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Enhanced Funnel Control Strategies for Wind Turbine Speed Regulation – FC Symmetric with scaling.

Zaina Ait Chekdhidh ^{a,*}, Aghiles Ardjal ^a, Maamar Bettayeb ^b

^a L2CSP Laboratory, Faculty of Electrical and Computer Engineering, Mouloud Mammeri University, Tizi-Ouzou, Algeria

^b Department of Electrical Engineering, University of Sharjah, Sharjah, United Arab Emirates

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ABSTRACT

This paper investigates a symmetric Funnel Control (FC) strategy enhanced with a gain scaling mechanism for wind turbine speed regulation. The proposed approach guarantees prescribed transient and steady-state performance by constraining the tracking error within identical upper and lower performance boundaries. Unlike classical funnel control, which offers limited tuning flexibility, the gain-scaled symmetric FC introduces an additional tuning parameter that significantly improves transient behavior while preserving stability and constraint satisfaction. A nonlinear wind turbine model including aerodynamic torque and drivetrain dynamics is considered. Simulation results obtained in MATLAB/Simulink demonstrate that increasing the scaling gain leads to substantial reductions in rise time, settling time, and tracking error. Quantitative performance indices such as IAE, ITAE, MSE, RMSE, and AMSE confirm the effectiveness of the proposed strategy. The results highlight the suitability of symmetric gain-scaled funnel control for practical wind energy applications operating under uncertainty and variable wind conditions.

1 Introduction

Wind energy conversion systems play a central role in modern renewable energy production. Their efficiency and reliability strongly depend on accurate control of the turbine rotor speed, particularly under variable and unpredictable wind conditions. Maintaining the rotor speed close to its optimal value enables maximum aerodynamic power extraction while limiting mechanical stress on the drivetrain and improving the overall lifetime of the system [1, 2].

Conventional linear control strategies, such as Proportional–Integral (PI) and Proportional–Integral–Derivative (PID) controllers, are widely implemented in industrial wind turbines due to their simplicity and ease of tuning. However, their performance often deteriorates when facing nonlinear aerodynamic behavior, parameter uncertainties, and external disturbances induced by wind turbulence. These limitations may lead to slower dynamic response, increased mechanical

* Corresponding author.

E-mail address: zaina.ait-chekdhidh@ummtto.dz

loading, and suboptimal energy capture [2, 3]. As a result, advanced nonlinear and adaptive control techniques have attracted increasing attention in recent years.

Funnel Control (FC) has emerged as a powerful model-free tracking control methodology capable of guaranteeing prescribed transient and steady-state performance. The fundamental idea of FC is to constrain the tracking error within a predefined time-varying boundary, referred to as the performance funnel [4]. By dynamically adjusting the control gain according to the distance between the error and the funnel boundary, FC ensures fast convergence and robustness without requiring precise system identification. Since its introduction, FC has been successfully applied to a wide range of systems characterized by structural uncertainty, actuator constraints, and unknown nonlinear dynamics, including several energy and mechatronic applications [5, 6].

Recent studies have extended Funnel Control to renewable energy systems, particularly wind turbines, by combining it with nonlinear control schemes such as sliding mode control, synergetic control, and fractional-order approaches. These works have demonstrated that FC-based strategies can effectively enhance robustness and tracking performance under wind disturbances and modeling uncertainties [7–10]. Nevertheless, many of these approaches rely on asymmetric funnel boundaries, hybrid controller structures, or additional dynamic layers, which may increase design complexity and limit practical implementation.

Despite its robustness, the classical formulation of Funnel Control offers limited flexibility in shaping the control action during transient phases. In particular, the convergence speed and initial control effort are strongly influenced by the choice of the funnel boundary. To address this limitation, gain scaling has been introduced as an extension of FC, providing an additional tuning degree of freedom while preserving the fundamental funnel properties [6]. Gain scaling allows the designer to directly influence the control intensity and transient response without modifying the prescribed performance boundary.

However, the systematic application of gain scaling within a strictly symmetric Funnel Control framework for wind turbine speed regulation has received limited attention in the existing literature. In particular, the impact of gain scaling on transient behavior, tracking accuracy, and control effort when identical upper and lower funnel boundaries are enforced remains insufficiently investigated.

In this context, the present paper focuses on the application of symmetric Funnel Control with gain scaling to wind turbine rotor speed regulation. The term symmetric refers to the use of identical performance boundaries for positive and negative tracking errors, ensuring balanced and unbiased transient behavior. The novelty of this work lies in the explicit integration of a gain scaling mechanism into the symmetric FC structure and in the comprehensive analysis of its influence on convergence speed, steady-state accuracy, and overall control performance in a wind energy application.

The main contributions of this paper can be summarized as follows:

- A symmetric Funnel Control strategy with gain scaling is formulated for wind turbine rotor speed regulation.
- The effect of gain scaling on transient response, steady-state accuracy, and control effort is systematically analyzed.
- A nonlinear wind turbine model is employed to validate the proposed approach under variable wind speed conditions.
- A comprehensive performance evaluation is conducted using time-domain indicators and error-based metrics such as IAE, ITAE, MSE, RMSE, and AMSE.

The remainder of this paper is organized as follows. Section 2 presents the principle of symmetric Funnel Control, including the performance funnel and the gain-scaled control law. Section 3 describes the wind turbine modeling used for control design and simulation. Section 4 provides the simulation results and discusses the impact of gain scaling on system performance. Finally, Section 5 concludes the paper and outlines directions for future research.

2 Symmetric Funnel Control Principle

2.1 Performance Funnel

The tracking error is defined as:

$$e(t) = y(t) - y_{ref}(t) \quad (1)$$

In symmetric Funnel Control, the tracking error is constrained by a single time-varying boundary such that:

$$|e(t)| < \Psi(t), \quad \text{for all } t \geq 0 \quad (2)$$

where $\Psi(t)$ is a strictly positive and smooth function selected to specify the desired transient and steady-state performance. The function $\Psi(t)$ defines a symmetric performance funnel that bounds the evolution of the tracking error over time.

To ensure feasibility of the prescribed performance constraint, the initial tracking error must satisfy

$$|e(0)| < \Psi(0)$$

This compatibility condition guarantees that the error trajectory starts inside the funnel and allows the controller to maintain the constraint for all future time.

The symmetric funnel is defined as

$$F(\Psi) = \{ (t, e) \in \mathbb{R} \geq 0 \times \mathbb{R} \mid |e(t)| < \Psi(t) \} \quad (3)$$

where $\Psi(t)$ is a continuously differentiable function belonging to class B_1 with a strictly positive initial value, i.e., $\Psi(0) > 0$ and $\Psi(t) > 0$ for all $t \geq 0$. In this case, the upper and lower funnel boundaries are symmetric with respect to zero and are given by $\Psi^+(t) = \Psi(t)$ and $\Psi^-(t) = -\Psi(t)$. Unlike the asymmetric funnel, no unilateral overshoot constraint is imposed, and the tracking error is required to evolve within a symmetric performance envelope centered at zero. This configuration guarantees identical transient performance limitations in both positive and negative directions while ensuring that the control gain increases automatically as $|e(t)|$ approaches $\Psi(t)$, thereby preventing violation of the funnel boundary.

The funnel boundary is assumed to satisfy

$$\Psi \in C^1(\mathbb{R} \geq 0), \inf_{t \geq 0} \Psi(t) > 0$$

Ensuring that the funnel remains strictly open and varies smoothly with time.

A commonly adopted exponential funnel boundary is given by:

$$\psi_{exp}(t) = (\lambda_0 - \lambda_\infty) \exp(-t/T) + \lambda_\infty \quad (4)$$

and Gaussian funnel boundary is given by

$$\psi_{gauss}(t) = (\lambda_0 - \lambda_\infty) \exp((-t/T)^2) + \lambda_\infty \quad (5)$$

where λ_0 represents the initial admissible error, λ_∞ defines the asymptotic error bound, and T is a positive time constant that controls the rate of convergence of the funnel boundary.

Figure 1 shows the Funnel Boundary Symmetric.

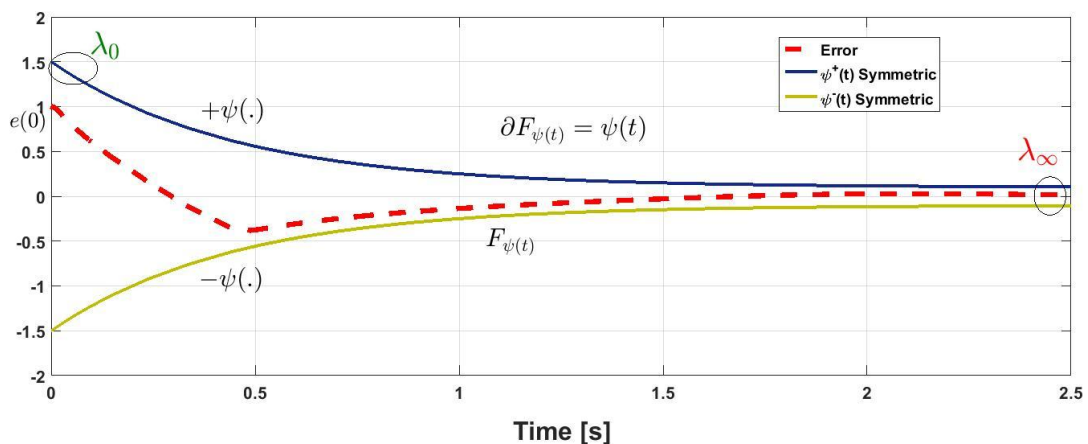


Fig. 1 –Funnel Boundary Symmetric

2.1.1 Classical Symmetric Funnel Control

For systems with a known sign of the high-frequency gain γ , the classical symmetric Funnel Control (FC) law [4, 6] is expressed as:

$$u(t) = \text{sgn}(\gamma) k(t) e(t) \quad (6)$$

Where the time-varying control gain [4, 11] is defined by:

$$k(t) = \frac{1}{(\psi(t) - |e(t)|)} \quad (7)$$

Although $k(t)$ increases as $|e(t)|$ approaches $\Psi(t)$, the closed-loop dynamics prevent the error from reaching the funnel boundary.

Consequently, no singularity occurs and the gain remains finite in closed-loop operation.

As the tracking error approaches the funnel boundary, the gain increases automatically, enforcing stronger control action and preventing violation of the prescribed performance constraint. Conversely, when the tracking error remains small, the gain decreases, which reduces control effort and limits sensitivity to measurement noise. This adaptive behavior is a key feature of Funnel Control and ensures robustness against disturbances and model uncertainties [5, 6].

Under these conditions, all closed-loop signals remain bounded and no finite escape time occurs, provided that the funnel boundary remains strictly positive.

2.1.2 Gain-Scaled Symmetric Funnel Control

To improve tuning flexibility and transient performance, a scaling function $\delta(t)$ is introduced into the gain expression as [6]:

$$k(t) = \frac{\delta(t)}{(\psi(t) - |e(t)|)} \quad (8)$$

A practical and effective choice for the scaling function [6, 9] is given by:

$$\delta(t) = \alpha \psi(t), \quad \alpha > 0 \quad (9)$$

Where α is a constant scaling gain. Increasing the value of α amplifies the control action, accelerates convergence, and improves tracking accuracy without redesigning the funnel boundary or violating the symmetric performance constraints. This gain-scaling mechanism preserves the fundamental properties of Funnel Control while offering additional freedom for transient performance tuning [6, 9].

3 Wind Turbine Modeling

The mechanical dynamics of the wind turbine rotor [1, 2] are described by the following equation:

$$\frac{J_t d\omega_r}{dt} = T_a - K_t \omega_r - T_g \quad (10)$$

where J_t denotes the total inertia of the turbine-generator system, T_a is the aerodynamic torque, K_t represents the viscous friction coefficient, and T_g is the generator torque acting as the control input.

The aerodynamic torque [2, 10] is expressed as:

$$T_a = 0.5 \pi \rho C_q(\lambda) R_r^3 w_s^2 \quad (11)$$

Where ρ is the air density, R_r is the rotor radius, and w_s denotes the wind speed. The tip-speed ratio [2] is defined by:

$$\lambda = \frac{\omega_r R_r}{w_s} \quad (12)$$

The control objective is to regulate the rotor speed toward the optimal reference value [1, 2]:

$$\omega_{ref} = G_r \frac{\lambda_{opt} w_s}{R_r} \quad (13)$$

Where G_r is the gearbox ratio and λ_{opt} is the optimal tip-speed ratio that maximizes the power coefficient. Tracking this reference ensures maximum power extraction during partial-load operation of the wind turbine.

4 Results and Discussions

To thoroughly evaluate the effectiveness of the proposed symmetric Funnel Control (FC) strategy, two distinct symmetric funnel boundary profiles were considered: an exponential funnel and a Gaussian funnel. Each boundary type was selected to serve a specific analytical purpose.

First, the exponential symmetric funnel was employed to demonstrate the fundamental behavior and stability properties of the symmetric FC formulation. Due to its monotonically decreasing structure, the exponential boundary provides a clear visualization of how the tracking error evolves from an initially wide admissible region toward a tighter steady-state constraint. This configuration allows direct observation of the prescribed performance enforcement, ensuring that the tracking error remains strictly confined within symmetric upper and lower bounds throughout the transient and steady-state phases.

Subsequently, a Gaussian symmetric funnel was introduced for comparative performance analysis between the classical FC and the gain-scaled FC. The Gaussian profile offers a smoother boundary evolution and a more flexible shaping of transient constraints, making it particularly suitable for highlighting differences in convergence dynamics and error attenuation. In this phase, two scaling factors were investigated ($\alpha = 50$ and $\alpha = 600$) in order to assess the influence of gain scaling intensity on system behavior.

The performance evaluation focused on both transient and steady-state characteristics. In addition to classical time-domain indicators such as rise time, settling time, and overshoot, quantitative error criteria were employed to provide a rigorous assessment of tracking quality. These included:

- Integral of Absolute Error (IAE), measuring the total accumulated tracking deviation.
- Integral of Time-weighted Absolute Error (ITAE), emphasizing long-duration errors and penalizing slow convergence.
- Mean Squared Error (MSE), reflecting the average quadratic deviation.
- Root Mean Squared Error (RMSE), providing a normalized measure of tracking precision.

These indices allow a comprehensive evaluation of controller performance in terms of accuracy, speed, and robustness.

Figure 2 shows the generator speed response under the symmetric exponential funnel, while Figure 3 illustrates the corresponding tracking error evolution. These results confirm that the symmetric FC ensures that the error remains strictly confined within the prescribed performance boundaries.

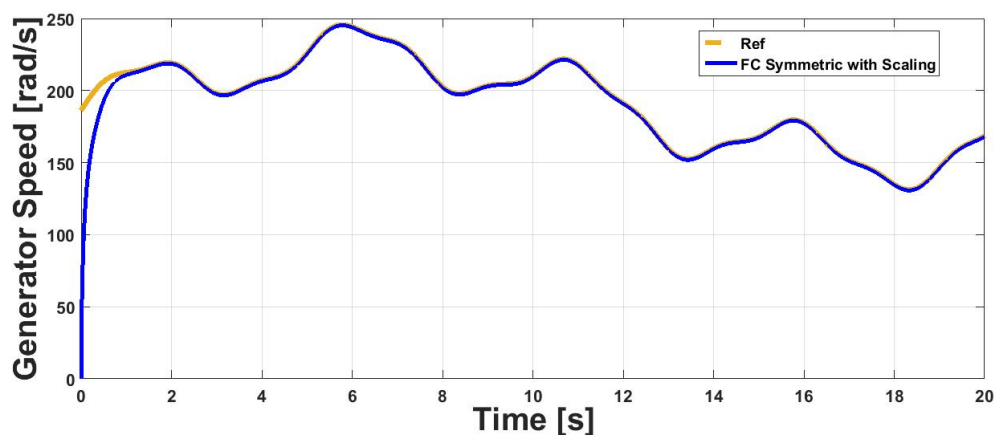


Fig. 2 –Generator Speed within Funnel Symmetric exponential

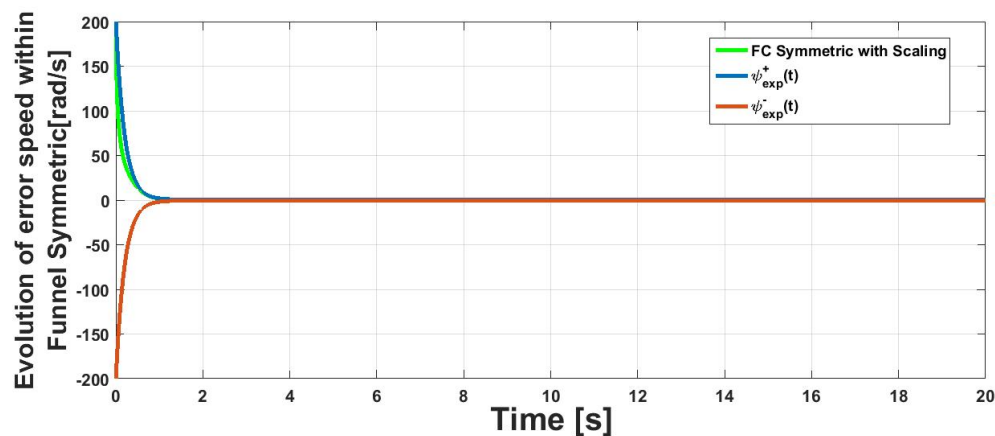


Fig. 3 –Evolution of error speed within Funnel Symmetric exponential

For the Gaussian symmetric funnel, Figure 4 shows the generator speed, Figure 5 depicts the tracking error evolution under classical FC and gain-scaled FC configurations. The results show that increasing the scaling factor accelerates error convergence and reduces transient oscillations. Figure 6 illustrates the corresponding power coefficient behavior. Improved speed tracking directly enhances aerodynamic efficiency, as the turbine operates closer to the optimal tip-speed ratio. The gain-scaled controller achieves faster stabilization of the power coefficient, indicating improved energy capture performance.

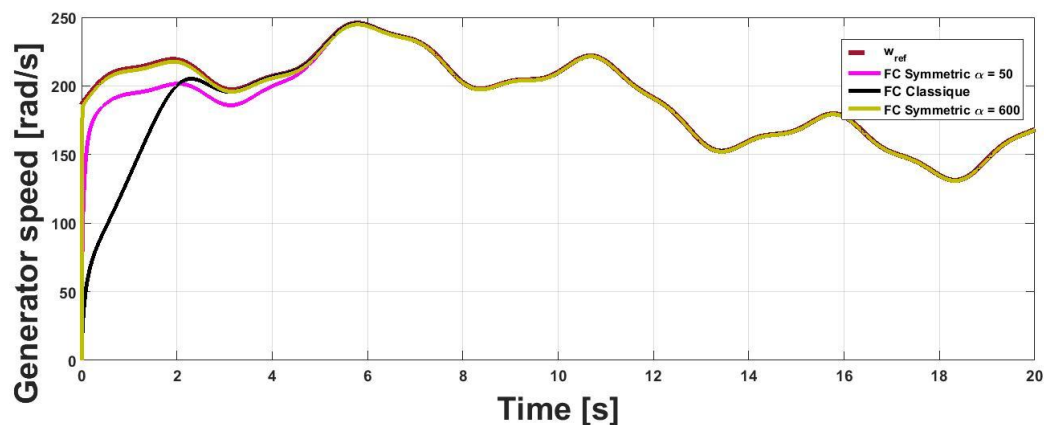


Fig.4 –Generator Speed within Funnel Symmetric Gaussian

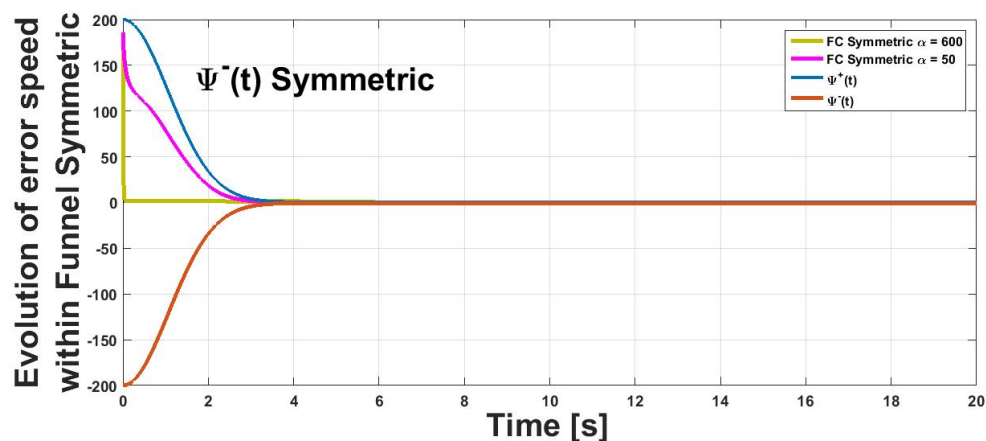


Fig.5 –Evolution of error speed within Funnel Symmetric Gaussian

Overall, the comparative analysis highlights that gain scaling significantly enhances dynamic responsiveness while preserving the intrinsic robustness of the symmetric Funnel Controller. Higher scaling factors lead to faster convergence and reduced error magnitudes; however, they also increase control activity, which must be considered when addressing actuator limitations and practical implementation constraints.

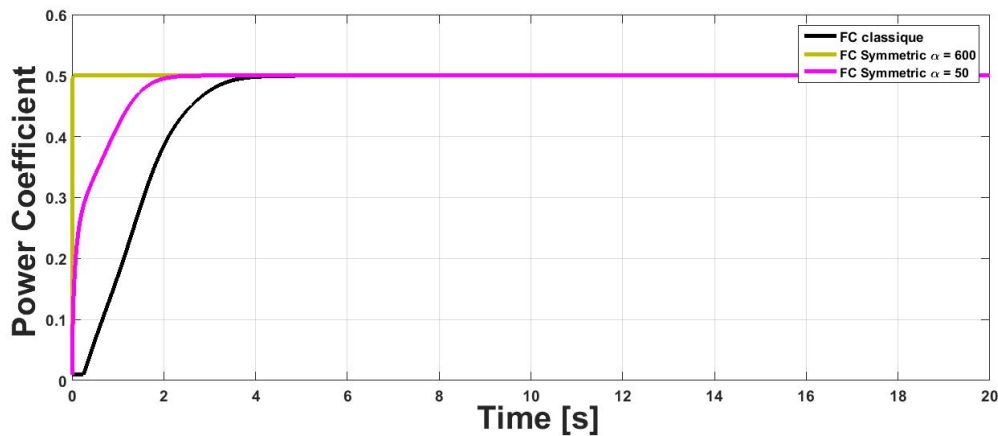


Fig. 6 –Power Coefficient within Funnel Symmetric Gaussian

4.1.1 Performance Comparison

The comparative analysis between the classical FC and the gain-scaled FC ($\alpha = 50$ and $\alpha = 600$) reveals a significant improvement in dynamic response when gain scaling is introduced.

- **Rise and Settling Times:** The rise time was drastically reduced from 2.453 s (classical FC) to 0.007 s ($\alpha = 600$). Similarly, the settling time improved from 4.185 s to 0.01 s, demonstrating much faster convergence toward the reference speed.
- **Steady-State Error:** The relative steady-state error decreased from 0.119% (classical FC) to 0.088% for the highest scaling factor, indicating enhanced steady-state accuracy.
- **Error Indices:** All performance indices (IAE, ITAE, MSE, RMSE) were significantly reduced as α increased, confirming improved tracking precision and reduced cumulative error.

These results clearly demonstrate that gain scaling enhances both transient and steady-state performance.

4.1.2 Visual Results

Figures 2 and 3 (exponential funnel) illustrate the confinement of the tracking error within symmetric bounds, validating the theoretical formulation of the symmetric FC.

Figures 5 and 6 (Gaussian funnel) compare the classical FC with the gain-scaled FC ($\alpha = 50$ and $\alpha = 600$). The visual analysis shows:

- Faster tracking of the reference speed
- Reduced oscillations
- Improved aerodynamic performance through better regulation of the power coefficient

The improvement becomes more pronounced as the scaling factor increases.

4.1.3 Discussion

The integration of gain scaling into the symmetric Funnel Controller significantly improves wind turbine speed regulation performance. The main observations are:

- Faster dynamic response and accelerated convergence
- Reduced tracking error and improved steady-state precision
- Better alignment with the reference trajectory, leading to improved aerodynamic efficiency
- Increased tuning flexibility through the scaling parameter α

However, excessively large scaling gains may increase control effort and potentially lead to actuator saturation. Therefore, careful tuning of α is necessary to balance performance improvement and practical implementation constraints.

5 Conclusion

This study presented a symmetric Funnel Control strategy combined with gain scaling for wind turbine speed regulation. The exponential symmetric funnel was first used to demonstrate the prescribed performance property of the symmetric FC. Subsequently, a Gaussian symmetric funnel enabled a comparative analysis between the classical FC and the gain-scaled FC.

By enforcing identical upper and lower performance bounds, the proposed controller guarantees predefined transient behavior while maintaining robustness against disturbances and uncertainties. The introduction of gain scaling significantly improves convergence speed, reduces tracking error, and enhances steady-state accuracy without compromising stability.

Simulation results confirm the effectiveness of the proposed approach and highlight its strong potential for practical wind energy applications. Future work will focus on experimental validation and robustness analysis under turbulent wind conditions.

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