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Article

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Design of real-time co-simulation platform for wind energy conversion system

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Abstract

This paper presents an all-digital real-time co-simulation platform of refined Wind Energy Conversion System (WECS) model. The proposed platform is based on the Real-time Digital Simulator (RTDS) and FAST developed by National Renewable Energy Laboratory (NREL). The detailed generator and converter models are implemented in RTDS to simulate the electromagnetic transient. The models of wind, blade, tower, nacelle, and drivetrain are implemented in FAST to simulate the aerodynamic, structure, and turbulence dynamics. In such way, the designed co-simulation platform can capture all the dynamics, which can significantly enhance the simulation accuracy. Conventionally, RTDS and FAST communicate by the analogue signals, whose number of the exchanged data is quite limited. To overcome this limitation, the all-digital interface technique between RTDS and FAST is proposed. The correctness of the platform is verified by the simulation result.

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Keywords: FAST; Hardware-in-loop test; Multi-time scale; Real-time co-simulation; RTDS; Refined model

1. Introduction

Wind Energy Conversion System (WECS) is a multi-coupling complex dynamic system with multi-time scales [1]. It includes aerodynamic, mechanical vibrations, and electromagnetic transients. Modules of a wind turbine are cross-coupling, including the aero-elastic coupling between aerodynamic model and mechanical vibration model [2], the electromechanical coupling between electromagnetic transients and torsional mechanical model. Consequently, it is meaningful to establish a platform for refined model of WECS and perform Hardware-In-Loop (HIL) simulation.

Most of the existing researches, however, used simplified models of the wind turbine for different research areas that are unable to take into account a number of significant characteristics. On the one hand, static power coefficient (C_p) model has been used to replace the aerodynamic model [3]. On the other hand, the two-mass shaft model which just takes the dominant torsional modal into account has been used instead of mechanical model [4]. The detailed

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aerodynamic model based on Blade Element Momentum is used to simulate aerodynamic characteristics but the mechanical model only considered the dominant vibration modal in [5]. Besides, the generator and converter are simplified to a one-order lag link in [6]. Several cross-platform co-simulation methods have also been proposed. A refined wind energy co-simulation platform has proposed in [7]. This platform based on Real-time Digital Simulator (RTDS) and Bladed built a refined model of WECS that both mechanical and electrical models are considered. However, the cost of this platform is quite high. It is demanded to find a cost-effective alternative to realize the same function.

FAST (Fatigue, Aerodynamics, Structures, and Turbulence) is a computer-aided engineering tool developed by the National Renewable Energy Laboratory (NREL) to simulate the dynamics of wind turbine [8]. Compared with Bladed, FAST is an open source software that greatly reduces the cost. FAST has been evaluated by Germanischer Lloyd WindEnergie (GL Wind). Moreover, FAST can be compiled to a dynamic link library called by S-Function interface in Simulink. With Simulink's desktop real-time module, the entire Simulink model containing FAST can run in real-time. The RTDS is used for real-time digital power system simulation for power system studies and closed-loop testing of protection and control equipment [9].

The refined all-digital real-time co-simulation platform based on the combination of FAST and RTDS, which can be used for HIL test, has been built in this paper. The platform can simulate the real WECS in an accurate manner compared with traditional wind energy simulation. Firstly, the complete mechanical and aerodynamic models of the wind turbine and the detailed electromagnetic dynamic model of the generator and converter are coupled in the co-simulation platform. It means that the platform has the ability to simulate the full dynamics of WECS. Secondly, the platform runs in real-time, so that it can be easily connected to the actual controller of the wind turbine or converter to perform commercial device level HIL test. Thirdly, the interfaces between FAST, RTDS and controller all adopt digital communication protocol which is more flexible and convenient. In addition, the generator rotor kinematics equation is used as the interface of the electromechanical coupling.

The paper is organized as follows. Section 2 introduces the all-digital real-time co-simulation platform layout. Section 3 introduces the control model used in the hardware controller. In Section 4, the proposed platform is tested by the hardware controller in the loop simulation. The conclusion is drawn in Section 5.

2. Layout of the all-digital real-time co-simulation platform

2.1. Overall layout of the platform

The design idea of the all-digital real-time co-simulation platform can be divided into three parts. Firstly, the mechanical model of a wind turbine is constructed in FAST, as well as the electrical model is constructed in RTDS. These two separate parts are coupled by the generator rotor kinematics equation. Secondly, the main controller is implemented in the Programmable Logic Controller (PLC). The PLC in this paper is selected as the TwinCat PLC developed by Beckhoff. The controller is responsible for controlling the startup/shutdown, protection and yawing, adjusting the pitch of the blade, maximum power point tracking (MPPT). Thirdly, all-digital communication is implemented to be interface between computation platform running FAST and RTDS in the platform.

According to the coupled interface between FAST and RTDS, the High-Speed Shaft (HSS) speed ω_g in FAST is sent to the RTDS to drive the generator model, while the electromagnetic torque T_e is delivered to FAST and used as feedback input of FAST. Moreover, the main controller implemented in a PLC will collect ω_g to calculate the commanded variables and send commanded pitch angle β^* to FAST to control wind turbine. And commanded electromagnetic torque T_e^* is sent to RTDS from the controller via the computer running FAST. In addition to the mentioned variables, the exchanged data in the platform also includes the wind speed, electrical power, commanded yaw position. The overall layout diagram is shown in Fig. 1.

2.2. Interface scheme of the platform

Wang et al. [10] point out that there are two options for interfacing with RTDS: analogue and digital interface, the latter is used in this paper. Compared with traditional analogue communication interface, the digital interface can exchange more data without being limited by the number of analogue output channels. The GTNET card offered by RTDS is used to interface to external equipment over a local area network connection, and the GTNET-SKT component is used to exchange data between RTDS and FAST to implement point-to-point two-way communication

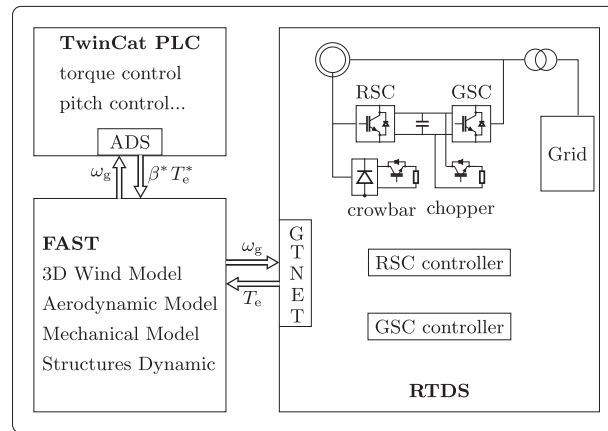


Fig. 1. Overall layout.

with low latency time. UDP (User Datagram Protocol) has been widely used in the communication process with high real-time requirements, due to its connectionless and the fast pace of communication characteristic. So the interface between FAST and RTDS is selected to be UDP that implemented on GTNET card.

Automation Device Specification (ADS) is developed by Beckhoff. ADS interface for Simulink is used for convenient data exchange between PLC and Simulink. It is used to be the communication interface between FAST and the PLC in this platform. The communication interface diagram is shown in Fig. 2.

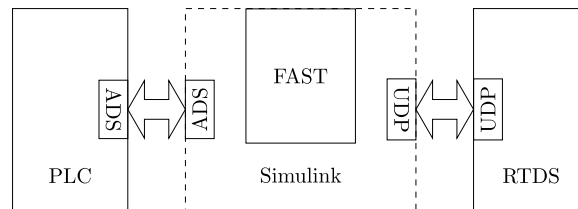


Fig. 2. Layout of the digital interface.

2.3. Guarantee of real-time running

In order to ensure the correctness of the entire co-simulation platform, the data interaction of each part should be synchronous. Because RTDS runs in real-time, so the key point is to guarantee that FAST runs in real-time. The Desktop Real-time module of Simulink can be used to keep FAST running in real-time. According to the principle of real-time simulation, the time required to compute the output of FAST at a given time-step must be shorter than the step time of simulation [11]. The size of the simulation time step has a great influence on the consumption of computing resources, so it is very important to select an appropriate simulation step size on the real-time simulation platform. To stabilize the entire co-simulation platform, the sampling interval of the interface should meet certain requirements.

3. Modelling of the hardware controller

In this platform, two basic control systems which are generator-torque and full-span rotor-collective blade pitch controller are used for the HIL test. The generator controller is used to regulate the electromagnetic torque according to the rotor speed. The blade pitch controller is used to regulate generator speed in the region above the rated rotor speed [12].

In the generator-torque controller, the generator torque corresponds to the rotor speed and is obtained by looking up a specific table which is divided into five control regions. In region 1, the rotor rotational speed is too slow to

start up the generator. In region 2, the HSS torque increases linearly with the HSS rotational speed. Region 3 is a control region for MPPT. Here the HSS torque is proportional to the square of the HSS speed. When the HSS speed reaches the critical point of Region 4, the HSS torque slope will correspond to the slope of an induction machine. When the power of the wind turbine reaches the rated value, the HSS torque will be inversely proportional to the HSS speed with the power being constant.

In region 5, the blade pitch controller will be activated and computed using a proportional integral control on speed error between the measured speed and rated generator speed. In addition, a gain-scheduled tabulated function is used to determine the gain coefficient in PI control. To compute the gain table, the equation of a simple free-body diagram of the drivetrain should be examined, the equation can be expressed as,

$$\begin{aligned} T_a - N_g T_g &= \left(I_r + N_g^2 I_g \right) \frac{d}{dt} (\Omega_0 + \Delta\Omega) \\ &= I_d \Delta\dot{\Omega}, \end{aligned} \quad (1)$$

where T_a is the Low-Speed Shaft (LSS) aerodynamic torque, T_g is the HSS electromagnetic torque, N_g is the gearbox ratio, I_d is the drivetrain inertia cast to the LSS, I_r is the rotor inertia, I_g is the generator inertia, Ω_0 is the rated LSS rotational speed, $\Delta\Omega$ is the small perturbation of the LSS rotational about the rated speed and $\Delta\dot{\Omega}$ is the LSS rotational acceleration.

In region 5, the generator power is maintained to the rated power, so the generator torque can be express as,

$$T_g = \frac{P_0}{N_g \Omega}, \quad (2)$$

where P_0 is the rated power and Ω is the LSS rotational speed.

Assuming the variation of aerodynamic torque with LSS rotational speed is neglected, the aerodynamic torque in region 5 is,

$$T_a(\theta) = \frac{P(\theta, \Omega_0)}{\Omega_0}, \quad (3)$$

where P is the mechanical power and θ is the blade pitch angle.

With a first-order Taylor series expansion used on Eqs. (2) and (3), we can get that,

$$T_g \approx \frac{P_0}{N_g \Omega_0} - \frac{P_0}{N_g \Omega_0^2} \Delta\Omega, \quad (4)$$

$$T_a \approx \frac{P_0}{\Omega_0} + \frac{1}{\Omega_0} \left(\frac{dP}{d\theta} \right) \Delta\theta, \quad (5)$$

in which, $\frac{dP}{d\theta}$ is the pitch sensitivity of power and $\Delta\theta$ is a small perturbation of the pitch angle about the operation point. In the PI controller, the $\Delta\theta$ can be expressed by the rotor speed perturbations by the equation as,

$$\Delta\theta = K_P N_g \Delta\Omega + K_I \int_0^t N_g \Delta\Omega dt + K_D N_g \Delta\dot{\Omega}, \quad (6)$$

where K_P , K_I , K_D are the proportional, integral and derivative gains of the PI controller, respectively.

Integrating all the above equations and simplifying, the rotor speed error can be expressed as,

$$\begin{cases} K_\varphi = \left[\frac{1}{\Omega_0} \left(-\frac{dP}{d\theta} \right) N_g K_I \right] \Delta\Omega \\ C_\varphi = \left[\frac{1}{\Omega_0} \left(-\frac{dP}{d\theta} \right) N_g K_P - \frac{P_0}{\Omega_0^2} \right] \Delta\dot{\Omega} \\ M_\varphi = \left[I_d + \frac{1}{\Omega_0} \left(-\frac{dP}{d\theta} \right) N_g K_D \right] \Delta\ddot{\Omega}, \end{cases} \quad (7)$$

with

$$K_\varphi + C_\varphi + M_\varphi = 0.$$

According to the equations above, the speed error will respond as a second-order system. The natural frequency $\omega_{\phi n}$ and the damping ratio ζ_{ϕ} can be expressed as,

$$\begin{cases} \omega_{\phi n} = \sqrt{\frac{K_{\phi}}{M_{\phi}}} \\ \zeta_{\phi} = \frac{C_{\phi}}{2M_{\phi}\omega_{\phi n}} \end{cases} \quad (8)$$

The pitch sensitivity $\frac{dP}{d\theta}$ is an aerodynamic property that depends on the wind speed, rotor speed, and pitch angle. It can be calculated at a number of given wind speeds with the rated rotor speed by FAST. In addition, $\frac{dP}{d\theta}$ varies over the region 5, so the PI gains will change accordingly. The calculated data indicates that the pitch sensitivity varies nearly linearly with pitch angle,

$$\frac{dP}{d\theta} = \left[\frac{\frac{dP}{d\theta}|_{\theta=0}}{\theta_k} \right] \theta + \left[\frac{dP}{d\theta}|_{\theta=0} \right], \quad (9)$$

where $\frac{dP}{d\theta}|_{\theta=0}$ is the rated pitch sensitivity and θ_k is the pitch angle where pitch sensitivity has doubled from the rated pitch sensitivity.

According to the Eqs. (7) and (8), and ignoring the damping $-P_0/\Omega_0^2$ in Eq. (7) from the generator torque controller, the PI gain can be expressed as,

$$K_P = \frac{2I_d\Omega_0\zeta_{\phi}\omega_{\phi n}}{N_g \left(-\frac{dP}{d\theta}\right)}, \quad (10)$$

and

$$K_I = \frac{I_d\Omega_0\omega_{\phi n}^2}{N_g \left(-\frac{dP}{d\theta}\right)}. \quad (11)$$

The linear relation between pitch sensitivity and the pitch angle presents a method for gain scheduling based on pitch angle. Using Eqs. (10), (11) and (9), one can see that,

$$K_P(\theta) = \frac{2I_d\Omega_0\zeta_{\phi}\omega_{\phi n}}{N_g \left[-\frac{dP}{d\theta}|_{\theta=0}\right]} G(\theta), \quad (12)$$

and

$$K_I(\theta) = \frac{I_d\Omega_0\omega_{\phi n}^2}{N_g \left[-\frac{dP}{d\theta}|_{\theta=0}\right]} G(\theta), \quad (13)$$

where $G(\theta)$ is the gain correction factor that is a function of θ ,

$$G(\theta) = \frac{1}{1 + \theta/\theta_k}. \quad (14)$$

Therefore, we could calculate the gain correction factor. In this HIL controller, the pitch angle from the previous time step is used to calculate the gain-correction factor used in next time step.

4. Simulation result

This section compares the co-simulation result with the off-line simulation based on FAST and simplified electrical model to verify the correctness of the platform. For the two kinds of simulation mentioned, the aerodynamic and mechanical models of the off-line simulation are the same as the co-simulation, but the electrical part in off-line simulation is just a simplified model. The same algorithm is used in the controller of both simulations. And the variables on slow time scale side are used to compare. The difference is that the co-simulation uses a detailed electrical model. In addition, the same turbulence wind is adopted to both simulations. Fig. 3a shows the horizontal component of the wind speed at the hub of the wind turbine.

As shown in Fig. 3b, the pitch angle in the co-simulation is approximately the same as the pitch angle in off-line simulation. It means that the hardware controller can collect data in time and calculate the control variables correctly.

The LSS speed is shown in Fig. 3c. The LSS speed of the two kinds of simulation can also be well matched. It means that the co-simulation platform can capture the dynamic response correctly. At the selected turbulence wind, the wind turbine exhibited four operating regions under full wind conditions.

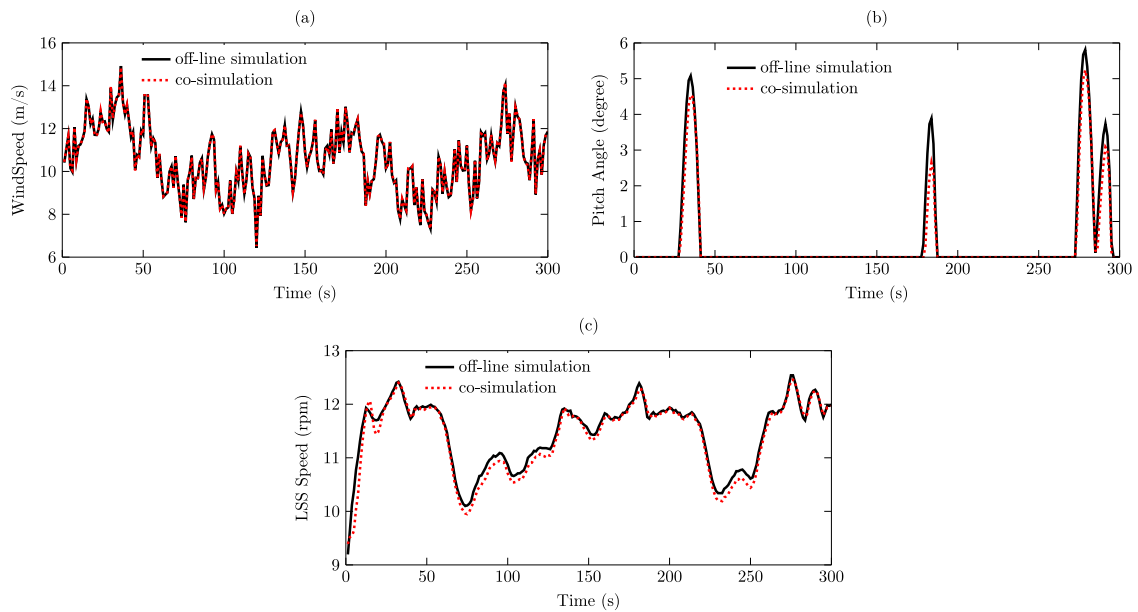


Fig. 3. Comparison of off-line simulation and co-simulation (a) Horizontal component of the wind speed, (b) pitch angle, (c) low speed shaft rotation speed.

Simulation results show that the curves of the co-simulation match well with the off-line simulation. Under the condition that the off-line simulation based on FAST has been verified by many tests, the comparison that has been shown is enough to prove that the design of the co-simulation platform is correct. To sum up, the established platform can simulate WECS correctly.

5. Conclusion

This paper presents an all-digital real-time co-simulation platform based on FAST and RTDS. The aerodynamic model, structural dynamic model and wind model are built in FAST which can accurately simulate the full dynamics of the wind turbine. RTDS is used to simulate the detailed electrical part of the WECS in real-time. As a result, the platform can perform complete and accurate dynamic response of the WECS. In addition, this platform also can be used for the HIL test to verify the performance of the hardware controller.

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