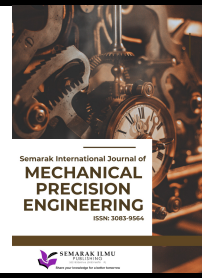




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Design of a Low RPM Vertical Axis Wind Turbine (PTLB) with a Three-Stage Gear System for Increasing Generator Rotational Speed

Aryo Adi Bhaskoro^{1,*}, Singgih Dwi Prasetyo¹, Ade Tafta Risqi¹, Junifan Faturrahman²

¹ Department of Energy Power Plant Engineering Technology, Faculty of Vocational Studies, State University of Malang.PT Kereta

² Api Indonesia DAOP 8 Surabaya, JL Gubeng Masjid No 39, Surabaya 60131, Indonesia

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ABSTRACT

The diminishing supply of fossil fuels has spurred the exploration of alternative energy solutions, with wind energy being a prominent option. Vertical axis wind turbines, or VAWTs, can function well with changing wind directions; nonetheless, they often operate at low rotational speeds, especially when wind speeds are low, which restricts the effectiveness of generators when they are directly connected. This research focuses on creating and producing a low-RPM vertical axis wind turbine that incorporates a three-stage gear transmission system to boost the rotational speed of the generator. The suggested system features a gear mechanism with three different diameters: 15 cm, 5 cm, and 2.5 cm. This design aims to amplify the rotational ratio from the turbine to the generator. The experimental data reveal that the multi-stage gearing arrangement considerably enhances the speed of the generator in comparison to the turbine's speed. Consequently, the generator can generate electrical power more effectively, even when operating at reduced speeds. These results suggest that the incorporation of a three-stage gear transmission can successfully boost the performance of generators and improve the efficiency of small wind energy conversion systems.

1. Introduction

The growing need for electrical power, coupled with the gradual exhaustion of fossil fuel reserves, has hastened the advancement of renewable energy technologies globally. Among the diverse renewable sources, wind energy has captured considerable attention due to its sustainable nature, positive environmental impacts, and broad accessibility. Wind turbines transform the kinetic energy present in wind into electrical power, making them appropriate for energy generation on both large and small scales. Specifically, small-scale wind energy solutions can enhance distributed energy supply in regions where traditional electricity access is limited or less dependable.

* Corresponding author.

E-mail address: Aryo.adi.2309346@students.um.ac.id

Wind turbines are typically divided into two primary categories: horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). HAWTs are favored due to their enhanced efficiency; however, they depend on steady wind direction and intricate control systems. On the other hand, VAWTs present benefits such as functionality in varying wind directions, more straightforward designs, lower installation heights, and simplified maintenance. These qualities render VAWTs better suited for urban settings and conditions with low wind speeds. Nevertheless, a significant drawback of VAWTs is their comparatively low rotational speed, particularly in light wind scenarios, which diminishes the performance of generators that need higher speeds for optimal electrical output.

Prior research has investigated different strategies to enhance the effectiveness of vertical axis wind turbines (VAWTs), including optimizing blade aerodynamics, utilizing generators with higher efficiency, and adopting mechanical transmission systems. Among these methodologies, gear-based transmission systems are regarded as one of the most efficient means to amplify rotational speeds before the energy is sent to the generator. Nevertheless, much of the current literature emphasizes either single-stage gear arrangements or the applications related to large wind turbines. There remains a noticeable lack of studies focusing on compact, effective multi-stage gear transmission systems tailored for low-RPM VAWTs, especially in small-scale contexts. This highlights a significant research void that must be filled to boost operational efficiency without greatly elevating complexity or costs.

Consequently, this research intends to design and evaluate a low-RPM vertical axis wind turbine featuring a three-stage gear transmission system aimed at increasing the rotational speed of the generator. The system proposed incorporates gears with sizes of 15 cm, 5 cm, and 2.5 cm to facilitate higher speeds at the generator shaft. Additionally, this study holds practical significance within the internship at PT Kereta Api Indonesia, where a consistent and stable power source is crucial for operating systems such as signaling, lighting, and monitoring equipment. In particular railway settings, particularly in remote regions with restricted access to the primary power grid, a small wind energy system can function as an alternative or supplementary energy source. Therefore, this research not only contributes to advancements in technology but also promotes the adoption of sustainable energy solutions in railway

2. Methodology

This research utilizes a methodology from engineering design alongside a hands-on experimental strategy, carried out through a systematic process that includes reviewing existing literature, designing a turbine, crafting a three-stage gear assembly, creating a prototype, conducting tests on the system, analyzing the data, and forming conclusions. The main aim is to increase the rotational velocity of a generator by implementing a vertical axis wind turbine that is paired with a multi-stage gear transmission system, which is specifically made to function at reduced rotational speeds and then assessed to check its effectiveness based on observed metrics like rotational speed (RPM) and the output from the generator.

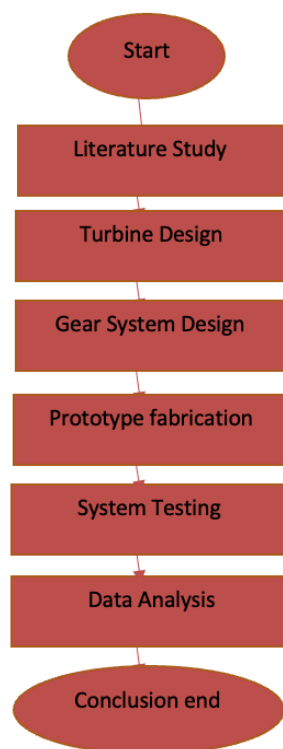


Fig. 1. Methodology

Figure 1 depicts the methodology used in this investigation, which starts with recognizing the issue and examining applicable literature. This is succeeded by the creation of a low-RPM vertical axis wind turbine along with a three-tier gear transmission setup. The sequence then moves on to constructing a prototype and conducting system tests to measure its performance across different working conditions. Ultimately, the data gathered is examined to determine the practicality and success of the suggested design. This organized technique guarantees that every phase of the research is rigorously confirmed, facilitating a thorough assessment of the system's performance and pinpointing areas for enhancement for forthcoming advancements.

2.1 Turbine Design

The layout of the vertical axis wind turbine created in this research is shown in Figure 2. This turbine is made to work at a slow speed and has a three-stage gear system to boost the generator's speed. The complete design consists of important parts like the turbine body, gear system, support frame, and the positioning of the generator.

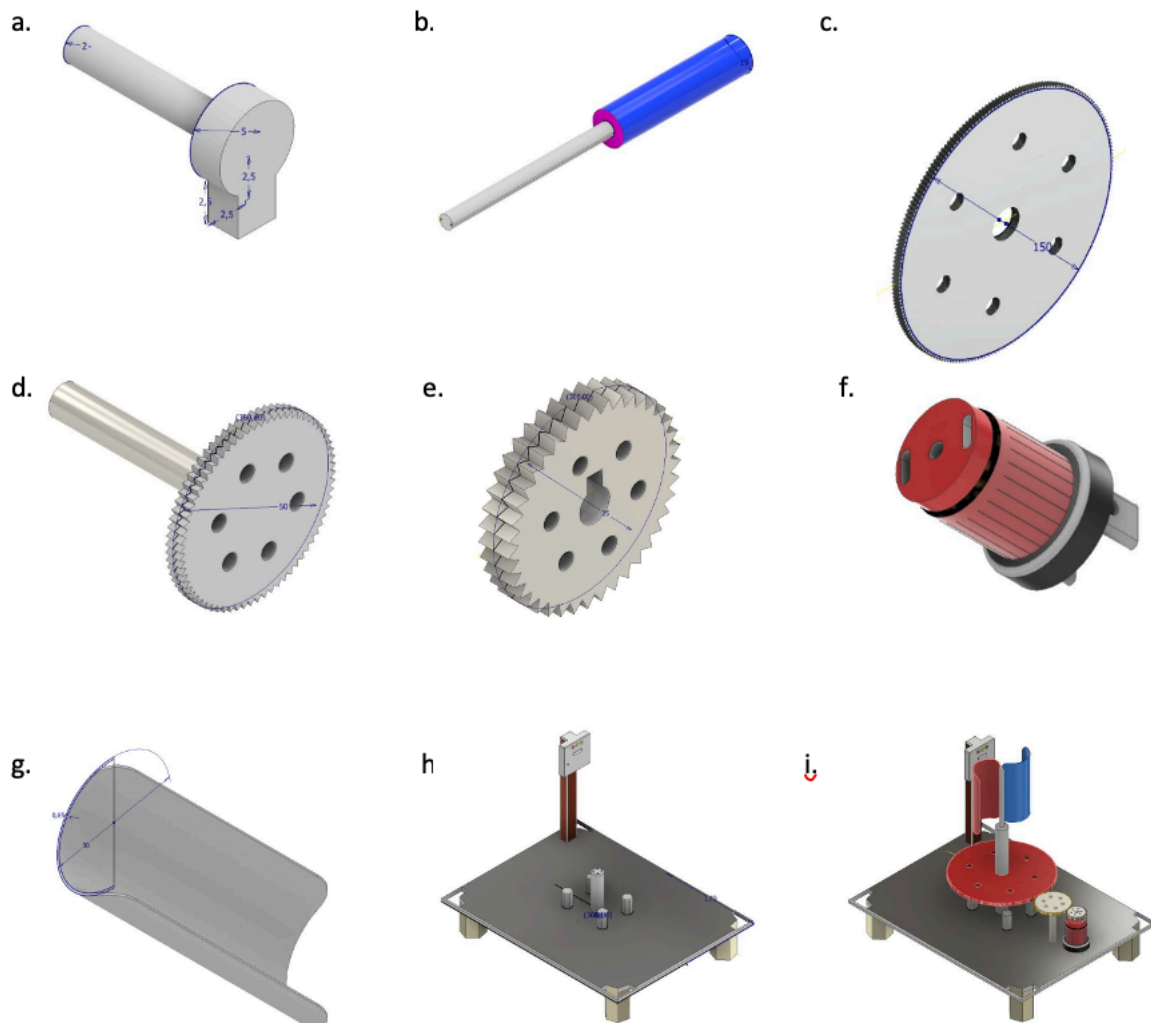


Fig. 2. Main components of the proposed vertical axis wind turbine system

Figure 2 presents the main components of the proposed vertical axis wind turbine system, including the generator shaft (a), turbine shaft (b), rotor plate (c), 150 mm gear (d), 50 mm gear (e), DC generator (f), turbine blade (g), base plate with electrical panel (h), and the complete turbine assembly (i).

2.2 Gear Transmission System

The gear transmission system helps boost the spinning speed from the turbine shaft to the generator. In this research, a gear setup with three stages, measuring 150 mm, 50 mm, and 25 mm in diameter, is used to transform the slow spinning of the vertical axis wind turbine into a quicker speed that works well for the generator. The gears are placed in a specific order to pass on and enhance the spinning movement from the turbine shaft to the generator shaft. This setup allows the generator to function more efficiently, even if the turbine turns slowly.

$$GR = D1/D2 \quad (1)$$

where GR is the gear ratio, D1 is the diameter of the driving gear, and D2 is the diameter of the driven gear, all expressed in millimeters.

$$N_2 = N_1 \times GR \quad (2)$$

where N1 represents the rotational speed of the turbine shaft in rpm, N2 denotes the rotational speed of the generator shaft in rpm, and GR refers to the gear ratio that relates the turbine speed to the generator speed.

$$\eta = n_{\text{real}} / n_{\text{ideal}} \times 100\% \quad (3)$$

The formula states that efficiency (η) is calculated as the ratio of the actual value (n_{real}) to the ideal value (n_{ideal}), multiplied by 100% to express the result as a percentage.

2.3 Data Analysis and Calculation

This part looks at how well the three-stage gear system works in boosting the spinning speed from the turbine shaft to the generator shaft. The evaluation uses the gear ratio and speed formulas that were provided in the earlier section. The gear system includes gears that are 150 mm, 50 mm, and 25 mm in diameter. Each level helps to raise the rotational speed. The gear ratio for every level is found by comparing the size of the driving gear to that of the driven gear. If we assume the turbine runs at a slow speed of 100 rpm, we can figure out the gear ratios for each level like this:

$$i_1 = 150 / 50 = 3 \quad (4)$$

$$i_2 = 150 / 25 = 2 \quad (5)$$

$$i_{\text{total}} = i_1 \times i_2 = 3 \times 2 = 6 \quad (6)$$

$$N_{\text{generator}} = N_{\text{turbine}} \times i_{\text{total}} \quad (7)$$

$$N_{\text{generator}} = 100 \times 6 = 600 \text{ rpm} \quad (8)$$

The computations indicate that the gear ratios for every level are derived from the diameters of the driving and driven gears, leading to figures of 3 for the initial stage and 2 for the subsequent stage; these ratios are then multiplied together to find the cumulative gear ratio of 6, which signifies the total enhancement in speed within the system. In addition, this overall gear ratio is utilized with the turbine's rotation speed of 100 rpm to ascertain the generator's speed, resulting in a concluding value of 600 rpm, which shows that the gear mechanism successfully boosts the rotation speed from the turbine to the generator.

3. Results

3.1 Functionality of the Gear Transmission System

According to the design outlined earlier, the three-stage gear transmission system achieves an overall gear ratio of 6:1. This indicates that the spinning speed of the generator shaft is expected to be six times faster than that of the turbine shaft. This finding supports the idea that the suggested

transmission system can overcome a significant problem of vertical axis wind turbines (VAWT), which is their low spinning speed when wind speeds are weak. By boosting the spinning speed, the generator can function near its ideal performance range, thus enhancing its capability to produce electrical power.

3.2 Characteristics of Rotational Speed

The generator's rotational speed characteristics were examined by utilizing the turbine's rotational speed and the relationship outlined in Equation (2). This examination is intended to assess how well the suggested gear transmission system conveys and enhances rotational energy from the turbine shaft to the generator shaft. Through investigating this connection, the research intends to analyze how efficiently the gear system elevates the speed of the generator under different operating conditions of the turbine, while also evaluating the reliability and effectiveness of the transmission system.

Table 1

Rotational velocity of the generator was assessed in relation to the turbine speed

Turbine RPM	Generator RPM Ideal	Generator RPM Real
50	300	255
100	600	510
150	900	765
200	1200	1020
250	1500	1275

Table 1 shows the rotational velocity of the generator was assessed in relation to the turbine speed by utilizing Equation (2) to determine the efficiency of the suggested gear mechanism. As illustrated in Table 3.1, there is a direct proportional rise in the generator speed corresponding to the turbine speed, adhering to the intended gear ratio. Nevertheless, the observed generator speed consistently falls short of the theoretical figures; for instance, with a turbine speed of 50 rpm, the generator achieves 255 rpm as opposed to the ideal 300 rpm, and at 250 rpm, it attains 1275 rpm rather than the expected 1500 rpm. This reveals an approximate efficiency reduction of 15%, primarily attributed to mechanical inefficiencies like friction, misalignment, and resistance from bearings. Regardless of this, the system displays reliable functionality and successfully enhances the generator's rotational speed.

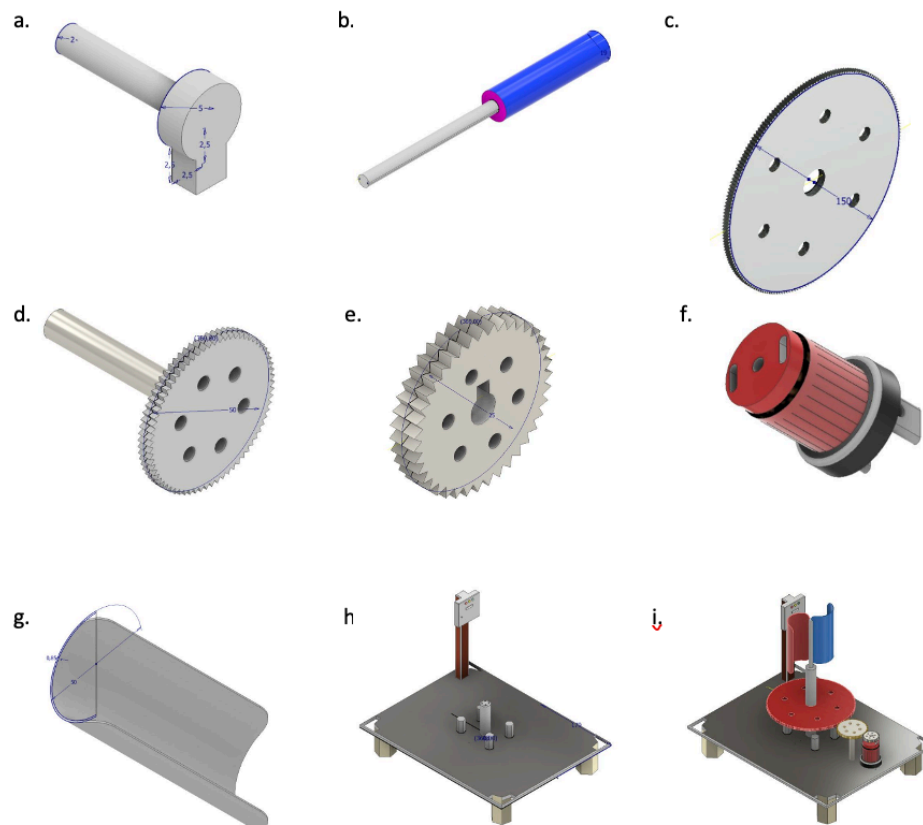


Fig. 2. Turbine speed correlates with generator speed

Figure 2 depicts how turbine speed correlates with generator speed in both perfect and real scenarios, demonstrating a straight-line pattern where the generator speed rises in direct relation to the turbine speed; the ideal line reflects a gear ratio of 6, whereas the real line shows a somewhat diminished slope because of losses in the system.

3.3 Discussion and Performance Analysis

The visual data reveals a straight-line connection between the speed of the turbine and the speed of the generator in both perfect and actual situations. The angle of the perfect curve matches a gear ratio of 6, whereas the actual situation displays a slightly decreased angle due to the mechanical losses involved. Even with this drop, the system continues to show a stable and predictable performance pattern.

Table 2

Mechanical loss and efficiency analysis

Turbine Speed (RPM)	Ideal Speed (RPM)	Real Speed (RPM)	Loss (RPM)	Efficiency (%)
50	300	255	45	85
100	600	510	90	85
150	900	765	135	85
200	1200	1020	180	85
250	1500	1275	225	85

The data presented in Table 2 indicates that mechanical losses rise in direct correlation with the speed of the turbine, demonstrated by the increase in loss metrics from 45 rpm to 225 rpm. Nevertheless, the efficiency of the system stays constant at approximately 85% regardless of the varying conditions. This suggests that the gearing system operates reliably, with the losses primarily resulting from friction, misalignment phenomena, and bearing resistance. In summary, the system is proficient at enhancing the generator speed even though mechanical losses are present.

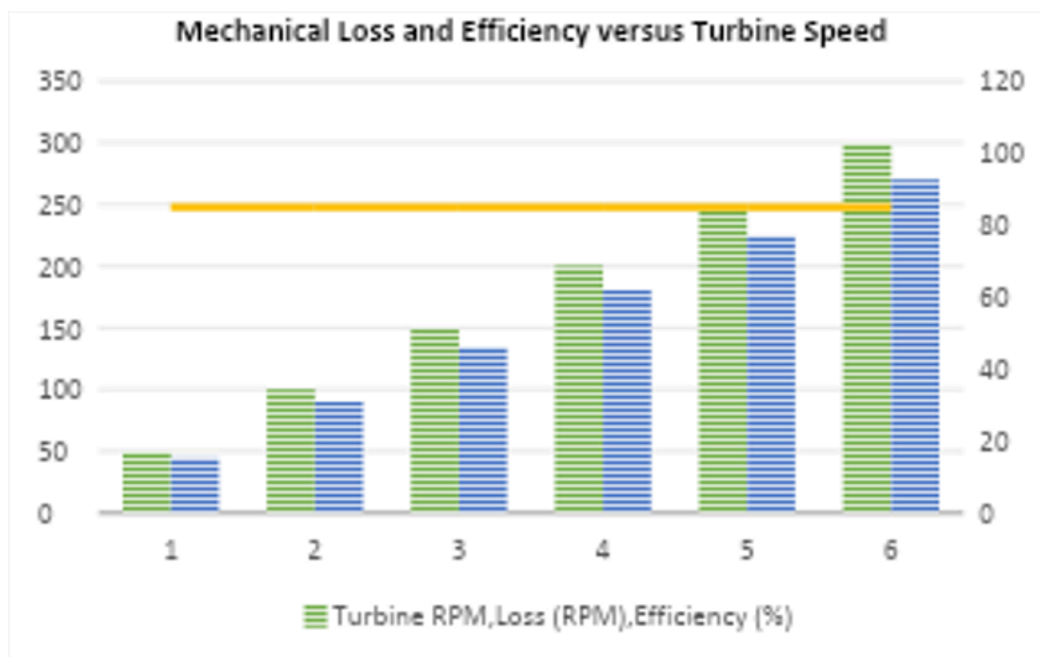


Fig. 3. Mechanical losses rise in direct relation to the turbine's speed

“In Figure 3, the chart shows that mechanical losses rise in direct relation to the turbine's speed, as evidenced by the gradual increase in loss figures corresponding to the growing RPM. Even with this escalation, the efficiency of the system stays fairly stable at around 85%, implying that the gear transmission system functions in a dependable and stable way. The continual efficiency suggests that even though faster speeds result in larger mechanical losses, mainly due to friction, misalignment, and bearing resistance, the system's overall performance remains largely unchanged. This illustrates that the system effectively preserves performance while increasing the speed of rotation.

3.4 Implication and System Evaluation

The findings from the earlier analysis show that using a three-stage gear system greatly improves how well a low RPM vertical axis wind turbine works. The system can increase the speed at which the generator turns by up to six times in ideal situations, proving that the design is effective.

From an engineering standpoint, this advancement is very helpful, especially for wind energy systems that function in areas with low wind speeds. When the turbine is directly connected to the generator in such situations, it often does not spin fast enough, which results in low power generation. By adding a gear system, the generator can operate at a better speed range, boosting the overall energy conversion effectiveness. Moreover, the straightforward link between the turbine speed and the generator speed makes it easier to model the system and predict its performance. This

feature facilitates smoother integration into real-world applications since it allows for accurate estimates of how the system will behave during operation. Nevertheless, the analysis also uncovers some mechanical losses, which somewhat lower the overall performance of the system. These losses mainly stem from friction, gear contact, and mechanical inefficiencies. Thus, careful design choices, including material selection, lubrication, and alignment, are crucial to reduce these losses. In summary, the suggested system provides a realistic and budget-friendly approach to enhancing the performance of small wind energy systems. Its straightforwardness, reliability, and efficiency make it a suitable choice for use in areas with low wind speeds and for decentralized energy solutions.

4. Conclusion

This study presents the development and assessment of a slow RPM vertical axis wind turbine that incorporates a three-stage gear mechanism aimed at boosting the generator's rotational speed. The results show that the suggested system can substantially amplify the generator's speed, achieving up to six times the turbine's speed in optimal conditions. The analysis also indicates that there is a consistent and linear correlation between the turbine speed and the generator speed, suggesting dependable and predictable operation.

Despite the presence of mechanical losses resulting in a minor drop in efficiency, the system still realizes an average efficiency of about 85%, which is deemed satisfactory for practical use. These losses largely stem from friction, gear contact, and bearing drag; however, they do not considerably compromise the overall stability of the system. Additionally, the findings confirm that the gear transmission system functions reliably across various operational conditions, validating its appropriateness for small-scale energy conversion applications. Moreover, the incorporation of the gear transmission system effectively overcomes the primary drawback faced by vertical axis wind turbines at low wind velocities. By elevating the generator's rotational speed, the system enhances the capability for producing electrical energy without necessitating intricate modifications or sophisticated control mechanisms. This aspect renders the proposed design more straightforward and easier to apply in practical situations. In summary, the suggested system presents a simple, economically viable, and efficient approach for small-scale wind energy projects, especially in areas with low wind speeds. Additionally, the modular design enables straightforward maintenance and offers options for future scalability.

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