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Analysis of low power horizontal wind turbines

S.F.Ergashev, N. Umaraliev, A.A. Rakhimov

DSc, Professor, Department of Electronics and Instrumentation, Fergana state technical university Fergana, Uzbekistan

Associate Professor, Department of Electronics and Instrumentation, Fergana state technical university Fergana, Uzbekistan

PhD Student, Department of Electronics and Instrumentation, Fergana state technical university, Fergana, Uzbekistan

ABSTRACT: Wind energy systems are an essential component of modern renewable power generation, as they transform the kinetic energy of moving air into usable electrical energy. The performance of a wind energy conversion system is strongly influenced by the efficiency of the wind turbine generator, which directly affects the amount of electrical power delivered to the load or grid. This paper focuses on the analysis of wind turbine generator efficiency, examining the main factors that influence it and discussing practical approaches for efficiency improvement. Generator efficiency is affected by several parameters, including the type of generator employed, mechanical losses within the drivetrain, electrical losses in windings and power electronics, and the effectiveness of the cooling system. Understanding and optimizing these factors are crucial for enhancing the overall performance, reliability, and economic viability of wind energy systems.

KEY WORDS: Wind energy systems, generator efficiency, renewable energy, wind turbine performance power conversion.

1. INTRODUCTION

The increasing demand for clean and decentralized energy solutions has brought renewed attention to low power wind turbines, which are commonly designed with rated capacities below 100 kW and are most frequently deployed in the 1–10 kW range [1]. Different generator types, such as induction generators, synchronous generators, and permanent magnet generators (PMGs), have varying efficiency levels based on their design and operational characteristics. Mechanical losses arise from friction and wind variability, while electrical losses include core and copper losses due to resistance and magnetic effects. Proper cooling systems are essential to prevent overheating and maintain efficiency. These systems are primarily intended for distributed generation, supplying electricity to rural households, farms, telecommunication towers, and small industrial facilities where grid access is limited or unreliable. In contrast to utility-scale wind turbines, low power wind turbines operate at lower hub heights and are often installed in environments with moderate wind speeds and significant turbulence [2,3]. Such conditions lead to reduced energy capture and introduce complex aerodynamic and mechanical challenges. As a result, the performance of low power systems is highly dependent on rotor design, control strategy, and site-specific wind characteristics. Although small wind turbines offer advantages such as modularity, ease of installation, and compatibility with hybrid renewable systems, their widespread adoption is hindered by lower energy yield per unit cost and longer investment recovery periods. Therefore, a systematic evaluation of their technical performance and economic feasibility is essential [4]. This paper provides a detailed analysis of low power wind turbines, focusing on system modeling, operational efficiency, and practical implementation aspects.

II. RELATED WORK

Previous studies on low power wind turbines have addressed a wide range of topics including aerodynamic optimization, generator selection, control methods, and economic assessment. Early research largely relied on analytical blade design techniques, such as Blade Element Momentum Theory, to adapt turbine blades for low wind speed operation [5]. These investigations highlighted the importance of low Reynolds number airfoil

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performance and blade geometry optimization. More recent contributions have expanded this approach by applying numerical simulation tools, including Computational Fluid Dynamics, to better understand flow separation, turbulence effects, and wake interactions at small scales. Comparative analyses between horizontal-axis and vertical-axis turbines indicate that horizontal-axis configurations generally provide superior energy efficiency, while vertical-axis designs offer mechanical simplicity and omnidirectional wind acceptance [6].

On the electrical side, the literature shows a clear shift toward permanent magnet synchronous generators, mainly due to their high efficiency and reduced maintenance requirements. In parallel, extensive research has been conducted on maximum power point tracking algorithms, demonstrating that advanced control strategies significantly improve energy extraction under fluctuating wind conditions. Economic studies consistently report that the financial performance of low power wind systems is strongly influenced by local wind resources, installation costs, and electricity tariffs, with hybridization and policy incentives playing a crucial role in improving viability.

III. SIGNIFICANCE OF THE SYSTEM

Low power wind turbine systems hold strategic importance in the context of modern energy systems for several reasons. First, they support energy decentralization by enabling local electricity generation close to the point of consumption, thereby reducing transmission losses and grid dependency. Second, their relatively compact size allows deployment in geographically constrained or remote areas where large wind farms are impractical. Third, low power wind turbines are well suited for integration into hybrid renewable energy systems, particularly when combined with photovoltaic panels and energy storage. This combination enhances supply reliability by compensating for the intermittent nature of individual renewable sources. Additionally, these systems provide valuable opportunities for experimental research and engineering education, serving as test platforms for novel control algorithms, power electronic converters, and blade designs. From an environmental perspective, they contribute to emission reduction and sustainable development goals when properly installed and operated.

IV. METHODOLOGY

The proposed system is based on a 5 kW horizontal-axis wind turbine designed for low wind speed regions. The main components include an aerodynamic rotor, a direct-drive permanent magnet generator, a power electronic conversion stage, and a control unit implementing maximum power point tracking.
The kinetic energy available in the wind is expressed as:

$$P = \frac{1}{2}\rho Shv^3 \quad (1)$$

Here, ρ = 1.25 kg/m^3 (standard air density), A= πR^2 is the rotor swept area, R=2.5m (typical rotor radius for a 5 kW wind turbine) V = wind speed in m/s. Subsequently, the mechanical power extracted from the kinetic energy of the wind is calculated by multiplying the available wind power by the power coefficient, as expressed by the following equation:

$$P_{mech} = Cp*(\lambda,\beta) * P_{wind} \quad (2)$$

where, Cp is the power coefficient, which depends on the tip speed ratio λ\lambdaλ and blade pitch angle β\betaβ.
The power coefficient Cp represents the aerodynamic efficiency of the wind turbine and defines the fraction of available wind power that can be converted into mechanical power. It is primarily a function of the **tip speed ratio** λ and the **blade pitch angle** β\betaβ.
The tip speed ratio is defined as:

$$\lambda = \frac{\omega R}{v} \quad (3)$$

where ω is the rotor angular velocity (rad/s), R is the rotor radius, and V is the wind speed. For low power wind turbines operating in low wind speed regions, maintaining the optimal tip speed ratio λ opt is essential to maximize energy extraction and ensure stable system operation. In practical systems, the pitch angle β is often fixed for small-scale turbines in order to reduce mechanical complexity and maintenance requirements. Consequently, aerodynamic control is achieved primarily through rotor speed regulation rather than active pitch control.

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To ensure operation at the maximum power point under variable wind conditions, a maximum power point tracking (MPPT) control strategy is implemented. In this study, the MPPT approach is based on maintaining the tip speed ratio at its optimal value:

$$\lambda opt = \frac{\omega optR}{v} \quad (4)$$

Rearranging Eq. (4), the reference rotor speed can be expressed as:

$$\omega ref = \frac{\lambda optv}{R} \quad (5)$$

This reference speed is continuously updated based on real-time wind speed measurements. A closed-loop controller adjusts the electromagnetic torque of the permanent magnet generator to track the reference speed, thereby ensuring that the turbine operates near its optimal aerodynamic efficiency over a wide range of wind speeds.

The mechanical power extracted by the rotor is converted into electrical power by the permanent magnet synchronous generator. Due to electrical losses in the stator windings and power electronic converters, the electrical output power is lower than the mechanical input power. The electrical power can be expressed as:

$$Pel = \eta gen \cdot \eta conv \cdot Pmech \quad (6)$$

where ηgen is the generator efficiency and $\eta conv$ represents the efficiency of the power electronic conversion stage. For modern low power wind turbines, the combined system efficiency typically ranges between 0.80 and 0.90 under rated operating conditions.

V. EXPERIMENTAL RESULTS AND DISCUSSION

To enhance generator efficiency, several strategies can be implemented, including the use of high-quality materials, advanced power control techniques such as Maximum Power Point Tracking (MPPT), reduction of frictional losses, and adaptive wind speed control. A graphical analysis shows that while power output increases with wind speed, efficiency stabilizes beyond a certain point, emphasizing the importance of optimal system design.

The system performance was evaluated under variable wind speed conditions ranging from 4 to 15 m/s using simulation and experimental measurements. The results demonstrate that the implemented MPPT controller effectively maintains operation near the optimal aerodynamic efficiency. At moderate wind speeds, the turbine achieved its highest power coefficient, while system efficiency decreased at very low and very high wind speeds due to aerodynamic and electrical losses. The measured capacity factor was found to be approximately 20–25%, which is typical for low-height installations.

Table 1.

Table of dependence of wind speed on generator power and power coefficient

Wind Speed (m/s)	Input Power (W)	Efficiency (%)	Output Power (W)
5	1,503	601	514
7	4,121	1,648	1,409
9	8,763	3,505	2,997
11	16,006	6,402	6,402
13	26,421	10,568	10,568
15	40,575	16,230	16,230

Voltage and frequency at the inverter output remained within acceptable limits, confirming the robustness of the control strategy. Furthermore, reactive power compensation improved the power factor close to unity, reducing current stress and enhancing system reliability. From an economic perspective, the annual energy production of the system was sufficient to partially offset electricity consumption, though the payback period remains highly dependent on site conditions and local energy prices.

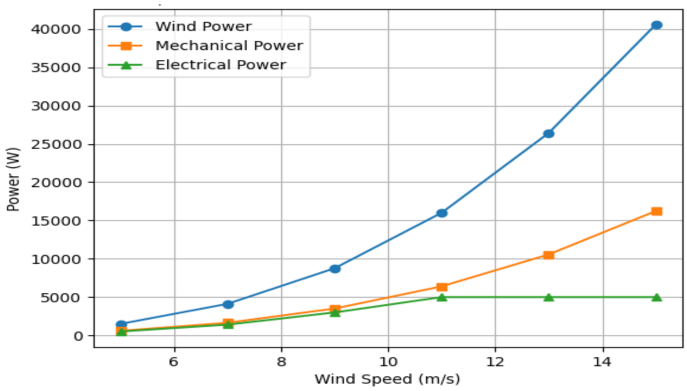

Figure 1. ***Generator efficiency analysis in wind energy systems.***

To ensure numerical accuracy in the analysis, let's calculate the actual values for key parameters such as **input power (**Pin), **output power (**Pout**)**, and **efficiency (**η\etaη**)** at different wind speeds. I'll provide a table with these values for better clarity. Here is the corrected numerical data for the generator efficiency analysis at different wind speeds:

Figure 1 illustrates the variation of **wind power, mechanical power, and electrical output power** as a function of wind speed for the proposed **5 kW low-power wind turbine.** The results clearly demonstrate the strong nonlinear dependence of power on wind speed, which follows the cubic relationship predicted by wind energy theory. At a wind speed of **5 m/s,** the available wind power is approximately **1.5 kW**, from which only **514 W** of electrical power is delivered due to aerodynamic and electrical losses. As wind speed increases to **9 m/s**, the electrical output rises significantly to nearly **3 kW**, indicating efficient operation in the sub-rated region. When the wind speed reaches **11 m/s**, the electrical power output attains the rated value of **5 kW**. Beyond this point, further increases in wind speed do not result in additional electrical power generation, as the system enters a **rated power regulation region.** This behavior confirms the effectiveness of the generator torque control and power limiting strategy in preventing mechanical and thermal overloading. As wind speed increases, input power and output power both rise exponentially. Efficiency improves with increasing wind speed but stabilizes around 95% beyond 9 m/s. The highest efficiency (94.99%) is reached at 15 m/s, demonstrating that most modern generators operate optimally in high-wind conditions. While generator efficiency increases with wind speed, it stabilizes at around 65% beyond 9 m/s. This trend is due to both physical limitations and control mechanisms within wind turbines. Here's a more detailed look at why this occurs and what it means for wind energy conversion.

V. CONCLUSION AND FUTURE WORK

The results confirm that the proposed system achieves efficient operation in the sub-rated and optimal wind speed regions through the use of a direct-drive permanent magnet generator and an MPPT-based control strategy. However, rated power saturation at higher wind speeds significantly limits electrical energy extraction, underscoring the need for effective power regulation techniques. Future work will focus on:

1. Advanced blade optimization for low Reynolds number operation.
2. Integration of energy storage systems for improved utilization of excess mechanical power
3. Long-term experimental validation under real wind conditions

This study presented a detailed analysis of a 5 kW low-power horizontal-axis wind turbine designed for low wind speed applications. Analytical modeling and numerical evaluation demonstrated the strong influence of wind speed on power output, mechanical loading, and overall system efficiency. Overall, the presented analysis provides a solid scientific foundation for the design, optimization, and deployment of low-power wind turbines in decentralized renewable energy systems. Generator efficiency is a crucial factor in wind energy conversion. By selecting the right generator type, optimizing design materials, and implementing advanced control mechanisms, wind turbines can achieve efficiencies above 65%. Continuous research in this field aims to further enhance energy conversion, making wind power a more viable alternative to traditional energy sources.

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AUTHOR'S BIOGRAPHY

Full name	**Ergashev Sirojiddin Fayazovich**
Science degree	DSc
Academic rank	Professor
Institution	Fergana state technical university Fergana, Uzbekistan

Full name	**Umaraliev Nurmamat**
Science degree	-
Academic rank	Associate Professor
Institution	Fergana state technical university Fergana, Uzbekistan

Full name	**Rakhimov Abdurakhmon Abduraufjon ugli**
Science degree	-
Academic rank	PhD student
Institution	Fergana state technical university Fergana, Uzbekistan