Hydrostatic Transmission for Small-Power Wind Turbines

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Abstract: *This research explores the use of a dual open-circuit hydrostatic transmission system for small-power wind turbines, replacing the traditional closed-circuit design. Through AMESim simulations, the system's performance was evaluated, focusing on power transmission, electric generator frequency regulation by a PID controller, and system stability. The results show that the proposed system reduces the nacelle's mass, simplifies maintenance, and ensures steady generator output frequency at 50 Hz. Bode plot and Root Locus analyses confirmed the system's robustness under varying wind conditions, demonstrating its potential as an efficient and cost-effective solution for small-scale wind energy generation.*

Keywords: *Dual open-circuit hydrostatic transmission, wind turbines, PID controller, system stability, reduction of nacelle mass*

1. Introduction

Wind energy is a rapidly growing sector in the renewable energy landscape, driven by the need to reduce greenhouse gas emissions and transition to sustainable energy sources. Small-power wind turbines, typically used for localized energy production in rural or off-grid areas, represent an important segment of this sector. However, achieving both efficiency and cost-effectiveness in small-scale wind energy systems presents several challenges, particularly with respect to the mechanical-to-electrical energy conversion process. One critical component in this process is the transmission system that converts the rotational energy from the wind turbine into a form suitable for driving an electric generator. Initially, this transmission was a mechanical one, but after 1980, hydrostatic transmission variants also appeared, due to specific advantages [1,2].

Traditionally, closed-circuit hydrostatic transmissions (HSTs) have been employed in wind turbines to transmit mechanical power from the turbine’s rotor to an electric generator. This type of transmission is highly efficient at converting rotational energy into hydraulic energy and then back into mechanical energy to drive a generator. However, closed-circuit HSTs are often bulky, heavy, and expensive, and their placement in the nacelle of a wind turbine complicates maintenance and increases the overall cost of the system.

In the light of these challenges, this study explores an alternative approach: the use of dual open-circuit hydrostatic transmissions in small-power wind turbines. This novel design separates the transmission system into two distinct units—one placed in the turbine’s nacelle with a fixed transmission ratio, and the other on the ground, near the electric generator, with a variable transmission ratio. The main objective is to reduce the mass of the nacelle by relocating the electric generator and part of the transmission system to the ground, thereby simplifying maintenance and reducing costs.

Problem Statement - One of the key limitations in small-power wind turbines is the weight and complexity of the transmission system. The conventional closed-circuit hydrostatic transmissions used in many wind turbines require heavy components to be placed in the nacelle, which adds to the structural demands of the turbine tower. Additionally, these systems require regular maintenance, and accessing them in the nacelle at elevated heights can be difficult and costly. Moreover, the high cost of closed-circuit components makes them less viable for small-scale wind turbine applications, where cost efficiency is critical.

Another challenge lies in regulating the speed of the electric generator to ensure a steady frequency output. For grid-connected wind turbines, maintaining a consistent generator output frequency—typically 50 Hz or 60 Hz depending on the region—is essential. Variations in wind speed lead to fluctuations in the rotational speed of the turbine, which in turn affect the generator's speed and output frequency. A control system is therefore required to adjust the transmission ratio and regulate the generator's speed in response to wind speed changes.

The dual open-circuit hydrostatic transmission system proposed in this study addresses both of these challenges by reducing the nacelle's weight and placing the electric generator on the ground for easier access. Additionally, the open-circuit design simplifies the transmission system, using less expensive and more readily available components. A key feature of this system is the use of a fixed transmission ratio in the nacelle, with a variable transmission on the ground that adjusts flowrate to regulate the generator's speed and frequency.

Objectives - The primary objective of this research is to evaluate the performance of a dual open-circuit hydrostatic transmission system in small-power wind turbines. Specifically, the study aims to:

- *Reduce the nacelle's weight* by relocating part of the transmission system and the electric generator to the ground.
- *Simplify maintenance* by reducing the complexity of the transmission system and providing easier access to the generator.
- *Ensure steady generator output* by integrating a control system that regulates the speed of the generator to maintain a consistent frequency output, despite variations in wind speed.
- *Analyze system stability and performance* using numerical simulations to assess the response of the transmission and control system to different operating conditions.

To achieve these objectives, the study uses a numerical simulation approach, employing the AMESim software to model the performance of the hydrostatic transmission system. The simulation network allows for the analysis of various parameters, including wind turbine power, shaft speed, hydraulic pressures, and flowrates in the two hydrostatic transmissions. Control system stability is assessed through Bode plots and Root Locus analyses, while the dynamic response of the system is evaluated by examining the frequency of the electric generator and control error.

Literature Review - Hydrostatic transmission systems have been widely used in various industrial applications, including wind turbines, because of their high efficiency and the ability to transmit power over relative long distances with minimal losses. In wind turbines, HSTs convert the mechanical energy of the rotating blades into hydraulic energy, which is then used to drive a hydraulic motor connected to an electric generator. While closed-circuit hydrostatic transmissions offer high efficiency, their complexity, cost, and maintenance challenges have limited their use in small-scale applications.

Several studies [3,4,5] have explored alternative transmission methods for wind turbines to improve efficiency and reduce costs. For instance, research on open-circuit hydrostatic transmissions has shown that they offer a simpler and more cost-effective solution compared to closed-circuit systems. However, most of these studies have focused on large-scale wind turbines, where the design and operational requirements differ significantly from small-power turbines. Few studies [6,7] have specifically addressed the unique challenges of small-power wind turbines, such as the need for lightweight and low-cost components that are easy to maintain.

In terms of control systems, PID (Proportional-Integral-Derivative) controllers have been widely used in wind turbines to regulate generator speed and ensure steady power output [8,9]. The effectiveness of PID controllers in maintaining system stability, particularly in the face of fluctuating wind speeds, has been well-documented. Bode plot and Root Locus analyses are commonly used to assess the stability of control systems in wind turbines, providing valuable insights into the dynamic performance of the transmission system and the overall wind turbine.

Contributions of This Research - This study builds on the existing research by investigating the potential of dual open-circuit hydrostatic transmissions for small-power wind turbines. The key contributions of this research include:

- A novel dual transmission design that relocates the electric generator to the ground, reducing nacelle weight and simplifying maintenance.
- A detailed analysis of the dynamic performance of the system, including the behavior of pressures and flowrates in both transmissions and the response of the PID-controlled generator.

- Stability analysis using Bode plots and Root Locus techniques to assess the effectiveness of the control system in maintaining a consistent generator frequency.
- Evaluation of the system’s overall feasibility as a low-cost, efficient solution for small-power wind turbines.

The results of this study provide valuable insights into the design and operation of hydrostatic transmission systems for small-scale wind turbines, offering a potential pathway for improving the cost-effectiveness and reliability of wind energy in distributed applications.
In the following sections, we present the methodology used for system design and simulation, the results of the simulation analysis, and a discussion of the findings in the context of existing research. Finally, the conclusions highlight the potential of the proposed system and future areas of exploration.

2. Material and Methods

Hydrostatic Transmission Design - The hydrostatic transmission (HST) system investigated in this study was modeled for a small-power wind turbine using the AMESim simulation platform. The proposed system consists of two open-circuit hydrostatic transmissions. One transmission is placed in the nacelle of the wind turbine and is designed with a fixed transmission ratio, while the second transmission is located on the ground near the electric generator and has a variable flow, allowing for secondary adjustment to regulate the speed of the synchronous generator by changing the displacement of the hydraulic servomotor.
The purpose of using two separate transmissions is to reduce the nacelle's weight by removing the heavy electric generator, which is conventionally housed in the nacelle. This design also makes maintenance more accessible and lowers the cost of components.
Simulation Setup - The entire hydrostatic transmission system was modeled in the AMESim environment, which provides a network-based approach to simulate mechanical, hydraulic, and control system behaviors. The AMESim simulation model depicted in **Figure 1** consists of various components that model the hydraulic transmission, including pumps, motors, pressure lines, pressure control valves, and the PID controller used to regulate the electric generator frequency.

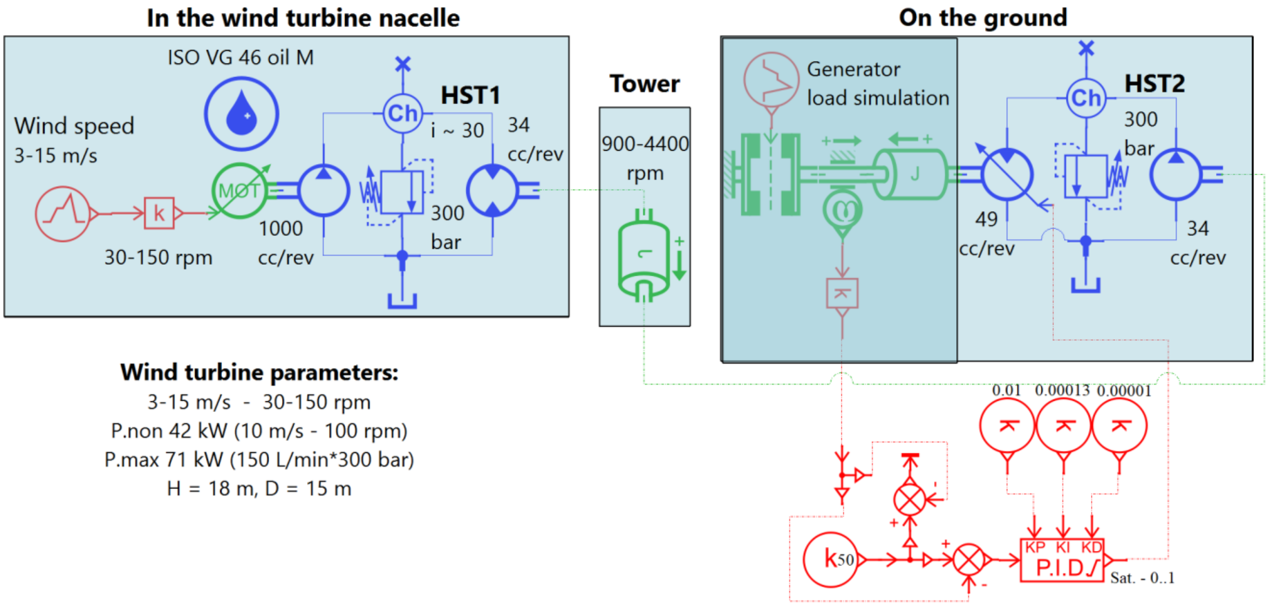

Fig. 1. AMESim simulation network of hydrostatic transmission for small-power wind turbines

The fixed-ratio transmission in the nacelle transfers mechanical energy from the wind turbine to the hydraulic transmission on the ground. The flowrate of the hydraulic pump located on the ground is sent to the servomotor, which is responsible for adjusting the shaft speed to match the required generator speed and maintain a steady output frequency of 50 Hz.

Control and Stability Analysis - A PID controller was integrated into the model to regulate the electric generator's output frequency. Bode plot was generated to analyze the system's frequency response and phase shift between the control signal and the system's response. The stability of the system was assessed through Root Locus analysis.
Data Collection and Processing - Simulation was performed with variable wind speeds, and the output data included the wind turbine power, shafts speed, pressures, and flowrates of the two hydrostatic transmissions. These values were then analyzed to assess the system's performance across various wind speeds and the response of the PID-controlled electric generator frequency.
Figure 1 shows the AMESim simulation network for the hydrostatic transmission system under study. The layout includes the fixed-ratio transmission in the nacelle and the variable-ratio transmission on the ground. Key components such as hydraulic pumps, motors, and pressure control valves are interconnected to represent the entire transmission system. The control loop incorporating a PID controller is managing the speed of the electric generator that operates at the required 50 Hz frequency. The simulation network effectively demonstrates how the energy generated by the wind turbine is transmitted hydraulically to the generator located on the ground.

3. Results and Discussion

The performance of the hydrostatic transmission system for small-power wind turbines was assessed through a simulation conducted in the AMESim environment. The results presented here focus on the operational characteristics of the wind turbine, the behavior of the two hydrostatic transmissions (HST1 and HST2), and the effectiveness of the PID controller in maintaining a steady output frequency. Key performance indicators such as power output, shaft speed, pressure, and flow rates were analyzed across varying wind speeds, highlighting the system’s response and stability under different operating conditions.
Figure 2 illustrates the relationship between wind speed, shaft speed, and the power output of the wind turbine. As expected, the power generated by the turbine increases with wind speed, which is characteristic of wind turbines. Additionally, the shaft speed of the turbine rises proportionally with wind speed. The graph shows that at lower wind speeds, the turbine operates at suboptimal efficiency, but as wind speed increases, both shaft speed and power output approach the turbine’s rated values. This characterization is essential for understanding how the hydrostatic transmission adapts to varying wind conditions to maintain efficient energy transfer and regulate the electric generator’s speed.
Figure 3 depicts the pressure and flow rate behavior in the two open-circuit hydrostatic transmissions (HST1 in the nacelle and HST2 on the ground) under varying wind conditions. The graph shows that the pressure in HST1 and HST2 is proportional to the wind turbine power. The flow rate in HST1 & HST2 shows a direct correlation with wind speed, increasing as the wind turbine generates more mechanical power.
Figure 4 presents the Bode plot, showing the magnitude and phase response of the system under the control of the PID regulator. The plot illustrates how the system reacts to changes in the control signal, with particular focus on the frequency of the electrical generator. The magnitude plot indicates a reduction in system response at higher frequencies, with a notable roll-off starting around 0.3 Hz, reflecting the system's decreasing sensitivity to rapid fluctuations in wind speed or load.
The phase plot shows a progressive phase lag as frequency increases, with a significant phase shift occurring between 0.3 Hz and 0.76 Hz. This indicates that at higher frequencies, the system response lags behind the control command, which is typical in systems with inertia, such as hydrostatic transmissions. The PID controller successfully maintains stability within the operating frequency range, with the phase remaining within acceptable limits to ensure that the system response is both steady and efficient. These results confirm that the PID controller is effective in regulating the electric generator's frequency, ensuring that the hydrostatic transmission system can adapt to changing wind conditions while maintaining a steady 50 Hz output for the electrical grid.

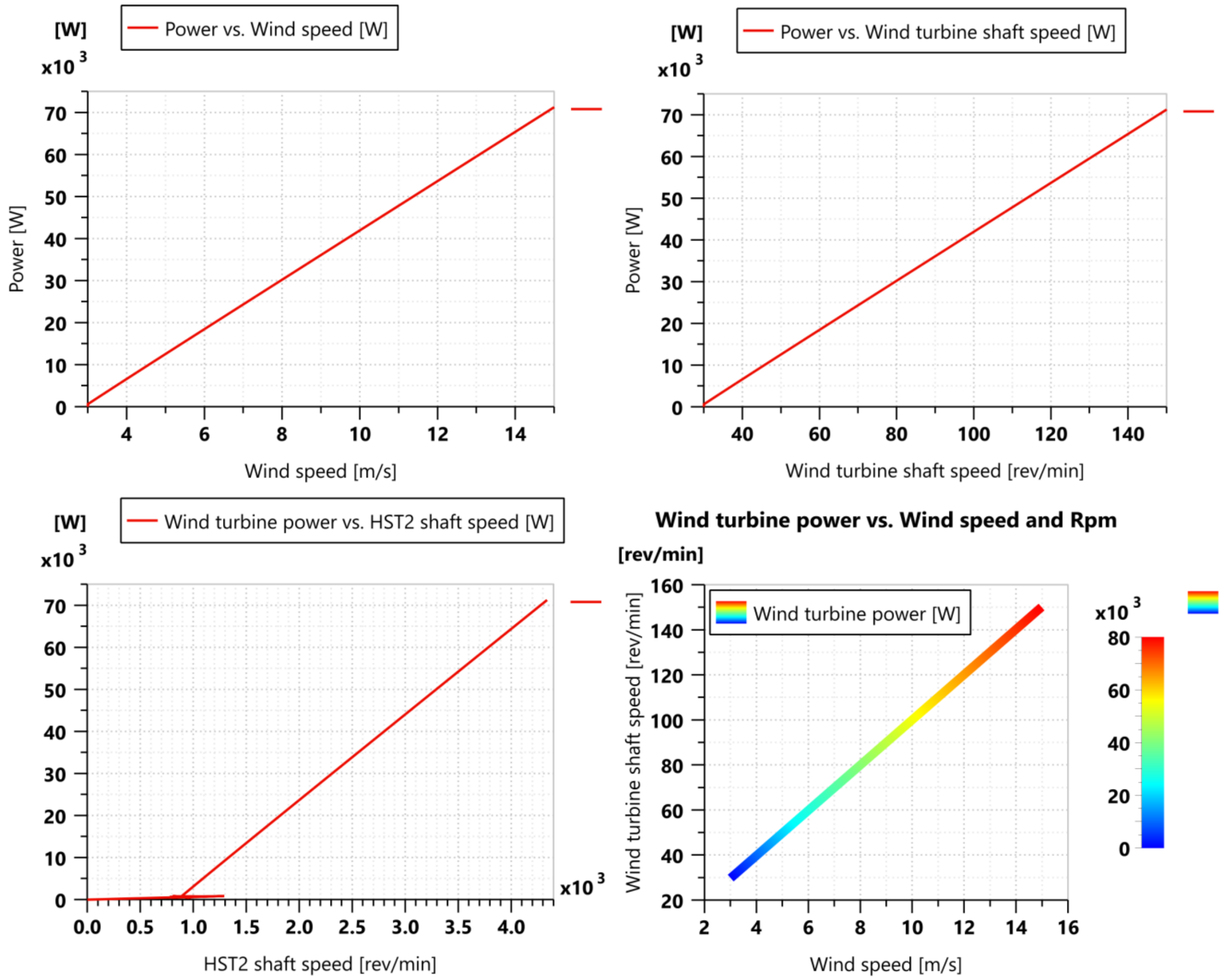

Fig. 2. Wind turbine characterization – power vs. wind speed, shaft speed

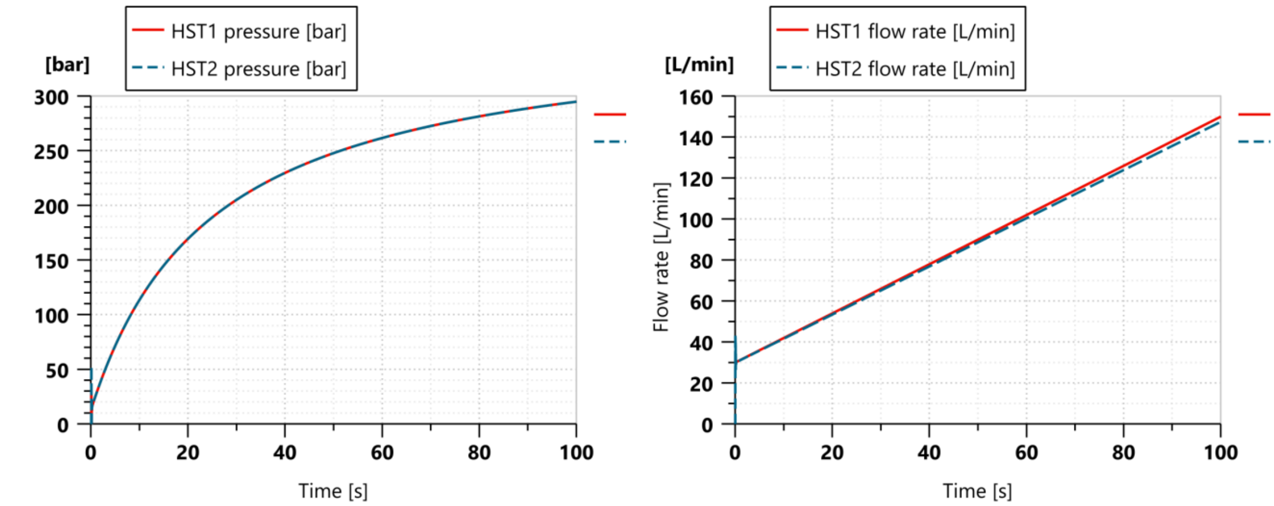

Fig. 3. Pressure and flowrate of the two hydrostatic transmissions (HST1 and HST2)

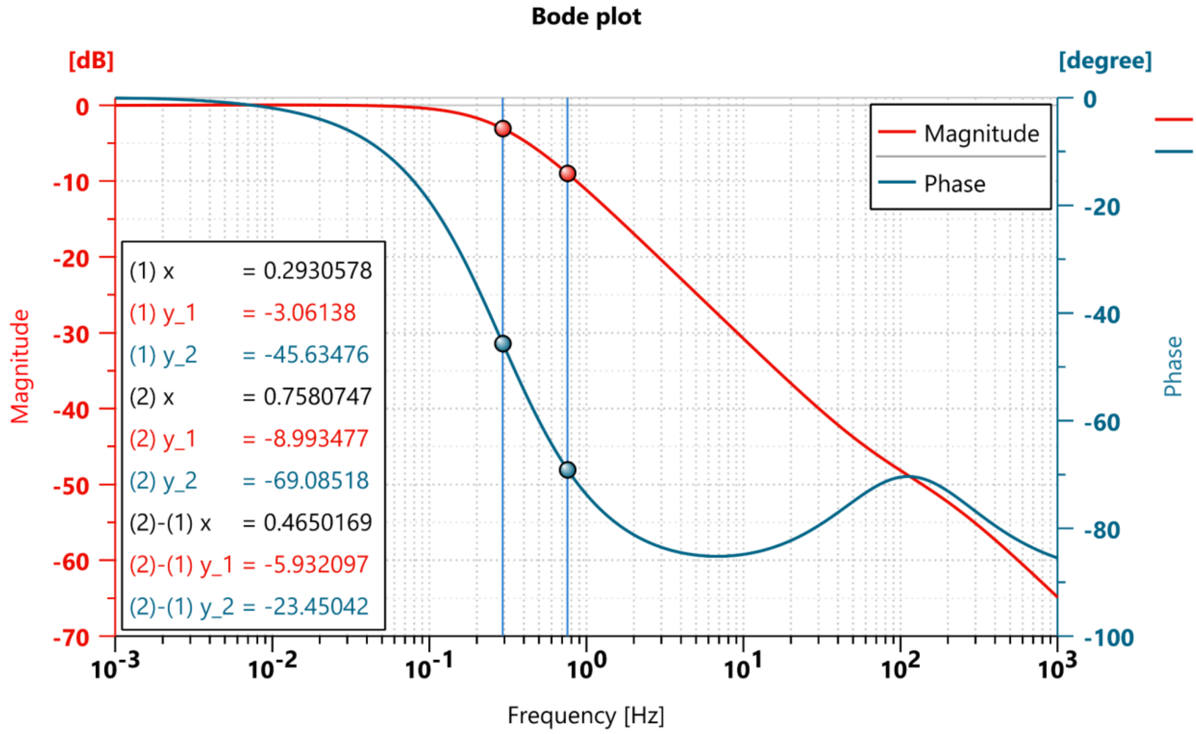

Fig. 4. Bode plot – magnitude and phase of the PID output (system command) and system response (electrical generator frequency)

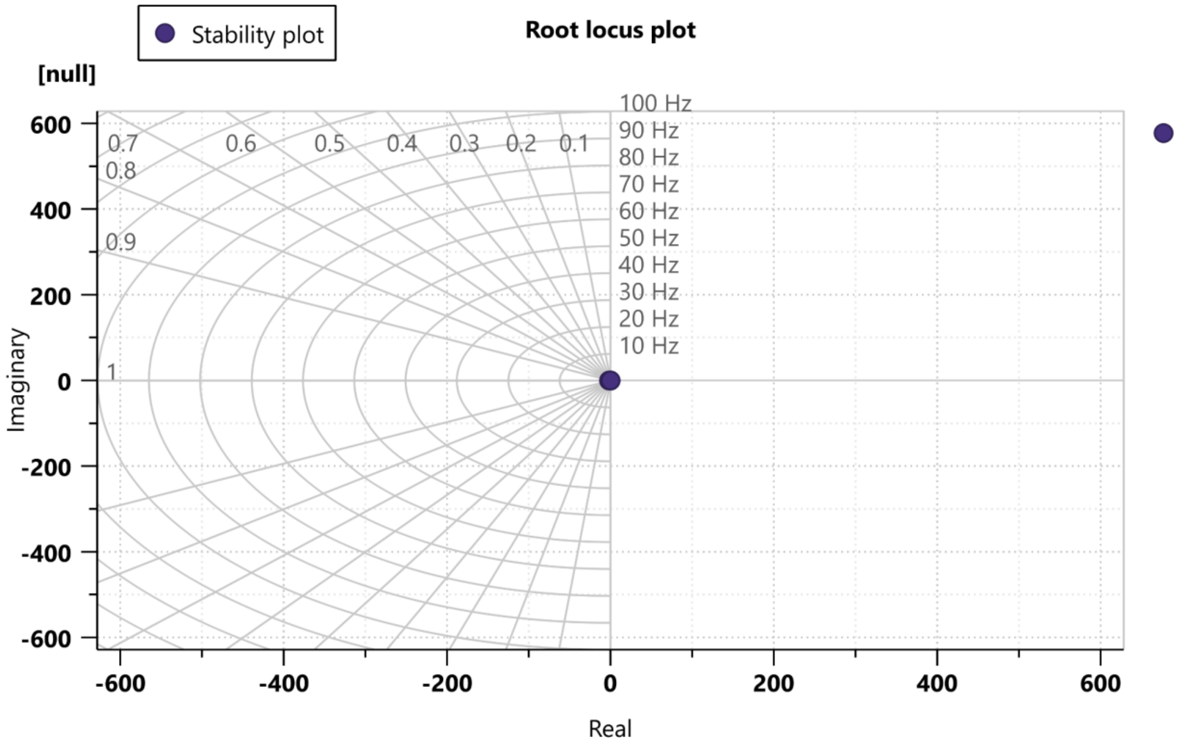

Fig. 5. Stability of the system – Root Locus plot

Figure 5 displays the Root Locus plot used to assess the stability of the PID-controlled hydrostatic transmission system. The plot shows the movement of the system poles as the gain of the PID controller varies. The Root Locus analysis is crucial for evaluating whether the system can maintain stability across a range of operating conditions. In this figure, one can see that the system poles remain in the left half of the complex plane for a wide range of gains, indicating that the system remains steady under these conditions. The poles are sufficiently far from the imaginary axis, ensuring that the system is both steady and responsive, with minimal risk of oscillatory or unsteady behavior.

Figure 6 provides a detailed view of the Root Locus plot, zooming in on the region where the poles are closest to the imaginary axis. This close-up highlights how small changes in the controller gain affect the system's stability margins. The detailed plot shows that, even in this sensitive region, the poles do not cross into the right half of the plane, confirming that the system remains steady throughout the range of gains tested. The proximity of the poles to the imaginary axis suggests that, while the system is steady, it may exhibit slower dynamic response at certain gain values, necessitating careful tuning of the PID controller to balance stability with performance. Together, **Figures 5 and 6** demonstrate that the hydrostatic transmission system is inherently steady under PID control, with sufficient margins to handle varying operating conditions while avoiding instability.

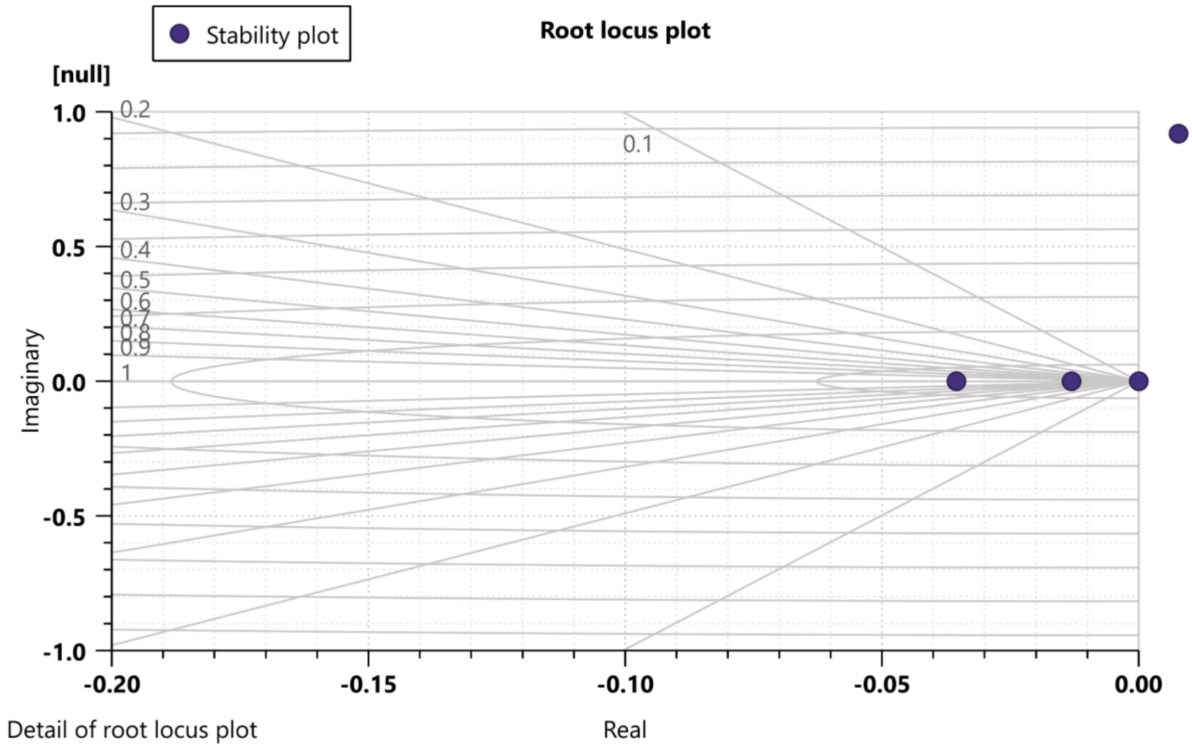

Fig. 6. Stability of the system – Root Locus plot (detail)

Figure 7 illustrates the dynamic behavior of the electric generator's output frequency and the associated control error over time. The graph compares the actual frequency of the generator with the desired setpoint of 50 Hz and tracks the error signal produced by the PID controller.

The frequency plot shows that the generator initially experiences deviations from the target frequency, particularly during transient periods when inertia of the system acts. However, the PID controller effectively adjusts the system to minimize these deviations, bringing the generator frequency back to the 50 Hz setpoint. Over time, the fluctuations become smaller, indicating that the control system successfully stabilizes the output.

The control error plot reveals the magnitude of frequency deviations and the controller's response. Initially, the error is higher due to the system's response to wind speed variations and inertia, but it decreases steadily as the PID controller compensates for these changes. The diminishing error confirms the system's ability to maintain a steady and accurate frequency output, which is critical for ensuring the reliability of the electrical grid connected to the wind turbine.

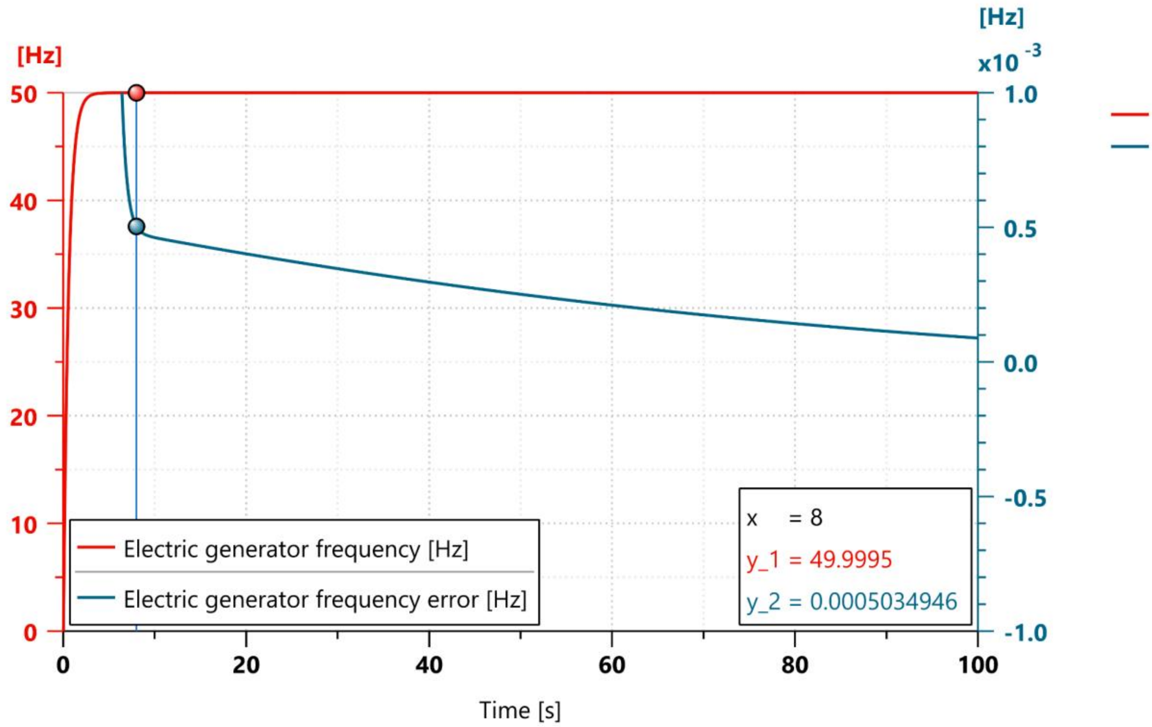

Fig. 7. Electric generator frequency and its control error

This figure highlights the efficiency of the PID-controlled hydrostatic transmission system in dynamically adjusting to varying wind conditions while keeping the generator frequency steady, with minimal error over time.

4. Conclusions

This study demonstrates the feasibility and advantages of employing a dual open-circuit hydrostatic transmission system for small-power wind turbines. By replacing the conventional closed-circuit transmission in the nacelle with two open-circuit systems—one in the nacelle with a fixed ratio and another on the ground with a variable ratio—several key benefits are achieved. These include a significant reduction in the mass of the nacelle, easier access to components for maintenance, and overall cost reduction.

The AMESim simulations confirmed the effectiveness of this setup in ensuring steady power transmission and efficient regulation of the electric generator frequency. The use of a PID controller successfully maintained the generator output frequency at 50 Hz, even under severely varying wind conditions. The system's dynamic response was validated through Bode plot analysis, and the stability was confirmed through Root Locus plots, showing robust performance across a wide range of operating conditions.

The results highlight the system's ability to handle pressure and flow variations effectively between the two hydrostatic transmissions, ensuring reliable performance. The control error analysis showed that the PID controller efficiently minimized frequency deviations, ensuring consistent output for grid integration.

In conclusion, this dual open-circuit hydrostatic transmission system provides a promising alternative for small-power wind turbines, offering advantages in terms of weight, cost, maintenance, and operational stability. Future work could explore further optimization of the controller and the performance of the system under fluctuant wind conditions.

Acknowledgments

This work was carried out through the Core Program within the National Research Development and Innovation Plan 2022-2027, carried out with the support of the Romanian Ministry of Research, Innovation and Digitalization (MCID), project no. PN 23 05.

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