Boosting Wind Harvest: FOPID Pitch Angle Controller for Turbines

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***Abstract*—Wind turbine blades are subjected to a variety of loads, including aerodynamic and gravitational loads. These loads produce aerodynamic strain and vibration in the blades, resulting in rotor blade damage and a reduction in the wind turbine's system efficiency. This could be prevented by implementing a proper pitch angle controller that plays a crucial role in boosting the energy capture and overall performance of wind power systems. The conventional Proportional-Integral-Derivative, PID, controller has been widely utilized for pitch control, but it often faces challenges in meeting the requirements of complex and dynamic wind conditions. To address these limitations, this study explores the implementation of the Fractional Order Proportional-Integral-Derivative, $FOPID$, controller for wind turbine pitch control. This paper presents a comparative analysis between the PID and $FOPID$ controllers for wind turbine pitch control. The performance of both controllers is evaluated through Simulink. The results demonstrate that the $FOPID$ controller exhibits superior performance in terms of faster response time, and improved steady-state error compared to the PID controller.**

***Index Terms*—PID Controller, $FOPID$ Controllers, Wind Turbine, Pitch Controller**

I. INTRODUCTION

Renewable energy is derived from natural processes that can provide sustainable, non-ending, energy with minimal impact on the environment. When fossil fuels are used to create energy, they emit dangerous greenhouse gases like carbon dioxide. To address the climate catastrophe, a shift from fossil fuels to renewable energy is essential [1]. There are multiple sources that produce clean energy such as solar, wind, water, heat, and nuclear. However, they differ in their location, equipment, and efficiency. Many studies proved that relying on sustainable energy sources decreases air pollution by lowering the reliance on burning fuels, emitting no greenhouse gases, diversifying the energy supply, and promoting economic growth.

Several utility organizations are investing in researching renewable energy sources that will be implemented as power generators. Some of these organizations have concentrated their research on specific sources of alternative energy, such as fuel cells, solar panels, wind turbines (WT), and micro-turbines. The main distinguishing feature of WT, in comparison to other power production systems, is that the power input rate cannot be regulated. However, wind speed and power demand in WT systems change based on numerous factors such as climatic conditions and time. WT systems deliver substantial obstacles due to their undefined parameters and unpredictable environmental disturbances. In addition, under different wind speed conditions, the WT system is subject to the aerodynamic, gravitational, centrifugal, gyroscopic, and operational loads. Nonetheless, these drawbacks can be overcome by adopting a pitch control system that enhances the WT's performance. This control strategy starts by utilizing a controller to check the turbine's power output multiple times per second. The rotor blades adjust the angle of attack by turning slightly out of the wind in response to a signal sent to the blade pitch mechanism if the wind speed exceeds the operational limit. These blades are reoriented toward the wind once it subsides.

The rotational speed of a WT refers to the speed at which the rotor blades are spinning. It is an essential factor in determining the performance and power output of the turbine. This rotational speed depends on various factors, including the design of the turbine, wind speed, and electrical grid requirements. WTs are designed to operate within a specific range of rotational speeds to maximize energy production while maintaining safe operating conditions. The rotational speed is influenced by the wind speed and the aerodynamic properties of the rotor blades. As the wind speed increases, the rotor blades experience greater aerodynamic forces, causing them to rotate at a faster speed. WTs are equipped with control

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systems that adjust the pitch angle of the blades to optimize power production and maintain a desired rotational speed. It's important to note that WTs have a cut-in, and a cut-out speeds. The cut-in speed is the minimum wind speed at which the turbine starts generating power, while the cut-out speed is the maximum wind speed at which the turbine is shut down for safety reasons. The rotational speed is controlled within the operational range between the cut-in and cut-out speeds. Monitoring and controlling the rotational speed of WTs is an integral part of their operation and is typically managed by the turbine's control system, which constantly adjusts the pitch angle and other parameters to optimize performance and ensure safe operation.

There is a diversity of control strategies including PID, Model Predictive Control, fuzzy logic, and adaptive control. Each of them can be employed based on the specific requirements and complexity of the system. One common closed-loop feedback method in commercial control systems is the PID controller. The difference between the desired set point and the measured process variable is used to determine an error value. By adjusting variables, the controller tunes the process in an attempt to reduce mistakes. Its three parameters are tweaked to guarantee that the system will stay stable. PID controllers are used in conjunction with WT to achieve the desired pitch angle [2]. $FOPID$ control has been applied in various fields, including robotics, chemical processes, power systems, and control systems with non-linear or time-delayed dynamics [3].

II. LITERATURE REVIEW

WT pitch angle control has been a subject of extensive research as documented in several scholarly papers. In [4], the authors investigated the performance of PI and fractional PI (FPI) controllers on WT pitch angle. Their results showed enhanced performance, greater reliability, and improved generation efficiency of FPI in comparison to PI. In [5], a fuzzy logic pitch angle controller was introduced as an alternative to the PI controller with a better performance. In [6], the authors suggested the use of the $FOPID$ controller in improving the WT's performance in conjunction with the Particle Swarm Optimization PSO to find the controller gains. In [7], the authors investigated the performance of $FOPID$ controller for pitch control in a a virtual 20 MW WT system, and by using "FAST" software. Their outcomes showed improved performance.

This study investigates the effectiveness of $FOPID$ controller in designing a WT pitch regulator. In addition, it provides a comparison with the PID controller in terms of the overshoot, rise time, and settling time. The paper is organized as follows. The structure, and operation of the WT are explained in Section II, while the methodology including the WT model, pitch control system using PID and $FOPID$ are given in Section III. The system simulation results are addressed in Section IV. Finally, conclusions are given in Section V.

III. WIND TURBINE STRUCTURE AND OPERATION

A WT is a device that converts the kinetic energy of wind into electrical energy. It typically consists of a tower, rotor blades, a nacelle, and a generator. The tower provides height to capture the stronger and more consistent wind at higher altitudes. The rotor blades, usually three in number, are mounted on a hub and rotate when exposed to the force of the wind. The nacelle sits atop the tower and houses the gearbox, generator, and control systems.The drive train consists of two main components: the gearbox and the generator. The gearbox is used to increase the speed of the low-speed shaft connected to the blades to match the speed of the high-speed shaft connected to the generator. The generator is used to convert the mechanical energy of the high-speed shaft into electrical energy that can be transmitted to the grid, Fig. 1.

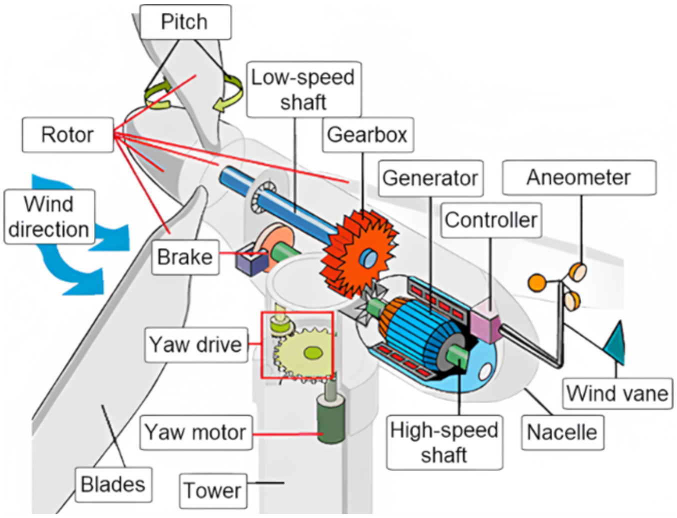

Fig. 1. The internal structure of a wind turbine and its components [8].

WTs are classified into two main types: horizontal-axis WTs ($HAWTs$) and vertical-axis WTs ($VAWTs$). The ($HAWTs$) have the rotor blades mounted on a horizontal axis, facing into the wind. The ($VAWTs$), on the other hand, have their rotor blades mounted on a vertical axis and can capture wind from any direction.

The operation of a WT is as follows. WTs are equipped with anemometers and wind vanes to measure wind speed and direction. These sensors provide crucial information for the turbine's operation and control systems. When the wind speed reaches a certain threshold, the WT's control system initiates the start-up sequence. The rotor blades begin to rotate slowly, driven by the wind's force. As the wind speed increases, the rotor blades rotate at a faster speed. The kinetic energy of the wind is transferred to the rotor, causing it to spin. The rotor is connected to a gearbox, which increases the rotational speed to match the optimal speed for the generator. The high-speed rotor shaft is connected to a generator within the nacelle. The generator converts the mechanical energy from the rotor into electrical energy. This electrical energy is typically in the form of alternating current AC. The generated AC

power from the generator is sent through power conditioning systems, such as power converters, to adjust the voltage and frequency to match the requirements of the electrical grid. This ensures compatibility with the existing power infrastructure. The conditioned electrical power is then transmitted through power lines to the electrical grid for distribution to consumers. WTs in wind farms are interconnected to create a collective power generation system, contributing to the overall electricity supply. WTs are equipped with sophisticated control systems that continuously monitor and optimize their performance. These systems adjust the pitch angle of the rotor blades to optimize power production, maintain safe operating conditions, and protect the turbine from extreme wind conditions. In cases of high wind speeds, severe weather conditions, or maintenance requirements, WTs can be automatically or manually shut down. The rotor blades are feathered (turned parallel to the wind) to minimize their exposure to strong winds, ensuring the safety and integrity of the turbine [9]. The operation of WTs is highly automated, with advanced control systems and monitoring technologies optimizing performance, maximizing energy production, and ensuring the safe and efficient operation of the turbines.

IV. METHODOLOGY

This study starts by an appropriate WT model, and followed by the PID and $FOPID$ pitch control system. The Simulink is utilized for the design and analysis of the two types of control systems.

A. Wind turbine model

There are three terms in any WT, which are the cut-in, cut-out, and rated speed values. The cut-in speed is at which WT starts running. Below this wind speed, the wind energy is not sufficient to overcome the inertia of the rotor and thus there is no generated power. At high wind speed, the turbine is programmed to stop to avoid damaging the turbine or its surroundings. The cut-out wind speed is the stop wind speed. The rated wind speed is at which the rated power is achieved. Fig. 2 shows the output power of a 400W WT. It shows that the turbine's output power drops sharply at lower wind speeds. In addition, it shows that the available wind power increases eight times for every doubling of wind speed and decreases eight times for every halving of the wind speed.

This study focuses on modeling two parts of the WT that affect the pitch angle which are the actuator and the drive train. The actuator model describes a dynamic behavior between the measured pitch angle β, and the desired value β_d. The drive-train model describes the conversion of the rotational motion of the blades (caused in proportion to the torque, T, in $N.m$) into electrical power (W in Watt). The proposed pitch control system is depicted in Fig. 3.

In [11], the authors derived a mathematical model of the actuator and the drive train of a $1MW$ WT, given in (1).

$$\frac{\beta}{\beta_d} = \frac{1}{0.5s+1}; \qquad \frac{W}{T} = \frac{0.5}{0.375s+1} \tag{1}$$

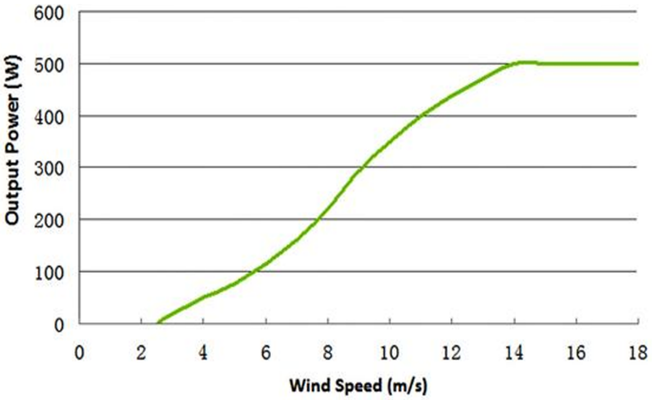

Fig. 2. The output power of X-400 WT [10].

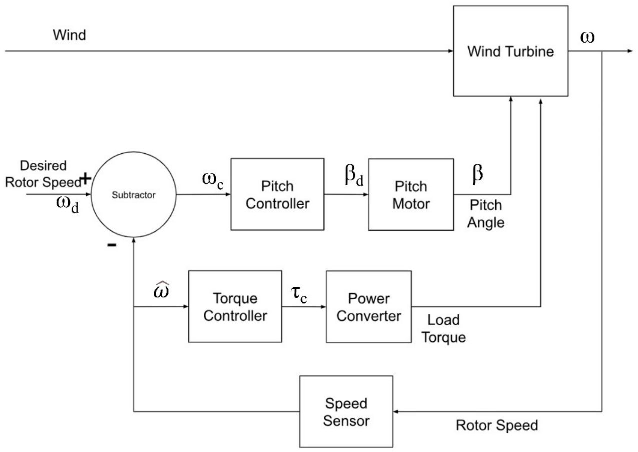

Fig. 3. Block diagram of the proposed pitch angle control system.

B. Pitch control systems

This study investigate two type of controllers which are the PID and the $FOPID$.

1) PID controller: Researchers have a variety of options when working with PID controller, including parallel, series, and the ideal configurations [12]. The parallel PID controller is expressed in (2).

$$\begin{gathered} G_{PID} = \frac{C(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d \times s \\ c(t) = K_p e(t) + k_i \int_0^t e(t)\,\mathrm{d}t + k_d \frac{de(t)}{dt} \end{gathered} \tag{2}$$

where $c(t)$ is the controller output at time t, $e(t)$ is the error signal at time t, K_p, K_i, and K_d are the proportional, integral, and derivative coefficients, respectively.

This study utilizes the three components (K_p, K_i, and K_d) of the ideal PID controller to adjust the pitch angle based on the difference between the desired angle and the actual angle measured by sensors. The control signal generated by the PID controller is used to adjust the pitch angle of the WT blades. The gains of the PID controller need to be tuned to achieve optimal performance. This tuning process involves adjusting the gains experimentally to ensure stable and responsive control without excessive overshooting or oscillations. Details about the PID controller and its tuning with applications are discussed in [13], and [14]. Fig. 4 shows the structure of the PID controller.

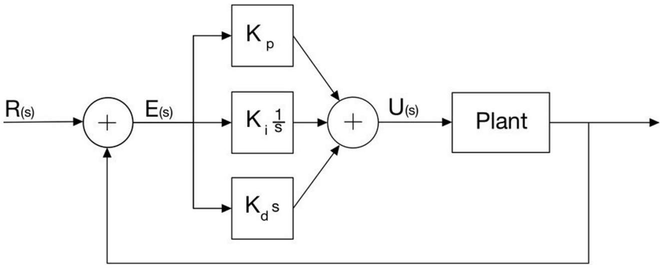

Fig. 4. Block diagram of PID controller.

2) $FOPID$ controller: This controller is an extension of the traditional PID control. It introduces fractional calculus concepts to enhance the control performance [15]. Fig. 5 depicts the block diagram of the $FOPID$ controller. Its transfer function is in (3).

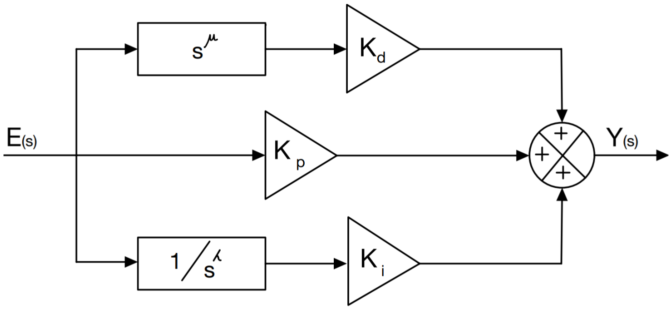

Fig. 5. Block diagram of $FOPID$ controller.

$$TF(s) = K_p + K_d \times s^{\mu} + K_i \times \frac{1}{s^{\lambda}} \tag{3}$$

C. Step performance

This study utilized the Simulink for the design and analysis of the WT pitch control system. The Matlab toolboxes: control system, optimization, and Fractional-order modeling and control of dynamic systems, $FOMCON$ are used. Fig. 6, 7, 8 display the Simulink design of the WT pitch control system without a controller, with a tuned PID controller, and with a tuned $FOPID$ controller.

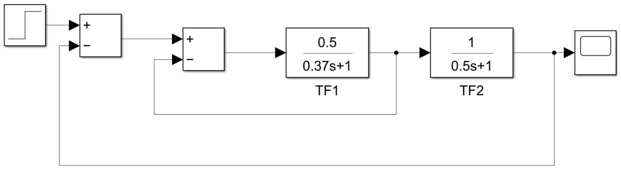

Fig. 6. Simulink diagram of uncontrolled wind turbine system.

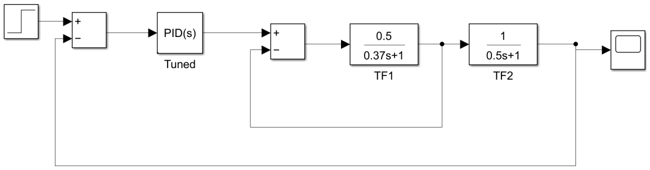

Fig. 7. Simulink of WT system controlled by a tuned PID.

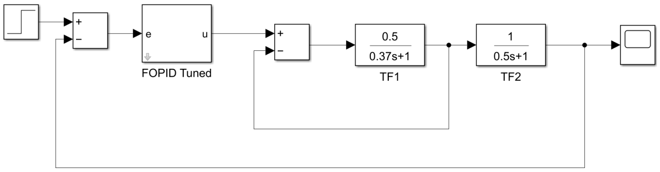

Fig. 8. Simulink of WT system controlled by a tuned $FOPID$.

V. RESULTS

The Simulink tuner is used to adjust the gain parameters of the PID and $FOPID$ controllers. The step time responses for the uncontrolled, un-tuned PID, tuned PID, un-tuned $FOPID$, and tuned $FOPID$ are given in Fig. 9. The measured gain values of the two controllers, and the associated response metrics are depicted in Table I, and Table II, respectively. The results shows the best performance of the pitch control obtained from $FOPID$. It has no time delay compared to the PID, less rise time, less settling time, and no steady-state error.

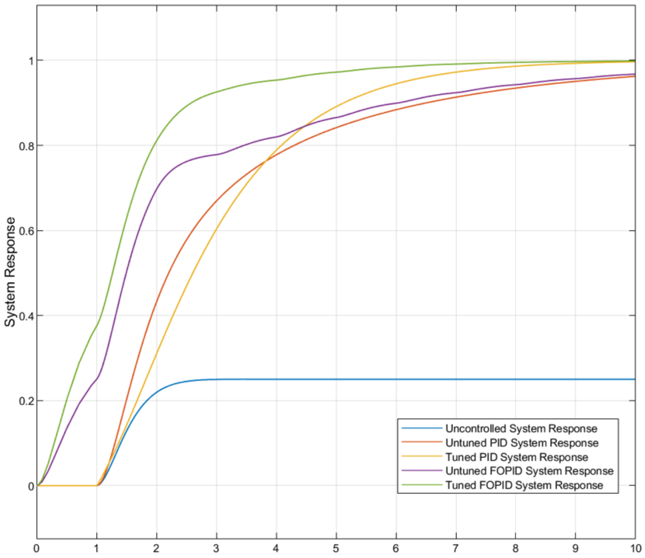

Fig. 9. Time response of the WT for all the scenarios.

VI. CONCLUSION

When it comes to pitch control in wind turbine systems, $FOPID$ controller has been investigated as a potential alternative to PID controllers. While PID controllers are commonly used in wind turbine applications, $FOPID$ controllers

TABLE I

Gain values of the controllers.

Methodology	K_p	K_i	K_d	N	λ	μ
Untuned PID	1.89	1.34	-1.156	0.56	NA	NA
Tuned PID	0.6	1.5	0.09	100	NA	NA
Untuned $FOPID$	1	1	0	NA	1	1
Tuned $FOPID$	0.6	1.5	0.001	NA	1.02	1.05

TABLE II

Performance metrics of all the controllers.

Controller Type	T_r	T_s	$\%OS$	SS
untuned PID	4.24 sec	8.5 sec	0	0.962
tuned PID	3.716 sec	7.25 sec	0	0.997
untuned $FOPID$	4.76 sec	8.33 sec	0	0.968
tuned $FOPID$	2.21 sec	4.91 sec	0	1.005

offer some advantages that can lead to improved performance in certain scenarios.

Wind turbine systems often exhibit complex and nonlinear behavior due to factors such as variable wind speeds, turbulence, and changes in blade aerodynamics. $FOPID$ controllers, with their increased degrees of freedom (fractional order elements) can provide faster response times compared to PID controllers, leading to a smoother and more stable pitch control performance.

However, it's important to consider that the successful implementation of $FOPID$ controllers in wind turbine pitch control requires careful tuning and parameter selection. The fractional order elements introduce additional complexity compared to PID controllers, and finding the optimal values for these parameters can be challenging.

PID and $FPID$ controller technologies have ethical implications and practical applications, particularly in environmental and safety contexts. Ethical considerations involve minimizing environmental impact, prioritizing safety, and addressing algorithm biases. Practical applications include industrial processes, energy management, environmental monitoring, and autonomous systems. To ensure responsible deployment, robust system design, continuous monitoring, ethical considerations, regulatory compliance, and stakeholder engagement are crucial. Balancing operational efficiency with environmental sustainability and prioritizing safety and fairness are essential in the implementation and use of these technologies.

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