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Speed Regulating of Wind Turbine Unit using Iterative Learning Control

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Abstract

Conventional control methods, such as Proportional Integral Derivative (PID) control, have been extensively utilized for speed regulation in renewable energy wind turbine units. However, the limitations and disadvantages of PID, including difficulties in handling nonlinearities and uncertainties inherent in wind turbine dynamics, necessitate the exploration of alternative approaches. This research paper proposes the adoption of Iterative Learning Control (ILC) as an intelligent controller for addressing the shortcomings of PID. By exploiting the repetitive nature of wind turbine operation, ILC offers the potential to enhance speed regulation performance by iteratively refining control actions based on past experiences for advancing renewable energy. Through simulation studies, the effectiveness of ILC in improving the transient response and tracking accuracy of wind turbine units is demonstrated.

Keywords: Wind turbine, PID, ILC, Renewable energy.

1. Introduction

The global pursuit of sustainable energy sources has led to increased reliance on renewable energy technologies, with wind energy playing a pivotal role in this transition. Wind energy harnesses the kinetic energy of moving air masses to generate electricity, offering a clean and abundant alternative to traditional fossil fuels [1]. At the heart of wind energy

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conversion systems are wind turbines, sophisticated machines designed to capture and convert wind energy into electrical power. A wind turbine comprises several essential components, including rotor blades, a nacelle, a generator, and a control system. As the wind flows over the rotor blades, they are set in motion, driving the rotor connected to a generator, which produces electrical power [2]. The control system governs various aspects of turbine operation, including speed regulation, to optimize energy production and ensure safe and efficient performance. Proportional-Integral-Derivative (PID) control is a widely employed technique for regulating the speed of wind turbines [3]. PID controllers adjust the turbine's blade pitch or generator torque based on the difference between the desired and actual rotational speeds. While PID control offers simplicity and ease of implementation, it suffers from several drawbacks in the context of wind turbine applications [4]. The nonlinear and time-varying nature of wind turbine dynamics presents challenges for PID controllers, leading to suboptimal performance under varying wind conditions. PID controllers often struggle to adapt to rapid changes in wind speed, resulting in reduced efficiency and stability [5]. Additionally, PID tuning parameters may need constant adjustment to maintain satisfactory performance, posing operational challenges and limiting scalability [6]. To overcome the limitations of traditional PID control, this research project proposes the adoption of Iterative Learning Control (ILC) as an intelligent alternative for wind turbine speed regulation [7]. ILC is a model-based control technique that utilizes the repetitive nature of wind turbine operation to iteratively refine control actions. By learning from past control errors, ILC algorithms adjust future control inputs to improve performance over time [8]. The application of ILC in wind turbine control holds significant promise for enhancing speed regulation accuracy and stability. Through iterative learning, ILC controllers can adapt to changing environmental conditions and disturbances, leading to improved energy capture and smoother operation [9]. By leveraging the benefits of intelligent control strategies, this research aims to advance the efficiency and reliability of wind energy conversion systems, contributing to the global transition towards sustainable energy solutions [10]. In this paper, we present a detailed investigation of the proposed methodology, including system modeling, controller design, simulation studies, by comparing the performance of ILC with traditional PID control, we aim to demonstrate the efficacy of intelligent control techniques in optimizing wind turbine operation and maximizing energy output. Through our research efforts, we seek to contribute to the ongoing development and implementation of renewable energy technologies, ultimately fostering a greener and more sustainable future for generations to come.

2. System Modeling

We present the mathematical model governing the dynamics of the wind turbine unit for speed regulation. The model is derived from the dynamic modeling of the wind turbine system and subsequent linearization to facilitate control design and analysis [4]. The key variables and parameters involved in the model are defined as follows:

- $\Delta\omega_t$: Change in angular shaft speed of the wind turbine.

- ε, δ: Linearization coefficients.

- J_t: Moment of inertia of the wind turbine.

- $\varDelta v_w(s)$: Laplace transform of the change in wind speed.

- $\varDelta \cup (s)$: Laplace transform of the change in turbine pitch angle.

- S, D: System parameters.

The dynamic model of the wind turbine can be expressed as:

$$\Delta\omega_t = \left[\frac{\varepsilon}{J_t}\varDelta v_w(s) + \frac{\delta}{J_t}\varDelta \cup (s)\right] \frac{1}{S - D} \tag{1}$$

This equation (1) describes the response of the wind turbine's angular shaft speed to variations in wind speed and turbine blade angle. The linearization coefficients ε andδcapture the linear relationships between input and output variables, enabling the approximation of the nonlinear dynamics of the wind turbine system into a linear form [4].

The mathematical model serves as a fundamental framework for analyzing the dynamic behavior of the wind turbine and designing control strategies for speed regulation as given in Figure 1. By understanding the relationships between system inputs and outputs, researchers can develop effective control algorithms, such as Iterative Learning Control, to optimize the performance of wind energy conversion systems [6]. This model forms the basis for subsequent simulation studies and experimental validation, contributing to the advancement of renewable energy technologies and the realization of a sustainable energy future.

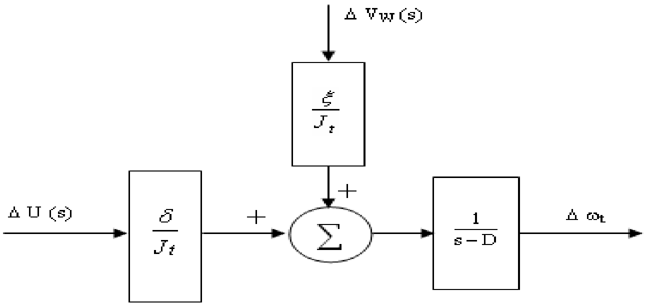

Figure 1. Mathematical Model of Wind Turbine [4]

3. Control Schemes

In Figure 2, it shows a block diagram of the control configuration considered in this work. It represents ILC control loop is connected in a parallel arrangement of a PID feedback controller. This control scheme has two main features: the design of a learning filter 'L' and a robustness filter 'Q'. The learning gain 'k' is determined to control the rate of convergence of the error signal, which is optimized to minimize tracking error during execution.

When simple ILCS is used in a nonlinear system, the ILC control loop doesn't work well. The location of the filter in the ILC scheme is also crucial for achieving good convergence and tracking performance.

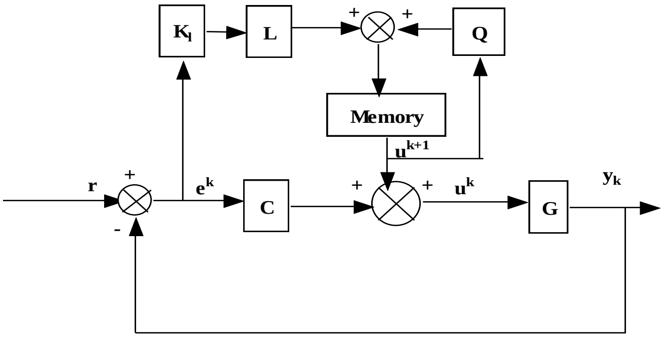

Figure 2. Simple Structure of ILC [9]

- **Design of L and Q Filter**

To design L & Q by considering below equation (2)

$$\left|Q\left(1-\frac{G}{1+GC}L\right)\right|<1 \qquad (2)$$

A suitable choice for L would be L= $\frac{1+GC}{G}$.

The L-inverse is process-sensitivity T= $\frac{G}{1+GC}$ i.e L = T^{-1}.

The instability and improper characteristics of the inverse complementary sensitivity prevent 'L' from functioning as a filter, but this issue is resolved by employing the Zero Phase Error Tracking Controller (ZPETC) algorithm [9].

We evaluate the ZPETC method by comparing the bode plot of the original “inverse complementary sensitivity” T^{-1} and the “approximated inverse complementary sensitivity” ‘L’.

The similarity in magnitude and phase plots suggests that 'L' serves as an approximation of the inverse plant model, with the phase plot accounting for delays; this comparison is illustrated in Figure 3, which displays the bode plot of the Inverse Complementary Sensitivity (Original vs ZPETC

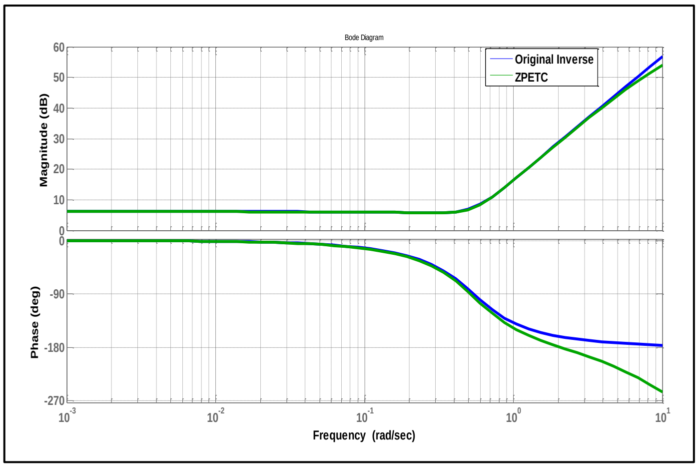

Figure 3. Inverse Complementary Sensitivity Bode Plot
(Original vs ZPETC) [8]

“A first order continuous time low pass filter is considered here. i.e. Q(s) = $\frac{\omega_c}{s+\omega_c}$,where ω_c is the cut-off frequency in rad /sec [9]. The cut-off frequency is obtained from the Bode plot of the wind turbine system unit that indicates a gain of 0.1, as depicted in Figure 4.

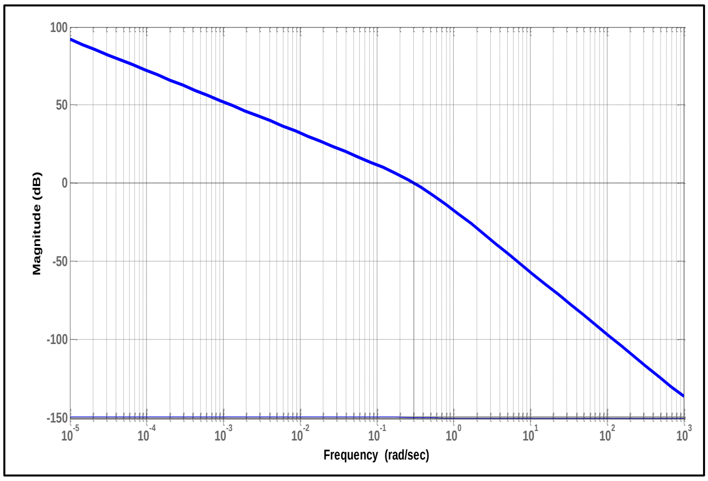

Figure 4. Bode Plot of the Wind Turbine System [8]

4. Results and Discussion

MATLAB Simulink is utilized to simulate the performance of PID control and ILC method (Figure 5) for wind turbine speed regulation. The simulation model incorporates the dynamic behavior of the wind turbine system, including aerodynamics, mechanical components, and control algorithms. Two scenarios are investigated to analyze the response of the PID controller and using intelligent controller with iterative learning control method:

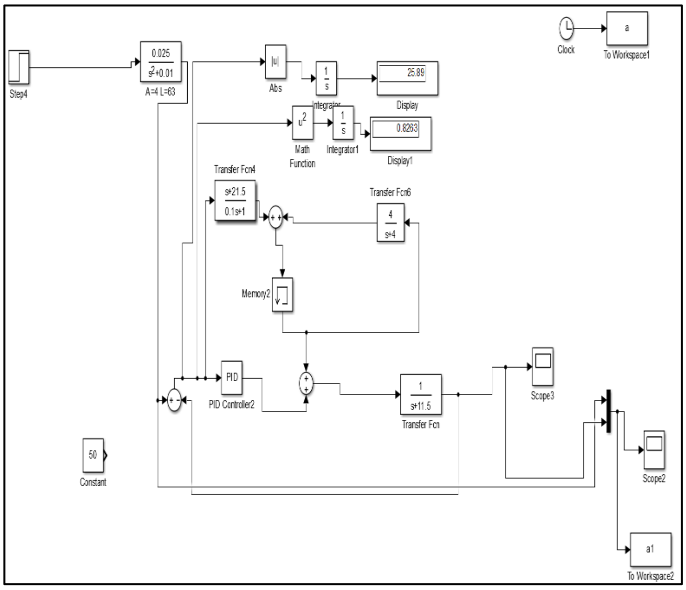

Figure 5. MATLAB Simulink Model of Intelligent Controller using ILC

Under steady state conditions, a step value of 50 rpm is given to wind turbine process with PID controller as dominant role and it is recorded in Figure 6. It is observed that it takes more time to settle on desired value and produces offset. To overcome this, an intelligent controller ILC is executed with the same value of rpm and it ensures precise speed regulation despite variations in wind as shown in Figure 7. By iteratively refining control actions, the controller minimizes deviations from the desired rpm, ensuring stable turbine operation.

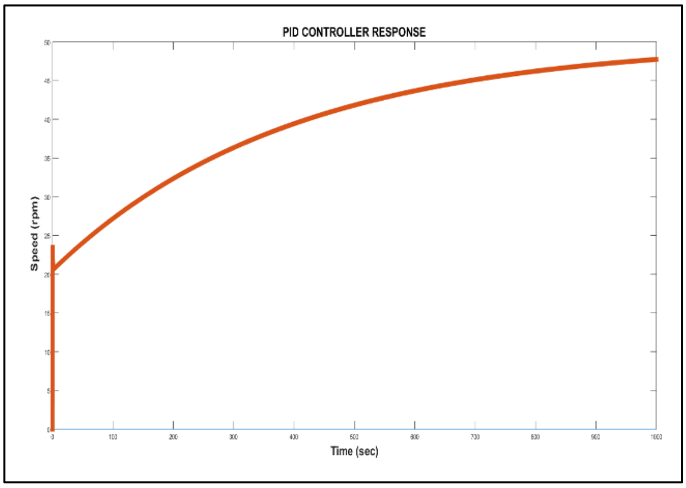

Figure 6. Step Response of PID

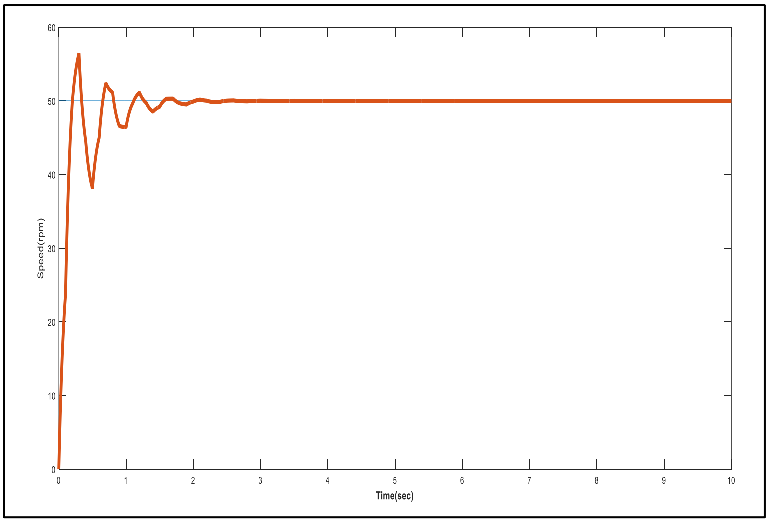

Figure 7. Step Response of ILC

To validate this study, we generate a sine wave with known period and amplitude, applying it to both the wind turbine system with conventional PID controller and with ILC. The tracking responses are recorded in Figures 8 and 9, while tracking errors are calculated and presented in Table 1. The results unequivocally demonstrate that ILC effectively tracks the desired RPM of the wind turbine unit with minimal tracking errors.

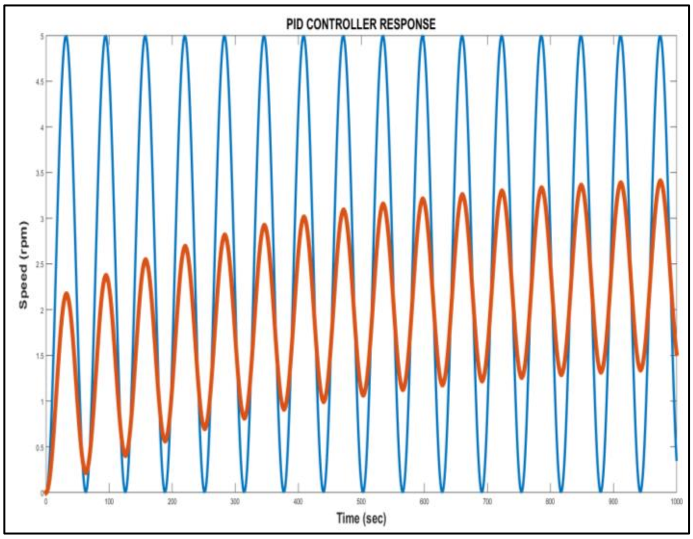

Figure 8. Periodic Response of PID

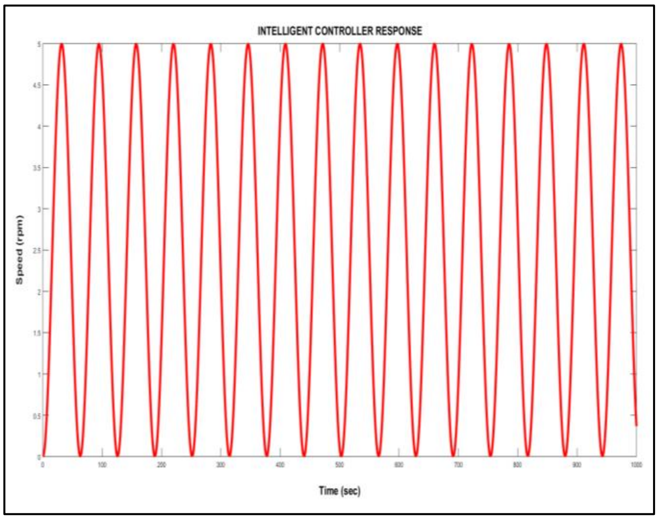

Figure 9. Periodic Response of ILC

Table 1. Tabulation of Tracking Errors

Descriptions	PID Controller	Intelligent Controller
ISE (Integral Square Error)	1504	0.8623
IAE (Integral Absolute Error)	1033	25.89
Settling Time	1.8 sec	0.3 sec

5. Conclusion

In summary, the proposed study demonstrates the efficacy of Iterative Learning Control (ILC) in regulating wind turbine speed. Through rigorous modeling and analysis, it proves superior to traditional PID methods, ensuring precise and adaptive speed regulation amidst varying wind conditions. Results exhibit enhanced efficiency, stability, and energy capture compared to PID. The dynamic adjustment capability of ILC, showcased in simulations, underscores its potential for optimizing wind energy conversion. By advancing renewable energy technologies, this study underscores ILC as a promising strategy for sustainable energy production, paving the way for future research and development in wind turbine control systems.

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