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Enhanced tracking of reference speed and aerodynamic performance through fractional PI control: comparison with conventional PI

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Abstract. Wind energy is now one of the major solutions for addressing energy and environmental challenges. Due to rapid and random fluctuations in wind speed, ensuring maximum power extraction remains a technological challenge. In this work, we compare the classic integral proportional regulator a the fractional FOPI controller by MPPT strategy of a wind turbine. Simulations using MATLAB/Simulink demonstrate that FOPI improves dynamic and steady-state performance from 0.035% to 0.015%, response time from 0.025 s to 0.002 s, and overshoot from 3.8% to 2.0%. It also keeps the maximum power coefficient Cp closer to its optimum. In addition, the FOPI controller offers better stability, accuracy, and robustness in tracking the TSR.

Introduction

The massive integration of wind energy into the global electricity grid has accelerated. Driven by increasing energy demand and the environmental imperatives of reducing greenhouse gas emissions. Aerodynamic-to-electrical energy conversion configured with a DFIG are very important in this context. This is due to the fact that they can operate at very different speeds and they limit the power that passes thru the power electronics to a fraction of the total installed power. At the same time, maximum power point tracking strategies play a key role in ensuring optimal extraction of available wind energy [1,2].

In the majority of doubly-fed wind turbines, the control of the converters is still based on classical proportional-integral regulators, chosen for their ease of implementation and direct physical interpretation. But this control reaches its limits when the system operates in a highly nonlinear environment, with variations in machine parameters, modeling uncertainties, and various disturbances related to the wind profile or the electrical grid. These elements degrade dynamic performance (overshoot, response time) and the grid-injected power quality (transient regimes, wind speed variations).

Therefore, various control strategies have been proposed to ensure improved the behavior of wind systems. Among these approaches, we can mention the optimal speed ratio adjustment [3] , predictive current control [4], artificial neural networks , direct torque control [5] , as well as MPPT algorithms adapted to variable wind speed [6] .

Given these limitations, fractional order controllers, particularly FOPI, offer a more robust solution than conventional PI controllers. With their additional degree of freedom, they better represent this frequency dynamics of the system and reduce sensitivity to parameter variations. Although their effectiveness has been proven in various electromechanical and energy applications, their detailed

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comparison with conventional PI in a DFIG-based WECS remains understudied, hence the interest of this study. In this context. This study compares traditional fixed-gain PI control with the FOPI regulator for MPPT in DFIG wind turbines. The structure of the article structured in the following manner: Chapter 2 discusses the development of detailed mathematical models for the entire wind energy conversion chain. Section 3 describes their design and tuning. Section 4 examines the comparative results of the simulations obtained in terms of optimal power capture along with enhanced power quality, and robustness. Finally, Section 5 concludes the study and suggests avenues for future work.

Mathematical modeling for the entire wind energy conversion chain and MPPT with speed regulation

The wind is an unpredictable variable, defined by its direction and velocity, which are affected by elements like geographical location and climatic conditions. The formulas for the input power, mechanical power, and torque of the wind turbine (WT) are stated below [7,8].

$$P_t = C_p(\lambda,\beta)\cdot\frac{\rho S V^3}{2}. \tag{1}$$

$$P_t^{opt} = C_p^{\max}(\lambda_{opt},\beta_{opt})\cdot\frac{\rho S V^3}{2}. \tag{2}$$

$$C_t = \frac{P_t}{\Omega_t}. \tag{3}$$

$$C_p(\lambda,\beta) = 0.0068\lambda + \frac{1}{2}\left(\frac{116}{\lambda_i} - \frac{2}{5}\beta - 5\right)\cdot\exp\left(\frac{-21}{\lambda_i}\right). \tag{4}$$

$$\frac{1}{\lambda_i} = -\frac{0.035}{\beta^3+1} + \frac{1}{\lambda+0.08\beta}. \tag{5}$$

$$\lambda = \frac{R_t\Omega_t}{V}. \tag{6}$$

To accomplish this, turbine rotational speed must vary proportionally with wind speed changes. The ideal turbine speed for achieving maximum power extraction can be articulated as[9]:

$$\Omega_t^{opt} = \frac{\lambda_{opt} V}{R}. \tag{7}$$

The MPPT controller computes the generator reference speed Ω_g^* needed to maintain λ_{opt} :

$$\Omega_g^* = \lambda_{opt}\times\frac{V}{R}\times G. \tag{8}$$

Fig. 1 depicts the functional diagram of the speed-based MPPT control architecture. Wind speed information is used to calculate the optimal reference speed that the speed controller seeks to achieve in order to generate torque commands.

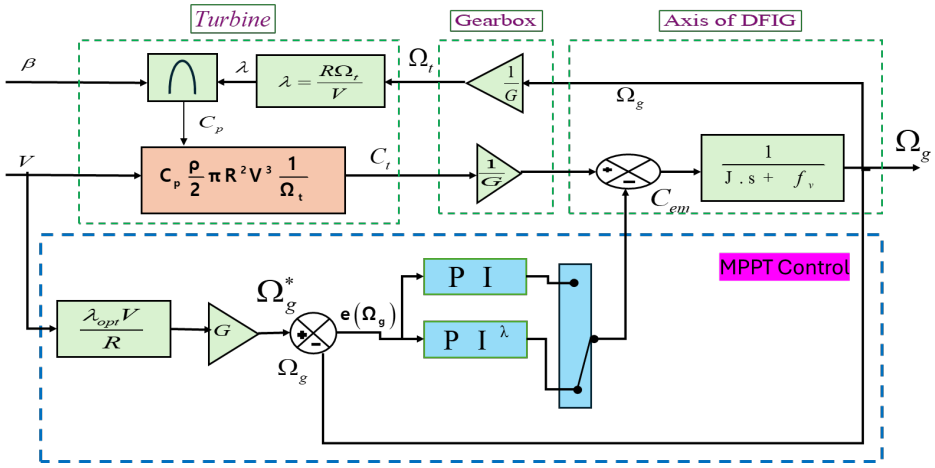


Figure 1: MPPT scheme incorporating speed regulation

Fractional-Order Control for MPPT in Wind Turbine Systems

The fractional calculator extends the conventional concepts of integration and differentiation to include non-integer orders, designated by a unique notation. In this case, the primary distinction between the FOPI regulator and the conventional PI regulator is rooted in the incorporation of fractional calculus. Consequently, by applying the Laplace transform, we can derive the transfer functions for both the FOPI and traditional PI controllers [10]:

$$C(s)=k_p\left(1+\frac{k_i}{s^{\lambda}}\right) \quad ; \quad C'(s)=k_p\left(1+\frac{k_i}{s}\right). \tag{13}$$

Fig. 2 shows the controller structure

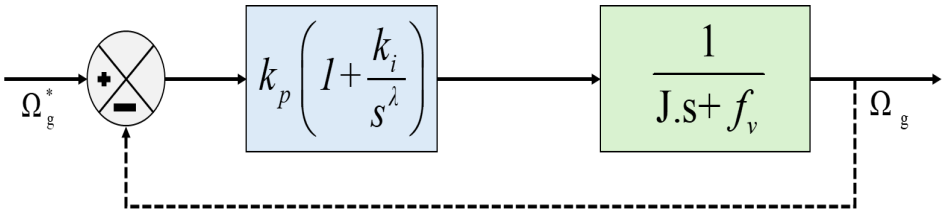


Figure 2: Block representation of the control scheme.

The dynamics of the turbine can be represented using a first-order model as follows:

$$H(s)=\frac{1}{J.s+f_v}. \tag{14}$$

The open-loop L(s) of the wind turbine speed after application of the FOPI controller is:

$$L(s)=H(s)C(s)=k_p\left(\frac{1}{J.s+f_v}\right)\left(1+\frac{k_i}{s^{\lambda}}\right). \tag{15}$$

In this article; the margin of phase and amplitude technique is used for the design of the robust controller [10,11].

Phase margin condition:

$$arg\left[L(j\omega_c)\right]=arg\left[H(j\omega_c).C(j\omega_c)\right]=-\pi+\gamma_m. \tag{16}$$

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Gain crossover frequency condition:

$$\left|L\left(j\omega_c\right)\right|dB = \left|H\left(j\omega_c\right).C\left(j\omega_c\right)\right|dB = 0\,. \tag{17}$$

Stability to fluctuations in system gain:

$$\left(\frac{d\ \left(arg\left|L\left(j\omega_c\right)\right|\right)}{d\omega}\right)_{\omega=\ \omega_c} = 0\,. \tag{18}$$

As indicated in the constraint regarding phase margin conditions, a connection can be formed between k_i and λ as:

$$k_i = \frac{-Tan\left[\,Arctan\left(T\omega_c\right)+\gamma_m\,\right]}{\omega_c^{-\lambda}\,sin\left(\lambda\frac{\pi}{2}\right)+\omega_c^{-\lambda}\,cos\left(\lambda\frac{\pi}{2}\right)\times Tan\left[\,Arctan\left(T\omega_c\right)+\gamma_m\,\right]}\,. \tag{19}$$

When robustness condition to the fluctuations in system gain, we can create another equation:

$$k_i = -\frac{-\sigma \pm \sqrt{\sigma^2 - 4C^2\omega_c^{-2.\lambda}}}{2\omega_c^{-2.\lambda}} \tag{20}$$

With $C = \left(\frac{1+\left(T\omega_c\right)^2}{T}\right)^{-1}$ and $\sigma = -\left[\lambda\omega_c^{-\lambda-1}\sin\left(\lambda\frac{\pi}{2}\right) - 2C\omega_c^{-\lambda}\cos\left(\lambda\frac{\pi}{2}\right)\right]$

k_p can be written as mentioned in Constraint Gain crossover frequency condition:

$$k_p = \frac{\sqrt{1+\left(T\omega_c\right)^2}}{k\sqrt{\left[1+k_i\omega_c^{-\lambda}\cos\left(\lambda\frac{\pi}{2}\right)\right]^2+\left[k_i\omega_c^{-\lambda}\sin\left(\lambda\frac{\pi}{2}\right)\right]^2}}\,. \tag{21}$$

These passages elucidate the procedures for tuning a fractional PI controller to satisfy frequency requirements. This procedure utilizes system parameters (inertia J) and viscous friction (f_v) to ascertain the equivalent constants of the model. To prevent reliance on a strictly analytical approach, a numerical solution is employed utilizing MATLAB. First, (ω_c) and the phase γ_m are established, and the fractional order (λ) is mechanically determined, guaranteeing consistency between the expression of (K_i) obtained from the phase condition (equation 19) and that derived from the system structure (equation 20). The solution exclusively preserves the physically valid solution, namely one with (K_P> 0) and (K_i> 0). Once (λ) is identified, the program computes (K_i) using the appropriate expressions and subsequently incorporates it into the module equation (equation 21) to determine (K_P), ensuring compliance with the conditions at the cutoff frequency. Finally, the MATLAB script generates the adjustment parameters for the proposed controller: ($\lambda = 0.2264,\ K_i = 15.6236,$) and ($K_P = 0.0309,$)),which comprehensively define the FOPI

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corrector employed in the subsequent simulations and analyses. Subsequently, the proposed controller can be depicted as follows:

$$C_1(s) = 0.0309\left(1 + \frac{15.6236}{s^{0.2264}}\right). \quad (22)$$

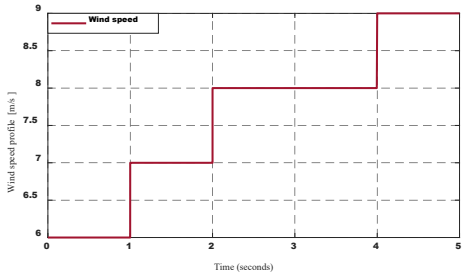
Results and Discussion

We used MATLAB/Simulink to model the energy conversion system that used a 1.5 MW wind turbine. The parameters used in the simulation study are as follows:

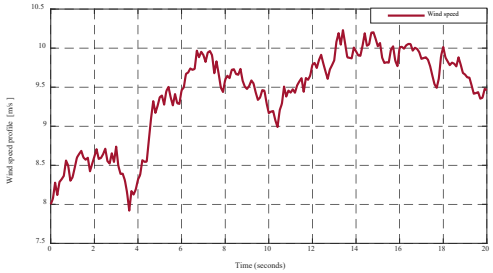
$$f_v = 0.0024\text{N.m.rad}^{-1}\text{.s} / \ \text{J} = 1000\ Kg.m^2 / R = 3525 \times 10^{-2} m \ / \rho = 1.225\ \text{kg}.m^{-3} \ / G = 90$$

The effectiveness of the suggested approaches is tested in the following distinct scenarios: one with sudden wind variations, and another based on actual speeds measured in Dakhla (Morocco). Mechanical speed control is analyzed under progressive variations in wind speed in Fig. 3 (a), and the illustration in Fig. 3 (b), How a real wind pattern is modeled for 20 seconds and it encompasses both sudden step changes (to evaluate transient response) and gradual adjustments (to assess tracking performance). This FOPI controller quickly reaches the maximum power factor value of 0.48 and maintains it with high accuracy. It demonstrates exceptional stability in steady state, as depicted in Fig. 3 parts (c) and (d), Both zones extend from this confirmation, demonstrating a rapid response at start-up and stability in steady state, thus ensuring perfect TSR maintenance. Fig. 3 (e), and Fig. 3 (f), show that the proposed controller maintains the TSR value around the target value of 8.16, while the PI controller exhibits slight fluctuations. Thus, the FOPI controller quickly brought the wind speed error back to zero, as depicted in Fig. 3 parts (i) and (j), The variations within the rotor's angular velocity for both controllers, as well as for the reference controller, are illustrated in Fig. 3 (g), and Fig. 3 (h). The FOPI controller demonstrated exceptional tracking behavior compared to the PI controller. When the system starts up, the proposed controller reaches the setpoint faster and with less overshoot than the PI controller. Table 1 in the previous conversation compares the PI model to the FOPI model in terms of accuracy and speed of execution.

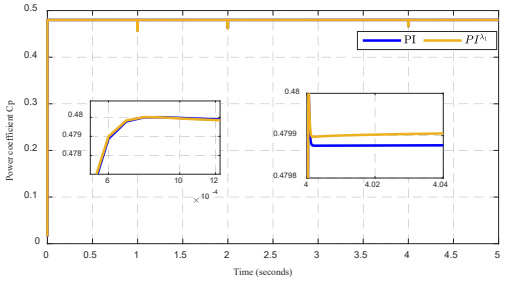
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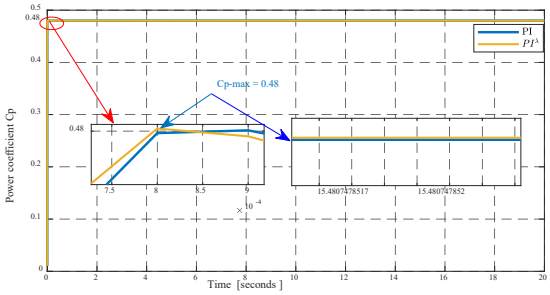
(a) profile step variations of *scenario 1*



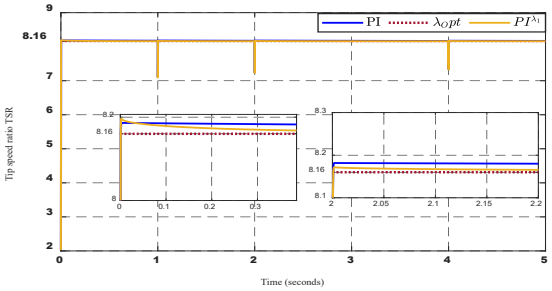
(b) real variations of *scenario 2*



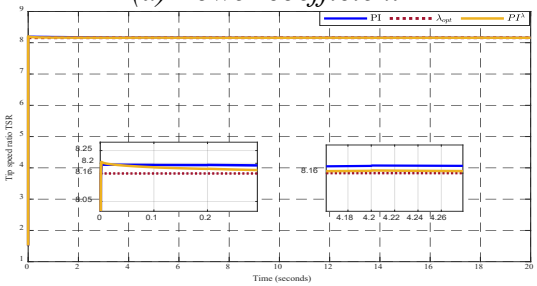
(c) Power coefficient



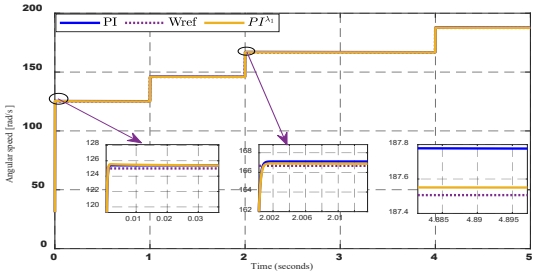
(d) Power coefficient



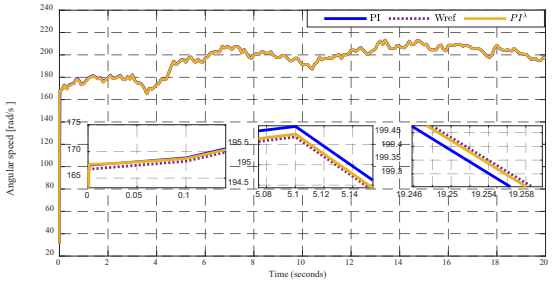
(e) TSR



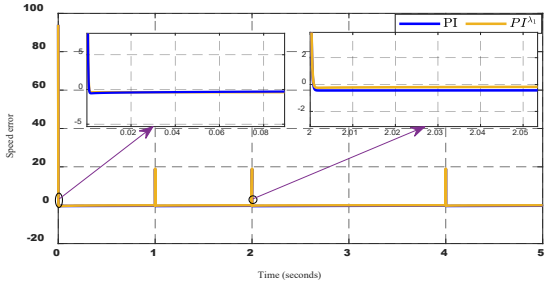
(f) TSR



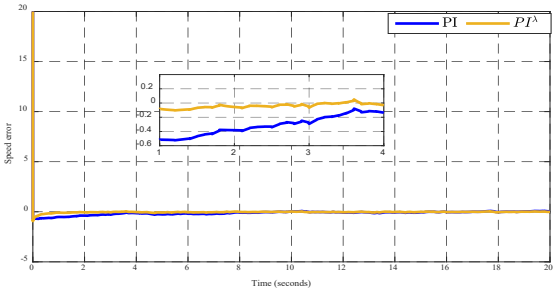
(g) Rotor Angular Speed



(h) Rotor Angular Speed



(i) wind Speed Error



(j) wind Speed Error

Figure 3: Results of the two scenarios.

Table 1: Quantitative Performance Comparison

Controller	Tracking Error at Steady State (%)	System Response Duration [s]	Peak overshoot (%)	Robust stability	Effectiveness of TSR	Robust Behavior
PI	0.035	25×10^{-3}	3.8	Satisfactory	Limited	Limited
PI^{λ}	0.015	2×10^{-3}	2.0	Excellent	Effective	Effective

In order to situate the proposed controller within the field of research related to reference speed tracking and aerodynamic performance, we have created Table 2, which summarizes the results obtained from the current literature and compares them to the performance of other proposed controllers. The findings distinctly indicate the likely advantages of our method. The OTC technique achieves average efficiency in setpoint tracking, whereas AFTISMC delivers satisfactory performance in this regard. In contrast, our approach is notable for its exceptionally quick responsiveness, delivering effective setpoint tracking with minimal steady-state error, nearly negligible static error, and swift system response, along with superior setpoint tracking abilities that considerably lower steady-state error.

Table 2: Quantitative Performance Comparison

Method	MPPT Strategy	Settling Time [s]	Offset Error (%)	Reference Following
[12]	Backstepping	0.00500	1.1000	Effective
[13]	ANN	0.00313	0.5200	Effective
[14]	AFTISMC	-	0.0751	Very good
Proposed	PI^{λ}	0.00200	0.0130	Highly Effective

Conclusions and future research directions

We analyzed the performance of a conventional PI controller with an FOPI controller designed for maximum power point tracking (MPPT) in a wind turbine using a DFIG. The results of various wind speed simulations reveal faster response time and lower overshoot and steady-state error for the proposed controller than for the simple PI controller, and improved performance in tracking the ideal C_p. These results corroborate the assertion that using the FOPI controller would increase energy recovery capacity, improve the quality of the energy produced, and minimize the mechanical impact on the system, avoiding the constraints of the conventional PI control approach. The proposed controller can be built in real time on a dSPACE DS1104 platform or an FPGA board (depending on computing needs and/or latency requirements) and is planned as future work in this area. This phase will include code generation, wind turbine emulator testing, and performance testing under simulated wind and power grid conditions. Real-time resilience, noise blocking, and actuator saturation management will also be addressed. In the event of significant variations in the operating scenario, an adaptive version of the FOPI controller may be considered. The actual objective will be to demonstrate robust and reproducible performance that complies with grid standards, is reproducible, and is adapted to the operating scenario applicable in real-world situations.

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