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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

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]:

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \qquad (1)$$

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.

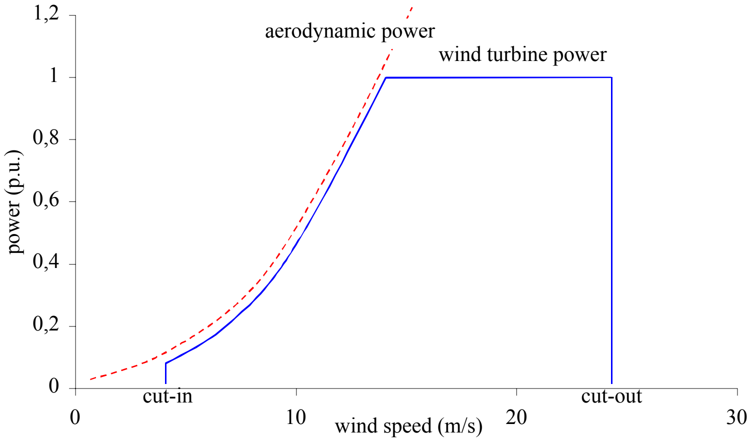

Fig. 2.1: Power curve of a wind turbine. 1 p.u. corresponds to the rated power of a wind turbine.

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.

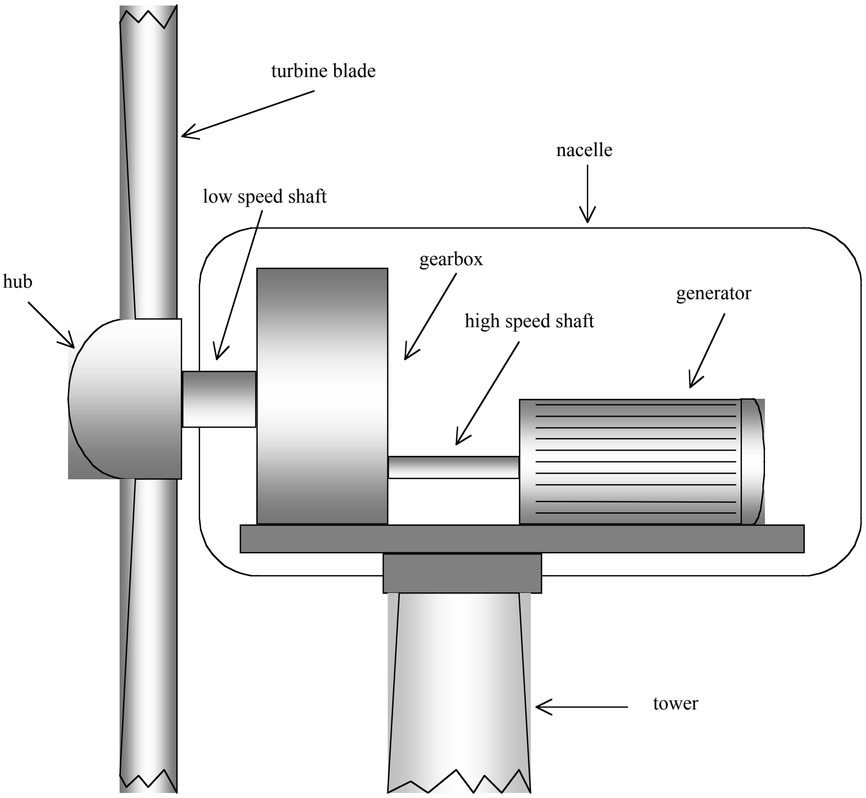

Fig. 2.2: Schematic figure of a typical fixed-speed wind turbine illustrating the major components.

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.

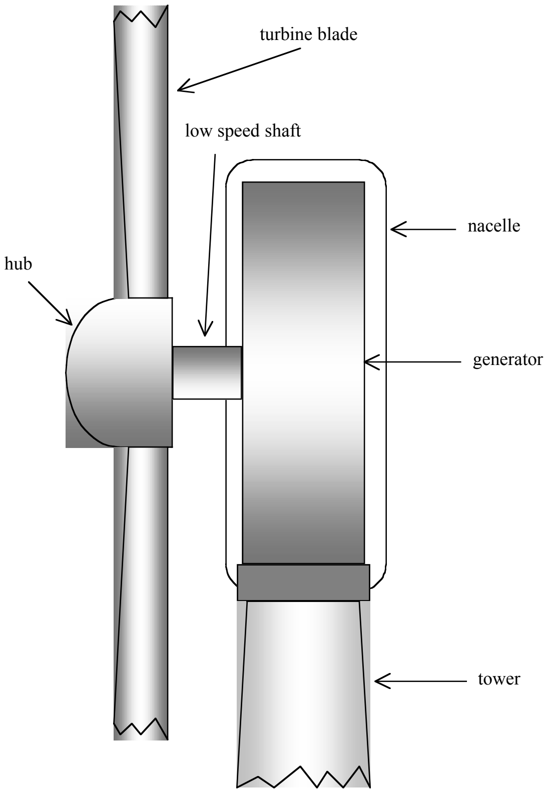

Fig. 2.3: Schematic figure of a typical variable-speed wind turbine illustrating the major components.

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.

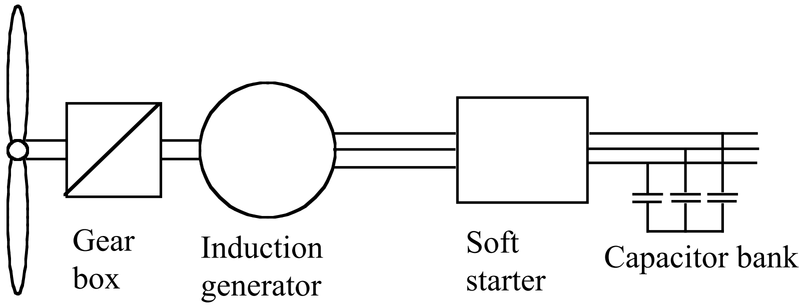

Fig. 3.1: Schematic figure of the electric system of a fixed-speed wind turbine.

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].

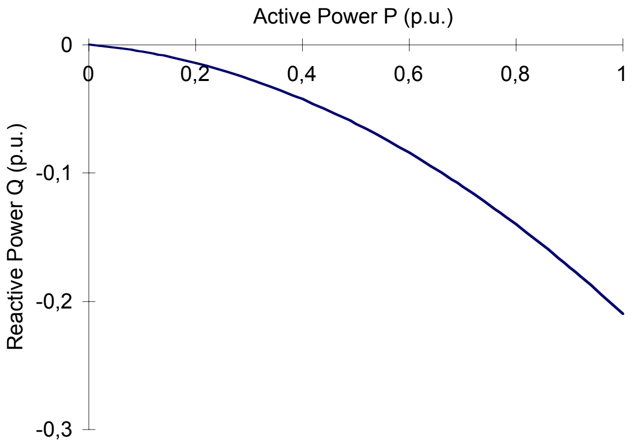

Fig. 3.2: Reactive power as a function of active power. 1 p.u. corresponds to the rated active power.

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.

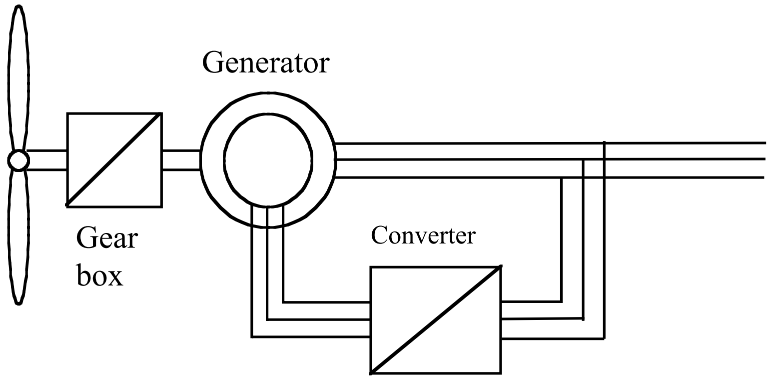

Fig. 3.3: Schematic figure of the electrical system of a variable-speed wind turbine equipped with a double-fed induction generator with a converter connected to the rotor circuit.

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.

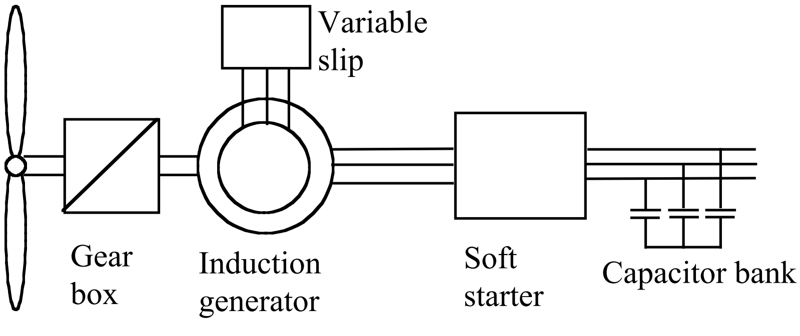

Fig. 3.4: Schematic figure of the electrical system of a wind turbine equipped with controllable rotor resistances.

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.

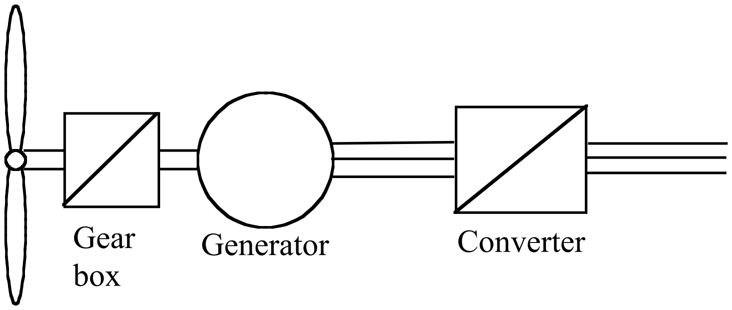

Fig. 3.5: Schematic figure of the electric system of a variable-speed wind turbine equipped with a converter.

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.

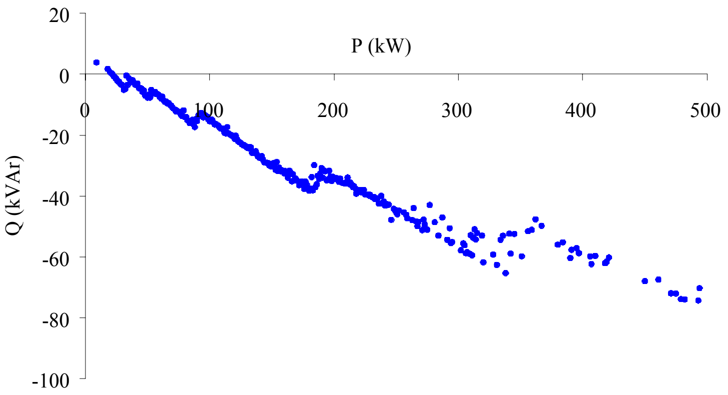

Fig. 3.6: Reactive power consumption as a function of active power of a variable-speed wind turbine equipped with a forced-commutated inverter.

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.

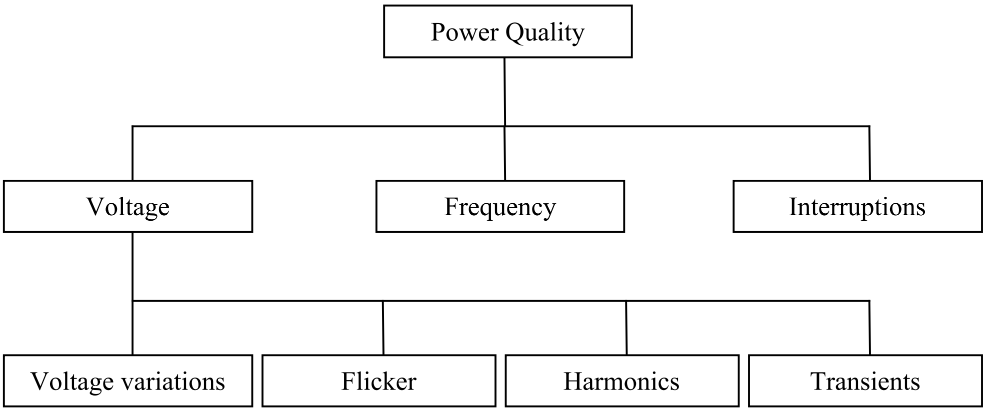

Fig. 4.1: Classification of different power quality phenomena.

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.

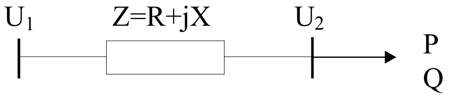

Fig. 4.2: Simple impedance model.

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.

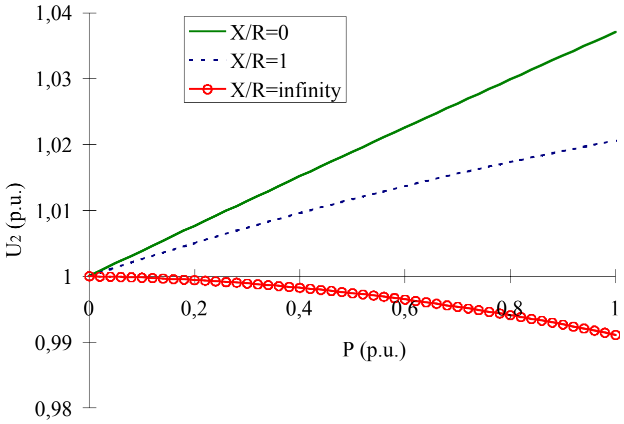

Fig. 4.3: Voltage variations at different *X/R* ratios. The short-circuit ratio is constant.

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.

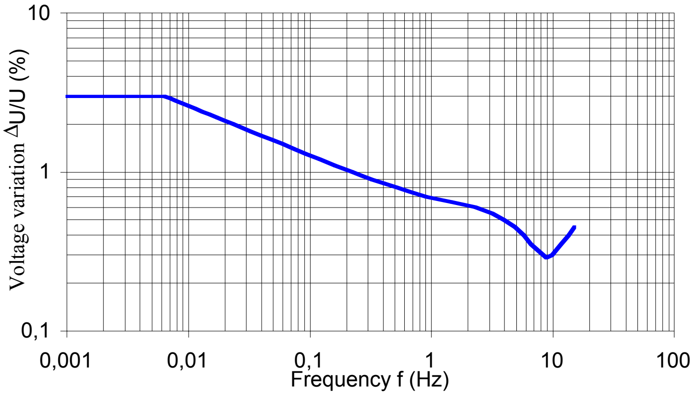

Fig. 4.4: Flicker curve according to IEC 60868.

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.

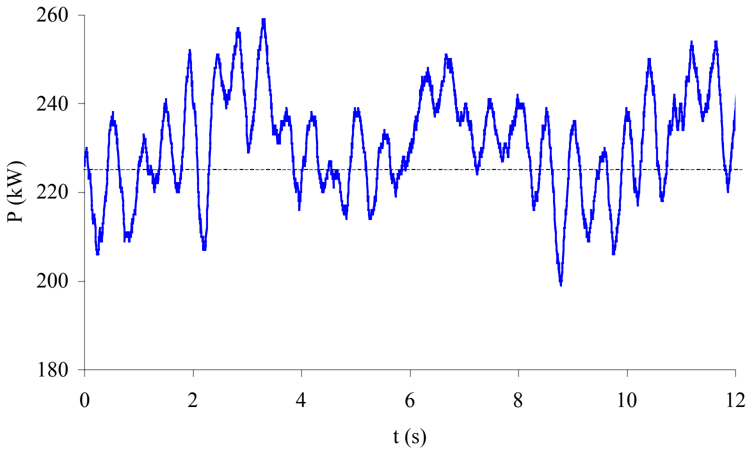

Fig. 4.5: Measured power during normal operation of a pitch-controlled fixed-speed wind turbine (solid line). In the figure the steady-state power is also plotted (dotted line).

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.

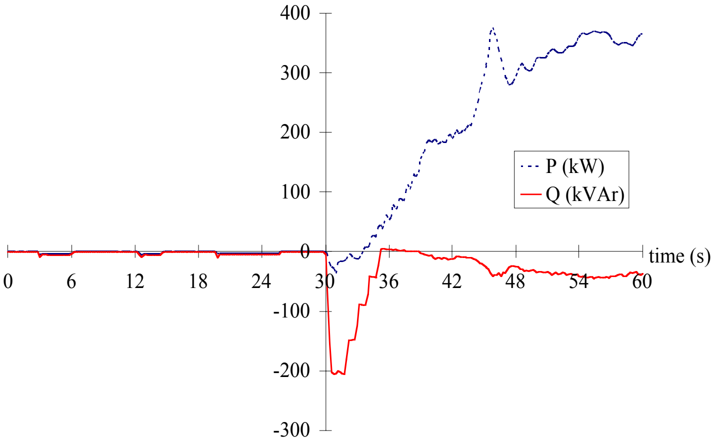

Fig. 4.6: Measured power during start of a fixed-speed pitch-controlled wind turbine. The rated power of the wind turbine is 600 kW. Active power (dotted line) and reactive power (solid line).

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.

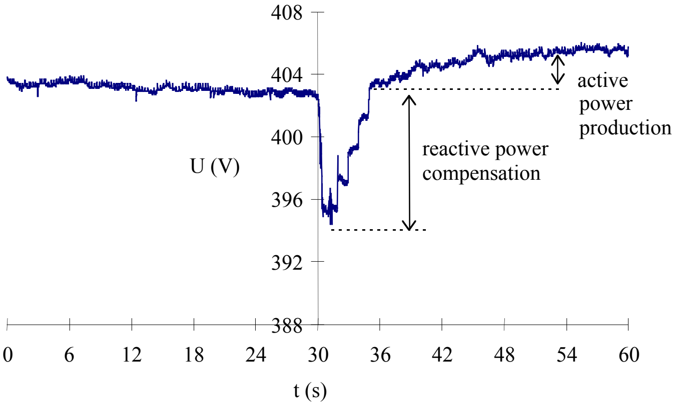

Fig. 4.7: Measured voltage during start of a fixed-speed pitch-controlled wind turbine.

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.

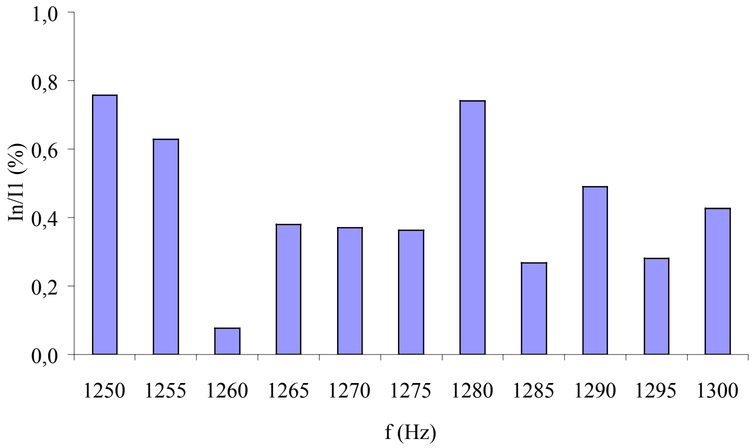

Fig. 4.8: Current inter-harmonic content between 1250-1300 Hz.

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.

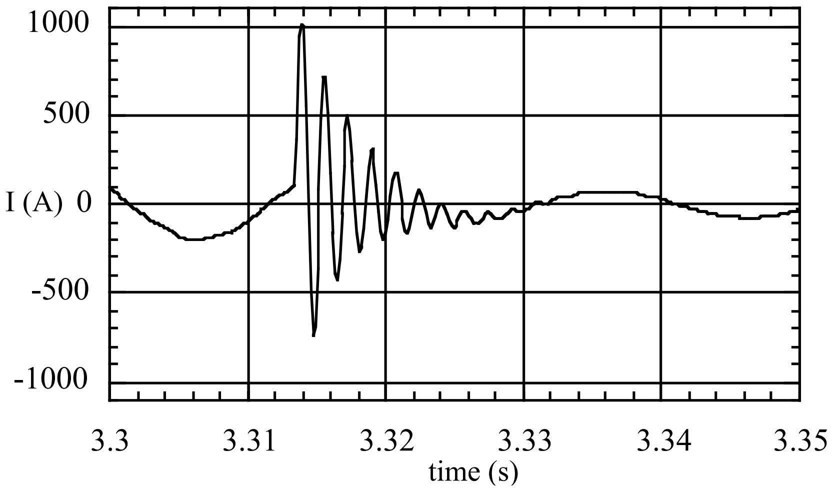

Fig. 4.9: Measured oscillating current caused by the connecting of shunt capacitors during the start-up sequence of a 225 kW wind turbine.

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.

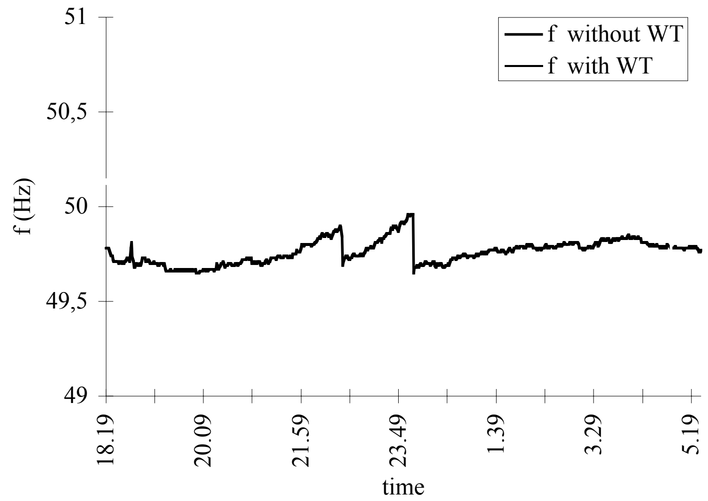

Fig. 4.10: Frequency variations on two nights. One night when the turbines were operating (gray line) and one night when the turbines were shut down due to lack of wind (black line). WT means wind turbines.

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.

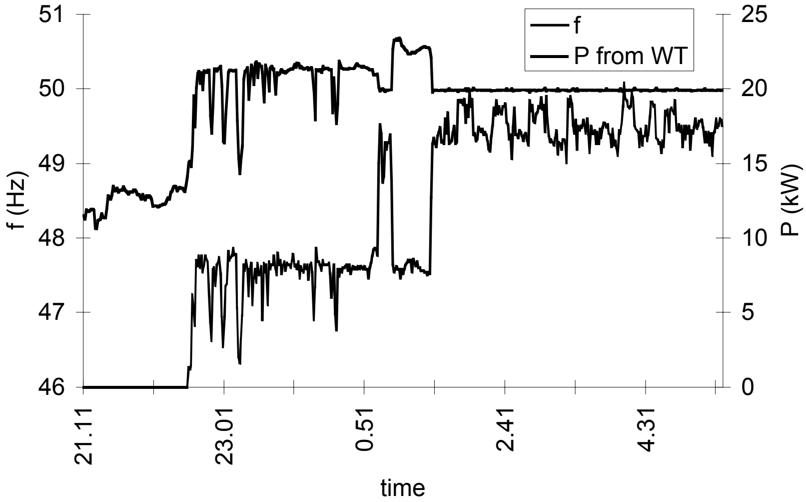

Fig. 4.11: Frequency variations (black line) and power output from the wind turbine (gray line) during one night.

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.

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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 world-wide, 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.

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).

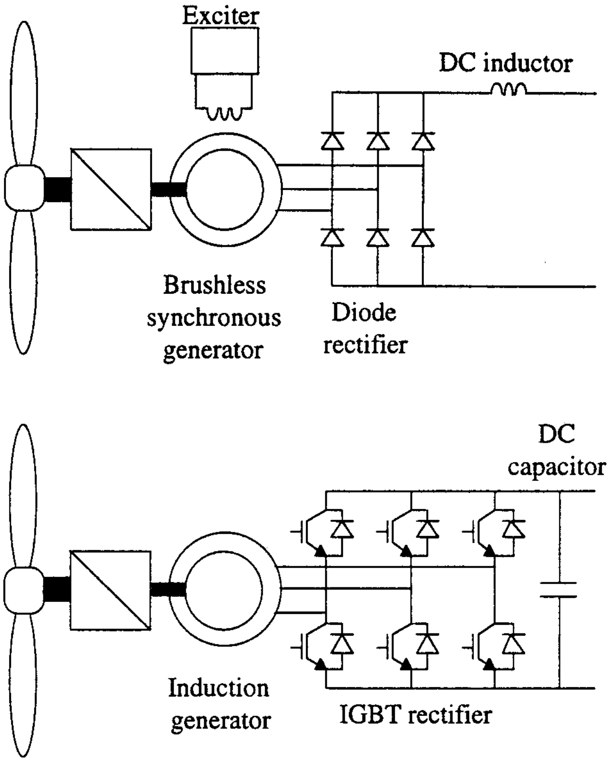

Figure 1: Two generator and rectifier alternatives.

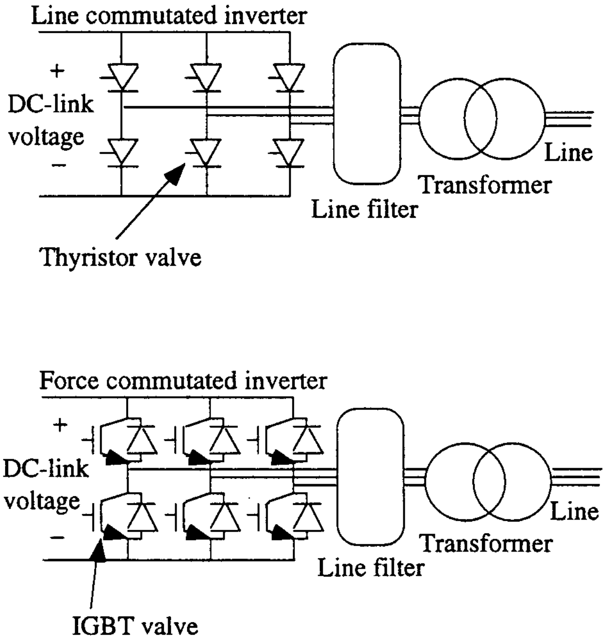

Figure 2: Schematic figures of a line commutated and a force commutated inverter.

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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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.

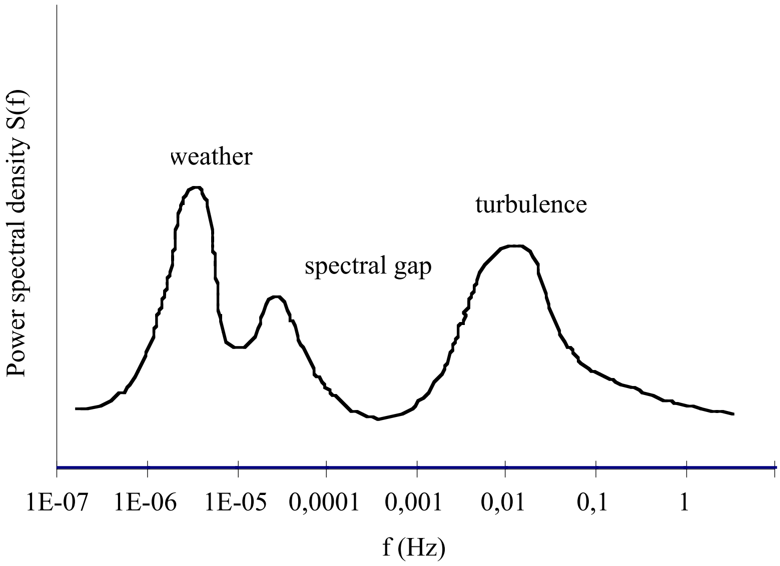

Figure 2.1: Schematic power spectrum of wind speed (according to van der Hoven).

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.

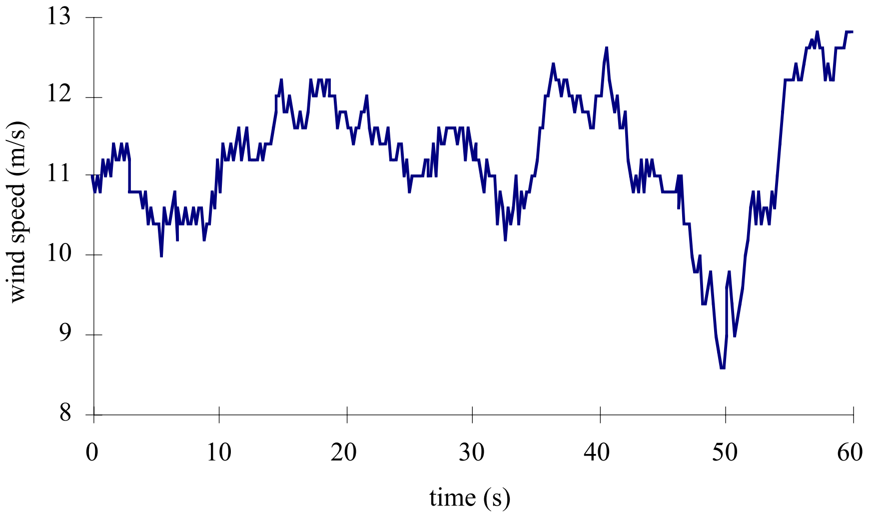

Figure 2.2: Wind speed measured at the harbour of Gothenburg, Sweden.

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.

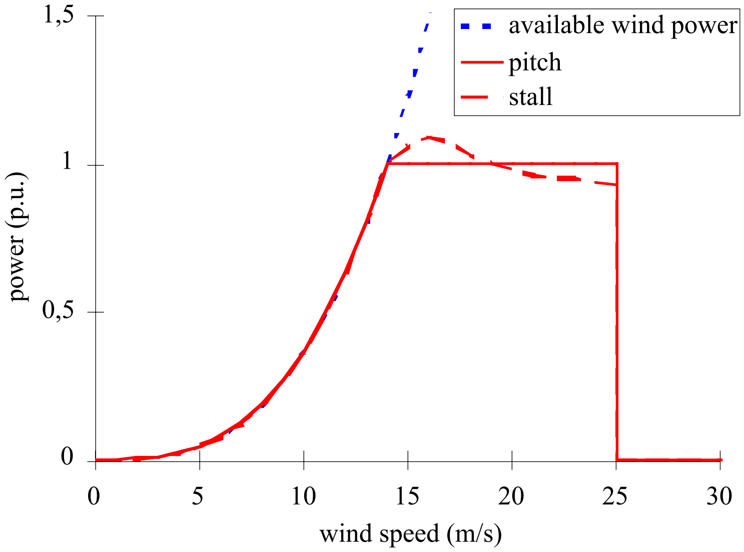

Figure 3.1: Available wind power (dotted line), power from a stall-regulated turbine (dashed line) and power from a pitch-regulated turbine (solid line).

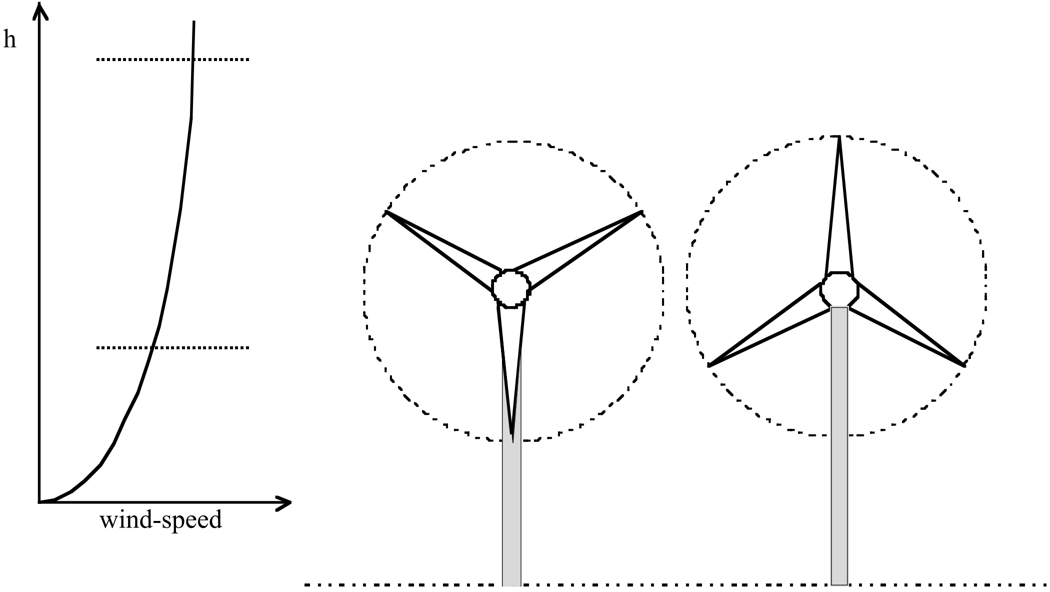

Figure 3.2: Different rotor positions of a three-blade turbine. The tower shadow and the wind gradient, both contribute to power fluctuations.

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.

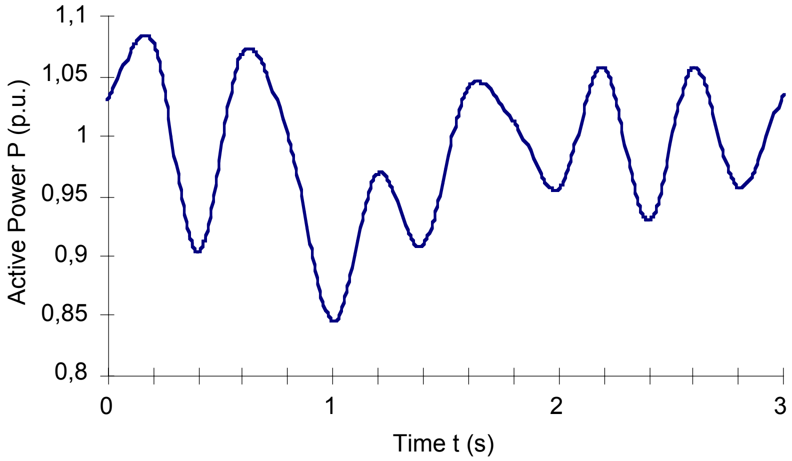

Figure 3.3: Measured power fluctuations from a fixed-speed pitch-regulated wind turbine.

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.

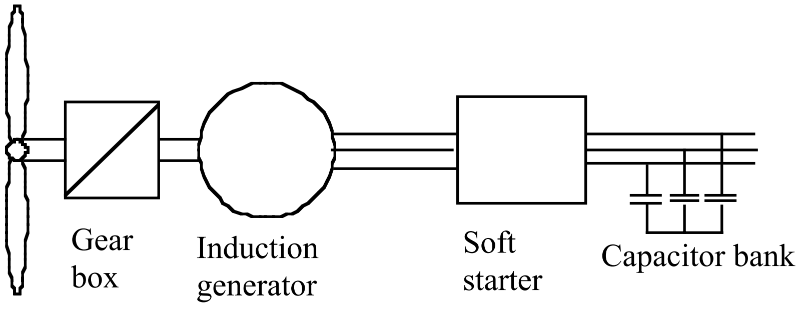

Figure 3.4: Schematic figure of the electric system of a fixed-speed wind turbine.

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.

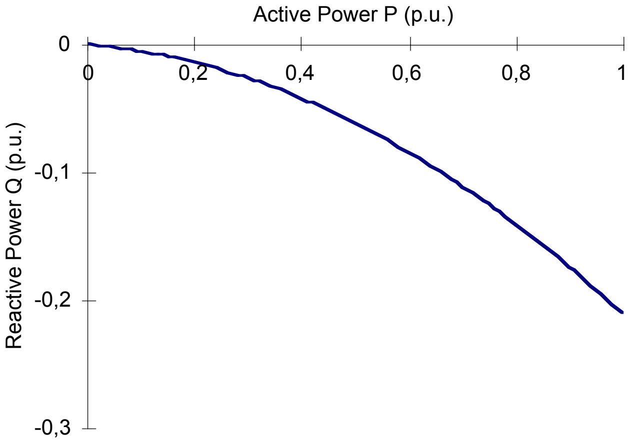

Figure 3.5: Reactive power as a function of active power. 1 p.u. corresponds to the rated active power.

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.

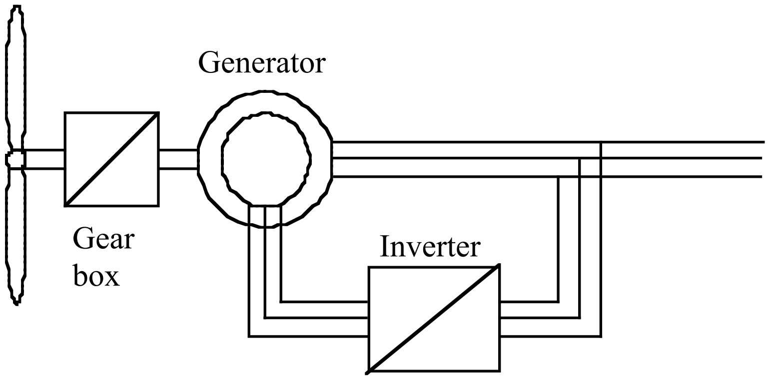

Figure 3.6: Schematic figure of the electrical system of a variable speed wind turbine equipped with a rotor cascade.

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.

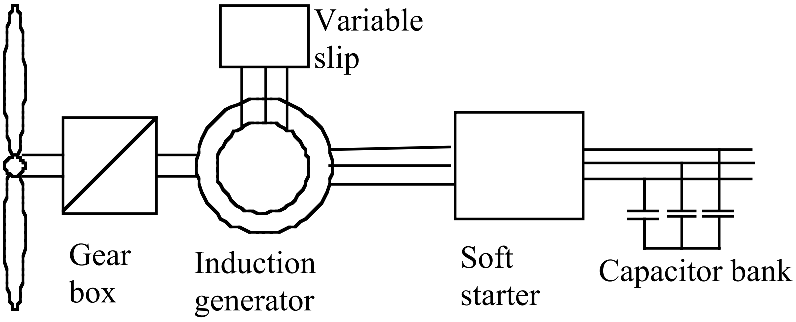

Figure 3.7: Schematic figure of the electrical system of a wind turbine equipped with controllable rotor resistances.

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.

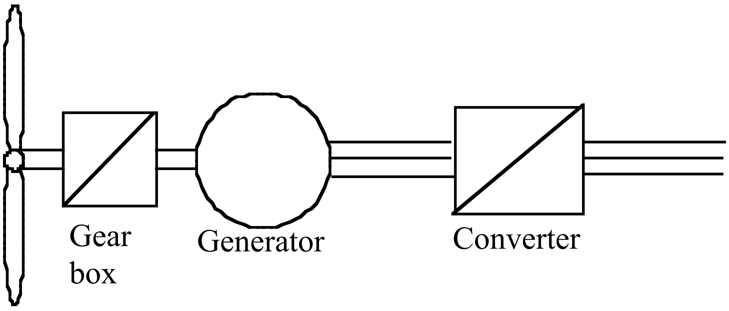

Figure 3.8: Schematic figure of the electric system of a variable-speed wind turbine equipped with an inverter.

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.

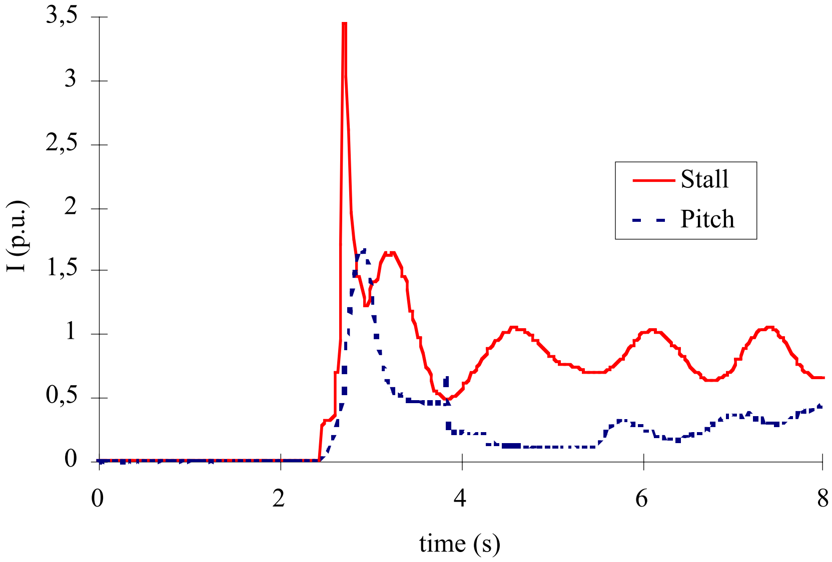

Figure 3.9: Measured current from a stall-regulated (solid line) and a pitch-regulated (dotted line) wind turbine.

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.

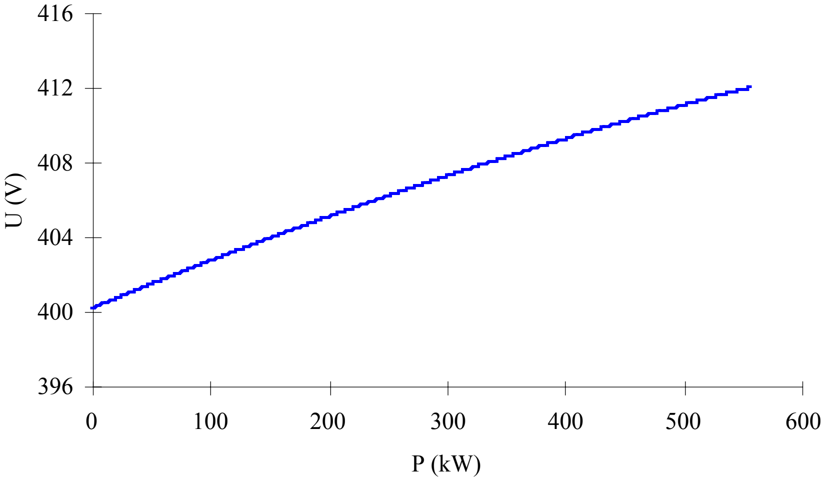

Figure 4.1: Measured voltage as a function of produced active power P from a 600 kW wind turbine located at Utteros in Sweden.

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.

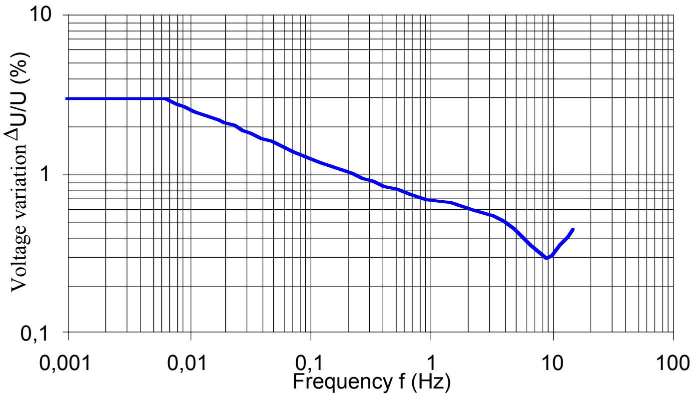

Figure 4.2: Flicker curve according to IEC 868.

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].

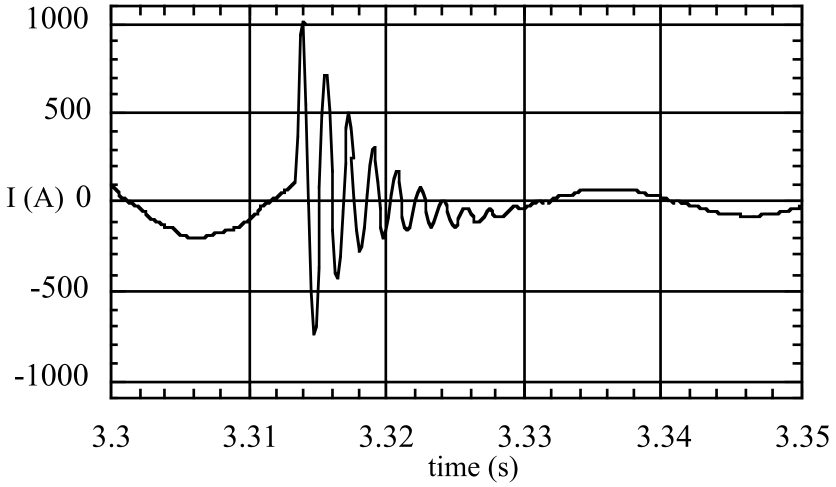

Figure 4.3: Measured oscillating current caused by the connecting of shunt capacitors during the start-up sequence of a 225 kW wind turbine at Risholmen, Sweden.

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.

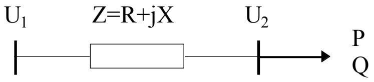

Figure 5.1: Simple impedance model.

The voltage at the PCC can be expressed as

$$U_2 = \sqrt{a + \sqrt{a^2 - b}} \qquad (1)$$

where

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

$$b = (P^2 + Q^2)Z^2 \tag{3}$$

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.

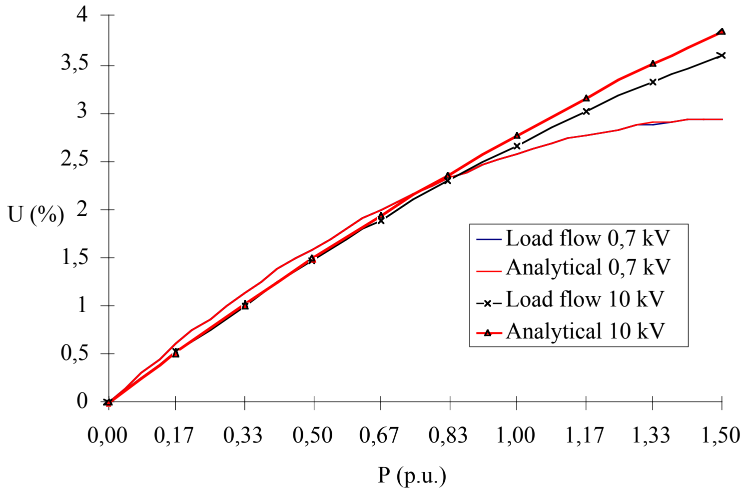

Figure 5.2: Comparison of calculated voltage variations using load flow calclation and the analytical method.

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:

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

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.

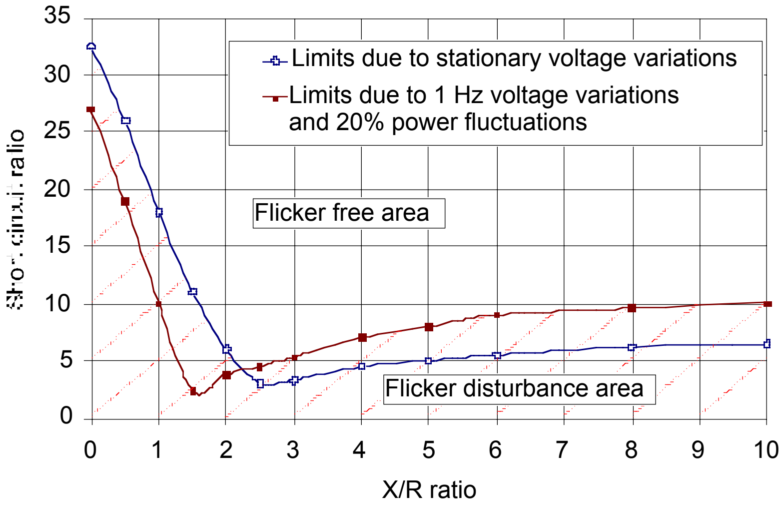

Figure 5.3: Minimum short-circuit ratio to avoid flicker caused by stationary voltage variations and 1 Hz voltage variations as a function of the grid *X/R* ratio.

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

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{5}$$

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.

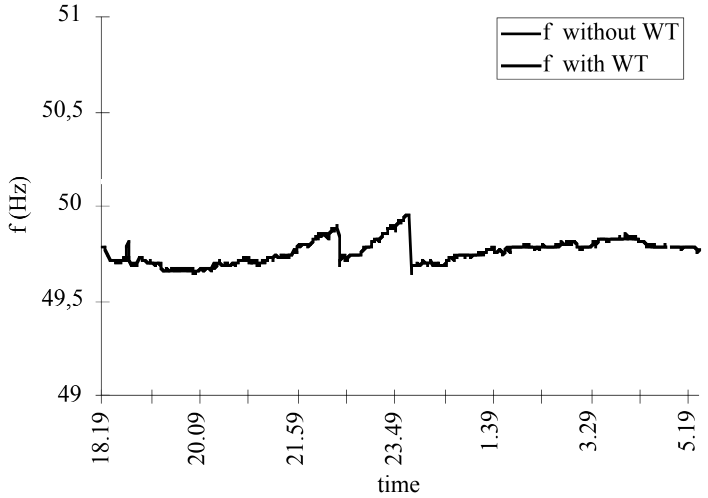

Figure 6.1: Frequency variations during two nights. One night when the turbines were operating (gray line) and one night when the turbines were shut down due to lack of wind (black line).

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.

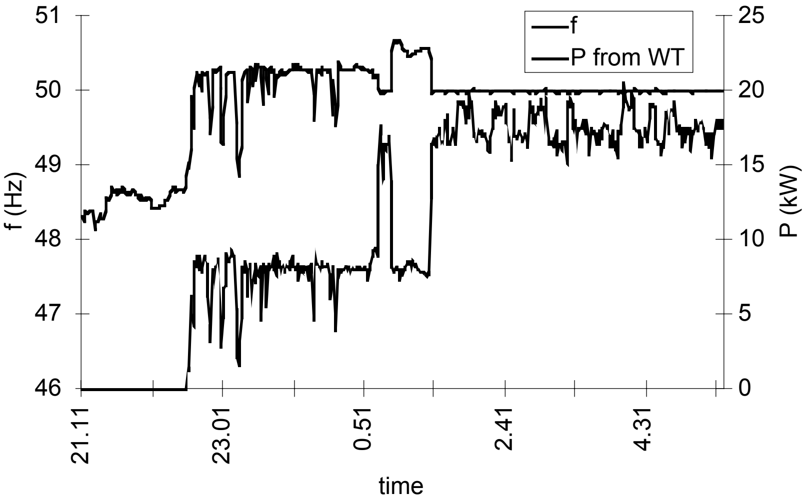

Figure 6.2: Frequency variations (black line) and power output from the wind turbine (gray line) during one night.

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.

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Paper 2A

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

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International Conference on Power System Transients (IPST '95)
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Measurements on and Modelling of Capacitor-Connecting Transients on a Low-voltage Grid Equipped with Two Wind Turbines

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Abstract - Capacitor connecting transients on a low-voltage grid equipped with two wind turbines are measured and calculated. As the phase-compensating capacitors of the wind turbines are connected, a large current peak, sometimes reaching twice the rated current, occurs. The damping of the transients is strongly influenced by skin and proximity effects.

INTRODUCTION

The majority of the wind energy converters installed today are equipped with an induction generator connected directly to the grid. Phase-compensating capacitors are connected at the wind turbines in order to compensate for the reactive power consumed by the generator. As the capacitors are connected, a transient occurs, which can cause problems to sensitive equipments connected to the same grid. For example, when two wind turbines were installed on the island of Hjärtholmen, close to Göteborg, an old relay indicated grid failure and started an emergency generator at a consumer nearby. An examination of the problem revealed that the reason was the connecting of the phase compensating capacitors.

It is possible to avoid or reduce the connecting transients. One possibility is to first magnetize the generator by capacitors and then synchronize it to the grid [1]. Another possibility is to use power electronic switches to connect the capacitors [2]. However, most wind turbine manufacturers of today use capacitors connected directly to the grid.

The resistance and inductance of cables and transformers vary as a function of the frequency due to the skin and proximity effects. Since the frequency of the connecting transients is usually several times higher than the fundamental grid frequency, the resistance values are substantially increased while the inductance values are somewhat reduced. The skin and proximity effects depend on several parameters, e.g. material and diameter of the conductor, distance between the conductor axes, number of wires and twists of the bundled wires in each conductor [3]. All these parameters make a detailed calculation of the frequency-dependent parameters difficult. The calculation can be made more accurately by using numerical methods, for example the finite element method in three dimensions and in time domain. The computation would, nevertheless, require both a powerful computer and plenty of time.

Knowing the conductor diameter, conductor material and spacing of the conducts it is possible to model the skin and proximity effects by analytical expressions [4–6]. Here, the IEC standard [6] is used.

The purpose of this paper is to study the influence of the skin and proximity effects on the connecting transients when the phase-compensating capacitors of wind turbines are connected to the grid. Another important goal is to compare the calculations with field measurements.

THE WIND TURBINE SITE

A. The site

In Fig. 1 the electrical configuration of the Hjärtholmen wind turbine site is presented together with the points of measuring. The two 225 kW pitch-regulated wind turbines are connected to a 500 kVA transformer by two 4*240 mm^2 aluminium cables each. The ratio between the short-circuit power of the low-voltage grid and the rating of the wind turbines is 20, which is the recommended value for example in Denmark. Phase-compensating capacitors are connected to the wind turbines in two stages, C_1 and C_2.

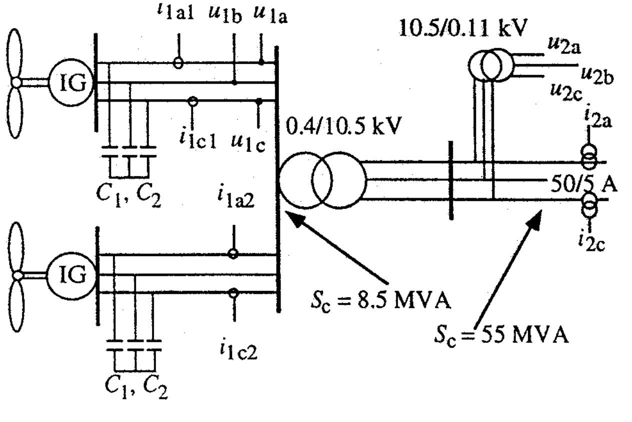

Fig. 1. The wind turbine site and the location of the points of measuring. (IG = induction generator and S_c = short-circuit power)

B. Measuring system

In order to obtain an isolating interface between the grid and the measuring system as well as a high bandwidth, the currents and voltages were measured using LEM-modules [7]. The instantaneous values of the voltages and currents were measured by a data acquisition system having a sampling rate of 7 kHz.

The three phase voltages and two phase currents from each wind turbine were measured on the low-voltage side of the transformer. There is only need to measure the currents in two of the phases since the neutral line is not connected. As a reference, the voltage and the current on the high-voltage side were measured by using voltage and current transformers. According to the manufacturer, the voltage transformers used on the high-voltage side can measure voltages up to a frequency of 1 000 Hz.

CONNECTING OF THE FIRST TURBINE

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 for limiting the current during the starting sequence.

A. Measurements

The measured connecting current of one wind turbine is presented in Fig. 2 as the other wind turbine is not operating. The induction generator is connected shortly after the measurement is started at the time $t = 0$, and the soft starter operates until $t = 2$ s and is then short-circuited. During this time, the current is kept well below the rated current of one turbine (peak value of 566 A). The first stage of capacitors C_2 is connected at $t = 3.3$ s and the second stage C_1 is connected at $t = 4.2$ s. The connection of the capacitors does not pass without problems.

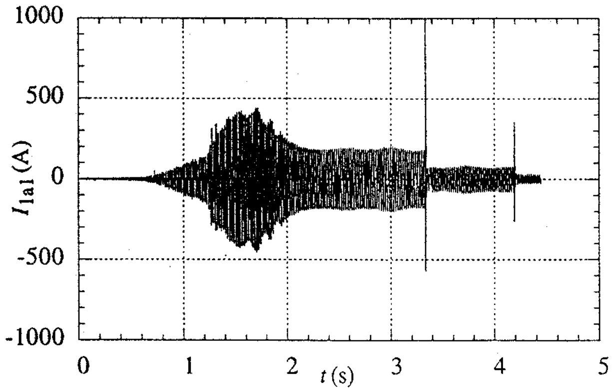

Fig. 2. Measured connecting current.

As can be seen in Fig. 2, there is a large current peak of 1000 A when the first stage of capacitors is connected, presented in detail in Fig. 3. Also the voltage of the 400 V grid is strongly affected by the connecting of the capacitors. As Fig. 4 shows, an oscillating component with a peak amplitude of 160 V is added to the phase voltages, which can cause problems to sensitive equipments connected to the 400 V grid. The voltage on the high-voltage side of the transformer is hardly affected at all by the connecting of the capacitors, as Fig. 5 shows. Also the connecting of the second capacitor stage gives rise to a current peak, presented in detail in Fig. 6.

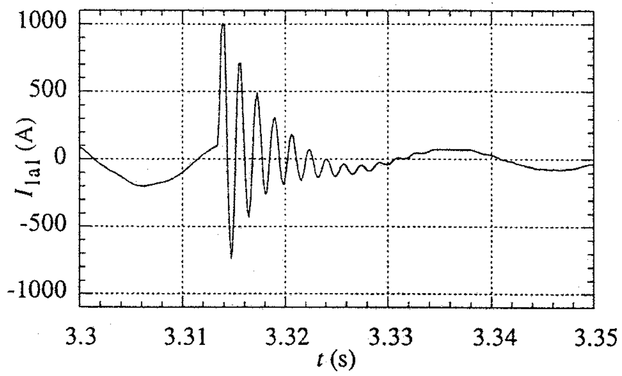

Fig. 3. Measured oscillating current caused by connecting the first stage of capacitors.

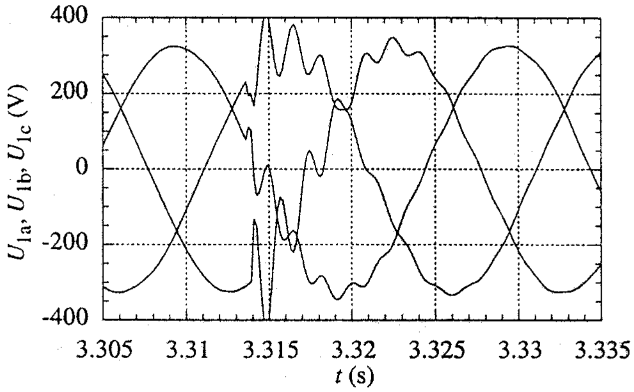

Fig. 4. Measured phase voltages on the low-voltage side when the first stage of capacitors is connected.

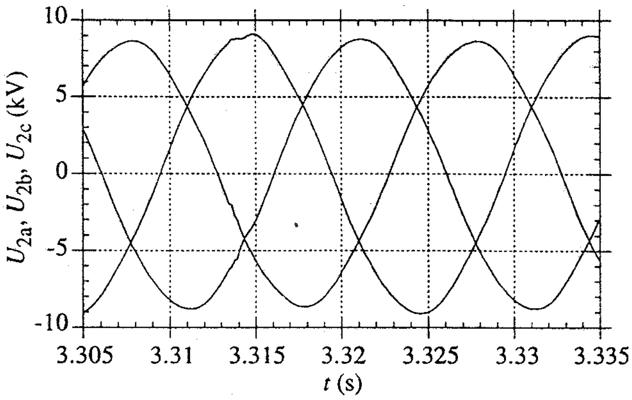

Fig. 5. Measured phase-voltages on the high-voltage side when the first capacitor stage is connected.

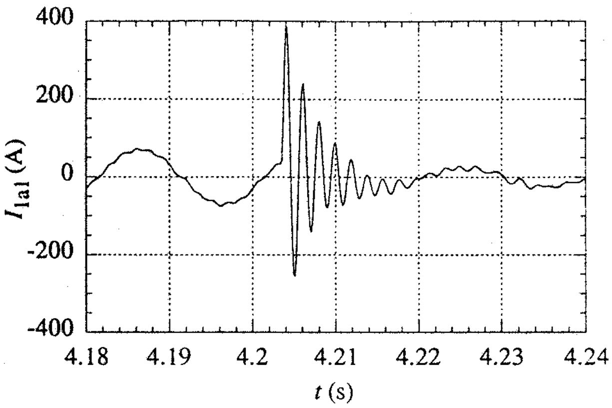

Fig. 6. Measured oscillating current caused by connecting the second stage of capacitors.

B. Calculations

A simplified configuration of the wind turbines is presented in Fig. 7 and the values of the components are given in Table 1. The frequency of the transients can approximately be determined by

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

if the influence of the induction machine is neglected. When the second wind turbine is not operating and the first stage of capacitors C_2 is to be connected $L = L_{cab} + L_{tr}$ and $C = C_2$ which gives a value of 570 Hz. The measured frequency of the connecting transient occurring when the first stage of capacitors is connected is 590 Hz

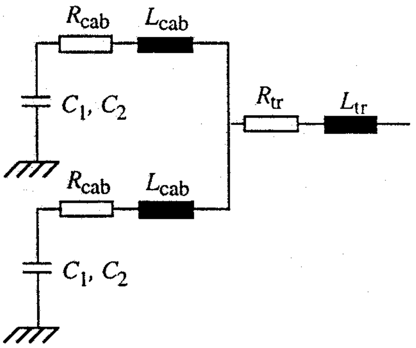

Fig. 7. A simple model of the wind turbine site.

Table 1. Values and description of components.

Description	Symbol	Value
Capacitor	C_1	0.5 mF
Capacitor	C_2	1.2 mF
Cable resistance	R_{cab}	9.4 mΩ
Cable inductance	L_{cab}	17 µH
Transformer resistance	R_{tr}	2.7 mΩ
Transformer inductance	L_{tr}	47 µH

When the second stage of capacitors is connected, $L = L_{cab} + L_{tr}$ and $C = C_1 + C_2$, which gives a frequency of 480 Hz. The measured frequency is in this case 510 Hz.

When the wind turbines had been installed, connecting the capacitors sometimes triggered a relay indicating grid failure, which started an emergency generator at a consumer nearby. The relay was later on replaced and the turbines could operate without interrupting other equipment.

In order to improve the calculations of the connecting current and voltage, a more detailed model than the one presented in Fig. 6 must be used. In this paper the transient course of event has been calculated by means of the Electro Magnetic Transient Program, EMTP. A single-phase diagram of the EMTP-model used is presented in Fig. 8.

The calculated transient determined using the 50-Hz values of the resistances and inductances is presented in Fig. 9. The calculated frequency of 600 Hz agrees well with the measured one while the calculated transient is less damped than the measured one. The main reason for this is that the resistances of the cable and transformer are frequency-dependent. This is due to two phenomena known as skin effect and proximity effect.

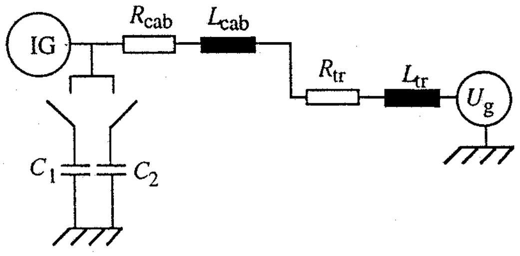

Fig. 8. Single-phase representation of one generator with the grid. (Ug is the grid voltage)

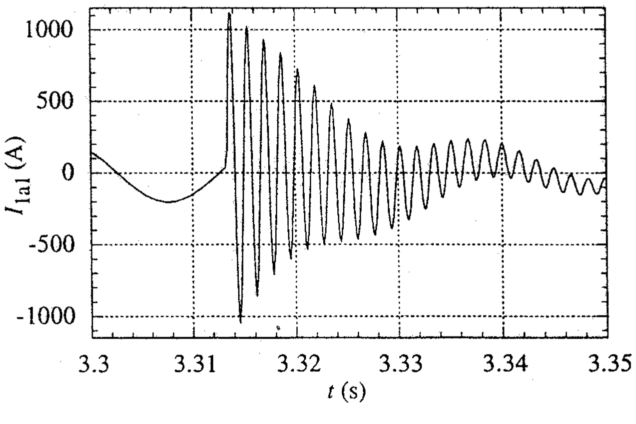

Fig. 9. Calculated current without skin and proximity effects taken into account.

The main influence of the skin and proximity effects is that the resistance increases for currents having a higher frequency. Another feature of these two phenomena is that the inductance is somewhat lowered as the frequency is increased. The skin effect increases the resistance of a conductor due to a current in the conductor while the proximity effect increases the resistance in a conductor due to a current in an adjacent conductor. [4–6] presents three different analytical methods to determine the increase of the resistance due to these effects. In Fig. 10 the resistance values predicted by the three methods are compared. As can be noted from Fig. 10, the methods predict similar resistance values. The values used are the ones predicted by the IEC standard which is represented by the solid curve.

Compared to the cable, the transformer is a much more complicated component. As a first step the transformer resistance is regarded to be constant. Moreover, the inductance of the transformer and cable is also considered to be constant.

The currents calculated taking the skin and proximity effects of the cable into account are presented in Figs. 11 and 12 . Fig. 11 presents the measured transient occurring as the first stage of capacitors is connected. Fig. 12 presents the measured connecting current when the second capacitor stage is connected. The results have been substantially improved compared to those reached when only using the 50 Hz value of the cable resistance. However, the damping of the oscillating current is still somewhat too low, as can be seen if the calculated transients presented in Figs. 11 and 12 are compared with the measured ones presented in Figs. 3 and 6. Still, the resistance increase in the transformer has not been taken into account. In [8] the resistance of a 263 MVA transformer was measured at different frequencies. The measurements indicated the effective resistance at 600 Hz to be 10 times the DC resistance. In [9] a similar resistance increase was calculated for 20, 100 and 500 MVA transformers. The inductance was considered to be constant.

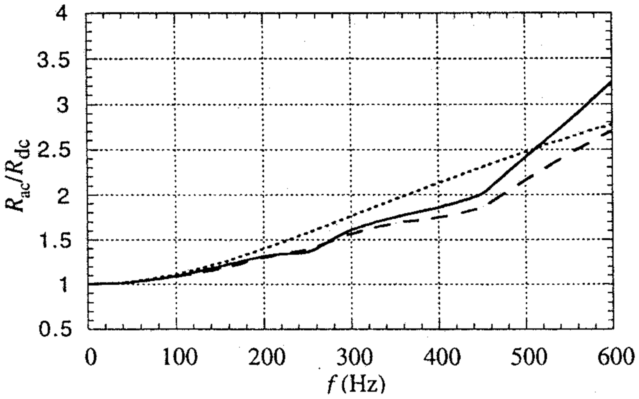

Fig 10. Calculated cable resistances. Solid curve according to IEC 287 [6], dashed curve according to [4] and dotted curve according to [5].

Fig. 13 presents the connecting current as the first stage of capacitors is connected using the assumption that the resistance is 10 times greater at 600 Hz compared to the DC-resistance value. As can be observed from Fig. 13, the calculated current now agrees very well with the measured one.

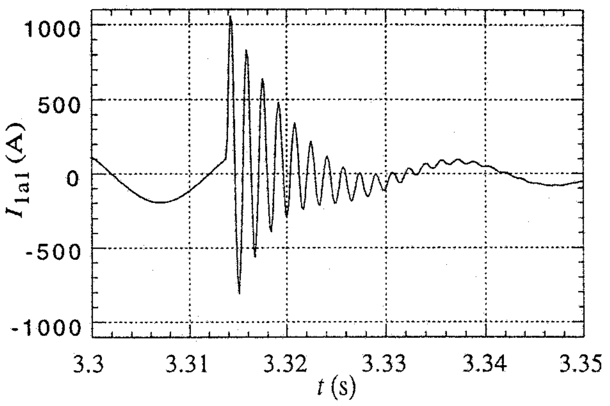

Fig. 11. Calculated current when connecting the first capacitor stage, taking the skin and proximity effects into account.

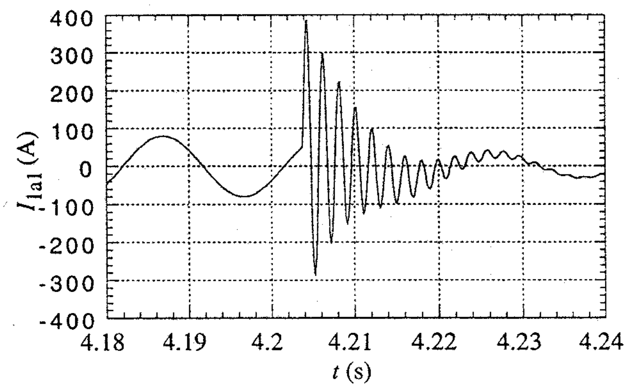

Fig. 12. Calculated current when connecting the second capacitor stage, taking the skin and proximity effects into account.

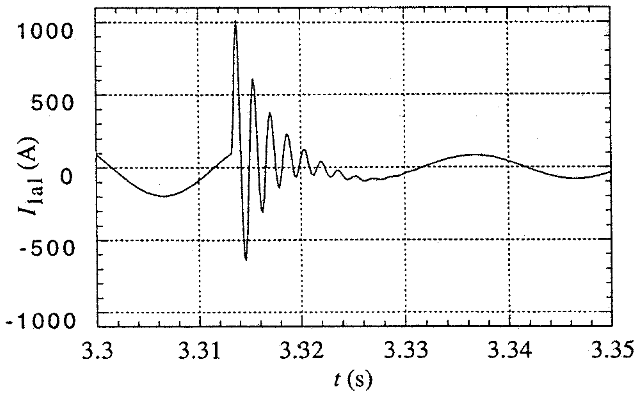

Fig. 13. Calculated current with skin and proximity effects both in cable and transformer taken into account.

CONNECTING OF THE SECOND TURBINE

The connecting of the first stage of capacitors of the second wind turbine causes two transients at different frequencies. One at a higher frequency which takes place between the two turbines and one at a lower frequency taking place between the two turbines and the grid. The frequency of the oscillations can be determined by using (1). In the first case $L = 2L_{\mathrm{cab}}$ and $C = C_2//(C_1 + C_2)$ giving a frequency value of 1000 Hz. In the second case $L = L_{\mathrm{cab}}/2 + L_{\mathrm{tr}}$ and $C = C_1 + 2C_2$ giving an oscillating frequency of 400 Hz. The two oscillating modes are illustrated in Fig. 14.

In Fig. 15 the measured current from the first wind turbine is presented as the second one connects the first stage of capacitors. Although the sampling rate of the data acquisition system is not high enough to catch the rapid transient accurately, the two oscillation modes are clearly visible.

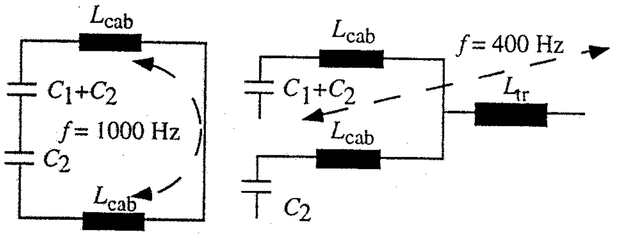

Fig. 14. Oscillating modes as the second wind turbine connects the first stage of capacitors.

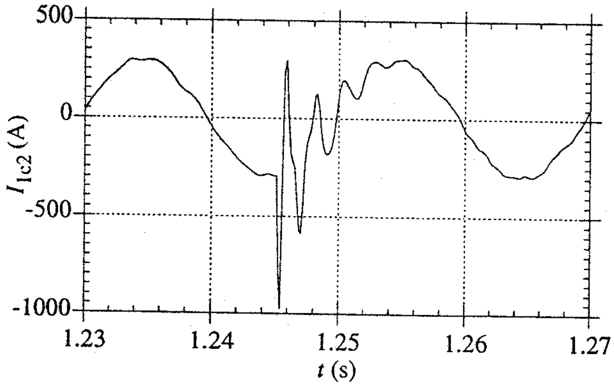

Fig. 15. Measured current from the first wind turbine is presented as the second one connects the first stage of capacitors.

CONCLUSION

As the phase-compensating capacitors are connected, a large current peak occurs. This transient sometimes reaches a value of twice the rated wind turbine current. Also the voltage on the low-voltage grid is substantially affected, which can disturb sensitive equipments connected to the same part of the grid as the wind turbines. The connecting of the second capacitor stage influences the grid less.

If the skin and proximity effects of the cable and transformer are not taken into account, the damping is much underestimated. When the increase of the cable resistance due to skin and proximity effects is taken into account, the calculated transients agree better with the measured ones. The calculations can be further improved by also taking the increase of the transformer resistance due to skin and proximity effects into account.

ACKNOWLEDGEMENT

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Paper 2B

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

Å. Larsson

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

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ABSTRACT: The aim of this paper is to compare the power quality of two different autonomous wind-diesel systems. The two sites differ in sizes and types of the wind turbines as well as in wind power penetration. Measurements on 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 with a maintained power quality.
Keywords: Wind-Diesel Systems, Autonomous Grid, Power Quality, Standards.

1. INTRODUCTION

In recent years there has been a growing interest in wind turbines interconnected with utility systems owing to environmental reasons. Wind turbines will, due to the natural variations in wind, give an intermittent power production. The introduction of a relatively small amount of wind power into the utility grid does not normally present interfacing or operational problems. In the utility grid the intermittent power production from wind turbines will be balanced by other power production units. However, in an autonomous grid supplied with diesel engines, the spinning reserve is limited. The limitation in spinning reserve will give rise to frequency fluctuations in the case of a sudden wind rise/ wind drop or fast load changes. Hence, in a wind-diesel system just like in a diesel system, the voltage and frequency fluctuations will be considerably greater than in an ordinary utility grid.

During the last decade, different types of wind turbines and wind-diesel systems for autonomous grids have been tested. Baryton et al. [1] has performed measurements on wind-diesel systems, using constant-speed wind turbines, with a relatively small amount of wind power. In order to save more diesel fuel, the penetration of wind power must be increased. The wind-diesel system becomes, hence, more advanced since some kind of energy storage system is needed. Such a system, using a flywheel, has been investigated by Bindner et al. [2]. Another system, where the power output from the wind turbine is controllable, has been investigated by Linders and Holmblad [3]. However, making a comparison between these wind-diesel systems is difficult, since the measurements are performed in different ways.

In this paper, measurements have been performed in a similar way at two different sites, on an island in Greece and 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, where the diesel generator and the wind turbine have been designed to work in collaboration with each other.

2. THE SITES

2.1 Andros

The island in Greece, Andros, is the northest island of the Kyklades. The length of the island is approximately 41 km, while its width varies from 6 to 17 km. In total, there are approximately 10.000 inhabitants living on Andros.

Andros has an electrical system consisting of diesel generators in the south and wind turbines placed in the windy parts of the north. On the island there are six diesel generators with a total rated power of 15 000 kW. Four of them have a rated power of 1850 kW and two have a rated power of 3800 kW. In 1994 the grid was extended with a wind farm consisting of seven pitch-regulated wind turbines. Each turbine has a rated power of 225 kW which gives a total rated power of almost 1 600 kW from the wind farm.

2.2 Svenska Högarna

The Swedish site, the island of Svenska Högarna, is a very small island in the outer part of the Stockholm archipelago. Only two families live on the island, running a meteorological station. Moreover, there is a mobile telephone link located on the island which needs electric supply for 24 hours day and night.

Svenska Högarna has an electrical system consisting of a wind turbine and a diesel generator equipped with a clutch and a flywheel. The diesel engine has a rated power of 20 kW and the synchronous generator has a rated power of 35 kVA. The wind turbine is a Swedish manufactured variable-speed turbine with a rated power of 21 kW. Moreover, the wind turbine is equipped with a thyristor-controlled line-commutated converter. The rotor is over-sized with a diameter of 17 m. acting as an energy storage. The rotational speed of the rotor is limited by a passive pitch control.

If the power output from the wind turbine is too low, the speed of the rotor will decrease and the diesel engine will start. If the power output from the wind turbine is too high, the speed of the rotor will increase and the passive pitch control will drop some of the wind energy until energy balance is achieved.

Altogether there are three different modes of operation: diesel mode, mixed mode and wind mode. The plant operates in wind mode when the wind speed exceeds 6 m/s. At these occasions the diesel engine is disengaged from the generator by means of the clutch and switched off. Only the synchronous generator and the flywheel are running in parallel with the wind turbine. When there is a wind speed between 3-6 m/s, the turbine is operating in parallel with the diesel generator, mixed mode. Naturally, when it is calm only the diesel generator is running and the plant is operating in diesel mode.

3. MEASUREMENTS

All measurements are performed using a Siemens Oscillostore P 513. The instrument is especially designed for power quality measurements [4]. All measurements in this paper have been performed using an average time of 1 minute. All measurements were performed close to the wind turbines, which means that, on Svenska Högarna the measurements were performed close to the diesel generator. On Andros the measurements were performed far away from the diesel generators.

When measuring power quality from a wind turbine on autonomous grids, it is essential to have knowledge about the power quality of the grid only, i.e. when the turbines are not operating. On an island, the frequency and the voltage vary widely not only depending on variations in the power from the wind turbines but also depending on load variations. On the island of Svenska Högarna, for example, the electrical system is limited with a small total rated power. Just switching an ordinary hob on Svenska Högarna makes a load step of almost 10 percent - imagine a similar load step on a normal utility grid.

4. DIESEL GENERATOR SET PROPERTIES

For diesel generators operating in parallel with each other two kinds of load division must be established. Active power as well as reactive power must be shared between the generators. Load division is affected by controlling the speed of the diesel engines, active power, and the field of the generator, reactive power [5].

When generators operate in parallel with each other, they 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 drop 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.

Reactive power is, in a similar way as the active power, shared between generators operating in parallel. Diesel engines normally have a voltage regulator with a voltage which is decreasing with an increasing generator load.

The mechanical losses in a diesel engine are roughly proportional to the speed of revolution and are, at fixed speed, fairly constant regardless of the load. When it comes to diesel generators, the speed of the engine is constant, except from the slope of the speed governor. Hence, the fuel consumption for a diesel generator set at no load is normally between 15 to 40 percent of the full load consumption, depending on the size of the engine.

Due to the no load fuel consumption, it is desirable to shut down as many diesel engines as possible at windy occasions when the load is being shared between the wind turbines and the diesel engines. But since the diesel engines need some start-up time, an energy storage is needed in the case of a wind drop or emergency shut-down of the wind turbines.

5. FREQUENCY VARIATIONS

5.1 Standard

According to Standard EN 50 160 the nominal frequency of the supply voltage has 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 has to 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.

5.2 Andros

The quality of the power from the wind farm on Andros was measured during two nights. During one night there was no wind at all. The other night was windy; the wind speed during that night varied from 5 to 14 m/s.

When the power demand is decreasing during nights, for example, some diesel engines are stopped. Stopping one diesel engine will decrease the spinning reserve with a certain amount. The load on the remaining diesel engines will, hence, increase with a frequency drop as a result. Stopping one additional diesel engine will decrease the spinning reserve with a larger amount, since the total spinning reserve is lower this time. The stop of the second diesel engine will consequently cause a larger frequency drop than the stop of the first one.

In Fig. 1 this phenomenon is clearly visible. In the figure, the frequency variations during the two nights are presented. As can be seen in Fig. 1, there are two frequency drops during the night when the turbines were shut down, one smaller at approximately 22.00, and one bigger 1.5 hours later.

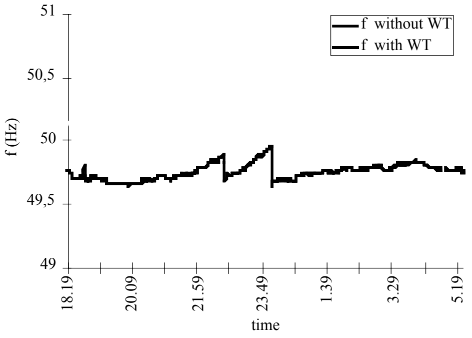

Figure 1: *Frequency variations on Andros during two nights. One night when the turbines were operating (grey line) and one night when the turbines were shut down due to lack of wind (black line).*

The other curve representing the frequency when the turbine was operating shows an increased frequency. The frequency was above 50 Hz during the whole night indicating that the utility kept some diesel engines running and the load was being shared between diesel engines and the wind turbines. Most likely, the utility is afraid of stopping all diesel engines in case of a sudden wind drop. Also this windy night two diesel engines were stopped. Since the load is shared between the wind turbines and the diesel engines, the diesel engines can be stopped earlier. The major frequency drop at approximately 05.00 seems to be a large diesel engine which was shut down.

A comparison between the two nights on Andros shows that the frequency variations are greater when the wind turbines are running.

The frequency variation was 1.2 Hz when the wind turbines were running and 0.3 Hz when the wind turbines were not operating.

5.3 Svenska Högarna

On Svenska Högarna, the quality of the power was measured during one night. During the night the wind speed varied from 3 to 15 m/s.

In Fig. 2 the frequency variations and the power output from the wind turbine during the night are presented. As can be seen, 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 mixed mode for approximately 4 hours. Finally, for the rest of the night the wind speed was high enough for the wind turbine to operate alone. In other words, all three operation modes: diesel, mixed and wind modes are presented in the same figure.

The frequency is raised from approximately 48 Hz in diesel mode to 50 Hz in mixed and wind modes. Apparently, this diesel seems to have a governor with a frequency of 50 Hz at no load to 48 Hz at full load. As soon as the wind turbine starts to operate in mixed mode, the load is decreasing at the diesel generator with a frequency rise as a result. In the figure this phenomenon is clearly visible. During the hour between approximately 22.30 and 23.30 there are several power drops from the wind turbine. Every time the power output from the turbine falls, the frequency on the grid also falls due to an increased load on the diesel generator.

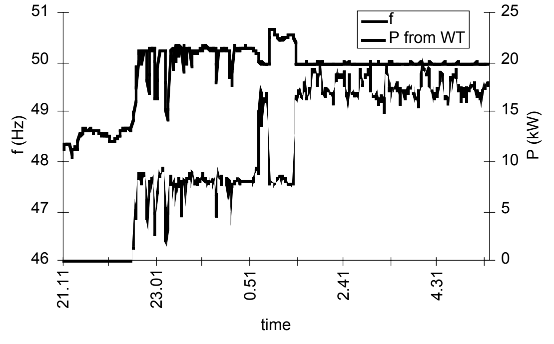

Figure 2: Frequency variations (black line) and power output from the wind turbine (grey line) during one night.

At approximately 02.00 the power output from the wind turbine is raised to at least 15 kW and the plant is running in wind mode for the rest of the night. As can be seen, the frequency is very stable when the plant is running in wind mode. In fact, the frequency is much more stable in wind mode than in the other two modes.

The frequency variations on Svenska Högarna were 2.5 Hz in diesel and mixed modes. When it comes to wind mode the frequency variations were below 0.1 Hz.

The total frequency variations are smaller on Andros compared with those on Svenska Högarna. The measurements on the grids solely without any wind turbines verify that the difference does not depend on the type of wind turbines used. The explanation is the big difference in size between the two sites. Andros has an installed diesel power of 15 000 kW compared to the 20 kW diesel power installed on Svenska Högarna. Hence, the spinning reserve is much larger on Andros compared to the spinning reserve on Svenska Högarna.

Worth pointing out is that the smallest frequency variation at the two sites occurs on Svenska Högarna in wind mode.

6. VOLTAGE VARIATIONS

6.1 Standard

The standard nominal voltage for public low voltage, according to Standard EN 50 160, is 230 V between phase and neutral. Under normal operating conditions during one week, 95 % of the 10 minutes average values of the supply voltage has to be within the range of 230 V ± 10 %.

6.2 Andros

The voltage of the grid on Andros during two nights is shown in Fig. 3. As can be seen, there are two voltage drops during the night when the turbines were shut down. One power drop at approximately 22.00 and the second one 1.5 hours later. These two power drops occur at exactly the same time as the frequency drops at the corresponding night in Fig. 1. As in the frequency case, these voltage drops are emanating from diesel engine stops. The voltage regulator on the diesel generator decreases the voltage when the load increases.

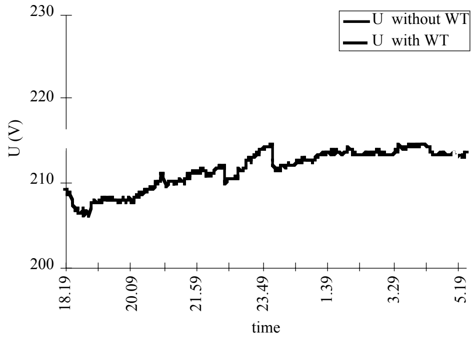

Figure 3: Voltage variations during two nights. One night when the turbines were operating (grey line) and one night when the turbines were shut down due to lack of wind (black line).

During the windy night, the voltage is higher. This is due to two phenomena. First the fact that the wind turbines will increase the voltage level on the bus-bars and secondly the voltage regulators of the diesel engines. The voltage regulators increase the voltage level when the load decreases, which is the case when the load is shared between the wind turbines and the diesel engines.

As can be seen in the figure, the voltage level this windy night does not have any specific pattern like the night when the wind turbines were not operating. Consequently, the wind turbines have a greater influence on the voltage level at the measuring point than the voltage regulator of the diesel generator.

On the island of Andros, the voltage variations are greater when the wind turbines are operating compared with when the wind turbines are shut down. When the wind turbines were running the voltage variations were 15 V. The other night when the wind turbines were not operating, the voltage variations were 9 V.

6.3 Svenska Högarna

The voltage of the grid during one night on Svenska Högarna is shown in Fig. 4. In the same figure, the power output from the wind turbine is shown. As can be seen in the figure, the voltage variations seem somewhat to be larger when only the diesel is operating. This is due to the former discussion regarding the voltage regulator on the synchronous generator.

The voltage is decreasing with an increasing generator load, i.e. decreasing frequency. Since the frequency is more stable when the wind turbine is working, the voltage also becomes more stable.

The voltage variations on Svenska Högarna were 4 V in diesel and mixed modes. When it comes to wind mode the voltage variations are 2.5 V.

Anyhow, the voltage variations are smaller on Svenska Högarna than they are on Andros. On Svenska Högarna the total voltage variations during the specific night were 5 V. On Andros the total voltage variations during the actual nights were 21 V. Worth pointing out is that the voltage variations at both sites are within the permitted limits, according to the EN 50 160 Standard.

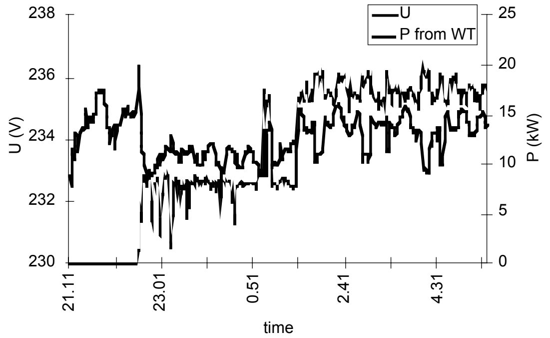

Figure 4: *Voltage variations (black line) and power output from the wind turbine (grey line) during one night.*

7. CONCLUSION

The quality of the power is affected by the wind turbines in a negative as well as in a positive way.

A comparison between the two sites shows that the total frequency variations are smaller on Andros than they are on Svenska Högarna. The measurements on the grids solely, without any wind turbines, verify that the difference does not depend on the type of wind turbines used. The explanation is the big difference in size between the two sites. Svenska Högarna is a very small island with a limited grid. The installed power on Svenska Högarna is only 0.2 % compared with the installed power on Andros. Just switching an ordinary hub on Svenska Högarna results in a load step of 10 %.

An examination of each site reveals something different. On the island of Andros, the frequency variations and the voltage variations are greater when the wind turbines are running compared with when they are not operating.

On Svenska Högarna the situation is the very opposite compared with Andros. The frequency variations and the voltage variations are both improved in the wind mode compared with diesel mode.

The frequency rise on Andros occurring when the wind turbines are operating implies that the utility is running diesel engines at part load. Since the fuel consumption for a diesel generator set at no load is 15-40 % of the full load consumption this control strategy is not economical.

On Svenska Högarna the specially designed wind-diesel system makes it possible to have 100 % wind penetration.

8. ACKNOWLEDGEMENTS

The author would like to thank Dimitris Michalopolous at PPC in Greece and Gunnar Hjärtstrand on Svenska Högarna for all arrangements during the measurements. The financial support given by the Swedish National Board for Industrial and Technical Development is gratefully acknowledged.

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Paper 2C

Flicker and Slow Voltage Variations from Wind Turbines

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Flicker and Slow Voltage Variations from Wind Turbines

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Abstract-The penetration of wind turbines into the grid has increased during the last decade, and this development will continue in the future. In this situation, the influence of wind turbines on the power quality of the grid has become an important issue. Flicker is one power quality phenomenon which can be caused by power fluctuations from wind turbines. In the paper, 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. Finally, the paper deals with the conditions under which flicker is likely to be the limiting factor when wind energy penetrates into the grid.

I. INTRODUCTION

Anything producing changes in supply voltage can be considered to be a possible source of flicker. To determine whether a source will produce flicker, some fundamental voltage drop considerations must be examined: Large loads produce larger voltage fluctuations in comprison with small ones. Loads connected to a weak system are more likely to produce noticeable amounts of flicker than the same loads connected to stiffer systems.

Wind turbines are often raised in areas where the grid is weak. When wind turbines are connected to a grid two different phenomena will occur: voltage fluctuations and stationary voltage variations emanating from the power produced in the turbine. Voltage fluctuations are mainly caused by the tower shadow effect. Due to the wind speed decrease in front or behind the tower, power output is reduced every time a rotor blade passes the tower. If the turbine has three blades, the power drop will appear three times per revolution of the turbine. Normally, this will give rise to power dips with a frequency of 1-2 Hz and a magnitude of approximately 20% [1].

Nevertheless, the recommendations given by power utilities often have no requirements for power fluctuations. Normally, recommendations regarding the short-circuit ratio between the short-circuit power of the grid and the rated power of the wind turbine are stated. In Sweden and Finland, for example, only stationary voltage variations are taken into consideration, and the utilities recommend a short-circut ratio greater than 20.

This paper deals with flicker and stationary voltage variations, by which wind turbines can affect other consumers connected to the grid. It is shown that not only does the short-circuit ratio of the grid affect the voltage fluctuations but the ratio between the reactance X and the resistance R of the grid in combination with the reactive power consumption of the load also has a significant impact on the voltage fluctuations. Depending on the *X/R* ratio of the grid, the minimum short-circuit ratio required for avoiding flicker will not be determined by stationary voltage variations. If the *X/R* ratio is high, the 1 Hz voltage variations emanating from the tower shadow effect will determine the minimum short-circuit ratio.

II. REACTIVE POWER DEMAND

Wind turbines can be divided into two main groups: constant-speed turbines and variable-speed turbines. The constant-speed operation of wind turbines is the most common type of operation. Normally, constant-speed wind turbines are equipped with an induction generator connected directly to the grid, which results in a simple electrical system. The induction generator has several advantages, such as a robust design, totally enclosed construction, low price and the ability to withstand overloads. The major disadvantage is that the machine needs reactive power. In order to reduce this reactive power demand, phase compensating capacitors are used. The capacitance of the capacitors must be limited due to the risk of the self-magnetization of the generator in case of grid failure. A rule of thumb is to compensate for reactive power up to a third of the nominal apparent power of the induction machine.

In Fig. 1 the reactive power from a constant-speed 450 kW wind turbine located at Risholmen in Sweden is shown as a function of active power. As can be seen in the figure, reactive power is compensated for up to the no-load reactive power demand limit of the generator.

Variable-speed wind turbines are equipped with a frequency converter between the grid and the generator. Depending on the type of inverter used, wind turbines have different reactive power demands. With a line-commutated inverter, the power factor is equal to or less than 0.9, while the power factor can freely be chosen if a forced-commutated inverter is used.

III. VOLTAGE VARIATIONS AND *X/R* RATIO OF THE GRID

The short-circuit power of the grid of a specific point can be calculated as

$$S_{sc} = \frac{U^2}{Z} = \frac{U^2}{\sqrt{R^2 + X^2}} \qquad (1)$$

where *U* refers to the voltage of the grid at the point of common connection (PCC) and *Z* is the impedance of the grid at the PCC. *R* and *X* refer to the resistance and the reactance of the grid in the PCC, respectively.

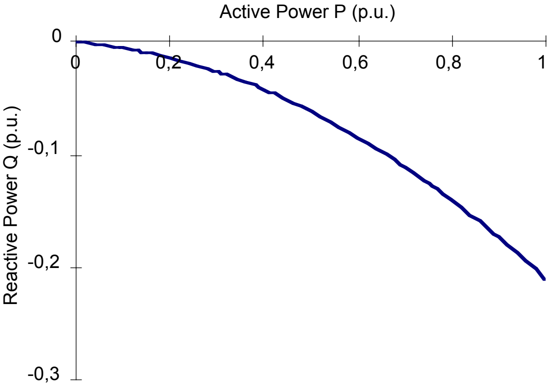

Fig. 1. Reactive power as a function of active power.

According to (1), the short-circuit power is constant at a constant voltage provided that the impedance is constant. It must, however, be noted that a given value of the impedance can be obtained at different *X/R* ratios. The *X/R* ratio of a grid may vary widely depending on the voltage level, grid configuration, type of lines and line geometry used. A 10 kV cable normally has a lower *X/R* ratio, varying from below 0.5 to over 2, while the *X/R* ratio may vary from 1 to 5 for an overhead line at the same voltage level.

A simple impedance model shown in Fig. 2 can be used to calculate the voltage variations caused by active power *P* and reactive power *Q*. U_1 is the voltage of the infinite bus and U_2 is the voltage of the wind turbine at the PCC. Impedance *Z* represents the grid between the infinite bus and the turbine.

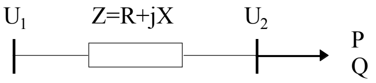

Fig. 2: Simple impedance model.

The voltage at the PCC can be expressed as

$$U_2 = \sqrt{a + \sqrt{a^2 - b}} \qquad (2)$$

where

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

$$b = (P^2 + Q^2)Z^2$$

The measured voltage variation of the wind turbine located at Risholmen is presented in Fig. 3. The calculated voltage variation obtained by (1) and (2) also is shown. The short-circuit ratio is 26 and the *X/R* ratio at the PCC is approximately 5.5. As can be seen in Fig. 3, the voltage variations are within tight limits, at this specific site, due to a high *X/R* ratio at the PCC.

Figure 4 shows the calculated voltage of the grid at the PCC at different *X/R* ratios and a constant short-circuit ratio of 26. The short-circuit ratio and the reactive power demand of the wind turbine are equal to the wind turbine site at Risholmen, shown in Fig. 1. As can be seen in Fig. 4, a low *X/R* ratio will

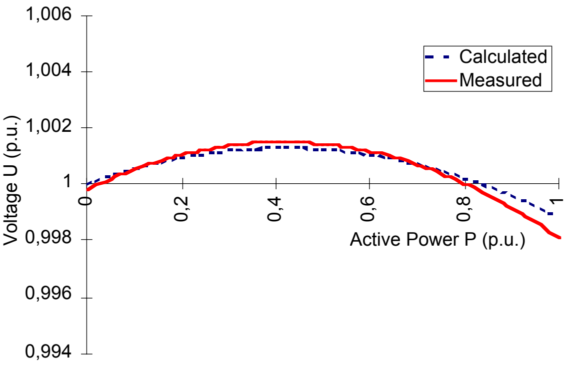

Fig. 3. Measured (solid line) and calculated (dashed line) voltage variations of the wind turbine site at Risholmen.

increase the voltage at the PCC while a high *X/R* ratio will lower the voltage.

IV. POWER FLUCTUATION

In [2], 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.

The measured power of the wind turbine located at Risholmen clearly shows a periodical component, as illustrated in Fig. 5. According to [1], this kind of power fluctuation is caused by the tower shadow effect and is different from the power variations caused by wind speed changes, wind fluctuations and by inhomogeneous wind flow.

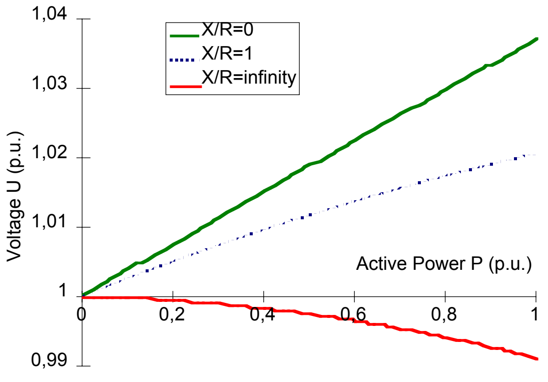

Fig. 4. Voltage variations at different *X/R* ratios. The short-circuit ratio is 26.

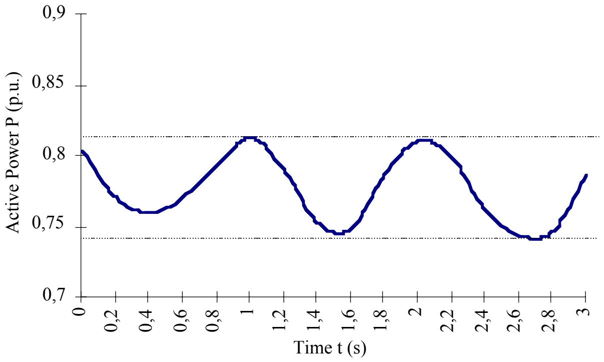

Fig. 5. Power fluctuation from a constant-speed wind turbine.

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”.

Power fluctuation depends on both the tower shadow effect and the wind gradient (i.e. wind speed increase with height). The left turbine in Fig. 6 shows the rotor position when one blade passes the tower. As can be seen, at this moment none of the remaining two blades are 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.

A two-blade and a three-blade wind turbine have been studied in [3]. Both turbines are pitch-regulated and operate at constant speed. For both wind turbines studied, the greatest power fluctuation occurs at rated power at the highest wind speeds.

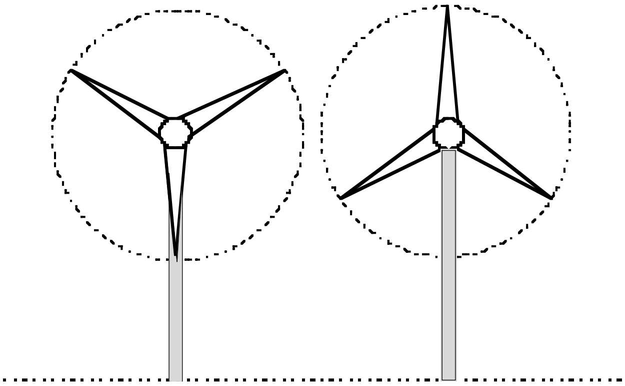

Fig. 6. Different rotor positions of a three-blade wind turbine.

This is natural, because absolute wind-speed fluctuations increase with wind-speed (even if turbulence intensity remains constant). The slope of the turbine power-wind-speed curve also increases above rated wind speed. This increase indicates that the greatest chance for flicker is at the highest wind speeds. According to [1], wind turbines equipped with induction generators operating at constant-speed generate power fluctuations up to 20 % of the average power. Measurements of a 3 MW two-blade wind turbine equipped with a synchronous generator are presented in [4]. Power fluctuations up to 1 MW (i.e. 33 %) at a frequency of 2.4 Hz occur.

Variable-speed wind turbines are equipped with a converter, which allows generator frequency to differ from grid frequency. Variable-speed wind turbines do not have any power fluctuations. Fig. 7 shows the measured power output from a variable-speed wind turbine equipped with a forced-commutated inverter.

V. 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. 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 luminence of the light-bulb. An excellent reference covering the history of voltage flicker is provided by Walker [5].

Flicker is treated in Standard IEC 868. The magnitude of maximum permissible voltage changes with respect to the number of voltage changes per second is plotted in compliance with Standard IEC 868. Flicker originating from wind turbines has periodical power fluctuations. In the flicker curve presented in Fig. 8 the magnitude of the maximum permissible percentage of the voltage change is shown as a function of frequency.

VI. CALCULATION OF VOLTAGE VARIATIONS AND FLICKER

Two different phenomena occur between the grid and the turbine. Both the stationary variation in the power production and power fluctuation will cause voltage variations. Stationary voltage variations emanate from the power produced by the turbine. Power production 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 start in high wind conditions. Power fluctuations occurring at a frequency of 1 to 2 Hz are mainly caused by the tower shadow. According to IEC 868 (Fig. 8) stationary voltage variations are allowed to be as large as 3%, while voltage variations occurring at 1 Hz may be only 0.7%.

In order to calculate voltage variations caused by stationary and 1 Hz power fluctuations, the simple impedance model in Fig. 2 can be used. Using (2) makes it possible to calculate the magnitude of voltage variations caused by power fluctuations at different *X/R* ratios and different short-circuit ratios. In Fig. 9, the minimum short-circuit ratios required to avoid flicker caused by stationary voltage variations and 1 Hz voltage variations are plotted for different *X/R* ratios

The wind turbine at Risholmen is used in the example presented in the figure, i.e. the reactive power demand is used as a function of active power according to Fig. 1. Moreover, power fluctuations have been assumed up to 20% of the rated power occurring at 1 Hz. Although this is a simplified calculation, some interesting conclusions can be made:

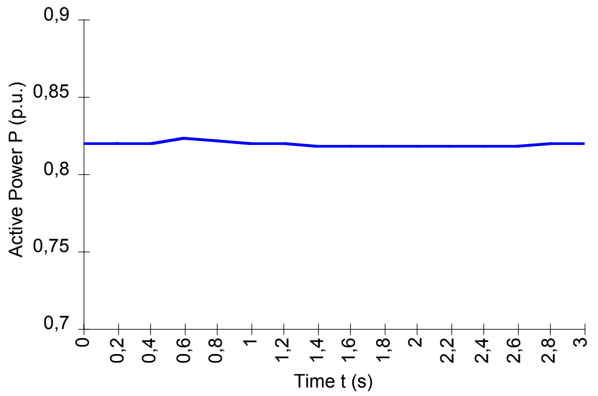

Fig. 7. Measured power fluctuation from a variable-speed wind turbine.

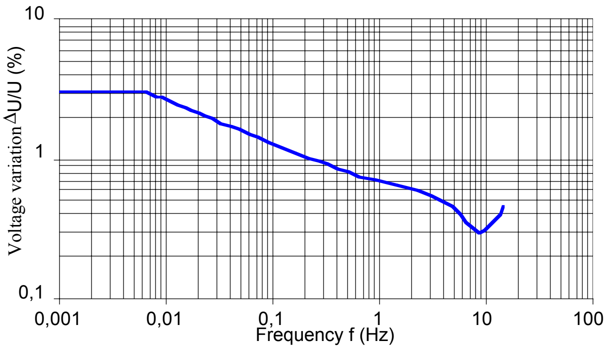

Fig. 8. Flicker curve according to IEC 868.

1. In grids having a low *X/R* ratio, the short-circuit ratio is limited by the stationary power fluctuations
2. In grids having a high *X/R* ratio, the short-circuit ratio is limited by the 1 Hz power fluctuations.
3. A minimum required short-circuit ratio is found at on *X/R* ratio of approximately 2.3.

A variable-speed wind turbine equipped with a line-commutated inverter has a power factor equal to or less than 0.9. Normally, filters are used in order to reduce the harmonics generated by the inverter. Due to the use of capacitors, the filters will produce reactive power. The reactive power demand from a line-commutated inverter may be assumed to be equal to the reactive power demand of a constant-speed wind turbine. Hence, the minimum short-circuit ratio for a variable-speed wind turbine equipped with an line-commutated inverter is equal to the limit due to stationary voltage variations for a constant-speed turbine shown in Fig. 9.

Consequently, if the *X/R* ratio of the grid at the PCC is below 2.3, there is no need for an expensive variable-speed wind turbine. The grid must be dimensioned for stationary voltage variations. Hence, constant-speed wind turbines equipped with ordinary direct-coupled induction generators might as well be used if only voltage variations are considered.

When the *X/R* ratio of the grid at the PCC exceeds 2.3, reinforcing the grid might be avoided if variable-speed wind turbines are used. As mentioned earlier, power fluctuation does not occur with variable-speed wind turbines.

If a variable-speed wind turbine is equipped with a forced-commutated inverter, the power factor can be controlled. Even if the power factor may be freely chosen, the power factor of inverters today are usually kept equal to 1.

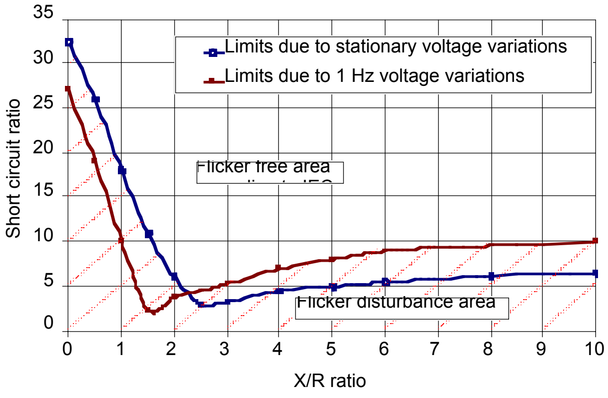

Fig. 9. Minimum short-circuit ratio at different grid *X/R* ratios to avoid flicker caused by stationary voltage variations and 1 Hz voltage variations.

In Fig. 10, the minimum short-circuit ratio for a variable-speed turbine with a power factor equal to 1 is compared with the ordinary constant-speed turbine used in Fig. 9. As can be seen, the minimum short-circuit ratio for a variable-speed wind turbine is higher at *X/R* ratios below 4 when the power factor is kept equal to 1.

As mentioned earlier, in a forced-commutated inverter, the power factor cannot only be kept equal to 1 but it can be chosen freely. If the *X/R* ratio is lower than 4, the minimum short-circuit ratio actually could be as low as or lower than that of a constant-speed turbine if the power factor is controlled in an intelligent way. Due to the reactive power, controlling the power factor will result in two things. First, a higher rated power will be required of the inverter, which will result in a higher cost for the inverter. Secondly, the losses in the transformer and the lines will increase.

VII. CONCLUSIONS

Two different phenomena occur between the grid and the wind turbine. Stationary voltage variations emanate from starting and stopping the turbine, and voltage fluctuations emanate from power fluctuations. According to the flicker curve in the IEC 868 Standard, stationary voltage variations are allowed to be as large as 3%, while voltage variations occurring at 1 Hz may only be 0.7%.

The *X/R* ratio of the grid has a significant impact on the minimum short-circuit ratio at the PCC. Calculations of a constant-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. At higher *X/R* ratios, the minimum short-circuit ratio is determined by the voltage variations caused by fluctuating power. Consequently, if the *X/R* ratio of the grid in the PCC is low, the grid must be dimensioned for stationary voltage variations.

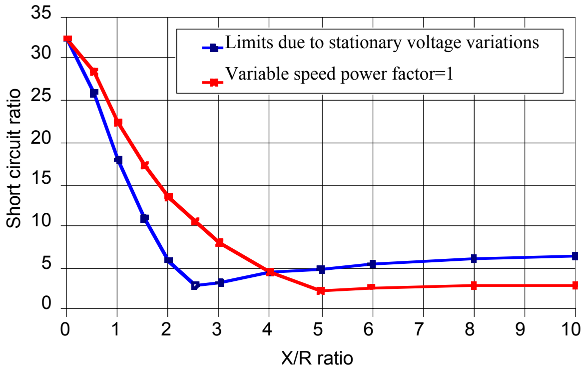

Fig. 10. Minimum short-circuit ratio at different grid *X/R* ratios to avoid flicker from constant- and variable-speed turbines.

Hence, there is no need for an expensive variable-speed wind turbine if only voltage variations are considered

A variable-speed wind turbine equipped with a forced-commutated inverter makes it possible to reduce the short-circuit ratio under certain conditions. On the one hand, if the *X/R* ratio is high, the short-circuit ratio can be reduced simply by keeping the power factor equal to 1. On the other hand, if the *X/R* ratio is low, the short-circuit ratio can be reduced only if the power factor is controlled. However, controlling the power factor increases the cost of the inverter and the losses in the transformer and lines.

VIII. ACKNOWLEDGEMENT

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X. BIOGRAPHY

Åke Larsson was born in Skellefteå, Sweden in 1957. He recieved his M.Sc. at Chalmers University of Technology in 1994 and is now working at the Department of Electric Power Engineering, division of Electrical Machines and Power Electronics. His area of interest is power quality, especially for wind energy applications.

Paper 2D

Grid Impact of Variable-Speed Wind Turbines

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GRID IMPACT OF VARIABLE-SPEED WIND TURBINES

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ABSTRACT: In this paper the power quality of variable-speed wind turbines equipped with forced-commutated inverters is investigated. Measurements have been taken of the same type of variable-speed wind turbines in Germany and Sweden. The measurements have been analysed according to existing IEC standards. Special attention has been paid to the aggregation of several wind turbines on flicker emission and harmonics. The aggregation has been compared with the summation laws used in the draft IEC 61400-21 “Power Quality Requirements for Grid Connected Wind Turbines“. The methods for calculating and summing 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 in the 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, according to the IEC 61000-4-7, Amendment 1 is of a great importance.

Keywords: Power Quality, Variable-Speed Operation, Grid, Power Factor

1 INTRODUCTION

The grid interaction and grid impact of wind turbines has been focussed on the past few years. The reason behind this interest is that wind turbines are among utilities considered to be potential sources of bad power quality. Measurements show that the power quality impact of wind turbines has been improved in recent years. Especially variable-speed wind turbines have some advantages concerning flicker. But a new problem is faced with variable-speed wind turbines. Modern forced-commutated inverters used in variable-speed wind turbines produce not only harmonics but also inter-harmonics.

The purpose of this work is to investigate the power quality of variable-speed wind turbines equipped with forced-commutated inverters. The measurements have been analysed according to IEC standards. Special attention has been paid to the aggregation of several wind turbines on flicker emission and harmonics.

2 SITES

Measurements have been taken on a wind farm consisting of five variable-speed wind turbines in Germany, and at one variable-speed wind turbine on the island of Gotland, Sweden.

In Germany, measurements at the Emden wind park have been performed by DEWI. The measurements were taken simultaneously on the low voltage sides of two Enercon E-40 wind turbines. The measurements are divided into two different types:

1. Flicker measurements performed at a sampling frequency of 800 Hz. From the measured voltages and currents, active power and phase angle have been calculated. The sampling frequency of the calculated values was 50 Hz and the length of each measurement was 10 minutes.
2. Harmonics measurements were performed at a sampling frequency of 12 800 Hz.

Chalmers University of Technology has performed measurements on the island of Gotland, Sweden. On Gotland, the site consists of two Enercon E-40, but measurements were taken only at one Enercon. The measurements have been divided into two different types:

1. Flicker measurements performed at a sampling frequency of 500 Hz. The cut-off frequency of the anti-alias filter was 104 Hz and the length of each measurement was 10 minutes.
2. Harmonics measurements performed at a sampling frequency of 5 000 Hz.

3 FLICKER

In order to determine the flicker emission produced by a wind turbine, measurements must be performed. 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 [1]. Two methods are proposed to overcome this problem. One is based on the measurement of active and reactive power, and the other method is based on the measurement 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.

The flicker has been calculated using a PC-program developed by Risø National Laboratory [2]. This program uses the IEC 60868, Amendment 1 to calculate the P_{st} [3-4]. The input to the program are time series of active and reactive power, short circuit power and the phase angle of the grid.

Figure 1 shows the short-term flicker emission Pst from an Enercon E-40 at different mean values of the produced power. In this particular case, a short-circuit power of 20 times the rated power of the wind turbine and a grid angle of 45 degrees have been used. As can be seen in Figure 1, the flicker emission P_{st} increases at higher wind speeds due to higher turbulence in the wind. The flicker level is low, almost 4 times lower than the flicker produced by the fixed-speed Wind World 600 kW. Measurements performed on the fixed-speed turbine using the same equipment and flicker algorithm gives the short-time flicker emission Pst=0,46.

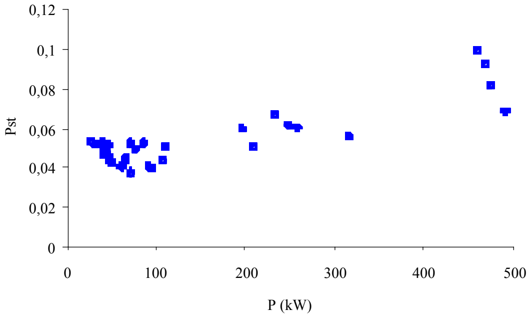

Figure 1: Short term flicker emission Pst from an E-40 at different mean value of the produced power.

3.1 Flicker Coefficient

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

$$c(\psi_k) = P_{st,fic}\frac{S_{k,fic}}{S_{ref}} \qquad (1)$$

where $c(\psi_k)$ is the flicker coefficient and S_{ref} is the rated active 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 flicker emission produced by a wind turbine connected to a grid with an arbitrary short-circuit power may then be recalculated by:

$$P_{st} = c(\psi_k)\frac{S_{ref}}{S_k} \qquad (2)$$

3.2 Summation of Flicker

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

$$P_{st\Sigma} = \sqrt{\Sigma P_{st,i}^2} \qquad (3)$$

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

Figure 2 shows the calculated short-term flicker emission from ten different measured time series of two Enercon

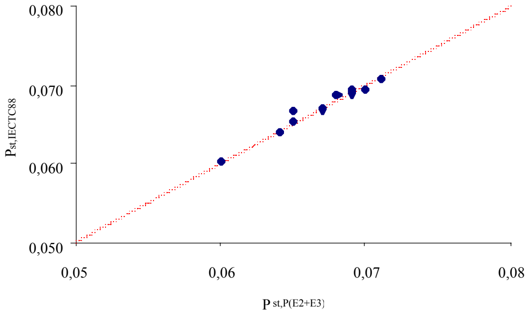

Figure 2: Calculated short-term flicker emission from ten different measured time series of two Enercon E-40.

E-40. The P_{st} is calculated in two different ways:

1. Directly by using the sum of the time series of power from the wind turbines.
2. By the use of Equation 3.

As can be seen in the figure, the short-term flicker emission varies due to variations in the wind, i.e. turbulence. The mismatch of the two different ways of calculating the flicker (i.e., deviation from the dotted line) is, however, small.

4 HARMONICS AND INTER-HARMONICS

Harmonics and inter-harmonics are defined in the IEC 61000-4-7 and Amendment 1 [5][6]. The definition of harmonics is components at 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 of frequencies located between the harmonics of the supply frequency.

The signal, which is to be analysed, is sampled, A/D-converted and stored. These samples form a window of time ("window width") on which discrete Fourier transformation is performed. The window width shall, according to the standard, 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. Figure 3 shows the inter-harmonic components of the measured current from an Enercon E-40 on Gotland. The current is analysed in accordance the IEC 61000-4-7.

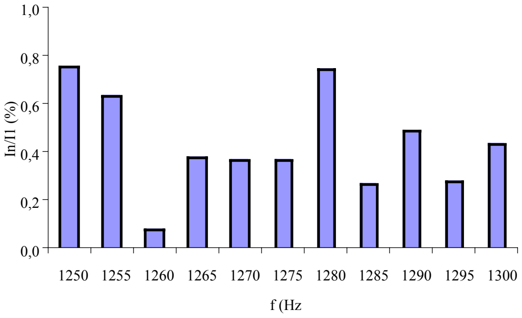

Figure 3: Current inter-harmonic content between 1250-1300 Hz.

The rms value of all inter-harmonic components between two consecutive harmonic frequencies forms an inter-harmonic group. The inter-harmonic group frequency is the centre frequency of the harmonic frequency between which the group is situated. That is, a group between the harmonic orders n and n+1 is designated as n+0.5, i.e. the group between n=5 and n=6 is designated n=5.5.

Figure 4 shows the harmonics and inter-harmonic groups of order 20 to 25 of the measured current from an Enercon E-40 at Gotland.

4.1 Impact of window size

The window width shall according to the IEC 61000-4-7 be 10 line-periods in a 50 Hz system. A 10 line-period window width gives, as illustrated in Figure 4, a distance between two consecutive inter-harmonic components of 5 Hz.

If a window width of 16 line-periods is used, the distance between two consecutive inter-harmonic components will be 3.125 Hz. The use of the larger window decreases the distance between two consecutive inter-harmonic components. As a consequence, each inter-harmonic component will have a lower content.

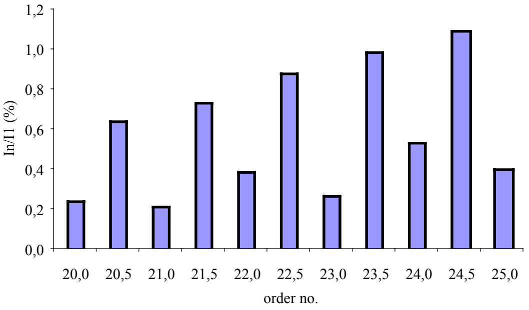

Figure 4: Current harmonics and inter-harmonic group.

Figure 5 shows the harmonic content in the same current using a window width of 10 and 16 line-periods. As can be seen, the harmonic content will be larger in the smaller window. Note: an exact comparison cannot be made since one window is 16 line-periods and the other just 10 line-periods.

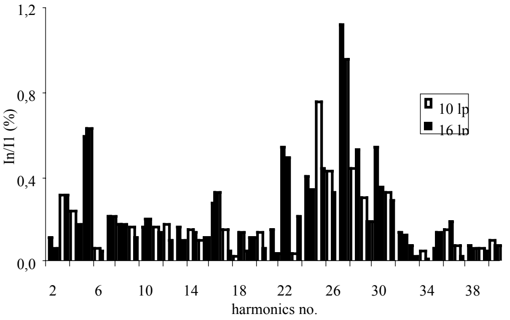

Figure 5: Harmonic content in current using a window width of 10 and 16 line-periods, respectively.

4.2 Harmonics

The Enercon wind turbine is equipped with a 12-pulse inverter using IGBT valves. This implies that the first harmonics should appear around the switching frequency of the IGBT. The switching frequency of IGBTs can be rather high (5-10 kHz). The switching frequency must not be fixed, the controller can either employ a PWM pattern or it can be of the simple on-off type having a small histories band which creates a lower limit for the time interval between two subsequent switching operations.

Figure 6 shows the harmonic content on the low voltage side of the Enercon E-40. The measurements originate from two different sites, Emden in Germany and Gotland in Sweden. As can be seen in the figure, the harmonic content in the current from the two sites is almost identical. The largest discrepancy is on the 2:nd-order harmonic, where the content on Gotland is 0.65% while it is only 0.2% in Emden. The large 2:nd order harmonic on Gotland most likely depends on a lack of phase-lock on the measurement equipment used on Gotland.

The switching frequency of the IGBTs is, as mentioned earlier, not fixed and it seems to be around 1 to 1.5 kHz, i.e. harmonics of the order 20 – 30. In the figure, a whole range of harmonics between 20 and 30 can be observed. The harmonic content in Figure 6 is calculated as a mean value over several seconds. The current also contains lower harmonics, for example, of the 3rd, 5th and 7th order. These harmonics may originate from two different sources. A simple control of an inverter is simply to generate a current with the same shape as the voltage. If the voltage contains a lower order harmonics, the current will also contain a lower order harmonics. In the Enercon, there are also other control equipment and inverters used. For example, each blade has an electrical pitch mechanism by means of an electrical drive system. Grid-commutated inverters generate harmonics of the orders 5th, 7th, 11th, 13th, etc. and single phase switched equipment generates harmonics of the 3rd order.

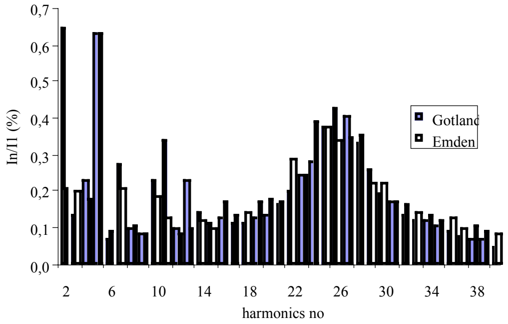

Figure 6: Current harmonic content on low side of trans-former.

4.3 Summations of Harmonics

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

$$I_{n,tot} = \sqrt[a]{\sum_i i_{n,k}^{a}} \qquad (4)$$

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 1.

Table 1: Summation exponents for harmonics.

a	harmonic order
1	h<5
1.4	5≤h≤10
2	h>10

Figure 7 shows the harmonic content from the sum of two Enercon and the calculated content.

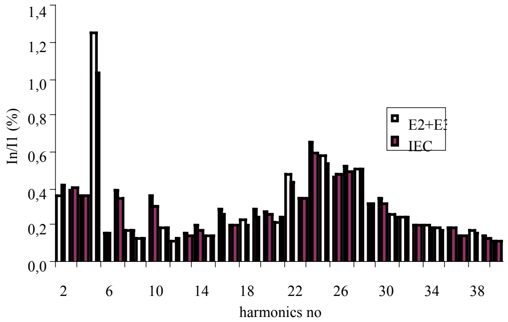

Figure 7: Calculated harmonic content from two different Enercon E-40 by means of the time series of current and by means of Equation 4.

The harmonic content of the sum of the two Enercon is derived from the sum of the measured time series of the current. The calculated harmonics content has been performed by Equation 4 and the harmonic content of each Enercon.

4.4 Inter-harmonics

Enercon wind turbines not only produce harmonics, they also produce inter-harmonics, i.e. harmonics which are not a multiple of 50 Hz. Since the switching frequency of the inverter is not constant but varies, the harmonics will also vary. Consequently, since the switching frequency is arbitrary the harmonics are also arbitrary. Sometimes they are a multiple of 50 Hz and sometimes they are not. Figure 8 shows the total harmonics spectrum from one Enercon. As can be seen in the figure, at lower frequencies there are only pure harmonics but at higher frequencies there are a whole range of harmonics and inter-harmonics. This whole range of harmonics and inter-harmonics represents variations in the switching frequency of the Enercon inverter.

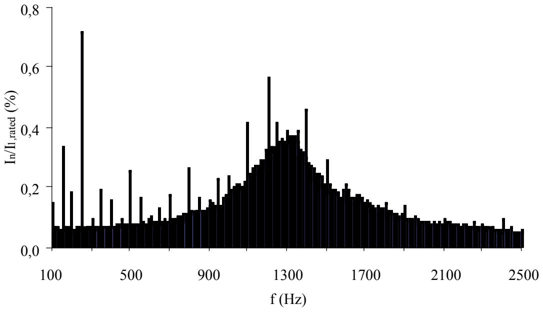

Figure 8: Harmonic and inter-harmonic content in current.

5 START

Figure 9 shows the active and reactive power during the start of the Enercon E-40 located on Gotland under high wind speed conditions. At the time, t=30 s., the generator is connected to the grid via the converter. The active power rises smoothly and gently from a standstill to rated power. The whole process takes approximately 50 s. During the time the active power rises, the reactive power is controlled in order to keep the power factor constant.

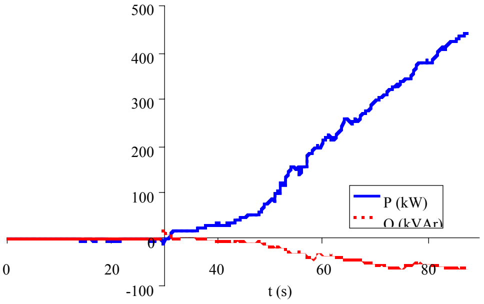

Figure 9: Active and reactive power during start. The upper (positive) curve is the active power and the lower (negative) curve is the reactive power.

6 CONCLUSIONS

The power quality of the variable-speed wind turbine shows a low flicker contribution, a controllable power factor and a smooth start/stop, which have minor impact on the grid. One drawback with the variable-speed wind turbine is the injection of current harmonics into the grid. This variable-speed wind turbine is equipped with a forced-commutated inverter. The current harmonics produced by the inverter are low compared with wind turbines equipped with grid-commutated inverters. Since the switching frequency of the inverter is not fixed the wind turbine not only produces harmonics but also inter-harmonics.

The methods for calculating and summing 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 in the 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, according to the IEC 61000-4-7 Amendment 1 is of great importance.

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Paper 3A

Standards for Measurements and Testing of Wind Turbine Power Quality

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STANDARDS FOR MEASUREMENTS AND TESTING OF WIND TURBINE POWER QUALITY

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ABSTRACT: The present paper describes the work done in 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 standardisation of measurement and verification of wind turbine power quality. The work has been organised in three major activities.

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.

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.

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 .

Kewords: Power Quality, Standards, Electrical System, Wind Farm.

1 INTRODUCTION

The increased size of standard grid connected wind turbines and the utilisation of wind turbines in larger scales has caused an increasing influence of wind turbines on voltage quality of the power system.

Methods to measure and quantify the power quality of wind turbines were early developed on national level, but the need for common reference across the boarders has initiated international standardisation work in the field.

The EU project "European Wind Turbine Standards" (EWTS) [3] funded by the Joule II Programme defined an "Electrical Power Quality Measurement Procedure" in February 1996, based mainly on the German standard. The EWTS procedure formed the basis for the Measnet measurement procedure on "Power Quality of Wind Turbines"[2].

IEC initiated the standardisation on power quality for wind turbines in 1995 as a part of the wind turbine standardisation in TC88, and ultimo 1998 IEC issued a draft IEC-61400-21 standard for "Power Quality Requirements for Grid Connected Wind Turbines"[1].

2 MEASUREMENT PROCEDURES

To verify the measurement procedures, all partners have measured power quality characteristics simultaneously on a 600 kW Bonus wind turbine in Hagshaw Hill wind farm in Scotland 13 - 17 October.

The power quality characteristics that were measured were reactive power, power variability, flicker, transients and harmonics. Both Measnet and IEC definitions have been applied.

2.1 Reactive power

The measured reactive power is shown vs. active power in Figure 1. Only data from a single hour is included, to avoid the influence of different voltage levels on the reactive power.

The figure reveals that Risø measures slightly lower values of consumed reactive power than DEWI and CRES. Analysis of the differences showed that the measurements were within the 2 % required in the Measnet procedure, and the requirements of the draft IEC61400-21.

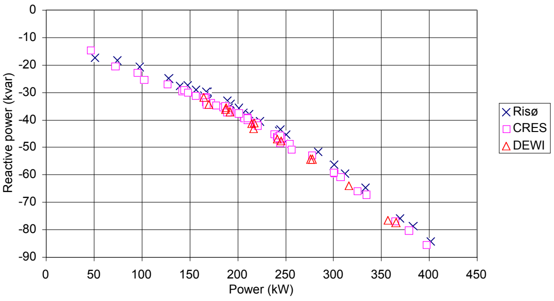

Figure 1. One minute mean values of reactive power vs. active power measured in the same period by Risø, DEWI and CRES.

2.2 Power variability

IEC and Measnet prescribes measurement of maximum instantaneous values of power as a characteristic for the power variations. Besides, a power variability is defined in the Measnet procedure as the relative standard deviation of the power.

The measured standard deviations of the power have shown to be very close. The maximum values show more deviations in the results. One reason for this has been the sampling rate. In Hagshaw Hill, CRES measured power with 20-25 samples per minute, which showed to be too little to measure the power peaks, because some of the power fluctuations are much faster.

2.3 Flicker simulation procedure

Flicker is defined in IEC 868 [4] and [5] to quantify the annoyance in the illumination from lamps. This annoyance depends on the voltage fluctuations at the consumers.

The voltage fluctuations at the consumers depend on fluctuating loads as well as fluctuating production in the power system. The power from wind turbines is fluctuating, and therefore the wind turbines contribute to the voltage fluctuations on the grid.

IEC 1000-3-7 [6] states a method to plan the voltage flicker level in the MV and HV level of a power system, based on the emission level of the individual loads on the system. The emission level of a fluctuating load is defined as the flicker level, which would be produced in the power system if no other fluctuating loads were present.

Measurements of power quality are done on real grids with other fluctuating loads. To eliminate the influence of the fluctuations of the other loads, a method has been developed to simulate the voltage, which would be on a power system with no other fluctuating loads.

The voltage is simulated as $u_{fic}(t)$ on the fictitious reference grid seen in Figure 2.

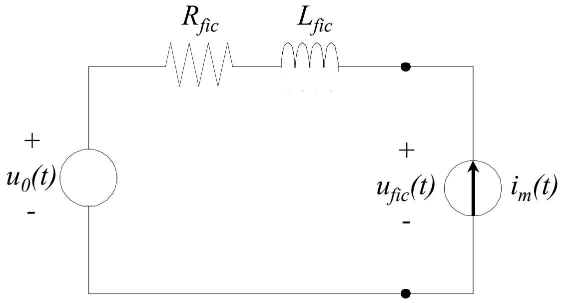

Figure 2. Simulation of voltage which would be on a power system with no other fluctuating loads.

The fictitious grid is represented by an ideal phase to neutral voltage source $u_0(t)$ and a grid impedance given as a resistance R_{fic} in series with an inductance L_{fic}. The wind turbine is represented by the current generator $i_m(t)$, which is the measured instantaneous value of the phase current.

With this simple model, the fluctuating voltage $u_{fic}(t)$ in the power system is given as

$$u_{fic}(t) = u_0(t) + R_{fic} \cdot i_m(t) + L_{fic} \cdot \frac{di_m(t)}{dt}$$

$u_{fic}(t)$ is then used as input to a voltage flicker algorithm as described in IEC 868.

2.4 Flicker during continuous operation

Table 1 shows measurements of flicker short term values with continuous operation of the Bonus 600 kW wind turbine in Hagshaw Hill. The measurements were synchronised manually, i.e. within 1-2 seconds.

Table 1. Simultaneously measured flicker Pst with short circuit ratio 20, grid impedance angles Ψ_k

Me. #	Ψ_k	CRES	DEWI	NEL	Risø
1	30	0.185	0.184	0.169	0.191
2	50	0.121	0.129	0.116	0.138
3	70	-	0.042	-	0..053
	85	-	0.025	-	0.041
4	70	0.074	0.060	0.074	-

Risø used active and reactive power measurements to predict the flicker level with a power based method described in [9], CRES and NEL used a Voltech power analyser with built in current flicker software, and DEWI used own software to simulate the flicker.

This and other results show that flickermeters have a minimum Pst value due to the the binning of the instantaneous flicker level in classes. The Voltech power analyser have a minimum Pst value of 0.074, even though it uses a more detailed binning than required in IEC 868.

Consequently, a weak reference grid (i.e. low short circuit power) shall be selected for the reference calculations. If a too strong grid is selected then the calculated flicker value will be the minimum value of the instrument. Using this Pst value to estimate Pst on weaker grids will only give a scaled minimum value.

2.5 Transients during switching

Wind turbines typically generate transient currents during cut-in and cut-out and switching between generators.

In the EWTS procedure, the transients were characterised by current spike factors, i.e. the ratio between the maximum RMS value of the current and the rated current.

In the Measnet procedure, the current spike factor was supplemented with a grid dependent switching factor, which can be used to predict the maximum voltage variation, taking into account the grid impedance angle.

The definitions in the draft IEC 61400-21 aim to specify characteristics, which can be used to assess the voltage fluctuations according to IEC 1000-3-7 [6]. Consequently, the IEC draft has omitted the current spike factor, but defines a voltage change factor almost similar to Measnets grid dependent switching factor. Moreover, the draft IEC 61400-21 defines a flicker step factor which can be used to predict the flicker influence of the switching operation.

A set of reference measurements logged by DEWI in Hagshaw Hill have been used to compare the calculation routines for flicker. The results of the calculated flicker step factors for the cut-in operation are shown in Figure 3.

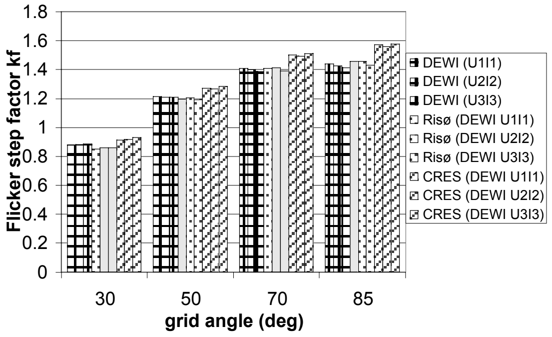

Figure 3. Comparison of calculated flicker step factors k_f during cut-in.

2.6 Harmonics

The harmonic measurements in Hagshaw Hill have also been compared. Generally, the harmonic emission was very low, because the wind turbines are not equipped with power electronics for power conversion. However, the comparisons have shown that the measurements and calculation software of the partners predict harmonics within the 0.1 pct. of rated current which is required in the draft IEC 61400-21.

3 CONSTANT SPEED WIND TURBINES.

The power quality measurements in Hagshaw Hill have been compared to measurements on the same type of 600 kW Bonus wind turbine in Gudum in Denmark. The wind turbine is stall regulated with one rotor speed.

The main difference between the two sites is the terrain. The Hagshaw Hill wind farm is sited in complex terrain, whereas the Gudum wind turbines are sited in a more flat terrain. Another difference appeared to be that the voltage level in Hagshaw Hill is higher than in Gudum.

3.1 Reactive power

Figure 4 shows 10 min mean values of the reactive power vs active power measured by Risø with the same power transducers in Hagshaw Hill and Gudum.

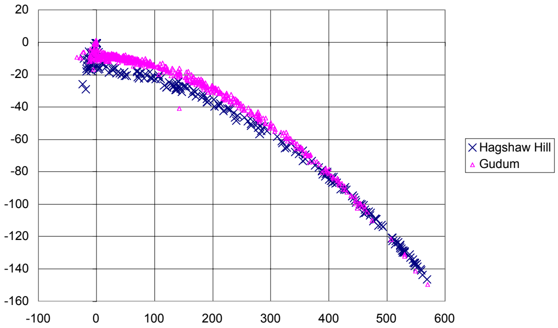

Figure 4. The reactive power consumption of the Bonus 600 kW wind turbine in Hagshaw Hill (Scotland) and Gudum (Denmark)

The analysis showed that the deviations in reactive power are due to a combination of different effects. First, the difference in reactive power consumption at low power levels is most likely due to deviations in the capacities in the capacitor banks. Secondly, the reactive power consumption increases more with power in Gudum than in Hagshaw Hill, which is implied by the higher voltage level in Hagshaw Hill. The lower voltage in Gudum gives higher currents, which again implies higher reactive power consumption in the leak inductance of the induction generator.

3.2 Flicker during continuous operation

The flicker level is effected by the terrain as illustrated in Figure 5. Generally, the Pst values are higher in Hagshaw Hill than in Gudum. This is as expected because of the complex terrain in Hagshaw Hill. But it is also seen that the flicker values increase faster with power in Gudum than in Hagshaw Hill. This is a very important point, because the requirements on flicker emission are based on 99% percentile values. Figure 5 indicates that even though the flicker level is 100% higher in Hagshaw Hill in the medium power range, the 99 % percentiles will only be approximately 20 % higher in Hagshaw Hill than in Gudum.

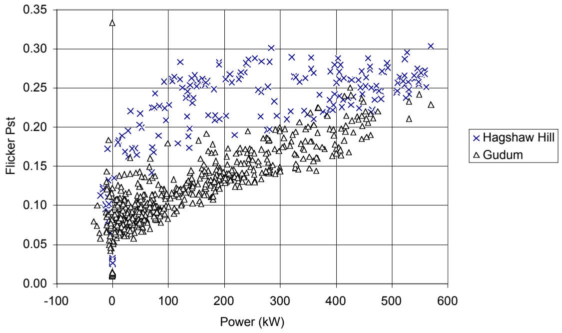

Figure 5. Flicker Pst values vs. power of Bonus 600 kW wind turbines in Hagshaw Hill (complex terrain) and Gudum (flat terrain) for grid angle 30 deg.

3.3 Transients during switching

The higher voltage level in Hagshaw Hill also effects the flicker emission during cut-ins of the wind turbine, and consequently the flicker step factor. The higher voltage level implies more reactive power to magnetise the induction generator at cut-in. This transient reactive power for magnetising has a decisive influence on the flicker emission during cut-in.

3.4 Summation of flicker

According to IEC 1000-3-7 [6], the combined flicker emission P_{st} from various loads can be found as

$$P_{st} = \sqrt[m]{\sum_i P_{st,i}{}^{m}}$$

where $P_{st,i}$ is the flicker emission from the i^th^ load, and m is an exponent depending on the type of the loads. Analyses have shown that for continuous operation of wind turbines, m=2 gives excellent results. For switching operations, m=3.2 is recommended because this value fits when the switching operations do not coincide.

3.5 Harmonics

The harmonic measurements in Hagshaw Hill have also been compared. Generally, the harmonic emission was very low, because the wind turbines are not equipped with power electronics for power conversion. However, the comparisons have shown that the measurements and calculation software of the partners predict harmonics within the 0.1 pct. of rated current which is required in the draft IEC 61400-21.

4 VARIABLE SPEED WIND TURBINES.

The analyses of power quality of variable speed wind turbines are based on measurements on Enercon E-40 wind turbines with power converters based on forced-commutated semiconductors.

4.1 Reactive power

The use of forced-commutated semiconductors makes it possible to control the power factor. Figure 6 shows the measured reactive power as a function of the active power from two different sites. The averaging time in the measurements are in both cases 1 minute. At Gotland the power factor is approximately 0,98 and at Skåne 0,99.

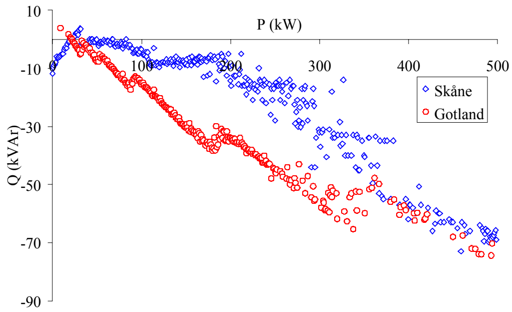

Figure 6. Reactive power as a function of active power from two different sites, Gotland and Skåne.

4.2 Transients during switching

With a combined variable speed control and pitch control of the Enercon wind turbine, the cut-ins and cut-outs can be controlled to a very low level of flicker emission.

4.3 Harmonics and interharmonics

The use of power converters implies a higher emission of harmonics and interharmonics on the grid. The traditional self-commutated semiconcuctors, i.e. thyristors, mainly emit harmonics at low orders. Modern power converters based on forced-commutated semiconductors like IGBTs can be controlled to switch at much higher frequencies. Besides, the emission is not concentrated on harmonics of the fundamental grid frequency, but distributed between the harmonics as interharmonics.

IEC has initiated a revision of 61000-4-7[7] in order to improve the measurement methods for interharmonics. The draft IEC 61400-21 keeps measurements of interharmonic under consideration, awaiting this revision. Meanwhile, Measnet will specify a method based on a CD of the revision [8].

5 CONCLUSIONS

The results from comparisons of simultaneous measurements in Hagshaw Hill show good agreement between the measurements of Risø, DEWI, NEL and CRES. Moreover, the comparison of calculation results based on a set of reference measurements showed very good agreement between the analysis software of Risø, DEWI and CRES.

Measnet and IEC define methods to measure power quality characteristics, which aim at being independent on 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, characterised by a 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 between measurements in complex terrain and in relatively flat terrain showed 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.

All these effects could be taken into account by advanced methods, but such methods would depend strongly on the technology. The strength of the existing methods is their simplicity combined with a high degree of independence of technology. Even the specified methods do have limits concerning the technology. For instance, the specified method to measure flicker emission is not relevant to characterise a wind turbine with a voltage controlling power converter.

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Paper 4A

Guidelines for Grid Connection of Wind Turbines

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GUIDELINES FOR GRID CONNECTION OF WIND TURBINES

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SUMMARY

In this paper, 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 proposed standard IEC 61400-21 "Power Quality Requirements for Grid Connected Wind Turbines" are discussed.

INTRODUCTION

In the past decade, wind energy technology and the wind industry have expanded remarkably. Increased efficiency, higher energy prices and environmental aspects are some of the reasons for the ongoing wind turbine boom. Moreover, the size of wind turbines has increased; 15 years ago, the rated power of a mass-produced wind turbine was 50 kW, today the rated power is up to 1 500 kW. However, among utilities wind turbines may be considered as potential sources of bad power quality. Increased rated power, uneven power production and weak feeder lines are some of the reasons for this.

The difficulty with wind power is not only uneven power production or 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. Moreover, the turbine can either be stall-regulated or pitch-controlled. The different types of wind turbines each have their advantages and disadvantages. They also have an impact on power quality in some way, either by improving power quality or by making it worse.

In this paper, the power quality of grid connected wind turbines is analysed. The features of wind turbines with respect to turbine regulation principles and electrical systems are described. Moreover, the proposed standard IEC 61400-21 is discussed [1] and the new recommendations in Denmark and Sweden concerning grid connections of wind turbines are described [2-3].

FEATURES OF WIND TURBINES

The power quality characteristics of wind turbines are determined by their regulation principles and the type of electrical system used.

Turbine Regulation Principles

The power output produced by the turbine is limited to the rated power of the generator at wind speeds from rated wind speed (normally 12-14 m/s) up to the shut-down wind speed (normally 20-25 m/s). Today, two different types of regulation principles are mainly used, stall-regulation or pitch-control.

Pitch-Control. Pitch-controlled wind turbines control the power by means of the pitch angle of the blades. Generally, advantages of this type of regulation are good power control, assisted start and built-in braking [4].

Good power control is that the mean value of the power output should be kept close to the rated power of the generator at high wind speeds. However, instantaneous power will fluctuate around the rated mean value of the power due to gusts and the speed of the pitch mechanism (i.e. limited bandwidth).

Stall-Regulation. Stall-regulation is the simplest regulation method. The angle of the blades is fixed and the power is controlled aerodynamically. This type of regulation has no assisted start [4]. From an electrical point of view, two aspects are worth mentioning: Since the power from the turbine is always controlled aerodynamically, stall-regulated wind turbines produce less fluctuating power than pitch-controlled turbines. Stall-regulated wind turbines do not have an assisted start, therefore, the power of the turbine cannot be controlled during the cut-in sequence.

Wind Gradient and Tower Shadow Effect

Regardless of the regulation principles used (stall-regulation or pitch-control) the power will fluctuate due to the wind gradient and the tower shadow. If the turbine has three blades, a power drop will occur three times per revolution of the turbine.

The turbine on the left in Fig. 1 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. In contrast, at the position of the right turbine in the figure one blade is at the top position and the two remaining blades are as far away from the tower shadow as possible.

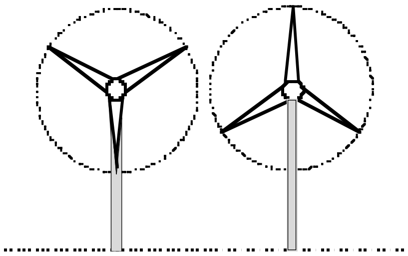

Fig. 1: Different rotor positions of a three-blade turbine. The tower shadow and the wind gradient both contribute to power fluctuations.

Electrical Systems in Wind Turbines

Electrical systems used in wind turbines can be divided into two main groups: fixed speed and variable speed.

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 set 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 generator having multiple windings. In this way, the generator can operate at different speeds. To avoid a large inrush current a soft starter is used to limit the current during the cut-in sequence [5].

The major disadvantage of this type of system is the power pulsation emanating from the wind gradient and tower shadow effects and the uncontrollable reactive power consumption of the induction generator. In order to compensate for the latter, shunt capacitor banks are used.

Variable-Speed Wind Turbines. Today several manufacturers are testing prototypes of variable-speed wind turbines. Only a few large manufacturers are mass-producing variable-speed wind turbines. If properly controlled, all kinds of variable-speed systems can reduce the power fluctuations emanating from the wind gradient and the tower shadow.

The electrical system becomes more complicated in the case of variable-speed operation. The variable-speed operation of a wind turbine can be obtained in many different ways, and different electrical systems are used for either a broad or a narrow speed range.

The most common arrangement today for a narrow speed range is to use controllable rotor resistances. A Danish manufacturer has produced a wind turbine where the slip of the induction generator, and thereby the speed of the rotor, can vary between 1 and 10%. The possibility of reducing power fluctuations emanating from the tower shadow is one advantage of this type of system. One drawback is the uncontrollable reactive power consumption.

Broad-range variable-speed systems are equipped with a frequency converter. The two most common types of inverters 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. A major drawback with line-commutated inverters is a poor power factor and a high content of harmonic current.

A forced-commutated inverter is normally equipped with Insulated Gate Bipolar Transistors (IGBT). In a forced-commutated inverter it is possible to choose a given power factor. Using Pulse Width Modulation (PWM) technique eliminates the low frequency harmonics and the first harmonic will then have a frequency around the switching frequency of the inverter. Hence, only a small grid filter will be needed because of the high switching frequency.

POWER QUALITY OF WIND TURBINES

Apart from uneven power production, other factors contribute to the power quality of wind turbines. IEC 61400-21 specifies the quantities characterising the power quality of a wind turbine. Measurement procedures for quantifying the characteristics are given, wind turbine requirements with respect to power quality are determined and methods for assessing wind turbine impact on power quality are suggested. Moreover, a procedure for determining the characteristics of the power output of a wind turbine, with respect to the impact on the voltage quality in a power system, is specified.

One of the characteristics of a wind turbine is the voltage variations caused by a start. Wind turbines normally cause a voltage drop during start-up. The voltage drop is mainly caused by reactive power consumption during magnetisation of the generator. Another power quality problem of wind turbines is the flicker emission produced during normal operation of the wind turbine. Flicker emission is mainly caused by variations in the produced power due to the wind gradient and the tower shadow effect.

Normal Operation

The power from wind turbines varies with wind speed. Since wind speed is not constant but varies with time, the power output also varies. Fig. 2 shows the measured active power under high wind speed conditions of a pitch-controlled fixed-speed wind turbine and a variable-speed wind turbine. In the figure, variations in the power produced by the wind turbines are shown. As previously mentioned, fixed-speed wind turbines produce power pulsation due to the wind gradient and the tower shadow.

In the figure, the power pulsation from the fixed-speed wind turbine is clearly visible. Such a power pulsation will cause voltage fluctuations on the grid, which in turn may cause flicker. The frequency of the power pulsation is equal to the number of blades multiplied by the rotational speed of the turbine.

The figure also indicates the power fluctuations caused by the pitch mechanism. Since the wind speed is not constant but varies due to gusts and turbulence, the output power will also vary due to the limited bandwidth of the pitch mechanism.

The power from the variable-speed wind turbine is smooth and does not show any power pulsation. Variable-speed wind turbines will, therefore, not have any flicker caused by such a pulsation.

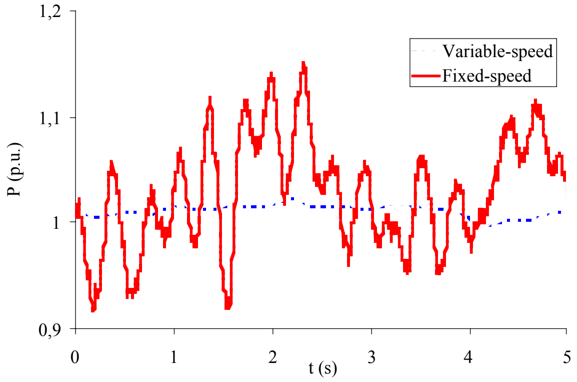

Fig. 2: Measured active power during normal operation of a pitch-controlled fixed-speed (solid line) and a variable speed (dotted line) wind turbine.

Standards. In order to determine the flicker emission produced by a wind turbine, measurements must be performed. 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. Two methods are proposed to overcome this problem. One is based on the measurement of active and reactive power, and the other method is based on the measurement 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.

Fig. 3 shows the short-term flicker emission, P_{st}, from a fixed-speed and a variable-speed wind turbine at different mean values of the produced power. The flicker is calculated using a PC-program developed by Risø National Laboratory [6]. This program uses IEC 60868, Amendment 1 to calculate the P_{st} [7-8]. The input to the program are time series of active and reactive power, short circuit power and the phase angle of the grid. In this particular case, a short-circuit power of 20 times the rated power of the wind turbine and a grid angle of 45 degrees are used. As can be seen in Fig. 3, for both types of turbines, the flicker emission P_{st} increases at higher wind speeds due to higher turbulence in the wind. At rated power the P_{st} is low at the variable-speed turbine due to the power control.

In order to calculate the flicker emission from a wind turbine connected to a specific grid, a flicker coefficient has to be determined. The flicker coefficient shall be specified for four different wind speed distributions with the annual average wind speed at hub heights of 6, 7.5, 8.5, and 10 m/s, respectively. The wind speed shall be assumed to be

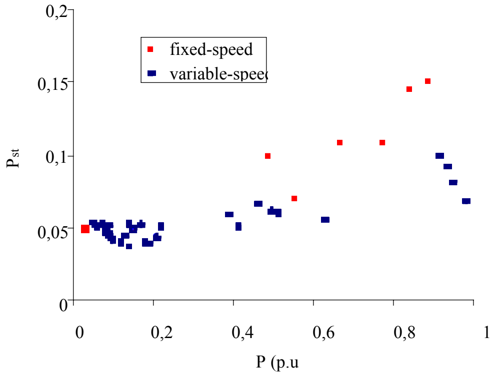

Fig. 3: Short term flicker emission Pst from a fixed-speed and a variable-speed wind turbine at different mean values of the produced power.

Rayleigh distributed. According to IEC 61400-21, the flicker coefficient from wind turbines shall be determined by applying:

$$c(\psi_k) = P_{st,fic}\frac{S_{k,fic}}{S_{ref}} \tag{1}$$

where $c(\psi_k)$ is the flicker coefficient and S_{ref} is the rated active 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:

$$\psi_k = \arctan\left(\frac{X_k}{R_k}\right) \tag{2}$$

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

$$P_{st} = c(\psi_k)\cdot\frac{S_{ref}}{S_k} \tag{3}$$

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

$$P_{st\Sigma} = \sqrt{\sum_i P_{st,i}^2} \tag{4}$$

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

Cut-in

The start sequences of variable-speed wind turbines and stall- and pitch-controlled fixed-speed wind turbines are all different. Generally, and due to the controllable speed of the turbine and the pitch-control, the cut-in sequence of variable-speed wind turbines is smoother than for fixed-speed wind turbines.

In fixed-speed wind turbines, the speed of the turbine increases during the starting sequence until the generator speed is close to the synchronous speed. The generator is, then, connected to the grid. As mentioned earlier, stall-regulated fixed-speed wind turbines do not have an assisted start. If the generator is not connected quickly, the turbine torque may exceed the maximum generator torque, thus, resulting in a turbine over-speed. Hence, the soft-starter on stall-regulated fixed-speed wind turbines normally operates during 10 line-periods which leads to a relatively high inrush-current.

In the case of pitch-controlled fixed-speed wind turbines, where the start is assisted, the torque of the turbine can be controlled. Hence, the cut-in of the generator can be performed in a smoother and more controlled way. The soft-starter in pitch-controlled turbines normally operates for two or three seconds, which gives a lower inrush current in comparison with a stall-regulated turbine.

Variable-speed wind turbines are normally equipped with pitch-control. Both the pitch-control and the speed control contribute to a smooth start. Fig. 4 shows the measured power during the cut-in of a pitch-controlled wind turbine with a controllable-slip.

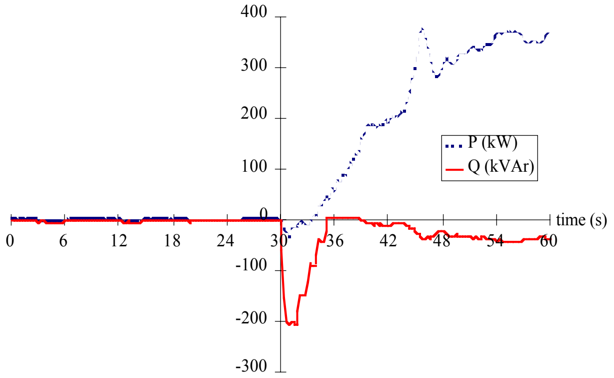

Fig. 4: Measured power during cut-in of a pitch-controlled wind turbine with controllable-slip. The rated power of the wind turbine is 600 kW. Active power (dotted line) and reactive power (solid line).

The wind turbine is cut-in at t=30 seconds. As can be seen, the wind turbine starts to consume reactive power in order to magnetise the generator. The soft-starter limits the reactive power for two or three seconds. The reactive power is, then, compensated by means of shunt capacitor banks. As can be observed, the capacitors are switched in four steps with a time delay of approximately 1 second.

In Fig. 5, the voltage of the wind turbine is shown for the same time period. The reactive power consumption causes a voltage drop. Once the capacitors are connected, the voltage increases.

Standards. According to the IEC 61400-21, measurements have to be performed for switching operations during wind turbine cut-in and when switching

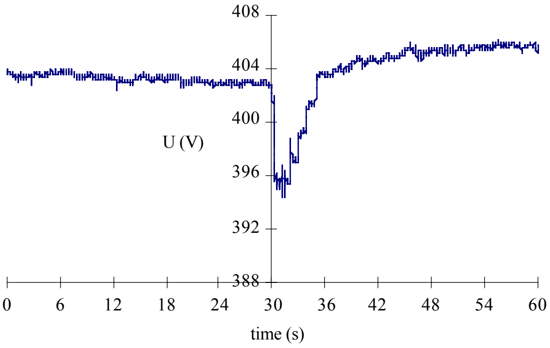

Fig. 5: Measured voltage during cut-in of a pitch-controlled wind turbine with controllable-slip.

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 shall be measured. Measurements and subsequent simulations and calculations shall 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:

$$\Delta U \leq k_u(\psi_k)\frac{S_{ref}}{S_k}\cdot 100 \qquad (5)$$

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 repeated numbers of voltage drops is calculated by [2]:

$$P_{lt} = \left(\frac{2{,}3\cdot N}{T}\right)^{\frac{1}{3{,}2}}\cdot F\cdot\frac{\Delta U}{U} \qquad (6)$$

where N is the number of voltage drops during T seconds. Since the equation refers to the 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 IEC 61000-3-7, [9].

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:

$$P_{lt} = 8\cdot k_f(\psi_k)\cdot(N)^{\frac{1}{3{,}2}}\cdot\frac{S_{ref}}{S_k} \qquad (7)$$

where $kf(\psi_k)$ 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.

Harmonics and Interharmonics

Fixed-speed wind turbines are not expected to cause significant harmonics and interharmonics. The standard IEC 61400-21 does not require specification of harmonics and interharmonics for this type of wind turbine.

For variable-speed wind turbines equipped with a converter the emission of harmonic currents during continuous operation shall be specified. These shall 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 is given in Table 1, [10]. The IEC 61800-3 further recommends the total harmonic distortion (THD) to be less than 5% of the fundamental rated current.

Table 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 for determining the harmonic currents from more than one source connected to a common point [11]

$$i_n = \sqrt[\alpha]{\sum_k i_{n,k}^{\alpha}} \qquad (8)$$

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 2. This recommendation is valid for wind farm applications.

Table 2: Exponent for harmonics.

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

RECOMMENDATIONS IN DENMARK AND SWEDEN

In both Denmark and Sweden, new recommendations regarding the grid connection of wind turbines have been accepted [2-3]. The two recommendations are quite similar and they are both derived from the proposed standard IEC 61400-21. The equations in the proposed standard have been revised in order to agree with the national standards concerning voltage quality.

In the recommendations, the impact from a wind turbine on the utility grid is determined from test results 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 number of switching operations for a period of two hours, the flicker coefficient and the harmonic content of the current. The test shall be performed in accordance with the proposed standard IEC 61400-21.

Steady-state Voltage

The steady-state voltage will vary in a grid from node to node depending on the connected loads and the production. In general, connecting loads to a grid will reduce the voltage, whereas connecting power producing units will increase the voltage. The following approximate relation can be used to calculate the percentage voltage drop:

$$\Delta U = \frac{R \cdot P + X \cdot Q}{U^2} \cdot 100 \qquad (9)$$

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 variation may not exceed 2,5% for a distribution feeder. If only wind turbines are connected to a feeder the voltage variation may not exceed more than 5%. In both cases the deadband of the voltage regulator of the transformer shall be taken into account.

Cut-in

According to Swedish Standard SS 421 18 11, the maximum voltage variation caused by a single motor start shall not exceed 4% [12]. This maximum voltage variation is directly applicable to wind turbines. Hence, the voltage step factor must be less than:

$$k_u(\psi_k) \leq \frac{4}{100} \cdot \frac{S_k}{S_{ref}} \qquad (10)$$

At low wind conditions, wind turbines may start and stop several times during a period of two hours. The long-term flicker emission, P_{lt}, produced by a repeated number of starts of a wind turbine is derived in Equation 7. The long-term flicker level from a single source in a medium-voltage distribution feeder may, according to the IEC 61000-3-7, not exceed P_{lt}=0,25 [9]. The required short-circuit power at the point of common connection must therefore, according to Equation 7, exceed

$$S_k \geq 32 \cdot N^{\frac{1}{3{,}2}} \cdot k_f(\psi_k) \cdot S_{ref} \qquad (11)$$

In Denmark and Sweden, the acceptable long-term flicker level is P_{lt}=0,5 if wind turbines are connected to their own feeder. The required short-circuit power at the point of common connection must, therefore, exceed

$$S_k \geq 16 \cdot N^{\frac{1}{3{,}2}} \cdot k_f(\psi_k) \cdot S_{ref} \qquad (12)$$

in the case of a feeder line to which only wind turbines are connected.

Normal Operation

The contribution to flicker from a wind turbine during normal operation was derived in Equation 3. Using the earlier mentioned emission levels for the long-term flicker, P_{lt}, the required short-circuit level at the point of common connection must exceed

$$S_k \geq 4 \cdot c(\psi_k) \cdot S_{ref} \tag{13}$$

in the case of a distribution feeder and

$$S_k \geq 2 \cdot c(\psi_k) \cdot S_{ref} \tag{14}$$

in the case of a feeder line to which only wind turbines are connected.

CONCLUSIONS

Different types of wind turbines are available on the market. The different types of wind turbines each have their advantages and disadvantages.

Fixed-speed wind turbine normally cause a voltage drop during start-up. The voltage drop is mainly caused by reactive power consumption during magnetisation of the generator. Another power quality problem of fixed-speed wind turbines is the flicker emission produced during normal operation of the wind turbine. Flicker emission is mainly caused by variations in the produced power due to the wind gradient and the tower shadow effect. Variable-speed wind turbines can reduce these power pulsation and will, therefore, not have any flicker caused by such a pulsation. A drawback with variable-speed wind turbines is the harmonic currents produced by the inverter. Consequently, in standards and recommendations concerning the grid connection of wind turbines, one should consider the type of wind turbine used.

In the IEC 61400-21, a procedure for determining the characteristics of the 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 proposed standard IEC 61400-21. The equations in the proposed standard have been revised in order to agree with national standards concerning voltage quality.

In the recommendations, the impact from a wind turbine on the utility grid is determined from 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.

ACKNOWLEDGEMENTS

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Paper 4B

Flicker Emission of Wind Turbines During Continuos Operations

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FLICKER EMISSION OF WIND TURBINES DURING CONTINUOUS OPERATION

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Abstract: This paper presents an analysis and the modelling of the flicker emission of wind turbines. Measurements compared with international standards are discussed. The paper concentrates on the theoretical aspects of the flicker algorithm, wind turbine characteristics and the generation of flicker during continuous operation of wind turbines.

Keywords: Flicker, Wind turbine, Power fluctuations.

I. INTRODUCTION

Among utilities wind power is sometimes considered to be a potential source for bad power quality. Uneven power production and weak connections due to long feeder lines are some of the factors behind this opinion. Not only the uneven power production but also other factors contribute to the power quality of wind turbines. One of these factors is flicker. Electrical flicker is a measure of the voltage variation which may cause disturbance for the consumer. Flicker emissions are not only produced during start-up, but also during the continuous operation of the wind turbine. The flicker emission produced during normal operation is mainly caused by variations in the produced power due to wind-speed variations, the wind gradient and the tower shadow effect. In areas where wind power is an emerging technology, some actions have been taken. One example is Germany, where power quality standards for grid connected wind turbines have been in use for some years. The German standard for grid connected wind turbines includes rules on power fluctuations and flicker.

The International Electrotechnical Commission, IEC, is currently working on power quality requirements for grid connected wind turbines. The work has resulted in a committee draft designated IEC 61400-21 [1]. This draft includes quantities to be specified for characterising the power quality of wind turbines and measurement procedures for quantifying the characteristics. Also wind turbine requirements with respect to power quality are given and methods for assessing wind turbine impact on power quality are suggested. The proposed standard pays particular attention to flicker. In addition to generic standards, flicker may become a serious limitation to wind power, at least in case of weak grids.

Flicker from wind turbines has become an important issue. A study of different types of wind turbines concluded that flicker emission in certain cases exceeds limits which are expected to be normative in the future [2]. In order to predict flicker produced by a wind turbine at the design stage, software tools are being developed [3][4]. For such software the physical dynamics of the turbine, the wind turbulence and the electrical dynamics of the generator and the network itself need to be modelled. The purpose of this paper is to provide a concise review of the analysis and modelling of the flicker emission of wind turbines, along with measurements and a comparison with international standards. This paper concentrates on the theoretical aspects of the flicker algorithm, wind turbine characteristics and flicker during continuous operation.

Section II in this paper provides a brief review of the flicker meter according to IEC Standard and the flicker algorithm. Section III presents the characteristics of the turbine. Finally, flicker during continuous operation is described in Section IV.

II. DESCRIPTION OF THE FLICKER METER

The level of flicker is quantified by the short-term flicker severity value P_{st}. The calculation of flicker severity takes into account the response of the light emission from incandescent lights to voltage variations and also the response of the human eye and brain in perceiving variations in illumination. The function and design of the flicker meter are specified in the Standard IEC Publication 868 [5]. The block diagram shown in Figure 1 describes the flicker meter architecture. Although the block diagram consists of five blocks, the flicker meter can be divided into two main parts, each performing one of the following tasks: (1) a simulation of the response of the lamp-eye-brain chain; and (2) an on-line statistical analysis of the flicker signal and presentation of the results. Blocks 2, 3 and 4 perform the first task while the second task is accomplished by block 5.

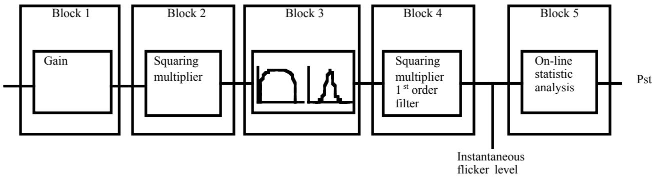

Fig. 1. Block diagram of the flicker meter.

”Block 1” performs the first step in the flicker meter. This block scales the input voltage to a reference level. ”Block 2” squares the input voltage in order to simulate the behaviour of a lamp. ”Block 3” is composed of a cascade of two filters where the first filter eliminates the D.C. and the double mains frequency. The second filter simulates the frequency response of voltage fluctuations of a light bulb combined with the human visual system. ”Block 4” is composed of a squaring multiplier and a first order low-pass filter with a time constant of 300 ms. Together they form a non-linear function. The output from ”Block 4” represents the instantaneous flicker level. ”Block 5” is the final flicker meter block, which makes an on-line statistical analysis of the instantaneous flicker level. The statistical analysis can be divided into two parts. First, the cumulative probability function of the instantaneous flicker level is established, and second, the short-term flicker severity value P_{st} is calculated using a multipoint method.

The cumulative probability function of the instantaneous flicker level from ”Block 4” gives percentages of observation time for which flicker levels have been exceeded. The cumulative probability, p(*l*), that the instantaneous flicker level exceeds *l* is defined as:

$$p(l) = \frac{t_l}{T} \tag{1}$$

where t_l is the duration of time which the signal remains above *l* and T is the total observation time. This method has been termed “time at level classification”. For practical purposes, only a limited number of p(l) curve points can be computed. The IEC 868 states that the analysis is to be performed with at least 6 bits resolution using at least 64 classes. The minimum sampling rate is 50 samples per second. After this classification, the short-term flicker severity value P_{st} is calculated using a multipoint method expressed by the equation:

$$P_{st} = 0{,}1 \cdot \sqrt{3{,}14P_{0,1} + 5{,}25P_{1s} + 6{,}57P_{3s} + 28P_{10s} + 8P_{50s}} \tag{2}$$

where the percentiles $P_{0,1}$, P_{1s}, P_{3s}, P_{10s} and P_{50s}, are the flicker levels exceeded for 0,1%, 1%, 3%, 10% and 50% of the time during the observed period, i.e., the instantaneous flicker levels exceeded for x% of the observed period. The suffix s in the equation indicates that the smoothed value should be used. These smoothed values are obtained by:

$$P_{1s}=(P_{0,7}+P_1+P_{1,5})/3 \tag{3}$$

$$P_{3s}=(P_{2,2}+P_3+P_4)/3 \tag{4}$$

$$P_{10s}=(P_6+P_8+P_{10}+P_{13}+P_{17})/5 \tag{5}$$

$$P_{50s}=(P_{30}+P_{50}+P_{80})/3 \tag{6}$$

The 300 ms time constant in ”Block 4” ensures that $P_{0,1}$ cannot change abruptly and no smoothing is needed for this percentile.

According to IEC standards the short-term flicker severity value P_{st} is based on a 10-min period. The short-term flicker severity evaluation is suitable for assessing disturbances caused by sources with a short duty-cycle. When flicker sources with long and variable duty-cycles are under consideration, it is necessary to provide a criterion for the long-term flicker severity. For this purpose, the long-term flicker severity, P_{lt}, is derived from the short-term severity values, P_{st}, using the formula:

$$P_{lt} = \sqrt[3]{\frac{\sum_{k=1}^{N} P_{st,k}^{3}}{N}} \tag{7}$$

where $P_{st,k}$ are consecutive readings of the short-term severity P_{st}. The long-term flicker severity value P_{lt} is calculated for N=12, i.e., a 2 hour period.

The method for measuring instantaneous flicker and the algorithm required for calculating P_{st} are rather complicated. A general analytical method of calculating P_{st} is not possible to find. However, there are methods for determining the total sum of flicker from a set of known flicker sources. In the Standard IEC Publication 61000-3-7 the following general relation for short-term flicker severity caused by various loads is stated [6]:

$$P_{st} = \sqrt[m]{\sum_{i} P_{st,i}^{m}} \tag{8}$$

where Pst,i is the individual level of flicker severity values from source i and m is a coefficient which depends upon the characteristics of the main source of fluctuation. If the fluctuation is coincident stochastic noise m=2 should be used.

III. TURBINE CHARACTERISTICS

Wind turbines have some kind of control for regulating the power from rated wind-speed up to the shutdown wind-speed. Today, two different types of regulation principles are mainly used; stall-regulation and pitch-control. Regardless of the regulation principle used, the power will fluctuate due to wind-speed variations, the wind gradient and the tower shadow effect. If the turbine has three blades, a power drop will appear three times per revolution. This frequency is normally referred to as 3-p. A two-blade and a three-blade wind turbine have been studied in [7]. Both turbines are pitch-controlled and operate at fixed speed. For both wind turbines studied, the greatest power pulsation occurs at rated power at the highest wind-speeds. According to [8], wind turbines equipped with induction generators operating at fixed speed generate power pulsations up to 20% of the average power.

Pitch-controlled turbines will also have power fluctuations caused by the limited bandwidth of the pitch mechanism in addition to fluctuations caused by the tower shadow. The power of pitch-controlled wind turbines is controlled by the angle of the blades. This means that the steady-state value of the power output should be kept close to the rated power of the generator at high wind-speeds, normally between 12-14 m/s to the cut-off wind-speed at 20-25 m/s. This is achieved by means of pitching the blades. The steady-state value of the power (solid line) as a function of wind-speed is shown in Fig. 2. The steady-state value of the power is, as illustrated in the figure, kept equal to rated power at wind-speeds above 12 m/s. However, pitching the blades implies that the power curve is transferred. This is illustrated in Fig. 2 where the dotted line shows the instantaneous power curve when the blades are pitched for rated power at a wind-speed of 15 m/s.

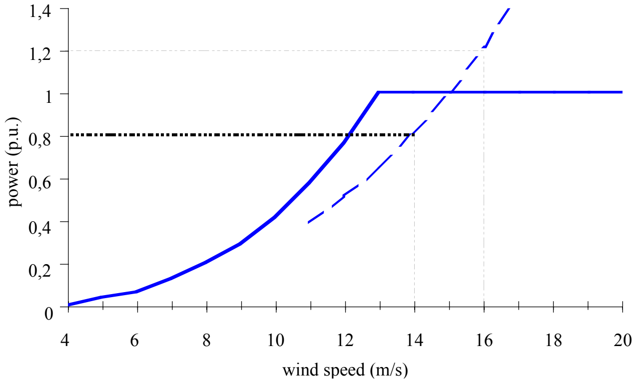

Fig. 2. Power as function of wind-speed from a pitch-controlled wind turbine.

Unfortunately, the wind-speed is not constant but varies all the time. Hence, instantaneous power will fluctuate around the rated mean value of the power due to gusts and the speed of the pitch mechanism (i.e., limited bandwidth). As can be seen in Fig. 2, variations in wind-speed of ± 1 m/s gives power fluctuations having a magnitude of ± 20%. Fig. 3 shows the power from a stall-regulated turbine under the same conditions as the pitch-controlled turbine in Fig.2. Variations in the wind-speed of the stall-regulated turbine also cause power fluctuations but they are small in comparison with a pitch-controlled turbine.

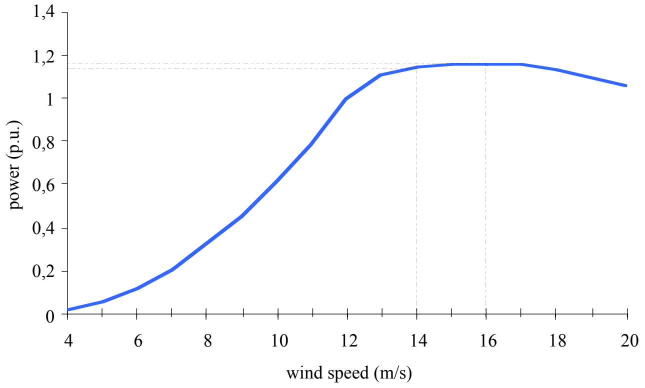

Fig. 3. Power as function of wind-speed from a stall-regulated wind turbine.

Fig. 4 shows the measured power of a pitch-controlled fixed-speed wind turbine with a rated power of 225 kW under high wind-speed conditions. In the figure, variations in the power produced by the wind turbine is shown. As previously mentioned, fixed-speed wind turbines produce power pulsations due to wind speed gradients and the tower shadow.

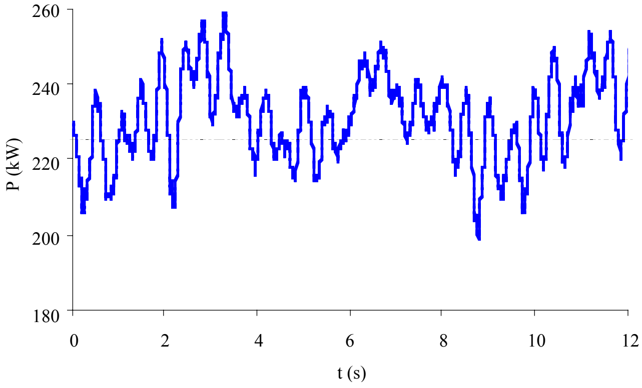

Fig. 4. Measured power during normal operation of a pitch-controlled fixed-speed wind turbine (solid line). In the figure also the steady-state power is plotted (dotted line).

The frequency of the power pulsations is equal to the number of blades multiplied by the rotational speed of the turbine, e.g., the 3-p frequency. The figure also indicates the power fluctuations caused by wind gusts and the speed of the pitch mechanism.

IV. FLICKER DURING CONTINUOUS OPERATION

The committee draft of IEC 61 400-21 suggests that the flicker from a single source should not be determined from voltage measurements, in order to avoid disturbance due to the background flicker on the grid. The method proposed for overcoming this problem is based on measurements of current and voltage. The short-term flicker from the wind turbine should be calculated using a reference grid where the measured current is the only load on the grid. This procedure is performed in two steps. First, the measured time-series of the current are used to calculate the time-series of voltage variations on the fictitious grid by the following equation:

$$u_{fic}(t) = u_0(t) + R_{fic}(t) \cdot i_m(t) + L_{fic}(t) \cdot \frac{di_m(t)}{dt} \qquad (9)$$

where $u_0(t)$ is an ideal voltage source, R_{fic} and L_{fic} is the resistance and the inductance of the fictitious grid, respectively. $i_m(t)$ is the measured instantaneous current. The ideal voltage source shall be given by:

$$u_0(t) = \sqrt{\frac{2}{3}} U_n \sin(\alpha_m(t)) \qquad (10)$$

where U_n is the rms value of the nominal voltage of the grid and $\alpha_m(t)$ is the electric angle of the fundamental of the measured voltage. Second, the voltage variation $u_{fic}(t)$ is used as an input to the flicker algorithm in compliance with the Standard IEC Publication 868.

Fig. 5 shows the short-term flicker at different cut-off frequencies of a fixed-speed wind turbine and a variable-speed wind turbine. Different cut-off frequencies have been achieved by means of filtering the measured time series in an 8th order Butterworth filter at different cut-off frequencies. For both wind turbines a short circuit ratio (SCR) of 20 and a phase angle of 45° has been used. The SCR is defined as the ratio between the short circuit power of the grid and the rated power of the wind turbine at the point of common connection (PCC). The phase angle is the tangent of ratio between the network reactance and the resistance. The short-term flicker has been calculated using a PC-program developed by Risø National Laboratory [9]. This program uses the Standard IEC Publication 868 with amendment 1 to calculate P_{st} [10]. The input to the program is a time series of active and reactive power, short circuit power and phase angle of the grid.

As shown in Fig.5, the calculated short-term flicker is considerably higher for the fixed-speed wind turbine as for the variable-speed wind turbine. At high cut-off frequencies the short-term flicker is 0.163 for the fixed-speed wind turbine and 0.051 for the variable-speed wind turbine. It is worth noting that approximately 30% of the total flicker emission produced by the fixed-speed wind turbine depends on power variations with a frequency above the 3-p frequency (2.15 Hz) of the turbine. This flicker contribution over the 3-p frequency emanates from the mechanical properties of the wind turbine, most likely the dynamics of the induction generator. This is due to the flicker curve and the dynamics of the induction generator. The flicker curve is most sensitive at 8.8 Hz and the dynamics of the induction generator have a resonance frequency of approx. 10 Hz. The flicker contribution from the variable-speed wind turbine is quite different. The variable-speed system has the ability to reduce 3-p pulsations from the turbine but the mechanical properties of the wind turbine seem to contribute to a higher flicker level at frequencies of approx. 10 Hz. As can be seen in Fig.5, the cut-off frequency of the measured time series from a wind turbine must exceed 50 Hz in order to achieve a good result.

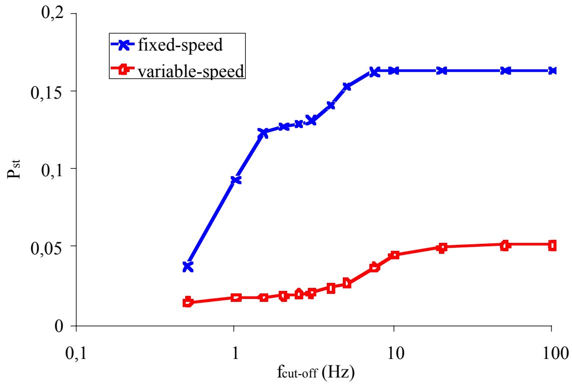

Fig. 5. Short-term flicker from a fixed-speed wind turbine and a variable-speed wind turbine calculated at different cut-off frequencies. The cut-off frequency has a logarithmic scale.

Fig. 6 shows the short-term flicker emission Pst from a fixed-speed and a variable-speed wind turbine at different power. The flicker is calculated using an SCR of 20 and a grid angle of 45°, i.e., the same conditions as the wind turbines presented in Fig. 5. As can be seen in Fig. 6, the flicker emissions increase at higher wind-speeds due to higher turbulence in the wind.

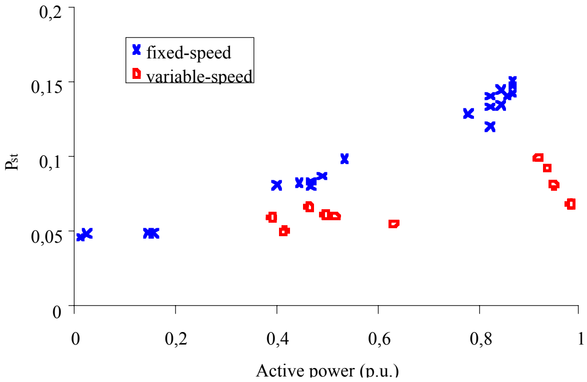

Fig. 6. Short term flicker from a fixed-speed and a variable-speed wind turbine at different power. The flicker emission P_{st} increases at higher wind-speeds due to higher turbulence in the wind.

In the case of the fixed-speed wind turbine, the flicker increases around three times from lower to higher wind-speeds. Even in the case of the variable-speed wind turbine, the flicker increases with an increase in wind-speed. Except for the flicker level, there is one fundamental difference between the fixed-speed and the variable-speed wind turbines. The flicker level increases at increasing wind-speed for the fixed-speed turbine while the flicker level decreases at rated wind-speed for the variable-speed wind turbine. As the wind turbine reaches rated power, the variable-speed system will smooth out the power fluctuations and, thereby, limit the flicker. However, the flicker level should be based on an annual wind speed distribution. Hence, flicker must be measured at all wind-speeds.

A. Flicker Coefficient

According to the committee draft of IEC 61 400-21 the flicker coefficient from wind turbines is to be determined by measurements and simulations. The three instantaneous phase currents and the three instantaneous phase-to-neutral voltages are to be measured at the wind turbine terminals. The cut-off frequency of the voltage and current measurement must be at least 400 Hz. Measurements are to be taken so that at least thirty ten-minute time-series of instantaneous voltage and current measurement are collected for each 1 m/s wind-speed bin between cut-in wind speed to a wind speed of 2 m/s above reference wind speed. The voltage time-series $u_{fic}(t)$ for each set of ten-minute measured voltage and current time-series are then to be calculated using (9) and (10). The voltage time-series $u_{fic}(t)$ is to be used as input to the flicker algorithm to give one flicker value $P_{st,fic}$ on the fictitious grid for each ten-minute time-series. The flicker coefficient is to be determined for each of the calculated flicker values by applying:

$$c(\psi_k) = P_{st,fic} \frac{S_{k,fic}}{S_{ref}} \tag{11}$$

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 level calculated at the short-circuit power level of a fictitious reference grid $S_{k,fic}$ defined as:

$$S_{k,fic} = \frac{U_n^2}{\sqrt{R_{fic}^2 + X_{fic}^2}} \tag{12}$$

The phase angle, ψ_k, of the fictitious grid is defined as:

$$\tan(\psi_k) = \frac{X_{fic}}{R_{fic}} \tag{13}$$

The flicker emission produced by a wind turbine connected to a grid with an arbitrary short-circuit power S_k may, then, be recalculated by:

$$P_{st} = c(\psi_k) \frac{S_{ref}}{S_k} \tag{14}$$

Fig. 7 shows the short-term flicker from a wind turbine calculated at different SCRs. The short-term flicker Pst in the figure has been calculated in two different ways: (1) by measurements and (9) on a reference grid using different SCRs (this method is called P_{st} in Fig. 7); (2) by using (11) and (14) according to the committee draft of IEC 61 400-21 (called IEC in Fig. 7). As can be seen in the figure, the two different methods for calculating Pst values agree well with each other.

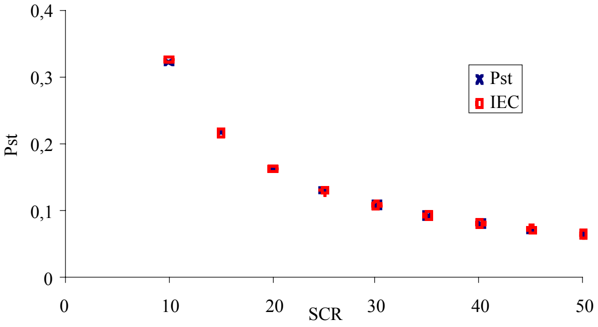

Fig. 7. Short-term flicker emission from a wind turbine calculated at different SCRs. The Pst dots are calculated directly by using measurements and the IEC dots by using equations according to the committee draft of IEC 61 400-21.

B.) Summation of Flicker

Wind turbines are often placed close to each other, e.g., in wind parks. Wind turbines located in a wind park will experience approximately the same mean value of the wind-speed. The mean value of the power from the wind turbines will, therefore, be correlated.

The flicker produced by each wind turbine during continuous operation emanates, as mentioned earlier, mainly from the tower shadow effect and wind turbulence. Since the wind turbines are not located on exactly the same place, but close to each other, they will not experience the same wind-speeds on the rotor disks. The variations in the wind-speeds and the position of the rotors are, therefore, not correlated. The power fluctuations and the flicker of two or more wind turbines are expected to be uncorrelated stochastic noise. Hence, according to the Standard IEC Publication 61000-3-7 (8) should be used to sum the total flicker during normal operation. Fig. 8 shows the calculated short-term flicker from thirty different measured time series of two fixed-speed wind turbines and ten different measured time series of two variable-speed wind turbines. The short-term flicker is calculated in two different ways. First, directly by using the sum of the measurements from each wind turbine, called $P_{st,tot}$ in Fig. 8. Second, by using the short-term flicker from each wind turbine and the summation law according to (8) with m=2, called $P_{st,IEC}$ in Fig. 8.

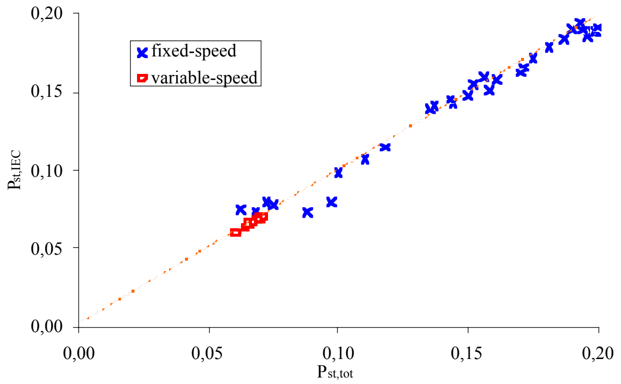

Fig. 8. Calculated short-term flicker from thirty different measured time series of two fixed-speed wind turbines (cross) and ten different measured time series of two variable-speed wind turbines (circle).

As can be seen in Fig. 8, the short-term flicker varies due to variations in the wind, i.e., turbulence. The mismatch of the two different ways of calculating the flicker (i.e., deviation from the dotted line), however, is small. The correlation coefficient, r=0.994.

According to the committee draft of IEC 61 400-21 the following equation is to be applied in determining the flicker contribution from a number of wind turbines connected to a common point:

$$P_{st\Sigma} = \sqrt{\Sigma P_{st,i}^{2}} \qquad (14)$$

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

V. CONCLUSIONS

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

The method for measuring instantaneous flicker and the algorithm required for calculating P_{st} is rather complicated. A general analytical method of calculation for determining the short term flicker P_{st} from a set of arbitrarily chosen voltage disturbances is not possible.

The committee draft of IEC 61 400-21 suggests that the flicker emission from a single wind turbine should be determined by measurements. The measurements should not be based on voltage measurements only, in order to avoid the measurements from being disturbed by the background flicker on the grid. The method proposed for overcoming this problem is based on measurements of current and voltage. The short-term flicker emission from the wind turbine should be calculated on a reference grid using the measured current as the only load on the grid.

Finally, a flicker coefficient is introduced. The use of the flicker coefficient makes it possible to calculate the flicker produced by the wind turbine connected to a grid with an arbitrary short-circuit power.

VI. ACKNOWLEDGEMENT

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VIII. BIOGRAPHY

Åke Larsson received his M.Sc. in electrical engineering from the Chalmers University of Technology, Göteborg, Sweden in 1994. At present, he is working towards the Ph.D. at Chalmers University of Technology in the area of electrical machines and power electronic. His research interests include power quality from wind turbines.

Paper 4C

Flicker Emission of Wind Turbines Caused by Switching Operations

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FLICKER EMISSION OF WIND TURBINES CAUSED BY SWITCHING OPERATIONS

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Abstract: This paper 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.

Keywords: Flicker, Wind Turbine, Start, Stop.

I. INTRODUCTION

Wind power is among the utilities considered to be potential sources for bad power quality. Uneven power production and, often, connections at the end of long feeder lines are some of the factors behind the statement. Not only the uneven power production from wind turbines but also other factors contribute to the power quality of wind turbines. One such factor is flicker. Electrical flicker is a measure of voltage variations which may cause disturbances to consumers. Flicker is outlined in Standard IEC Publication 868 [1].

Flicker from grid connected wind turbines has been the subject of several investigations. Most of these investigations have focused on flicker during the continuous operation of wind turbines. For example, different types of computer models for predicting flicker during continuous operation have been developed [2][3]. Published work presenting results from the IEC also only deal with flicker due to continuous operation [4]. Flicker produced during continuous operation is caused by power fluctuations. Power fluctuations 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.

In addition, switching operations will produce flicker, except in continuous operation. Typical switching operations are the start and stop of wind turbines.

This paper describes the start of wind turbines, the flicker produced during start and a comparison of flicker limitations at wind parks. Measurements of the start and stop of wind turbines are presented in Section II of the paper. This section also describes the different methods used at start and stop by stall-regulated and pitch-control, fixed-speed as well as variable-speed wind turbines. Section III presents equations for flicker caused by switching operations. Finally, Section IV presents an investigation of flicker limitation at wind parks. In this investigation flicker produced during continuous operation is compared to flicker caused by switching operations. The investigation covers stall-regulated and pitch-control, fixed-speed as well as variable-speed wind turbines.

II. FLICKER DURING SWITCHING OPERATIONS

Switching operations will produce flicker. Typical switching operations are the start and stop 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. Hence, even switching operations must be considered in wind turbine grid design.

A. Starting sequence

The starting sequences of variable-speed and fixed-speed wind turbines are 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.

1) Fixed-speed

With fixed-speed wind turbines, the speed of the turbine is raised during the starting sequence until the generator speed is close to the synchronous one. The generator is then connected to the grid. In the case of a stall-regulated turbine the generator must be connected quickly. If the generator is not connected quickly, the turbine torque may exceed the maximum generator torque resulting in a turbine over-speed. Hence, the soft-starter on stall-regulated turbines normally operates for 0.2 seconds which leads to a relatively high in-rush current.

In the case of pitch-controlled wind turbines, the torque of the turbine can be controlled. Hence, the start of the generator can be performed in a smoother and more controlled way. The soft-starter in pitch-controlled turbines normally operates for two or three seconds, which gives a lower in-rush current compared with a stall-regulated turbine. Fig. 1 shows the measured power during the start of a pitch-controlled wind turbine at t=30 s.

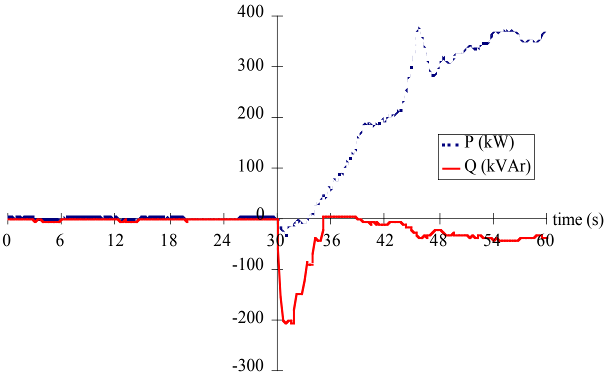

Fig. 1. Measured power during start of a fixed-speed, pitch-controlled wind turbine. The rated power of the wind turbine is 600 kW. Active power (dotted line) and reactive power (solid line).

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 being switched in four steps with a time delay of approximately 1 second. As all capacitor banks have been switched on at approx. t=35 s., the blade of the turbine is pitched which results in an increase in power production. The power production also affects the reactive power consumption. The reactive power consumption of induction generators increases with increased power.

In Fig. 2, the corresponding voltage of the wind turbine is shown. The voltage change caused by the start of the wind turbine can be divided into 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 being connected and the reactive power consumption goes 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 starts to rise.

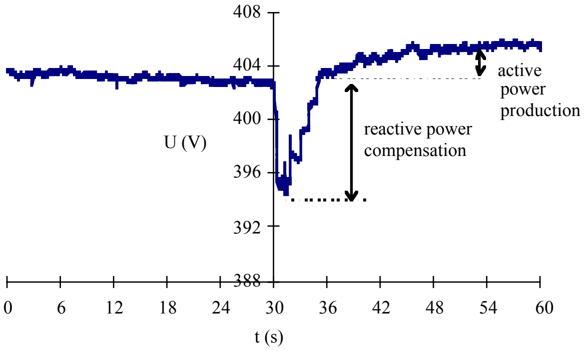

Fig. 2. Measured voltage during start of a fixed-speed pitch-control wind turbine.

2) Variable-speed

Figure 3 shows the active and reactive power during the start of a variable-speed wind turbine under high wind-speed conditions. The generator is connected to the grid via the converter at the time t=30 s. The active power rises smoothly and gently from zero to half the rated power in 30 s. During the time the active power rises, the reactive power is controlled in order to keep the power factor constant. At this particular site, a power factor of 0.98 has been chosen.

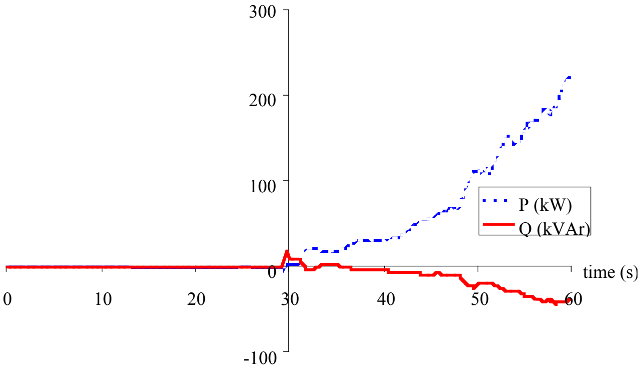

Fig. 3. Measured power during start of a variable-speed wind turbine. The rated power of the wind turbine is 500 kW. Active power (dotted line) and reactive power (solid line).

B. Shutting down

If the wind-speed becomes either too low or too high, the wind turbine will stop automatically. In the first case the wind turbine will be stopped in order to avoid a negative power flow. In the second case it will be stopped to avoid high mechanical loads. At low wind speeds (3-4 m/s) the active power is almost zero. The stop will be rather soft and the impact on the voltage in the point of common connection, PCC, small at these low wind speeds. The impact may be more significant at high wind speeds (>25 m/s) since the turbine on these occasions produces rated power. When the turbine is being stopped and the power goes from rated power to zero production, then, the voltage at the PCC will be affected.

1) Fixed-speed

Figure 4 shows the stop of a stall-regulated wind turbine with a rated power of 600 kW. The power production is approximately half of the rated at the time the turbine is stopped. As the wind turbine is being stopped the capacitor bank for reactive power compensation is switched off. After a couple seconds is the turbine speed reduced by means of brakes. As can be seen in Fig. 4, the turbine is being braked at the time t=15 s. In order to secure the stop of the turbine, the generator is disconnected when the power is reversed.

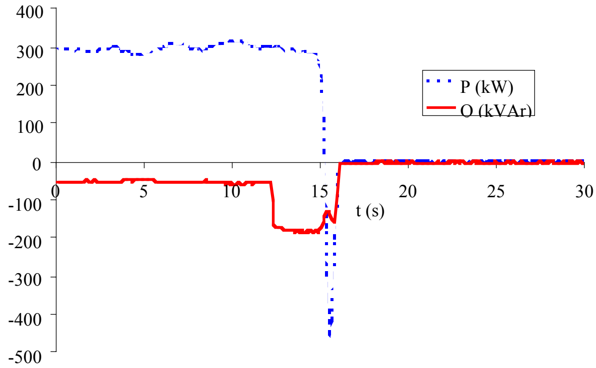

Fig. 4. Measured power during stop of a fixed-speed, stall-regulated wind turbine. The rated power of the wind turbine is 600 kW. Active power (dotted line) and reactive power (solid line).

2) Variable-speed:

Figure 5 shows the stop of a variable-speed wind turbine under high wind conditions. The wind turbine is operated at rated power. The power from the wind turbine begins to decrease at the time, t=6 s. Four seconds later, the power has decreased from rated power down to zero. The stop is, just as in the case with the start, very gentle and smooth.

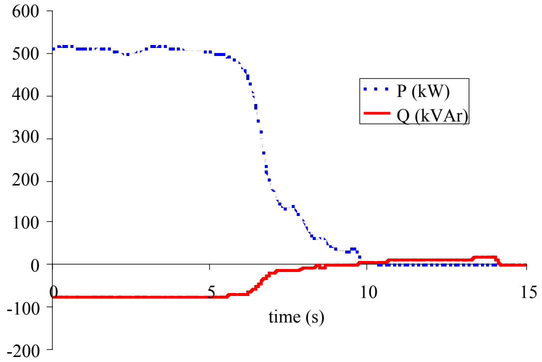

Fig. 5. Measured power during stop of a variable-speed wind turbine. The rated power of the wind turbine is 500 kW. Active power (dotted line) and reactive power (solid line).

III. FLICKER CALCULATION

The Standard IEC Publication 61000-3-3 describes a method to determine flicker from a limited number of independent voltages changes [5]. The time duration between the end of one voltage change and the start of the next one must exceed 1 second. Under such conditions the long-term flicker may be expressed as:

$$P_{lt} = \sqrt[3.2]{\frac{\sum_i 2.3\left(F_i \cdot d_i\right)^{3.2}}{T}} \qquad (1)$$

where d_i is the maximum relative voltage change in percent and F_i is a form factor of the i^{th} voltage change. F_i is one in case of a step function. T is the observed time period in seconds.

The voltage drop caused by a single start of a wind turbine may be determined by:

$$\Delta U = I_{start} \cdot Z \qquad (2)$$

where I_{start} is the current during start and Z is the short circuit impedance of the grid defined as:

$$Z = \frac{U}{I_k} \qquad (3)$$

where U is the voltage of the grid and I_k is the three phase short-circuit current. Hence, the relative voltage change in percent can be expressed as:

$$d = \frac{\Delta U}{U} \cdot 100\% = \frac{I_{start}}{I_k} \cdot 100\% \qquad (4)$$

Equation (4) can be expressed as:

$$d = \frac{I_{start} \cdot I_n \cdot U}{I_k \cdot I_n \cdot U} \cdot 100 = k_i \cdot \frac{S_{ref}}{S_k} \cdot 100 \qquad (5)$$

where k_i is the ratio between the starting current I_{start} and the rated current I_n. S_{ref} is the reference power of the wind turbine and S_k is the short-circuit power at the PCC.

If all voltage drops have the same form, F, and the same maximum relative voltage change, d, (1) can be rewritten as:

$$P_{lt} = \left(\frac{2.3 \cdot N}{T} \right)^{\frac{1}{3.2}} \cdot F \cdot d \qquad (6)$$

where N are the total number of voltage drops. Equation (6) can, by means of (5), be expressed as:

$$P_{lt} = \left(\frac{2.3 \cdot N}{T} \right)^{\frac{1}{3.2}} \cdot F \cdot k_i \cdot \frac{S_{ref}}{S_k} \cdot 100 \qquad (7)$$

The long-term flicker, P_{lt}, is calculated for 2 hours, that is 7 200 seconds. If the case of a step change in the voltage then F=1. Equation (7) can then be written as:

$$P_{lt} = \left(\frac{2.3 \cdot N}{7200} \right)^{\frac{1}{3.2}} \cdot 1 \cdot k_i \cdot \frac{S_{ref}}{S_k} \cdot 100 \approx 8 \cdot N^{\frac{1}{3.2}} \cdot k_i \cdot \frac{S_{ref}}{S_k} \qquad (8)$$

where N should be the number of possible starts within a period of 2 hours. If more than one wind turbine of the same type is connected at the PCC, N should be the total number of all starts.

Equation (8) is based on the fact that the same type of wind turbine being connected to the PCC. On the assumption that two different types of wind turbines are connected to the PCC, one wind turbine will have maximum relative voltage changes d_1 with a form factor F_1, and the other wind turbine will have maximum relative voltage changes d_2, with a form factor F_2. Equation 1 can be expressed as:

$$P_{lt} = \sqrt[3.2]{\frac{2.3 \cdot N_1 (F_1 d_1)^{3.2}}{T} + \frac{2.3 \cdot N_2 (F_2 d_2)^{3.2}}{T}} \qquad (9)$$

Analogous to (6), (9) can be written as:

$$P_{lt} = \sqrt[3.2]{\left[\left(\frac{2.3 N_1}{T} \right)^{\frac{1}{3.2}} F_1 d_1 \right]^{3.2} + \left[\left(\frac{2.3 N_2}{T} \right)^{\frac{1}{3.2}} F_2 d_2 \right]^{3.2}} \qquad (10)$$

which is equal to:

$$P_{lt} = \sqrt[3.2]{P_{lt,1}^{3.2} + P_{lt,2}^{3.2}} \qquad (11)$$

or more general:

$$P_{lt} = \sqrt[3.2]{\sum_k P_{lt,k}^{3.2}} \qquad (12)$$

According to the committee draft of the IEC 61400-21, measurements are to be performed for switching operations during wind turbine start and switching between generators [6]. 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 calculation are to be prepared to determine a voltage change factor, k_u, and a 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:

$$\Delta U \le k_u(\psi_k) \frac{S_{ref}}{S_k} \cdot 100 \qquad (13)$$

where $k_u(\psi_k)$ is the voltage change factor calculated at the grid angle ψ_k.

Wind turbines may start and stop several times under low wind conditions. In the committee draft of the IEC 61400-21, a flicker is an introduced step factor. The flicker step factor is calculated from the measured voltage drop caused by the start of the generator. The flicker step factor is calculated according to the following definition:

$$k_f(\psi_k) = \frac{1}{100} \cdot \left(\frac{60}{2.3} \right)^{\frac{1}{3.2}} \cdot \frac{S_k}{S_{ref}} \cdot P_{st} \qquad (14)$$

where $k_f(\psi_k)$ is the flicker step factor calculated at a grid with short circuit power S_k and P_{st} is the short-term flicker value. The flicker emission caused by a repeated number of starts of the wind turbine can, then, be determined by using the flicker step factor as:

$$P_{lt} = 8 \cdot k_f(\psi_k) \cdot N^{\frac{1}{3.2}} \cdot \frac{S_{ref}}{S_k} \qquad (15)$$

where $k_f(\psi_k)$ is the flicker step factor calculated at the grid angle ψ_k, N is the maximal number of switching operations during a period of two hours. One advantage of using a definition of the flicker step factor according to (15) is that the flicker caused by a repeated number of starts can be calculated using the same equation as k_i in (8).

IV. FLICKER FROM WIND PARKS

In order to reduce costs and to utilize land in windy areas wind turbines are often placed in wind parks. All wind turbines in a wind park are normally connected to the same PCC. The grid at the PCC must, therefore, be designed to withstand the total flicker disturbance produced by all the wind turbines in the wind park. Wind turbines produce flicker at continuous operation, as well as at switching operations. Switching operations do not occur during continuous operation. Flicker during continuous operation may, therefore, be calculated independent of the flicker caused by switching operations. Hence, the dimensioning parameter for the grid, due to flicker, is the operating mode requiring the highest short circuit ratio, SCR. SCR is defined as the ratio of the short circuit power of the grid at PCC and the total reference power of the installed wind turbines.

Just as in switching operations, flicker is produced during the continuous operation of wind turbines as defined in the committee draft of the IEC 61400-21. If the same kind of wind turbines are used in a wind farm, the SCR can be calculated as:

$$\frac{S_k}{S_{ref}} = \frac{1}{P_{lt}} \cdot c_f(\psi_k) \cdot \sqrt{k} \tag{16}$$

where $c_f(\psi_k)$ is the flicker coefficient and S_{ref} is the reference power of one wind turbine. k is the total number of turbines connected to the PCC. P_{lt} is the maximum acceptable flicker emission level in the PCC. The required SCR at the PCC, as shown in Equation 16, increases with the square root of the number of wind turbines.

The required SCR at switching operation, according to (8) and (12) is similar:

$$\frac{S_k}{S_{ref}} = 8 \cdot \frac{1}{P_{lt}} \cdot k_f(\psi_k) \cdot N^{\frac{1}{3.2}} \cdot \sqrt[3.2]{k} \tag{17}$$

According to (17), the required SCR at the PCC increases with a little more than the cubic root of the number of wind turbines.

Figure 6 shows the required SCR to obtain P_{lt}=1 at the PCC. The required SCR has been plotted as a function of the number of wind turbines for flicker produced during continuous operation and caused by switching operations, i.e., (16) and (17).

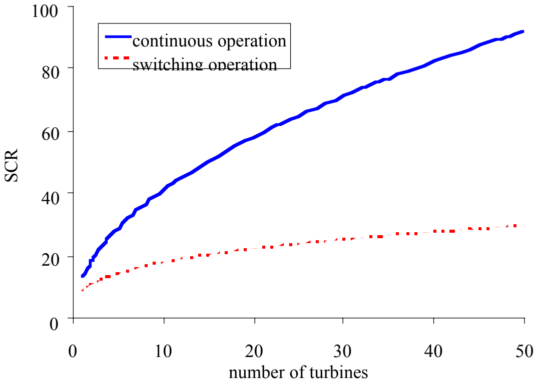

Fig. 6. Calculated SCR as a function of number of pitch-controlled, fixed-speed wind turbines due to continuous operation (solid line) and switching operations (dotted line).

As can be seen in Fig. 6, flicker produced during continuous operation will need a higher SCR than flicker caused by switching operations. The parameters in this particular case are taken from a Danish manufactured, 600 kW, pitch-controlled wind turbine, having a flicker coefficient c_f=13 and a flicker step factor k_f=0.5. The parameters used in Fig. 6 are typical for pitch-controlled, fixed-speed wind turbines, i.e., a rather high flicker coefficient and a rather low flicker step factor. The high flicker coefficient is mainly due to the wind gradient, the tower shadow effect and power fluctuations caused by the limited bandwidth in the pitch mechanism. The power fluctuations from pitch-controlled turbines are almost twice the power fluctuations from stall-regulated turbines [7]. The low flicker step factor is mainly due to the controllable torque from the turbine during start.

The parameters for stall-regulated, fixed-speed wind turbines are normally the very opposite. Stall-regulated turbines have a lower flicker coefficient and a higher flicker step factor compared to pitch-controlled turbines. The high flicker step factor is caused by the uncontrollable torque during start, and the low flicker coefficient is due to low power fluctuations. Fig. 7 shows the required SCR for obtaining P_{lt}=1 at the PCC. The required SCR has been plotted as a function of the number of stall-regulated, fixed-speed wind turbines for flicker produced both during continuous operation and switching operations, i.e., the same conditions as in Fig. 6. The SCR needed to prevent high flicker levels is, as a result of the high flicker step factor set by switching operations. The parameters used is taken from a Danish manufactured, 600 kW, stall-regulated wind turbine, having a flicker coefficient c_f=6 and a flicker step factor k_f=1.3.

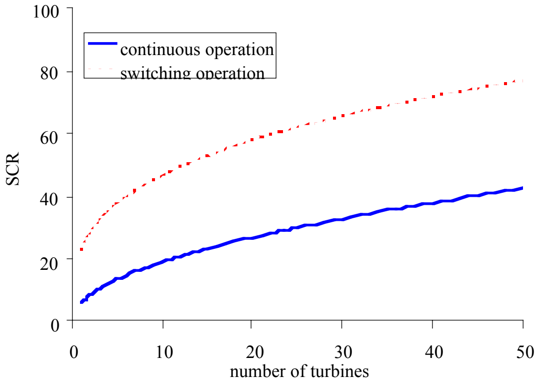

Fig. 7. Calculated SCR as a function of number of stall-regulated fixed-speed wind turbines due to continuous operation (solid line) and switching operations (dotted line).

The required SCR needed to prevent flicker disturbances produced by different numbers of stall-regulated and pitch-controlled fixed-speed wind turbines is plotted in Fig. 8. As shown in Fig. 7 is the SCR decided by switching operations in the case of stall-regulated turbines. In the case of pitch-controlled turbines the SCR is, as shown in Fig. 6, decided by continuous operation.

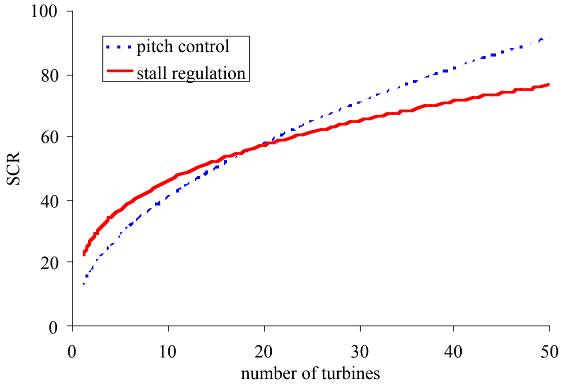

Fig. 8. Calculated SCR as a function of number of turbines due to flicker from stall-regulated and pitch-controlled fixed-speed wind turbines.

If a wind park consists of a small number of fixed-speed wind turbines stall-regulated turbines, due to uncontrollable torque during start, will produce higher flicker emission, compared to pitch-controlled turbines. If the number of fixed-speed wind turbines is high, pitch-controlled turbines will produce higher flicker emissions.

V. CONCLUSIONS

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 start of the generator can be performed in a smooth and controlled way. The soft-starter in pitch-controlled turbines normally operates for two or three seconds which gives a lower inrush current compared with a stall-regulated, fixed-speed turbine. Generally, due to the controllable speed of the turbine and the pitch-control, the start sequence of variable-speed wind turbines is smoother than for fixed-speed wind turbines. In addition, the stop of variable-speed wind turbines is, just as in the case with the start, very gentle and smooth.

Under low wind conditions, wind turbines may start and stop several times. In the committee draft of the IEC 61400-21 a flicker step factor is defined. The flicker step factor is calculated from the measured voltage drop caused by the start of the generator. The flicker emission caused by a repeated number of starts can be determined by using the flicker step factor.

All wind turbines in a wind park are normally connected to the same PCC. The grid at the PCC must, therefore, 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 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.

If a wind park consists of a small number of fixed-speed wind turbines then stall-regulated turbines due to uncontrollable torque during start, will produce higher flicker emission. If the number of fixed-speed wind turbines is high, pitch-controlled turbines will produce higher flicker emissions.

VI. ACKNOWLEDGEMENT

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VIII. BIOGRAPHY

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