Assessment of wind power plant performance using turbine performance and power curves: a case study of PLTB TOLO I Jeneponto

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Abstract

Jeneponto Regency in South Sulawesi possesses significant wind potential, making it an ideal location for the development of Wind Power Plants (WPP). However, these WPPs are intermittent due to the inconsistent nature of wind energy, presenting challenges that affect the performance and efficiency of turbines in generating electricity. Therefore, this study aims to evaluate the performance of the SWT-3.6-130 wind turbines at the Tolo 1 WPP in Jeneponto to determine their capability in converting wind energy into electrical energy at specific wind speeds. The evaluation results indicate that the performance of the SWT-3.6-130 wind turbines at the Tolo WPP in February 2022 was not optimal. The maximum output power generated by these turbines approached the maximum capacity of 3.6 MW, with Turbine 06 producing 3.57 MW at a wind speed of 13.07 m/s, Turbine 09 producing 3.57 MW at a wind speed of 12.27 m/s, and Turbine 013 producing 3.58 MW at a wind speed of 12.11 m/s. Although the power generated was close to the maximum capacity, the performance variation among turbines indicates the need for further evaluation to address factors reducing efficiency. Power coefficient analysis shows that Turbine T13 exhibited the best performance, with the fewest instances of power coefficient values not meeting standards. This study provides crucial insights for improving performance and preventing failures at the Tolo WPP in the future.

Keywords: *wind speed, Maximum power output, Wind Turbine, assessment, Power Coefficient.*

I. INTRODUCTION

Renewable energy, particularly wind energy, has increasingly become a primary focus in reducing dependence on non-renewable fossil energy sources and mitigating their negative environmental impacts [1]. Wind Power Plants (WPP) present a promising solution to meet electricity demands by harnessing wind potential, especially in regions with strong wind resources [2], [3]. Jeneponto Regency in South Sulawesi, Indonesia, is known for its significant wind potential, making it an ideal location for WPP development [4].

A field study was conducted by constructing a wind measurement tower (met mast) approximately 135 meters above ground level. The study results indicated that the average wind speed in the area falls within the strong wind category (10.8-13.8 m/s or 39-49 km/h based on the Beaufort scale) [5]. The topographical conditions in Tolo vary between flat and undulating, making it highly suitable for WPP development.

The SWT-3.6-130 wind turbine is an appropriate choice for Jeneponto [6]. This onshore turbine begins operating at a wind speed of 4 m/s, with optimal efficiency at 12 m/s. However, WPPs are intermittent due to their reliance on renewable energy sources. Additionally, other challenges affect turbine performance and efficiency, leading to energy losses. Turbine efficiency is characterized by the power coefficient (Cp).

An analysis of turbine performance based on the power curve is necessary. The power curve records data in the form of a curve and has normal and abnormal limits. The results of this analysis can be used as a reference and evaluation to address factors causing reduced turbine efficiency and to prevent failures at the Tolo WPP.

Therefore, this study will evaluate the performance of the Tolo 1 Wind Power Plant in Jeneponto based on the power curve of wind turbine performance

II. LITERATURE STUDY

A. Wind Power Plants

Wind Power Plants, also known as Wind Energy Conversion Systems (WECS), are a type of renewable energy power plant that is environmentally friendly and exhibits high operational efficiency compared to other renewable energy sources [7]. These plants convert the kinetic energy in the air into mechanical energy, causing the generator to rotate and produce electrical current [8]. Wind energy is used to turn the blades, which in turn rotate the rotor. As the rotor spins, the generator automatically generates electrical energy, as illustrated in Figure 2.1 [9]:

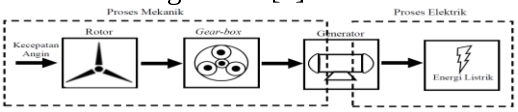

Figure 1. PLTB working process

B. Wind Turbines

Wind turbines are the primary components of wind power plants used to generate electricity by converting the kinetic energy of wind [10], [11], [12]. Initially, wind turbines were developed to meet farmers' needs for milling and irrigation. Early wind turbines were constructed in Denmark, the Netherlands, and other European countries and were known as windmills. Since the commercial use of wind turbines for electricity generation in the 1980s, their characteristics, efficiency, capacity, and design have improved significantly [13]..

In a wind turbine, the amount of wind energy captured depends on the size and wind speed of the turbine blades. According to several documents, the wind speed required for wind turbines ranges from 3 m/s to 20 m/s. The wind energy potential in Indonesia typically exceeds 5 meters per second (m/s) [14]. Mapping results from the National Institute of Aeronautics and Space (LAPAN) at 120 locations indicate that wind speeds in several regions exceed 5 m/s, including East Nusa Tenggara, West Nusa Tenggara, South Sulawesi, and the southern coast of Java, reaching up to 20 m/s [15].

C. SWT-3.6-130 Wind Turbine

The SWT-3.6-130 wind turbine is manufactured by Siemens Wind Power A/S, a Danish company that has been in business since 2004. In 2017, Siemens Wind Power A/S ceased operations and was subsequently acquired by Siemens Gamesa Renewable Energy. The rated power of the Siemens SWT-3.6-130 is 3.60 MW. The wind turbine begins operation (cut-in) at a wind speed of 4.0 m/s and ceases operation (cut-out) at a wind speed of 25.0 m/s [9].

The rotor diameter of the Siemens SWT-3.6-130 is 130.0 m, with a rotor area of 13,300.0 m². The wind turbine is equipped with three rotor blades. The maximum rotor speed is 12.8 rpm. The Siemens SWT-3.6-130 utilizes a direct drive system. Its generator is configured with a permanent magnet synchronous system. The manufacturer has employed a single generator for the SWT-3.6-130, with a maximum generator speed of 12.8 rpm. The voltage is 690.0 V, and the electrical frequency is 50 Hz. For tower construction, the manufacturer uses steel tubing. To protect against corrosion, Siemens focuses on painting the exterior of the tower. There is no model for this wind turbine, and the power curve is shown in Figures 4 and 5 below:

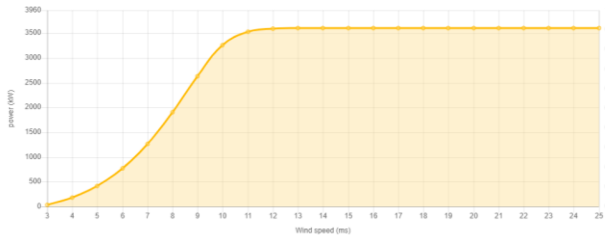
Figure 4. Power Curve Turbin SWT-3.6-130

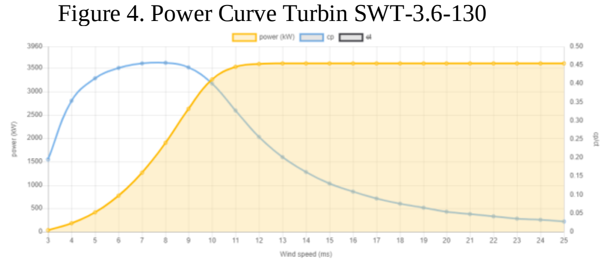
Figure 5. Comparison of Turbine Power Curve with Power Coefficient

D. Power Curve

The power curve monitoring method for wind turbines was developed to prevent turbine failures in wind farms (WPP) [16], [17]. Compared to other methods, the algorithm in this SCADA application automatically calculates the power curve limits for monitoring purposes, and most abnormal data are recorded in the output power data of wind speed measured at the wind turbine. Additionally, the algorithm automatically generates alarm messages when the wind speed or power data measured at the wind turbine deviates from the power curve limits, particularly in cases where the measured data fluctuates between warning zones and alarm zones.

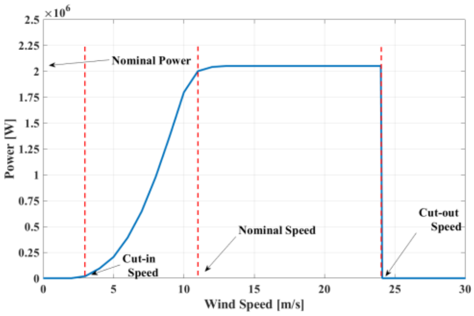

Figure 6. Example of Power Curve

As shown in Figure 6, the power curve illustrates the power behavior of the generator, indicating whether it is fault-free, abnormal, or experiencing deviations that can be classified as anomalies or faults. According to Figure 6, faults can lead to a reduction in the production capacity of a wind turbine, which is reflected in the power curve. Causes include down-rating, pitch control failures, ice or snow on the turbine blades, erosion, wind speed measurement errors, dirt or bugs on the blades, and other factors [9].

Power Coefficient The Power Coefficient (Cp) is the ratio of the rotor's output power to the total power passing through the rotor's cross-sectional area [18], [19]. The power coefficient value of a wind turbine indicates the turbine's efficiency in converting the kinetic energy of wind into electrical energy. This value typically ranges from 0.25 to 0.45, depending on the type and design of the wind turbine used [20]. The power coefficient will not exceed the ideal value of 0.5932. Under optimal conditions, the percentage of wind energy converted into electrical energy by the turbine does not exceed 60%, with the highest limit given as 0.593. The power coefficient significantly influences the performance of wind turbines and is affected by the turbine's construction and energy conversion principles, which can be formulated as follows :

$$Cp = \frac{P_{out}}{P_{in}} \qquad (1.1)$$

Notation :
Pout :Power generated by the wind turbine (Watt)
Pin :Power at the rotor cross-section (Watt)
Cp : Power coeffient

$$P_{in} = C_p \cdot \frac{1}{2} \cdot \rho_a \cdot A \cdot v^3 \qquad (1.2)$$

Notation :
P_A : Wind Power (watt)
C_p : Power coeffient
A : Cross-sectional/blade area (m^2)
v : Wind Speed (m/det)
ρ_a : Air density (kg/m^3)

III. RESEARCH METHODOLOGY

Data collection in this study was conducted using the SCADA (Supervisory Control and Data Acquisition) application located in the control building of the Tolo 1 Wind Power Plant. The monitoring of all wind turbines and supporting data, such as wind speed, was carried out using this application. Initially, a reference power curve under normal conditions provided by the manufacturer was required. This reference served as the standard for all test cases and was used to analyze the power curve under fault conditions. Subsequently, raw data obtained from SCADA were processed to extract wind speed and output power data. Once all data were collected, data visualization was performed using graphs, followed by an analysis of these graphs. Finally, calculations were conducted to determine the power coefficient (Cp) or the extent to which electrical energy could be converted from wind kinetic energy using the formula in Equation 1.1

IV. RESULTS AND DISCUSSION

A. Wind Turbine Performance in February 2022

The following figure presents the performance data graphs for wind turbines T06, T09, T12, T13, and T16 at the Tolo Wind Power Plant in February 2022, derived from the raw turbine data

Table 2. Daily data of wind speed and active power of wind turbine T06*

Recording Time	Wind Speed (m/s)	Active Power (kW)
00:00	6,591109276	825,5244751
00:10	6,596529484	798,1812744
00:20	5,675075054	518,9650269
…	…..	…….
23:50	8,247551918	1512,180054

* Data Collection Date: February 1, 2022

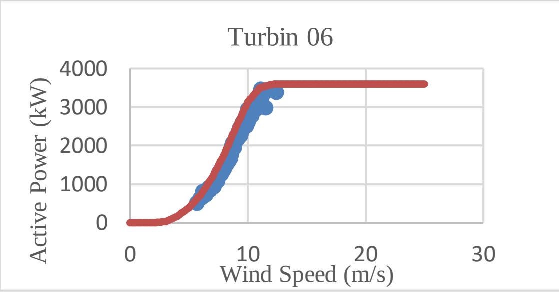

Figure 7. Performance Power Curve of Turbine T06 on February 1, 2022

The power curve performance of turbine T06, as depicted in Figure 7, illustrates the power output data of Turbine 06 based on wind speed, with the blue curve representing power output and the red curve representing parameter values. As wind speed increases from 0 m/s, the power generated by the turbine also rises sharply. The graph indicates that the power output of the turbine increases with wind speed, reaching its peak at approximately 12-15 m/s, with a maximum power output of around 3600 kW. Anomalies in the power output graph of Turbine 06, based on wind speed, are attributed to environmental factors. Detailed data can be found in Appendix 2

Table 3. Daily data of wind speed and active power of wind turbine T09*

Recording Time	Wind Speed (m/s)	Active Power (kW)
00:00	5,846326351	549,8377686
00:10	5,703861237	482,4072571
00:20	5,376627445	475,3831482
…	…..	…….
23:50	7,432094574	1199,568359

* Data Collection Date: February 1, 2022

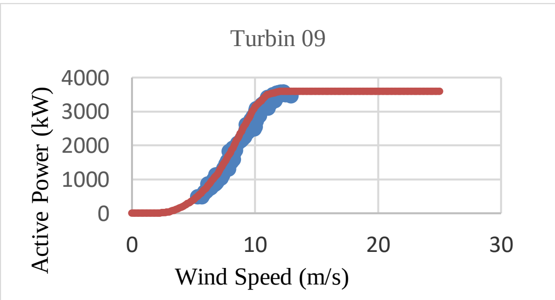

Figure 8. Performance Power Curve of Turbine T09 on February 1, 2022

The power curve performance of turbine T09, as depicted in Figure 8, presents the power output data of Turbine 09 based on wind speed, with the blue curve representing power output and the red curve representing parameter values. As wind speed increases from 0 m/s, the power generated by the turbine also rises sharply. The graph indicates that the power output of the turbine increases with wind speed, reaching its peak at approximately 12-15 m/s, with a maximum power output of around 3600 kW. There are no anomalies in the above curve, indicating that the turbine operates under normal conditions. Detailed data can be found in Appendix 3

Table 4. Daily data of wind speed and active power of wind turbine T13*

Recording Time	Wind Speed (m/s)	Active Power (kW)
00:00	6,709965706	951,1233521
00:10	6,602739334	895,3196411
00:20	5,255161285	477,7576904
…	…..	…….
23:50	8,320677757	1773,37207

* Data Collection Date: February 1, 2022

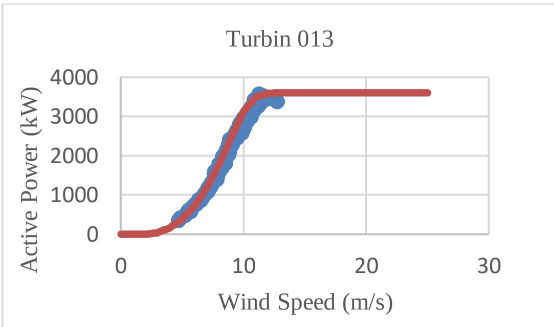

Figure 9. Performance Power Curve of T13 Turbine on February 1, 2022The power curve performance of turbine T013, as depicted in Figure 9, presents the power output data of Turbine 013 based on wind speed, with the blue curve representing power output and the red curve representing parameter values. As wind speed increases from 0 m/s, the power generated by the turbine also rises sharply. The graph indicates that the power output of the turbine increases with wind speed, reaching its peak at approximately 12-15 m/s, with a maximum power output of around 3600 kW. The power curve of Turbine 013 shows point anomalies caused by environmental factors. Detailed data can be found in Appendix 4.

B. Relationship Between Power Coefficient and Wind Speed for the SWT-3.6-130 Wind Turbine

The calculation of the power coefficient (Cp) utilizes raw turbine data, including wind speed and active power data recorded every ten minutes on February 1, 2022. These calculations are performed using Equation 1.2 to determine the wind power (Pin) and Equation 1.1 to calculate the wind turbine efficiency or power coefficient.

Table 5. Raw data samples for calculations

No	Time	Name	Wind Velocity (m/s)	Active Power (kW)
1	01/02/ 2022 00.10	T06	6,59652948	798,18

To calculate P_{in} the required value of A (cross-sectional area) for the rotor/blade of each turbine, the following circle area formula is used

$A = 1/4\pi d^2$

$A = 0{,}25 \times 3{,}14 \times 130^2$

$A = 13.273{,}23\ m^2$

After determining the rotor's cross-sectional area, the wind power P_{in} (Pin) is calculated using Equation 3.3.

$$P_{in} = \frac{1}{2} A \cdot v^3 \cdot \rho$$

$$P_{in} = 0{,}5 \times 13.273{,}23 \times 6{,}59^3 \times 1{,}225$$

$$P_{in} = 2.333.615\ W$$

$$P_{in} = 2.333{,}61\ kW$$

After determining the rotor's cross-sectional area, the wind power (Pin) is calculated using Equation 3.3.

$$Cp = \frac{Pout}{Pin}$$

$$Cp = \frac{798{,}18}{2.333{,}61}$$

$$Cp = 0{,}34$$

Therefore, the power coefficient or efficiency of the wind turbine at a wind speed of 6.59 m/s is 34%. Generally, the power coefficient is considered normal when it ranges from 0.25 to 0.45. Subsequently, the results of the power coefficient calculations that do not meet the performance standards of the Tolo 1 Wind Power Plant were processed using Microsoft Excel to generate a power coefficient graph

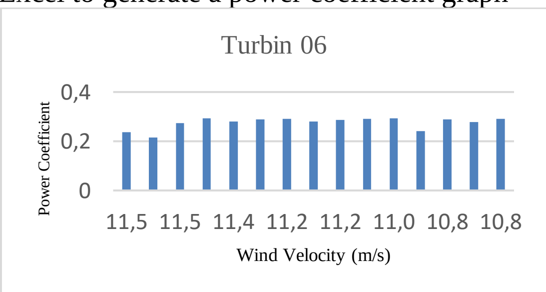

Figure 10. Power Coefficient Graph of Turbine 6 which does not meet the performance standards of the Tolo PLTB

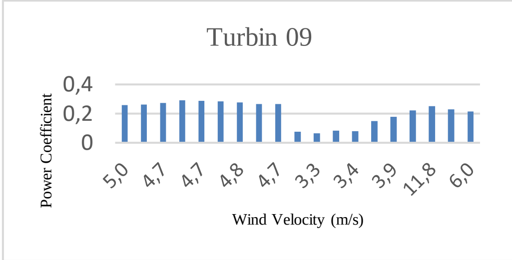

Figure 11. Power Coefficient Graph of Turbine 9 which does not meet the performance standards of the Tolo PLTB

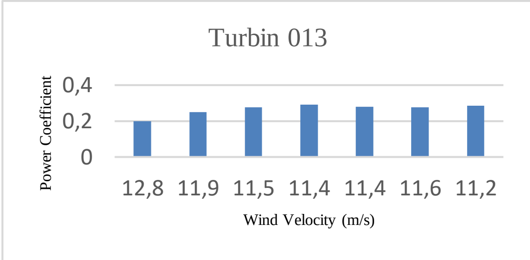

Figure 12. Power Coefficient Graph of Turbine 13 which does not meet the performance standards of the Tolo PLTB

The above figure displays the Power Coefficient Graph of the turbine that does not meet the performance standards of the Tolo Wind Power Plant. From the figures above, it can be used as a reference to determine which turbine is the least efficient in converting wind energy into electrical energy. The power coefficient value of a wind turbine indicates the turbine's efficiency in converting the kinetic energy of wind into electrical energy. This value typically ranges from 0.25 to 0.45, depending on the type and design of the wind turbine used. The power coefficient will not exceed the ideal value of 0.5932. Based on the above graph, Turbine 13 has the fewest abnormal power coefficient data points compared to the other turbines.

V. CONCLUSION

Based on the evaluation results, the following conclusions can be drawn:

1) The performance of the SWT-3.6-130 wind turbines at the Tolo Wind Power Plant in February 2022 was not optimal. The maximum output power generated by each turbine was as follows: Turbine 06 produced 3.57 MW at a wind speed of 13.07 m/s, Turbine 09 produced 3.57 MW at a wind speed of 12.27 m/s, and Turbine 013 produced 3.58 MW at a wind speed of 12.11 m/s. The power output of these

turbines approached the maximum potential power of 3.6 MW.

2) Among the three analyzed turbines, Turbine T13 had the fewest power coefficient values that did not meet performance standards, as shown in Figure 12. Specifically, Turbine T13 had only seven power coefficient values that did not meet the performance standards of the Tolo 1 Wind Power Plant in Jeneponto..

APPENDIX

https://bit.ly/DataHarian-TurbinAngin

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