GUIDELINES ON GRID CONNECTION OF WIND TURBINES

Kurt Kølbæk Jensen
DEFU, Denmark
P.O. Box 259
DK-2800 Lyngby
Tel.: +4545881400
Fax: +4545931288
e-mail: kkj@defu.dk

INTRODUCTION

In 1988 the research institute of the Danish utilities (DEFU) made recommendations on grid connection of wind turbines. Since then the amount of wind power installed in Danish networks has increased drastically. Furthermore, the size of the individual wind turbine has increased into the Megawatt range.

At the end of 1997 the energy produced by wind turbines amounted to approximately 6 % of the energy demand in Denmark. The capacity of the wind turbines installed amounts to approximately 10 % the total production capacity in the Danish power system.

A DEFU report with revised recommendations was issued in 1998. The aim of this CIRED report is to inform about the recommendations and about a future IEC-standard on power quality requirements for grid connected wind turbines.

VOLTAGE RANGE

Up to recently wind turbines were connected to MV feeders used to supply loads. The power produced by the wind turbines increases the voltage level on these feeders. It must be assured that the voltage supplied to consumers stay within the limits defined for good power quality in EN 50160.

The voltage increase in a feeder due to a wind turbine can be calculated from the following formula:

$$\frac{\Delta U}{U} \cong \frac{R \cdot P + X \cdot Q}{U^2} \qquad (1)$$

R: The resistance between the main substation and the point of connection of the wind turbine
X: The reactance between the main substation and the point of connection of the wind turbine
P: The active power produced by the wind turbine
Q: The reactive power consumed by the wind turbine allowing for reactive power compensation
U: Line voltage

Generator conventions are used for the direction of active and reactive power flow. If several wind turbines are connected to the feeder, the voltage increase in a node may be found by adding together the contributions from the individual wind turbines.

In the DEFU report a distinction is made between wind turbines connected to feeders from HV/MV substations with constant-voltage regulation and variable-voltage regulation (compounding).

Constant-voltage regulation

The voltage variation at the consumers must be within + 6 %, -10 %. If the dead band of the voltage regulator is set to ±1.5% a voltage variation of less than 13 % has to be shared between the MV feeder, a MV/LV transformer and a LV feeder. Loads as well as wind turbines connected to the feeder contribute to the voltage variations. As it is very costly to obtain a voltage drop of less than 5 % in public LV networks it leaves little room for a voltage increase due to wind turbines.

The voltage increase in existing 10 kV feeders due to the wind turbines and other decentralised production units are recommended limited to 1% at the point of common coupling. If more than approximately 1,5 MW of wind power has to be installed in a distance of some kilometres from the substation, it is normal practice to connect the wind turbines to the substation directly through a dedicated line. It is too expensive to limit the voltage rise through reinforcements.

Variable-voltage regulation (compounding)

Wind turbines in operation have the effect of reducing the voltage on the MV busbar in the main substation. If the wind turbines are connected through a dedicated feeder it may be an advantage to exclude the influence by adding the current in the dedicated feeder bay to the current in the transformer bay, taking the transformation ratios of the current transformers into account.

If wind turbines are connected to a feeder supplying loads, a higher voltage increase along the feeder due to the wind turbines is acceptable as they reduce the voltage on the MV busbar in the substation. Unfortunately the lower busbar voltage leads to lower voltages at consumers supplied through MV feeders with only loads connected.

Voltage regulators in substations may have compounding units taking the direction of power flow into account or not. If the wind power can exceed the minimum load, only compounding units taking the direction of power flow into account should be used. Otherwise the busbar voltage may be increased instead of decreased, when the wind turbines are producing rated power.

From the settings of a compounding unit it is possible to calculate a constant (u_{down}) which is the percentage reduction in the busbar voltage for each megawatt installed wind power in the substation supply area. Using this constant the following rules of thumb can be formulated:

Acceptable voltage increase due to wind turbines in the feeders to which they are connected:

$$u_{increase}\,(\%) = 1 + u_{down}\,\Sigma P_{WT} \qquad (2)$$

Acceptable voltage drop at peak load in feeders with no wind turbines connected:

$$u_{drop}\,(\%) = u_{planning} - u_{down}\,\Sigma P_{WT} \qquad (3)$$

$u_{planning}$ being a planning figure for the voltage drop in conventional MV feeders. A commonly used figure by Danish utilities is 5 %.

The assumptions on which the rules of thumbs are based can be found in literature [1].

In some cases there is a need for load flow calculations. The following combinations of load and production conditions should then be investigated:

- Low-load without wind turbine output
- Low-load and maximum wind turbine output
- Peak load without wind turbine output
- Peak load and maximum wind turbine output

However, the technical and economical consequences of not using compounding should be assessed first, as constant-voltage regulation simplifies planning and operation of MV networks. In literature [1] additional reasons are mentioned. In some cases, this assessment will show the non-compounding option to be too expensive – especially if the wind turbines are distributed on the feeders of a substation. In such cases, compounding should be used to compensate, not only for voltage drops, but also for voltage increases.

FLICKER

Rapid variations in the RMS value of the voltage cause flickering of the electric light. The perturbation (P) experienced by a "normal person" when the light flickers can be measured with a flicker meter. The power quality is outside the limits defined for good power quality in EN 50160 if a P-value higher than one is measured.

Wind turbines contribute to the flicker in the voltage supplied to consumers. It is practical to distinguish between flicker emission due to power fluctuations and flicker emission due to generator switching. Often, within a given range of wind variations, one or the other will be predominant.

It is recommended to limit the flicker emission from a single wind turbine to P_{lt}=0.25. The index refers to a weighted two-hour average of the measured flicker. It is also recommended to limit the flicker due to the total numbers of wind turbines in a MV network to P_{lt}=0.5 in any node of the network.

Flicker caused by power fluctuations

The flicker emission can be found by multiplying a the flicker coefficient, $c_c(\psi_k)$ with the wind turbine reference power (approximately equal to the rated power) and dividing with the short circuit power in the point of common coupling.

$$P_{lt} = c_c(\psi_k)\cdot\frac{S_r}{S_k} \qquad (4)$$

Many wind turbine manufacturers can provide information on the flicker coefficient, $c_c(\psi_k)$, which is measured only once and then normalised, so that it generally applicable. As the flicker emission depends on the network impedance angle, flicker coefficients for a range of impedance angles are specified on the bases of measurements of instantaneously values of current and voltage followed by calculations on a fictive network.

When more wind turbines are connected to the same MV network, the total flicker emission is the square root of the sum of squares of the flicker emission due to the individual wind turbine

Flicker caused by generator switching

In the late eighties small wind turbines were connected to MV/LV transformers also supplying loads. Generator switching caused annoying flicker which was reduced to an acceptable level by introducing “soft starters” and using oversized transformers. Later - as the ratings of the wind turbines increased – the wind turbines were connected to the MV network through dedicated transformers and the point of common coupling shifted from the LV- to the MV-level. This reduced the flicker in consumer installations. However, as the wind turbines now are having ratings around one MW the flicker caused by generator switching again requires attention.

Flicker emission due to generator switching may be calculated from the following formula:

$$P_{lt} = \left(\frac{2.3 \cdot N}{T} \right)^{\frac{1}{3.2}} \cdot F \cdot \frac{\Delta U}{U} \qquad (5)$$

or

$$P_{lt} \cong \left(\frac{2.3 \cdot N}{T} \right)^{\frac{1}{3.2}} \cdot F \cdot k_i \cdot \frac{S_r}{S_k} \cdot 100 \qquad (6)$$

T: The considered time period in seconds, in this case 7200 seconds.
N: The number of switchings during T seconds.
$\Delta U/U$: The voltage change attributable to switching in, expressed as a percentage.
F: A shape factor used to convert a relative voltage change with a given curve shape to a flicker-equivalent instantaneous voltage change (step change).
k_i: Ratio between the maximum inrush current and the reference current
S_r: The reference power of the wind turbine.
S_k: The short circuit power at the point of common coupling

If several wind turbines are connected to the same point of common coupling, "N" should be substituted by the maximum total number of switching operations for the wind turbines in the considered time period (assuming the wind turbines are identical).

Example: Six 1 MW wind turbines are connected to a 10 MVA transformer. Each wind turbine generator connect 8 times to the grid during a two hours period. As the flicker contribution should be kept lower than P_{lt}=0.5 the ratio between the maximum inrush current and the reference current must not exceed approximately 1.5.

The calculation method described above is not accurate. The shape factor is set to one as it is unknown and the impedance angle of the network is not taken into account. Furthermore, the inrush current will be heavily distorted if "soft starters" are used. Therefore a new method has been develop by an IEC working group. The method is described in a draft proposal, which is sent out for comments January 1999, see literature [2].

According to the new method the flicker emission can be found by applying a the flicker step factor $k_f(\psi_k)$:

$$P_{lt} = 8 \cdot k_f(\psi_k) \cdot N^{\frac{1}{3.2}} \frac{S_r}{S_k} \qquad (7)$$

The flicker step factor $kf(\psi k)$ should be measured only once for each type of wind turbine and normalised with the short circuit power. As the flicker emission due to generator switching depends on the network impedance angle, flicker step factors for a range of impedance angles should be specified on the base of measurements of instantaneously values of currents and voltages followed by calculations on a fictive network. In the near future wind turbine manufacturers are expected to be able to specify a flicker step factor for their products.

VOLTAGE DISTORTION

The wind turbines in Denmark have with only a few exceptions induction generators directly connected to the grid. Therefore no Danish experience with variable speed wind turbines is available. To be prepared for a change in concepts the acceptable emission of harmonic currents were studied assuming that the acceptable total emission in the MV network should be shared equally between loads and wind turbines. The outcome was not surprisingly that the lower order harmonics should be 4 % at highest. This is achievable with inverters based on new technologies.

POWER FACTOR

As mentioned above the wind turbines in Denmark are equipped with induction generators directly connected to the grid. The induction generators consume reactive power. The utilities have up to now required each wind turbine equipped with capacitor batteries with a rating equal to the generator's consumption of reactive power at no load. No problems with this practice have been observed.

As wind power is no longer marginal compared to the power demand in Denmark, there is an increasing interest in reducing the reactive power consumed by wind turbines. On fixed speed wind turbines this could be achieved by adding more capacitor batteries with a switching scheme minimising the exchange of reactive power with the grid. The main problem in changing from the existing requirements of no-load compensation to full range compensation is the increased overvoltages in possible islanding situations. These problems will be discussed below.

If a group of compensated wind turbines in the network - an "island" - is isolated from the rest of the electrical system, the voltage and/or frequency may reach unacceptable values. Therefore, the wind turbines must brake and cut out automatically when they are operated in island mode. However, cut out is not instantaneous, which means that an overvoltage may occur until the wind turbines have cut out.

The highest overvoltages occur when several of the following conditions are present at the same time:

- The wind turbines are producing maximum power.
- The island network operates at minimum load.
- The wind turbines have full range compensation.

Immediately after island operation has been initiated, the wind turbine speed is unchanged, but the frequency may be slightly above 50 Hz due to the slip and the released torsion of the main axe. The voltage will change in order to balance output from the capacitor batteries and the reactive power consumed by the wind turbine generators. The time taken to establish this balance depends on the electrical time constants of the generators, i.e. a few cycles.

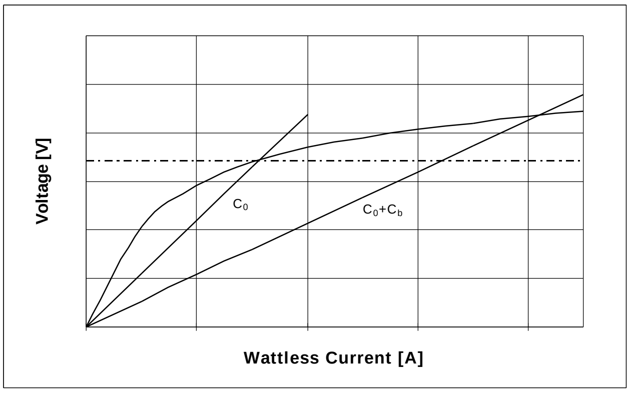

Figure 1. Example of the magnetising characteristic of a generator and the wattless current provided by capacitor banks while compensating for the generator's consumption of reactive power at no load (Co) and full load (Co+Cb), respectively.

Figure 1 shows an example of the magnetising characteristic of a generator. The correlation between the current through and the voltage across the capacitor banks is plotted as straight lines. The two lines indicate capacitor batteries with ratings equal to the generator's consumption of reactive power at no-load and full load, respectively. The point of equilibrium is located at the intersection between the curve and the straight lines. The corresponding voltage range from 0% to approx. 20% above the rated voltage of the generator, depending on the loads in the island and so on. If a certain load exists, reactive power will be consumed in the stray reactances of the generators. This leaves less reactive power available for magnetising the generators.

Figure 1 is based on a frequency of 50 Hz. Considering the fact that the frequency will actually exceed 50 Hz due to the slip etc., the equilibrium point will shift to the right, indicating higher voltages. The example ignores the presence of current harmonics due to the non-linear magnetisation characteristic.

With no-load compensation no significant overvoltages will occur immediately after the change to island-mode. If, however, the wind turbines produce more active power than can be taken by the island network, the wind energy will be used to accelerate the wind turbines. This causes an increase in the frequency, and thus in the output of reactive power from the capacitor banks. In addition, the generator characteristic changes. The equilibrium point in Figure 1 shifts to condition of overvoltage. The rate of increase is determined by the power available for accelerating the wind turbines and by the inertia of the latter. In this case, the voltage takes several hundreds of milliseconds to build up.

When the voltage increases, the amount of reactive power consumed by the loads in the island increases too, due to such factors as the non-linear magnetisation characteristics of motors etc. As island operations most frequent are caused by faults on the feeder to which the wind turbines are connected, overvoltages may normally only occur in consumer installations if the wind turbines are connected to a feeder supplying loads. Furthermore, the fault will partly discharge the capacitor batteries thereby eliminating the risk of overvoltages.

The question of when an overvoltage becomes critical for consumer appliances has been discussed with manufacturers of electronic equipment. It was concluded that voltages exceeding the rated voltage of electric appliances by more than 30% may cause immediate break down of electrolytic capacitors and switch transistors. Overvoltages in the order of 15…30% may after some milliseconds damage electrolytic capacitors, as the leakage current through a capacitor increases exponentially with the voltage. Longer lasting overvoltages may destroy transformers installed in appliance power supplies because of saturation.

Table 1. Protective functions

	Voltage setting (Un: WT rated voltage)	Time lag between setting over-shoot and contactor cut-out	
		Wind turbine	Compensation system
Undervoltage	0.90·Un [V]	60 seconds	
Overvoltage 1	1.06·Un [V]	60 seconds	50 seconds
Overvoltage 2	1.10·Un [V]	≤0.2 second	≤0.1 second
Underfrequency	47 [Hz]	0.2 second	
Overfrequency	51 [Hz]	≤0.2 second	≤0.1 second

The requirements set up by the Danish utilities to the wind turbine control system appear from table 1. The voltage setting "overvoltage 1" may deviate from the figure in the table, as it is aimed at protecting all LV networks against overvoltages irrespective of the transformation ratio of the MV/LV transformers, which may vary along a MV feeder.

CONCLUSIONS

The increased ratings of wind turbines make it appropriate to connect even smaller groups of wind turbines to a dedicated MV feeder. The increased ratings once again bring the flicker contribution from wind turbines into focus. Special concern should be given to flicker caused by generator switching. A future IEC-standard on power quality requirements for grid connected wind turbines will give recommended methods of measuring characteristic power quality data of a wind turbine. With these data it will be easy in advance to evaluate the flicker contribution from wind turbines at specific grid connections. A draft of the IEC standard was sent out for comments in January 1999.

As the amount of wind power increases the reactive power consumed by direct grid connected induction generators is no longer marginal. Power factor compensation can be carried out either by capacitor banks in the grid or by capacitor batteries integrated into the wind turbines. In the latter case the capacitor batteries must be disconnected as fast as practically possible in a possible island situation to avoid critical overvoltages. This is especially important if full range compensation is used.

REFERENCES

1. “Connection of wind turbines to low and medium voltage networks.” October 1998. 2. edition. DEFU committee report 111-E
2. “Power quality requirements for grid connected wind turbines.”. Draft. IEC 61400-21. November 1998. IEC TC88 WG 10.