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Terrain Concentration,
a Hypothesis for Multiple Power Levels

G.P. Corten

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Gustave P. Corten
ECN Solar and Wind Energy, the Netherlands Energy Research Foundation ECN, Westerduinweg 3, NL 1755 ZG Petten, The Netherlands, email Corten@ecn.nl

ABSTRACT Complex terrain can concentrate the wind at a wind turbine. The concentration will depend on the wind direction. As a consequence a turbine (pitch- or stall regulated) is expected to have multiple power levels depending on the wind direction under such circumstances. These multiple power levels are expected in particular below rated wind speed.

Introduction

About 15 years ago the first observations were made that wind turbines could have more than one power level in apparently the same wind. The first publication on the phenomenon was made by Madsen [1].

At several turbine parks in California one noticed different power levels, of which the lowest was about half the design-level, see figure 1. The phenomenon, often referred to as 'Double Stall' or 'Multiple Stall' demonstrates the production losses (up to 25%) that may be involved. Several initiatives were taken to understand and solve the problem, see for example the paper of Dyrmose and Hansen [2], the Joule project on Multiple Stall [3] and the publication from Risœ [4].

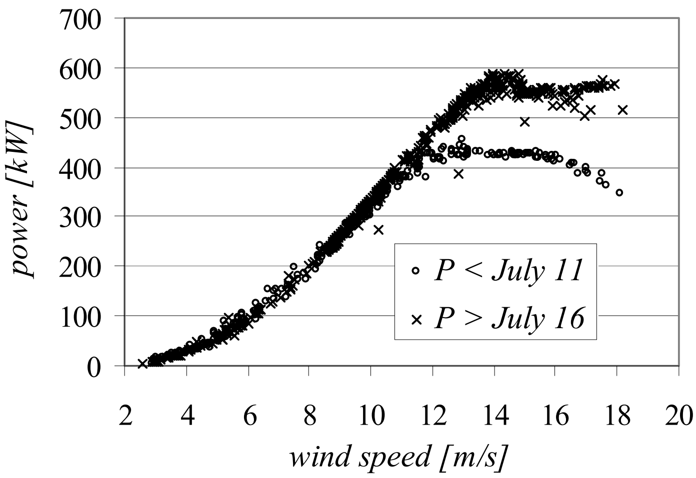

figure 1 *This figure shows an example of the power levels measured by Oak Creek Energy on a NEG Micon 700/44. The cause of this behaviour was unknown.*

Since the cause remained uncertain, we studied a 44m HAT at a Californian site as well. Here we made an inventory of the hypotheses, yielding a list of 10 [5]. Our working hypothesis was 'the Tip Commands'[6], a model that seemed to give a good description of what might happen - but at the end of the project we came up with the 'the Insect Hypothesis' [7], which was confirmed by three crucial experiments.

At different sites and at different moment there can be different causes for multiple power levels. On September 3rd 2000 we formulated the first possible cause not related to stall, it is described by the Terrain Concentration Hypothesis. The Terrain Concentration Hypothesis is a possible cause of multiple power levels, with the characteristic that the power is affected especially below rated wind speed. The expected effect on the power curve (simulated in figure 2) is much different from the observations in California. At this moment, we have no experimental confirmation for such behaviour, we only have theoretical arguments that such curves may exist.

The hypothesis assumes that in hilly terrain, the surrounding of the turbine can act as a concentrator, and that this can lead to a non-unique relation between the wind speed and the power.
To explain the hypothesis, we start with a brief overview of the principles of concentration as described by de Vries 1979 [8]. A concentrator is a static device (we exclude tip vane like concentrators) that influences the distribution of hydrostatic and kinetic energy in the flow. If the static pressure decreases from p_0 to p_-, it follows with the Bernoulli equation, that the speed at the rotor increases with U_+ relative to the undisturbed speed U_0.

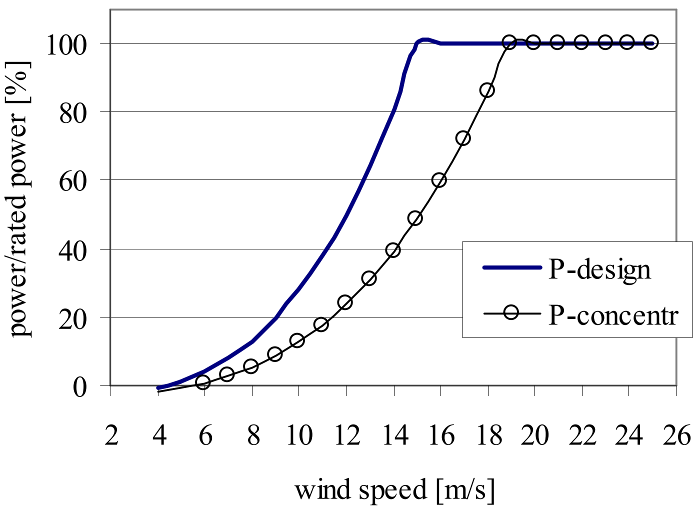

figure 2 *In the terrain concentration model the power is affected especially below rated power.*

$$p_0 + \tfrac{1}{2}\rho U_0^2 = p_- + \tfrac{1}{2}\rho (U_0 + U_+)^2 \ , \quad (1)$$

where ρ is the density of air. So, when a wind turbine it located in the low pressure area, the wind speed increases with respect to the undisturbed speed with U_+. One may think that the turbine therefore can extract a factor $((U_0+U_+)/U_0)^3$ more energy, but then one forgets that the flow still has to move away from the turbine. By doing so, it will slow down by opposing the pressure gradient. In fact the increase of the kinetic energy per unit air mass, moving into the concentrator corresponds precisely to the static pressure drop, so also precisely this energy is required to let the flow move out of the low pressure area induced by the concentrator, see figure 3. In other words, the increase of the kinetic energy *per unit air mass* cannot be extracted, but more energy can be extracted simply because the mass flow increased with a factor $(U_0+U_+)/U_0$.

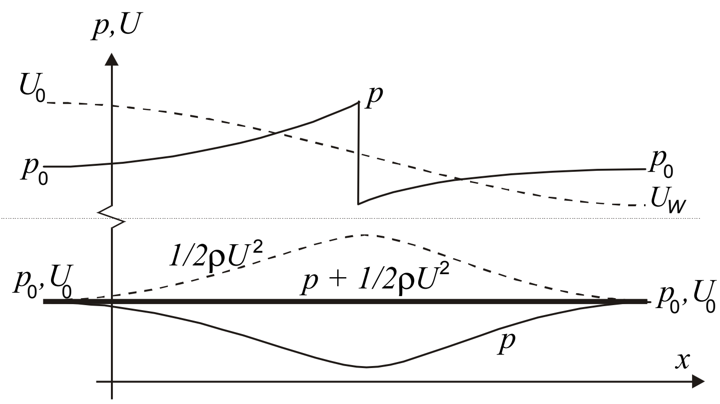

figure 3 *The lapse of pressure and speed for a wind turbine and a concentrator.*

Now we return to the Terrain Concentrator hypothesis. When the terrain around a turbine has such a shape that it can act as a concentrator, and, since the turbine will turn with the wind and the terrain will not, the concentration will depend on the wind direction. So at one wind direction the terrain increases the mass flow and at another wind direction it won't, see figure 4. An anemometer nearby the turbine or on the nacelle cannot make a difference between those situations. And we, as observers, not aware of the terrain concentration, do expect that the power P corresponds to (assuming a power coefficient c_p, and a swept area A) the wind speed indicated by the anemometer speed U_a, via the relation

$$P = c_p \tfrac{1}{2} \rho A U_a^3 , \qquad (2)$$

however the wind speed at the anemometer consisted of an undisturbed wind speed and a concentrator induced speed, $U_a = U_0 + U_+$, so the power that can be extracted is in fact

$$P_c = c_p \tfrac{1}{2} \rho A U_0^3 \frac{U_0 + U_+}{U_0} \text{ and not}$$

$$P = c_p \tfrac{1}{2} \rho A (U_0 + U_+)^3 . \qquad (3)$$

Furthermore, the turbine is not designed for the case of concentrated flow, it will therefore operate (below rated) at a too high induction. So it extracts too much energy *per unit air mass* and may come into the less efficient turbulent wake state and as a consequence, extract even less power.

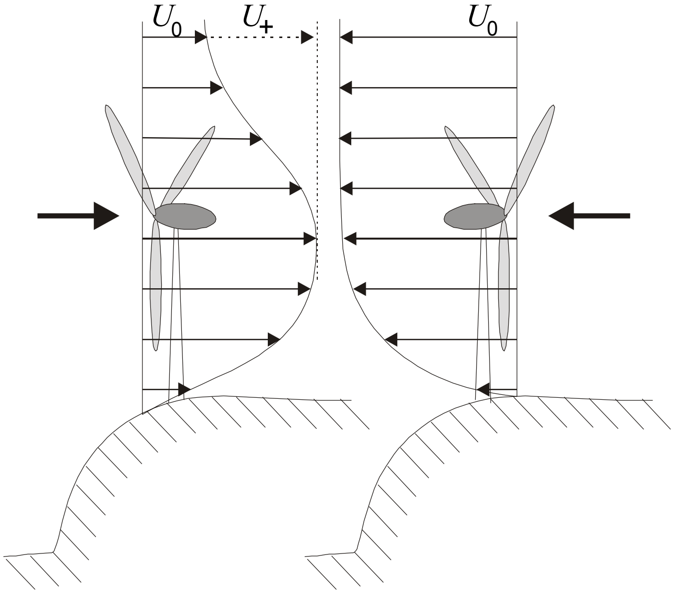

figure 4 *The terrain concentration hypothesis. The wind speed measured on the nacelles of both turbines are equal, but the turbine on the left-hand side can extract less energy.*

Estimate of the Effect

For an efficient ring-shaped concentrator U_+ can be almost $2U_0$, for a terrain with concentrator properties we expect a maximum of $U_+ = ½U_0$. In that case the our turbine produces power proportional to $U_0^3(U_0+U_+)/U_0 = 3/2U_0^3$, while we expect $(3/2U_0)^3 = 27/8U_0^3$, which is a factor 2¼ higher. Or the obtained power can be about half the expected power. The situation in figure 2 corresponds to this ‘worst’ case. This mechanism is not restricted to stall turbines but will affect pitch regulated turbines as well.

The geometric scale of pressure field induced by the concentrator relative to that induced by the turbine is also important. When they are of the same scale the above analysis holds, when the concentrator is of a much larger scale, so that entire pressure lapse induced by the turbine takes place in the low pressure zone of the concentrator, then the power at the turbine increases with a third power of (U_0+U_+). So the Terrain-Concentration hypothesis can have large influence on the power, but this depends much on the relative size of the turbine compared to that of the concentrator and on the efficiency of the terrain concerning its concentration properties.

Site Calibration

It is common practice (IEC 61400-12) to calibrate a future wind turbine site in complex terrain. The procedure means that one measures both the wind speed at the locus of a fictive turbine and on a metmast some distance away. Then one tries to find the function that predicts the first wind speed by using the second. When this function is known for all wind directions, the site calibration is complete. Subsequently the turbine is erected and the power is measured. This power is referred to an estimate for the undisturbed wind speed at the locus of the turbine. This estimate is calculated with the function obtained above together with the wind speed from the metmast.

In this procedure the possible effect of concentration is ignored, while it can be large. The estimate for the undisturbed wind speed exists in general of a part that contributes to the power, proportional to a third power and a part that contributes only in a linear sense. The partition depends again on the relative scales of the natural concentrator and the turbine and on the efficiency of concentration. Both parameters are difficult to estimate in practice.

Measurement of the Effect

There may be options to measure the effect of concentration, for example by measuring the power as a function of the wind speed with a ‘calibrated’ wind turbine, which we define as one with a known power curve determined in flat terrain. The measurement of the static pressure drop is not a simple option. If the undisturbed wind speed U is 10 m/s for example and concentration adds $U_+ = 5$ m/s, then the static pressure decreases with 80 Pa, which is less then 0.1% of atmospheric pressure.

Conclusions

The T errain–Concentration hypothesis, predicts multiple power levels even *below* rated power and for both stall regulated and *pitch* regulated wind turbines. It predicts that the site calibration procedures have no valid physical basis. The effect of concentration cannot be measured in a simple manner, so measurement of a reliable power curve may demand flat terrain.

References

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