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.

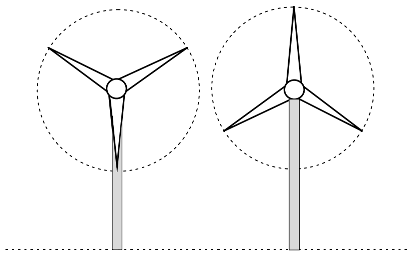

Fig. 1: Different rotor positions of a three-blade turbine. The tower shadow and the wind gradient both contribute to power fluctuations.

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.

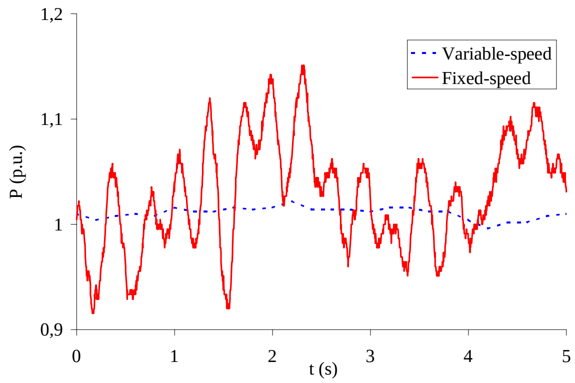

Fig. 2: Measured active power during normal operation of a pitch-controlled fixed-speed (solid line) and a variable speed (dotted line) wind turbine.

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

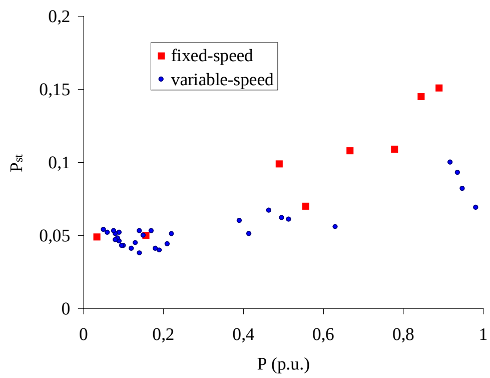

Fig. 3: Short term flicker emission Pst from a fixed-speed and a variable-speed wind turbine at different mean values of the produced power.

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

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

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 grid angle is defined as:

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

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

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

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

$$P_{st\Sigma} = \sqrt{\sum_i P_{st,i}^2} \qquad (4)$$

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.

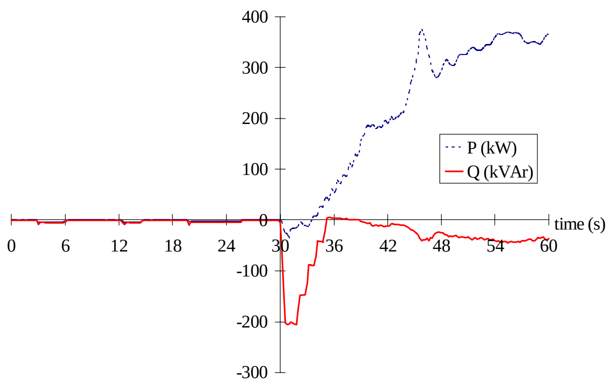

Fig. 4: Measured power during cut-in of a pitch-controlled wind turbine with controllable-slip. The rated power of the wind turbine is 600 kW. Active power (dotted line) and reactive power (solid line).

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

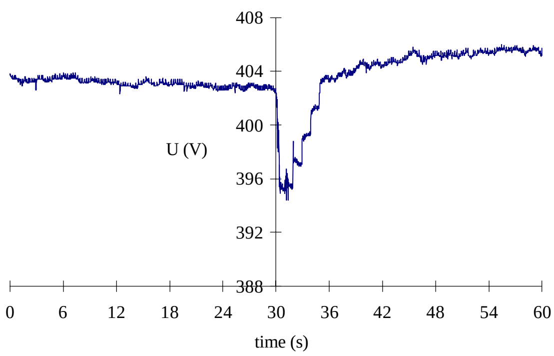

Fig. 5: Measured voltage during cut-in of a pitch-controlled wind turbine with controllable-slip.

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:

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

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]:

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

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:

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

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]

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

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:

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

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:

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

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

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

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

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

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

The author gratefully acknowledges the financial support obtained from ELFORSK AB.

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