Short Term Power Variations in the Output of Wind Turbines

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Windpower engineers have some preferred explanations to various phenomena. One such opinion is that the tower shadow is the key explanation to the periodic variations of the power output of wind turbines. Such prejudice is of course a challenge to the concerned mind! Thus the reason to make this analysis.

The example in Fig.1 demonstrates that the electrical output from a wind turbine generator operating at a constant speed is characterised by a clear variation at the rate of the rotational speed, but that there are also stochastic variations. When making a frequency analysis of the output, as in Fig. 2, the 2p frequency appears to be dominating, besides variations near zero frequency. "2p" means "two per revolution", i.e. twice the rotational frequency. This is natural, since each blade produces a power peak. With three blades one instead achieves three power peaks per revolution (3p) as the basic frequency. The result is valid if not the drive train of the wind turbine (turbine, shafts, gear and generator combined) has some un-damped resonance that may result in the domination of another frequency.

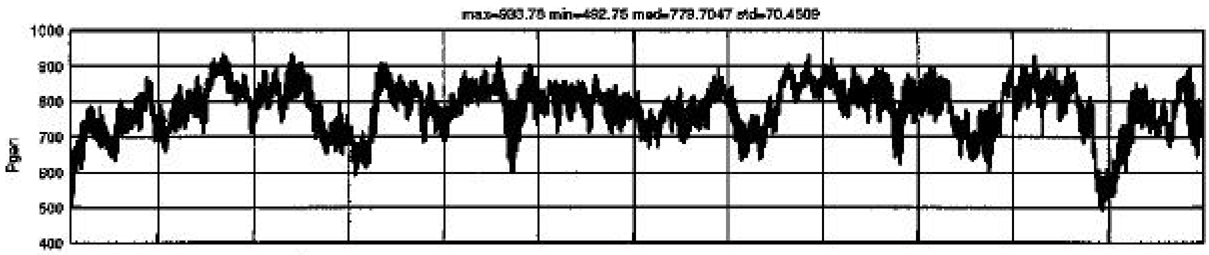

Fig. 1. The electrical power output of a Nordic 1000 from a 10 minute simulation. Mean wind speed 12 m/s, turbulence intensity 10%, exponent for wind shear 0,24, tower shadow according to [2-3].

In this example the wind turbine is constant speed (or rather almost constant speed, since the rpm of an induction generator may vary a few per cent). If instead a variable speed wind turbine is studied, the output power will appear much smoother. The variations in moment and thus power that affect the turbine blades then will result in momentary variations in the turbine rpm. Due to the same reason, the variations in power decrease when the slip of the induction generator is increased, e.g. by introducing extra resistors in the rotor circuit. The Nordic 1000, which is the subject of this investigation, is furnished with such a generator.

The variations of the power output are important in many ways. They appear as disturbances of the electrical grid ("flicker"), which may determine the needed strength of the grid, at a cost. They are also an indication of the forces and moments that affect the turbine and thus contribute to its cost.

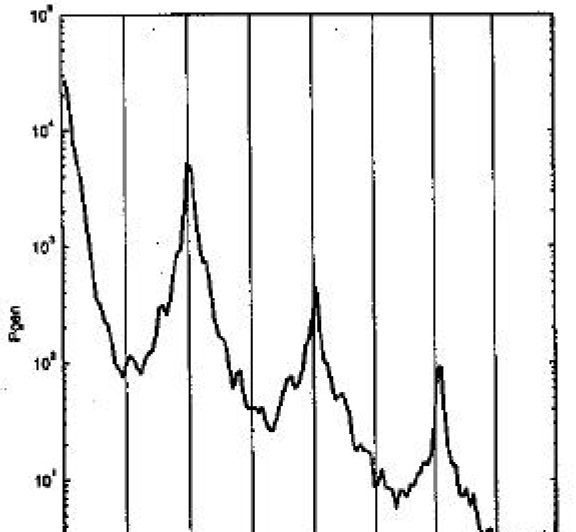

Fig. 2. Frequency analysis of the power signal in Fig.1. 1p equals the rotational frequency, 2p is the double rotational frequency etc. Normal rotational speed is 25 rpm = 0,41 Hz.

Origins of power variations

The most obvious reason to the output power variations observed is admittedly the tower shadow, which is the region around a wind turbine tower where the air stream is disturbed. Behind the tower the disturbance is very severe, which thus will affect downwind wind turbines. The Nordic 1000, as practically all contemporary wind turbines, has an up-wind

wind turbine. Also in this case the air stream is disturbed by the tower, which then is one of the explanations to the power variations observed. The power decreases every time a blade passes the tower, which results in a 2p or 3p frequency as discussed previously. Another obvious reason to variations of the output power is the wind shear, which makes the mean wind speed higher during the upper part of the rotation than during the lower one. Also this disturbance has a basic frequency of 2p or 3p.

A third cause is the turbulence, i.e. the stochastic variations of the wind, which are characterised by an even frequency distribution. Due to this reason one does not expect to find an uneven frequency distribution in those power variations that are caused by turbulence. On second thoughts one however may realise that this is the case. A gust may last for one or some tens of seconds, which corresponds to a length of some tens or hundreds of meters (at a 10-20 m/s wind speed) and a corresponding measure in the plane of the turbine. This means the wind turbine blades in most cases will only partly hit the gust, and thus experience a wind speed that is varying during the rotation. One rotation of the turbine typically lasts for two seconds (at 25 rpm), and each blade will then hit the same gust several times. This is the reason why also the turbulence is the cause of disturbances with the basic frequency of 2p or 3p.

Analysis possible through simulation

In the real world it is not possible to measure the sole contribution of e.g. wind shear, since the natural wind, which is experienced by the turbine, includes all the components. When simulating the operation of a wind turbine in a computer model, one therefore has to use a synthetic wind, which is created in a way to achieve a good representation of the natural wind, in time and in space. The output variations of Fig. 1 actually are the results of such a simulation. Here, as in other simulations in the paper, the results have been produced by the simulation programme "Vidyn", developed by Teknikgruppen AB. The synthetic three dimensional wind according to IEC [1] was generated with a turbulence intensity of 10% and covering 18x18 grid points, 3,5 m apart from each other. The simulated wind field thus covers 63x63 m. The wind field is updated each 0,175 seconds, which corresponds to the frequency 5,7 Hz. This is reasonably high compared with normal turbine rpm, e.g. the rpm of Nordic 1000 is 25 = 0,41 Hz. The descriptions of the tower shadow is based on work within the Joule-project ROTOW [2, 3], which was conducted by Teknikgruppen AB and FFA. In this project the extent of the tower shadow was studied both theoretically and by measurements at wind turbine towers. The wind shear is represented in power form, with the exponent 0,24, which is a value representative for areas with some vegetation and other roughness elements.

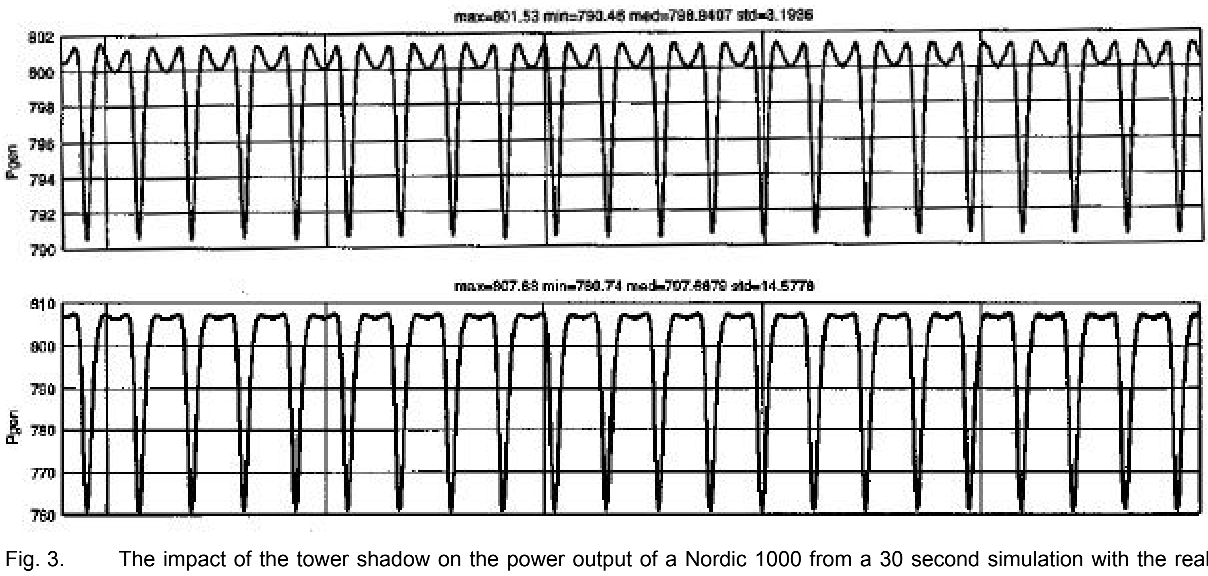

Fig. 3. The impact of the tower shadow on the power output of a Nordic 1000 from a 30 second simulation with the real tower diameter (top) and with the double tower diameter (bottom). Tower shadow according to [2-3], mean wind speed12 m/s.

Conclusion: Total dominance by turbulence

Simulations were conducted individually for the three components at three mean wind speeds. Fig. 3 depicts the results from the simulation at 12 m/s, with tower shadow but without wind shear and turbulence. In the upper graph the actual tower of the Nordic 1000 is simulated, which results in an output power varying between 790 and 801 kW, with a minor standard deviation of 3,2 kW. Since this tower is unusually slender (2,3 m diameter in the upper part), also a doubling of the tower diameter was tested. This simulation resulted in a standard deviation of the output power of 14,6 kW.

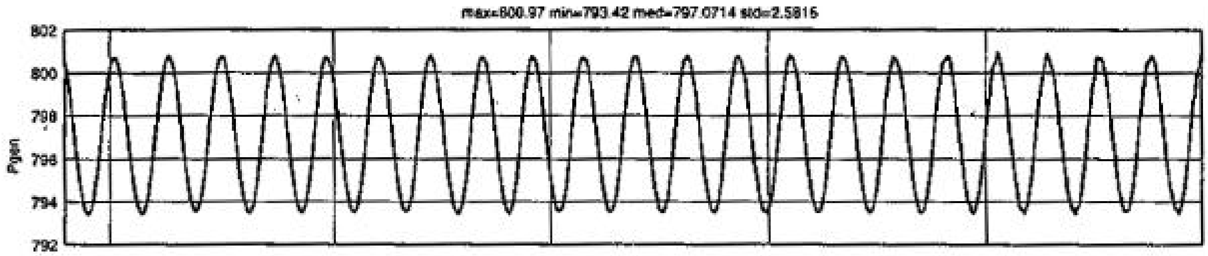

Fig. 4. The impact of the wind shear on the power output of a Nordic 1000 from a 30 second simulation. Wind shear exponent 0,24, mean wind speed 12 m/s.

The influence of the wind shear is demonstrated in Fig. 4, at the same mean wind speed. The effect here is even smaller, resulting in a standard deviation of 2,6 kW.

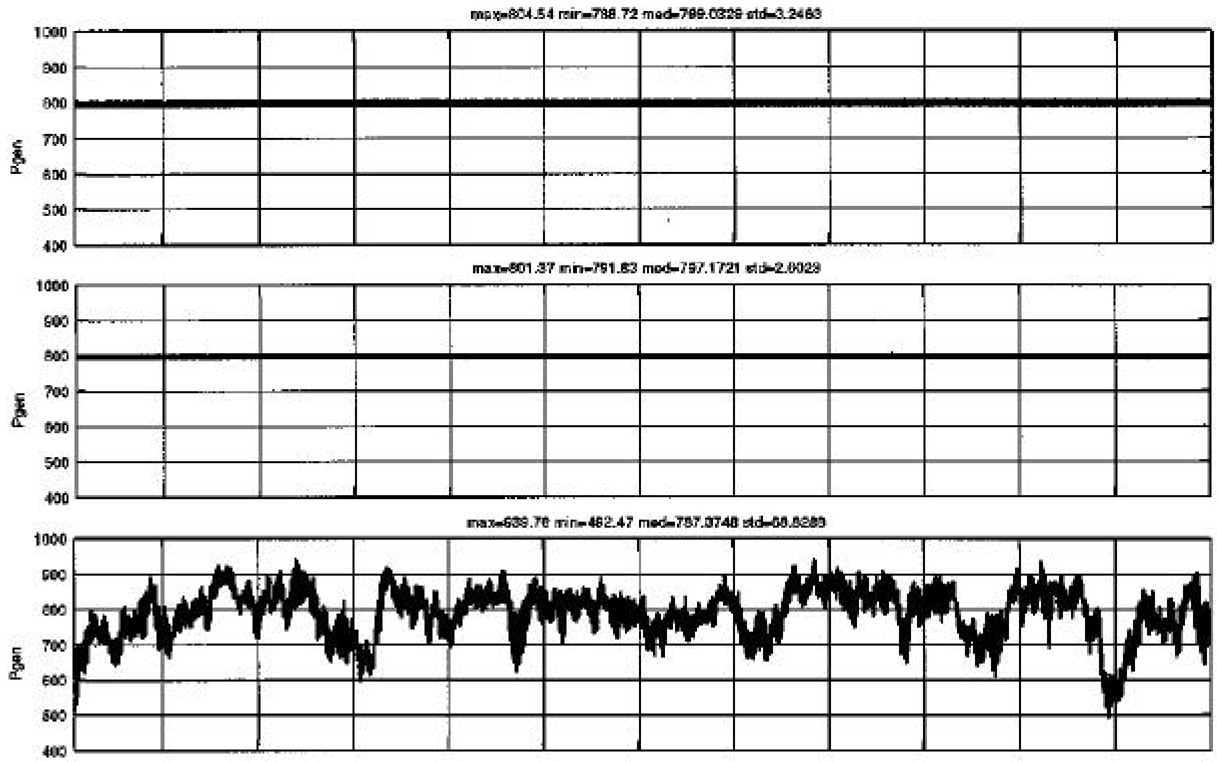

Fig. 5. The power output from a 10 minute simulation of a Nordic 1000 at the mean wind speed of 12m/s and tower shadow only (top), wind shear only (middle) and turbulence only (bottom). Turbulence intensity 10%, exponent for wind shear 0,24, tower shadow according to [2-3].

Fig. 5 finally depicts the effect of all components, in the same scale and at the same mean wind speed. Now it is obvious that the tower shadow and the wind shear are quite insignificant for the variations of the power output, while the influence of the turbulence alone looks the same as the influence of the sum of all components in Fig. 1. A frequency analysis of the turbulence signal is depicted in Fig. 6 and reveals only minor differences compared to Fig. 2. Thus it is clear that the turbulence totally dominates as the main cause of the origin of the variations of the power output, at least at the frequencies below 8p that have been studied here.

The conclusion that the turbulence is dominating is further supported by Table 1, where the variations have been quantified as the standard deviation of the power output. For the turbulence the influence is reported both during one minute and during ten minutes, where it is clear that the deviations increase during a longer period. This is natural, since a longer time period statistically will produce larger deviations. For the tower shadow and the wind shear, on the other hand, the influence is identical during each rotation of the turbine. The dominance of the turbulence is so large that the other components hardly have any impact on the final result. The conclusion is further supported by the fact that the simulations were conducted at a turbulence content of 10%, whereas a certification according to IEC demands 16 or 18%, i.e. a significantly larger turbulence content.

Another interesting observation is that the variations are largest at 12 m/s, which is just under the rated wind speed, even though the wind speed variations are larger at higher wind speeds. This is explained by the impact of the power limitation, in this case based on aerodynamic stall, which will suppress the power variations above the rated wind speed of around 15 m/s.

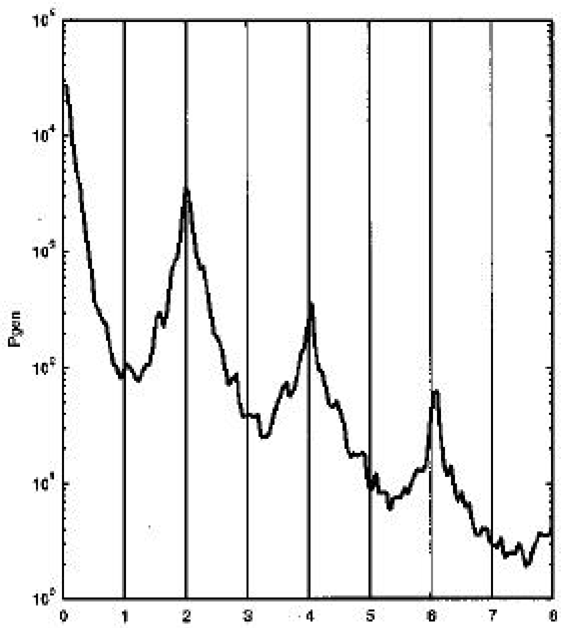

Fig. 6. Frequency analysis of the turbulence signal in Fig. 5.

Mean wind speed, m/s	Tower shadow	Wind shear	Turbulence (l min)	Turbulence (10 min)	Total (10 min)
6	1,2	0,4	13,2	29,4	29,4
12	3,2	2,6	26,7	68,8	70,4
18	1,8	1,8	17,8	23,8	25,2

Tab. 1. Standard deviation for power (kW).

The Nordic 1000 wind turbine, on which the analysis is based, is two-bladed and furthermore furnished with a teeter-hub, which in general decreases the impact of un-symmetrical variations in the wind field, regardless of their origin. It is probable that the conclusions in a qualitative way can be applied on all wind turbines, although there may be differences in the quantitative impact.

References:

[1] IEC 61400 Ed. 2: Wind turbine generator systems - Part 1: Safety requirements.

[2] Anders Björck. Blade-Tower Interaction: Calculations Compared to Wind Tunnel Test Results. Report prepared for ROTOW 4th meeting 13-14 December 1999. FFAP-V-107. FFA The Aeronautical Research Institute of Sweden. 1999.

[3] J.M.R Graham and C.J. Brown. ROTOW Investigation of the Aerodynamic Interaction between Wind-Turbine Rotor Blades and the Tower and its Impact on Wind-Turbine Design. FOI-S-0005-SE. Aeronautics Division, FFA. 2001.