

A Novel Adaptive Pitch Angle Control to Enhance Wind Farm Power Management

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Abstract: The role of wind farms in primary and secondary frequency control has become paramount for ensuring grid stability. This study proposes an adaptive PI control strategy sensitive to the grid Rate of Change of Frequency (ROCOF). The model under discussion involves using a control system that allows wind turbines to maintain a specific power reserve by implementing a de-loading strategy. This, in turn, enables the turbines to respond more rapidly and effectively to variations in frequency. The adaptive PI controller dynamically updates the PI gains using the grid frequency variation rate, thus allowing the power generation to adapt to grid conditions in real-time. Tests conducted in the MATLAB/Simulink environment demonstrate that the proposed adaptive control method provides enhanced dynamic performance compared to conventional PI control and substantially improves grid frequency regulation. The findings underscore the necessity for advanced control strategies to facilitate the integration of wind farms into active frequency control.

Keywords: adaptive control; deloading power; pitch angle; primary frequency control; ROCOF; wind farm

1 INTRODUCTION

As stated in the "WWEA Annual Report 2023", there has been a considerable increase in the share of renewable energy sources, particularly wind energy, in energy production in recent years [1]. As the share of renewable energy in total energy generation increases, innovative methods are required to balance supply and demand. In interconnected power systems, frequency control assumes paramount importance [2]. When energy production exceeds consumption, the grid frequency rises above its nominal value; a drop in frequency indicates a supply deficit. Maintaining frequency stability is crucial for reliable grid operation; deviations from nominal frequency indicate imbalances in power supply and demand [3, 4].

Conventionally, Primary Frequency Control has been entrusted to large power plants. Those plants can change their output within seconds to correct small frequency deviations, helping stabilise the system. Conversely, Secondary Frequency Control is initiated by the grid operator's directives, mandating power output adjustment over a more protracted timeframe. In recent years, the increasing penetration of renewable energy sources, especially wind energy, has brought their participation in these control mechanisms to the agenda [5, 6].

Wind turbines are generally designed to operate at maximum power under given wind conditions. However, during grid disturbances, turbines running at full capacity lack the headroom to support additional frequency regulation. A range of de-loading power strategies has been developed to address this situation. This strategy entails the creation of a power reserve that can be expeditiously activated to assist in regulating grid frequency by operating turbines below their maximum power point. This power reserve, known as 'deloading power', allows turbines to respond dynamically to frequency deviations, enhancing grid flexibility [7-9].

As an example, a large-scale outage across the Iberian Peninsula - particularly Spain and Portugal - on 28 April 2025 highlighted the consequences of inadequate implementation of control strategies. When the system encountered uncontrolled high renewable production, it was unable to withstand frequency/voltage fluctuations due to low mechanical inertia and inadequate voltage

control. In this situation, it became clear that instead of focusing solely on maximum power production, the necessity of prioritising grid stability and energy quality in control strategies was evident.

Pitch angle control is a highly effective method of regulating the power output of wind turbines. This adjusts the angle of the blades relative to the wind [10]. By varying the pitch angle, the turbine can modulate the kinetic energy captured, thereby enabling precise control over the amount of power produced. Furthermore, the incorporation of pitch angle adjustments into the operational framework of wind turbines enables the execution of deloading power operations, thereby allowing turbines to function below their maximum potential capacity. This, in turn, facilitates an augmentation in output when the grid frequency undergoes a decline below its nominal level [11, 12].

The modelling is inaccurate in most publications that have examined the role of wind farms connected to the interconnected grid in primary frequency control. The model [3] assumes that a wind farm in the interconnected system is a strong factor contributing directly to the grid frequency change. However, modelling all generation generators in the interconnected system and their total contribution has revealed that frequency change can also be observed in the context of these generators. Consequently, the simulation of grid frequency change is impossible through the reduction or increase in generation in a standalone wind farm. Consequently, the wind farm's production control power value change according to the grid frequency must be measured. In these controls, it is assumed that the production change rate of the wind farm is equally distributed across all turbines, and the model is derived accordingly. A pitch angle change PI controller is generally preferred in this model. The gain parameters (K_p , K_i) are constant in PI and similar controllers. However, it should be noted that controllers with constant gain parameters exhibit reduced efficiency in dynamic systems. This paper proposes a novel control method to adapt to system changes rapidly. This method offers an alternative perspective on the K_p and K_i coefficients in the PI controller. The generation power is adjusted according to the fluctuating demand by considering the frequency change, which is the balance indicator between production and consumption. In the context of wind farms contributing to grid frequency regulation, the most critical

variable is the ROCOF (rate of change of frequency) value [13]. The rate of change of frequency enables the adjustment of the system's response through the modulation of the K_p and K_i parameters. The model under consideration incorporates a controller designed according to this method and designated as the adaptive PI controller. To validate the efficacy of this approach, a series of experiments were conducted utilising a MATLAB simulation model.

2 MATERIALS AND METHODS

2.1 Deloading Power

The generation plant must have power reduction and increased capabilities to keep the frequency balance in power systems. Additional production capacity is needed to increase the power capability of the facility. To meet this need, wind turbines are produced at a certain rate below the maximum power. The power left below the maximum power capacity is the operating reserve for the wind turbine [3], denoted by ΔP , as shown in Fig. 1 and Eq. (1).

$$P_{res} = P_{rated} - \Delta P \tag{1}$$

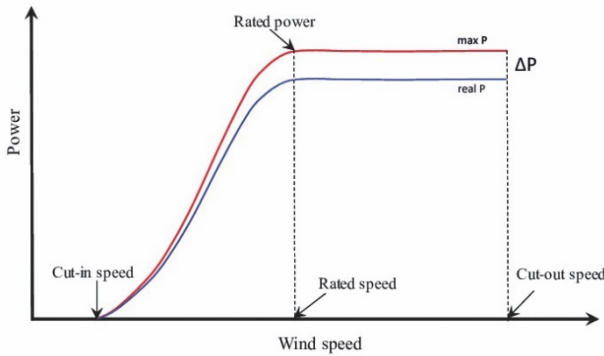


Figure 1 Deloading power in WT

2.2 Frequency Control in Power Systems

Electricity grid codes are defined as rules that determine a power system's rules for stable and reliable electricity generation. These grid codes differ from power system to power system. The grid electricity should be at a nominal frequency. Frequency control methods are activated against deviations from nominal frequency. As shown in Fig. 2, primary frequency control is activated up to 20-30 seconds, and secondary frequency control is activated in the following 5-10 minutes. In primary frequency control, the production facility acts quickly and automatically. The authority carries out secondary frequency control.

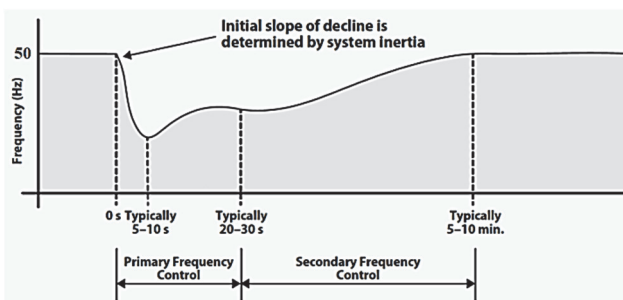


Figure 2 Timeline for frequency control

2.3 The Rate of Change of Frequency

It expresses the rate of change of frequency. This value has been considered in line with protection systems for a long time. *ROCOF* relays act according to their magnitude. *ROCOF* relay disconnects embedded generators from the line. Thanks to the rate of change of frequency, urgent measures can be taken. This paper will update adaptive PI control coefficients according to the *ROCOF* change. In particular, the coefficients K_p and K_i will be redetermined at each step according to the *ROCOF* value in Eq. (2). This update creates a faster control response according to the need at each step.

$$ROCOF(t) = \frac{\Delta f(t)}{\Delta t} \tag{2}$$

2.4 Pitch Angle Control

The turbine generation power is controlled by adjusting the blades angularly. The blades take position according to the wind speed and ensure maximum production [14]. However, the turbine power can be changed instantaneously by changing the pitch angle [15]. Thanks to this angle adjustment, turbine power generation control is performed for grid frequency control. The blade angle control is determined as approximately 10 %/s during normal operation [16]. The wind turbine power coefficient, C_p , is a function of Tip Speed Ratio (TSR), λ and pitch angle, β . $C_p = f(\lambda, \beta)$. The power coefficient can be expressed as a function of λ and β in Eq. (3,4).

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3\beta - C_4 \right) e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

The coefficient C_p , a function of the pitch angle (β), directly affects the wind turbine power (P_t) in Eq. (5).

$$P_t = \frac{1}{2} \rho C_p A v^3 \tag{5}$$

where ρ is the air density, C is the coefficient of wind power, A is the frontal area, v is the velocity of the wind.

In Fig. 3, the pitch angle control example block is shown. The difference between the measured instantaneous power and the required power is the error value, which is the input value of the PI controller. The output value of the PI controller instantly updates the pitch angle value. A limited pitch reference value is generated using PI control. The pitch angle is obtained with angle variations [16].

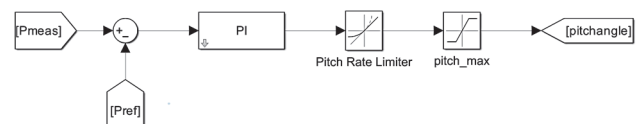


Figure 3 Pitch angle PI controller

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt \quad (6)$$

K_p is defined as proportional gain; K_i is defined as integral gain. K_p : reacts to the instantaneous value of the error (provides speed and power). K_i : It reacts to the sum of past mistakes (provides a stable target). In classical PI controllers, gain parameters (K_p , K_i) cannot respond fast enough for dynamic systems in Eq. (6).

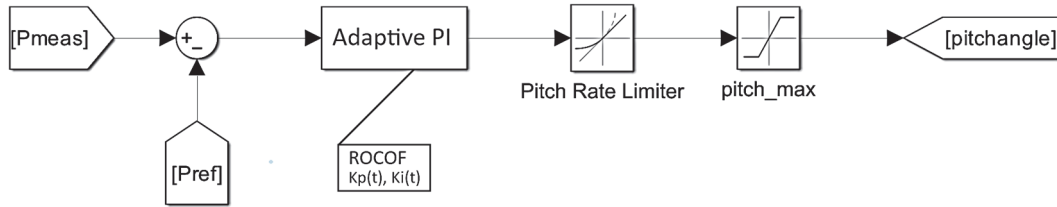


Figure 4 Pitch angle adaptive PI control

Adaptive PI control in Eqs. (7), (8), (9):

$$u(t) = K_p(t) e(t) + K_i(t) \int_0^t e(t) dt \quad (7)$$

$$K_p(t) = K_{p0} + \alpha * |ROCOF(t)| \quad (8)$$

$$K_i(t) = K_{i0} + \beta * |ROCOF(t)| \quad (9)$$

In Eqs. (7), (8), (9), K_{p0} , K_{i0} are nominal PI gains under steady-state conditions, α and β are the adaptation coefficients tuned empirically, $|ROCOF(t)|$, absolute value of the $ROCOF$ at time, $K_p(t)$ and $K_i(t)$ are the adapted PI gains used at time.

Here, α and β are experimentally determined tuning coefficients. This rule-based adaptation enhances the controller's ability to react swiftly during sudden

2.5 Adaptive PI Control

Adaptive PI control is a type of PI control whose gain parameters change instantaneously [17]. This enables the controller to adapt rapidly to dynamic conditions. In this study, adaptive PI is preferred over classical PI to ensure faster response to frequency changes by adjusting gains based on the $ROCOF$ value.

disturbances without resorting to complex machine learning methods.

2.6 Simulation Model

As a wind turbine model, studies were carried out on the Doubly Fed Induction Generators (DFIG) model in Fig. 5. Wind turbines DFIG consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to 50 Hz. Grid, while the rotor is fed at variable frequency via an AC/DC/AC converter. DFIG technology optimises the turbine speed, ensuring maximum energy from the wind at low wind speeds while minimising mechanical stresses on the turbine during wind gusts. The wind farm in the model consists of 6 turbines with a generation capacity of 1.5 MW, with a total generation capacity of 9 MW [18]. The simulation model simulates the wind farm and grid connection. All sources and loads in the inter-connected system should be added to the model for grid frequency variation effects.

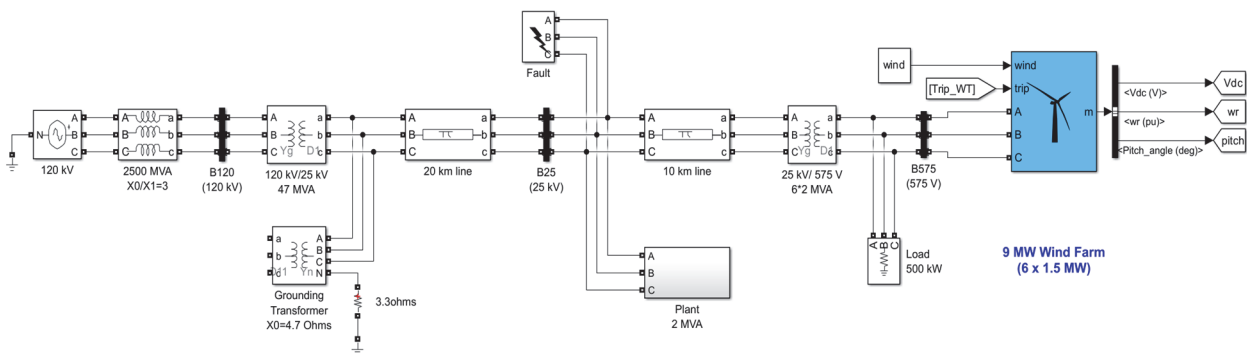


Figure 5 Wind farm model

Table 1 Parameters of wind turbines

Parameter	Value
Rated Power	9 MW
Rated Frequency	50 Hz
Rated Speed	11 m/s
Cut in Speed	3 m/s
Cut out Speed	30 m/s
Maximum Rate of Change of Pitch Angle	10 deg/s
Wind Turbine Inertia Constant	4.32 s
Nominal DC Bus Voltage	1150 V

3 RESULTS AND FINDINGS

In the simulation setup, the farm generation power change response and blade angle values will be observed, as well as the grid frequency change. In all simulations, it is assumed that 10% deloading power is applied in the wind farm. The simulations compare the results of classical PI control and adaptive PI control methods. The adaptive PI

control method uses the simulation model, *ROCOF* value. The wind farm power value is 1 (pu) unit at full capacity.

3.1 In the Case of Grid Frequency Drop (Wind 15 m/s)

In the case of 15 m/s wind speed (higher than the rated speed), there is a decrease in the grid frequency. A drop in grid frequency triggers an increase in power generation from the wind farm. As shown in Fig. 6, the output ramps up around the 30th second in response to this demand. It is seen that the operational redundant (0.9 pu) production state in the wind farm has passed to full capacity. The pitch angle is reduced to increase the power, as seen in Fig. 7.

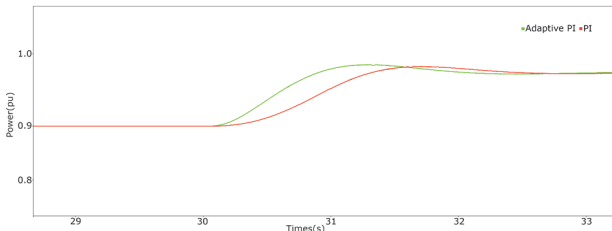


Figure 6 Wind farm power

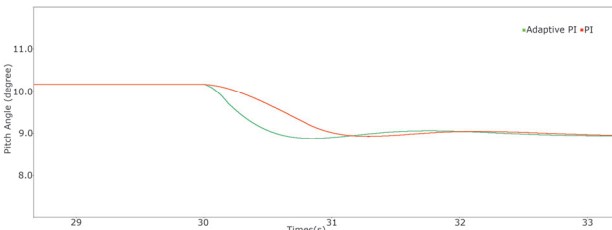


Figure 7 Pitch angle

3.2 In the Case of Grid Frequency Boost (Wind 15 m/s)

In the case of 15 m/s wind speed (higher than the rated speed), there is an increase in grid frequency. When the grid frequency rises, generation is curtailed to maintain stability. Fig. 8 illustrates the corresponding reduction in wind farm output starting at the 30-second mark. The power generation reduction was realised by maintaining the operational redundant generation status in the wind farm. To reduce the power, the pitch angle increases, as seen in Fig. 9.

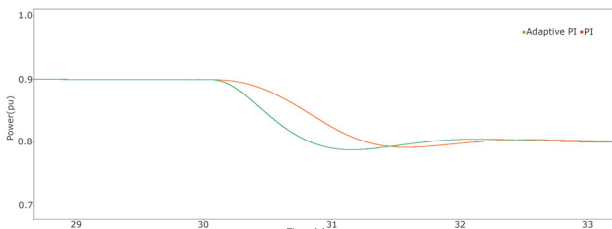


Figure 8 Wind farm power

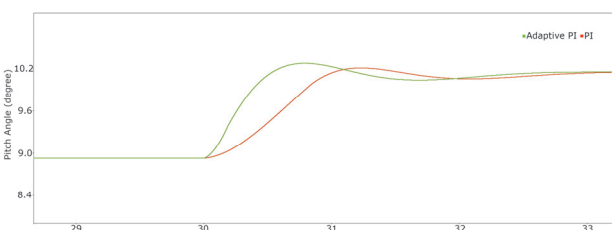


Figure 9 Pitch angle

3.3 In the Case of Grid Frequency Drop (Wind 10 m/s)

In the case of 10 m/s wind speed (lower than the rated speed), there was a decrease in the grid frequency. The increase in farm power with the need to increase the power of the grid resources (at the 30th second) is seen in Fig. 10. The power generation increase was realised by maintaining the operational redundancy in the wind farm. The pitch angle increases to increase the power, as seen in Fig. 11.

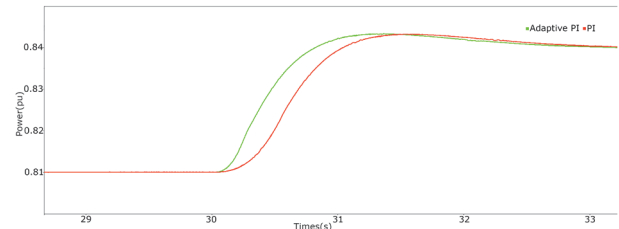


Figure 10 Wind farm power

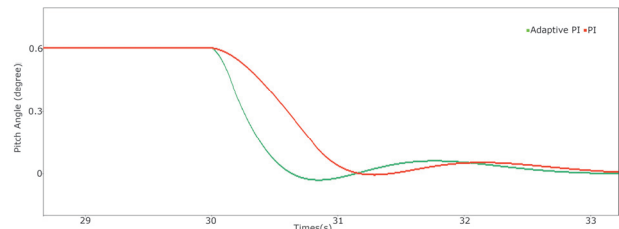


Figure 11 Pitch angle

3.4 Theoretical Sensitivity Assessment of ROCOF-Based Pitch Control

This section presents a theoretical evaluation of how the proposed adaptive PI pitch controller responds to variations in wind speed and *ROCOF* magnitude. The assessment is based on the gain adaptation mechanism:

$$K_p(t) = K_{p0} + \alpha * |RoCoF(t)| \tag{8}$$

$$K_i(t) = K_{i0} + \beta * |RoCoF(t)| \tag{9}$$

3.4.1 Wind Speed Dependence

Low wind speeds (below rated): The aerodynamic torque reserve is limited, so even with higher gains from large *ROCOF* events, the absolute pitch-induced power change is small. The controller can still react quickly, but frequency support capability remains constrained.

Rated wind speed region: Gain adaptation is most effective in this range. Moderate-to-high *ROCOF* values result in proportionally higher gains, enabling rapid pitch changes while maintaining stability.

High wind speeds (above rated): The system has greater aerodynamic margin for power modulation. However, gain limits and pitch rate constraints are essential to avoid excessive mechanical stress.

3.4.2 ROCOF Magnitude Dependence

Small *ROCOF* values (< 0.1 Hz/s): Minimal gain increase, leading to slower pitch adjustments but maintaining stable and smooth frequency support.

Moderate *ROCOF* values (0.1-0.3 Hz/s): Gains increase significantly, producing faster pitch actions and quicker power output correction.

High *ROCOF* values (> 0.3 Hz/s): Gains approach the predefined upper limits. While this enables maximum possible pitch rate, actuator saturation and mechanical load limits must be considered to avoid instability.

To ensure robust operation, the adaptive gains are bounded:

$$K_p(t) \in [K_{p\min}, K_{p\max}], K_i(t) \in [K_{i\min}, K_{i\max}] \quad (10)$$

These bounds guarantee that pitch adjustments remain within safe mechanical and control stability margins under all evaluated conditions in Eq. (10).

4 CONCLUSION

The results of this study demonstrate that adaptive PI control based on *ROCOF* can significantly enhance the responsiveness and stability of wind turbines participating in frequency regulation. The simulation outcomes confirm that the proposed control strategy ensures faster and more effective grid support compared to classical PI control.

While the present study focuses on simulation-based validation under selected operational scenarios, a comprehensive sensitivity analysis covering a wider range of wind speeds and *ROCOF* values is planned as part of future work. This extended investigation will allow for a more detailed assessment of the controller's robustness and adaptability, and will be addressed in a subsequent publication.

In terms of real-world application, several challenges must be addressed. Accurate and real-time measurement of *ROCOF* requires high-resolution sensors and low-latency communication systems. Additionally, the tuning of adaptation coefficients (α , β) must be carefully validated under operational variability such as grid strength, turbine type, and ambient wind profiles. Hardware limitations and computational constraints may also affect real-time performance in embedded turbine control units.

Despite these challenges, the proposed method is promising for practical deployment, especially as modern wind turbines are increasingly equipped with intelligent controllers and grid support functionalities. The method aligns well with the ongoing transition to grid-forming and grid-following hybrid capabilities in renewable-dominated networks.

For future work, the proposed approach can be extended to a multi-agent wind farm control structure, where coordinated adaptive control among turbines can improve aggregated frequency support. Moreover, data-driven or machine learning-based gain tuning can be explored to further optimize controller performance under stochastic conditions. Finally, real-time implementation and testing through Hardware-in-the-Loop (HIL) platforms is recommended to validate the robustness of the proposed method under real grid events.

With the growing share of renewable energy, especially wind turbines, power generation should shift from pure output maximization to control-oriented operation that supports grid stability. This approach will help renewables provide services once reserved for conventional plants. Future work will focus on improving

control methods to make responses more adaptive, robust, and efficient under changing conditions.

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