Nacelle Orientation based Health Indicator for Wind Turbines

Yanjun Yan

Department of Engineering and Technology
Western Carolina University
Cullowhee, NC 28723
Email:yyan@wcu.edu

***Abstract*—A nacelle is the center hub of a wind turbine, with blades attached to it, and it is a key component to be controlled to ensure that the wind turbine face the incoming wind to capture the most energy. Ideally, the nacelle orientation and the wind direction should be opposite to each other. However, a non-effective control system may not be able to adjust the nacelle to its proper position, which can be a soft failure; or, in the worst case scenario like a spindle failure, the nacelle orientation is completely fixated at one direction since the turbine is shut down, which is a hard failure. Besides the well-known diagnostics tools using power and wind data to estimate the health state of a wind turbine, nacelle orientation is yet another informative variable to be added to the set of diagnostics tools, especially to detect the soft failures. In the SCADA (supervisory control and data acquisition) data set of wind turbines, there are dozens of measurement variables, on ambient weather, power, other electrical quantities, and some mechanical quantities. We have observed that the nacelle orientation exhibits a much more irregular or volatile pattern than the other variables, but the relationship between the wind direction and nacelle orientation is still effective to indicate an abnormal health state. We develop a metric to use nacelle orientation as the health indicator of wind turbines, and evaluate it using the data of nearly a hundred of wind turbines at a wind farm. Our method to construct the health indicator by nacelle orientation is driven by the SCADA data, without any pre-determined modeling, and hence it is automatic, adaptive and widely applicable on arbitrary number of wind turbines.**

***Index Terms*—Wind turbine, nacelle orientation, signal processing**

I. Introduction

Wind turbines extract energy from the wind, and most modern wind turbines are of horizontal axis, with blades facing the upcoming wind to maximize energy extraction. The nacelle is the center hub of a wind turbine where the blades are attached to, and the rotation of the nacelle is driven by the yaw system on the wind turbine [1]–[3]. The nacelle's dynamic movement can be estimated [4]–[6]. However, even without a complicated modeling of nacelle movement, we can detect whether the wind turbine is working properly or not, based on nacelle orientation data and the wind direction reference measurements collected at the meteorological tower.

There have been several diagnostics tools designed to test the nacelles [7], [8] and to monitor the wind turbine conditions [9]. In certain types of turbines such as the floating ones, nacelles can also be an important input in the control system [10]. In this paper, our focus is the wind turbine's overall health, and based on nacelle orientation and the reference wind direction, as well as other wind turbine's behavior across the wind farm, abnormality is readily observed, and further investigation can be carried out to find out the root cause of that abnormality.

The rest of the paper is organized as follows. The circular statistical metrics are introduced in section II, and then based on the statistics, an individual wind turbine test is developed in section III. Besides the single-turbine test, a full wind farm comparison turns out to be an effective indicator of outlier wind turbines in section IV. We conclude this paper and outline some future research areas in section V.

II. Circular Statistics

Nacelle orientation and wind direction measurement are periodic in 360 degrees, and hence the arithmetic mean and standard deviation do not always yield the desired result. For instance, two samples of 10 degrees and 350 degrees yield an arithmetic mean of 180 degrees, but apparently their average angle should have been 0 degree. To address this problem, circular statistics [11] are utilized to describe the distributions of nacelle orientation and wind direction.

A. Mean

An angle, α_i, can be represented by a unit vector, v_i, in the cartesian coordinate as

$$v_i = [\cos(\alpha_i), \sin(\alpha_i)]. \tag{1}$$

Then multiple angles, $\{\alpha_i\}$ $(i = 1, \cdots, N)$, can be represented by a cluster of unit vectors, $\{v_i\}$. The average vector is

$$\bar{v} = \frac{1}{N}\sum_{i=1}^{N} v_i, \tag{2}$$

which points to the average angle of the angle set. The average angle is then transformed from the average vector using the four quadrant inverse tangent function so that the average angle, $\bar{\alpha}$, is in the range of $[0, 360)$ degrees.

$$\bar{\alpha} = \angle\bar{v}. \tag{3}$$

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B. Variance

Given a set of angles, the length of the average vector, $|\bar{v}|$, is in the range of $[0, 1]$. Suppose $\bar{v} = R + iI$, then

$$|\bar{v}| = \sqrt{R^2 + I^2}. \tag{4}$$

Note that

$$\bar{v} = [\ |\bar{v}|\cos(\bar{\alpha}),\ \ |\bar{v}|\sin(\bar{\alpha})\ ] \tag{5}$$

If the unit vectors of the angles are either uniformly distributed or opposite in pairs on the unit circle, then the average vector is 0 with a length of 0; On the other hand, if the set of angles are all the same, then the average vector is the same unit angle vector, with length of 1. The angles are often in between these two extreme cases, and the resultant average vector has a length between 0 and 1. The closer it is to 0, the more spread or the more opposite the angles are; the closer it is to 1, the more concentrated the angles are.

As a result, the *circular variance* of a set of angles is

$$S = 1 - |\bar{v}|. \tag{6}$$

Note that $S \in [0, 1]$, but not in an arbitrary linear scale as the regular variance. An S value close to 0 indicates that the angles are concentrated around the average angle. However, an S value close to 1 does not necessarily indicate that the angles are uniformly distributed, as they can be oppositely distributed, too.

There are several related quantities that can be also used to describe the spread of the angle. For instance, the *angular variance* is

$$V = 2S = 2(1 - |\bar{v}|); \tag{7}$$

the *angular standard deviation* is

$$SD = \sqrt{V} = \sqrt{2(1 - |\bar{v}|)}; \tag{8}$$

and the *circular dispersion* is

$$D = \frac{1 - |\bar{v}|}{2|\bar{v}|^2}. \tag{9}$$

For our purpose to describe the spread of the angles, we will use circular variance, S, hereafter.

III. Single Nacelle Orientation Test Using Met Tower Wind Direction as a Reference

The met tower placed on the wind farm measures the wind direction, which can be used as a reference to expect where the wind turbine nacelle should point to. The nacelle should turn towards the incoming wind, and hence the nacelle orientation should be opposite to the met tower wind direction.

With a SCADA data rate to record the average values every 10 minutes, there are $6 \times 24 = 144$ data records per day. The wind direction changes rather rapidly and the nacelle responds quickly, and hence these variables can vary considerably within a day.

Based on the mean and variance metrics defined above, several cases are extracted from the two year and half data to show the faulty and healthy responses below.

A. Bad Responses

The first case is illustrated in Figure 1. If only the mean values of nacelle orientation and the met tower wind direction are considered, they appear to be opposite; however, the nacelle orientation shows an extremely small variance, which turns out to be a spindle failure and total shutdown.

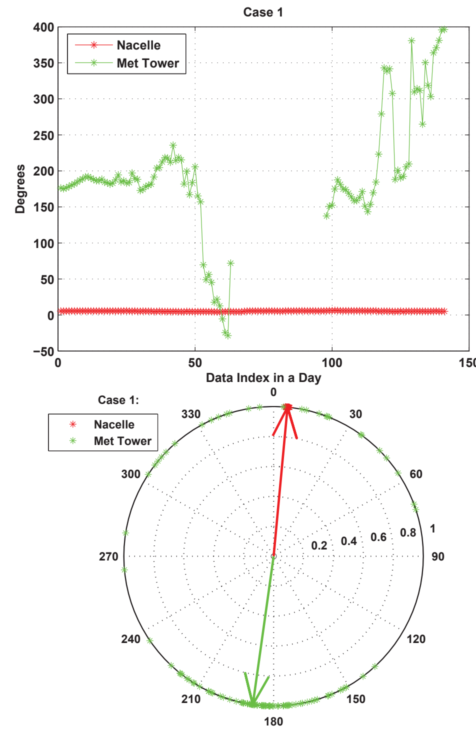

Fig. 1: Case 1: A hard failure where the opposite means are deceptive, but the variance clearly indicates a failure.

The second case is illustrated in Figure 2, where both the mean and the variance clearly indicate a hard failure.

B. Other Faulty Responses

The third case is illustrated in Figure 3, where the wind turbine is running, but the nacelle orientation is more volatile than the met tower wind direction, although their mean values are opposite. Further examination shows that the met tower's wind direction measurements do not seem to change, and it is a met tower issue, but not the wind turbine issue.

The fourth case is illustrated in Figure 4, where the wind turbine appears to face at some limited directions, while the wind direction is changing. Further examination shows that the nacelle is fixated around 75 degrees in the latter half of the day, but otherwise it responds reasonably, so the fixed angle could be due to scheduled maintenance or inspection when the turbine is braked.

The fifth case is illustrated in Figure 5, where both the mean and the variance indicate a failure, but the turbine is still running and its nacelle orientation over time is reasonable. The failure turns out to be a calibration issue in the met tower. Soft failures are not as dramatic or easily discernable as hard failures, and hence it is more valuable to find such soft failures.

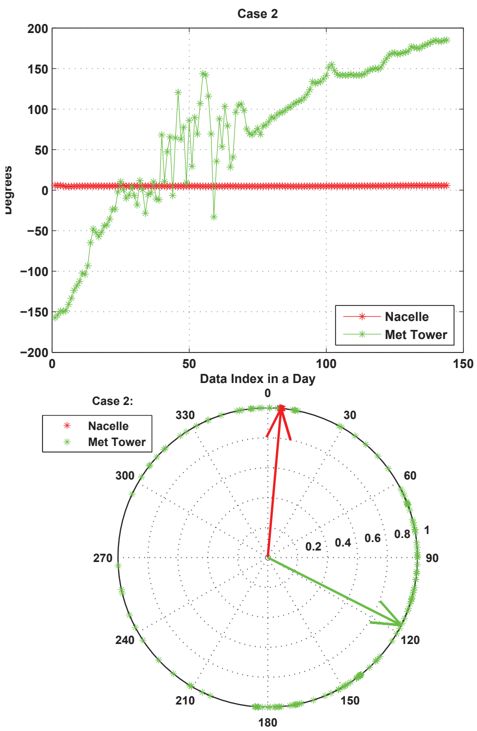

Fig. 2: Case 2: A hard failure where both the mean and the variance clearly indicate a failure.

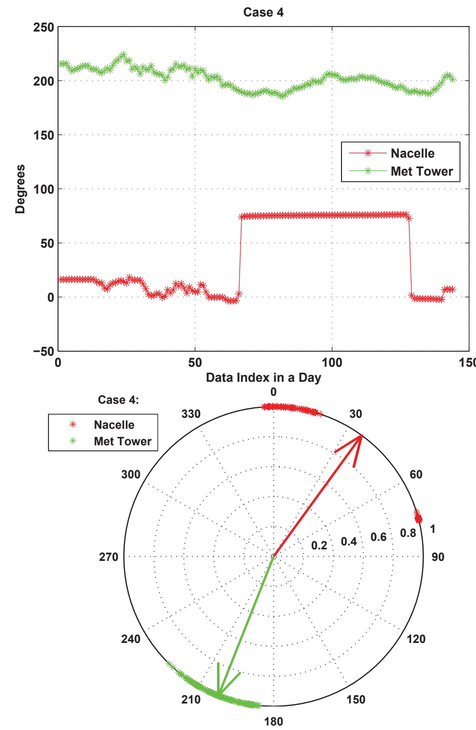

Fig. 4: Case 4: A case where the wind turbine appears to face around limited number of angles, while the wind direction changes over time.

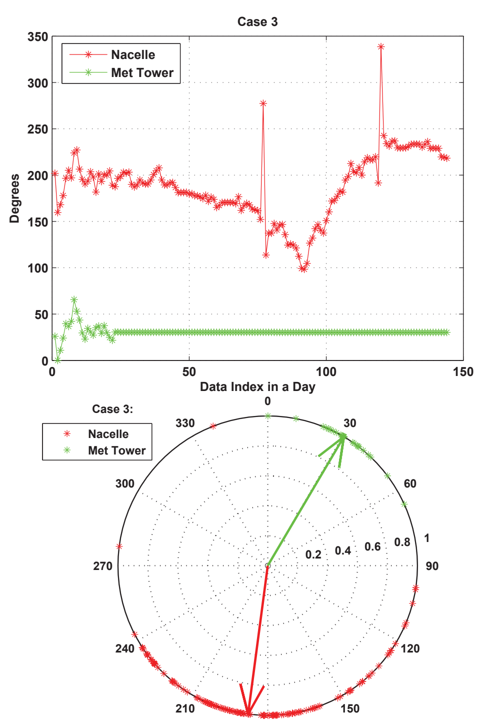

Fig. 3: Case 3: A met tower issue where the wind direction measurements appear not to change.

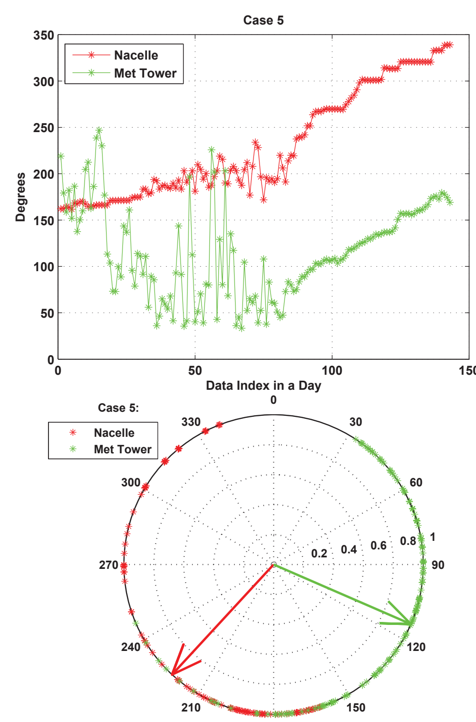

Fig. 5: Case 5: A soft failure in met tower where both the mean and the variance clearly indicate a failure.

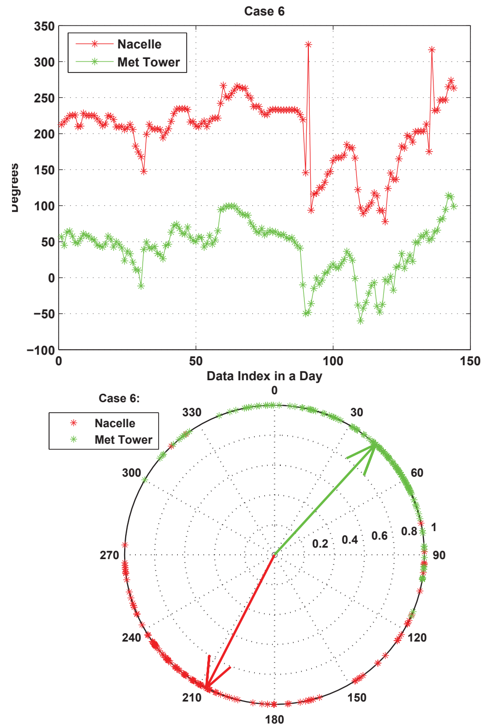

Fig. 6: Case 6: A normal working response for a single wind turbine.

C. A Good Response

The sixth case is illustrated in Figure 6, which is a normal case and can be often seen on the wind farm.

A common rule is derived from aforementioned examples. Let S_n denote the circular variance of a wind turbine's nacelle orientation, S_m be the one of met tower's wind direction measurement, $\bar{\alpha}_n$ be the average angle of the nacelle, and $\bar{\alpha}_m$ be the average wind direction. Suppose τ_1 is a threshold close to 0, τ_2 is close to 1, and they are used to gauge how concentrated or spread the nacelle orientations are. Suppose γ is a threshold close to 0 degree to gauge how much the average nacelle orientation differ from its expected angle based on the average wind direction. Then,

if $S_n < \tau_1$ **then**
  Check wind turbine's status, possibly in hard failure.
else if $S_n > \tau_2$ **then**
  if $S_m < \tau_2$ **then**
    Check wind turbine's status, possibly in soft failure.
  end if
else if $mod(\bar{\alpha}_n - \bar{\alpha}_m - 180, 180) > \gamma$ **then**
  Check wind turbine's status, possibly in soft failure.
end if

IV. Full Wind Farm Analysis by Comparing the Nacelle Orientations of All the Turbines

Besides each turbine's own nacelle orientation test based on the met tower's reference wind direction, the wind turbines on the same wind farm should share similar nacelle orientations if the wind direction is nearly the same over the entire wind farm [12]. Therefore, if there are some wind turbines that behave drastically different from others, they may be in a faulty state. Based on this rational, the daily comparison of all the wind turbines on the wind farm is carried out.

Despite the relatively fast changing wind direction and the corresponding nacelle orientation during a day, the average direction during the day among all the wind turbines on the wind farm is relatively stable. The outlier wind turbines on the wind farm are identified according to the rule below.

1) For each wind turbine, calculate its average nacelle orientation during a day, r_i, using circular mean definition, where $i = 1, \ldots, N$, and N is the total number of turbines in the region of analysis. In this data set, $N = 99$.
2) Evaluate the wind farm average of nacelle orientation across all the wind turbines. $r = \overline{\{r_i\}}$ using circular mean definition.
3) Calculate the average wind direction measured by a meteorological tower during the same day, m. Check whether m is roughly opposite to r: if yes, continue to the next step; if not, the meteorological tower might be temporarily unavailable on that day.
4) Using r as the reference angle, convert all the r_i's into the range of $(r - 180°, r + 180°]$ and sort them.
5) The set of r_i in the range of $(r - 180°, r)$ is the left hand side of r. The set of r_i in the range of $(r, r + 180°]$ is the right hand side of r. Exhaust the list of r_i's on both the left hand side and right hand side from the r_i's closer to r to the r_i's farther away from r. Record the step difference between any two consecutive r_i's.
6) The step difference is an indicator to tell whether the average nacelle orientation of next turbine is close to that of the previous turbines. The wind turbines on the wind farm tend to share similar average nacelle orientations, and the step differences in the earlier part of the turbine list are small. If the step difference becomes more than 2°, the remaining turbines on the exhaustion list are outliers.

Several typical cases are presented below.

A. Full Farm Comparison Case 1

The first case of full-farm comparison is illustrated in Figure 7. In the top two subplots, each column is corresponding to a wind turbine on the wind farm, and its nacelle orientation values are binned by 1 degree angle so that each row represents the number of angles that fall into that degree. The image on the left and the contour plot on the right both indicate similar information, and the rows different from others are the outliers shown in the bottom subplot.

In the bottom subplot of Figure 7, the average nacelle orientation of each wind turbine is shown as a red asterisk, and the circular mean of the average nacelle orientations is shown as the purple arrow. The range of the clustered average nacelle orientation is shown between the purple lines, where the difference of any two consecutive angles is no bigger than 2°. The green arrow shows the average wind direction measured by the met tower.

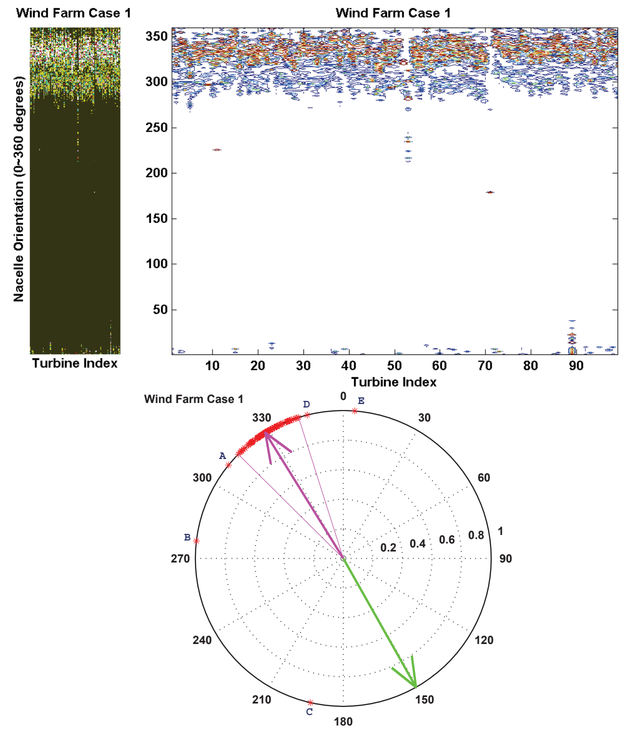

Fig. 7: Full Farm Comparison Case 1: There are a few outliers, marked as A-E.

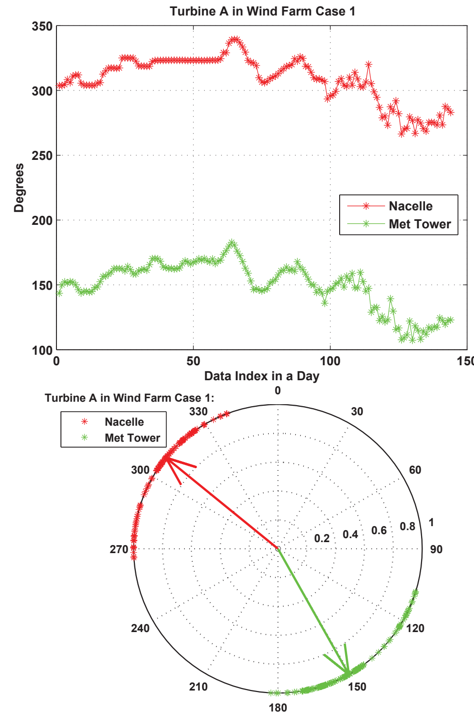

Fig. 8: Outlier turbine A on the day of Wind farm Case 1.

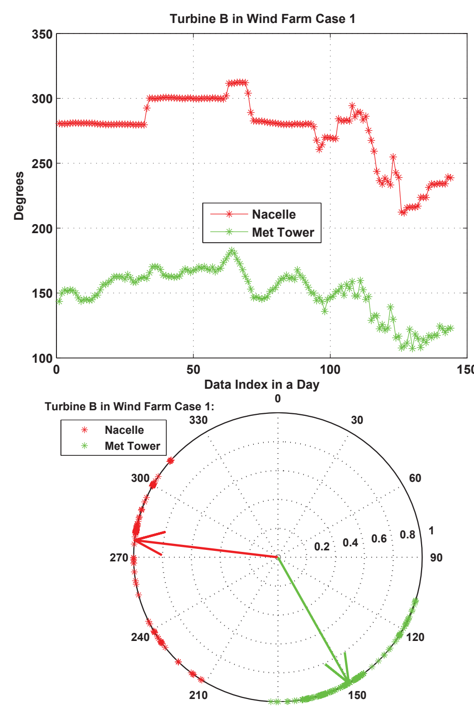

Fig. 9: Outlier turbine B on the day of Wind farm Case 1.

The outlier wind turbines are picked out and their data on this day are presented in Figures 8-12. Turbines A, B, and C are on the left hand side. Turbines D and E are on the right hand side. The daily average nacelle orientations of turbines A and D are still close to the cluster of the majority of the wind turbines, and their daily trends follow the wind direction well so they are decided to be healthy. Turbines B and E, however, fixed their orientations for several extended periods of time, causing the angle discrepancies and in soft failure. Turbine, C, had the biggest angle discrepancy, with missing data records while it was in repair.

B. Full Farm Comparison Case 2

The second case of full-farm comparison is illustrated in Figure 13. The circular mean of all the wind turbines' nacelle orientation is still clustered, but as seen from the top two subplots, there is some variation across the landscape of the wind farm, and the resultant average nacelle orientation across the wind farm is not exactly opposite to the average wind direction, but close.

C. Full Farm Comparison Case 3

The third case of full-farm comparison is illustrated in Figure 14. This case is similar to case 1, as in both cases, the nacelle orientations of each wind farm is concentrated around certain value, but there are more outliers in this case. The analysis of turbine health is similar to that of Case 1.

D. Full Farm Comparison Case 4

The fourth case of full-farm comparison is illustrated in Figure 15. On a day when the wind blows in various directions, the nacelle orientations are adjusted to follow that, and hence they can be very scattered. However, using the average nacelle

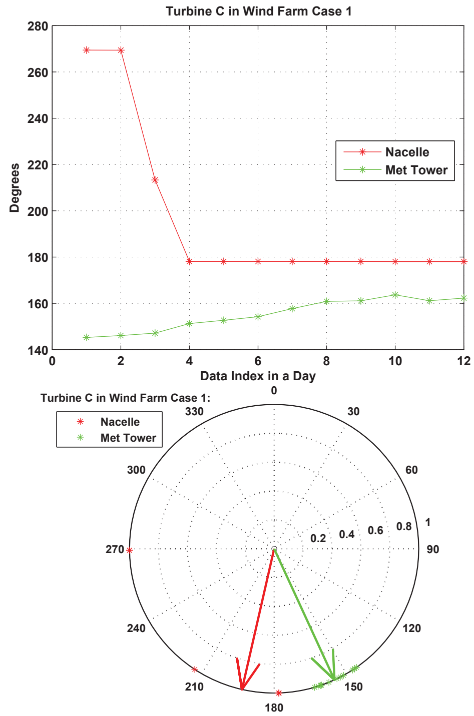

Fig. 10: Outlier turbine C on the day of Wind farm Case 1, due to missing data records.

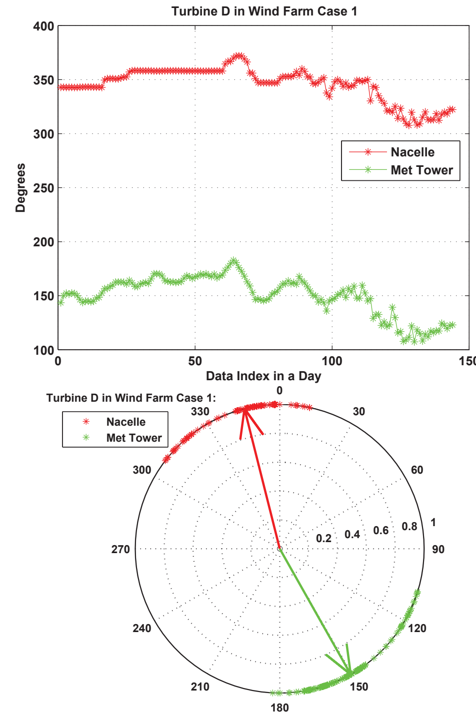

Fig. 11: Outlier turbine D on the day of Wind farm Case 1.

orientation of each turbine, and compare it with other turbines on the same wind farm, the wind farm average is still focused, and opposite to the reference wind direction.

V. Conclusions and Future Work

Nacelle is a critical component of a wind turbine that attaches blades and houses the control system, and its orientation is continually adjusted to face the upcoming wind to maximize wind energy extraction. We used circular statistics to describe the distributions of the volatile nacelle orientations and reference wind directions, and such statistics are effective to identify the hard failure and soft failure of a wind turbine. Meanwhile, we can compare the circular mean of all the wind turbines' nacelle orientations on the same day, and the outlier wind turbines are clearly identifiable as candidates for further investigation. In the future, we will combine the nacelle orientation test with other diagnostic tests such as power curve test, pitch angle test, and rotor speed test, to examine the overall system health of a wind turbine.

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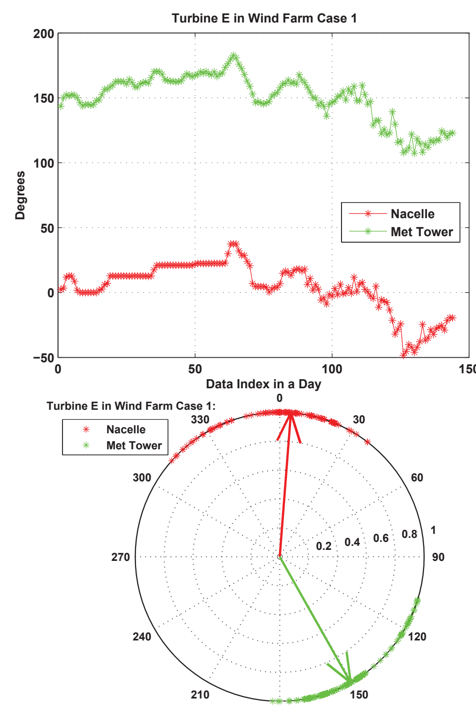

Fig. 12: Outlier turbine E on the day of Wind farm Case 1.

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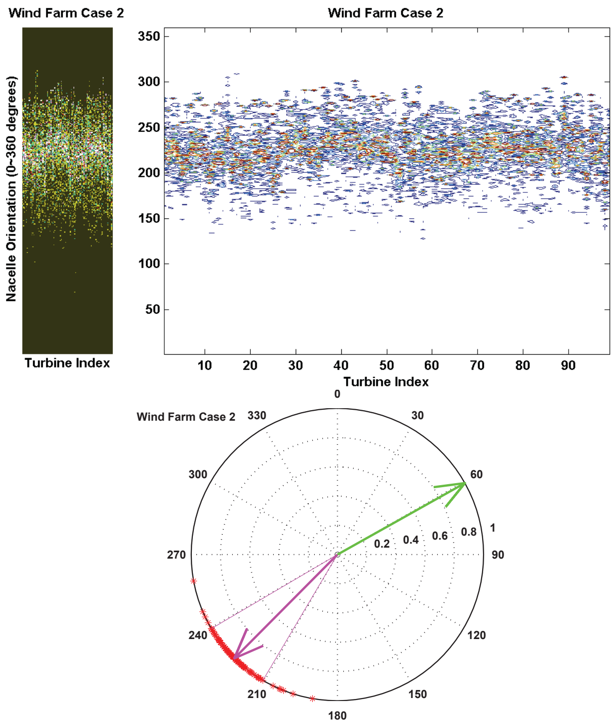

Fig. 13: Full Farm Comparison Case 2: There is slight variation of nacelle orientation across the farm, causing the average orientation is not exactly opposite to the wind direction.

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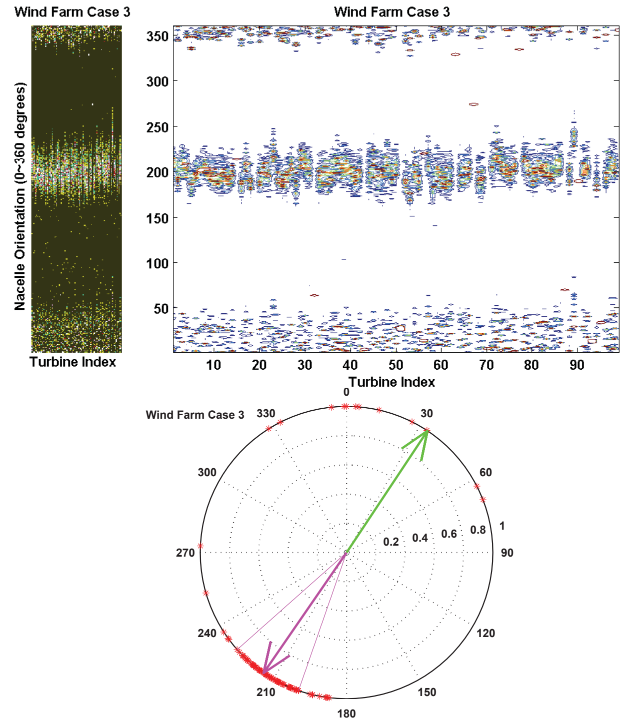

Fig. 14: Full Farm Comparison Case 3: This case 3 is similar to case 1 in that the nacelle orientations are concentrated, but they differ in that there are more outliers here.

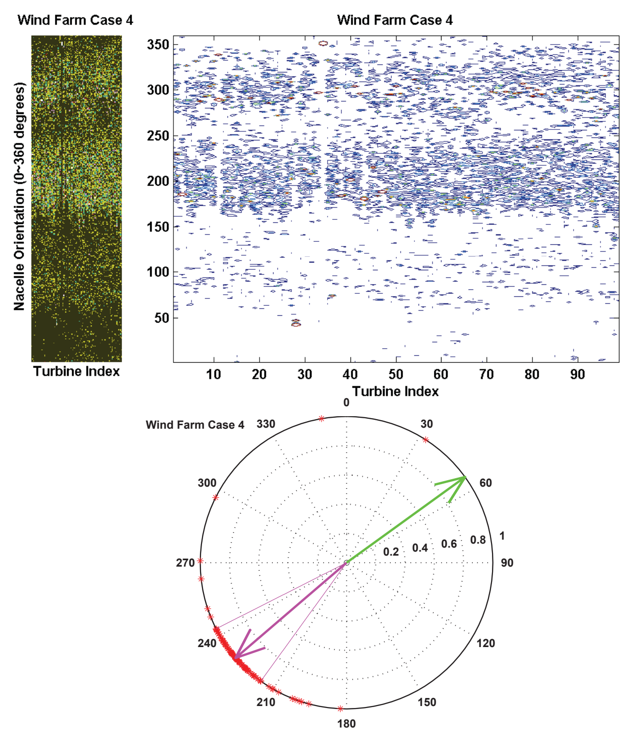

Fig. 15: Full Farm Comparison Case 4: The nacelle orientations of all the wind turbines are spread out, due to volatile wind directions on that day.