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Yaw Misalignment and Power Curve Analysis

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Abstract

Yaw misalignment is causing a significant loss of production; we have conducted measurements on around 300 different wind turbines and more than 50% showed significant static (average) yaw misalignment.
The Spinner Anemometer ("iSpin") consists of three ultrasonic sensors, mounted at the spinner of a wind turbine measuring wind speed, yaw misalignment, inclination angle and from 10Hz measurements turbulence hitting the turbine.
Results: We will present key statistics on the severity of their inability to yaw straight into the wind, how different wind turbines compare and are controlled in terms of yawing. In addition, we will illustrate through power measurement combined with iSpin, how yaw misalignment is causing the turbine to underperform.
We will compare different wind turbines from our database, to show how different designs handle dynamic yaw misalignment, and how some of the poorer performing turbines could get a significant energy boost by actively yawing more like the majority of wind turbines.
Through active power measurement combined with iSpin, we will present power curve heat maps, showing the effect of yaw misalignment on a wind turbine's measured power curve. Additionally we will show detailed studies of average power produced, in 10min wind speed bins, as a function of degrees of yaw misalignment compared with the theoretical losses according to the Cosine Cubed and Cosine Squared rules.
Conclusion: Correcting yaw misalignment increases the wind turbine's energy yield, according to Cosine Cube theory below rated power, though its annual energy production "AEP" more closely approximates to Cosine Squared.
The majority of wind turbines have a good yaw control system with little benefit to be gained from further optimization, but a few could increase their AEP by up to 2% if they improved their yaw strategy

More than 50% of wind turbines are misaligned to the wind direction.
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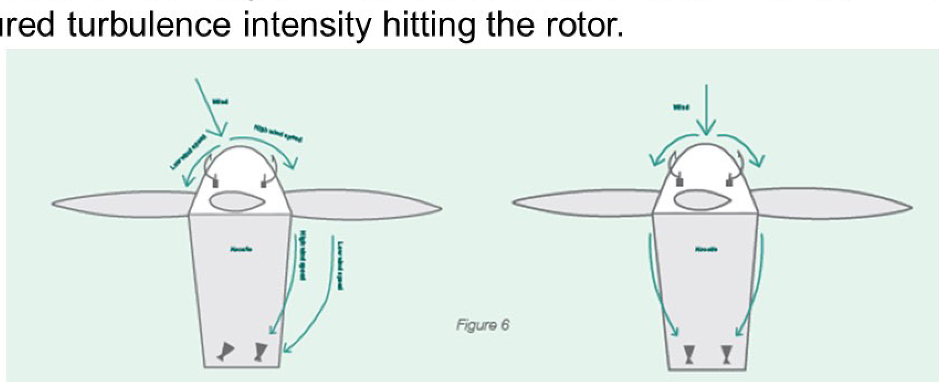
Measurement on +300 wind turbines 1.7% annual power is lost

ROMO Wind's iSpin consists of 3, 1D ultrasonic anemometers mounted on the spinner of a wind turbine, basically turning the spinner of the turbine into a very precise wind measurement tool, the advantages of measuring the wind on the spinner as opposed to traditional nacelle anemometers are the well-known flow conditions before the rotor and nacelle structure which cause very complex flow through the blades and around the nacelle itself.

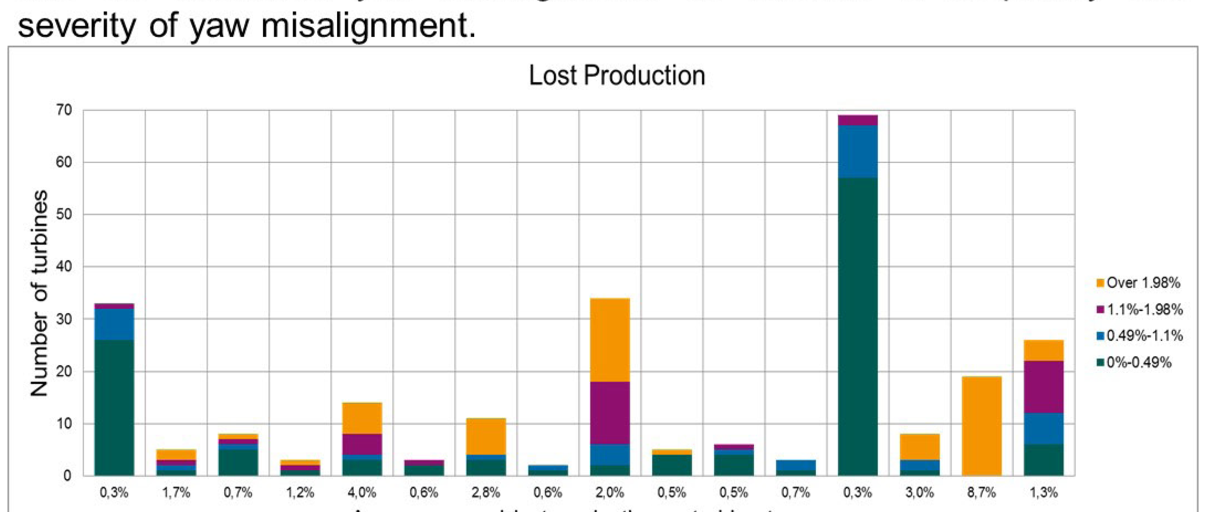
iSpin works simply by patented advanced mathematics, converting the measured wind speed in the 3 ultra sonic sensor paths, through the tilted and rotating spinner coordinate system onto horizontal and vertical relative to ground level-[1,2], with 3 instantaneous measurements iSpin measures the 3D wind vector, and can output horizontal wind speed, yaw angle and inflow angle, from 10Hz measurements it also accurately measured turbulence intensity hitting the rotor.



Basic principle of iSpin, if the wind comes perpendicular onto the rotor, the measured wind speed by all 3 sensors will be the same for a full rotation of the rotor, but if the resulting wind vector hits the rotor at and angle, we measure a sinusoidal wind speed as a function of the azimuth position of the individual sensors, the azimuth position is determined using a accelerometer in the socket of the ultra sonic sensor arms.

Static yaw misalignment:

In our database which today consists of over 300 wind turbines, we still observe that over half of all wind turbines have sever issues yawing correctly into the incoming wind direction. Additionally we are now capable of differentiating different wind turbines, and have found some wind turbine models which do not appear to have severe issues and are in general good at yawing and only 10-20% of these turbines have a minor yaw error from 4 to 8 degrees. Below is an extract of different wind turbines types and the measured yaw misalignment, as function of frequency and severity of yaw misalignment.

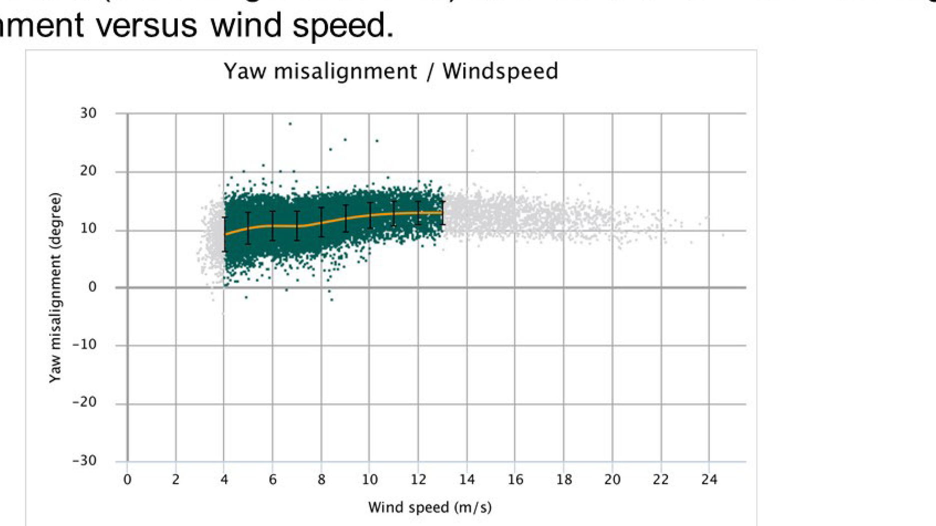


All presented turbine types are multi megawatt, only excluding those from our database where we only have one or two prototype turbines working with the turbine manufactures. We have detected some turbine models even in flat terrain, where every single wind turbine has an inherent critical yaw misalignment exceeding 10 degrees, using the Cos2 assumption on AEP gain, all of these turbines were loosing above 3% annual energy, the combined loss for all turbines were in this case 8.7% as some of the turbines had very large yaw misalignment close to 20 degrees.

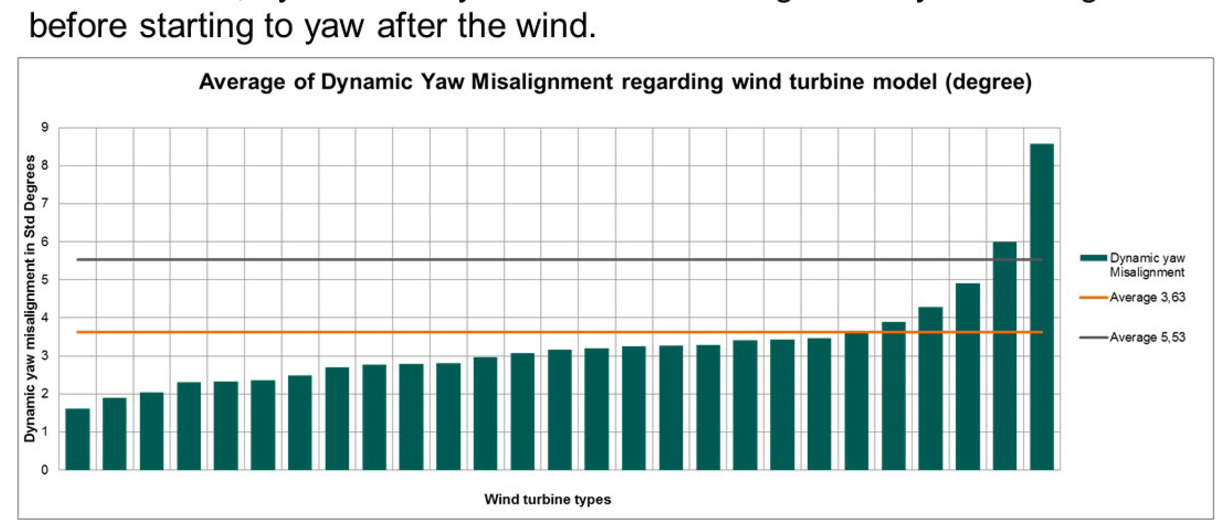
This was confirmed by the turbine owner, as first we measured on half of the wind farm, and after a year the client approach us to have the last of the wind farm calibrated to not have yaw misalignment as he could see the increased performance of the already corrected turbine.

Dynamic Yaw Misalignment

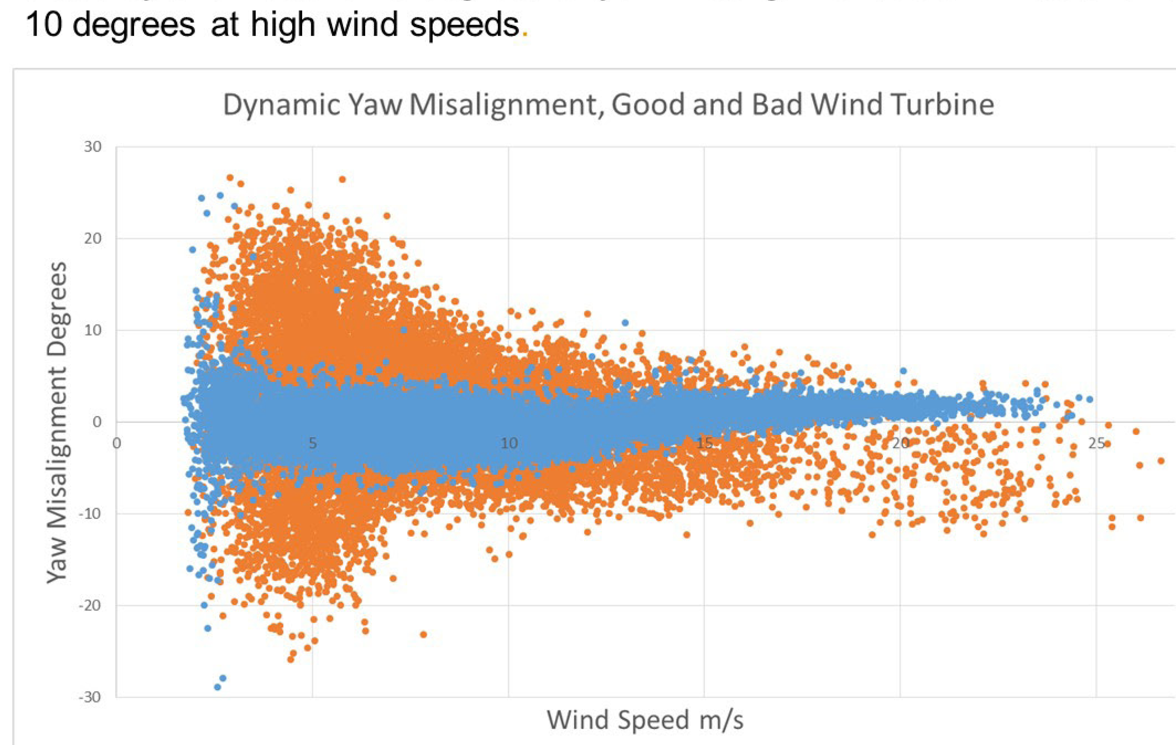
Dynamic Yaw Misalignment:
Is defined as the variation "dynamic" around the mean "static" yaw misalignment, in terms of standard deviation in degrees, shown as error bars in image below. Static yaw misalignment, is defined as the average yaw Misalignment (the orange centerline) as a function of 10min average yaw misalignment versus wind speed.



Wind turbines have shown to be operated with very different yaw control:
If we look at dynamic yaw misalignment we have identified that the majority of wind turbines have a small dynamic yaw misalignment below 4 degrees in standard deviation.
Indicating that on average the majority of wind turbines are operated to start yawing after the wind direction, if an offset between nacelle direction and wind direction is above 4 degrees.
But a select few turbine models have a very different operational characteristic, by which they allow above 20 degrees of yaw misalignment before starting to yaw after the wind.



Above illustrates 27 different turbine models capability of dynamic yaw misalignment, set as standard deviation in degrees of the scatter around the average yaw misalignment. In general we find that wind turbines have a good yaw control.
A wind turbine will always have some dynamic yaw misalignment, the very best turbines are actively yawing after the wind when it detect 1.5 to 2 degrees offset at higher wind speeds, and 90% of the turbine we have measured on are all below 4 degrees. For all these turbines it would most likely not be worth the effort to optimize the yaw algorithm of the turbine versus the potential increase in loads on the yaw system as the theoretical improvement potential is in the area of 0.1% on AEP.
But for one turbine design where we have measured on 2 different manufactures using this yaw design and turbine control, we have seen that they allow above 20 degrees of yaw misalignment below 7m/s and +/-10 degrees at high wind speeds.



Above illustrated in blue the dynamic yaw capability of a good turbine, and in orange a poor performing turbine in terms of dynamic yaw misalignment.

Both turbines have on average a Static yaw misalignment below 1 degree, and both showing a small wind speed dependency of a few degrees.

But clearly the bad performing turbine is allowing substantial energy to be ignored simply due to a "lazy" yaw design of the turbine, every single point here is from a 6-month measurement campaign for both turbines, and each dot represent a 10min average yaw misalignment measurement as function of wind speed.

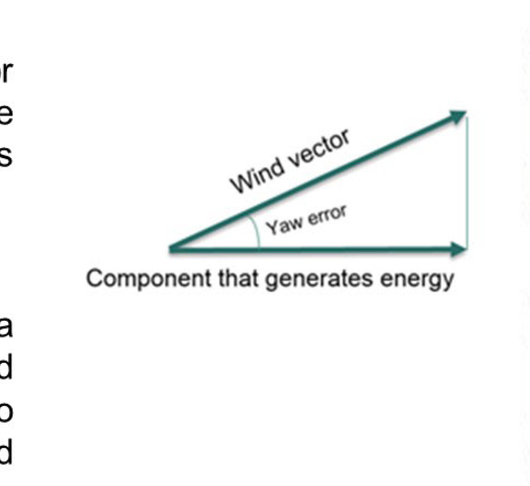
Thus every single orange measurement which is visible is an underperformance of the "lazy" turbine compared to a good turbine.

Note that ROMO cannot know about design load complications, and that the "lazy" turbine design is warranted under its current operational characteristics thus owners of this type of turbines are not seeing under performance due to this very high dynamic yaw misalignment.

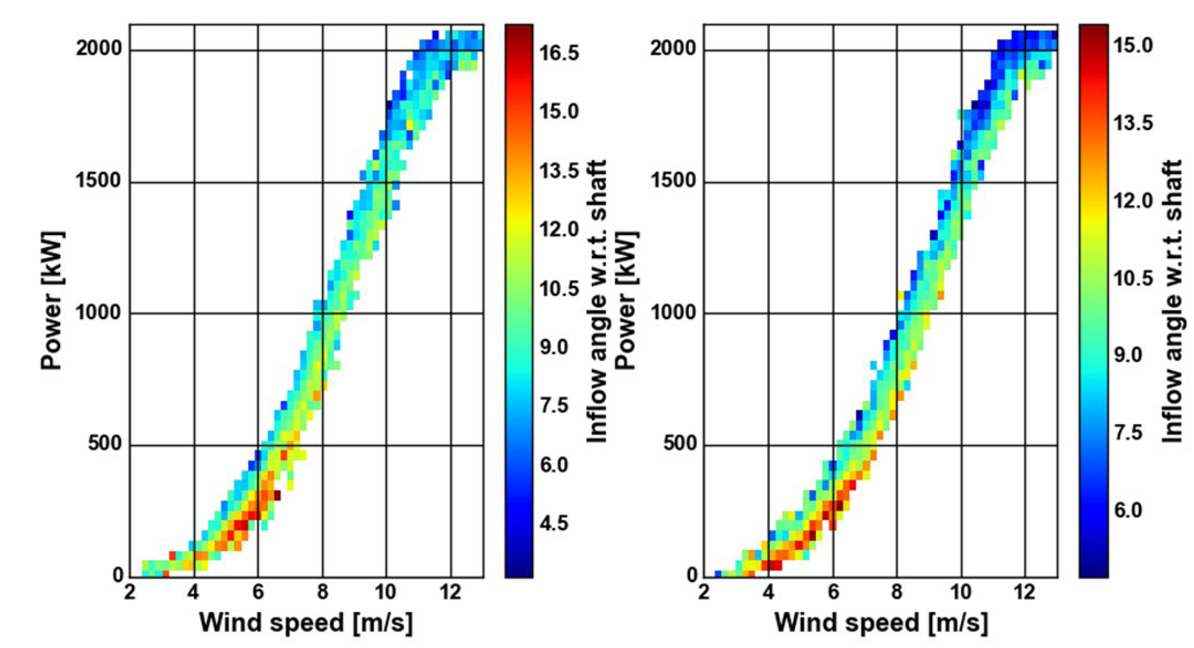
It would just be possible with "presumed" very little effort, like a remote parameter change of the yaw settings in the turbine control, to increase the annual energy performance of this turbine type on a entire fleet level by 1 to 1.2% depending on the average wind speed of the sites they are installed.

Power losses due to Yaw Misalignment

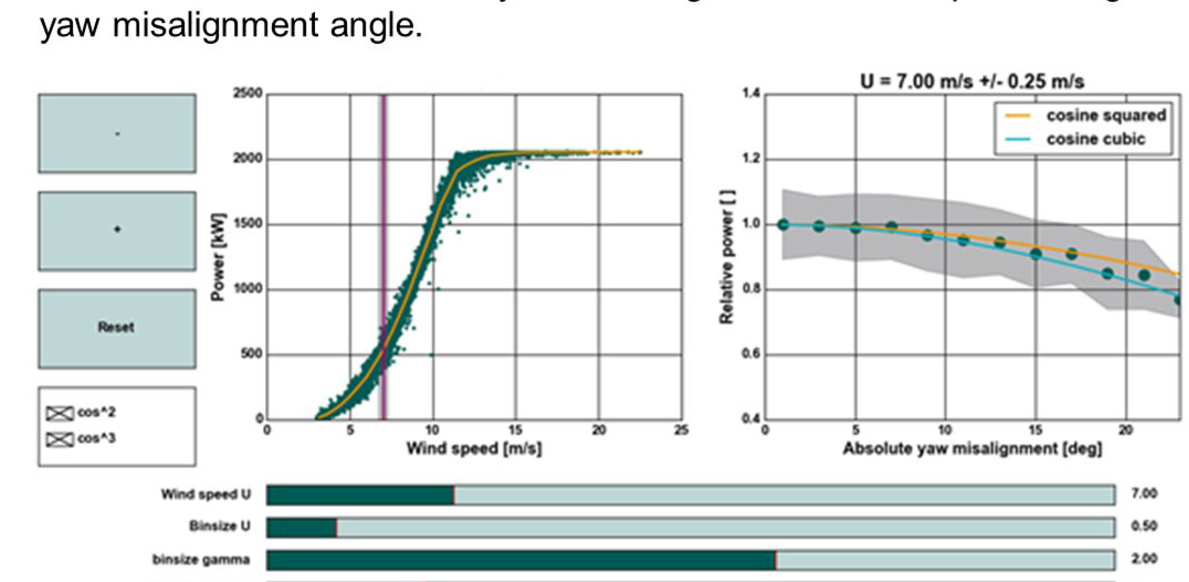
Theory-[3]:
The component of the wind vector that comes in perpendicular to the rotor of a wind turbine produces energy.



Real live measurements:
Below image illustrates through a "heat map", a typical measured scatter power curve from two different multi mega watt wind turbines.
The scatter curve is further color coded as a function of the 10min average power measurements vs wind speed, with the measured Vector inflow angle to the Rotor axis.
It is clearly visible that large inflow angles to the rotor leads to lower performance, see the "red" areas where the resulting wind vector to the rotor is exceeding 15 degrees. And when the wind vector is nearly perpendicular to the rotor area, "blue" the turbines yields its optimum performance.



Further dissecting the measured power curve, looking strictly at a small wind speed bin, its also possible using the accurate measured yaw misalignment angle by iSpin to plot the reduction in turbine performance as a function of yaw misalignment.
Below image illustrates a "lazy" turbine e.g. this type allow +/-20 degrees of dynamic yaw misalignment before it will start to turn into the wind.
This allows us to have a very broad range of measured power at given yaw misalignment angle.



Above to the right illustrates the measured average power from this wind turbines at 7m/s wind speed bin, and in 2 degrees yaw misalignment the average power normalized to the average power the turbine yields when its operated with zero degrees of yaw misalignment. The grey area marks the measured standard deviation of power for the same bin conditions.

So directly from measured power output from the turbine, its visible that at extreme angles the turbines looses over 20% of the energy potential compared to a good turbine which only allows 2-4 degrees yaw dynamic yaw misalignment.

Conclusions

Over 50% of all wind turbines in the 300 turbine sample have problems yawing into the incoming wind direction, resulting in severe losses of annual productions.

The vast majority of turbine types have acceptable average dynamic yaw control, only allowing between 2-4 degrees on average before they start yawing after the changed wind direction, but a selected few from the same turbine design is showing a great opportunity for improving energy yield by as much a 1.2% annually.

Energy losses related to static yaw misalignment have been shown to follow a cosine relationship, on average for all turbines in ROMO's database the energy could be improved for all of these turbines combined by more than 1.7% annually. For most wind parks where we conduct yaw misalignment correction, the return on investment is from one to five years depending on the local energy tariff and turbine type.

Contact ROMO wind should you be interested on further information.

References

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