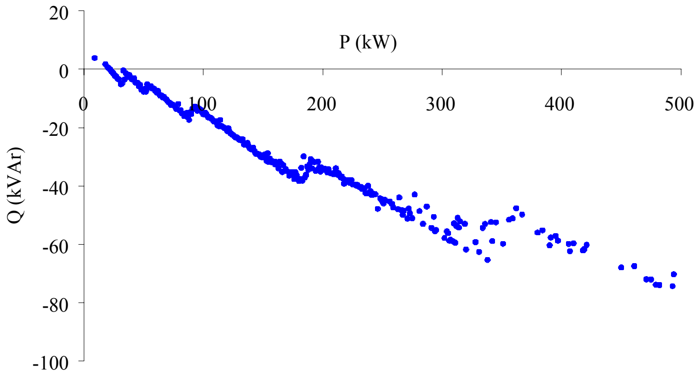

Fig. 3.6: Reactive power consumption as a function of active power of a variable-speed wind turbine equipped with a forced-commutated inverter.

By using the Pulse Width Modulation (PWM) technique low frequency harmonics will be eliminated and the first harmonic will have a frequency around the switching frequency of the inverter. Usually, when IGBT-valves are used, the switching frequency is about 5 to 10 kHz. Only a small grid filter will be needed because of the high switching frequency.

4 Power Quality of Wind Turbines

Perfect power quality means that the voltage is continuous and sinusoidal having a constant amplitude and frequency. Power quality can be expressed in terms of physical characteristics and properties of electricity. It is most often described in terms of voltage, frequency and interruptions. The quality of the voltage must fulfil requirements stipulated in national and international standards. In these standards, voltage disturbances are subdivided into voltage variations, flicker, transients and harmonic distortion [31, 32]. Fig. 4.1 shows a classification of different power quality phenomena.

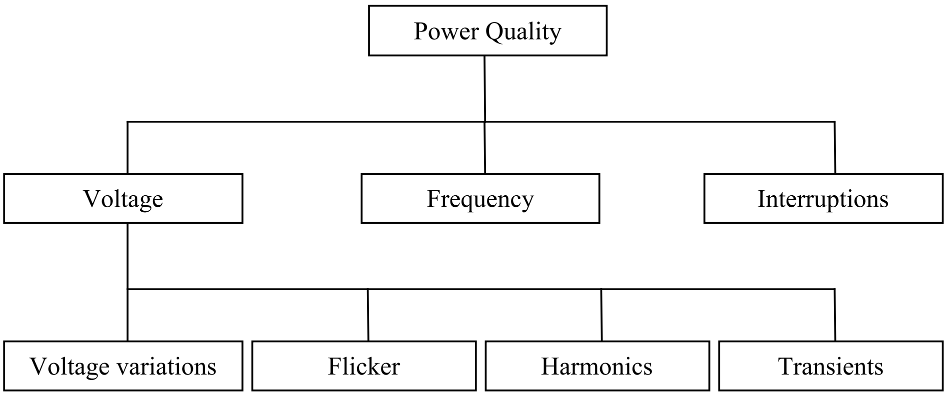

Fig. 4.1: Classification of different power quality phenomena.

Grid-connected wind turbines do affect power quality. The power quality depends on the interaction between the grid and the wind turbine. Most of this chapter deals with the different aspects of voltage disturbances. The frequency of large power systems is normally very stable and therefore no problem. On autonomous grids where, for example, diesel engines are used, wind turbines may cause frequency variations which are further discussed at the end of this chapter. A wind turbine normally will not cause any interruptions on a high-voltage grid. Interruptions therefore will not be considered in this report. This chapter also presents methods for determining power quality from grid-connected wind turbines.

4.1 Voltage Variations

Voltage variations can be defined as changes in the RMS value of the voltage occurring in a time span of minutes or more. National standards often state allowable variations in nominal voltage over an extended period, for instance 24 hours. IEC Publication 38 recommends 230/400 V as the standard voltage for 50 Hz systems [33]. Under these conditions, the voltage at the user's terminal must not differ more than ±10% from the rated voltage.

Voltage variations on the grid are mainly caused by variations in load and power production units. When wind power is introduced, voltage variations also emanate from the power produced by the turbine. The power production from wind turbines may vary widely and not only due to variations in the wind. It may also momentarily go from full to zero power production in the event of an emergency stop or vice versa at a start under high wind conditions.

All kinds of wind turbines cause voltage variations. Voltage variations are due to the variation in the energy content of the wind. Several methods are used to calculate voltage variations. For example, there are several computer programs for load flow calculations available on the market. Utility companies use this software for predicting voltage variations caused by load variations. Load flow calculations can advantageously be used to calculate variations in the voltage caused by wind turbines. Another analytical method is simply to calculate the voltage variation caused by the grid impedance Z, the active power P and reactive power Q [34]. In the analytical method, a simple impedance model shown in Fig. 4.2 is used. U_1 is the fixed voltage at the end of the power system and U_2 is the voltage at the point of common connection, PCC.

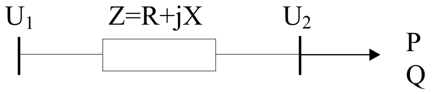

Fig. 4.2: Simple impedance model.

The voltage at the PCC can be expressed as

$$U_2 = \sqrt{a + \sqrt{a^2 - b}} \tag{2}$$

where

$$a = \frac{U_1^2}{2} - (RP + XQ) \tag{3}$$

$$b = (P^2 + Q^2)\left|Z^2\right| \tag{4}$$

Fig. 4.3 shows the calculated voltage of the grid at the PCC at different *X/R* ratios and at a constant short-circuit ratio. The short-circuit ratio is defined as the ratio between the short-circuit power of the grid at the PCC and the rated power of the wind turbine. As can be seen in Fig. 4.3, a low *X/R* ratio will increase the voltage at the PCC while a high *X/R* ratio will lower the voltage.

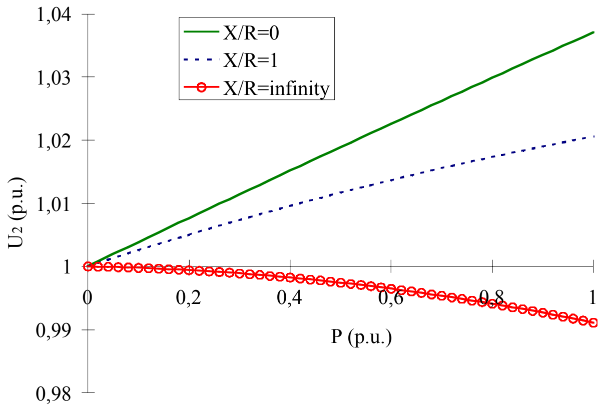

Fig. 4.3: Voltage variations at different *X/R* ratios. The short-circuit ratio is constant.

A simplified version of Equation 2 is used in the new Danish and Swedish regulations for grid-connected wind turbines [35, 36].

$$\frac{\Delta u}{U} = \frac{R \cdot P + X \cdot Q}{U} \cdot 100\% \tag{5}$$

where R is the resistance and X the reactance of the line. U is the voltage of the overhead line, P is the produced active power and Q is the produced reactive power of the wind turbine.

In Denmark and Sweden, voltage variations may not exceed 2,5% for a distribution feeder. If only wind turbines are connected to a feeder the voltage variation may not exceed 5%.

4.2 Flicker

Flicker is an old way of quantifying voltage fluctuations. The method is based on measurements of variations in the voltage amplitude, i.e., the duration and magnitude of the variations. Flicker is treated in Standard IEC 60868 and Amendment 1 [37, 38]. Fig. 4.4, shows the magnitude of maximum permissible voltage changes with respect to the number of voltage changes per second, according to Standard IEC 60868.

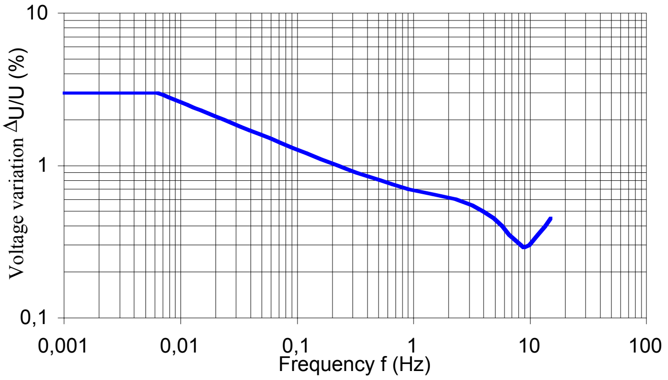

Fig. 4.4: Flicker curve according to IEC 60868.

The fluctuations are weighted by two different filters. One filter corresponds to the response of a 60 W light-bulb and the other filter corresponds to the response of the human eye and brain to variations in the luminance of the light bulb [39].

Flicker from grid-connected wind turbines has been the subject of several investigations [16, 40–42]. Flicker from wind turbines originates in two different modes of operation; continuous operation and switching operations.

4.2.1 Continuous Operation

Flicker produced during continuous operation is caused by power fluctuations. Power fluctuations mainly emanate from variations in the wind speed, the tower shadow effect and mechanical properties of the wind turbine. Pitch-controlled turbines also have power fluctuations caused by the limited bandwidth of the pitch mechanism. Fig. 4.5 shows the measured power of a pitch-controlled fixed-speed wind turbine with a rated power of 225 kW under high wind-speed conditions. The figure shows variations in the power produced by the wind turbines. As previously mentioned, fixed-speed wind turbines produce a power pulsation due to wind gradient and tower shadow.

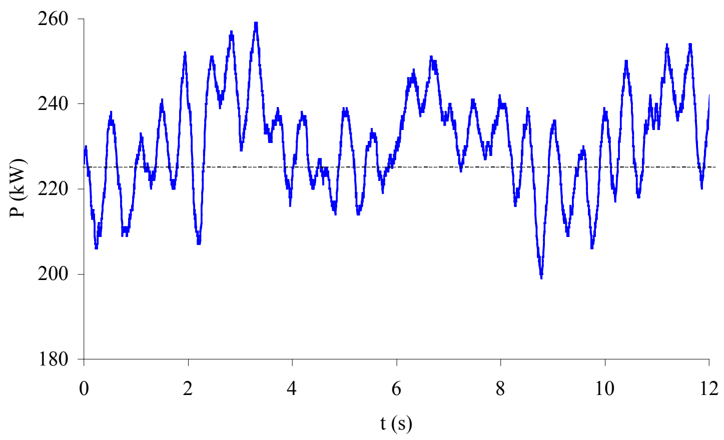

Fig. 4.5: Measured power during normal operation of a pitch-controlled fixed-speed wind turbine (solid line). In the figure the steady-state power is also plotted (dotted line).

In order to determine flicker emission produced during the continuous operation of a wind turbine, measurements have to be made. The IEC 61400-21 warns that flicker emission should not be determined from voltage measurements, as this method will be influenced by the background flicker of the grid [43]. The method proposed to overcome this problem is based on measurements of current and voltage. The short-term flicker emission from the wind turbine should be calculated by means of a reference grid using the measured active and reactive power as the only load on the grid. According to the

IEC 61400-21, the flicker coefficient from wind turbines is to be determined by applying:

$$c(\psi_k) = P_{st,fic}\frac{S_{k,fic}}{S_{ref}} \tag{6}$$

where $c(\psi_k)$ is the flicker coefficient and S_{ref} is the rated apparent power of the wind turbine. $P_{st,fic}$ is the flicker emission level calculated at the short-circuit power of a fictitious reference grid $S_{k,fic}$ with grid angle ψ_k. The grid angle is defined as:

$$\psi_k = \arctan\left(\frac{X_k}{R_k}\right) \tag{7}$$

where X_k is the reactance and R_k is the resistance of the grid. The flicker emission produced by a wind turbine connected to a grid with the arbitrary short-circuit power S_k may then be calculated by

$$P_{st} = c(\psi_k)\cdot\frac{S_{ref}}{S_k} \tag{8}$$

According to the IEC 61400-21, the following equation applies when determining the flicker contribution from several wind turbines connected to a common point:

$$P_{st\Sigma} = \sqrt{\sum_i P_{st,i}^2} \tag{9}$$

where $P_{st,i}$ is the flicker emission from each individual wind turbine.

4.2.2 Switching Operations

Switching operations will also produce flicker. Typical switching operations are the start and shut down of wind turbines. Start, stop and switching between generators or generator windings will cause a change in the power production. The change in the power production will cause voltage changes at the point of common connection, PCC. These voltage changes will in turn cause flicker. The start sequences of variable-speed wind turbines as well as stall-regulated and pitch-controlled fixed-speed wind turbines are all different. Variable-speed wind turbines are normally equipped with pitch-control. Generally, due to the controllable speed of the turbine and the pitch-control, the starting sequence of variable-speed wind turbines is smoother than for fixed-speed wind turbines.

Fig. 4.6 shows the measured power during the start of a pitch-controlled wind turbine. The start of the wind turbine occurs at t=30 s. As can be seen, the wind turbine consumes reactive power in order to magnetize the generator. The soft-starter operates for two or three seconds in order to limit the current to the rated value. The reactive power is then compensated for by means of shunt capacitor banks. It can be seen that the capacitors are switched in four steps with a time delay of approximately 1 second. As all capacitor banks have been switched in at approx. t=35 s., the blades of the turbine are pitched which results in an increase in power production. The power production also affects the reactive power consumption.

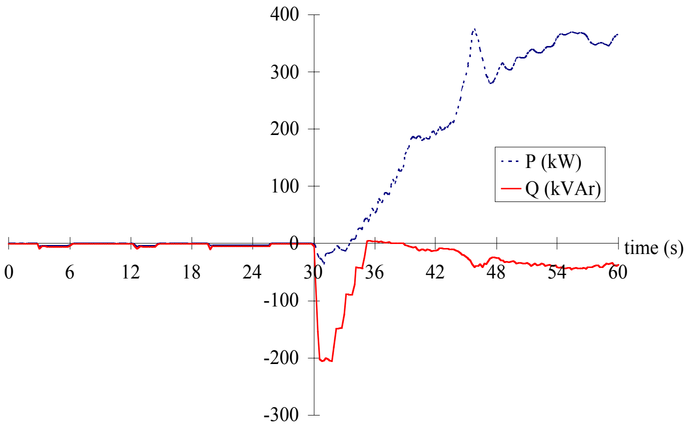

Fig. 4.6: Measured power during start of a fixed-speed pitch-controlled wind turbine. The rated power of the wind turbine is 600 kW. Active power (dotted line) and reactive power (solid line).

In Fig. 4.7, the corresponding terminal voltage of the wind turbine is shown. The voltage change caused by the start of the wind turbine can be divided in two parts. The first part is caused by the reactive power consumption of the generator. As can be seen, the reactive power consumption causes a voltage drop. As the capacitors are connected and the reactive power consumption falls back to zero, the voltage level is restored.

The second part is caused by the power production. As the power production increases, the voltage level begins to rise.

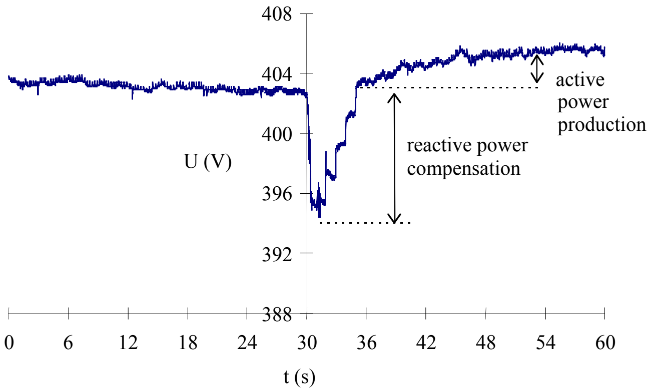

Fig. 4.7: Measured voltage during start of a fixed-speed pitch-controlled wind turbine.

According to the IEC 61400-21, measurements have to be taken of the switching operations during wind turbine cut-in and when switching between generators. The switching between generators is only applicable to wind turbines with more than one generator or a generator with multiple windings. The three phase currents and the three phase-to-neutral voltages are to be measured. Measurements and subsequent simulations and calculations are to be performed to determine the voltage change factor k_u and the flicker step factor k_f for each of the switching operations at different grid angles Ψ_k. The voltage drop in percent caused by a single start of the wind turbine may then be determined by:

$$\Delta U \leq k_u(\psi_k)\frac{S_{ref}}{S_k} \cdot 100 \tag{10}$$

where $k_u(\psi_k)$ is the voltage change factor calculated at the grid angle ψ_k. Under low wind conditions, wind turbines may start and stop several times. The resulting flicker emission caused by a repeated number of voltage drops is calculated by [35]:

$$P_{lt} = \left(\frac{2{,}3 \cdot N}{T} \right)^{\frac{1}{3,2}} \cdot F \cdot \frac{\Delta U}{U} \tag{11}$$

where *N* is the number of voltage drops during *T* seconds. Since the equation refers to long-term flicker, a period of two hours is used. *U* is the voltage and *F* is the form factor of the voltage drop *ΔU*. The form factor for different types of voltage drops is treated in the committee draft IEC 61000-3-7, [44].

In the IEC 61400-21, a flicker step factor is introduced. The flicker step factor is calculated from the measured voltage drop caused by the cut-in of the generator. The flicker emission caused by a repeated number of cut-ins of the wind turbine can be determined by using the flicker step factor as:

$$P_{lt} = 8 \cdot k_f(\psi_k) \cdot (N)^{\frac{1}{3,2}} \cdot \frac{S_{ref}}{S_k} \tag{12}$$

where $k_f(\psi_k)$ is the flicker step factor calculated at the grid angle ψ_k. *N* is the maximum number of switching operations during a period of two hours.

4.3 Harmonics

Voltage harmonics are virtually always present on the utility grid. Non-linear loads, power electronic loads, rectifiers and inverters in motor drives etc., are some sources which produce harmonics. The effects of the harmonics include overheating and equipment failure, faulty operation of protective equipment, nuisance tripping of a sensitive load and interference with communication circuits [45].

Harmonics and inter-harmonics are defined in the IEC 61000-4-7 and Amendment 1 [46, 47]. Harmonics are components with frequencies which are multiples of the supply frequency, i.e., 100 Hz, 150 Hz, 200 Hz, etc. Inter-harmonics are in a similar way defined as components having frequencies located between the harmonics of the supply frequency.

The signal which is to be analyzed, is sampled, A/D-converted and stored. These samples form a window of time ("window width") on which a discrete Fourier transformation is performed. The window width, according to the standard, is to be 10 line-periods in a 50 Hz system. This window width will give a distance between two consecutive inter-harmonic components of 5 Hz. Fig. 4.8 shows the inter-harmonic components of the measured current from a variable-speed wind turbine. The current has been analyzed in accordance the IEC 61000-4-7.

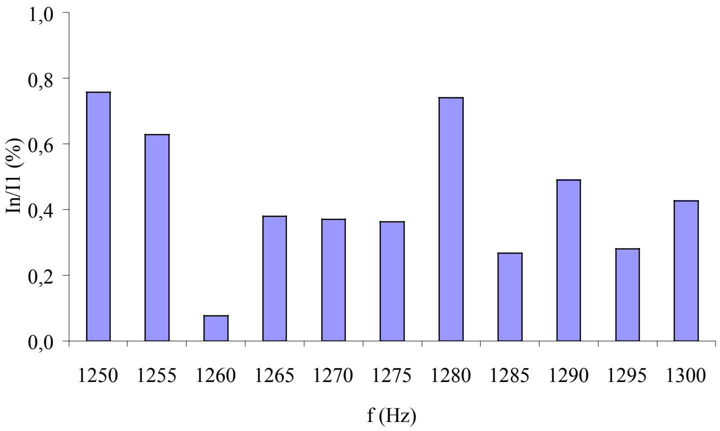

Fig. 4.8: Current inter-harmonic content between 1250-1300 Hz.

Fixed-speed wind turbines are not expected to cause significant harmonics and inter-harmonics. The standard IEC 61400-21 does not require any specification of harmonics and inter-harmonics for this type of wind turbine. For variable-speed wind turbines equipped with a converter the emission of harmonic currents during continuous operation is to be specified. These are to be specified for frequencies up to 50 times the fundamental grid frequency, as well as the total harmonic distortion and the emission of the individual harmonics. The relevant emission limits according to the IEC 61800-3 are given in Table 4.1, [48]. The IEC 61800-3 further recommends the total harmonic distortion (THD) to be less than 5% of the fundamental rated current.

Table 4.1: Emission limits according to IEC 61800-3.

Harmonic order	Odd harm. current (% of I_{rated})	Even harm. current (% of I_{rated})
n<11	4,0	1,0
11≤n≤17	2,0	0,5
17≤n≤23	1,5	0,4
23≤n≤35	0,6	0,2
35≤n≤50	0,3	0,1

According to the IEC 61000-4-7, the following equation applies when determining the harmonic currents from more than one source connected to a common point:

$$i_n = \sqrt[\alpha]{\sum_k i_{n,k}^{\alpha}} \qquad (13)$$

where i_n is the harmonic current of the order n, $i_{n,k}$ is the harmonic current of the order n from source number k and α is an exponent chosen from Table 4.2. This recommendation is valid for wind farm applications.

Table 4.2: Exponent for harmonics.

α	harmonic number n
1	n<5
1,4	5≤n≤10
2	n>10

4.4 Transients

Transients seem to occur mainly during the start and shut down of fixed-speed wind turbines [49]. The start-up sequence of a fixed-speed wind turbine is performed in two steps. First, the generator is switched. To avoid a large inrush current a soft starter is used. As the soft starter begins operating and the generator is connected to the grid the shunt capacitor banks is switched. The shunt capacitor banks are switched directly to the grid without any soft switching devices. As the shunt capacitor banks are connected, a large current peak occurs, see Fig. 4.9.

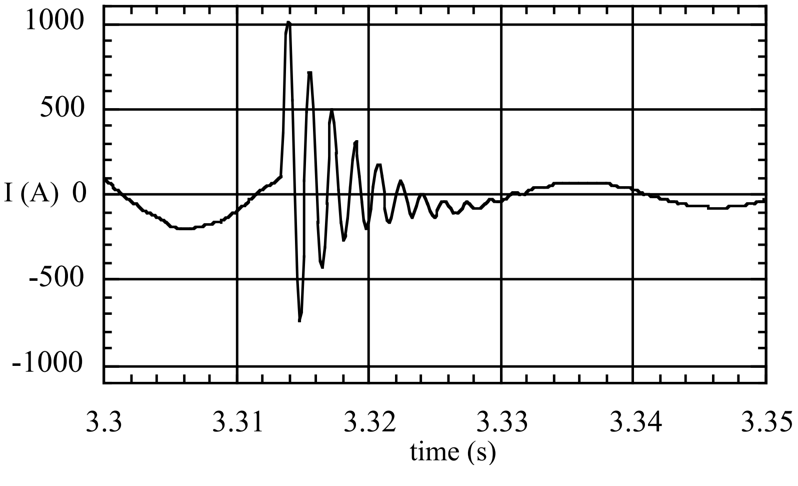

Fig. 4.9: Measured oscillating current caused by the connecting of shunt capacitors during the start-up sequence of a 225 kW wind turbine.

This transient sometimes reaches a value of twice the rated wind turbine current and may substantially affect the voltage of the low-voltage grid. The voltage transient can disturb sensitive equipment connected to the same part of the grid [26].

The amplitude of the current emanating from the switching of a unloaded capacitor is determined by the impedance of the grid and the capacitance of the capacitor. The frequency of the transient can approximately be determined by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{14}$$

where L is the inductance of the grid and C is the capacitance of the capacitor.

In order to improve the calculations of the connecting current and voltage, a more detailed model must be used. The use of the Electro Magnetic Transient Program (EMTP) makes it possible to use frequency-dependent parameters. In [26], calculations of switching transients on a low-voltage grid equipped with two wind turbines are presented.

4.5 Frequency

On the one hand, [50] states that the introduction of a relatively small amount of wind power into the utility grid does not normally present interfacing or operational problems. The intermittent power production from wind turbines is balanced by other production units. On the other hand, the effect of wind power is very important in autonomous power systems. The spinning reserve is small in an autonomous grid supplied by diesel engines. The small spinning reserve will give rise to frequency fluctuations in case of a sudden wind rise or wind drop. Hence, in a wind-diesel system, the voltage and frequency fluctuations will be considerably greater than in an ordinary utility grid.

In the past decade, different types of wind turbines and wind-diesel systems for autonomous grids have been tested. The most common are fixed-speed wind turbines equipped with induction generators. Fig. 4.10 shows measurements taken at a wind-diesel system with a relatively small amount of wind power on two different nights.

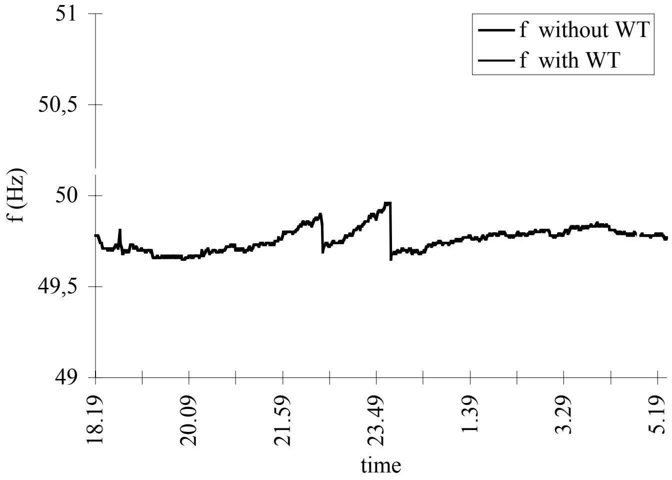

Fig. 4.10: Frequency variations on two nights. One night when the turbines were operating (gray line) and one night when the turbines were shut down due to lack of wind (black line). WT means wind turbines.

The installed wind power was approximately 10% of the total diesel power on the island. The frequency from the wind farm was measured on two different nights, one night with wind turbines and one night without wind turbines. There are two frequency drops during the night when the turbines were not operating. These two drops most likely emanate from the stop of one of several diesel engines. The other curve which represents the frequency when the turbines were operating shows an increase in frequency. The frequency was above 50 Hz throughout night indicating that some diesel engines were running at low load. Most likely, the utility company was afraid to stop too many diesel engines in case of a sudden wind drop. If the fraction of wind power is further increased, i.e., if the wind-diesel system is supposed to operate solely on wind power under high-wind conditions, the power from the wind turbine must be controllable. Measurements of such a specially designed wind-diesel system, using a pitch-controlled variable-speed wind turbine, are shown in Fig. 4.11.

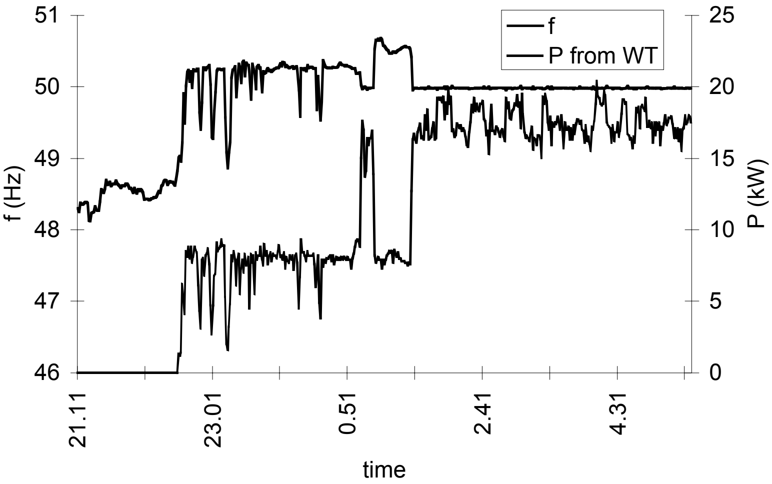

Fig. 4.11: Frequency variations (black line) and power output from the wind turbine (gray line) during one night.

The figure shows the power from the wind turbine and the frequency measured during one night. As can be seen in the figure, the wind turbine is switched off and is not producing any power during the first 1.5 hours. During this time, the plant is operating in diesel mode. The plant is then turned into the mixed mode and the wind turbine begins working in parallel with the diesel for approximately 4 hours. Then after this and for the rest of the night the wind speed was high enough for the wind turbine to operate alone. The total power consumption is rather constant and a little bit over 15 kW. The criteria for wind mode in the plant is that the rotational speed of the wind turbine exceeds a predetermined value, in this case 60 rpm.

The frequency rises from approximately 48 Hz in the diesel mode to 50 Hz in the mixed and wind modes. The diesel seems to have a governor with a frequency of 52 Hz at no-load and up to 48 Hz at full-load. For the rest of the night, the plant runs in the wind mode. As can be seen, the frequency is very stable when the plant is running in the wind mode. In fact, the frequency is much more stable in the wind mode than in the other two modes.

According to the European Standard EN 50 160, the nominal frequency of the supply voltage is to be 50 Hz. Furthermore, under normal operating conditions the average value of the fundamental frequency measured over 10 seconds in distribution systems with no synchronous connection to an interconnected system is to be within a range of 50 Hz ± 2 % (i.e. 49 Hz to 51 Hz) for 95 % of a week or 50 Hz ± 15 % (i.e., 42.5 Hz to 57.5 Hz) for 100 % of a week.

5 Contributions and Conclusions

During the last ten years, the rated power of mass-produced wind turbines has risen from 200 kW to 2 000 kW. As the rated power of wind turbines increases even the technology changes. The small 200 kW wind turbines built ten years ago operated at fixed-speed while the large 2 000 kW wind turbines of today operate at variable-speed. The increased rated power and the rising numbers of wind turbines contribute to making the power quality issue more important.

As a result, a lot of effort has been put into measuring and analyzing the power quality of grid connected wind turbines. During recent years this work has resulted in drafted versions of new national and international standards. As a consequence, early published papers have become out-of-date.

5.1 Short Summaries of Papers which are Part of the Thesis

Paper 1A (1995)

The aim of Paper 1A is to present a survey of the various electrical systems used in wind turbine applications. Synchronous generators and induction generators are investigated. Line-commutated thyristor converters are compared with force-commutated transistor converters. System characteristics are investigated regarding power quality, damping capability, mechanical resonances, losses and costs. Several recommendations, i.e., IEC/TC 88, TAMP, DAMP regarding wind turbines and grid connection are discussed.

This paper outlines the most common electrical system which is a turbine- induction generator combination directly connected to the grid. In the future, variable-speed operation will be more common. For variable-speed operation the thyristor inverter has the highest efficiency and the lowest price compared with the IGBT inverter. However, the IGBT inverter has the capability of providing good power quality to the grid.

Paper 1B (1997)

In this report, power quality problems are discussed from a wind power point of view. Aerodynamic and mechanical principles of wind turbines are explained. The electrical systems used for fixed-speed and variable-speed operation and the power quality effects they can cause are described in detail. Moreover, wind power related power quality aspects are discussed and methods for calculating various voltage disturbances are derived. Finally, the report discusses the power quality of autonomous wind-diesel grids and some of the protection devices with which wind turbines are equipped.

In this report, it is affirmed that different kinds of wind turbines are available on the market. From an electrical point of view, wind turbines may be divided into two main groups, i.e., fixed-speed and variable-speed operation. Both groups of wind turbines have advantages and disadvantages in terms of interaction with the grid and power quality.

Paper 2A (1995)

The purpose of Paper 2A is to study the damping of transients by the skin effect and proximity effects when the phase-compensating capacitors of wind turbines are connected to the grid. Transient measurements were performed at a small wind park consisting of two pitch-regulated wind turbines. When the phase-compensating capacitors were connected, a large current peak, up to twice the rated current, occurred. This dynamic event was calculated by means of the Electro Magnetic Transient Program, EMTP. In order to get a proper result, the skin effect and proximity effects on the cable and the transformer must be taken into account.

Paper 2B (1996)

The power quality of two different autonomous wind-diesel systems has been compared. Measurements have been performed at two different sites, one located on an island in Greece, the other on an island in Sweden. The island in Greece has a conventional wind-diesel system consisting of a wind farm working in parallel with some diesel generators. The Swedish system is a specially designed wind-diesel system in which the diesel generator and the wind turbine work in collaboration with each other. Measurements of the voltage and frequency variations during the operation of the wind turbines at different wind speeds and different load situations are compared. The paper shows that using a wind turbine with a controllable power output makes it possible to have 100 percent wind penetration while maintaining a specified power quality.

Paper 2C (1996)

Paper 2C deals with flicker and slow voltage variations generated by wind turbines affecting other consumers connected to the grid. Measurements of power fluctuations and voltage variations caused by wind turbines are presented. The means by which wind turbines can produce flicker and the factors which affect its severity are discussed. The paper also deals with the conditions under which flicker is likely to become a limiting factor when wind energy becomes an increasing part of the total generation.

It is shown that the short-circuit ratio of the grid affects voltage fluctuations. Moreover, the ratio between the reactance X and the resistance R of the grid in combination with the reactive power consumption of the load has a significant impact on voltage fluctuations.

Paper 2D (1999)

In Paper 2D, the power quality of variable-speed wind turbines equipped with forced-commutated inverters is investigated. Measurements have been made on the same type of variable-speed wind turbines located in Germany and in Sweden. The measurements have been analysed and compared with existing IEC standards. Special attention has been given to flicker emission and harmonics due to the aggregation of several wind turbines. This aggregation has been compared with the summation laws used in the committee draft of the IEC 61400-21 “Power Quality Requirements for Grid Connected Wind Turbines“.

In the paper, it is shown that the methods for calculating flicker proposed by IEC Standards are reliable. Harmonics and inter-harmonics are treated in the IEC 61000-4-7 and IEC 61000-3-6. The methods for summing harmonics and inter-harmonics as described in IEC 61000-3-6 are applicable to wind turbines. In order to obtain a correct magnitude of the frequency components, the use of a well-defined window width is of great importance.

Paper 3A (1999)

Paper 3A describes the work done in the power quality subtask of the project "European Wind Turbine Testing Procedure Developments" funded by the EU SMT program. The objective of the power quality subtask has been to make analyses and new recommendation(s) for the standardization of the measurement and verification of wind turbine power quality. The work has been organized as three major activities. (i) The first activity has been to propose measurement procedures and to verify existing and new measurement procedures. This activity has also involved a comparison of the measurements and data processing of the participating partners. (ii) The second activity has been to investigate the influence of terrain, grid properties and wind farm summation on the power quality of wind turbines with constant rotor speed. (iii) The third activity has been to investigate the influence of terrain, grid properties and wind farm summation on the power quality of wind turbines with variable rotor speed .

The results of comparisons of simultaneous measurements in Hagshaw Hill show good agreement with the measurements made at Risø, DEWI, NEL and CRES. Moreover, the comparison of calculation results based on a set of reference measurements have shown very good agreement with the analysis software at Risø, DEWI and CRES. Measnet and the IEC define methods for measuring power quality characteristics which aim at being independent of the grid where the measurements are done. The measured power quality characteristics can then be applied to calculate the influence on the voltage quality on another grid characterized by short circuit power and an impedance angle. The present work has illustrated that the grid properties still have an influence on the specified power quality characteristics. Another factor, which influences the results, is the terrain.

The comparison of measurements in complex terrain and in relatively flat terrain has shown a significant difference between the measurements of power variability and flicker at low and medium wind speed, but the designing 99% percentiles were less sensitive to the terrain.

Paper 4A (1999)

In Paper 4A, the power quality of grid connected wind turbines is investigated. Special emphasis is on stationary voltages, flicker and harmonics. In addition, the aggregation of several wind turbines on flicker emission and harmonics is considered. The new Danish and Swedish guidelines for the grid connection of wind turbines and the committee draft of the IEC 61400-21 ”Power Quality Requirements for Grid Connected Wind Turbines” are discussed.

In the committee draft of the IEC 61400-21, a procedure for determining the characteristics of wind turbine output with respect to its impact on the voltage quality in a power system is specified. In both Denmark and Sweden, new recommendations regarding the grid connection of wind turbines have been accepted. The two recommendations are quite similar and they are both derived from the committee draft of the IEC 61400-21. The equations in the committee draft have been revised in order to agree with national standards concerning voltage quality.

In the recommendations, the impact of a wind turbine on the utility grid is determined by means of a wind turbine power quality test. The test results shall contain information regarding the power factor, the maximum power, the voltage change factor, the flicker step factor, the maximum numbers of switching operations for a period of two hours, the flicker coefficient and the harmonic content of the current.

Paper 4B (2000)

Paper 4B presents the modelling and analysis of the flicker emission of wind turbines, along with measurements and a comparison with international standards. The paper is an extension of a part of the work presented in Paper 4A. The paper concentrates on the theoretical aspects of the flicker algorithm, wind turbine characteristics and flicker during the continuous operation of wind turbines.

Flicker emissions are produced during the continuous operation of wind turbines. The flicker is caused by power fluctuations which mainly emanate from variations in wind-speed, the tower shadow effect and mechanical properties of the wind turbine. Pitch-controlled turbines also have power fluctuations caused by the limited bandwidth of the pitch mechanism.

Paper 4C (2000)

Paper 4C is a continuation of Paper 4B and presents the modelling and analysis of the flicker of wind turbines. Special emphasis is on explaining the start-up procedure and deriving equations for the calculation of flicker produced by switching operations. The derived equations are compared with international standards. The paper includes measurements of the start and stop of different types of turbines. Finally, the paper makes a comparison of flicker limitations at wind parks.

Switching operations will produce flicker. Typical switching operations are the start and stop of wind turbines. The start and stop of different types of wind turbines are different. For example, in the case of pitch-controlled fixed-speed wind turbines, the torque of the turbine can be controlled. Hence, the connection of the generator can be performed in a smooth and controlled way.

All wind turbines in a wind park are normally connected at the same point of common connection, PCC. The grid at the PCC, therefore, must be designed to withstand the total flicker disturbance produced by all the wind turbines in the wind park. Wind turbines produce flicker under continuous operation, as well as under switching operations. The required short circuit ratio, SCR, caused by flicker under continuous operation increases with the square root of the number of wind turbines, whereas the required SCR caused by switching operations increases with a little more than the cubic root of the number of wind turbines. Generally, fixed-speed wind turbines need a higher SCR compared to variable speed wind turbines. If a wind park consists of a small number of fixed-speed wind turbines then stall-regulated wind turbines, due to uncontrollable torque during start, will produce higher flicker emission. If the number of fixed-speed wind turbines is high, pitch-controlled wind turbines will produce higher flicker emissions.

5.2 Conclusions

In this thesis the power quality of grid-connected wind turbines has been investigated. Furthermore, electrical systems used for fixed-speed and variable-speed wind turbines and their characteristics have been focused on.

From an electrical point of view, wind turbines may be divided into two main groups, i.e., fixed-speed and variable-speed operation. Both groups of wind turbines have advantages and disadvantages regarding interaction with the grid and power quality. Wind turbines have an uneven power production following the natural variations in the wind. Uneven power production is the same for all kinds of wind turbines. Each time a turbine blade passes the tower, it enters into the tower shadow. If the turbine is operating at fixed-speed, the tower shadow and wind speed gradients will result in fluctuating power. Both uneven power production and power fluctuation cause voltage variations. Load flow calculations can be used to calculate slow variations in the voltage caused by the uneven power production of wind turbines. The power fluctuations of the wind turbine may cause flicker disturbances. In order to calculate the impact on flicker, measurements and subsequent flicker calculations must be performed.

Apart from possible oscillations between the grid impedance and the shunt capacitor banks for power factor correction, fixed-speed wind turbines do not produce any harmonics. When it comes to variable-speed wind turbines, however, the situation is the opposite. Depending on the type of inverter used, different orders of harmonics are produced.

Transients seem to occur mainly when wind turbines are started and stopped. A large inrush current and thereby a voltage dip can be avoided if the wind turbine is equipped with a soft-starter. As the shunt capacitor bank is switched on, a large current peak occurs. The current peak may substantially affect the voltage on the low-voltage side of the transformer.

In an autonomous grid supplied by diesel engines, the spinning reserve is limited and gives rise to frequency fluctuations when fast load changes occur. Hence, the frequency of an autonomous grid is normally not as stable as that of a large grid. When wind power is introduced to an autonomous grid, a sudden wind rise or wind drop will affect the power balance with frequency variations as a result. The use of sophisticated variable-speed wind turbines can eliminate this problem and actually improve the frequency balance.

The new committee draft of the IEC 61400-21 and the Swedish regulation AMP provide tools for predicting the interaction between the wind turbines and the grid. Wind turbine types, which in combination with the grid are likely to cause power quality problems, can, at an early stage of planning, be rejected and replaced by a more suitable type of wind turbine.

5.3 Future Research

This thesis proposes methods for assessing the power quality of wind turbines. It also shows that these methods are reliable for wind turbines connected to a normal grid having rotating synchronous generators and passive loads. The control strategy used today is to disconnect the wind turbines in the event of a grid failure. With a significant amount of wind power in the grid, disconnecting the wind turbines may result in voltage instability and voltage collapse. One aspect of this work to be given further study is the power system stability with a large amount of wind power in the grid.

Another aspect for further study is the electronic stability in grids which use a large number of wind turbines. The manufacturers of wind turbines use power electronics in order to achieve the variable speed for their large wind turbines. The main reasons for using variable speed are the reduction of mechanical loads and the improvement of power quality. Even the manufacturers of consumer products use power electronics in their products in order to save energy. Examples of such products are heat pumps, ventilation systems, drilling machines, vacuum cleaners, computers, televisions, etc. If a large amount of power is fed to the grid through converters and an increasing part of the load uses inverters, then electronic instability of the entire network cannot be excluded.

References

[1] Andersen, P.D., “Global Perspectives for Wind Power”, *Proceedings of the European Wind Energy Conference* (EWEC '99), March 1999, Nice, France, p. 71 - 76.

[2] Jenkins, N., ”Embedded generation”, *Power Engineering Journal*, June 1995, p. 145 - 150.

[3] Openshaw, D., “Embedded Generation in Distribution Networks: With Experience of UK Commerce in Electricity”; *Wind Engineering*, Vol. 22, No. 4, 1998, p. 189 – 196.

[4] Paap, G.D., Teklu, D., Jansen, F., van der Sluis, L., “The Influence Of Large-Scale Dispersed Co-Generation On Short Circuits In Rural Networks”*, Proceedings of the 15th International Conference on Electricity Distribution* (CIRED ´99), June 1999, Nice, France.

[5] Craig, L.M., Davidson, M., Jenkins, N., Vaudin, A., “Intergration of Wind Turbines on Weak Rural Networks”, *Proceeding of the Opportunities and Advances in International Power Generation,* Conference Publication No. 419, March 1996, p.164 – 167.

[6] Salman, S.K., Jiang, F., “Impact of Embedded Wind Farms on Voltage Control and Losses of Distribution Networks”, *Proceedings on International Conference on Electric Power Engineering*, Budapest, Hungary, 1999. p. 43.

[7] Jhutty, A.S., “Embedded generation and the Public Electricity System”, *IEE Colloquium on System Implication of Embedded Generation and its Protection and Control*, Birmingham, UK, February 1998, p. 9/1 – 9/14.

[8] Mutale, J., Strbac, G., Curcic, S., Jenkins, N., “Allocation of losses in distribution systems with embedded generation”, *IEE Proceedings on Generation, Transmission and Distribution*, Vol. 147, No. 1, January 2000, p. 7 – 14.

[9] Tzschoppe, J., Haubrich, H-J., Bergs, D., Nilges, J., “MV-Network-Connection of Disperced Generation: Network Reinforcements vs. Optimised Operation”, *Proceedings of the 15th International Conference on Electricity Distribution* (CIRED ´99), June 1999, Nice, France.

[10] Haslam, S.J., Crossley, P.A., Jenkins, N., “Design and field testing of a source based protection relay for wind farms”, *IEEE Transactions on Power Delivery*, Vol. 14, No. 3, July 1999, p. 818 – 823.

[11] van Vyk, J.D., “The Issue of Power Quality”, *Proceedings on the European Conference on Power Electronics and Application* (EPE `93), September 1993, Brighton, UK, p. 17 – 32.

[12] Heier, S., *Grid Integration of Wind Energy Conversion Systems*, John Wiley & Sons Ltd, U.K., 1998, 385 p.

[13] Sørbrink, K.H., Stöber, R., Schettler, F., Bergmann, K., Jenkins, N., Ekanayake, J., Saad-Saoud, Z., Lisboa, M.L., Strbac, G., Pedersen, J.K., Pedersen, K.O.H., *Power Quality Improvements of Wind Farms*, ISBN No. 87-90707-05-2, Søndergaard Bogtryk og Offset, Fredrica, June 1998.

[14] Jørgensen, P., Tande, J.O. Vikkelsø, A., Nørgård, P., Christensen, J.S., Sørensen, P., Kledal, J.D., Søndergård, L., “Power Quality and Grid Connection of Wind Turbines”, *Proceedings of the International Conference on Electricity Distribution* (CIRED ´97), IEE Conference Publication No. 438, 1997, p. 2.6.1 – 2.6.6.

[15] Jørgensen, P., Tande, J.O., “Probablistic Load Flow Calculation using Monte Carlo Techniques for Distribution Network with Wind Turbines”, *Proceedings of the 8th International Conference on Harmonics and Quality of Power* (ICHQP '98), Athens, Greece, October 1998, p. 1146 - 1151.

[16] Saad-Saoud, Z., Jenkins, N., “Models for Predicting Flicker Induced by large Wind Turbines”, *IEEE Transactions on Energy Conversion*, Vol. 14, No. 3, September 1999, p. 743 - 748.

[17] Jørgensen; P., Christensen, J. S., Tande, J. O., Vikkelsø, A., Nørgård, P., ”Elkvalitet ved nettilslutning af vindmøller Del 3: Overtoner og driftforhold ved invertertilsluttede vindmøller”, Roskilde, Information Service Department, Risø National Laboratoy, 1996, 95 p. (in Danish)

[18] Hatziargyriou, N.D., Lorentzou, M.I., Cotton, I., Jenkins, N., “Transferred Overvoltages by Windfarm Grounding Systems”, *Proceedings of the 8th International Conference on Harmonics and Quality of Power* (ICHQP '98), Athens, Greece, October 1998, p. 342 - 347.

[19] Tande, J.O.G., Jenkins, N., “International Standards for Power Quality of Dispersed Generation” *Proceedings of the 15th International Conference on Electricity Distribution* (CIRED ´99), June 1999, Nice, France.

[20] Koulouvari, M., Ladakakos, P., Foussekis, D., Morfiadakis, E., “Measurement Systems Dedicated to Wind Turbine Power Quality Applications”, *Proceedings of the 8th International Conference on Harmonics and Quality of Power* (ICHQP '98), Athens, Greece, October 1998, p. 911 - 916.

[21] Johnson, G.L., *Wind Energy Systems*, Prentice Hall International Inc., New Jersey, USA, 1985, 360 p.

[22] Richardson, R. D., McNerney, G. M., ”Wind Energy Systems”, *Proceedings of the IEEE*, Vol. 81, No. 3, March 1993, p. 378 - 389.

[23] Freris, L.L. (ed.), *Wind Energy Conversion Systems*, Prentice Hall International (UK) Ltd, 1990, 388 p.

[24] Freris, L. L., ”Harnessing the wind*”. Power Engineering Journal*, September 1992, p. 251 - 260.

[25] Grauers, A., “Direct driven generators – Technology and development trends”, *Proceedings of the Nordic Wind Power Conference 2000 (NWPC 2000)*, Trondheim, Norway, Mars 13-14, 2000, p. 127 – 131.

[26] Larsson, Å., Thiringer, T., ”Measurements on and Modelling of Capacitor-Connecting Transients on a Low-voltage Grid Equipped with Two Wind Turbines”, *Proceedings of the International Conference on Power System Transients* (IPST '95), Lisbon, Portugal, Sept. 1995, p. 184 - 188.

[27] Jenkins, N., “Engineering wind farms”, *Power Engineering Journal*, April 1993, p. 53 – 60.

[28] Larsson, Å., Carlson, O., Sidén, G., ”Electrical Generating Systems in Wind Turbine Applications”, *Proceedings of the IEEE/KTH Stockholm Power Tech Conference*, Vol. Electrical Machines and Drives, June 1995, p. 205 - 210.

[29] Vestas, Technical description of the Optislip feature, Item no. 947525, 1995.

[30] Thorborg, K., *Power Electronics*. Prentice Hall International (UK) Ltd, 1988. 504 p.

[31] Svensk Standard, SS 421 18 11, Spänningsgodhet i lågspänningsnät för allmän distribution, 1989. (in Swedish)

[32] European Committee for Electrotechnical Standardization, CENELEC, EN 50 160, Voltage Characteristics of Electricity Supplied by Public Distribution Systems, 1994.

[33] International Electrotechnical Commission, IEC Standard, Publication 60038, Standard voltages, Ed. 6, 1983.

[34] Ballard, L. J., Swansborough, R., H. (ed.), ”Recommended Practices for Wind Turbine Testing: 7. Quality of Power. Single Grid-Connected WECS”, Roskilde, Elsgaards bogtrykkeri, Edition 1, 1984.

[35] Tilslutning af vindmøller til lav- og mellemspændingsnet, DEFU Institut for forskning og udvikling inden for elforsyningsområdet, Komité rapport 111, 1998. (in Danish)

[36] Anslutning av Mindre Produktionsanläggningar till elnätet (AMP), Sveriges elleverantörer, 1999. (in Swedish)

[37] International Electrotechnical Commission, IEC Standard, Publication 60868, Flickermeter – Functional and Design Specifications, 1990.

[38] International Electrotechnical Commission, IEC Standard, Amendment 1 to Publication 60868, Flickermeter – Functional and Design Specifications, 1990.

[39] Walker, M. K., ”Electric Utility Flicker Limitation”, in *Proceeding of the Power Quality Conference*, Long Beach, California, October 1989, p. 602 - 613.

[40] Gardner, P., ”Flicker from Wind Farms”. *Proceedings of the BWEA/SERC RAL Workshop on Wind Energy Penetration into Weak Electricity Network*, Rutherford, U.K., June 1993, p. 27 - 37.

[41] Gerdes, G., Santjer, F., ”Power Quality of Wind Turbines and their Interaction with the Grid”. *Proceedings of the European Wind Wnergy Conference (EWEC ‘94)*, Thessaloniki, Greece, 10-14 October 1994, p. 1112 - 1115.

[42] Sørensen, P., Tande, J.O., Søndergaard, L.M., Kledal, J.D., *”Flicker Emission Levels from Wind Turbines”*, Wind Engineering, Vol. 20, No. 1, 1996, p. 39 - 45.

[43] International Electrotechnical Commission, IEC Standard, Publication 61400-21, Power Quality Requirements for Grid Connected Wind Turbines, Committee Draft, 1998.

[44] International Electrotechnical Commission, IEC Standard, Publication 61000-3-7, Electromagnetic compatibility, Limitations of voltage fluctuations and flicker for equipment connected to medium and high voltage power supply, Committee draft, 1995.

[45] Reid, E. W., ”Power Quality Issues - Standards and Guidelines”, *IEEE Transactions on Industry Applications*, Vol. 32, No. 3, May/June 1996, p. 625 - 632.

[46] International Electrotechnical Commission, IEC Standard, Publication 61000-4-7, Electromagnetic Compatibility, General Guide on Harmonics and Inter-harmonics Measurements and Instrumentation, 1991.

[47] International Electrotechnical Commission, IEC Standard, Amendment 1 to Publication 61000-4-7, Electromagnetic Compatibility, General Guide on Harmonics and Inter-harmonics Measurements and Instrumentation, 1997.

[48] International Electrotechnical Commission, IEC Standard, Publication 61800-3, Adjustable speed electrical power drive systems, EMC product standard including specific test methods, 1996.

[49] Demoulias, C. S., Dokopoulos, P., ”Electrical Transients of Wind Turbines in a Small Power Grid”, *IEEE Transactions on Energy Conversion*, Vol. 11, No. 3, September 1996, p. 636 - 642.

[50] Hunter, R., Elliot, G., *Wind-Diesel Systems*, Cambridge University Press, Great Britain, 1994, 249 p.

Paper 1A

Electrical Generating Systems in Wind Turbine Applications

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Electrical Generating Systems in Wind Turbine Applications

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Abstract**-**The aim of this paper is to give a survey of the electrical systems used in wind turbine applications. Synchronous as well as induction generators are investigated. Line-commutated thyristor converters are compared with force-commutated transistor converters. System characteristics are investigated regarding power quality, capability of damping resonance, losses and costs. Several recommendations, (IEC/TC 88, TAMP, DAMP) regarding the turbine and the connection to the grid are discussed.

I. INTRODUCTION

During the last decade wind turbine technology has been developed and an industry has been built up around it. The installations of wind turbines have grown remarkably so that today more than 3,000 MW of wind power are installed worldwide, of which 1,700 MW in the US and Canada. Between 5,000 and 10,000 new wind power plants are being planned, are in construction, or are already in operation in the US, (1).

European Industry produces wind turbines with an installed power of 250 MW/year and with a production capacity of 800 MW/year. There are more than 20 manufacturers in Europe and the wind sector has created more than 10,000 jobs. Wind energy supplies the electricity needs of 2,5 million people. The forecast for the installed wind power in Europe in 1996 is 5,000 MW, (2).

In light of these facts, the electrical generating systems applied in wind turbines will be discussed. Wind turbines can be divided into two different types, constant speed and variable speed. The constant speed operation of a wind turbine is the most common type of operation. The generator is connected directly to the grid which gives a simple electrical system. The constant speed operating systems are equipped with a soft starter which reduces the inrush current to rated current.

The variable speed operation of a wind turbine is obtained by means of a frequency converter. Several different electrical systems are used for a broad and a narrow speed range.

Rotor cascades of the induction generator for a narrow speed range can be used. This type of cascade was investigated, (3), and is in operation in the German wind turbine, Growian, and the US. Mod 5B. Another possible arrangement is to use controllable rotor resistances, (4).

The synchronous generator with a rectifier and a line commutated thyristor inverter is the most common system for the wide speed range. Another interesting system is the induction generator with a force commutated inverter. Earlier, it has often been said that the losses in the frequency converter of a variable-speed system are a drawback. However, the total energy losses do not have to increase because of the frequency converter, (5). The generator and gear losses can be reduced when the converter is used, and this reduction is large enough to compensate for the losses in an efficient converter.

II. ELECTRICAL SYSTEM

The electrical system for constant speed operation is, as indicated in the introduction, very simple. It usually consists of an induction generator directly coupled to the grid.

The electrical system becomes more complicated when it comes to variable speed operation. The alternating current need to be first rectified and the chopped to alternating current again. The electrical system must, therefor, consist of three main parts: generator, rectifier and inverter. The choice of these three main parts can be subdivided into two almost independent choices. The generator and rectifier must be chosen as a combination and the inverter can be chosen almost independently of the generator and rectifier used, (6).

A. Synchronising to the grid

Since the inrush current is high during the connection of the generator to the grid the inrush current must be limited to the rated current. There are several methods used to limit the inrush current, the most common is a thyristor switched soft-starter. In a soft-starter the fire-angle of the thyristors is increased during the start procedure and the current is kept well below the rated peak current. Another method used is magnetising the induction generator by means of capacitors. These methods have been investigated, (7), and the capacitor method is currently being used in the 3 MW wind turbine at Näsudden on Gotland.

Wind turbines operating at variable speed may be synchronised to the grid with no problem, since the current can be controlled from zero to rated value by the inverter.

B. Generators

The most common generator in wind turbines is the induction generator. This generator has several advantages such as a robust design, no need for maintenance, well enclosed (IP 54), produced in large series and, thereby, low price, well damped and, furthermore it can withstand overloads. The major disadvantage in variable speed operations is that the stator needs a reactive magnetising current, preferably from the rectifier.

The synchronous generator is mechanically more complicated compared to the induction generator. It has more parts and is cooled with ambient air internally (IP 23), which according to TC 88, (8), is the lowest enclosure for electrical equipment. The enclosure can be rised to IP 45 with filters and outer shields on the generator. The synchronous generator is only used in a couple of wind turbines in constant speed operation. These generators are often used in large turbines up to 4 MW, and may be considered as special cases.

When it comes to variable speed operation, the synchronous generator has one clear advantage compared with the induction generator: It can be directly connected to the simple diode rectifier.

C. Rectifiers

A good rectifier alternative is the diode rectifier because of its simplicity, low cost and low losses. The efficiency is 99,5 % in normal operation, (9). The drawback is an uncontrollable generator voltage and generator current. Therefore, the generator must control the voltage and the inverter must control the current. A force commutated rectifier is another alternative. It can control both generator voltage and generator current. The force commutated rectifier can be made with different types of power electronic switches, but it has been found that the Insulated Gate Bipolar Transistor, IGBT, will be the best choice in the near future, Figure 1.

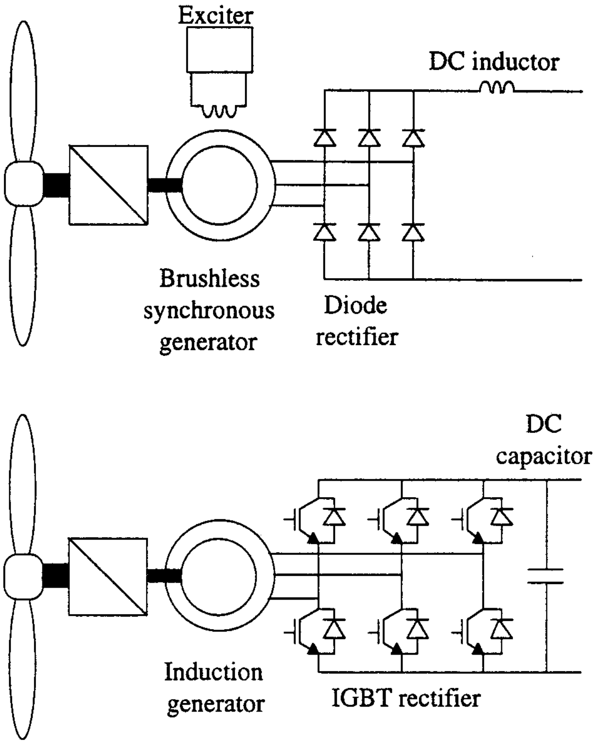

Figure 1: Two generator and rectifier alternatives.

D. Inverters

The two most common types of inverters, line commutated and force commutated, are compared. These two types of inverters produce different types of harmonics and hence do need different line filters. The line commutated inverter is equipped with thyristors which must be connected to the grid in order to operate. The line commutated inverter can be seen in Figure 2. The current on the grid side is proportional to the current on the DC-side of the inverter. Moreover, the power factor varies with the DC-side voltage and is equal to or less than 0.9. The line commutated inverter is well known, it is a mature product and the thyristor valves can be overloaded without any damage. The line commutated inverter is available up to 5 MW. To protect the line commutated inverter, when the grid voltage disappears, a special break circuit must be installed, (10). The line commutated inverter control has a maximum dead time of 3.3 ms and a bandwidth of approximately 20 Hz, (11). The efficiency is 99% of the thyristor inverter, (9).

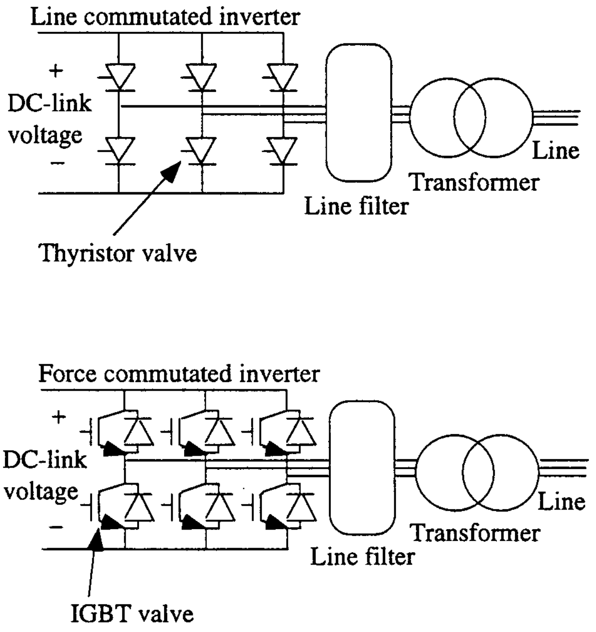

Figure 2: Schematic figures of a line commutated and a force commutated inverter.

The line commutated inverter produces not only fundamental current but also harmonic current which are turned into voltage harmonics on the grid. To eliminate these frequency harmonics a large grid filter must be used. One positive side-effect when using a grid filter is that the filter produces reactive power. This production increases the power factor for the whole inverter system.

In a force commutated inverter it is possible to freely choose when to turn on and when to turn off the valves. This possibility means that the force commutated inverter can create its own three-phase voltage system and if the inverter is connected to the grid, the inverter can freely choose which power factor to use and in which direction the power should flow. By the use of Pulse Width Modulation technique, PWM, the low frequency harmonics will be eliminated and the first harmonics will have a frequency around the switching frequency of the inverter. Usually, when the IGBT is used, the switching frequency is about 5 to 10 kHz. The manufacturers offer IGBT components which make it possible to handle 600 kVA with a single six-pulse inverter. The fastest control method is the vector control with a bandwidth of approximately 100 Hz. The efficiency is 97.5% of the IGBT inverter, (9).

III. POWER QUALITY

Wind turbines with power electronic equipment have become more and more frequent in the networks. Therefore, the interest in the interaction between the wind turbine and the grid has increased. The power quality of the grid can be reduced to levels unacceptable to the utility, by using unsuitable converters and filter combinations.

A. Definition

Perfect power quality means that the voltage is continuous and virtually purely sinusoidal, with a constant amplitude and frequency. The quality of the power which depends on the interaction between the grid and the source can be expressed in terms of the physical characteristics and properties of the electricity. It is most often described in terms of:

- Voltage stability
- Frequency stability
- Phase balance
- Electromagnetic interference effects
- Telephone interference factors

The electromagnetic interference effects and the telephone interference factors will not be discussed in this paper. The frequency of larger power systems is normally very stable and, therefor no problem. When the penetration of wind power plants increases, the fluctuating output from these may cause an unstable frequency. But, that would demand a large amount of wind turbines and at the moment we are far from that level. Moreover, under normal conditions when only three-phase loads are connected to the grid there would be no phase unbalance. Consequently, the most important characteristic among the above, especially when converters are used, is the voltage stability.

It is obvious that poor power quality from a wind turbine will affect the grid, but it is worth pointing out that the reversed case is also valid. In other words, poor power quality on the grid will affect the wind turbine.

B. Relevant Standards of Voltage Stability

Definitions and information regarding the characteristics of irregularities are normally given in national or international standards. The present standards in Europe are, however, not easy to use. For example, only the maximum allowed voltage distortion in the network is stated. There are no specifications regarding the level of the highest allowed harmonic current from a single source. The harmonic current generated from a converter is easy to predict, but determining the exact value of the impedance of the grid is both difficult and time-consuming, especially since the impedance has different values for each harmonic. As a consequence, voltage harmonics are very difficult to predict.

Voltage stability can be subdivided into slow voltage variations, rapid voltage fluctuations (flicker), harmonic voltage distortion and voltage dips. These voltage irregularities will be discussed in detail, moreover, Table 1 shows a short summary of the different voltage irregularities together with a specification of the Swedish standard SS 421 18 11. In the same table some different reasons for these irregularities are listed along with the way they will cause disturbances.

1) Slow voltage variations: Slow voltage variations can be defined as changes in the RMS value of the voltage occurring in a time span of minutes or more. National standards often state allowable variations in nominal voltage over an extended period, for instance, 24 hours. IEC Publication 38 recommends 230/400 V as the standard voltage for 50 Hz systems. Under these conditions, the voltage at the user's terminal must not differ more than ± 10% from normal voltage.

2) Flicker: Due to the historical association with effects on lighting, rapid voltage fluctuations have come to be commonly termed as voltage flicker. Rapid voltage fluctuations or flicker are a series of changes with intervals shorter than approximately one minute, and they are defined in IEC Publication 555-3. Maximum permitted voltage changes as a function of the possible fluctuation rate are given in this standard.

3) Harmonic voltage distortions: Harmonic voltage distortions can be caused by the flow of harmonic currents in the system. The harmonic distortion can be quantified by several different methods. One of the most common methods is Total Harmonic Distortion, THD. An other method for quantifying harmonics is individual harmonic distortion. The maximum total harmonic distortion allowed, according to the Swedish standard SS 421 18 11, is 6%. Maximum permitted value of any odd individual component is 4%.

Table 1. Voltage irregularities on low voltage systems according to the Swedish standard SS 421 18 11.

Voltage	Specification	Reason	Causes
Slow voltage variation	+ 6 % - 10 %	Load variations	
Sudden changes in the rms of the voltage	"Flicker curve"	Switching loads Utility switching Motor starting	Flicker Computer system crashes
Voltage fluctuation			
Harmonics	Odd ≤ 4 % Even ≤ 1 % THD ≤ 6 % (n = 2 - 40)	Non-linear loads Motor speed controllers Inverters	Additional losses in generators and transformers Increasing current in capacitors
Inter harmonics	≤ 3 %	Frequency converters	Unstable operation of sensitive electronic equipment

4) Voltage dips: Voltage dips are sudden reductions in the supply voltage with a magnitude between 10% and 100% of the supply voltage followed by a voltage recover after a short period. The duration of a voltage dip is conventionally between 10 ms and 1 minute.

C. Power Quality Applied to Wind Turbines

When it comes to the power quality of wind turbines, only some specific voltage irregularities are of interest.

A conventional wind turbine, equipped with an induction generator connected directly to the grid, gives a fluctuating active power output and has a reactive power demand. This characteristic may lead to slow voltage variations. The design criteria of the local grid are based on the slow voltage variation standard.

Voltage flicker may be of interest only when wind turbines are connected to a weak grid.

As mentioned earlier, inverters do inject harmonic currents into the grid and will, due to the grid impedance, cause harmonic voltages. As a result, voltage harmonics are the most interesting type of irregularity when converters are used.

A simple converter may, due to current harmonic content and reactive power demand, make the power quality worse. Using an advanced converter makes it possible to control the reactive power and thereby the voltage level. An advanced converter can also operate as an active filter, (12). These two characteristics make it possible to even improve the power quality at the point of common connection.

IV. RECOMMENDATIONS FOR THE ELECTRICAL GENERATING SYSTEM

Several recommendations and standards for wind turbines have been developed during the last decade. In Sweden, electrical connection of wind turbines to the grid is regulated by the technical instructions, TAMP, (13), and the dimensioning instructions, DAMP, (14). Both are produced by the electric power distributors union, Svenska Elverksföreningen. Moreover, a new IEC-standard for wind turbines, TC-88, has been accepted. The IEC standard not only contains regulations about the electrical equipment, but also mechanical regulations concerning aerodynamics, inertial and gravitational loads. However, in this paper some headlines from the IEC regulation concerning electrical systems will be discussed in detail and, where possible, compared with the national Swedish regulations TAMP and DAMP. Some inputs to these recommendations are coming from the Danish wind turbine experiences, (15).

A. Recommendations

1) General: According to TC-88, wind turbine operation and safety should be governed by a control and a protection system. The control system should keep the operating parameters within their normal limits.

The design of the electrical system should ensure minimal hazards to people and livestock, as well as minimal potential damage to the connected electrical system during operation.

2) Enclosures: Motors, controllers and other electrical components should be enclosed in order to obtain a suitable degree of protection, at least IP 23. Swedish regulations show no consideration for the enclosure.

3) Operating conditions: The manufacturer should state values for the rated current, voltage, frequency and short-circuit current.

4) Protective devices: Protection should specially provide under/over voltage and over current, due both to overload and short-circuits. In addition, protection should be provided for the loss of phase and phase reversal and under/over frequency. Equipment should also shut down the wind turbine safely in the event that operating conditions which will not allow safe operation.

Earthing should allow the wind turbine to withstand lighting strikes and still remain in a safe condition. The protection system should also include surge protection devices.

In TAMP the same type of protection devices are stated.

5) Power collection systems, conductors: All electrical cables, devices and assemblies shall be installed, wired and connected in accordance with relevant IEC standards. According to DAMP, voltage variation in the cable between the wind turbine and the transformer may not exceed 2.5%. In order to keep the voltage variations within these limits, some easily readable graphs concerning choice of cable are presented in DAMP.

6) Phase compensating capacitors: If a capacitor bank is connected, for power factor correction, a suitable switch is required to disconnect the capacitors. This precaution is due to the risk for self-excitation of the generator in the case of grid failure. Swedish regulations, TAMP and DAMP, includes rules concerning power factor correction and the maximum size of capacitor banks. According to TAMP, a the rule of thumb is to compensate for reactive power up to a third of the generators apparent power. This compensation will correspond to a power factor between 0.9-0.95. In order to avoid voltage fluctuations, the capacitors should, according to DAMP, be switched in steps of 30-40 kVAr.

7) Harmonics and power conditioning equipment: The power conditioning equipment, such as inverters, power electronic controllers and static VAR compensators, shall be designed so the harmonic current and the voltage wave form distortion are minimised and do not interfere with protective relaying. At the point of common connection the voltage wave form distortion should be within the limits of the grid. In DAMP, harmonics are allowed in accordance with the Swedish standard SS 412 18 11 presented in part III Power Quality.

8) Special regulations in TAMP and DAMP: With the exception of the headings presented above there are some additional regulations in TAMP and DAMP. The ratio between the short circuit power and the rated power of the wind turbine must be at least 20. The transformer must be chosen in accordance with a table in DAMP. For example, a 600 kW wind turbine must be connected to a 800 kVA transformer.

V. COSTS

A. Costs for Electrical Connection of a Wind Turbine

Depending on the grid stiffness and configuration, the costs of connecting wind turbines to the grid will vary widely from site to site. The easiest way to connect a wind turbine to the grid is via the low voltage side of an existing distribution transformer. A lot of wind turbines in Sweden are connected in that way, especially if the site is close to a densely built-up area. The opportunity will, however, demise with increasing generator power due to limitations caused by the voltage drop.

The connection cost of a 225 kW generator to a transformer, with a free compartment is 3 % of the total investment. This cost is due to the fact that only cable, digging and wiring are needed.

Since wind turbines has become larger, the ordinary size today is 600 kW, it will often be necessary to install a new transformer especially for the wind power plant. The connection costs will, consequently, increase not only because of the transformer but also for the transformer station. A customary concrete station will cost about 15 kECU, a simple metal-sheet station will amount to 10 kECU. The connection cost for a 600 kW generator to the 10 kV grid will, thus, end up in 7 % of the total cost. The total cost is estimated to 200 kECU.

B Needs for Strengthening the Grid

In this paper no consideration is taken of possible needs for strengthening the electrical grid, which will be required when building wind turbines in a larger scale. In (16) the increased costs for the network in the case of introducing wind power is discussed. With 2 TWh 1995/97 and 5 TWh in 2010 within the Swedish network, the costs will increase 2-3%/kWh based on a production cost of 0.035 ECU/kWh.

C. Possible Progress in the Future

When the installed capacity of wind power increases there are opportunities to make the connecting to the grid more efficient. Here are some examples:

It is possible to use a higher voltage. With 690 V instead of 400 V as line-to-line voltage the current and the voltage drop decrease correspondingly. The power losses in the transformer and cable will be reduced, thinner cables may, therefor, be used.

It is possible to use capacitor banks to get fewer slow voltage fluctuations on the grid when the power production from the wind turbines varies. This measure will increase the possibility of connecting wind turbines to existing distribution transformers.

It is possible to place the transformer and the electricity meter inside the towers. The transformer station will hence not be necessary.

It is possible to use the wind turbine control system, i. e. in a wind turbine with pitch-control, to limit the power output if there is an risk for high temperature in the cable or the transformer. This measure makes it possible to connect an increased number of wind turbines to the same power line.

The Swedish DAMP recommendations have a rather good margin for transformers. It is hardly necessary to select a transformer with higher apparent power than the apparent power of the connected wind turbine including capacitor banks.

VI. CONCLUSION

The electrical power produced by wind turbines is increasing every day and will continue to increase for many years to come.

The most common electrical system in wind turbines, today, is the induction generator directly connected to the grid. In the future, it will be more common with variable speed operations. For variable speed operation a system with a synchronous generator and a diode rectifier is the best choice of generator system. For the inverter system has the thyristor inverter the best efficiency and the lowest price compared with the IGBT inverter. However, the IGBT inverter has the capacity to provide good power quality to the grid. Power quality regarding wind turbine operation is discussed in the paper.

Several recommendations and standards for wind turbines have been developed during the last decade and are, today, available in an useful form. TAMP and DAMP from the Svenska elverksföreningen and TC-88 from IEC.

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IX. REFERENCES

1. Swanekamp R., 1995, "Wind Power Surfaces as Near-term Generation Option," Power, January 1995, p. 36 40.
2. Musgrove P., "CEC News," Wind directions, Volume XIII, No. 3, 1994, p. 8-9.
3. Hylander, J., "Stator Current Frequency Spectra and the Torque Pulsations in Induction Machines with Rotor Converter Cascades," Technical report No. 163, Department of Electrical Machines and Power Electronics, Chalmers University of Technology, Göteborg, Sweden, 1986.
4. Zweygbergk S., Carlson O. , Karlsson R., "Investigation of a Method to Control the Output from a Wind Power Induction Generator by using a Pulse Controlled Resistance connected to the Rotor Circuit," Symposium on electrical systems and components for wind energy converter systems, Hindås, Sweden, 1984,
5. Grauers A., "Synchronous Generator and Frequency Converter in Wind Turbine Applications: System Design and Efficiency," Technical report No. 175 L, Department of Electrical Machines and Power Electronics, Chalmers University of Technology, Göteborg, Sweden, 1994.
6. Carlson O., Grauers A., Svensson J., Larsson Å., "A Comparison between Electrical Systems for Variable Speed Operation of Wind Turbines," EWEC '94, Thessaloniki, Greece, 1994.
7. Carlson O., Hylander J., "Some Methods to Connect a Wind Power Induction Generator to the Utility Network," International colloquium on wind energy", Brighton, UK, 1981.
8. International Electrotechnical commission, TC 88, 1994.
9. Svensson J., Grauers A., Carlson O., "Förstudie av elsystem till vindkraftverk med variabelt varvtal," Department of Electrical Machines and Power Electronics, Chalmers University of Technology, Göteborg, Sweden, 1993.
10. Kübart G., "DC-breaker for a Thyristor Inverter," Department of Electrical Machines and Power Electronics, Chalmers University of Technology, Göteborg, Sweden, 1995.
11. Ludl F., "Akselmoment hos en synkrongenerator med variabelt turtall," Department of Electrical Machines and Power Electronics, Chalmers University of Technology, Göteborg, Sweden, 1994.
12. Akagi, H., "Trends in Active Power Lines Conditioner," IEEE Transaction on Power Electronics, vol. 9, No. 3, 1994, p. 263-268.
13. TAMP, Svenska Elverksföreningen, 1992.
14. DAMP, Svenska Elverksföreningen, 1994.
15. DEFU, "Spaendningskvalitet i lavspaendingsforsyningsnet", 1987.
16. Statent Energiverk, "Vindkraftens ekonomi", 1985.

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Paper 1B

Power Quality of Wind Turbine Generating Systems and their Interaction with the Grid

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Abstract

In this report, power quality from wind turbine generating systems is identified. The interaction between the wind turbine generating systems and the grid, the utility grid as well as stand alone grid, is analysed. Measurements at different wind turbine sites have been performed in order to identify disturbances caused by wind turbine generating systems. The results predicted by various models and calculation methods are compared and validated. When connected to the grid, wind turbines have some characteristics which must be considered. Depending on grid configuration and type of wind turbine used, different kinds of power quality problems arise. Introduction of wind power into the utility grid does not normally present any interfacing or operational problems, except for the voltage disturbances caused by an uneven wind speed and the wind turbine. Stationary voltage disturbances caused by the wind turbine generator system can be predicted by means of load flow calculations. Transient disturbances can be predicted by means of the EMTP program. In the utility grid, the intermittent power production from wind turbines is balanced by other production units. In an autonomous grid, however, the situation is the opposite. Since the spinning reserve in an autonomous grid is small, sudden changes in the wind speed may cause not only voltage variations but also frequency variations.

Keywords

wind turbine generator systems, power quality, flicker, voltage variations, harmonics, autonomous grid, frequency deviation

Contents

1 Introduction

During the last decade the wind energy technology has advanced and the wind industry has expanded remarkably. Increased efficiency of the wind turbine generator system, higher energy prices and environmental aspects are some of the reasons for the ongoing wind power boom. However, wind turbines are among utilities considered as potential sources for bad power quality. Uneven power production, the use of power electronics and in many cases location at the end of a long feeder line are some of the factors behind the statement.

The difficulty with wind power, seen from an electric point of view, is not only the uneven power production and the different types of grids used. There are also different types of wind turbines available on the market. Wind turbines operate either at fixed speed or variable speed. Variable-speed wind turbines are equipped with various converter types and use various control methods. Moreover, the turbine can either be stall- or pitch-regulated. The different types of wind turbines have all their advantages and disadvantages. They also contribute in some way to the power quality, either by improving the power quality or by making it worse.

A large number of papers presenting measurement results from various sites has been written, dealing with a wind turbine connected to some grid [1][2][3]. However, none of the known papers has tried to map out what specific kind of power quality problem a specific kind of wind turbine actually causes. There are, for example, software simulations performed, but they only deal with power fluctuations [4][5]. There are also many papers concerning power quality in general and the effects of bad power quality on the grid [6][7][8]. Moreover, there is a survey of wind power which just briefly discusses power quality effects from wind turbines [9].

In this report, power quality problems are discussed from the wind power point of view. Aerodynamical and mechanical principles for wind turbines are explained. The electrical systems used for fixed-speed and variable-speed operation and the power quality effects they will cause are described in detail. Moreover, wind power related power quality aspects are discussed and calculation methods for various voltage disturbances are derived. Finally, the report discusses the power quality of autonomous wind-diesel grids and some of the protection devices with which wind turbines are equipped.

2 Characteristics of the Wind

To be able to understand the performance of the wind turbines it is essential to have some knowledge of the behaviour and structure of the wind. They vary from site to site depending of the general climate of the region, the physical geography of the locality, the surface condition of the terrain and various other factors. The study of wind structure has lead to the following conclusions: Wind speed increases with height due to ground friction at ground level. There are continuous wind speed fluctuations, i.e. turbulence. The turbulence is spread over a broad range of frequencies [10].

In Figure 2.1, a schematic power spectrum is plotted according to van der Hoven. The left part of the power spectrum is determined by meteorological and climatic conditions of the site. The wind climate varies over the year. For example, in Sweden there are higher wind speeds during the winter season than during the summer.

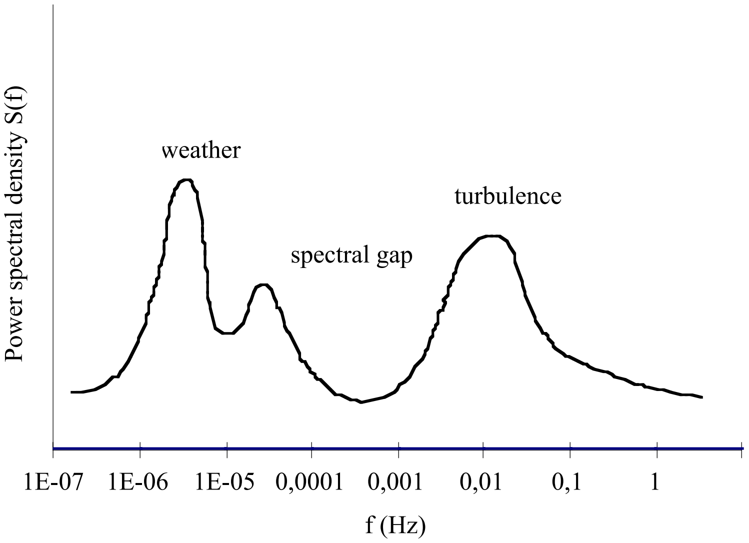

Figure 2.1: Schematic power spectrum of wind speed (according to van der Hoven).

The right side of the curve represents the energy in gusts and convective turbulence. There are variations in the amount of energy contents in the short cycles of gusts up to one second or even a part of a second. Figure 2.2 shows the wind speed measured at the harbour of Gothenburg, Sweden during one minute.

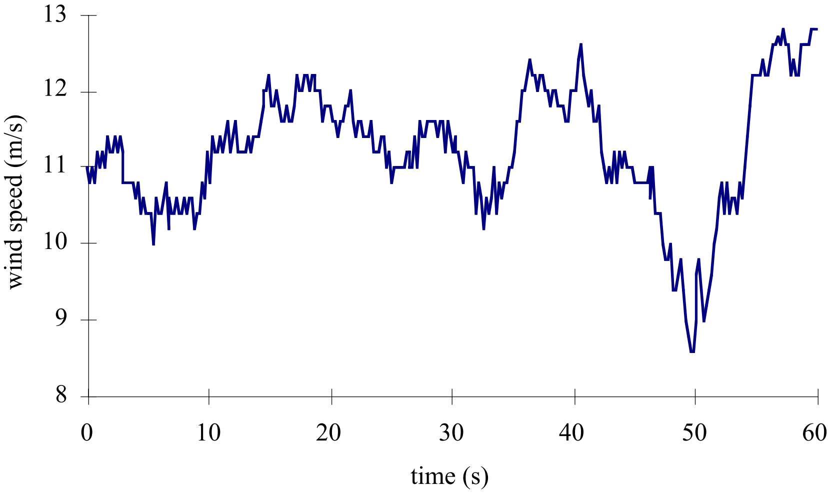

Figure 2.2: Wind speed measured at the harbour of Gothenburg, Sweden.

3 Wind Turbines

The mechanical and electrical principles as well as the aerodynamical behaviour of wind turbines are important issues. This chapter describes the operational criteria of wind turbines and the difference between stall- and pitch-regulation. Also the electrical systems used in fixed- and variable-speed wind turbines are described.

3.1 Operation Criteria for Wind Turbines

The energy available in the wind increases with the cube of the wind speed. Since the energy content of the wind is low during low wind speed conditions, wind turbines are cut in at the wind speed of 3-4 m/s. When the wind speed is further increased, the power output also increases. Depending on the type of wind turbine used, rated power is reached at a wind speed of 8-14 m/s. At higher wind speeds the power output is limited to the rated power of the generator. Hence, the power from the turbine must be limited. This limitation in power from the turbine used to be achieved in two different ways: either by pitching the turbine blades away from the wind mechanically (pitch regulation) or by an aerodynamic limitation of the power (stall regulation) [9]. At high wind conditions, above 25 m/s, wind turbines are shut down. In Figure 3.1, the available wind power, as well as the power from a stall-regulated and from a pitch-regulated turbine are shown.

Regardless of regulation principle used (stall or pitch regulation) power fluctuations will appear. A horizontal axis wind turbine always has some kind of a tower. The tower always disturbs the wind flow both upstream and downstream [11]. Each time a turbine blade passes the tower, it gets into the tower shadow with a power dip as a result. If the turbine has three blades, a power drop will appear three times per revolution of the turbine.

The left turbine in Figure 3.2 shows the rotor position when one blade passes the tower. As can be seen, at this moment none of the remaining two blades is at the top position where the wind speed is the highest. Both the tower shadow effect and the wind gradient contribute to a power dip. In contrast, the position of the right turbine in the figure does not produce a tower shadow effect, nor does the wind gradient reduce power. Consequently, at this rotor position the power will be at its maximum.

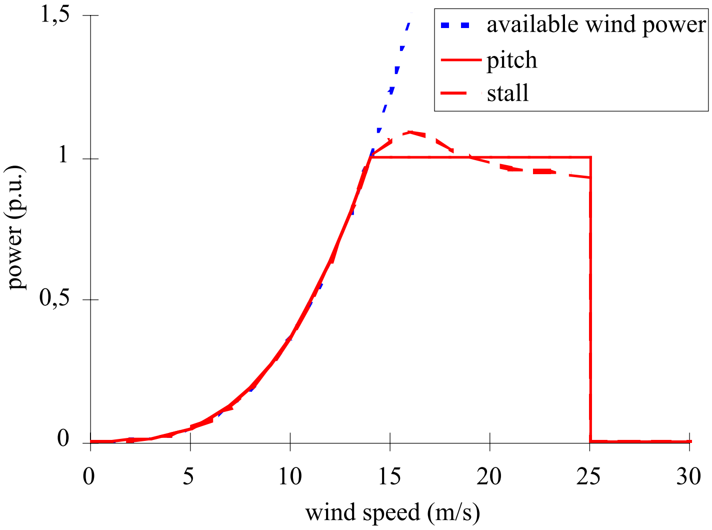

Figure 3.1: Available wind power (dotted line), power from a stall-regulated turbine (dashed line) and power from a pitch-regulated turbine (solid line).

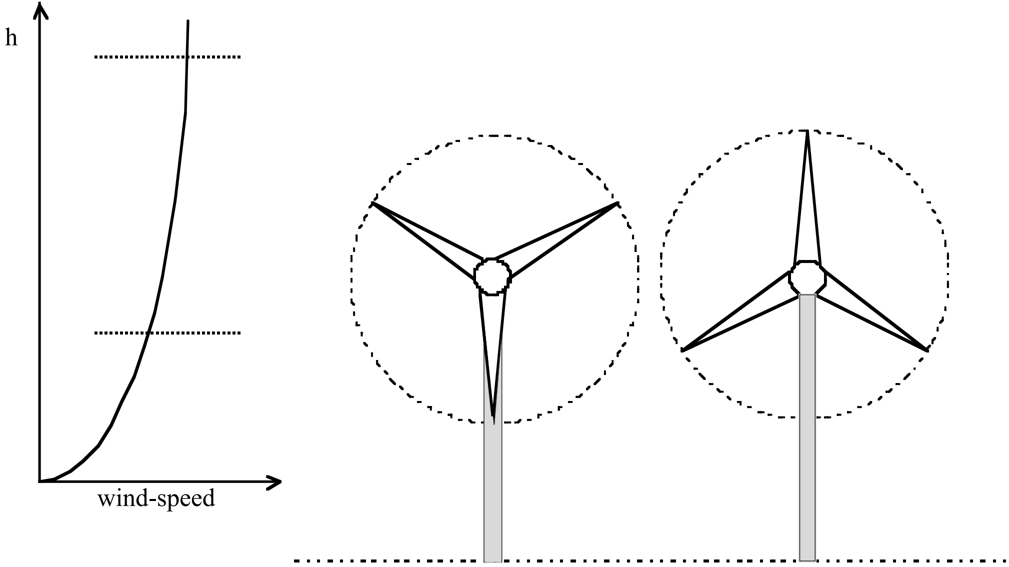

Figure 3.2: Different rotor positions of a three-blade turbine. The tower shadow and the wind gradient, both contribute to power fluctuations.

The torque at the rotor shaft when the rotor passes the tower has been calculated in [12]. The power from the two-bladed rotor decreases to 40 kW as a blade goes by the tower and increases to 120 kW as the blade passes the tower. This power dip will be smoothed out by the inertia and the damping of the system but will still appear in the electrical power output curve.

The measured power produced by fixed-speed wind turbines clearly shows periodical power fluctuations. In Figure 3.3, measured power fluctuations from a fixed-speed pitch-regulated wind turbine are shown. The frequency of the power fluctuation corresponds to the rotational speed of the rotor multiplied by the number of blades. This frequency is normally referred to as the “3p frequency“.

A two-blade and a three-blade wind turbine have been studied in [13]. Both turbines are pitch-regulated and operate at fixed speed. For both wind turbines studied, the greatest power fluctuation occurs at rated power at the highest wind speeds. According to [14], wind turbines equipped with induction generators operating at fixed speed generate power fluctuations up to 20% of the average power.

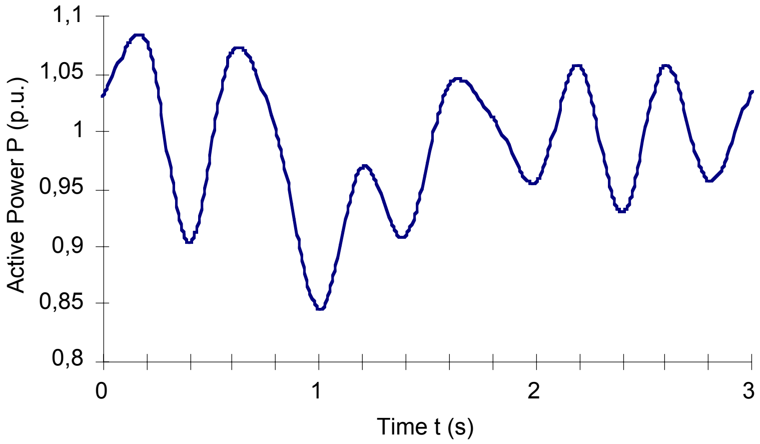

Figure 3.3: Measured power fluctuations from a fixed-speed pitch-regulated wind turbine.

3.1.1 Pitch Regulation

Pitch-regulated wind turbines control the power flow by means of the pitch angle of the blades. Generally, advantages of this type of regulation are good power control, flatwise aerodynamical damping, loads reducing with wind speed, assisted start and built-in braking. Some of the disadvantages are extra complexity, reducing reliability as well as cost of pitch mechanism and control systems [11].

From an electrical point of view, good power control means that the mean value of the power output is kept close to the rated power of the generator at wind speeds from rated wind speed up to the shut-down wind speed. The instantaneous power will, due to gusts and the speed of the pitch mechanism (i.e. limited band-width), fluctuate around the rated mean value of the power.

3.1.2 Stall Regulation

Stall regulation is the simplest and cheapest control method. Some of the disadvantages are loss of energy, high stationary loads and no assisted start [11]. From an electrical point of view, two things are worth pointing out.

Since the power from the turbine is always controlled aerodynamically, stall-regulated wind turbines do not produce fluctuating power caused by the pitch mechanism. Unfortunately, stall-regulated wind turbines may have a power output which sometimes is above the rated one, due to variations in the density of the air and imperfections in the aerodynamics.

Stall-regulated wind turbines do not have assisted start, which implies that the power of the turbine cannot be controlled during the connecting sequence. The start sequence of wind turbines is described in detail in Section 3.2.3.

3.2 Electrical Systems in Wind Turbine Generator Systems

Electrical systems in wind turbine generator systems can be divided into two main groups, fixed speed and variable speed. Fixed-speed wind turbines, equipped with a generator connected directly to the grid, are the most common type. The major advantage of the fixed-speed turbine is the simplicity and the low price of the electrical system used.

Variable-speed wind turbines are today not so common as fixed-speed wind turbines, although they will in the future most likely be the dominating type. The advantages by using variable-speed turbines are increased power quality, noise reduction and reduced mechanical stress on the wind turbine. Variable-speed wind turbines are equipped with a converter, which allows the generator frequency to differ from the grid frequency.

3.2.1 Fixed-Speed Wind Turbines

Almost all manufacturers of fixed-speed turbines use induction generators connected directly to the grid. Since the frequency of the grid is fixed, the speed of the turbine is settled by the ratio of the gearbox and by the number of poles in the generator. In order to increase the power production, some fixed-speed turbines are equipped with a pole change generator and can thereby operate at two different speeds. In order to avoid a large inrush current, a soft starter for the limitation of the current during the start sequence is used [15]. In Figure 3.4, a schematic figure of the electric system of a fixed-speed wind turbine is shown.

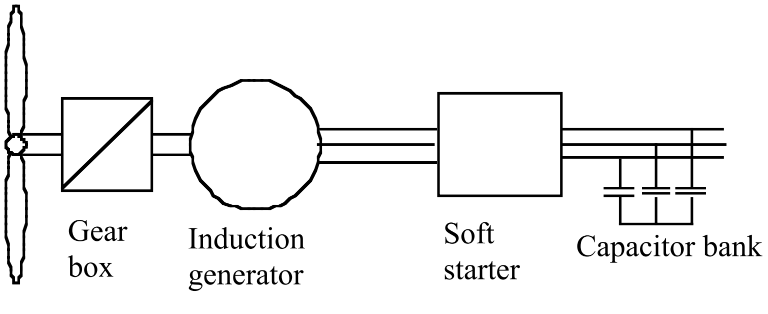

Figure 3.4: Schematic figure of the electric system of a fixed-speed wind turbine.

The induction generator has several advantages such as a robust design, no need for maintenance, well enclosed, produced in large series. It has, thereby, low price and can withstand overloads. The major disadvantage is the uncontrollable reactive power consumption of the induction generator. In order to compensate for the reactive power consumption, shunt capacitor banks are used. Figure 3.5 shows the measured reactive power consumption *Q* of an induction generator as a function of the active power *P*. The generator in the figure is equipped with shunt capacitors which compensate for the no-load reactive power consumption of the induction generator.

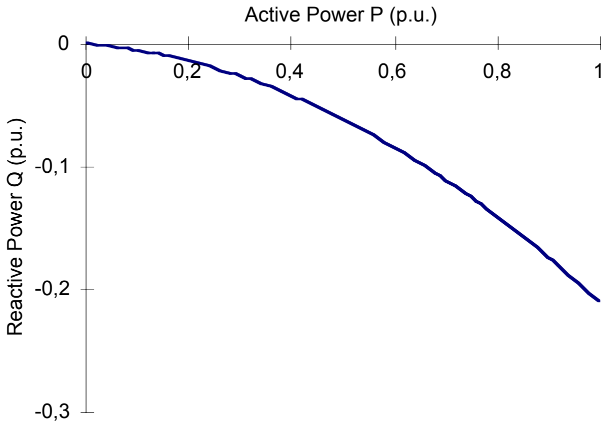

Figure 3.5: Reactive power as a function of active power. 1 p.u. corresponds to the rated active power.

3.2.2 Variable-Speed Wind Turbines

Today, several manufacturers are testing prototypes of variable-speed wind turbines. Only a few but large manufacturers, are mass-producing variable-speed wind turbines. Controlled in a proper way, all kinds of variable speed systems can reduce power fluctuations emanating from the tower shadow.

The electrical system becomes more complicated when it comes to variable-speed operation. The variable-speed operation of a wind turbine can be obtained in many different ways, and several different electrical systems are used for a broad or a narrow speed range. The difference between broad and narrow speed ranges is mainly the energy production and the capability of noise reduction. A broad speed range increases the power production and reduces the noise further compared with a narrow speed range.

3.2.2.1 Narrow Speed Range

For a narrow speed range, a rotor cascades of the induction generator can be used [16]. This type of cascade has been used in for example the US. Mod 5B. A schematic figure of a rotor cascade is shown in Figure 3.6.

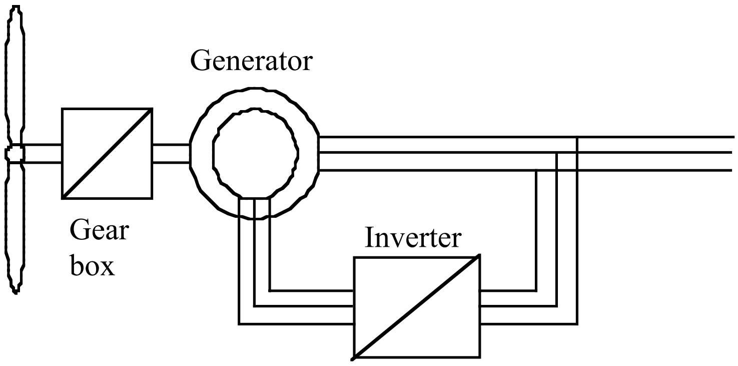

Figure 3.6: Schematic figure of the electrical system of a variable speed wind turbine equipped with a rotor cascade.

Another possible arrangement is to use controllable rotor resistances. A Danish manufacturer is producing a wind turbine where the slip of the induction generator, and thereby the speed of the rotor, can vary by 1-10%. The system uses an optically controlled converter by which the resistance of the rotor in the generator can be varied. In Figure 3.7, a schematic figure of the electrical system of a wind turbine equipped with controllable rotor resistances is shown.

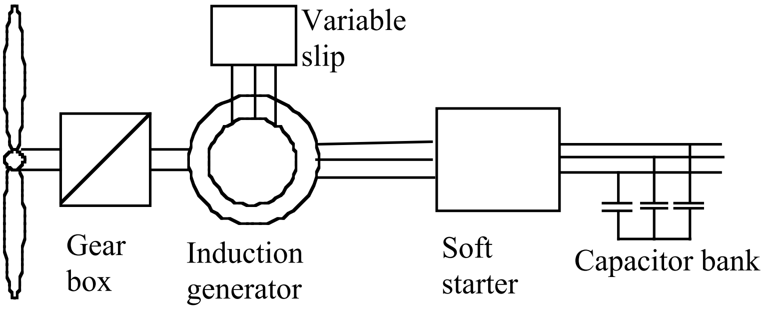

Figure 3.7: Schematic figure of the electrical system of a wind turbine equipped with controllable rotor resistances.

3.2.2.2 Broad Speed Range

Broad-range variable-speed systems are equipped with a frequency converter. In such a system, the alternating current from the generator needs first to be rectified and then inverted into alternating current before being fed into the grid. The electrical system must, therefore, consist of three main parts: generator, rectifier and inverter. The choice of these three main parts can be subdivided into two almost independent choices. The generator and rectifier must be chosen as a combination and the inverter can be chosen almost independent of the generator and rectifier used. When it comes to power quality aspects, only the inverter is of interest. In Figure 3.8 a schematic figure of a variable-speed wind turbine equipped with an converter is shown.

The two commonets types of inverters used are the line-commutated and the forced-commutated ones. These two types of inverters produce harmonics of different orders and hence need different types of filters. The line-commutated inverter is equipped with thyristors which must be connected to the grid in order to operate. Moreover, the power factor of the line-commutated inverter varies and is at most 0.9. The line-commutated inverter produces not only fundamental current but also harmonic current which will cause voltage harmonics at the grid. A six-pulse line-commutated inverter produces odd harmonics which are not multiples of 3. If the RMS value of the fundamental current is $I_{(1)}$=1 p.u., the relative RMS values of the harmonics are $I_{(n)}$=1/n p.u. where n=5, 7, 11, 13, 17, 19, ... [17]. A large grid filter must be used to eliminate these harmonics. One positive side effect when using a grid filter is that the filter produces reactive power. This production of reactive power increases the power factor of the wind turbine generator system.

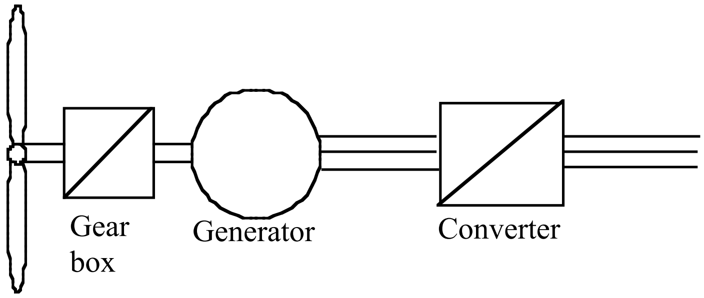

Figure 3.8: Schematic figure of the electric system of a variable-speed wind turbine equipped with an inverter.

In a forced-commutated inverter it is possible to freely choose when to turn on and when to turn off the valves. This possibility means that the forced-commutated inverter can create its own three-phase voltage system. If the inverter is connected to the grid, the inverter can freely choose which power factor to use. Even if the power factor may be freely chosen, the power factor of inverters today are usually kept equal to 1 (unity power factor). By the use of Pulse Width Modulation (PWM) technique the low frequency harmonics will be eliminated and the first harmonic will have a frequency around the switching frequency of the inverter. Usually, when IGBT-valves are used, the switching frequency is about 5 to 10 kHz. Only a small grid filter will be needed because of the high switching frequency.

3.2.3 Start of Wind Turbines

The start sequences of stall- and pitch-regulated fixed-speed wind turbines are different. As mentioned earlier, stall-regulated wind turbines do not have an assisted start. During the start sequence, the speed of the turbine is raised until the generator speed is close to the synchronous one. The generator is then connected to the grid. If the generator is not connected quickly, the turbine torque may exceed the maximum generator torque with a turbine over-speed as a result. Figure 3.9 shows the measured current during the cut-in sequence from a stall-regulated and a pitch-regulated wind turbine.

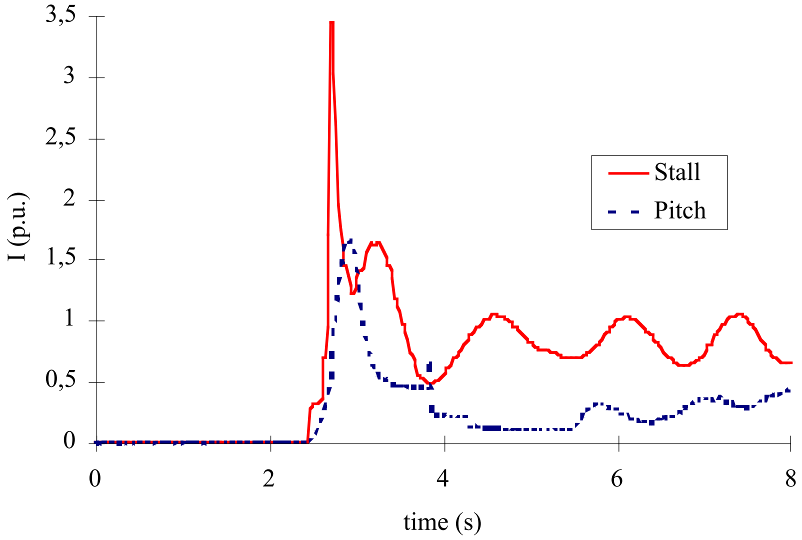

Figure 3.9: Measured current from a stall-regulated (solid line) and a pitch-regulated (dotted line) wind turbine.

As can be seen, the stall-regulated turbine has a high current peak followed by an oscillation. The peak current is caused by the electrical and mechanical features of the stall-regulated wind turbine. Since the generator needs to be connected to the grid quickly, the soft starter operates only for a very short period causing a fairly high inrush current. Moreover, the capacitor bank is connected immediately after the generator is connected to the grid. The connection of the capacitor bank also contributes to the current peak. The mechanical contribution to the peak current is the torque produced by the wind speed and the inertia of the turbine as it is brought from a small over-speed to a constant speed. The oscillating current after the connection is a mechanical oscillation caused by the abrupt generator connection.

In the case of the pitch-regulated turbine, where the start is assisted, the torque and the speed of the turbine can be controlled. Hence, the cut in of the generator can be performed in a smoother way. As can be seen, the current is raised slowly and the speed of the turbine is brought to a constant speed in a more controlled way. The smooth connection of the generator is a result of a controlled speed and a long operation time of the soft starter. The switching action of the capacitor banks is also performed a short time after the soft starter has stopped. The first capacitor switching is visible at the time just before 4 sec. The second switch is performed just after 4 sec. In Chapter 4.5, the impact of capacitor switching is described more in detail. The figure illustrates the difference between assisted and non-assisted starts, although the wind conditions during the start of the two wind turbines are not exactly the same.

4 Power Quality

Perfect power quality means that the voltage is continuous and virtually purely sinusoidal, with a constant amplitude and frequency. The power quality, which depends on the interaction between the grid and the wind turbine, can be expressed in terms of physical characteristics and properties of the electricity. It is most often described in terms of voltage stability, frequency stability and phase balance.

Voltage stability can be subdivided into slow voltage variations, voltage dips, flicker, transients and harmonic voltage distortion. Most of this chapter deals with the different aspects of the voltage stability.

The frequency of large power systems is normally very stable and therefore no problem. At autonomous grids where for example diesel engines are used, wind turbines may cause frequency variations. Frequency variations on autonomous grids are further discussed in Chapter 6.

A wind turbine will actually improve the phase balance on the grid when it is connected in a fashion similar to balanced three-phase loads [18]. Phase imbalance will therefore not be considered in this report.

4.1 Slow Voltage Variations

Slow voltage variations can be defined as changes in the RMS value of the voltage occurring in a time span of minutes or more. National standards often state allowable variations in nominal voltage over an extended period, for instance 24 hours. IEC Publication 38 recommends 230/400 V as the standard voltage for 50 Hz systems. Under these conditions, the voltage at the user's terminal must not differ more than ±10% from the normal voltage.

Slow voltage variations on the grid are mainly caused by variations in load and power production units. When wind power is introduced, voltage variations also emanate from the power produced by the turbine, see Figure 4.1.

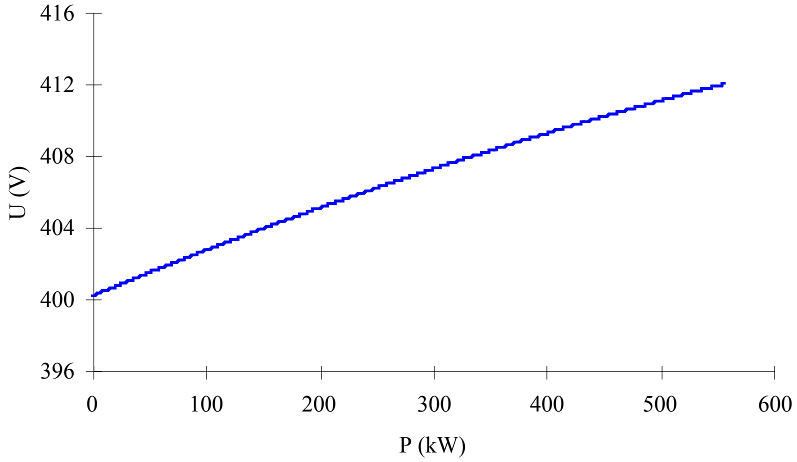

Figure 4.1: Measured voltage as a function of produced active power P from a 600 kW wind turbine located at Utteros in Sweden.

The power production from wind turbines may vary widely and not only due to variations in the wind. It may also momentarily go from full to zero power production or vice versa in the event of an emergency stop or a start in high wind conditions.

According to the national standards and regulations, there is a large variation in the permitted voltage variation caused by wind turbines connected to the utility grid. In Denmark, wind turbines may not cause a voltage variation exceeding 1% at the high-voltage line at the Point of Common Connection (PCC) [19]. In Germany and Sweden the corresponding limits are 2% and 2.5%, respectively [20][21].

4.2 Voltage Dips

A voltage sag, or voltage dip, is a reduction in the supply voltage by a duration of between one cycle and a few seconds. Voltage sags are caused by motor starting, short circuits and fast re-closing of circuit breakers [22]. Properly equipped with soft starters, wind turbines do not cause any voltage sags. In [23] a test of starting a wind turbine with and without a soft starter was carried out. With the soft starter disabled, the initial voltage drop was 28%. With the soft starter in service, the voltage drop was limited to 1.5%. According to the Swedish Standard SS 421 18 11, the voltage drop during the start-up sequence of motors should be limited to 5%.

In the case of a voltage sag occurring at the grid, wind turbines will be shut down. Due to increased losses in the rotor windings, the induction machines are sensitive to a reduction of the supply voltage.

4.3 Flicker

Flicker is an old way of quantifying voltage fluctuations. The method is based on measurements of variations in the voltage amplitude, i.e. the duration and magnitude of the variations. Flicker is treated in Standard IEC 868. Figure 4.2, shows the magnitude of maximum permissible voltage changes with respect to the number of voltage changes per second according to Standard IEC 868.

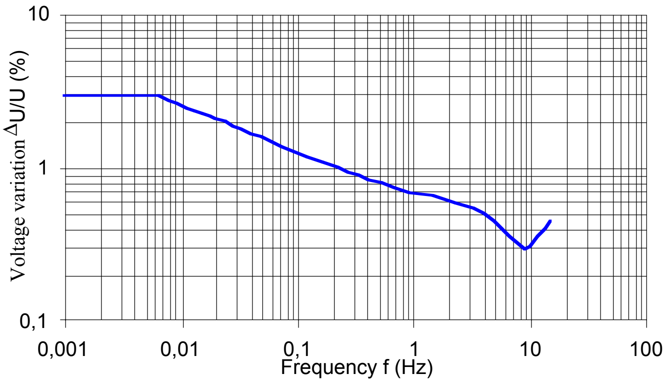

Figure 4.2: Flicker curve according to IEC 868.

The fluctuations are weighted by two different filters. One filter corresponds to the response of a 60 W light-bulb and the other filter corresponds to the response of the human eye and brain to variations in the luminance of the light bulb [24].

4.4 Voltage Harmonics

Voltage harmonics are virtually always present on the utility grid. Non-linear loads, power electronic loads, rectifiers and inverters in motor drives etc. are some sources which are producing harmonics. The effects of the harmonics include overheating and failure of equipment, mis-operation of protective equipment, nuisance tripping of sensitive load and interference with communication circuits [6].

As soon as the shunt capacitor banks are connected to the grid, an oscillating circuit with the inductance of the grid is created. Since there are always harmonics on the grid, the oscillating circuit will amplify a single harmonic [25]. Commonest is an amplification of harmonics of the orders 7 or 11. The size of the capacitance and the inductance determine which harmonics will be amplified.

Harmonic voltage distortions can be caused by the flow of harmonic currents in the system. The harmonic distortion can be quantified by several different methods. One of the most common methods is Total Harmonic Distortion (THD). An other method for quantifying harmonics is the individual harmonic distortion. In, for example, Standards IEC 1000-2-2 and CENELEC EN 50160 the maximum THD and maximum permitted value of an individual component are stated. Today, the national and international standards do not include harmonics between 2-10 kHz. If forced-commutated inverters are used, the low-order harmonics will be replaced by higher-order harmonics. By using PWM the low frequency harmonics are eliminated and the first harmonic will have a frequency around the switching frequency (5 to 10 kHz) [26].

4.5 Transients

Transients seem to occur mainly when starting and stopping fixed-speed wind turbines [3]. The wind turbines are connected to the grid when the wind speed exceeds 3 - 4 m/s. During the connecting sequence, the speed of the turbine is raised until the generator speed is close to the synchronous one. The generator is then connected to the grid. In order to avoid a large inrush current, a soft starter is used to limit the current during the starting sequence. As the shunt capacitor banks are connected, a large current peak occurs. This transient sometimes reaches a value of twice the rated wind turbine current, see Figure 4.3. Also the voltage of the low-voltage grid is substantially affected, which can disturb sensitive equipment connected to the same part of the grid as the wind turbines [15].

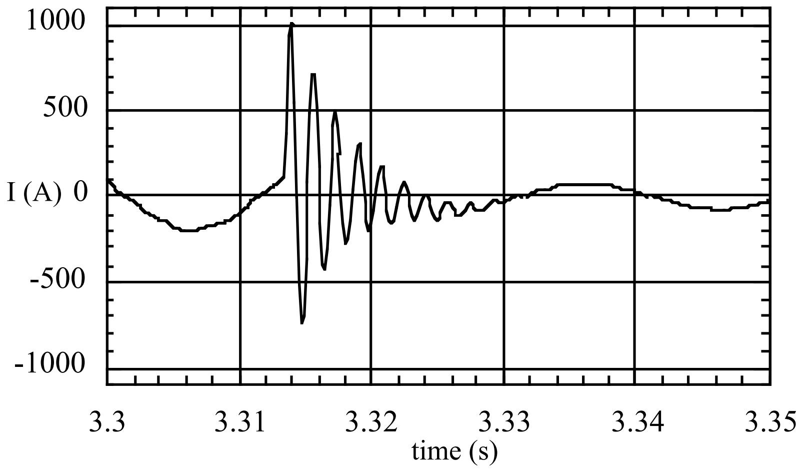

Figure 4.3: Measured oscillating current caused by the connecting of shunt capacitors during the start-up sequence of a 225 kW wind turbine at Risholmen, Sweden.

4.6 Frequency

In [2] it is stated that the introduction of a relatively small amount of wind power into the utility grid does not normally present interfacing or operational problems. The intermittent power production from wind turbines is balanced by other production units.

In the case of a grid fault where the overhead lines are disconnected, island operation with frequency deviation as a result may occur. If for example a fixed-speed wind turbine equipped with an induction generator is over-compensated for reactive power, self-excitation may occur. At these occasions, the wind turbine may support the remaining load with power. Normally, since there is a mismatch between the load and the power production, it will lead to frequency deviations. In

[27] a case where four wind turbines were operating at a self-exciting mode for 15 minutes is documented. In order to avoid self-excitation, reactive power is normally only compensated for up to the no-load reactive power demand of the induction generator. Moreover, wind turbines are normally equipped with over voltage, under voltage and frequency protection relays. In the event of an abnormal operating condition, the wind turbine is shut down.

According to the European Standard EN 50 160, the nominal frequency of the supply voltage shall be 50 Hz. Furthermore, under normal operating conditions the average value of the fundamental frequency measured over 10 seconds in distribution systems with no synchronous connection to an interconnected system shall be within a range of 50 Hz ± 2 % (i.e. 49 Hz to 51 Hz) during 95 % of a week or 50 Hz ± 15 % (i.e. 42.5 Hz to 57.5 Hz) during 100 % of a week.

5 Calculations of Voltage Disturbances

All kinds of wind turbines cause slow voltage variations. Slow voltage variations are due to the variation in the energy content of the wind. In addition to slow voltage variations, different kinds of wind turbines give rise to different types of voltage disturbances.

Fixed-speed wind turbines mainly produce flicker. Flicker is caused by the power fluctuations emanating from the tower shadow effect.

Variable-speed turbines do not cause any flicker. Variable-speed wind turbines will, however, produce current harmonics, which may cause disturbances on the grid.

5.1 Slow Voltage Disturbances

Several methods are used to calculate slow voltage variations. For example, there are several computer codes for load flow calculations available on the market. Utilities use those codes for normally the prediction of voltage variations caused by load variations. Load flow calculations can, with advantage, be used to calculate slow variations in the voltage caused by wind turbines. Another, analytical method is simply to calculate the voltage variation caused by the grid impedance *Z*, the active power *P* and reactive power *Q* [28]. In the analytical method, a simple impedance model shown in Figure 5.1 is used. U_1 is the voltage of the infinite bus and U_2 is the voltage of the wind turbine at the point of common connection, PCC.

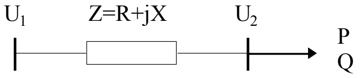

Figure 5.1: Simple impedance model.

The voltage at the PCC can be expressed as

$$U_2 = \sqrt{a + \sqrt{a^2 - b}} \tag{1}$$

where

$$a = \frac{U_1^2}{2} - (RP + XQ) \qquad (2)$$

$$b = (P^2 + Q^2)Z^2 \qquad (3)$$

A simplified version of that equation is used in the Danish and Swedish regulations [19][21][29].

In Figure 5.2, a comparison between a load flow calculation and the analytical method is made. The two different methods are used to calculated the voltage variations caused by a cluster of three wind turbines. In this example, the three wind turbines are feeding a 130 kV stiff grid via a 40 MVA 135/11 kV transformer and a 10 kV cable. Each wind turbine is connected to the 10 kV grid via a 0.7/10.5 kV transformer. In Figure 5.2 the voltage variation, caused by the power production in per unit (p.u.) on the 0.7 kV and the 10 kV side of the wind turbine transformers is presented.

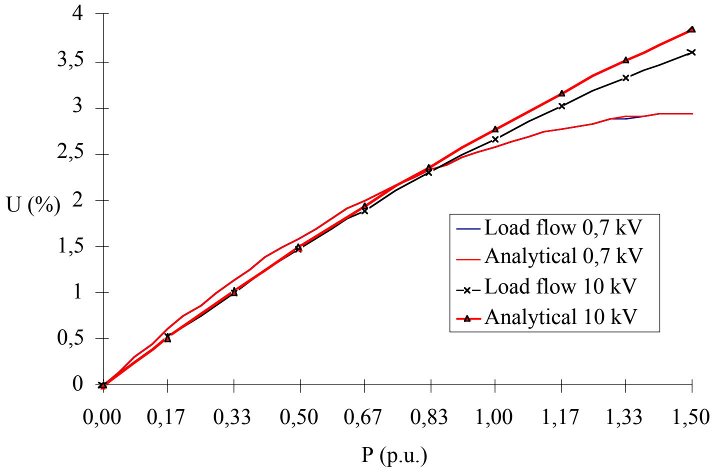

Figure 5.2: Comparison of calculated voltage variations using load flow calclation and the analytical method.

At the 0.7 kV side of the transformer, the analytical and the load flow calculations give the same result. On the 10 kV side of the transformer, the two methods give different results. This is due to the losses in the transformer, which are not taken into account by the analytical method. It is worth mentioning that the analytical method over-estimates the voltage variation, which makes the method useful as a first approximation.

5.2 Flicker Disturbances

Power fluctuations occurring at a frequency of 1 to 2 Hz are mainly caused by the tower shadow. According to IEC 868, voltage variations occurring at 1 Hz may be only 0.7%. The magnitude and the frequency of the active power fluctuations and the corresponding reactive power fluctuations must be known in order to calculate the flicker. The frequency of the fluctuations from a fixed-speed turbine can easily be calculated. Moreover, the reactive power consumption is determined as a function of the active power from the technical data given by the manufacturer. Unfortunately, the magnitude of the active power fluctuations are normally not given by the manufacturer.

If the flicker emission from a wind turbine is already known, a method to calculate the flicker emission from wind turbines connected to the grid is presented and verified in [30]. The idea of the method is to measure the flicker emission level from a wind turbine under reference conditions and to use these measurements to calculate a flicker coefficient for that specific wind turbine type. The flicker coefficient can then be used to calculate the flicker emission level from any wind turbine of that type in any grid and wind conditions. The maximal long-time perturbation flicker emission level from a single wind turbine is, according to the Danish regulation, P_{lt}=0.35 [31].

In the U.K. the Engineering Recommendation P28 indicates that flicker from more than one source may be combined as:

$$P_{st} = \sqrt[3]{(P_{st1})^3 + (P_{st2})^3} \qquad (4)$$

According to [32], the ratio between the reactance X and the resistance R of the grid has a significant impact on the minimum short-circuit ratio at the PCC. Calculations of the power fluctuations caused by the tower shadow effect of a fixed-speed wind turbine reveal that the minimum short-circuit ratio is determined by the stationary voltage variations if the *X/R* ratio of the grid is low at the PCC, as illustrated in Figure 5.3. The short-circuit ratio is defined as the ratio between the short-circuit power of the grid at the PCC and the rated power of the installed wind turbine. At high *X/R* ratios, the minimum short-circuit ratio is determined by the voltage variations caused by fluctuating power. However, if the *X/R* ratio of the grid in the PCC is low, the grid must be dimensioned for stationary voltage variations.

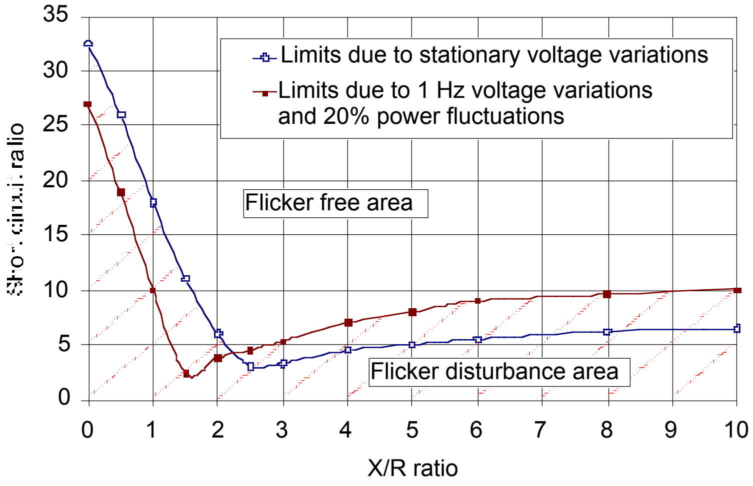

Figure 5.3: Minimum short-circuit ratio to avoid flicker caused by stationary voltage variations and 1 Hz voltage variations as a function of the grid *X/R* ratio.

In the Swedish recommendations the grid connection of wind turbines, the flicker is not taken into consideration. It is only stated that the short-circuit ratio would be 20 times.

5.3 Harmonic Voltage Disturbances

Variable-speed wind turbines produce current harmonics, which may cause disturbances on the grid. The magnitude of the disturbances depend on the type of inverter used. The variable-speed operation of a wind turbine may be obtained in many different ways, and several different electrical systems are used for a broad and a narrow speed range. The harmonic current produced by the different types of inverters is described in Chapter 3.

In [33] measurements on single wind turbines and a wind farm consisting of variable-speed wind turbines equipped with PWM converters are performed. In the paper it is stated that harmonics generated by PWM-inverter wind turbines are low compared to 6- or 12-pulse inverter systems. The distortion of the output current has a stochastic characteristic and does not lead to any single high-amplitude harmonics but to a broad range of low-amplitude distortions. Due to the stochastic characteristic, the currents of the single wind turbines within the wind farm superimpose by vector addition. The cumulative distortion increases with growing number n of wind turbines as $\sqrt{n}$. Thus, the specific distortion of a single wind turbine in the wind farm is decreasing as $1/\sqrt{n}$.

The propagation of harmonics into the grid is determined by the impedance characteristics of the grid, i.e. the grid impedance as a function of the frequency. The impedance of overhead lines increases with increasing frequency, while it decreases in a cable grid. Hence, in Denmark filters for reduction of the harmonics are required if a wind turbine equipped with an inverter is connected to an overhead line [34]. In the Swedish recommendations regarding grid connection of wind turbines, voltage harmonics are not mentioned.

5.4 Voltage Transient Disturbances

Transients seem to occur mainly when starting and stopping fixed-speed wind turbines [3]. Fixed-speed wind turbines are equipped with shunt capacitor banks which are connected during the start-up sequence. As the shunt capacitor banks are connected, a large current peak occurs. This transient sometimes reaches a value of twice the rated wind turbine current and may substantially affect the voltage of the low-voltage grid. The voltage transient can disturb sensitive equipment connected to the same part of the grid [15].

The amplitude of the current emanating from the capacitor switching is normally declared on the data sheet from the wind turbine manufacturer. The frequency of the transient can approximately be determined by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \qquad (5)$$

where L is the inductance of the grid and C is the capacitance.

In order to improve the calculations of the connecting current and voltage, a more detailed model must be used. The use of the Electro Magnetic Transient Program (EMTP) makes it possible to use frequency-dependent parameters. In [15], calculations of switching transients in a low-voltage grid equipped with two wind turbines are presented.

In the national and international recommendations regarding grid connection of wind turbines, limitation of the start current is stated. In the Swedish Standard SS 421 18 11, it is stated that voltage drops caused by motor starts may not exceed 5%.

6 Autonomous grids

The effect of wind power is very important in autonomous power systems. The spinning reserve is small in an autonomous grid supplied by diesel engines. The small spinning reserve will give rise to frequency fluctuations in the case of a sudden wind rise or wind drop. Hence, in a wind-diesel system, the voltage and frequency fluctuations will be considerably greater than in an ordinary utility grid. In order to understand the characteristics of an autonomous grid, the properties of diesel generator sets must be known.

6.1 Diesel Generator Set Properties

Two kinds of load divisions must be established for diesel generators operating in parallel with each other: the active power as well as the reactive power must be shared between the generators. The load division between diesel generators is affected by controlling the speed of the diesel engines (active power) and the field of the generator (reactive power) [35].

When generators operate in parallel with each other, they run at synchronous speed and behave just as if they were mechanically coupled. When the load increases, the frequency of the system falls until the total output of all the units matches the new load. Active power load is shared between the generators in accordance with the speed drops of their engine governors. Diesel engines normally have a governor giving a frequency of 52 Hz at no-load and 50 Hz at full-load. Hence, since the load in the grid varies, the frequency also varies.

The reactive power is shared between generators operating in parallel in the same way as the active power. Diesel engines normally have a voltage regulator with the voltage decreasing with an increasing generator load.

6.2 Frequency Variations

During the last decade, different types of wind turbines and wind-diesel systems for autonomous grids have been tested. Commonest are fixed-speed wind turbines equipped with induction generators. Figure 6.1 shows measurements performed during two nights at a wind-diesel system with a relatively small amount of wind power. The installed wind power is approximately 10% of the total diesel power on the island. The frequency from the wind farm was measured during two nights, one night with wind turbines and one night without wind turbines. There are two frequency drops during the night when the turbines were shut down. These two drops are most likely emanating from diesel engine stops. The other curve representing the frequency when the turbines were operating shows an increased frequency. The frequency was above 50 Hz during the whole night indicating that some diesel engines were running at low load. Most likely, the utility is afraid to stop all diesel engines in case of a sudden wind drop.

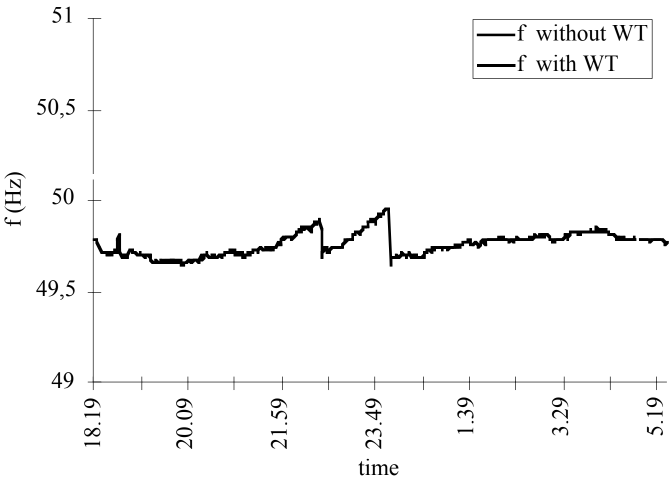

Figure 6.1: Frequency variations during two nights. One night when the turbines were operating (gray line) and one night when the turbines were shut down due to lack of wind (black line).

If the penetration of wind power is further increased, i.e. the wind-diesel system is supposed to operate with solely wind power at high-wind conditions, the power from the wind turbine must be controllable. Measurements on such a specially designed wind-diesel system, using a pitch-controlled variable-speed wind turbine, are shown in Figure 6.2.

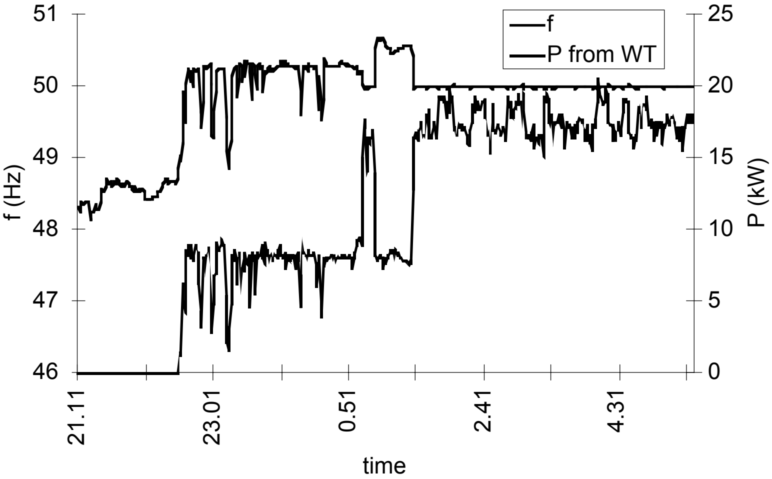

Figure 6.2: Frequency variations (black line) and power output from the wind turbine (gray line) during one night.

The figure shows the power from the wind turbine and the frequency measured during one night. As can be seen in the figure, the wind turbine is shut down and the plant is operating in diesel mode during the first 1.5 hours. The plant is then turned into the mixed mode and the wind turbine is working in parallel with the diesel for approximately 4 hours. Finally, for the rest of the night the wind speed was high enough for the wind turbine to operate alone.

The frequency is raised from approximately 48 Hz in the diesel mode to 50 Hz in the mixed and wind modes. This diesel seems to have a governor with a frequency of 50 Hz at no-load to 48 Hz at full-load. For the rest of the night, the plant is running in the wind mode. As can be seen, the frequency is very stable when the plant is running in the wind mode. In fact, the frequency is much more stable in the wind mode than in the other two modes.

7 Wind Turbine Protection

Power quality does not only consider disturbances caused by a device connected to the grid. Power quality also considers disturbances occurring in the grid. In order to maintain a high reliability and security in the grid and in the wind turbines, these must be disconnected from the grid in the event of a malfunction of the grid and vice versa.

Several national and international recommendations and standards for the connection of wind turbines to the grid have been written during the last decade. In almost all national recommendations, the same protection devices are used as in the IEC-standard TC 88 for wind turbines [20][21][29][36][37]. According to the IEC-standard, wind turbine protection should provided for under voltage, over voltage and over current, due to both overload and short-circuits. In addition, protection should be provided for the loss of phase and phase reversal as well as under frequency and over frequency. The equipment should also shut down the wind turbine safely in the event of operating conditions which will not allow safe operation. For example in Sweden, it is stated that wind turbines shall be equipped with relays which disconnect the turbine from the grid within 5 seconds in the event of a voltage level lower than 90% or exceeding 106% of nominal voltage and frequency deviations from nominal frequency exceeding ±1 Hz. Normally, this protection device is an integral part of the control system of the wind turbine.

8 Conclusions

There are different kinds of wind turbines available on the market. Wind turbines can be classified in different categories. From an electrical point of view, wind turbines may be divided into two main groups, fixed-speed and variable-speed operation. Both groups of wind turbines have advantages and disadvantages regarding the interaction with the grid and the power quality. A summary of different power quality phenomena caused by fixed- and variable-speed wind turbines is made in Table 8.1.

Table 8.1: Power quality phenomena caused by fixed- and variable-speed wind turbines. The symbols indicate that the phenomena exist ”X”, do not exist ”-” and only exist partly or under certain conditions ”(X)”.

Power quality phenomena	Fixed speed	Variable speed	Comments
Voltage variations	X	X	Caused by an uneven power production
Voltage dips	-	-	If properly equipped with soft starter
Flicker	X	-	Caused by the tower shadow effect
Voltage harmonics	(X)	X	Caused by inverters or oscillation
Transients	X	(X)	Caused by capacitor switching
Frequency variations	(X)	(X)	Mainly in autonomous grids

Wind turbines have an uneven power production following the natural variations of the wind. The uneven power production is the same for all kinds of wind turbines. Each time a turbine blade passes the tower, it gets into the tower shadow. If the turbine is operating at fixed-speed, the tower shadow will result in a fluctuating power. Both the uneven power production and the power fluctuation cause voltage variations. Load flow calculations can, with advantage, be used to calculate slow variations in the voltage caused by the uneven power production from wind turbines. The power fluctuations caused by the tower shadow may cause flicker disturbances. In order to calculate the impact on flicker, the magnitude of the power dips or the flicker emission from the wind turbine must be known.

Apart from oscillation between the grid impedance and the shunt capacitor banks for power factor correction, which may amplifying a specific harmonic, fixed-speed wind turbines do not produce any harmonics. When it comes to variable-speed wind turbines, the situation is the opposite. Depending on the type of inverter used, different orders of harmonics are produced.

Transients seem to occur mainly when wind turbines are started and stopped. Properly equipped with a soft-starter, a large inrush current and thereby a voltage dip can be avoided. As the shunt capacitor bank is switched on, a large current peak occurs. The current peak may affect the voltage on the low-voltage side of the transformer substantially. The effect on the voltage emanating from transient currents and transient switching actions can be calculated by proper computer codes, for example the Electro Magnetic Transient Program (EMTP).

In an autonomous grid supplied by diesel engines, the spinning reserve is limited. The limitation in spinning reserve gives rise to frequency fluctuations in the case of fast load changes. Hence, the frequency of an autonomous grid is normally not as stable as that of a large grid. When wind power is introduced to an autonomous grid, a sudden wind rise or wind drop will affect the power balance with frequency variations as a result. The use of sophisticated variable-speed wind turbines can eliminate this problem and actually improve the frequency balance.

The standards and regulations used today are insufficient and incomplete. All different kinds of power quality phenomena are not taken into consideration. The calculation methods and models used are too simplified.

In order to predict the interaction between the wind turbines and the grid, new and better models which include all features of wind turbines are needed. These models could be useful tools in order to predict the power quality from wind turbines. Wind turbine types which in combination with the grid are likely to cause power quality problems could at an early stage of planning be rejected and replaced by a more proper type of wind turbine.

References

[1] Thiringer, T., ”Power Quality Measurements Performed on a Low-voltage Grid Equipped with Two Wind Turbines”, *IEEE Transactions on Energy Conversion*, Vol. 11, No. 3, September 1996, p. 601 - 606.

[2] Larsson, Å., ”Voltage and Frequency Variations on Autonomous Grids: A Comparison of Two Different Wind-Diesel Systems”, *Proceedings of the European Union Wind Energy Conference* (EUWEC '96), May 1996, Göteborg, Sweden, p. 317 - 320.

[3] Demoulias, C. S., Dokopoulos, P., ”Electrical Transients of Wind Turbines in a Small Power Grid”, *IEEE Transactions on Energy Conversion*, Vol. 11, No. 3, September 1996, p. 636 - 642.

[4] Keller, J. G., ”A Methology by Power Quality Measurements for Wind Turbines and Remote Communities”, Wind Engineering, Vol. 18, No. 2, 1994, p. 87 - 91.

[5] Chan, S. M., Cresap, R. L., Curtice, D. H., ”Wind Turbine Cluster Model”, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, No. 7 July 1984, p. 1692 - 1698.

[6] Reid, E. W., ”Power Quality Issues - Standards and Guidelines”, *IEEE Transactions on Industry Applications*, Vol. 32, No. 3, May/June 1996, p. 625 - 632.

[7] Phipps, J. K., Nelson, J. P., Sen, P. K., ”Power Quality and Harmonic Distortion on Distribution Systems” *IEEE Transactions on Industry Applications*, Vol. 30, No. 2, March/April 1994, p. 476 - 478.

[8] Wagner, V. E., et.al., ”Effects of Harmonics on Equipment”, *IEEE Transactions on Power Delivery*, Vol. 8, No. 2, April 1993, p. 672 - 680.

[9] Richardson, R. D., McNerney, G. M., ”Wind Energy Systems”, *Proceedings of the IEEE*, Vol. 81, No. 3, March 1993, p. 378 - 389.

[10] Freris, L. L., ”Harnessing the wind”. *Power Engineering Journal*, September 1992, p. 251 - 260.

[11] Freris, L.L. (ed.), *Wind Energy Conversion Systems*, Prentice Hall International (UK) Ltd, 1990, 388 p.

[12] Johnson, G.L., *Wind Energy Systems*, Prentice Hall International Inc., New Jersey, USA, 1985, 360 p.

[13] Gardner, P., ”Flicker from Wind Farms”. *Proceedings of the BWEA/SERC RAL Workshop on Wind Energy Penetration into Weak Electricity Network*, Rutherford, U.K., June 1993, p. 27 - 37.

[14] Gerdes, G., Santjer, F., ”Power Quality of Wind Turbines and their Interaction with the Grid”. *Proceedings of the European Wind Wnergy Conference (EWEC ‘94)*, Thessaloniki, Greece, 10-14 October 1994, p. 1112 - 1115.

[15] Larsson, Å., Thiringer, T., ”Measurements on and Modelling of Capacitor-Connecting Transients on a Low-voltage Grid Equipped with Two Wind Turbines”, *Proceedings of the International Conference on Power System Transients* (IPST '95), Lisbon, Portugal, Sept. 1995, p. 184 - 188.

[16] Larsson, Å., Carlson, O., Sidén, G., ”Electrical Generating Systems in Wind Turbine Applications”, *Proceedings of the IEEE/KTH Stockholm Power Tech Conference*, Vol. Electrical Machines and Drives, June 1995, p. 205 - 210.

[17] Thorborg, K., *Power Electronics*. Prentice Hall International (UK) Ltd, 1988. 504 p.

[18] Jenkins, N., ”Embedded generation Part 2”, Power Engineering Journal, October 1996, p. 233 - 239.

[19] Jørgensen; P., Christensen, J. S., Tande, J. O., Vikkelsø, A., Nørgård, P., ”Elkvalitet ved nettilslutning af vindmøller Del 1: Stationære spændningsforhold”, Roskilde, Information Service Department, Risø National Laboratoy, 1996, 118 p. (in Danish)

[20] VDEW Publication, ”Technische Richtlinie Parallelbetrieb von Eigenerzeugungsanlagen mit dem Mittelspannungsnetz des Elektrizitätsversorgungs-unterhmens (EVU)”, Frankfurt am Main, VWEW-Verlag, 1994, 48 p. (in German)

[21] Tekniska anvisningar för anslutning av mindre produktionsanläggningar till distributionsnät (TAMP), Svenska Elverksföreningen, 1992. (in Swedish)

[22] Bollen, M. H. J., ”Voltage sags: effects, mitigation and predicts”, Power Engineering Journal, June 1996, p. 129 - 135.

[23] Craig, L.M., Jenkins, N., ”Performance of Wind Turbine Connected to a Weak Rural Network”, Wind Engineering, Vol. 19, No. 3, 1995, p. 135 - 145.

[24] Walker, M. K., ”Electric Utility Flicker Limitation”, in *Proceeding of the Power Quality Conference*, Long Beach, California, October 1989, p. 602 - 613.

[25] Girgis, A. A., Fallon, C. M., Rubino, J. C. P., Catoe, R. C., ”Harmonics and Transient Overvoltage Due to Capacitor Switching”, *IEEE Transactions on Industry Applications*, Vol. 29, No. 6 November/December 1993, p. 1184 - 1188.

[26] Bose, B. K., Power Electronics and AC Drives, Prentice Hall, 1986. 402 p.

[27] Zaininger Engineering Company, Inc., ”Electrical Behavior of Wind Power Stations”, Electric Power Research Institute (EPRI), Project 1996-24, June 1987, p. 4-4 - 4-10.

[28] Ballard, L. J., Swansborough, R., H. (ed.), ”Recommended Practices for Wind Turbine Testing: 7. Quality of Power. Single Grid-Connected WECS”, Roskilde, Elsgaards bogtrykkeri, Edition 1, 1984.

[29] Dimensioneringsrekommendationer för anslutning av mindre produktionskällor till distributionsnät (DAMP), Svenska Elverksföreningen, 1994. (in Swedish)

[30] Sørensen, P., Tande, J.O., Søndergaard, L.M., Kledal, J.D., *”Flicker Emission Levels from Wind Turbines”*, Wind Engineering, Vol. 20, No. 1, 1996, p. 39 - 45.

[31] Jørgensen; P., Christensen, J. S., Tande, J. O., Vikkelsø, A., Nørgård, P., ”Elkvalitet ved nettilslutning af vindmøller Del 2: Flicker”, Roskilde, Information Service Department, Risø National Laboratoy, 1996, 62 p. (in Danish)

[32] Larsson, Å, ”Flicker and Slow Voltage Variations from Wind Turbines”, *Proceedings of the 7th International Conference on Harmonics and Quality of Power* (ICHQP '96), Las Vegas, U.S.A. October 1996, p. 270 - 275.

[33] Berding, J., Santier, F., Gerdes, G., *”Netzrückwirkungen von Windenergianlagen in Windparks”*, DEWI Magasin Nr. 9, Augusti 1996, p. 30 - 36. (in German)

[34] Jørgensen; P., Christensen, J. S., Tande, J. O., Vikkelsø, A., Nørgård, P., ”Elkvalitet ved nettilslutning af vindmøller Del 3: Overtoner og driftforhold ved invertertilsluttede vindmøller”, Roskilde, Information Service Department, Risø National Laboratoy, 1996, 95 p. (in Danish)

[35] Mahon, L.L.J., Diesel Generator Handbook, Butterworth-Heinemann Ltd, 1992.

[36] Association of Energy distribution companies in the Netherlands, ”Technical terms of connection to the public network for local production units”, Arnhem, EnergieNed, 1994.

[37] International Electrotechnical Comission, TC 88, 1994.

Paper 2A

Measurements on and Modelling of Capacitor-Connecting Transients on a Low-Voltage Grid Equipped with Two Wind Turbines

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T. Thiringer

Presented at
International Conference on Power System Transients (IPST '95)
Lisbon, Portugal
September 3-7, 1995

Paper 2B

Voltage and Frequency Variations on Autonomous Grids: A Comparison of Two Different Wind-Diesel Systems

Å. Larsson

Presented at
European Union Wind Energy Conference (EUWEC '96)
Göteborg, Sweden
May 20-24, 1996

Paper 2C

Flicker and Slow Voltage Variations from Wind Turbines

Å. Larsson

Presented at
International Conference on Harmonics and Quality of Power (ICHQP '96)
Las Vegas, USA
October 16 - 18 1996

Paper 2D

Grid Impact of Variable-Speed Wind Turbines

Å. Larsson
P Sørensen
F. Santjer

Presented at
European Wind Energy Conference (EWEC '99)
Nice, France
Mars 1-5 1999

Paper 3A

Standards for Measurements and Testing of Wind Turbine Power Quality

P Sørensen
G. Gerdes
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F. Santjer
N. Robertson
W. Davy
M. Koulouvari
E. Morfiadakis
Å. Larsson

Presented at
European Wind Energy Conference (EWEC '99)
Nice, France
Mars 1-5 1999

Paper 4A

Guidelines for Grid Connection of Wind Turbines

Å. Larsson

Presented at
15th International Conference on Electricity Distribution (CIRED ´99)
Nice, France
June 1-4, 1999

Paper 4B

Flicker Emission of Wind Turbines During Continuos Operations

Å. Larsson

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IEEE Transactions on Energy Conversion
August 2000

Paper 4C

Flicker Emission of Wind Turbines Caused by Switching Operations

Å. Larsson

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