A control-oriented wind turbine dynamic simulation framework which resolves local atmospheric conditions

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ABSTRACT: Wind turbines may experience local weather perturbation, which is not taken into account by the commonly-used wind turbine simulation packages. Without this information, it is extremely challenging to evaluate the controller performance with regard to the effect of the variation of local atmospheric conditions. On the other side, it is too late and costly to wait until field test time. To fill this gap, in this paper, we develop a control-oriented turbine dynamic simulation framework to evaluate the controller performance considering the perturbation of local atmospheric conditions. This goal is achieved by integrating an internal wind turbine (IWT) model in the Weather Research and Forecasting (WRF) simulation tool. The proposed framework is implemented on a 5MW reference wind turbine, where the effects of the local atmospheric conditions are illustrated. The controller performance results are compared with those derived from the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) simulator as a validation. Simulation results show that the proposed WRF-IWT model is able to capture the turbine dynamics and controller performance regarding the perturbation of the complex local atmospheric conditions. The proposed framework can be leveraged to assist in designing controllers, which is more applicable to real-world wind conditions.

1 INTRODUCTION

In past decades, wind energy has received an increasing attention in the international energy market. This motivates more research on developing efficient wind turbine controller to optimize power generation and alleviate structural loads. However, it remains a challenge to simulate the generated power and the structural loads in real-world conditions, due to the complex time-varying meteorological phenomena that are involved. In addition, there is a lack of simulation tools oriented to wind turbine control that can account for the local atmospheric conditions during the controller design process. Finally, waiting for field tests to evaluate the influence of such local conditions on controller performance is neither timely, nor economically convenient. Therefore, there is an urgent need to develop a control-oriented numerical approach to simulate the interaction of a wind turbine with local atmospheric effects.

The generalized actuator disk (GAD) and the generalized actuator line (GAL) are two widely used turbine models to compute the aerodynamic loads under a given incoming flow field (Boersma et al. 2017). To capture the aerodynamic performance, they are integrated with the flow model in control-oriented numerical simulation tools, such as the Simulator for Wind Farm Applications (SOWFA) (Churchfield et al. 2012) and the Flow Redirection and Induction in Steady-state (FLORIS) (Gebraad et al. 2016) numerical model. Although very effective, these models usually assume that the vertical shape of the wind flow can be ideally approximated by the uniform, power law, logarithmic wind profile models or a given boundary condition (Sharma et al. 2018). However, such an assumption is not always verified when a wind farm experiences short-term local weather perturbation (Liu et al. 2017). This, due to the lack of the atmospheric information, will lead to the sub-optimal design of the control system of the wind turbine. Thus, the designed controller based on these simulation tools might be less applicable for the wind turbine operating in the real world (Rai et al. 2017).

To consider a condition which is more representative of actual ones, the wind field can be derived by a physics-based model. WRF is an advanced atmospheric prediction system that integrates fully compressible, non-hydrostatic Euler equations (Ska-
marock et al. 2021]. The solver of WRF has the ability to resolve the flow around the wind turbine in a realistic, time-varying atmospheric environment. For this reason the wind field solution produced by WRF is widely used in SOWFA as an initial condition (Churchfield et al. 2013) [Maché, M. et al. 2014].

A WRF based large eddy simulation (LES) model with control strategies was developed to consider the local atmospheric condition above complex terrains in (Wang et al. 2020). A control-oriented LES model was designed to simulate the wind turbine wake, considering the Coriolis force, in (Qian et al. 2022). Nevertheless, these numerical simulation methods use a one-directional coupling from the flow to the turbine, where the effects that turbines have on the surrounding wind field are not be considered. Thus, the finer details of the actual atmospheric conditions around turbines cannot be resolved.

To derive a more accurate atmospheric conditions, in previous literature a turbine simulator is developed by two-way coupling between a turbine model and WRF-GAD model is integrated in the WRF code (Mirocha et al. 2014). The proposed model is able to simulate the turbine aerodynamic performance in realistic atmospheric condition. Nevertheless, it simplifies the model of rotation speed of the turbine by a piece-wise linear function versus wind speed, where the generator dynamics and control law are not captured. Thus, it leads to a limited capability of serving for control-oriented simulation in realistic atmospheric conditions. In addition, both the WRF-GAD model and the WRF-LES models mentioned above are not able to consider the turbine structural dynamics model. Thus, they are not able to simulate the turbine structural vibration and capture its effects, such as the influence of the relative wind speed at the rotor due to the tower movement.

To fill this gap, in this paper we develop a control-oriented wind turbine dynamic simulation framework which can be used to validate a given control design under local atmospheric conditions. This goal is achieved by integrating an internal wind turbine (IWT) model in the Weather Research and Forecasting (WRF) simulation tool. WRF is a physics-based meteorological simulation tool, which is capable of generating a variety of local atmospheric characteristics by a series of parameterized physical schemes. Thus, it is able to simulate the perturbation of local atmospheric conditions. In addition, the IWT model includes a generalized actuator disk (GAD) model, drive-train dynamics and a tower top vibration model. It is then integrated in WRF such that the turbine and control dynamics under the time-varying local atmospheric conditions can be taken into account. We employ the proposed model to numerically simulate a 5MW wind turbine developed by the US National Renewable Energy Laboratory (NREL) (Jonkman et al. 2009). The turbine is situated near the Oceanic Platform of the Canary Islands (PLOCAN) site. The effects of the local atmospheric conditions are illustrated on the 5MW turbine with a BTC. Simulation results show that the proposed WRF-IWT model is able to capture the turbine dynamics and controller performance regarding the perturbation of the complex local atmospheric conditions. The results of controller performance are compared those derived from the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) simulator. The comparison validates the drive-drain dynamics and controller works properly in the proposed WRF-IWT model. The results show a significant potential for using the proposed framework to develop and validate wind turbine control law under time-varying realistic atmospheric conditions.

The remainder of this paper is organized as follows: Section 2 outlines the theoretical framework of WRF and GAD models. Section 3 introduces the tower top vibration model, where its effects on the relative wind speed is elaborated. In Section 4, a case study is carried out to exhibit its potential for controller design and to verify the results. Finally, conclusions are drawn in Section 5.

2 NUMERICAL MODEL

This section introduces the theoretical framework of the GAD model developed in WRF, the drive-drain dynamics and the BTC algorithms.

2.1 WRF-GAD Model

The schematic of GAD model in presented in Fig.1 where $x$ is the streamwise direction aligned with the incoming wind speed $V_0$. $V_1$ is the velocity normal to the disk, which is reduced from its upstream value as a result of the widening of the stream tube. The induction factor $a_n$ is introduced to account for this effect, then we have:

$$V_1 = V_0(1-a_n).$$

A similar expression can be derived for the downstream velocity $V_2$ based on Bernoulli’s equation (Burton et al. 2011) as:

$$V_2 = V_0(1-2a_n).$$

In GAD model, the turbine blades are represented by a rotating disk model, where the lift and drag forces are calculated based on the blade element theory (Burton et al. 2011). The forces and angles on an airfoil section are presented in Fig.2. The relation of the angles then is derived by:

$$\beta = \psi - \alpha - \xi,$$

where $\beta$ is the pitch angle, $\alpha$ is the angle of attack, $\psi$ is the advance angle, $\xi$ is the twist angle. The lift
$F_L$ and drag $F_D$ produced by the wind can be derived (Manwell et al. 2002) as:

\[ F_L = \frac{1}{2} \rho V_r^2 c C_l \]
\[ F_D = \frac{1}{2} \rho V_r^2 c C_d \]

where $\rho$ is the air density, $V_r$ is the relative wind speed over the airfoil, $c$ is the chord length of the blade, and $C_l$ and $C_d$ are the coefficients of lift and drag, respectively.

Then the axial force $F_n$ and the tangential force $F_t$ of each unit length can be derived by:

\[ F_n = F_L \cos \psi + F_D \sin \psi \]
\[ F_t = F_L \sin \psi - F_D \cos \psi \]

The projection of $dF_n$ and $dF_t$ onto the $[x, y, z]$ coordinate system in presented in Fig. 3. The relations can be derived (Mirocha et al. 2014) as:

\[ F_x = F_n \cos \Phi + F_t \sin \zeta \sin \Phi \]
\[ F_y = F_n \sin \Phi - F_t \sin \zeta \cos \Phi \]
\[ F_z = -F_t \cos \zeta \]

where $\Phi$ and $\zeta$ describe the orientation of $P$ on the actuator disk with respect to $[x, y, z]$ coordinate system.

Figure 1: GAD model schematic.

Figure 2: Forces and angles on an airfoil section, where $\alpha$ is the advance angle, $V_r$ is the relative wind speed.

Figure 3: The projection of $dF_n$ and $dF_t$ onto the $[x, y, z]$ coordinate system in WRF

in WRF. Then $F_x$, $F_y$, and $F_z$ are added to the momentum equation in WRF (Mirocha et al. 2014) as:

\[ \frac{\partial u}{\partial t} = -\frac{1}{2 \pi r \rho} G (d_n) F_x \]
\[ \frac{\partial v}{\partial t} = -\frac{1}{2 \pi r \rho} G (d_n) F_y \]
\[ \frac{\partial w}{\partial t} = -\frac{1}{2 \pi r \rho} G (d_n) F_z , \]

where $u$, $v$, and $w$ are the three components of velocities. And $G (d_n)$ is a normal distribution, which is used to avoid numerical instabilities due to the strong forces applied at isolated grid points. $G (d_n)$ is with 0 mean and a standard standard deviation that is set to be the grid size.

Based on the above momentum analysis, $F_t$ is derived by Eq.(2). Then the aerodynamic power $P_t$ is defined as:

\[ P_t = \sum F_t r dr . \]

Then we can derived $T_t$ by:

\[ T_t = P_t / \omega_t . \]

2.2 Drive Train Dynamics

For the WT dynamics, we model the turbine, drivetrain and generator as a single rotational system, with generator speed $\omega_g$ in rad/s, and rotor speed $\omega_r (t) = \omega_g / N$ in rad/s, where $N$ is the gear ratio of the drivetrain. We let $J_g$ and $J_r$ denote the inertia of the generator and rotor, respectively, and we let $J = J_g + J_r / N^2$ denote the equivalent inertia at the generator shaft. Neglecting losses, the dynamics is given by (Hovgaard et al. 2015) as:

\[ J \dot{\omega}_g(t) = T_r(t)/N - T_g(t) , \]

where $T_r(t)$ and $T_g(t)$ are the rotor and generator torque, respectively.
2.3 Baseline Torque Control Algorithms

Then we develop the BTC based on the $K\omega^2$ torque control law (Jonkman et al. 2009) as:

$$\tau_g = \frac{K\omega^2}{N},$$

where $\tau_g$ is the generator torque. $K \in \mathbb{R}^+$ is the optimal mode gain derived by:

$$K = \frac{\pi \rho R^5 C_p(\lambda, \beta)}{2 \lambda^3},$$

where $R$ is the rotor radius, $\beta$ is the blade pitch angle, $v_w$ is the wind speed, $\lambda$ is the tip-speed ratio. $C_p$ is the power coefficient, which can be derived from a lookup table.

3 WRF-IWT MODEL

In this section, the tower vibration model in WRF-IWT framework is introduced, as well as its influence on the relative wind speed between the rotor and the inflow wind.

3.1 Tower Top Vibration Model in WRF

The thrust on an annular cross-section $dT$ can be determined by the following expression that uses $a_n$ (Mirocha et al. 2014, Manwell et al. 2002) as:

$$dT = BF_n dr,$$

where $F_n$ is derived by Eq. (2), $B$ is the number of blades, which equals to 3. Then the total thrust force $T$ is calculated as:

$$T = \sum dT.$$

The dynamics of the fore-aft bending mode of the tower is modeled as a second-order system as Eq. (9) (Shaltout et al. 2017):

$$M_T \ddot{x}_T + B_T \dot{x}_T + K_T x_T = T,$$

where $x_T$ is the fore-aft displacement of the tower top, and $M_T$, $B_T$ and $K_T$ are the tower equivalent mass, structural damping, and bending stiffness, respectively.

3.2 Interaction between Tower Vibration and Inflow Wind

To construct an accurate turbine simulation approach, it is important to consider the effects on relative wind speed due to the turbine vibration. As shown in Fig. 4, the tower fore-aft vibration $\vec{V}_{fa}$ is along the axial of the turbine, the same direction as $\vec{V}_r$. Then we can derive the actual relative wind speed $\vec{V}_{ac}$ as:

$$\vec{V}_{ac} = \vec{V}_r + \vec{V}_{fa}.$$
grid scale fit for the individual turbine simulation. The
details of the nesting method are presented in Table
[3]. This nesting method is designed according to the
nesting strategy and analysis in [Talbot et al. (2012)].
The wind turbine locates in the 5th domain, where
the horizontal grid size is set to be 10 meters. The
first two domains are used for mesoscale simulations,
while the finest three are used for the large-eddy simu-
lation (LES) technique to simulate the turbine aerody-
namics performance. Therefore, the Mellor-Yamada-
Janjic (MYJ) scheme is selected as planetary Boundary
layer (PBL) of the first 2 domains, while the
LES is selected for the finer 3 domains. Here, MYJ
scheme is an Eta operational scheme, which is a
one-dimensional prognostic turbulent kinetic energy
scheme with local vertical mixing (Peckham et al.
2017). The Grell scheme is only used in the coarsest
domain because in a clear day the scheme is not rele-
vant (Talbot et al. 2012). The Smagorinsky closure is
chosen as it is recommended for real-data case (Peck-
ham et al. 2017). More details of physics options used
for the five domains are presented in Table 2.

The simulations last for 180 seconds. The first 60s
are truncated to avoid the instability at the beginning
periods. The output data from WRF is derived every
second.

4.3 Results and Discussion

The wind speed at the hub height is presented in
Fig. 5. To get a knowledge of the wind profile around
the disc area, the wind field in the vertical plane
around the turbine at $t = 90$ is presented in Fig. 6. In
Fig. 6(a), the positive value refers to the north direc-
tion; In Fig. 6(b), the positive value refers to the east
direction; In Fig. 6(c), the positive value refers to the
upper direction. As shown in Fig. 6-Fig. 7, the wind speed
varies in the overall disk district. Besides, the pro-
posed WRF-IWT model is able to capture the wakes
dynamics. In Fig. 7, the horizontal view of wakes at
hub height is presented. As shown in Fig. 6-Fig. 7,
the proposed WRF-IWT model is able to capture the
turbine’s influence on the surrounding wind field, as
well as the wake influence.

In addition, the proposed WRF-IWT model has
the capability to simulate the turbine dynamics and
controller performance. Under the wind condition
presented in Fig. 5, the wind speed is below the
rated wind speed $11.4$ m/s. Thus, the BTC is acti-
vated (Jonkman et al. 2009). In Fig. 8, the controller
performance is presented and compared with results
derived from FAST. In Fig. 8(a), the comparison of
the captured rotor power $P_r$ is presented. As shown
in the plot, it matches quite well with the results
derived by FAST. Besides, it is able to capture the

| Parameter                                      | Magnitude                  |
|-----------------------------------------------|-----------------------------|
| Rated power, $P_{g,\text{rated}}$             | 5 MW                       |
| Rotor diameter, $D_r$                         | 126 m                      |
| Tower height, $H_t$                           | 87.5 m                     |
| Cut-in wind speed                             | 3 m/s                      |
| Cut-out wind speed                            | 25 m/s                     |
| Rated wind speed                              | 11.4 m/s                   |
| Rated generator speed, $\omega_{g,\text{rated}}$ | 122.9096 rad/s             |
| Minimum generator speed, $\omega_{g,\text{min}}$ | 41.6470 rad/s              |
| Maximum generator speed, $\omega_{g,\text{max}}$ | 159.7824 rad/s             |
| Maximum generator torque, $T_g$               | $4.3094 \times 10^4$ N·m   |
| Generator efficiency, $\eta$                 | 0.9440                     |
| Gear ratio, $G$                               | 97                          |
| Generator inertia, $J_g$                      | 35,444,067 kg/m$^2$        |
| Mass nacelle, $M_N$                           | 35,444,067 kg/m$^2$        |
| Mass hub, $M_H$                               | 534.116 kg/m$^2$           |
| Mass blade, $M_B$                             | 24,0000 kg                 |
| 1st tower fore-Aft natural frequency, $f_1$  | 17848.770 kg               |
| 1st mode damping ratio, $d_1$                | 0.3240 Hz                  |
Table 2: WRF Grids Design

| Domain |
|--------|
| MYJ |
| NJSM |
| LES |
| LES |
| LES |

| Closure |
|=========|
| Smagorinsky |
| Smagorinsky |
| Smagorinsky |
| Smagorinsky |
| Smagorinsky |

| Parameterization |
|------------------|
| Grell scheme |
| - |
| - |
| - |
| - |

| Radiation |
|-----------|
| RRTM |
| RRTM |
| RRTM |
| RRTM |
| RRTM |

*NJSM: Noah Land Surface Model; RRTM: Rapid Radiative Transfer Model.

*The Radiation includes both longwave and shortwave radiation.

Table 3: WRF Grids Design

| nx  | ny  | dx/m | dy/m | Lx/km | Ly/km |
|-----|-----|------|------|-------|-------|
| 105 | 105 | 2250 | 2250 | 236.25| 236.25|
| 103 | 103 | 750  | 750  | 7725  | 77.25 |
| 101 | 101 | 150  | 150  | 15.15 | 15.15 |
| 201 | 201 | 30   | 30   | 6.03  | 6.03  |
| 301 | 301 | 10   | 10   | 3.01  | 3.01  |

Figure 6: Wind field around the GAD region, at \( t = 90 \) s.

(a) U component  
(b) V component  
(c) W component  
(d) Total wind speed

Figure 7: Wind turbine wake at the hub height, in the horizontal plane, at \( t = 90 \) s.

Figure 8: Wind field around the GAD region, at \( t = 90 \) s.

Figure 9: Wind turbine wake at the hub height, in the horizontal plane, at \( t = 90 \) s.

Figure 10: Wind field around the GAD region, at \( t = 90 \) s.

In summary, the proposed WRF-IWT model is capable to capture the influence of a turbine with BTC on the local wind conditions, as well as the turbine dynamics influenced by the local atmospheric perturbation. Thus, it achieves to simulate the two-way coupling interaction between the local atmospheric con-
ditions and a turbine with BTC. The simulation results not only provides an insight of the important information, but also show a potential of the proposed model to assist power optimization and tower fatigue load reduction controller development.

5 CONCLUSIONS

In this paper, we develop a control-oriented wind turbine dynamic simulation framework considering time-varying local atmospheric conditions. This is achieved by integrating an internal wind turbine (IWT) model in the weather research and forecast (WRF) simulation tool. The IWT is composed of a generalized actuator disk (GAD) model, the drive-train dynamics and a tower top vibration model. The GAD model and drive-train dynamics developed in WRF enables it to simulate the turbine dynamics and controller performance under short-term local atmospheric condition. By introducing the tower top vibration model, the proposed framework is able to capture the tower top motion and its effect on the relative wind speed between the rotor and the inflow wind speed. The proposed WRF-IWT framework is employed to verify the performance of a baseline torque controller (BTC) on the National Renewable Energy Laboratory (NREL) 5MW reference wind turbine situated near PLOCAN site. Simulation results illustrate that the WRF-IWT model is able to simulate the wind turbine and control dynamics where the local atmospheric condition around the PLOCAN site is considered. The results derived from the WRF-IWT model matches well with those derived from the Fatigue, Aerodynamics, Structures, and Turbulence (FAST) simulator.
Thus, the proposed framework shows high potential in assisting developing more applicable controllers for the wind turbine operating in the real world conditions, for both power optimization and tower fatigue load reduction objectives. Besides, in further research the current WRF-IWT framework has the potential to be extended to consider wakes effects for simulation of offshore wind turbines.

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