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Fractional-Order Time Delay-Considered Inertia Compensation Strategy Optimization for Wind Turbine Dynamic Simulation System

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Abstract. The wind turbine dynamic simulation system enables the transfer of complex and challenging field tests to a controlled laboratory environment, making it widely applicable for wind turbine equipment testing and wind power strategy validation. However, when simulating real wind turbines, the system requires inertia compensation. During the execution of command reception and dispatch, the system is affected by fractional-order time delay, leading to an acceleration deviation component in the dynamic simulation process and resulting in speed fluctuation issues. To address this problem, this paper proposes an inertia compensation strategy for the wind turbine dynamic simulation system based on fractional-order time delay deviation suppression. First, a mathematical model of the wind turbine dynamic simulation system is established to analyze the existing acceleration deviation component and abnormal speed fluctuation in conventional inertia compensation strategies. Second, a deviation suppressor is designed based on the zero-pole placement principle. Finally, the stability of the system with the suppressor is verified, and a simulation model is constructed to demonstrate the effectiveness of the proposed method.

Keywords: Wind Turbine Dynamic Simulation System; Inertia Compensation; Fractional-Order Time Delay; Acceleration Deviation Component.

1. Introduction

With the development of wind power generation, the construction of wind turbine dynamic simulation systems (hereafter referred to as wind turbine simulators) has become a critical tool for exploring wind power technologies and validating control strategies in laboratory environments. Since the rotational inertia of experimental systems is far smaller than that of real wind turbines, inertia compensation is required to replicate the mechanical dynamics of real turbines. Current inertia compensation methods primarily include hardware-based and software-based compensation. References [1,2] increased the physical inertia of experimental systems by adding mechanical flywheels. However, this hardware-based approach lacks flexibility. In contrast, References [3-6] adopted software-based compensation, dynamically compensating the drive torque through algorithms to bridge the gap between the simulator and real turbines. This method offers greater controllability, adaptability, and simpler hardware configurations. References [7,8] revealed that communication delays during inertia compensation could trigger oscillatory divergence in compensation torque. To address this, Reference [7] designed a high-order filter to suppress the deviation component, while Reference [8] further proposed a feedforward deviation suppressor, enhancing deviation suppression and increasing inertia compensation multiples. However, both studies assumed communication delays as integer multiples of the control cycle, whereas Reference [9] demonstrated that delays in practical systems often appear as fractional multiples of the control cycle. Reference [10] introduced a digital corrector to mitigate torque oscillations under fractional-order time delay but failed to resolve persistent speed fluctuations caused by excessive torque deviation components.

To overcome these limitations, this paper proposes an inertia compensation method with a fractional-order time delay deviation suppressor, which suppresses torque deviation components to

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eliminate speed fluctuations. Results confirm the significant effectiveness of the proposed method in stabilizing rotational speed.

2. Fractional-Order Time Delay-Incorporated Discretized Model Analysis for Wind Turbine Simulator

2.1 Mathematical Model of Wind Turbine Simulator and Inertia Compensation Strategy

As shown in Fig. 1, a real wind turbine is compared with a wind turbine simulation system based on a motorized drag platform.

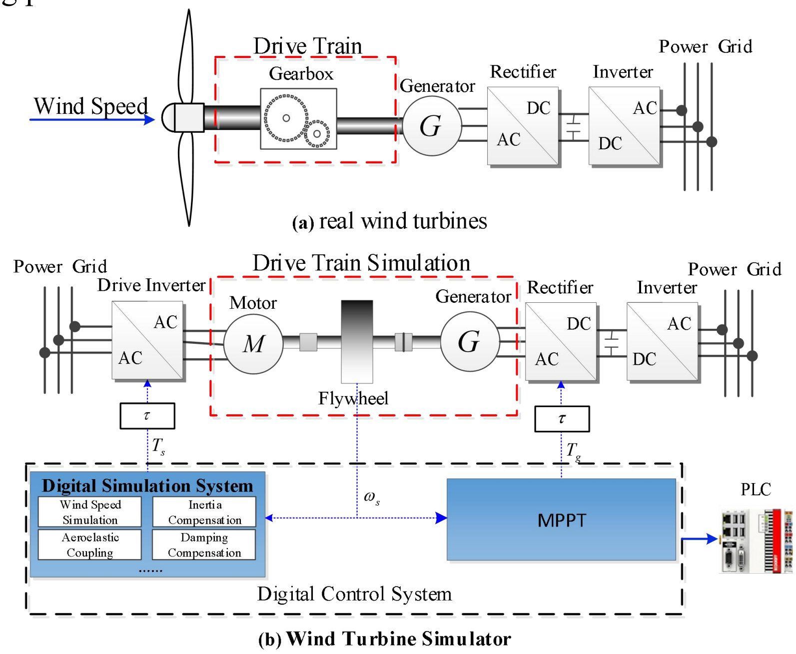

Fig. 1 Wind Turbine Simulator

This paper focuses on the drive train section, where the input to the drive train is the aerodynamic torque of the wind turbine, and its expression is:

$$T_a = 0.5\rho\pi R^2 v^3 C_{\mathrm{p}} / \omega \tag{1}$$

Where: ρ is the air density; R is the rotor radius; v denotes the wind speed; ω is the angular velocity on the low-speed side of the wind turbine and C_{p} represents the power coefficient, which is a nonlinear function of the tip-speed ratio and the pitch angle.

The simulated turbine model is scaled to match the electrical capacity, while maintaining the mechanical dynamics of the real turbine. The motion equation of the wind turbine drive train, modeled as a single-mass system, is given by[11]:

$$\frac{T_{\mathrm{a}} / n_{\mathrm{g}}}{n_{\mathrm{s}}} - \frac{T_{\mathrm{g}}}{n_{\mathrm{s}}} = J_t \dot{\omega}_{\mathrm{g}} \tag{2}$$

Where: J_t is the rotational inertia of the real wind turbine; T_{g} is the electromagnetic torque of the generator; n_s is the capacity scaling factor; n_g is the gearbox ratio; $\dot{\omega}_{\mathrm{g}}$ is the rotational speed.

The motion equation of the drive train for the wind turbine simulation system is given by:

$$T_{\mathrm{s}} - \frac{T_{\mathrm{g}}}{n_{\mathrm{s}}} = J_{\mathrm{s}} \dot{\omega}_{\mathrm{s}} \tag{3}$$

To ensure that the experimental system exhibits the same mechanical dynamics as the real wind turbine, Solving equations 1 and 2 simultaneously yields the following equation:

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$$T_s = \frac{T_a / n_g}{n_s} - (J_t - J_s) \cdot \dot{\omega}_s = \frac{T_a / n_g}{n_s} - T_{comp} \quad (4)$$

The above equation indicates that the mechanical dynamic characteristics of a real fan can be simulated by compensating the driving torque with T_{comp}.

2.2 Discretized Model of Equivalent Drive Train with Fractional-Order Time Delay

In wind turbine simulators, both the process of issuing commands and data acquisition require a finite time to complete, manifesting as communication delays within the system, as indicated in Fig. 1. The time delay identification method proposed in Reference [9] demonstrates that these delays exhibit fractional-order characteristics. Consequently, the equivalent drive train model of the wind turbine simulator should be updated to the configuration shown in Fig. 2.

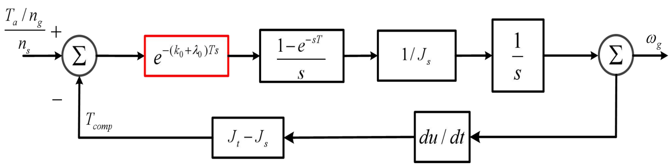

Fig. 2 Drive Train Model

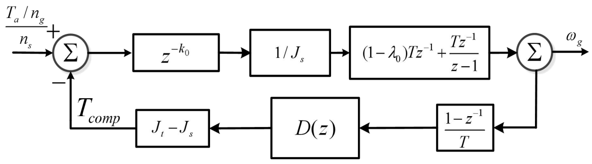

Fig. 3 Discretized Drive Train Model

In the diagram, the red box represents the Fractional-Order time delay component, where: k_0 is the integer-order delay; λ_0 is the Fractional-Order Delay; T is the control cycle of the Programmable Logic Controller (PLC), Ultimately, the converter tracks the drive torque command through a Zero-Order Holder. The equivalent drive train model incorporating fractional-order time delay is discretized using the extended transformation method[12]:

$$Z\left[\frac{1-e^{-sT}}{J_s s^2} e^{-(k_0+\lambda_0)Ts}\right] = \frac{1}{J_s} z^{-k_0}\left((1-\lambda_0)Tz^{-1} + \frac{Tz^{-1}}{z-1}\right) \quad (5)$$

Building on this foundation, Reference [10] proposed a digital corrector to stabilize the wind turbine simulator with fractional-order time delay, whose expression is given by Eq. (6) where: M is the inertia compensation multiple. The equivalent discretized drive train model is illustrated in Fig. 4, representing the existing inertia compensation strategy specifically designed for discretized systems with fractional-order time delays.

$$D(z) = \frac{z^{k_0+2}}{Mz^{k_0+2} - 0.5(M-1)z - 0.5(M-1)} \quad (6)$$

3. Feedforward Deviation Suppression-Based Inertia Compensation Strategy Considering Fractional-Order Time Delay

3.1 The problem of Abnormal Speed Fluctuation of Existing Inertia Compensation Strategy

By taking the unbalanced torque $\Delta T = T_a / n_g / n_s - T_g$ as the input and the angular acceleration as the output, the transfer functions of the real wind turbine drive train and the wind turbine simulator drive train are as follows:

$$H_{wt}(z) = \frac{1}{J_t}, H_{wts}(z) = \frac{1}{J_t z^{k_0+2} + 0.5(J_s - J_t)z + 0.5(J_s - J_t)} \quad (7)$$

Using a unit sinusoidal signal as the input, the time-domain response characteristics of the wind turbine simulator and the real wind turbine under different inertia compensation multiples are analyzed by applying the inverse z-transform to the derived equations[13]. The results indicate that the acceleration deviation component generated by the wind turbine simulator with the digital

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corrector, compared to the real turbine, increases with larger inertia compensation multiples, as shown in Fig. 4.

When the inertia compensation multiple is set to 20, the amplitude of the acceleration deviation significantly exceeds that of the real wind turbine, indicating that the wind turbine simulator undergoes more aggressive acceleration and deceleration compared to the real turbine. This result leads to high-frequency speed fluctuations that intensify with increasing inertia compensation multiples. By inputting the turbulent wind speed shown in Figure 6 through simulation, comparing the acceleration and speed of the wind turbine simulation system with those of the real wind turbine, it is clearly evident from Figures 7 and 8 that there are significant acceleration deviation components and abnormal fluctuations in speed (see Section 4 for simulation conditions).

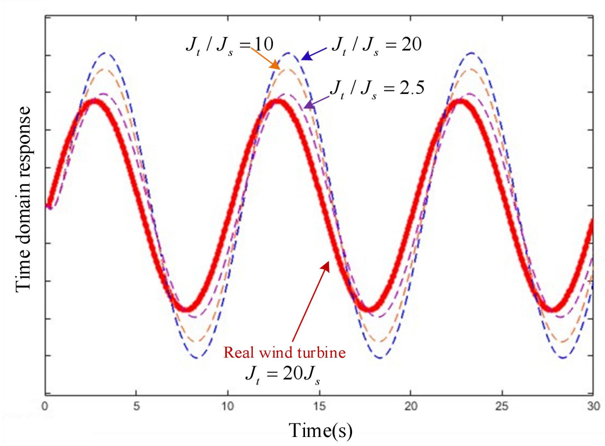

Fig. 4 Time-Domain Response of Deviation Component vs. Inertia Compensation Multiple

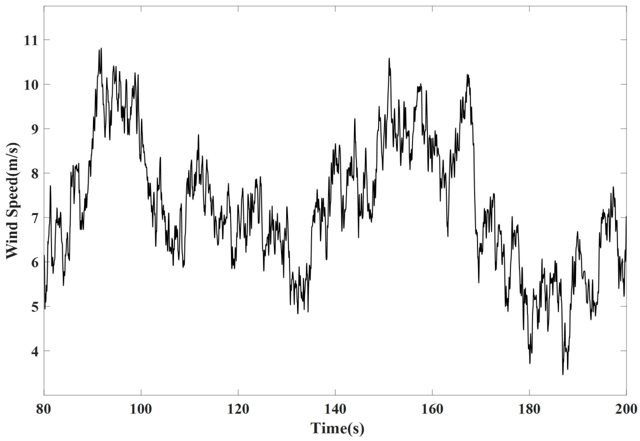

Fig. 5 Turbulent Wind Speed Input

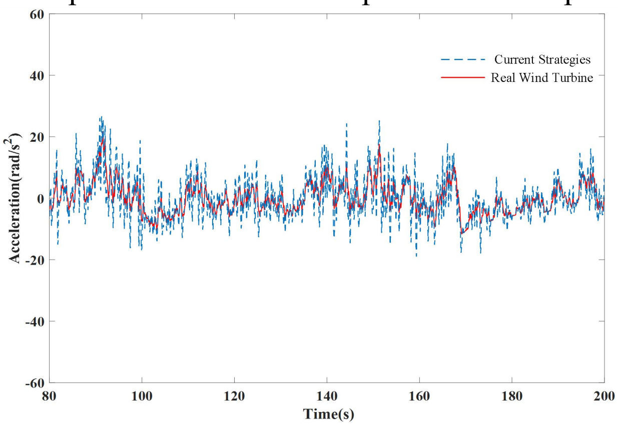

Fig. 6 Acceleration Comparison

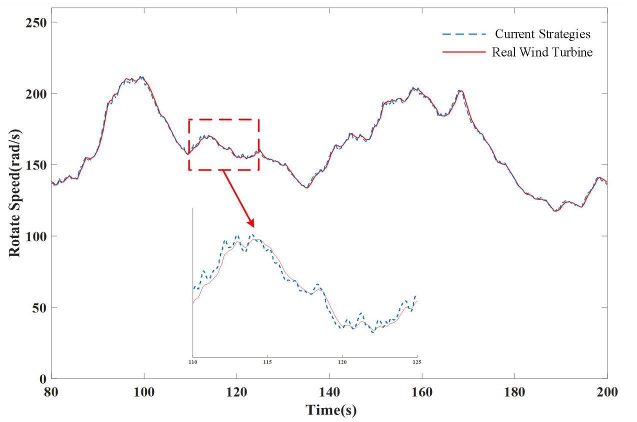

Fig. 7 Rotate Speed Comparison

3.2 Fractional-Order Time Delay-Incorporated Feedforward Deviation Suppressor Design

The above analysis indicates that existing inertia compensation strategies based on fractional-order time delay generate significant acceleration deviation components in the compensation loop, leading to speed fluctuation issues. If this deviation component is suppressed prior to dispatching the aerodynamic torque command—by dynamically adjusting the command value based on the detected deviation—the existing inertia compensation strategy can be optimized.

Based on the zero-pole placement principle, the improved transfer function of the wind turbine simulator drive train is defined as:

$$H_{wts}'(z) = H(z)\frac{T\left(\lambda_0 + z - \lambda_0 z\right)[J_t z^{k_0+2} + (J_s - J_t + J_t\lambda_0 - J_s\lambda_0)z + J_s\lambda_0 - J_t\lambda_0]}{J_s J_t z^{2k_0+4} - J_s J_t z^{2k_0+3}} \tag{8}$$

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Establish the following equation to ensure that the simulator drive train possesses the same mechanical dynamic characteristics as the real wind turbine drive train:

$$H_{wts}'(z) = \frac{z^{-k_0}[(1-\lambda_0)Tz^{-1} + \frac{Tz^{-1}}{z-1}]}{J_t} \tag{9}$$

The expression for the feedforward deviation suppressor as:

$$H(z) = \frac{J_s z^{k_0+2}}{J_t z^{k_0+2} + (J_s - J_t + J_t\lambda_0 - J_s\lambda_0)z + J_t\lambda_0 - J_s\lambda_0} \tag{10}$$

The discretized transmission chain model with the feedforward bias suppressor is shown in Fig. 8.

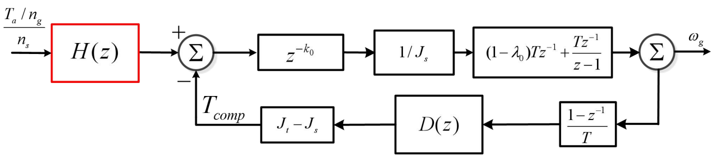


Fig. 8 The improved inertia compensation strategy

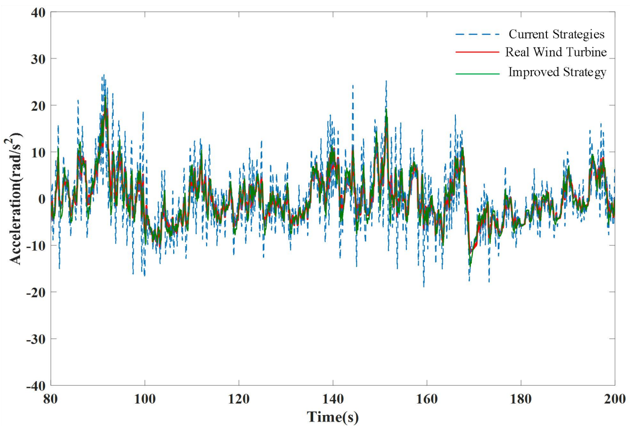
Since the effect of time delay on a real fan only exists in its response to wind speed and does not affect the stability of the real fan's transmission chain, the zero-pole configuration of the transfer function of the above transmission chain model is equivalent to that of a real fan. Therefore, the transmission chain of the fan simulation system proposed in the above method, which includes the feedforward bias suppressor, will not experience instability issues.

4. Simulation Verification

To verify the effectiveness of the feedforward bias suppressor in suppressing high-frequency speed fluctuations under different inertia simulation multiples, simulations were conducted using the turbulent wind speed shown in Figure 6 and the simulation parameters listed in Table 1. The simulation results are shown in Figures 9 to 12.

Table 1. Simulation Parameters

Parameter Name	Parameter Value
Control Period T	40ms
Experimental System Inertia J_s	0.72kgm^2
Time Delay (k_0, λ_0)	(4,0.5)



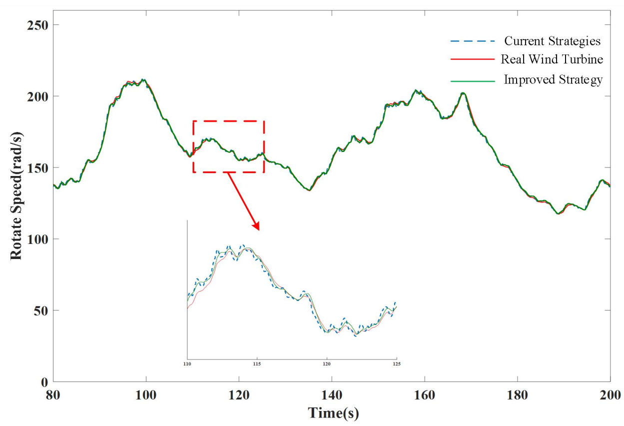


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Fig. 9 Inertia Compensation Multiplier of 2.5 Acceleration Comparison

Fig. 10 Inertia Compensation Multiplier of 2.5 Rotate Speed Comparison

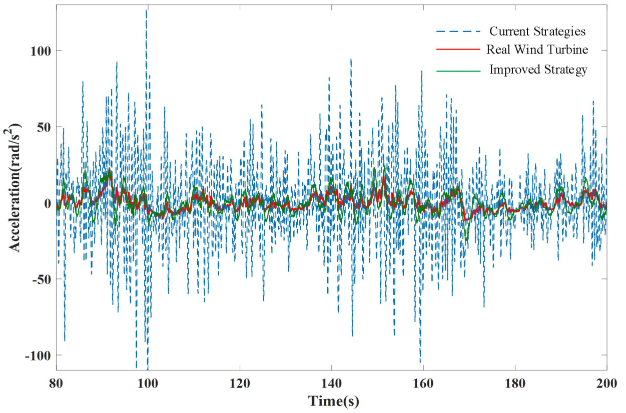

Fig. 11 Inertia Compensation Multiplier of 10 Acceleration Comparison

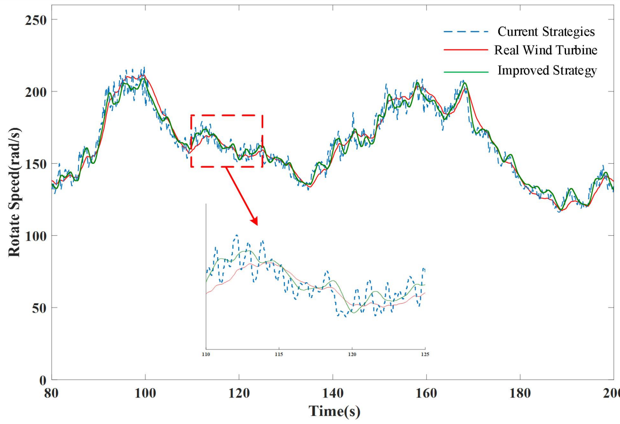

Fig. 12 Inertia Compensation Multiplier of 10 Rotate Speed Comparison

Figures 9 to 12 show the comparison between two strategies and the real wind turbine. From the aforementioned simulation results, it is evident that by adding a bias suppressor before the aerodynamic torque dispatching stage, the acceleration deviation component was significantly suppressed at inertia amplification multiples of 2.5 and 10, thereby reducing abnormal fluctuations in speed. This effectively addresses the issue of speed fluctuations caused by the use of a digital bias suppressor to stabilize the wind turbine simulation system under fractional-order time delays.

5. Summary

This study found that even with existing inertia compensation strategies for wind turbine simulation systems, speed fluctuations may still occur when considering fractional-order time delays. To address this issue, this paper proposes an improved inertia compensation strategy that incorporates a feedforward bias suppressor based on zero-pole configuration principles, taking into account fractional-order time delays. Through simulations based on both the wind turbine simulation system and the real wind turbine model, it has been verified that the method proposed in this paper can effectively eliminate high-frequency speed fluctuations under fractional-order time delays, thereby better simulating the mechanical dynamic processes of large-inertia wind turbines.

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