Wind Energy Analysis Using Python

Introduction

Wind turbines are equipped with Supervisory Control and Data Acquisition (SCADA) systems that continuously monitor operational, mechanical, and environmental parameters. Analysis of this data helps in understanding turbine performance and identifying early signs of component degradation.

In this project, SCADA data from multiple wind turbines is analyzed to study temperature trends, operational consistency, and abnormal operating conditions. Key parameters such as,

- Gearbox oil temperature
- Generator bearing temperature
- Wind speed
- power output
- Rotor speed
- Generator speed
- Blade pitch angle

are evaluated using time-series and scatter-plot analysis to support condition monitoring and predictive maintenance.

Objective

The objectives of this analysis are:

- To identify early indications of failure using temperature vs time analysis
- To detect abnormal operating points through wind speed and power relationships
- To verify operational consistency between rotor and generator rpm speeds.

Dataset Information:

- **Timestamp** – Time of data acquisition
- **Turbine_ID** – Unique identifier for each turbine
- **Amb_WindSpeed_Avg (m/s)** – Average ambient wind speed
- **Grd_Prod_Pwr_Avg (kW)** – Power delivered to the grid
- **Rtr_RPM_Avg (rpm)** – Rotor rotational speed
- **Gen_RPM_Avg (rpm)** – Generator rotational speed
- **Gear_Oil_Temp_Avg (°C)** – Gearbox oil temperature
- **Gen_Bear_Temp_Avg (°C)** – Generator bearing temperature
- **Blds_PitchAngle_Avg (deg)** – Blade pitch angle

```
 #    Column
---   ------
 0    Turbine_ID
 1    Timestamp
 2    Gen_RPM_Avg
 3    Gen_Bear_Temp_Avg
 4    Gear_Oil_Temp_Avg
 5    Rtr_RPM_Avg
 6    Amb_WindSpeed_Avg
 7    Amb_Temp_Avg
 8    Blds_PitchAngle_Avg
 9    Grd_Prod_Pwr_Avg
```

Fig 1 : Dataset Description obtained from cell output (from wind_energy_analytics.py)

Methodology :

Tools used : Python (pandas and matplotlib)

Approach :

- Python was used as the primary tool for data preprocessing, analysis, and visualization due to its strong support for numerical and time-series data handling.
- Pandas was used to load the SCADA dataset, clean the data, convert timestamp values into datetime format, sort the data chronologically, and filter turbine-specific records. Its DataFrame structure enabled efficient handling and manipulation of large tabular datasets.
- Matplotlib was used to generate time-series and scatter plots for visual analysis. It enabled clear visualization of temperature trends, power curves, and operational relationships, which are essential for detecting anomalies and early failure indicators.
- Timestamp values were converted to datetime format and sorted to ensure accurate time-series visualization and trend analysis.
- A single turbine (T01) was selected for temperature trend analysis to avoid mixing operational behaviors from multiple turbines, which could obscure early failure patterns.
- Scatter-based analysis was performed using data from all turbines to study general operational relationships, identify anomalies, and verify the expected linear relationship between mechanically linked parameters.

Data Analysis and Insights

Task : 1 - Early Failure Indicator Analysis

Description :

Temperature is a critical indicator of mechanical health. Gradual increases in gearbox oil temperature or generator bearing temperature under similar operating conditions may indicate increased friction, wear, or cooling inefficiency.

Analysis performed :

- Gear Oil Temperature vs Time (T01)
- Generator Bearing Temperature vs Time (T01)

Observations :

- Both temperatures show ==gradual variation over time.==
- Certain periods exhibit a slow increasing trend even when wind speed and power output remain relatively constant.

Conclusion :

==Gradual temperature rise== under stable operating conditions indicates potential early-stage component degradation and highlights the importance of continuous temperature monitoring.
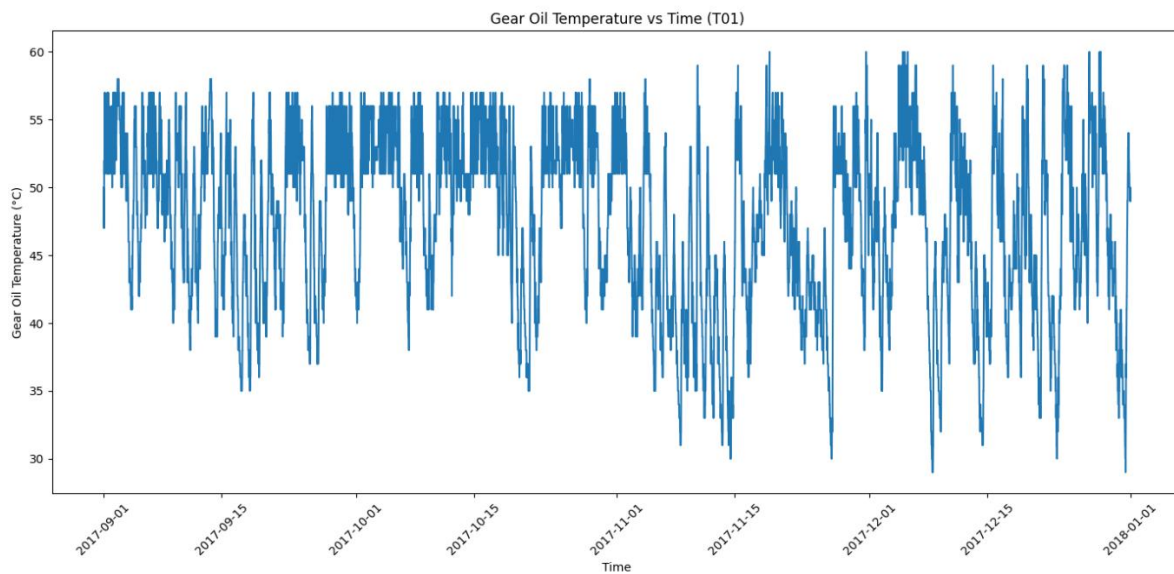
Fig 2 : Gear_Oil_Temp_Avg vs time (from wind_energy_analytics.py)
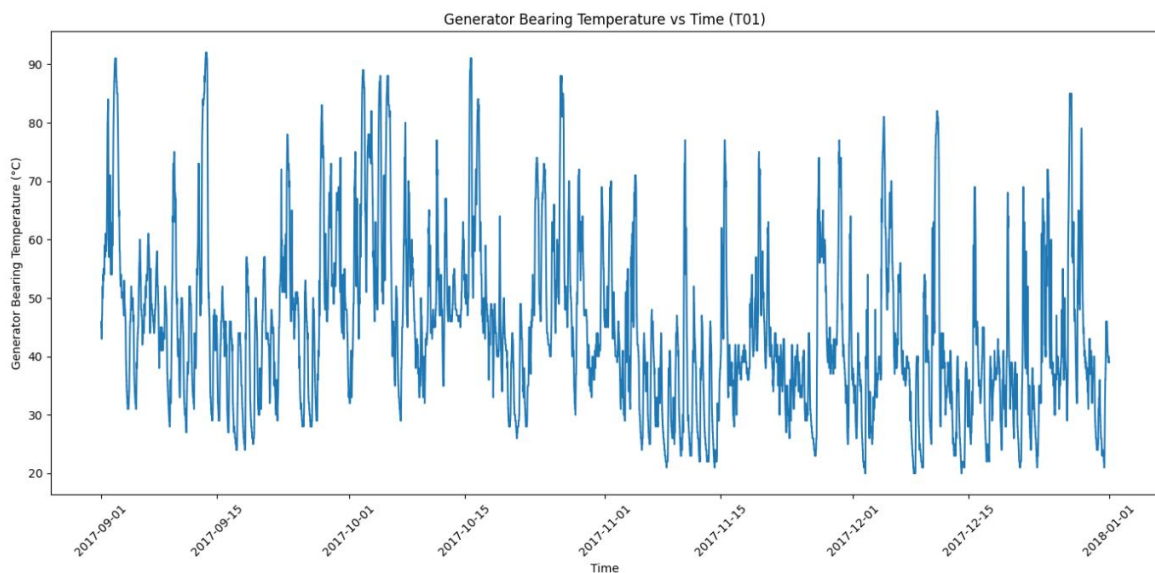
Fig 3 : Gen_Bear_Temp_Avg vs time (from wind_energy_analytics.py)

Task : 2 - Anomaly Detection Using Scatter Plots

Description :

The relationship between wind speed and power output defines the turbine power curve. Deviations from this curve indicate operational anomalies.

Analysis Performed :

Plotting of Ambient Wind Speed vs Generated Power (all turbines)

Observations :

- Most points follow the expected power curve.
- Some points(Operational Anomalies) lie outside the normal curve, showing low or zero power at sufficient wind speeds.

Conclusion :

These deviations represent operational anomalies that may occur due to curtailment, shutdowns, grid limitations, or sensor errors. Scatter-based anomaly detection provides a fast and intuitive method to identify underperforming turbines without requiring complex models.
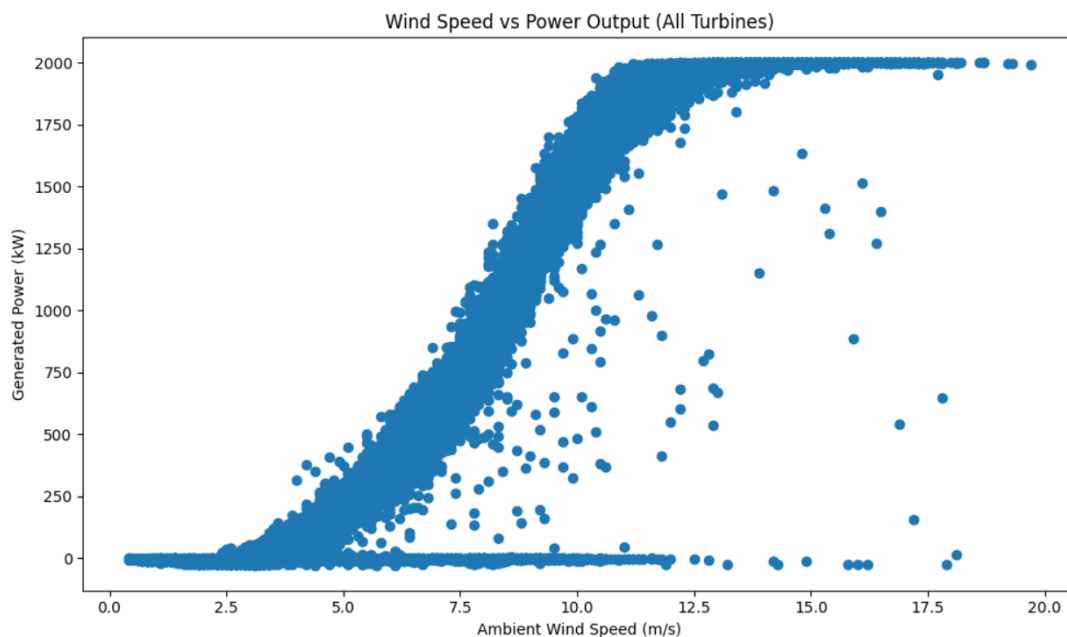
Fig 4 : Amb_WindSpeed_Avg vs Grd_Prod_Pwr_Avg. (from wind_energy_analytics.py)

Task : 3 - Operational Consistency Check

Description :

Rotor and generator speeds are mechanically linked through the gearbox. A linear relationship is expected during normal operation.

Analyis Performed :

- Scatter plot of Rotor RPM vs Generator RPM (all turbines)

Observations :

- A ==strong linear relationship is observed==.
- ==Minor deviations== from the trend exist.

Conclusion :

The linear relationship confirms normal mechanical operation. Deviations may indicate gearbox inefficiency or measurement issues. Hence ==most of the points satisfies the linear relationship.== Maintaining a consistent rotor to generator speed ratio is critical for efficient power conversion and mechanical reliability.
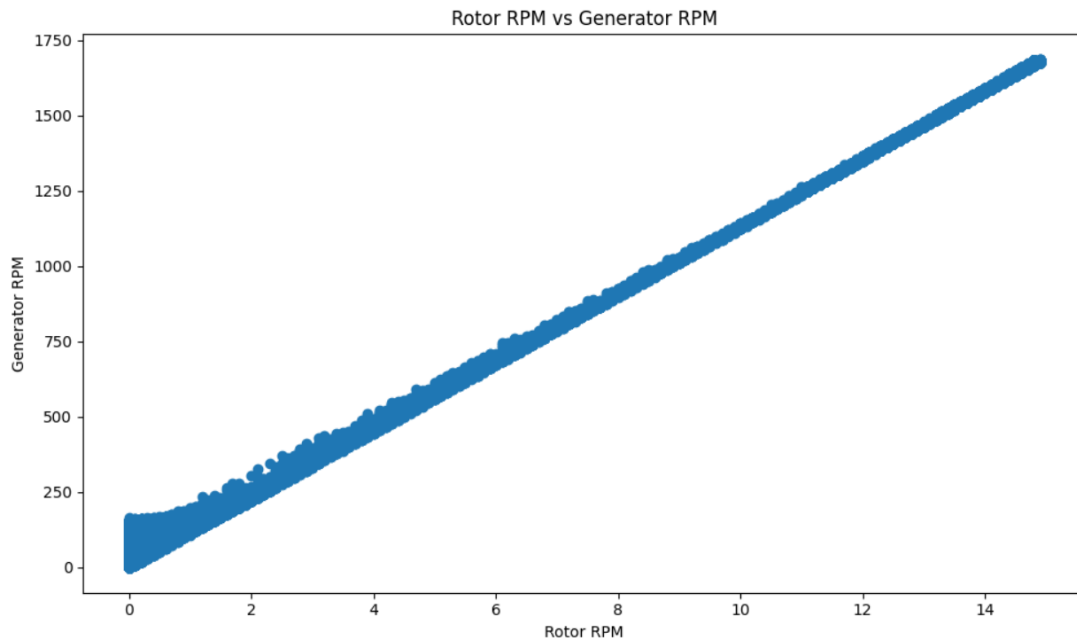
Fig 5 : Rtr_RPM_Avg vs Gen_RPM_Avg (from wind_energy_analytics.py)

Task 4: Simple Predictive Trend Analysis

Description :

The relationship between turbine power output and component temperature helps assess thermal loading and predict potential overheating risks at higher operating loads.

Analysis Performed :

Plotting of **Generated Power vs Gear Oil Temperature** and fitting a simple trend line to observe temperature behavior with increasing load.

Observations :

- ==Gear oil temperature increases gradually with power output.==
- At lower power levels, temperature rise is more noticeable due to increasing mechanical load.
- ==At higher power levels==, temperature tends ==to stabilize==, indicating ==effective cooling==.

Conclusion :

The observed trend suggests that gear oil temperature remains within safe operating limits even at higher power outputs. Trend-based analysis helps in predicting thermal stress and enables early identification of abnormal heating conditions before component failure occurs.
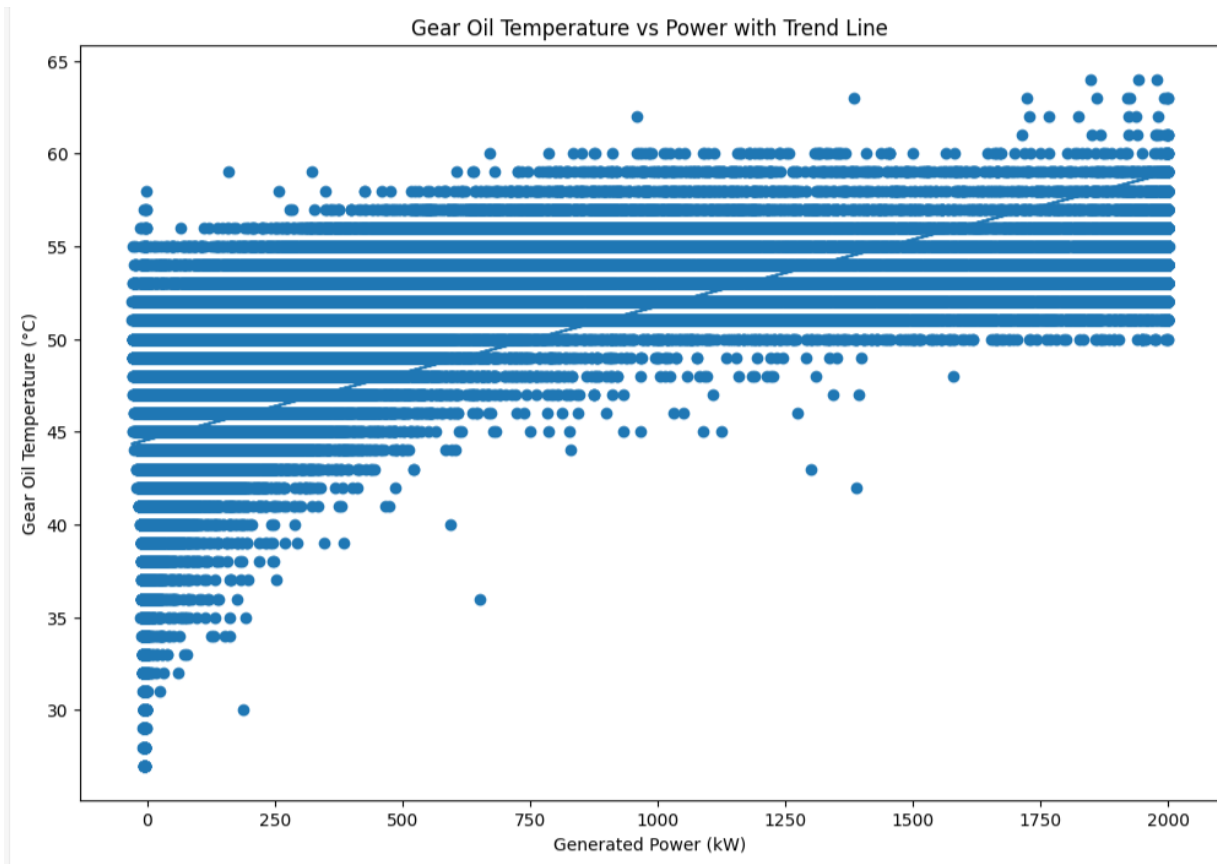
Fig 6 : gear_oil_temp VS power - With Trend line (from wind_energy_analytics.py)

Task 5: Blade Pitch Health Check

Description :

Blade pitch angle variation with wind speed reflects the effectiveness of the turbine's pitch control system in regulating aerodynamic power and protecting the turbine at high wind speeds.

Analysis Performed :

Plotting of **Blade Pitch Angle vs Ambient Wind Speed** to examine the smoothness and consistency of pitch response across operating conditions.

Observations :

- Blade pitch angle increases smoothly with increasing wind speed.
- No prolonged high pitch angles were observed at constant wind speeds.
- No abrupt fluctuations or irregular pitch behavior were detected.

Conclusion :

The blade pitch control system is operating normally, showing smooth and stable response to wind speed variations. This indicates healthy pitch actuators and control logic, with no evidence of control instability or mechanical degradation.
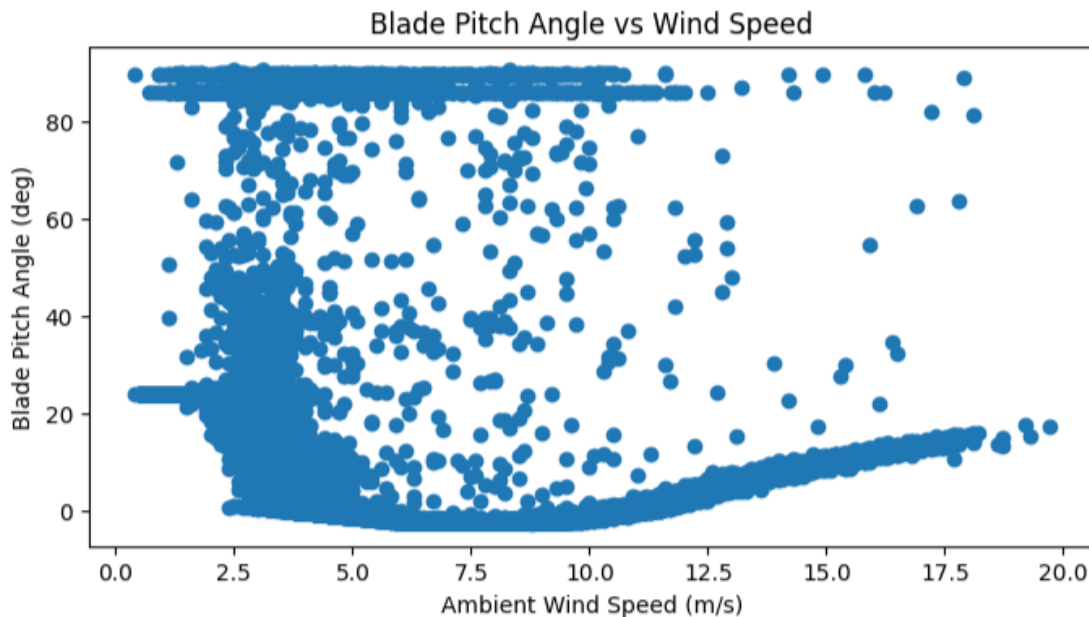
Fig 7 : Blade_pitch_angle VS Wind_speed (from wind_energy_analytics.py)

Final Conclusion :

This analysis demonstrates the effective use of SCADA data for monitoring wind turbine health and operational performance. Temperature trend analysis enabled the identification of potential early stage component degradation, while wind speed–power relationships helped detect abnormal operating conditions. The operational consistency check further confirmed the mechanical reliability of the turbine drivetrain.

By combining time-series analysis with relationship-based scatter plots, this study highlights how multiple parameters can be jointly analyzed to improve condition monitoring and support predictive maintenance strategies. Such an approach helps reduce unplanned downtime, improve turbine reliability, and enhance overall operational efficiency.

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