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

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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.

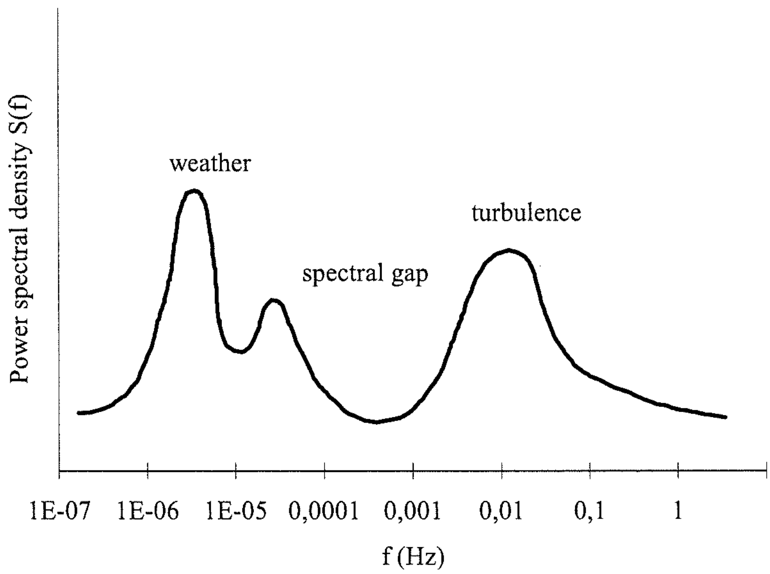

Figure 2.1: Schematic power spectrum of wind speed (according to van der Hoven).

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.

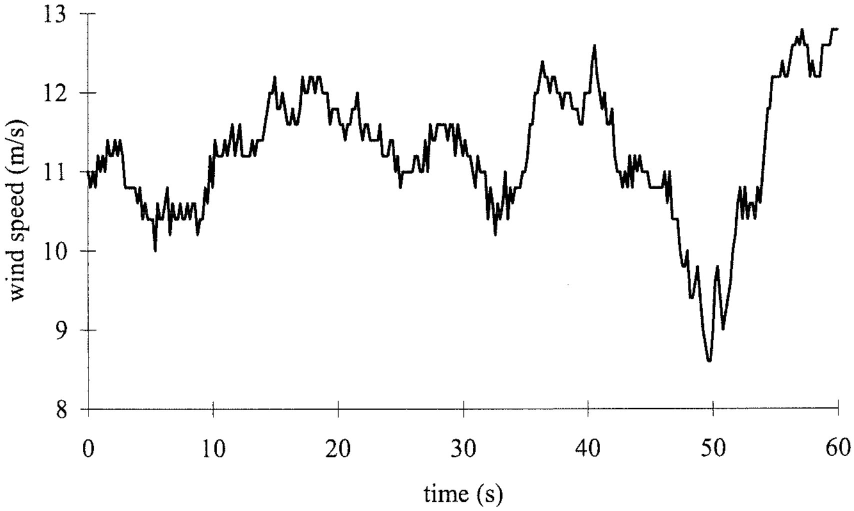

Figure 2.2: Wind speed measured at the harbour of Gothenburg, Sweden.

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.

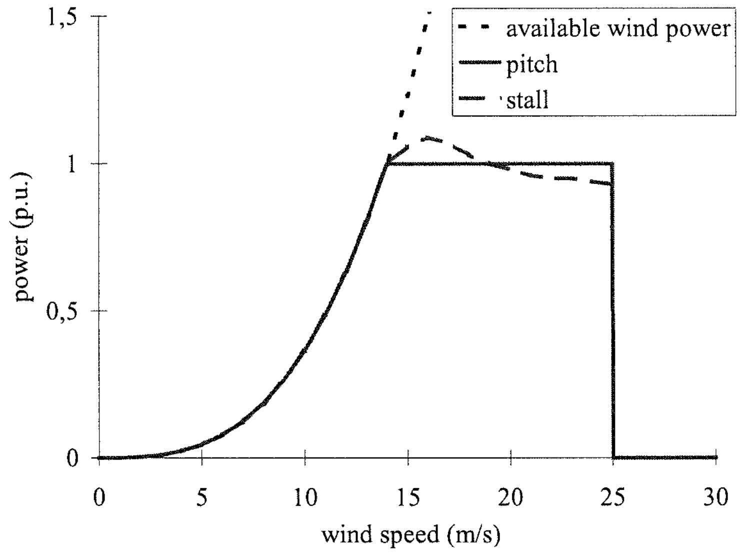

Figure 3.1: Available wind power (dotted line), power from a stall-regulated turbine (dashed line) and power from a pitch-regulated turbine (solid line).

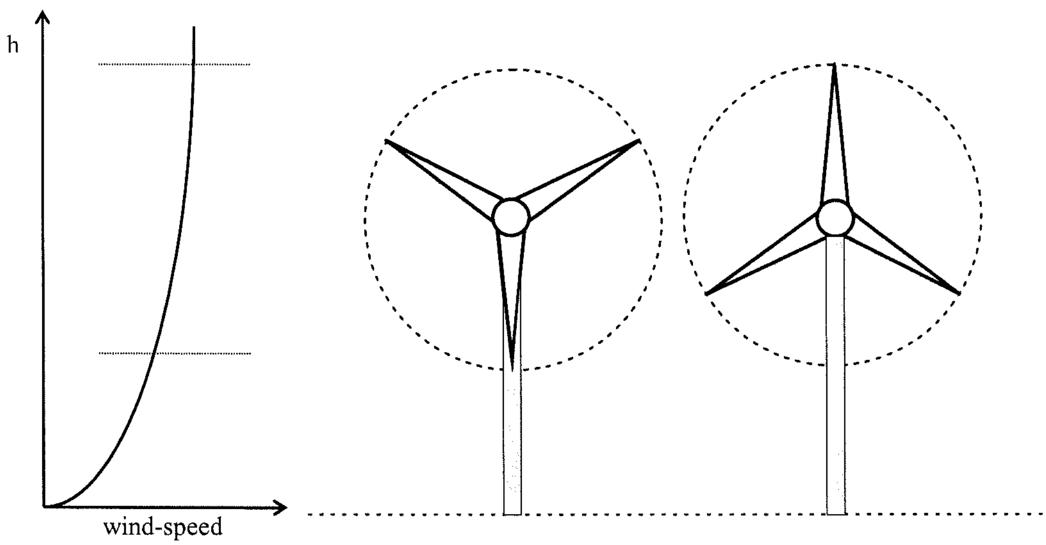

Figure 3.2: Different rotor positions of a three-blade turbine. The tower shadow and the wind gradient, both contribute to power fluctuations.

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.

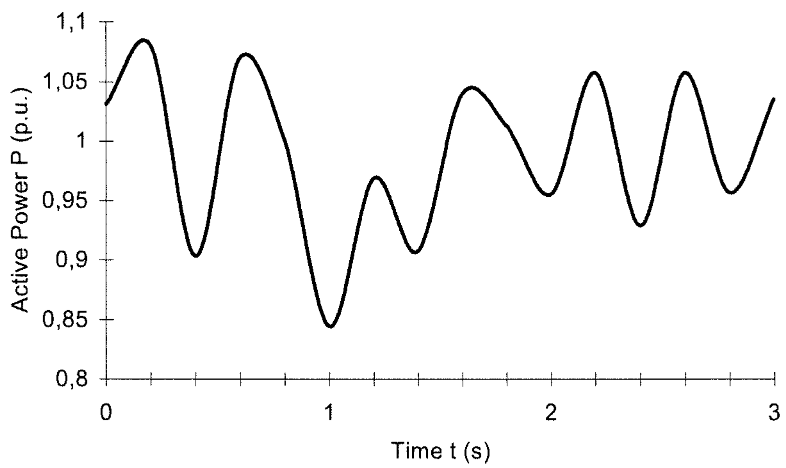

Figure 3.3: Measured power fluctuations from a fixed-speed pitch-regulated wind turbine.

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.

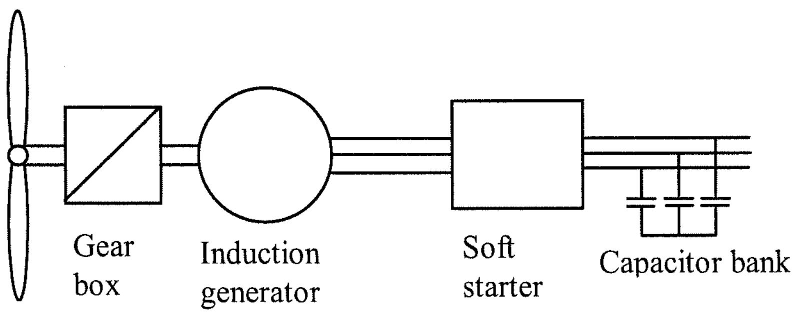

Figure 3.4: Schematic figure of the electric system of a fixed-speed wind turbine.

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.

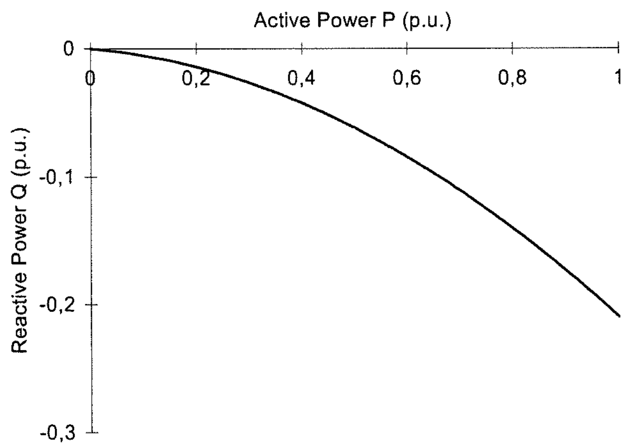

Figure 3.5: Reactive power as a function of active power. 1 p.u. corresponds to the rated active power.

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.

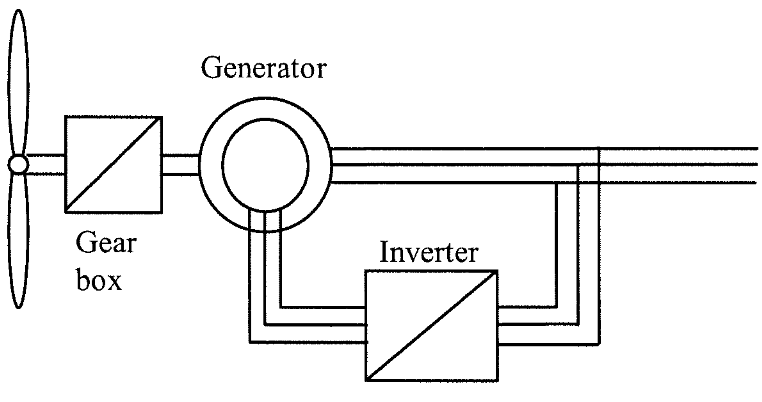

Figure 3.6: Schematic figure of the electrical system of a variable speed wind turbine equipped with a rotor cascade.

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.

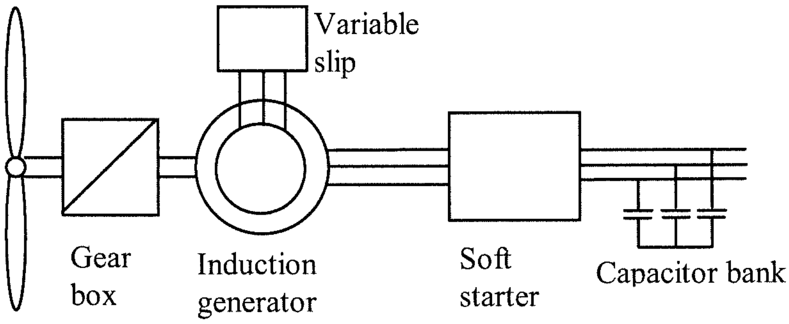

Figure 3.7: Schematic figure of the electrical system of a wind turbine equipped with controllable rotor resistances.

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

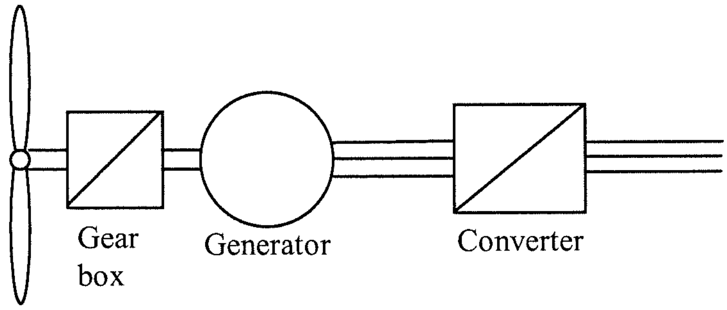

Figure 3.8: Schematic figure of the electric system of a variable-speed wind turbine equipped with an inverter.

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.

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

3.2.3 Start of Wind Turbines

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

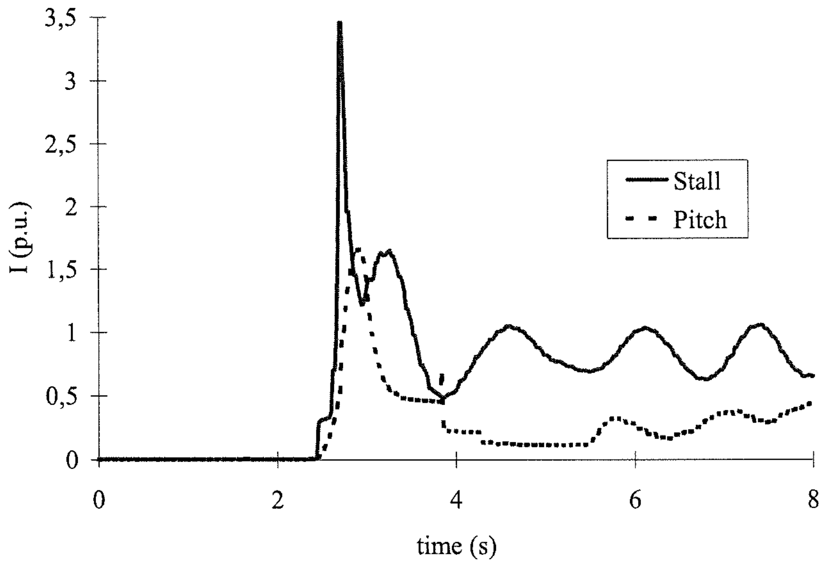

Figure 3.9: Measured current from a stall-regulated (solid line) and a pitch-regulated (dotted line) wind turbine.

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

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

4 Power Quality

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

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

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

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

4.1 Slow Voltage Variations

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

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

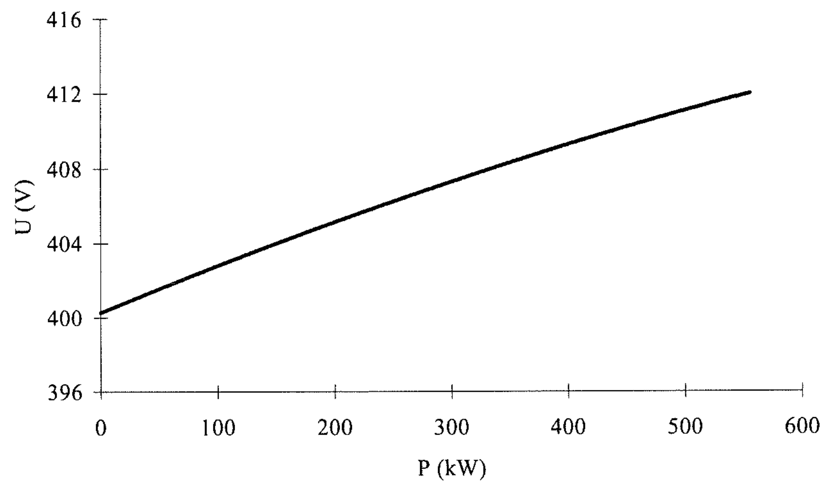

Figure 4.1: Measured voltage as a function of produced active power P from a 600 kW wind turbine located at Utteros in Sweden.

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

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

4.2 Voltage Dips

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

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

4.3 Flicker

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

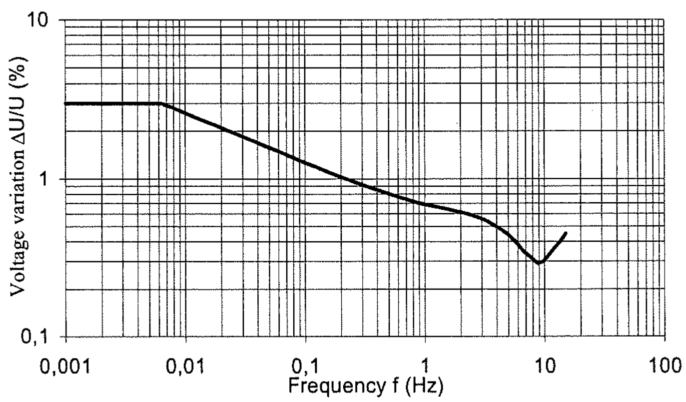

Figure 4.2: Flicker curve according to IEC 868.

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

4.4 Voltage Harmonics

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

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

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

4.5 Transients

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

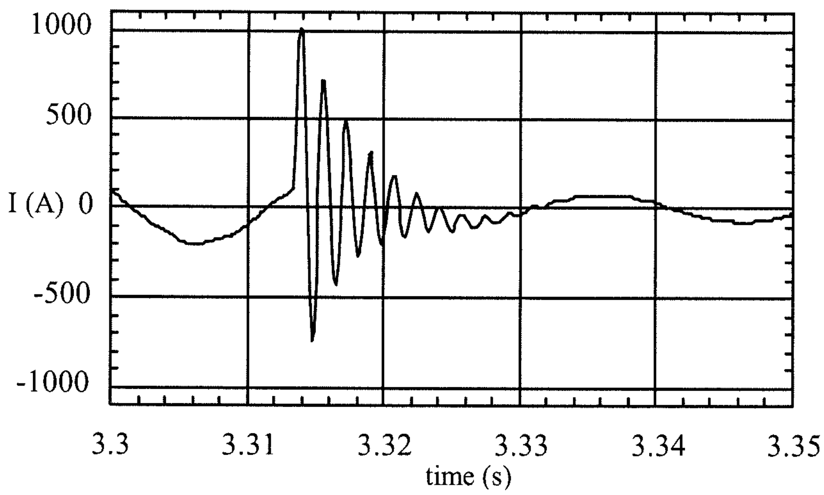

Figure 4.3: Measured oscillating current caused by the connecting of shunt capacitors during the start-up sequence of a 225 kW wind turbine at Risholmen, Sweden.

4.6 Frequency

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

In the case of a grid fault where the overhead lines are disconnected, island operation with frequency deviation as a result may occur. If for example a fixed-speed wind turbine equipped with an induction generator is over-compensated for reactive power, self-excitation may occur. At these occasions, the wind turbine may support the remaining load with power. Normally, since there is a mismatch between the load and the power production, it will lead to frequency deviations. In [27] a case where four wind turbines were operating at a self-exciting mode for 15 minutes is documented. In order to avoid self-excitation, reactive power is normally only compensated for up to the no-load reactive power demand of the induction generator. Moreover, wind turbines are normally equipped with over voltage, under voltage and frequency protection relays. In the event of an abnormal operating condition, the wind turbine is shut down.

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

5 Calculations of Voltage Disturbances

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

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

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

5.1 Slow Voltage Disturbances

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

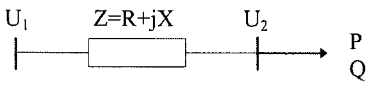

Figure 5.1: Simple impedance model.

The voltage at the PCC can be expressed as

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

where

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

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

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.

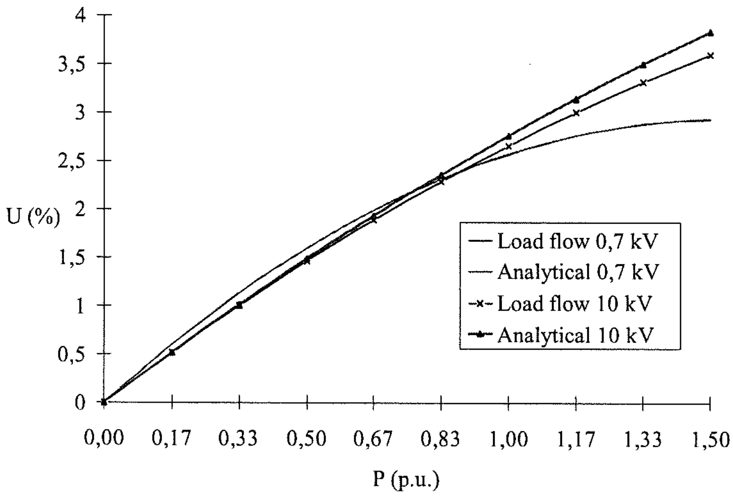

Figure 5.2: Comparison of calculated voltage variations using load flow calclation and the analytical method.

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:

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

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

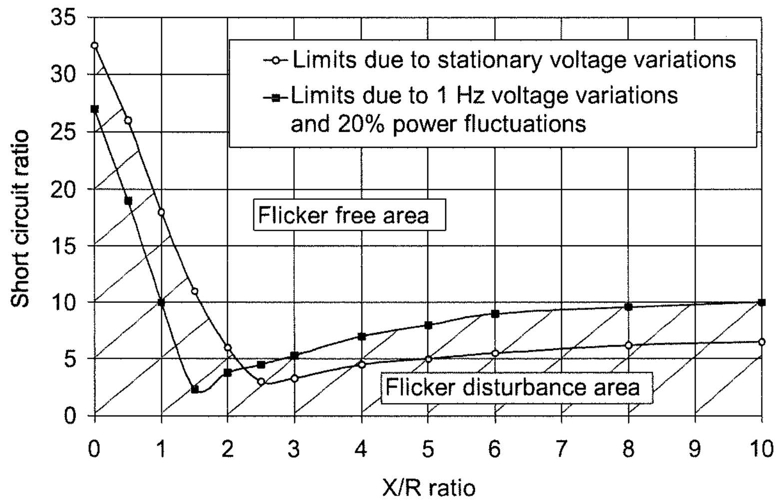

Figure 5.3: Minimum short-circuit ratio to avoid flicker caused by stationary voltage variations and 1 Hz voltage variations as a function of the grid *X/R* ratio.

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

5.3 Harmonic Voltage Disturbances

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

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

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

5.4 Voltage Transient Disturbances

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

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

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

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

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

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

6 Autonomous grids

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

6.1 Diesel Generator Set Properties

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

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

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

6.2 Frequency Variations

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

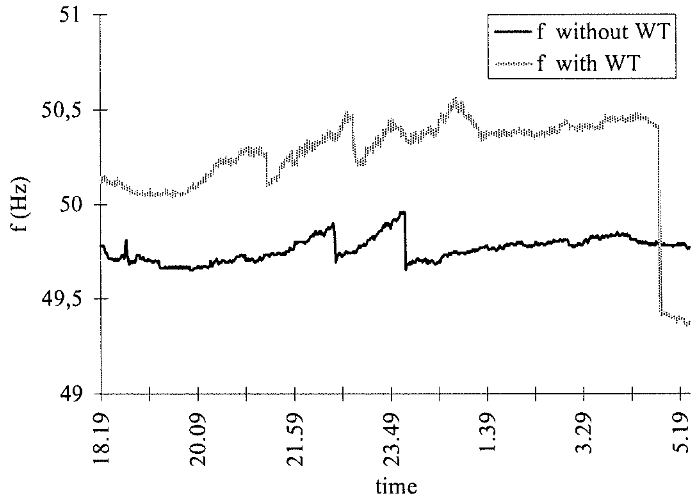

Figure 6.1: Frequency variations during two nights. One night when the turbines were operating (gray line) and one night when the turbines were shut down due to lack of wind (black line).

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

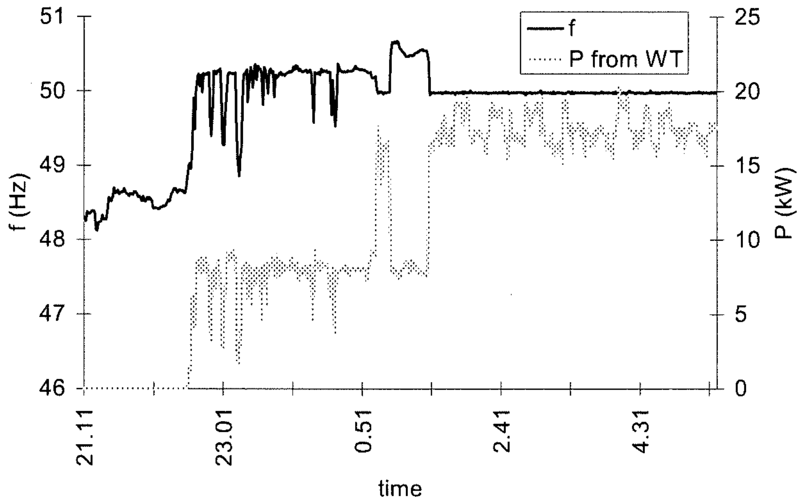

Figure 6.2: Frequency variations (black line) and power output from the wind turbine (gray line) during one night.

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

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

7 Wind Turbine Protection

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

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

8 Conclusions

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

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

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

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

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

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

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

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

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

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