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Real-time Power Optimization of Floating Wind Farms via Platform Repositioning

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SUMMARY:
The performance of wind turbines operating in the wakes of upwind ones within a wind farm is severely impacted by the reduced incoming wind speeds and increase in turbulence intensity. As a consequence, wind energy production is decreased along with an increased dynamic loading applied on the downwind turbines. Therefore, real-time monitoring and online-control have become significantly important to increase the performance of the wind farms and to meet the demand from electricity grid. One promising way to reduce wake effects is to take advantage of the additional degrees of freedom of floating wind turbines by optimizing the wind farm layout in real time. Applying such a strategy will result in a decrease in wind loads experienced by the turbines and an increase in power productivity. This study focuses on the enhancement of the power output of a floating wind farm made up of 3x3 turbines. Layout optimization is achieved by passively using the aerodynamic forces on the turbines to achieve the repositioning task through model predictive control (MPC). Two scenarios are investigated where in the first one the total wind farm power is maximized and in the second one, a target power is prescribed. The simulations are performed on a dynamic floating wind farm model, using a realistic wind profile for the free stream inflow. The results show a 7% increase in energy production for one-hour simulation compared to fix layout. In addition, the repositioning mechanism with the MPC controller allows for proper stabilization of the power production around a target value.

Keywords: Floating offshore wind turbines, position control, layout optimization, model predictive control

1. DYNAMIC FLOATING WIND FARM MODEL

The dynamic wind farm model used in this study is represented in Fig. 1. The model consists of two main modules: an aerodynamics module that computes the effective wind speed at the rotor of each turbine and a floating turbine dynamics module that determines the rate of change of the different turbine states as well as the power output of each turbine. These modules are briefly presented in the following paragraphs.

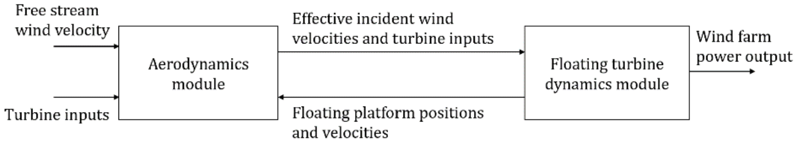

Figure 1. Block diagram of the floating wind farm model

1.1. Aerodynamics Module

The aerodynamics module simulates the downstream wake dynamics for each turbine based on three characteristics: the wake centerline position, the wake average velocity, and the wake diameter. For each turbine, these values are determined from the momentum conservation equation, represented as (Kheirabadi & Nagamune, 2021):

$$\frac{\partial \mathbf{v}_{\mathrm{w}}(\hat{x},t)}{\partial t} + \left(U_\infty(t) - v_x(t)\right)\frac{\partial \mathbf{v}_{\mathrm{w}}(\hat{x},t)}{\partial \hat{x}} = \dot{\mathbf{V}}_\infty(t) - \mathbf{v}(t) + \frac{2}{D_{\mathrm{w}}(\hat{x},t)}\frac{dD_{\mathrm{w}}(\hat{x},t)}{dt}\left(\mathbf{V}_\infty(t) - \mathbf{v}(t) - \mathbf{v}_{\mathrm{w}}(\hat{x},t)\right) \qquad (1)$$

where $\mathbf{v}_{\mathrm{w}}(\hat{x},t)$ is the wake average velocity vector, $\mathbf{V}_\infty(t)$ is the free stream wind velocity vector where $U_\infty(t)$ is its component in the $\hat{x}$ direction, , $\mathbf{v}(t)$ is the turbine velocity vector where $v_x(t)$ is its component in the $\hat{x}$ direction, and $D_{\mathrm{w}}(\hat{x},t)$ is the wake diameter.

1.2. Floating Wind Turbine Dynamics Module

In this module, each turbine is represented by its position and translational velocity in a 2-D plane and has three control inputs: blade pitch angle, generator torque and nacelle yaw angle. Based on these inputs, the model determines the effective velocity vector for each turbine by solving the following equation:

$$\dot{\boldsymbol{v}}(t) = \frac{\mathbf{F}(t)}{m+m_a} \qquad (2)$$

where m is the mass of the floating turbine, m_a is the added mass accounting for hydrodynamic loads and $\mathbf{F}(t)$ is the total force impacting the turbine. The model assumes that each turbine is subject to three forces including the aerodynamic thrust force, the hydrodynamic drag force, and the mooring line forces (i.e., $\mathbf{F}(t)$ is the sum of these three forces). The power output for each turbine is determined from the actuator disk theory in steady state.

2. CONTROL DESIGN

The controller used in this study is based only on the control inputs which are readily available in most wind turbines, namely the blade pitch angle, the nacelle yaw angle and the generator torque. It consists of a power regulator and a position controller as shown in Fig. 2. The power regulator is based on the constant-power strategy (Jonkman et al., 2009) and regulates the generator torque actuator so that the controlled turbine produces power equivalent to the power output target. This controller ensures that the desired power is generated during turbine repositioning and position regulation.

The position controller passively adjusts the aerodynamic force impacting the turbine structure, through the blades and nacelle actuators, to control its position. It is a model predictive controller (MPC) whose internal model is based on a linearized representation of a simplified dynamic model (Homer & Nagamune, 2018). The MPC controller regulates the position of the turbine by minimizing the rotor overlap areas (to mitigate the wake effects and increase power generation), the rotational speed of the rotor/generator and penalizes the rotational oscillations of the platform to ensure the structural integrity of the floating wind turbine.

It should be noted that although several control algorithms have been proposed, including the proportional-integral-derivative controller, the linear quadratic integrator, the gain-scheduled Proportional-Integral controller and the $\mathrm{H}\infty$ state feedback controller, they might not be robust enough as opposed to the MPC controller to deal with the challenging FWT environment which involves the multiple-input multiple-output mechanism and includes large environmental disturbances (e.g., wind and wave).

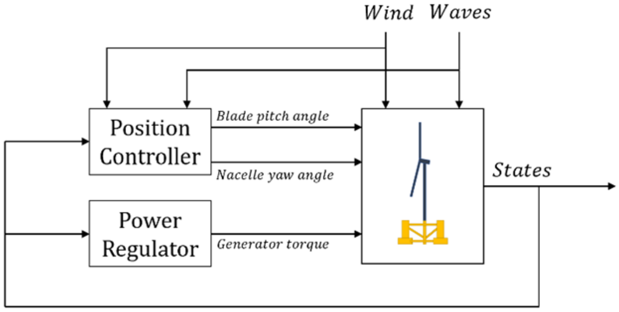

Figure 2. Block diagram of the used controller

3. APPLICATION

3.1. Simulation parameters and problem description

In this study, a wind farm consisting of 3x3 NREL 5MW Semi-Submersible turbines is simulated where wind turbines are separated longitudinally by 7 times their rotor diameter and laterally by 4 times this diameter. An average wind of 16m/s is considered at rotor height along the x-direction, and turbulence is modeled using the Von Karman spectrum. The wind turbulence is shown in Fig. 3.

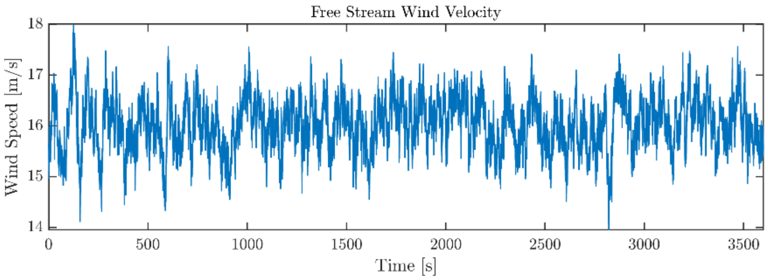

Figure 3. Wind speed record

Two scenarios are proposed. The first scenario will compare the maximum power output between two wind farms; one ordered to extract the maximum power without repositioning while in the other, the wind turbines are allowed to move in their movable range to mitigate the wake effects. In a second scenario, a constant power demand will be imposed on the wind farms. The objective is then to ensure a stable and constant power production through turbine repositioning.

3.2. Results

The wind farm power output for both scenarios are shown in Fig. 4 and Fig. 5. In the first scenario, and for a lateral spacing up to +/- 5m (imposed by the mooring lines length), even if the wake effect is not totally avoided, a significant increase in the power output is obtained due to the effective repositioning. The wind farm can then produce its maximum power for most of the time, with a gain in energy production of 7% for a one-hour simulation compared to a fixed layout.

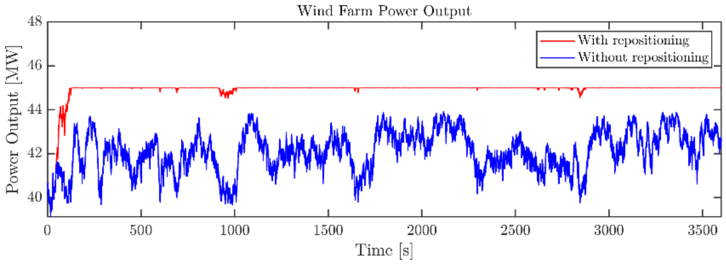

Figure 4. Wind farm power output for the first scenario

In the second scenario, the wind farm was asked to supply 42 MW of constant power. Figure 5 depicts the power capacity that is generated with and without repositioning to meet the power demand. Due to the repositioning through the MPC controller, the wind farm's power output is significantly more stable, making it easier to operate and satisfy the grid demand.

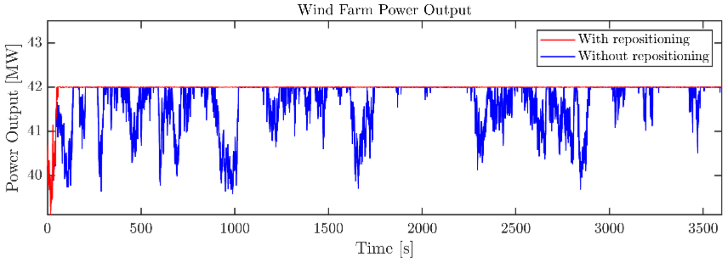

Figure 5. Wind farm power output for the second scenario

4. CONCLUSION

In this study, the real-time repositioning approach for wake mitigation and power optimization of floating wind farms was investigated based on model predictive control. Two scenarios, involving a realistic wind flow and a position controller, demonstrated the ability of this method to mitigate the wake effects while maximizing or regulating the power generation output. Since, no hardware modification is required in the proposed approach (i.e., the aerodynamic thrust force is directly manipulated), it can be readily applied to real-time monitoring and online-control schemes for new or existing wind farms.

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