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Experimental Evaluation and Selection of Generator Topologies for a 10 kW Vertical Axis Wind Turbine

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Abstract

The selection of an appropriate generator topology is an important factor influencing the efficiency, reliability and annual energy production of vertical axis wind turbines (VAWTs). This study experimentally evaluates four generator–drivetrain configurations for a 10 kW VAWT: a geared asynchronous machine, a direct-drive axial flux permanent magnet generator (PMG), a direct-drive classical radial flux PMG, and a geared synchronous reluctance machine (SynRM). A dedicated laboratory test bench incorporating an active front-end frequency converter, torque sensor and energy metering system was developed to evaluate the electromechanical performance of the investigated configurations over a wide range of torque and rotational speed operating conditions representative of VAWT operation. The results show that the asynchronous machine configuration exhibits insufficient efficiency at low and medium power levels and is therefore unsuitable for the intended application. Both PMG configurations achieved high efficiencies, with the classical radial flux PMG demonstrating a broader high-efficiency operating range and the highest estimated annual energy production of 15,715 kWh. The axial flux PMG performed best at low power levels but experienced a pronounced efficiency decline at higher loads. The SynRM configuration demonstrated competitive efficiency near rated power and represents a promising rare-earth-free alternative. Overall, under the investigated operating conditions, the classical direct-drive PMG was identified as the most suitable generator topology for the investigated 10 kW VAWT.

Keywords: vertical axis wind turbine (VAWT); generator technology; permanent magnet generator (PMG); synchronous reluctance machine (SynRM); generator topology selection; wind energy conversion systems

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1. Introduction

The global transition toward a low-carbon energy economy has positioned wind energy as a cornerstone of the renewable energy portfolio. According to the International Renewable Energy Agency (IRENA), the global installed wind power capacity has seen an exponential increase over the last decade, driven by significant reductions in the Levelized Cost of Electricity (LCOE) and advancements in turbine aerodynamics [1]. While the market is currently dominated by horizontal axis wind turbines (HAWTs), their deployment in complex environments—such as turbulent urban landscapes and deep-water offshore sites—presents inherent mechanical and logistical challenges [2].

In recent years, there has been a renewed scientific interest in vertical axis wind turbines (VAWTs). Unlike their horizontal counterparts, VAWTs are omnidirectional, meaning they can harness wind from any direction without the need for complex yaw systems [3]. This characteristic is particularly advantageous in the built environment, where wind flow is characterized by high turbulence and rapid directional shifts. Furthermore, VAWTs may offer maintenance-related advantages because the drivetrain and generator can be located near the base of the supporting structure, potentially simplifying maintenance operations and reducing structural loading. These characteristics make VAWTs a promising option for future floating offshore wind applications, although this technology is still under active development and requires further large-scale validation [4].

Despite their potential, VAWTs face several technical hurdles that limit their widespread commercial adoption. These include lower aerodynamic efficiency compared to the Betz limit (approx. 59.3%), self-starting issues in lift-type rotors, and cyclic aerodynamic loading, which leads to premature fatigue of the blade materials [5]. Current research is therefore focused on optimizing rotor geometries—such as helical blades and hybrid Savonius–Darrieus configurations—to enhance power coefficients (Cp) at low tip speed ratios [6].

Recent studies have further advanced VAWT aerodynamic optimization through numerical optimization techniques, improved blade geometries and parametric design methodologies. Baca et al. [7] demonstrated that optimization of airfoil geometry using computational fluid dynamics and surrogate modeling techniques can significantly improve the aerodynamic performance of Darrieus-type VAWTs. Similarly, Díaz-Canul et al. [8] proposed a parametric design methodology for H-type VAWTs that simultaneously considers aerodynamic performance, startup behavior and structural constraints. These developments demonstrate that considerable progress has been achieved in VAWT aerodynamics; however, optimization of the electrical drivetrain remains equally important for maximizing the overall electrical energy production of the system.

In Northern European regions, including the Baltic Sea basin, the integration of small-scale VAWTs into microgrids represents a promising approach for improving the seasonal balance of renewable electricity generation. Wind resources in these regions are generally stronger during autumn and winter, when solar photovoltaic (PV) generation is reduced and electricity demand for heating is typically higher. Consequently, wind and PV generation exhibit a complementary seasonal production profile, making hybrid renewable energy systems particularly attractive for decentralized energy applications [9].

Recent review papers indicate that VAWT research has evolved from improving individual turbine components toward integrated system optimization. Current development trends include advanced blade geometries, hybrid rotor concepts, floating offshore applications, distributed generation in urban environments, and hybrid renewable energy systems combining wind, photovoltaics and energy storage. At the same time, increasing attention is being devoted to electrical subsystems, including generator technologies, power electronic converters and advanced control strategies that improve energy capture, grid integration and operational reliability. These developments demonstrate that the future competitiveness of VAWTs depends not only on aerodynamic improvements but also on coordinated optimization of the complete wind energy conversion system [10,11].

This paper explores the technical feasibility and power generation potential of VAWTs by analyzing generator performance under representative operating conditions and evaluating the influence of generator topology on overall system performance.

1.1. Overview of Generator Technologies for Vertical Axis Wind Turbines

While significant research efforts have focused on improving the aerodynamic performance of vertical axis wind turbines (VAWTs), the electrical drivetrain remains a critical

component influencing overall energy conversion efficiency, reliability, and economic viability. In small- and medium-scale VAWT systems, generator selection is particularly important because relatively low rotor rotational speeds result in high torque requirements, while variable wind conditions require efficient operation over a broad torque–speed range.

Historically, squirrel cage induction generators have been widely adopted in wind energy systems because of their robust construction, relatively low manufacturing cost, and established industrial reliability. However, induction machines require magnetizing current to establish the air gap magnetic field, and rotor and stator losses can reduce efficiency, particularly under partial-load conditions. Comparative investigations of wind energy conversion systems have demonstrated the importance of considering generator technology and operating conditions when evaluating induction and permanent magnet alternatives [12].

Permanent magnet generators (PMGs) represent an attractive solution for variable-speed and direct-drive wind turbine applications. Their rotor magnetic field is provided by permanent magnets, eliminating the need for electrical rotor excitation and its associated losses. This enables high efficiency and facilitates low-speed, high-pole-count machine designs. Recent experimental research has continued to investigate alternative PM generator topologies. Farahzadi et al. [13] designed and experimentally validated an outer-rotor, double-permanent-magnet-excited flux-switching generator for direct-drive wind turbine applications, demonstrating ongoing development of specialized electrical machines for low-speed energy conversion.

Axial flux permanent magnet generators (AF-PMGs) have attracted considerable attention because of their compact axial geometry and potential for high torque density. These characteristics can be advantageous in direct-drive wind energy applications, where relatively high torque must be produced at low rotational speeds. Reviews of axial flux machine technologies have highlighted their potential benefits and associated electromagnetic, mechanical, and thermal design challenges [14]. More recently, Ravindran et al. [15] investigated axial flux PMG designs for small-scale wind energy conversion, incorporating electromagnetic modeling and experimental validation. Such investigations provide useful information on the design and performance of permanent magnet machines, although the suitability of a particular generator for a VAWT also depends on its efficiency over the expected operating range and its interaction with the power electronic converter.

Despite the advantages of permanent magnet technologies, concerns regarding magnet material costs, supply chain dependencies, and environmental impacts have stimulated interest in magnet-free alternatives. Synchronous reluctance machines (SynRMs) generate electromagnetic torque through rotor magnetic anisotropy without requiring permanent magnets or rotor windings. Recent developments in machine design and converter-based control have improved their potential for variable-speed applications [16,17]. Selma et al. [18] investigated an intelligent control approach for wind energy conversion systems employing synchronous reluctance generators, illustrating the importance of suitable control strategies when applying this technology to renewable energy generation.

Another important consideration is the choice between direct-drive and geared drivetrain architectures. Direct-drive systems eliminate the gearbox and its associated mechanical losses, wear mechanisms, and maintenance requirements, but generally require larger, higher-torque electrical machines. Geared systems allow the use of more compact, higher-speed generators but introduce additional mechanical components and transmission losses. Previous studies have demonstrated that the advantages of these architectures depend on the turbine rating, operating profile, and drivetrain design [19,20]. Consequently, generator selection should be considered at the drivetrain level rather than solely on the basis of electrical machine characteristics.

The interaction between turbine aerodynamics, generator operation, and power electronic control is also important for VAWTs. Aerodynamic torque varies with the wind speed, tip speed ratio, and blade position, potentially producing torque fluctuations and challenging operating conditions for the electrical drivetrain [3,5]. Bouhafs et al. [21] investigated the modeling of a VAWT coupled with an axial flux permanent magnet synchronous generator, illustrating the relevance of integrating turbine and generator characteristics in wind energy conversion analysis. Although aerodynamic optimization can improve the available mechanical power, the resulting electrical energy production also depends on generator efficiency, drivetrain losses, and converter operation.

These developments demonstrate the importance of evaluating generator technologies as components of an integrated wind energy conversion system. The specific limitations of existing comparative investigations and the contribution of the present study are discussed in the following section.

1.2. Research Gap and Contribution

Recent investigations have contributed to the development of electrical generator technologies and experimental methodologies for wind energy conversion systems. Farahzadi et al. [13] focused on the design and experimental validation of a permanent magnet flux-switching generator for direct-drive wind turbines, while Ravindran et al. [15] investigated axial flux permanent magnet generator designs for small-scale wind energy applications through modeling and prototype validation. Boubakar and Ameur [22] compared two axial flux generator arrangements associated with wind turbine prototypes using three-dimensional finite element modeling. These investigations provide valuable evidence regarding the design and performance of permanent magnet machines, but their scope is primarily restricted to individual generator topologies or comparisons between related machine designs.

Other studies have addressed generator control and complete drivetrain performance. Selma et al. [18] investigated control strategies for wind energy conversion systems employing synchronous reluctance generators, whereas Bouhafs et al. [21] examined the modeling of an integrated VAWT and axial flux permanent magnet generator system. Zhang et al. [23] investigated the experimental determination of wind turbine drivetrain efficiency using a nacelle test bench, with particular emphasis on measurement methodology and uncertainty evaluation. These studies demonstrate the importance of considering generator control, drivetrain integration, and measurement procedures when assessing wind energy conversion performance.

Although these investigations address important aspects of generator design, control, and drivetrain characterization, their objectives and experimental configurations differ from those of the present study. In particular, the reviewed publications do not provide a direct experimental comparison of the four generator–drivetrain architectures considered here: a geared squirrel cage induction machine, a direct-drive axial flux permanent magnet generator, a direct-drive radial flux permanent magnet generator, and a geared synchronous reluctance machine. Moreover, efficiency results obtained using different experimental arrangements, operating conditions, and measurement procedures cannot necessarily be compared directly without accounting for methodological differences. This identifies a specific need for a comparative system-level evaluation of alternative generator–drivetrain configurations under common laboratory conditions.

To address this research gap, the present study experimentally evaluates four commercially available generator–drivetrain configurations intended for a 10 kW vertical axis wind turbine using a dedicated laboratory test bench and a consistent measurement procedure. The investigation considers the combined performance of the generator–drivetrain

assemblies over a broad range of torque and rotational speed operating conditions representative of the intended VAWT application. Particular attention is given to electromechanical conversion efficiency, converter compatibility, and startup operation. The experimentally obtained efficiency characteristics are subsequently incorporated into an annual energy production calculation to assess the influence of generator selection on the expected electrical energy output.

The principal contribution of this study is therefore a comparative, system-level experimental assessment of four fundamentally different generator–drivetrain architectures under common laboratory conditions, rather than the development of a new electrical machine topology. By examining efficiency characteristics across the operating range and relating them to estimated annual energy production, the investigation provides an application-oriented basis for generator selection in small-scale VAWTs. The conclusions are limited to the investigated configurations and operating conditions, taking into account the measurement limitations discussed in Section 4.4.

1.3. Objectives of the Study

The objective of this study is to identify the optimal electrical generator configuration, including the potential integration of a gearbox, for a 10 kW vertical axis wind turbine (VAWT). The selection process evaluates electromechanical efficiency, torque–speed characteristics, startup performance, controllability, and overall system reliability under variable wind conditions. The generator is interfaced with the utility grid via an active front-end (AFE) frequency converter, enabling bidirectional power flow alongside independent control of generator torque and rotational speed. This AFE topology accommodates a wide rotor speed range while maintaining a stable DC link voltage and high power quality.

Due to the aerodynamic characteristics of VAWTs—specifically the dependence of aerodynamic torque on the instantaneous blade position and tip speed ratio (λ)—the turbine may exhibit insufficient self-starting capability under specific wind conditions and rotor angular positions. Consequently, the drive system must apply positive accelerating torque to the rotor during startup to ensure reliable initiation of rotation from standstill and enhance low-wind operational performance. Accordingly, the generator and power electronic control systems are designed to support motoring operation during startup, followed by a seamless transition to a generating mode once the rotor reaches a self-sustaining rotational speed. The main contribution of this work lies in investigating the coupled influence of the generator type, gearbox ratio, converter control strategy, and startup torque capability on overall system performance. The aerodynamic and structural design of the investigated vertical axis wind turbine, together with its theoretical background and practical validation, is presented in [24].

2. Generator Technologies for Vertical Axis Wind Turbines

To determine the optimal drivetrain configuration for the 10 kW vertical axis wind turbine (VAWT), a systematic evaluation framework was established. This methodology comprises four sequential phases: candidate selection, topology compatibility assessment, integrated back-to-back testing, and multi-criteria optimization decision-making.

To test generator + frequency converter efficiency, as well as evaluating overall generator + frequency converter compatibility, a testing stand seen in Figure 1 has been designed and produced.

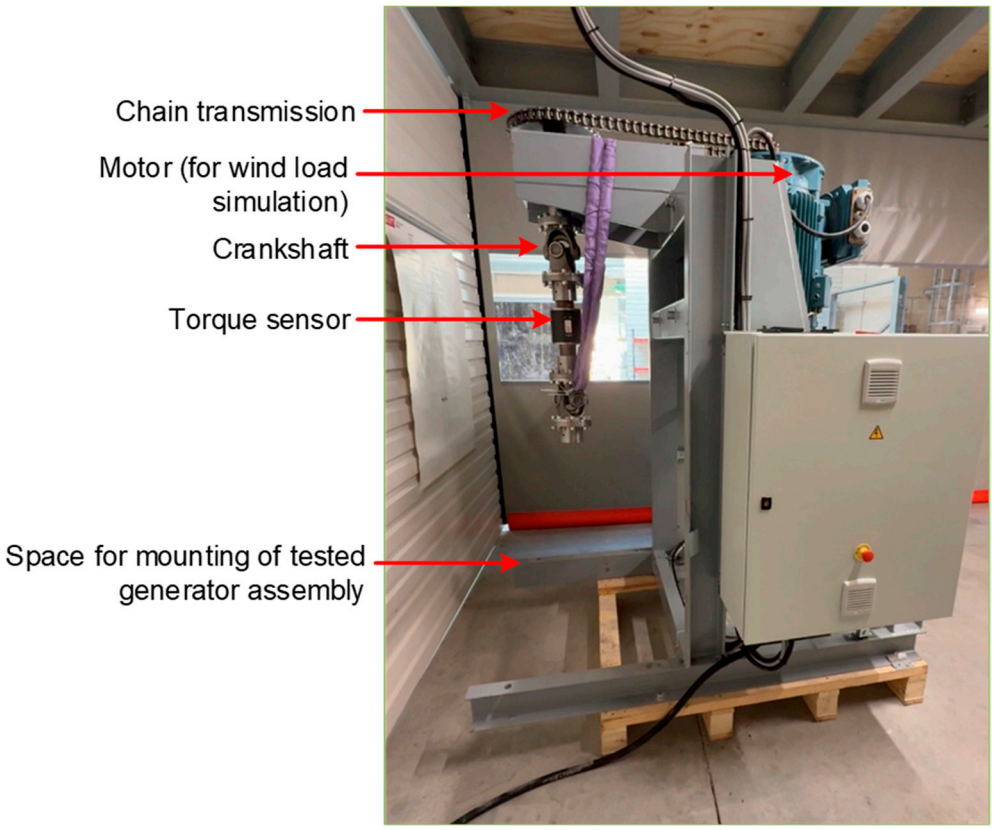


Figure 1. Generator test bench without generator mounted.

2.1. Methodological Framework

The investigative process was executed according to the following discrete steps:

1. Selection of Generator Candidates: A diverse group of four electrical machine topologies was chosen based on industrial relevance, cost-effectiveness, and suitability for small-scale wind energy conversion.
2. Frequency Inverter Compatibility Evaluation: Each generator candidate was assessed for operational compatibility with an active front-end (AFE) frequency converter, focusing on field-oriented control (FOC) alignment, motoring startup dynamic tracking, and grid synchronization capabilities.
3. Integrated Efficiency Testing (COP): The combined performance of the generator inverter subsystem was tested across a wide operational spectrum. To evaluate the complete electromechanical-to-electrical energy conversion path, the combined efficiency is defined and further referred to as the Coefficient of Performance (COP).
4. Optimal Drivetrain Selection: A final comparative analysis evaluated the compiled COP maps alongside the startup torque density, reliability, and maintenance requirements to isolate the optimal generator option.

2.2. Evaluated Generator Topologies (Configurations)

The evaluation encompasses two high-speed geared solutions and two low-speed direct-drive options to balance the trade-offs between mechanical complexity and electromagnetic volume. The main technical specifications of the four evaluated generator–drivetrain configurations are summarized in Table 1, and their individual characteristics are described below:

- Configuration 1: Geared Asynchronous Configuration
  This architecture pairs a standard squirrel cage induction machine with a mechanical

speed-increasing gearbox. While this configuration benefits from low initial generator cost and high structural robustness, the gearbox introduces mechanical friction losses, acoustic noise, and an increased maintenance burden. Since the task at hand is to choose the optimal solution for a VAWT that will work in a wide range of torque/speed values, it is essential to understand if an asynchronous machine can provide acceptable efficiency levels at lower torque and/or speed conditions, as a rotating magnetic field in this type of machines is created by actively feeding current from the grid, which in some cases may offset energy generation from wind flow to unacceptable levels.

Table 1. Generator–drivetrain configuration.

Parameter	Configuration 1	Configuration 2	Configuration 3	Configuration 4
Nominal generator speed	1500 rpm	70 rpm	50 rpm	1500 rpm
Gearbox ratio	1:26.38	Direct drive	Direct drive	1:26.38
Nominal powertrain speed	56.9 rpm	70 rpm	50 rpm	56.9 rpm
Machine topology	Squirrel cage induction machine	Axial flux permanent magnet generator	Radial flux permanent magnet generator	Synchronous reluctance machine
Rotor excitation	Electromagnetic induction	Permanent magnets	Permanent magnets	Reluctance rotor
Nominal power	11 kW	10 kW	10 kW	11 kW

- Configuration 2: Direct-Drive Axial Flux PMG
  Configuration 2 utilizes an ironless or disk core axial flux permanent magnet generator (AF-PMG). Due to its axial air gap plane, this layout yields a high torque density and an ultra-low cogging torque profile, which can theoretically eliminate the typical self-starting deficiencies associated with VAWT rotors at low wind speeds. This type of generator is considered a promising venue for wing generator applications, where much of the generation is being done at sub-nominal speed and torque values if measured by time in production, but at the same time, as most of the wind farm grid-fed power comes from peak wind hours, efficiency at near-nominal power levels still needs to be carefully evaluated.
- Configuration 3: Direct-Drive Classical PMG
  This configuration features a standard radial flux permanent magnet synchronous generator (RF-PMG). Directly coupled to the turbine shaft, it omits mechanical transmission losses. It offers high nominal efficiency but exhibits higher cogging torque compared to Configuration 2, which poses a unique challenge during the motoring startup sequence. Due to the fact of a higher cogging torque, while evaluating this configuration, it is extra important for frequency inverter to be able to smoothly transition between Speed-Torque I. and II. Quadrants in startup mode.
- Configuration 4: Geared Synchronous Reluctance configuration
  Configuration 4 investigates a magnet-free synchronous reluctance motor (SynRM) combined with a gearbox. This alternative addresses the global price volatility and environmental concerns surrounding rare-earth permanent magnets. It offers low rotor thermal losses and high structural reliability, though its inherently lower power factor demands precise active control from the AFE converter. One of the main downsides of SynRM technology is the fact that the technology is not as widespread as asynchronous machines and classical PMGs; hence, compatibility with the chosen active front frequency inverter poses a challenge. If, however, compatibility is satisfactory, SynRMs

may present a compromise between cheaper, less efficient asynchronous machines and more efficient and costly PMG solutions.

The investigated generator assemblies are commercially available machines representing four fundamentally different electrical machine technologies suitable for VAWT applications. Since the objective of the present work is the comparative experimental evaluation of complete generator–drivetrain assemblies under identical operating conditions, detailed electromagnetic design characteristics—such as the winding layout, magnetic material specification and thermal design—were not considered. Instead, the comparison focuses on system-level performance indicators relevant to practical generator selection, including efficiency, startup capability, converter compatibility and estimated annual energy production.

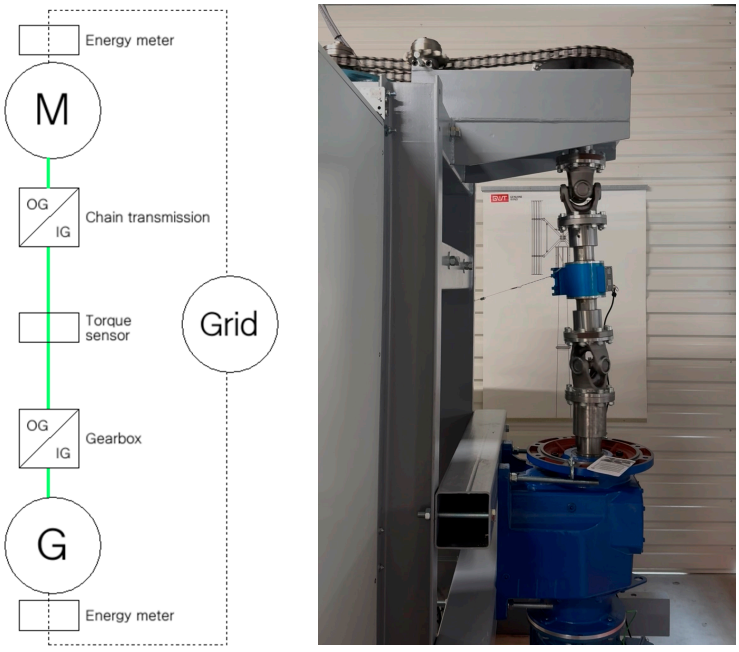
2.3. Mechanical Construction

Mechanically, the testing stand consists of a motor that is being used to simulate load from a wind rotor and a reduction chain drive from the motor to the drive shaft. The drive shaft is con-nected to the generator shaft with a cardan shaft to compensate for misalignment in the generator's installation. A torque sensor (torque transducer) is built into the cardan shaft.

2.4. Electrical and Mechanical Data Collection

The structure of power flow and used elements is clearly visible on the stand's control HMI interface. As shown in Figure 2, the testing stand is equipped with several electronic devices that allow us to collect and analyze data, including:

- Motor (that simulates wind load) and generator (that is being tested) frequency inverters;
- Laboratory-grade torque sensor;
- Energy meters.



(**a**) (**b**)

Figure 2. Test bench structure of generator testing stand: (**a**) schematic overview of element diagram and power flow; (**b**) photo of actual generator assembly tested (Configuration 1—asynchronous machine with gearbox).

2.5. Efficiency Measurement and Calculation Methodology

In this document, efficiency (η) shall be defined as the ratio of electrical power (that is being measured by a generator power meter) to mechanical power (that is being measured by a torque sensor).

$$\eta = \frac{P_e}{P_m}$$

By using this stand's HMI datalogging functionality, it is possible to get η characteristics for each generator in different speed and torque combinations. To best evaluate η, it was decided to get a reading of 0–100% torque values at different motor speeds.

2.6. Experimental Test Procedure

1. Initial testing to evaluate feasibility and eliminate candidate if obviously unacceptable (e.g., not compatible with frequency inverter or apparently too low efficiency).
2. Enable generator frequency inverter with 0% as the torque set point.
3. Set motor to fixed speed (e.g., 10 rpm).
4. After fixed time interval (e.g., 10 s), increase torque by fixed value (e.g., 5%).
5. Repeat Step 4 until generator nominal torque is exceeded. At this point, return to Step 2, then in Step 3, increase motor speed by fixed value (e.g., 10 rpm) and read variable torque characteristics at this new speed.
6. Repeat procedure until generator nominal speed is exceeded. At this point, test procedure for given generator is finished.

3. Test Results

3.1. Configuration 1—Asynchronous Motor + Gearbox

Initial testing of the asynchronous motor with a gearbox at 50 rpm showed relatively low efficiency at lower mechanical power levels, as illustrated in Figure 3. While it can also be observed that at higher power levels (closer to motor's nominal), the efficiency increases substantially, that is still unacceptable for our VAWT application due to the fact that most of the time, the wind turbine will work at mid-rotation speeds and low to medium power, while reaching nominal power only at peak wind hours. Given all the above, it was decided not to continue with testing other speed curves for Configuration 1, as the expected efficiency at lower speed levels is even worse.

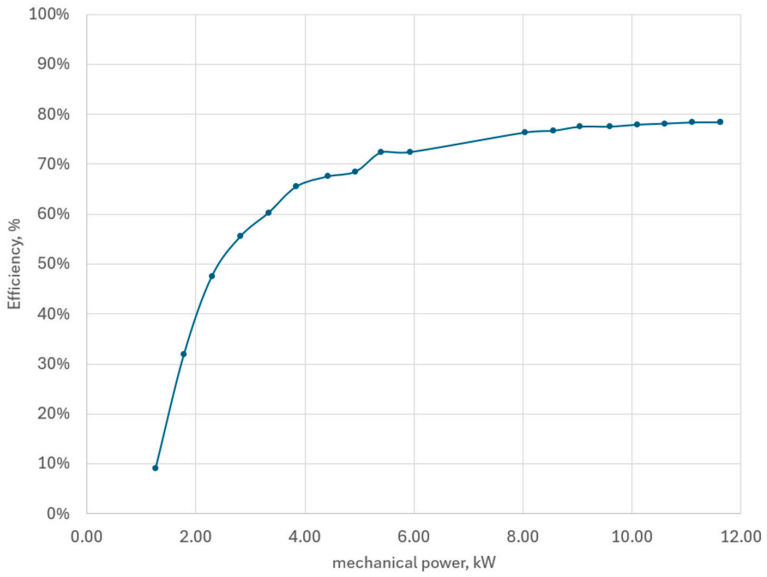


Figure 3. Efficiency as a function of mechanical power for Configuration 1.

3.2. Configuration 2—Flux PMG

The synchronous flux-type generator proved to be much more efficient at lower torque values, but at higher torque values, the efficiency dropped significantly. As can be seen in Figure 4, the efficiency graphs for each rotation speed have a distinct peak value that represents the optimal torque value for a given speed to work at. The fact that the peak efficiency value is significantly lower than the generator nominal (e.g., for nominal rotation speed of 70 rpm, peak efficiency is at 2–3 kW mechanical power), it could suggest that this generator is best suited for applications where nominal power is rarely reached and most of the generation occurs at lower (20–30% of generator power nominal) levels.

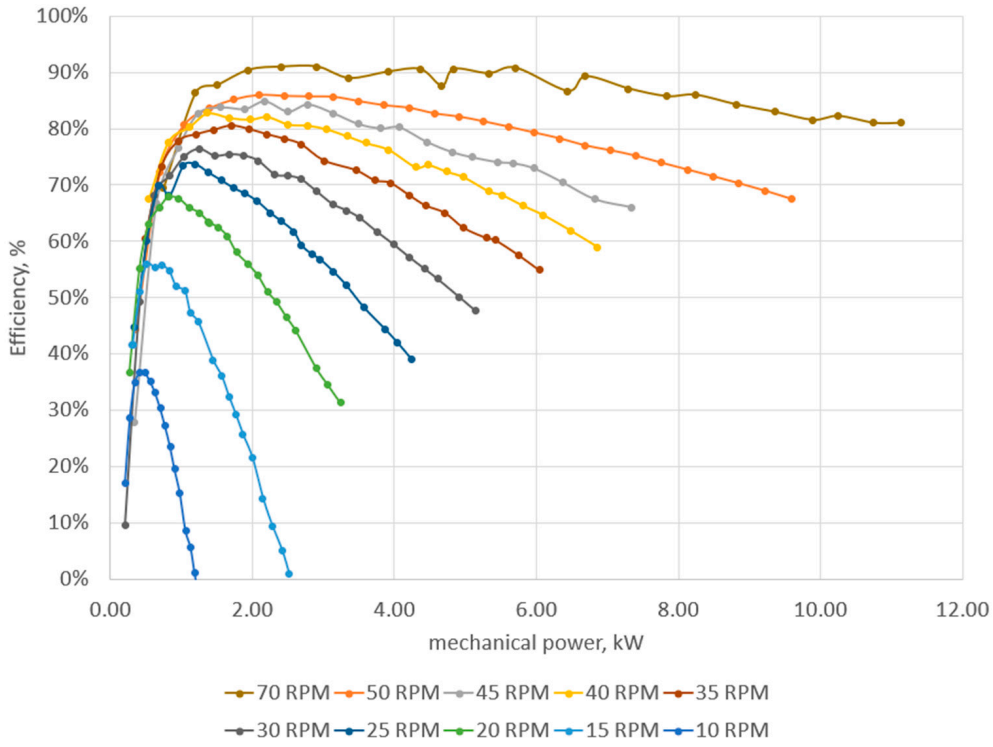


Figure 4. Efficiency as a function of mechanical power for Configuration 2.

It was determined that this generator is acceptable for application, but efficiency-wise should be compared against alternatives.

3.3. Configuration 3—Classical PMG

The classical design PMG showed solid efficiency values both at lower and higher torque values. As seen in Figure 5, the efficiency graphs for each rotation speed have peak values close to 60% of nominal (e.g., for 50 rpm, peak efficiency is approx. 90% at 6 kW mechanical power).

When comparing Configuration 3 to Configuration 2, it can be said that while both configurations display a drop in efficiency closer to nominal power, Configuration 3 has a much higher optimal power zone and displays a much slower drop in efficiency closer to nominal.

Although Configuration 2 was more efficient at lower torque values, this Configuration 3 option was much more efficient at higher torque values, thus being more suitable for applications where torque time distribution is more even.

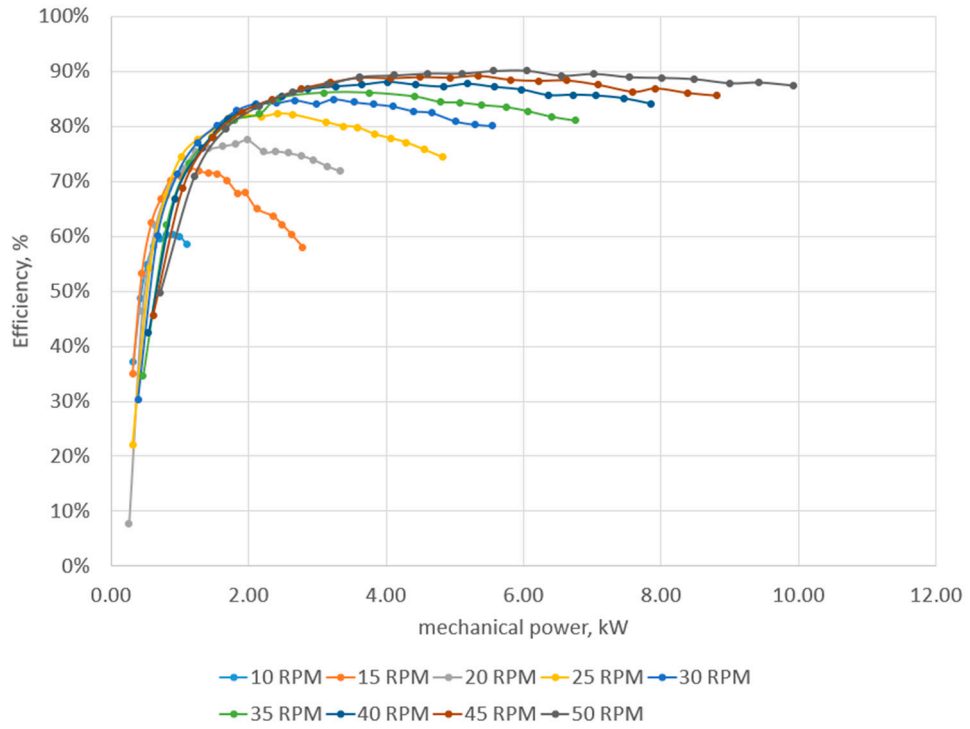


Figure 5. Efficiency as a function of mechanical power for Configuration 3.

3.4. Configuration 4—SynRM Motor + Gearbox

As seen in Figure 6, the SynRM-type motor with a gearbox has lower efficiencies than Configurations 2 and 3 when working at the low-to-mid-power range; however, it displays very good efficiency levels at a higher power range (from 50 to 100% of nominal power). While not being able to reach 90% efficiency levels (that both Configurations 2 and 3 were able to achieve—each at its own optimal power level), it comes very close.

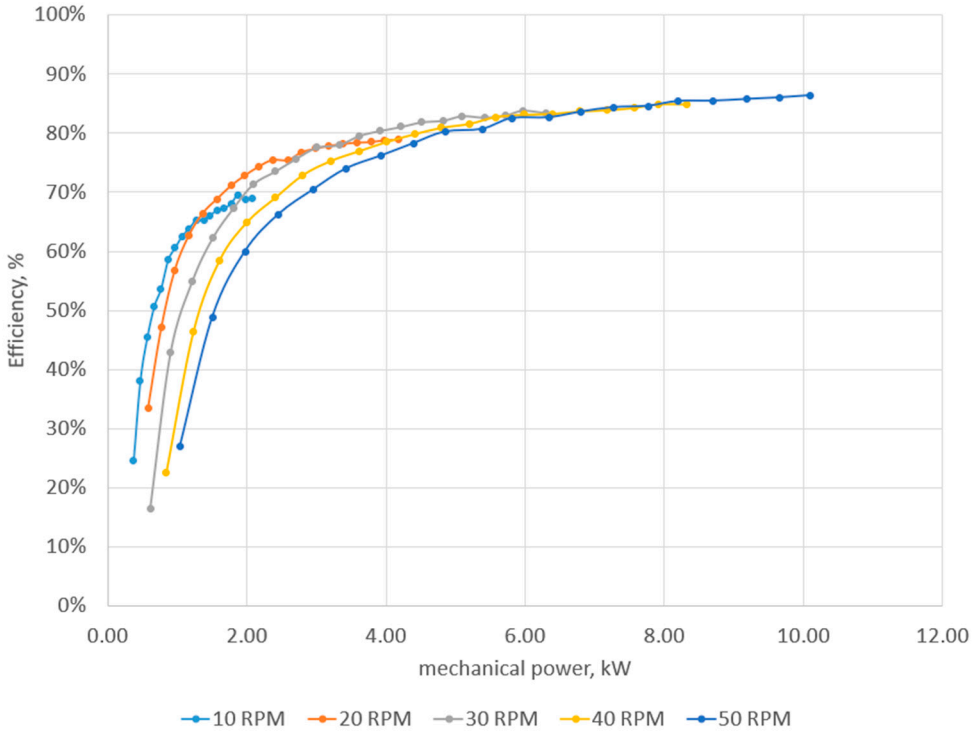


Figure 6. Efficiency as a function of mechanical power for Configuration 4.

It is also worthwhile noting that this motor did not indicate an efficiency drop at levels close to nominal power that can be interpreted as this motor being a bit oversized compared to the Configuration 2 and Configuration 3 PMGs (or vice versa—that Configuration 3 and especially Configuration 2 are undersized and manufacturer-indicated nominal power should be regarded as maximum power, not nominal power that should provide the best performance).

3.5. Technological Comparison of Tested Generators

When selecting the optimal generator configuration, it is necessary to distinguish between the electrical machine technologies used in each alternative, since their efficiency characteristics, drivetrain requirements, material dependencies, and supply chain risks differ substantially.

The asynchronous machine combined with a gearbox represents a technologically mature and widely available solution that is generally considered economically attractive. This technology is mechanically robust, widely available, and does not require permanent magnets. However, its efficiency is less favorable over a wide load range. The rotor current required for electromagnetic torque production introduces additional rotor losses, while the magnetizing current contributes to reactive power demand and reduced part-load efficiency. In low-speed applications, the need for a gearbox further increases the mechanical losses, maintenance requirements, and drivetrain complexity. Therefore, although the induction generator configuration is economically attractive, it is not the preferred option where high efficiency across a broad operating spectrum is the main design criterion.

A conventional permanent magnet generator, understood here as a radial flux PMG, provides higher efficiency and better part-load performance because rotor excitation is supplied by permanent magnets rather than by induced rotor current. This eliminates rotor copper losses and allows a high-pole-count, low-speed generator design, potentially reducing or eliminating the need for a gearbox. The main disadvantages are higher capital cost, dependence on rare-earth magnet materials, and sensitivity to magnet temperature limits and demagnetization risk. The supplier base for small-power PMGs below 50 kW is also geographically concentrated, which introduces additional logistics, lead time, and geopolitical supply chain risks.

The axial-flux permanent magnet generator (AF-PMG) represents an alternative to conventional radial-flux machine topologies. Its disk-shaped magnetic circuit can provide a high torque density, short axial length, and good suitability for low-speed, high-torque operation. In principle, this makes axial-flux PMGs attractive for compact direct-drive configurations. However, the technology is less standardized than conventional radial-flux PMGs. Manufacturing tolerances, air gap control, thermal management, and mechanical stiffness of the rotor–stator assembly represent important design and manufacturing challenges. Based on the authors' practical experience during the generator selection process, axial-flux PMGs appear to be more readily available in the small-power range than conventional radial-flux PMGs. Nevertheless, their more complex construction, tighter manufacturing tolerances, and stricter quality control requirements may contribute to higher manufacturing costs. The synchronous reluctance machine represents a magnet-free synchronous generator technology. Its torque production is based on rotor magnetic anisotropy, i.e., the difference between direct axis and quadrature axis inductance, rather than on permanent magnets or rotor windings. As a result, the rotor contains neither permanent magnets nor conductive windings, reducing rotor losses and eliminating rare-earth magnet dependency. In the present comparison, the SynRM configuration is most appropriately compared with the asynchronous machine configuration, since both are assumed to require a gearbox for the considered low-speed application. Compared with an induction generator, the SynRM

has a more complex rotor geometry and typically requires converter-based control, but it can offer improved efficiency, especially under variable-load operation.

The economic considerations presented in this section are based on practical engineering experience and preliminary communication with potential suppliers during the generator selection process. Direct quantitative cost comparisons were not considered sufficiently reliable because available quotations concerned individual units and varied depending on manufacturer, technical specifications, production volume, transportation requirements, and delivery conditions. Furthermore, detailed manufacturing information was not consistently available. Consequently, the relative cost assessments are qualitative and should not be interpreted as generalized manufacturing cost ratios or the results of a formal techno-economic analysis.

3.6. Efficiency Comparison of Tested Combinations (Configurations)

To best compare efficiencies between tested configurations, efficiencies measured at the same speed (e.g., 30 rpm) can be shown on a single graph. We choose 30 rpm since for a wind turbine, it is quite common to work in mid-range speed most of the time, while reaching maximum speed only during peak wind speed hours.

As seen in Figure 7, Configuration 2 (flux PMG) shows rapid growth in efficiency when increasing the power from 0 to 1 kW, followed by a peak efficiency value of ~77% at ~1.2–1.3 kW mechanical power. Afterwards, efficiency is in a steady and distinct decline, reaching sub-50% efficiency at higher loads.

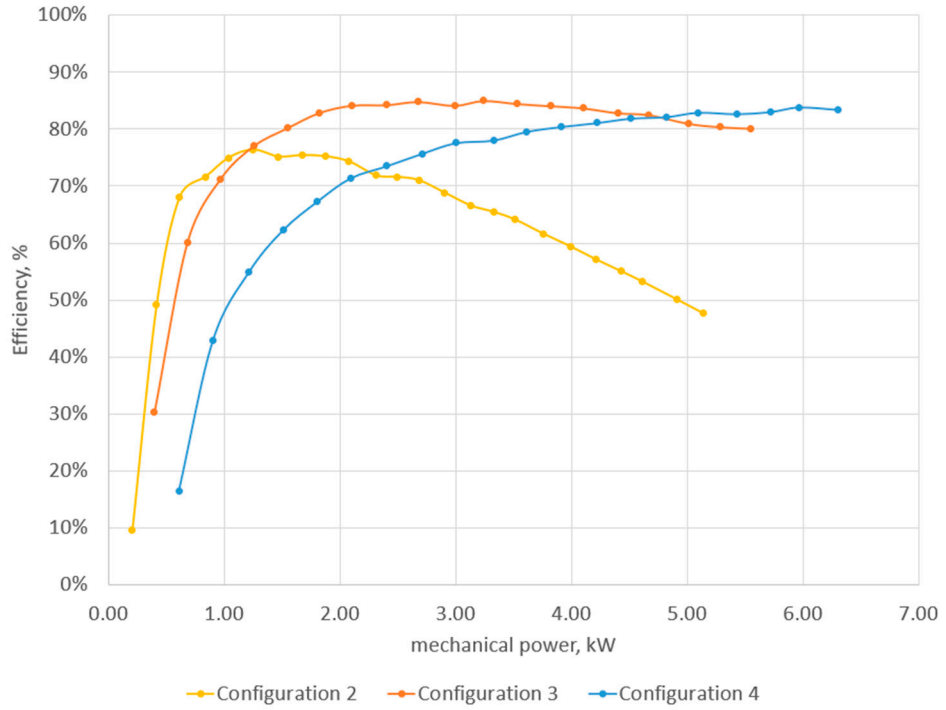


Figure 7. Efficiency comparison of Configurations 2, 3 and 4 as a function of mechanical power.

On the other hand, Configuration 3 displays a similar rapid growth in efficiency from 0 to 1 kW, followed by an increasing efficiency up to ~3 kW mechanical power levels. Afterwards, efficiency is declining closer to the maximum mechanical load, while still being above the 80% level.

By comparison, while Configuration 4's efficiency is lagging compared to Configuration 2 and Configuration 3, it is steadily increasing in all mechanical power ranges, exceeding

Configuration 2's efficiency at ~2.2 kW level and Configuration 3 at the ~4.7 kW level, reaching ~84% efficiency at higher mechanical load levels.

3.7. Energy Production Comparison

When evaluating the economic attractiveness of generators for commercial wind turbines, one of the main criteria is the amount of energy produced for each configuration. The precise energy amount is dependent on each specific turbine location; however, we can calculate the theoretical energy amount based on the standard annual wind distribution. The standard wind distribution presented in Table 2 describes the statistical occurrence of wind speeds at a given site over a defined period (in our calculation—on a per annum basis). This distribution is used to estimate the expected energy production. These are standardized reference wind conditions specified in the international standard IEC 61400-1-12, based on a Weibull distribution and corresponding to Class IV (Very Low Wind).

Table 2. Standard wind distribution.

Wind Speed, m/s	Hours per Annum
4	963
5	1210
6	1320
7	1220
8	1000
9	700
10	438
11	262
12	131
13	52
14	28
Total	**7324**

To estimate the annual electrical energy production of each generator–drivetrain configuration, the annual wind speed distribution presented in Table 2 was combined with the aerodynamic rotor model and the experimentally obtained generator efficiency characteristics. For each wind speed bin, the corresponding rotor mechanical power and rotational speed were first determined. The experimentally obtained efficiency map of each generator–drivetrain configuration was then used to determine the electrical conversion efficiency at the corresponding operating point.

The rotor swept area is calculated as

$$A = DH \tag{1}$$

where A is the rotor swept area (m^2), D is the rotor diameter (m), and H is the rotor height (m).

The tip speed ratio (TSR) is defined as

$$\lambda = \frac{\omega R}{V} \tag{2}$$

where λ is the tip speed ratio, ω is the rotor angular velocity (rad/s), $R = D/2$ is the rotor radius (m), and V is the wind speed (m/s).

The relationship between the rotational speed and angular velocity is

$$\omega = \frac{2\pi n}{60}, \tag{3}$$

where n is the rotor rotational speed in revolutions per minute (rpms).

Combining Equations (2) and (3), the rotor rotational speed can be expressed as

$$n = \frac{60\lambda V}{\pi D}. \tag{4}$$

The available power in the wind passing through the rotor swept area is

$$P_{\text{wind}} = \frac{1}{2}\rho A V^3, \tag{5}$$

where ρ is the air density (kg/m^3).

The aerodynamic power extracted by the rotor is

$$P_{\text{aero}} = \frac{1}{2}\rho A V^3 C_p, \tag{6}$$

where C_p is the rotor power coefficient. In general, the power coefficient is a function of the tip speed ratio,

$$C_p = C_p(\lambda). \tag{7}$$

Therefore, the aerodynamic rotor power at a given wind speed can be written as

$$P_{\text{aero}}(V) = \frac{1}{2}\rho A V^3 C_p[\lambda(V)]. \tag{8}$$

For each generator configuration j, the electrical output power is determined as

$$P_{\text{el},j} = \eta_j P_{\text{aero}}, \tag{9}$$

where η_j is the generator efficiency.

Since the generator efficiency varies with the operating point, the electrical output power for a given wind speed bin V_i is expressed as

$$P_{\text{el},j}(V_i) = \eta_j(V_i)\, P_{\text{aero}}(V_i). \tag{10}$$

The electrical energy generated within the i-th wind speed bin is

$$E_{j,i} = P_{\text{el},j}(V_i)\, t_i, \tag{11}$$

where t_i is the annual duration of the corresponding wind speed bin (h).

The annual energy production (AEP) of each generator configuration is obtained by summing the energy production over all wind speed bins:

$$\text{AEP}_j = \sum_{i=1}^{N} E_{j,i} \tag{12}$$

Equivalently,

$$\text{AEP}_j = \sum_{i=1}^{N} P_{\text{el},j}(V_i)\, t_i, \tag{13}$$

where N is the total number of wind speed bins considered in the analysis.

The calculated annual electric energy is summarized in Table 3.

Table 3. Annual electric energy produced (calculation).

Configuration	Calculated Annual Electric Energy Output, kWh
Configuration 1 (geared asynchronous motor)	11,879
Configuration 2 (flux PMG)	13,573
Configuration 3 (classical) PMG	15,715
Configuration 4 (SynRM + gearbox)	13,976

4. Discussion

4.1. Comparison with Previous Studies

The experimental results obtained in the present study are generally consistent with the established technical characteristics of the investigated electrical machine technologies. Permanent magnet generators eliminate the need for rotor excitation current and can provide favorable efficiency characteristics in variable-speed applications, while induction machines remain attractive because of their robustness, technological maturity, and relatively simple construction [12]. Synchronous reluctance machines offer an alternative that avoids permanent magnet materials, although their performance depends on machine design and suitable converter control [16,17]. Under the investigated operating conditions, both direct-drive permanent magnet configurations exhibited favorable efficiency characteristics, whereas the geared induction machine configuration demonstrated comparatively low efficiency, particularly at partial load. The geared synchronous reluctance configuration achieved competitive efficiency at higher power levels.

Recent experimental investigations provide additional context for interpreting these results. Farahzadi et al. [13] experimentally validated a specialized permanent magnet generator intended for direct-drive wind turbine operation, while Ravindran et al. [15] investigated axial flux generator designs for small-scale wind energy conversion. Boubakar and Ameur [22] compared alternative axial flux generator arrangements associated with wind turbine prototypes. These studies contribute to the development and evaluation of permanent magnet generator technologies. However, their principal objectives concern machine design and the performance of individual or closely related generator topologies, rather than a system-level comparison of induction, axial flux permanent magnet, radial flux permanent magnet, and synchronous reluctance technologies.

The interaction between the electrical machine and its power electronic control system is another important consideration. Selma et al. [18] investigated a control approach for wind energy conversion systems employing synchronous reluctance generators, while Bouhafs et al. [21] examined the modeling of a VAWT coupled with an axial flux permanent magnet generator. These investigations highlight the relevance of generator–converter interaction and integrated system modeling. In the present study, converter compatibility and the ability to support the required operating conditions were considered alongside experimentally determined efficiency characteristics. This provides an application-oriented comparison of the investigated generator–drivetrain assemblies.

The experimental methodology also distinguishes the present investigation from studies concentrating on individual generator designs. All four configurations were evaluated using the same laboratory test bench and a consistent measurement procedure, reducing differences associated with instrumentation and test methodology. Nevertheless, the use of common equipment does not eliminate measurement uncertainty. Zhang et al. [23] demonstrated the importance of documented measurement procedures and uncertainty evaluation in wind turbine drivetrain efficiency testing. In contrast, the present experimental campaign was originally intended for comparative engineering assessment and did not include a formal measurement uncertainty analysis or dedicated repeatability study. Consequently, the reported efficiency characteristics should be interpreted primarily as comparative results for the investigated configurations, rather than high-precision absolute efficiency measurements.

An important finding of the present study is that generator suitability depends on the complete efficiency characteristic rather than the maximum efficiency value alone. The axial flux permanent magnet generator demonstrated favorable efficiency at relatively low power levels but experienced a more pronounced efficiency reduction at higher loads. The radial flux permanent magnet generator maintained a broader high-efficiency operating

range and achieved the highest estimated annual energy production of 15,715 kWh. The synchronous reluctance configuration demonstrated competitive performance at higher power levels, suggesting that it may represent a technically viable magnet-free alternative for applications where material availability and supply chain considerations are important.

The principal performance characteristics and practical engineering trade-offs of the investigated generator–drivetrain configurations are summarized in Table 4.

Table 4. Comparison of experimentally evaluated performance characteristics and qualitative engineering considerations for the investigated 10 kW VAWT generator–drivetrain configurations.

Criterion	Configuration 1 Asynchronous + Gearbox	Configuration 2 Axial Flux PMG	Configuration 3 Radial Flux PMG	Configuration 4 SynRM + Gearbox
Drivetrain	Geared	Direct drive	Direct drive	Geared
Estimated annual energy production	11,879	13,573	15,715	13,976
Peak efficiency	Moderate	High	Very high	High
Part-load efficiency	Low	High	High	Moderate
Startup capability	Good	Excellent	Excellent	Good
Converter compatibility	Excellent	Moderate	Moderate	Moderate
Gearbox required	Yes	No	No	Yes
Relative manufacturing cost	Low	High	Moderate–High	Low–Moderate
Relative maintenance complexity	Moderate	Low	Low	Moderate
Rare-earth material required	No	Yes	Yes	No

Table 4 combines the experimentally observed performance characteristics, calculated annual energy production, and qualitative engineering assessments. Efficiency-related classifications are based on the measured characteristics presented in Section 3, while annual energy production is calculated according to the methodology described in Section 3.7. Drivetrain architecture, gearbox requirements, and permanent magnet dependence are determined from the investigated configurations. Relative manufacturing cost and maintenance complexity are qualitative assessments based on drivetrain architecture, expected component requirements, and the authors' practical experience with generator selection and potential suppliers. The overall suitability classifications refer specifically to the investigated 10 kW VAWT application and are primarily informed by the measured efficiency characteristics and estimated annual energy production. These qualitative assessments should not be interpreted as experimentally validated manufacturing costs, maintenance requirements, reliability, or lifetime indicators.

The qualitative ratings for startup capability and converter compatibility reflect the practical ease of achieving stable operation and implementing the required control functions during laboratory testing, whereas the efficiency classifications represent relative comparisons among the four tested configurations rather than predefined numerical performance thresholds.

The comparison demonstrates that no generator topology is universally optimal across all technical and economic criteria. For the investigated 10 kW VAWT and the adopted wind speed distribution, the radial flux permanent magnet generator provided the highest estimated annual electrical energy production. However, alternative configurations may be preferable when different operating profiles, material requirements, manufacturing costs, or maintenance considerations are prioritized. Generator selection should therefore be based

on the expected operating conditions and the performance of the complete electromechanical conversion system.

4.2. Interpretation of Experimental Results

The experimental results demonstrate that the suitability of a generator–drivetrain configuration for vertical axis wind turbines should be evaluated over the complete operating range rather than on the basis of peak efficiency alone. Since VAWTs operate under continuously varying wind conditions, annual electrical energy production depends on the efficiency characteristics across the entire operating range, particularly under partial-load conditions where wind turbines operate for a substantial proportion of their lifetime.

The two permanent magnet generator configurations exhibited the highest overall efficiencies, resulting in the greatest estimated annual electrical energy production. Although the axial flux permanent magnet generator demonstrated favorable efficiency at lower power levels, the radial flux permanent magnet generator maintained a more balanced efficiency characteristic over a wider operating range, resulting in the highest estimated annual energy production. This finding demonstrates that the overall shape of the efficiency curve is more important than the maximum efficiency value when selecting generator technologies for wind energy applications.

The induction machine configuration exhibited the lowest overall performance because the combined influence of gearbox losses and lower machine efficiency reduced the energy conversion efficiency over much of the operating range. In contrast, the synchronous reluctance machine demonstrated competitive performance near the rated operating conditions while eliminating the need for permanent magnets. Although its estimated annual energy production remained below that of the permanent magnet generators, the results indicate that synchronous reluctance technology represents a technically viable alternative where reduced dependence on rare-earth materials is an important design consideration.

Overall, the experimental results confirm that generator selection for vertical axis wind turbines should be based on a comprehensive evaluation of the complete electromechanical conversion system, including efficiency over the expected operating range, startup capability, converter compatibility and the resulting annual electrical energy production, rather than on maximum efficiency alone.

4.3. Practical Engineering Implications

The experimental results demonstrate that generator selection for small- and medium-scale vertical axis wind turbines should not be based solely on peak efficiency values. Instead, the selection process should consider the complete operating characteristics of the generator–drivetrain system together with the intended application requirements. Although the classical radial flux permanent magnet generator achieved the highest estimated annual electrical energy production, each investigated generator topology exhibited distinct engineering advantages and practical trade-offs.

Direct-drive permanent magnet generators eliminate the need for mechanical speed multiplication, thereby reducing drivetrain complexity and gearbox-related maintenance requirements. Their high efficiency over a broad operating range makes them particularly suitable for applications where maximizing annual energy production and minimizing maintenance are the primary design objectives. These advantages, however, are accompanied by potential cost implications associated with permanent magnet materials and continued dependence on rare-earth materials.

In contrast, induction machine and synchronous reluctance machine configurations reduce or eliminate the use of rare-earth materials, potentially reducing dependence on costly permanent magnet materials and improving supply chain resilience. However, in the

investigated configurations, both technologies required a gearbox to achieve appropriate operating speeds, introducing additional mechanical losses, maintenance requirements and potential reliability concerns. Although the synchronous reluctance machine demonstrated competitive efficiency near the rated operating conditions, its overall annual electrical energy production remained below that of the direct-drive permanent magnet generators because of reduced efficiency under partial-load operation and gearbox losses.

Consequently, the selection of an appropriate generator topology should be based on application-specific priorities. Where maximum annual energy production and minimum maintenance are the primary objectives, direct-drive permanent magnet generators appear to provide the most suitable solution. Conversely, where reduced dependence on rare-earth materials, supply chain resilience or potential generator cost advantages are of greater importance, synchronous reluctance machines may represent a technically viable alternative despite the associated gearbox requirements.

The results presented in this study therefore provide practical guidance for selecting generator–drivetrain configurations according to the technical, economic and operational requirements of future small- and medium-scale vertical axis wind turbine installations.

4.4. Limitations and Future Research

The present study experimentally compared four generator–drivetrain configurations for a 10 kW vertical axis wind turbine under controlled laboratory conditions. Although the obtained results provide valuable insights into the influence of generator topology on electromechanical performance and estimated annual electrical energy production, the findings are subject to several limitations.

First, the experimental investigation was performed using a laboratory test bench representing a single turbine power rating and operating conditions. Consequently, the results may not be directly transferable to VAWTs of substantially different sizes or applications without further validation. Second, the study focused primarily on electromechanical performance and did not include long-term field testing, detailed techno-economic analysis or lifecycle assessment of the investigated generator technologies.

The experimental test bench was originally developed for comparative engineering evaluation rather than for metrological characterization of the investigated machines. Consequently, a formal measurement uncertainty analysis, dedicated repeatability study and statistical evaluation of measurement variability were not performed during the original experimental campaign. The reported efficiency values should therefore primarily be interpreted as comparative system-level results obtained using a common test bench and measurement methodology rather than as high-precision absolute efficiency measurements. Future experimental investigations should include documented sensor calibration, measurement uncertainty and repeatability analysis.

5. Conclusions

Using the dedicated generator test bench presented in Figures 1 and 2, four generator–drivetrain configurations were experimentally evaluated to determine their suitability for a 10 kW vertical axis wind turbine (VAWT). Based on the obtained efficiency characteristics and annual energy production estimates, the following conclusions can be drawn:

1. Although all investigated configurations are technically capable of operating as grid-connected VAWT generators, the geared asynchronous machine configuration (Configuration 1) exhibited insufficient efficiency under low- and medium-power operating conditions, which represent a substantial portion of the expected VAWT operating range. Consequently, this configuration is not considered a competitive solution for the investigated application.

2. Both permanent magnet generator (PMG) configurations demonstrated superior efficiency compared with the geared alternatives. The axial flux PMG (Configuration 2) achieved its highest efficiency at relatively low power levels, making it potentially attractive for installations operating predominantly under low-wind conditions. However, its efficiency decreased significantly at higher loads.
3. The classical radial flux PMG (Configuration 3) exhibited the most favorable overall performance, maintaining high efficiency across a broad operating range while achieving the highest estimated annual energy production of 15,715 kWh. Based on the conducted tests, this configuration represents the most suitable generator solution for the investigated 10 kW VAWT.
4. The synchronous reluctance machine with a gearbox (Configuration 4) demonstrated competitive performance at medium and high power levels and showed no significant efficiency degradation near the nominal operating conditions. Although its overall energy yield was lower than that of Configuration 3, the absence of permanent magnets and reduced dependence on rare-earth materials make this topology an attractive alternative for applications where supply chain security, sustainability, or material cost considerations are important.
5. The present work contributes new experimental evidence regarding the comparative system-level performance of alternative generator–drivetrain configurations evaluated under identical laboratory conditions representative of VAWT operation.

Future work should include long-term field testing under real wind conditions and a comprehensive techno-economic assessment incorporating capital costs, maintenance requirements, drivetrain reliability, and lifecycle energy production.

6. Future Work

Future research should extend the present laboratory investigation through long-term field validation of the selected generator–drivetrain configuration under real VAWT operating conditions. Such testing should evaluate the influence of variable wind conditions, environmental factors, mechanical wear and converter control strategies on system performance, reliability and maintenance requirements.

The experimental methodology should also be extended to VAWTs with different power ratings and wind resource conditions in order to assess the broader applicability of the conclusions obtained for the investigated 10 kW system. Particular attention should be given to the influence of turbine operating profiles on partial-load efficiency and annual electrical energy production.

Further research should investigate advanced converter control strategies and their interaction with different generator technologies, particularly during startup, low-speed operation and transitions between motoring and generating modes. Comprehensive techno-economic analyses and lifecycle assessments should also be performed to quantify the economic and environmental trade-offs between direct-drive permanent magnet generators and geared magnet-free alternatives.

Finally, the experimental methodology presented in this work could be applied to emerging generator topologies and hybrid drivetrain concepts, enabling their direct comparison with the generator–drivetrain configurations investigated in the present study.

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Abbreviations

The following abbreviations are used in this manuscript:

VAWT	Vertical axis wind turbine
PMGs	Permanent magnet generators
AF-PMGs	Axial flux permanent magnet generators
SynRMs	Synchronous reluctance machines
AFE	Active front-end
FOC	Field-oriented control
COP	Coefficient of performance
HMI	Human–machine interface

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