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Digital twin-driven dynamic repositioning of floating offshore wind farms

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Abstract

This paper presents a novel approach to optimize wind farm layout during operation based on digital twin and dynamic repositioning. The technology offers a possibility to increase the total energy production of floating wind farms by minimizing the wake effect. We assume each of the individual wind turbine is completed with a propulsion system and is allowed to reposition itself anywhere in the restricted domain. The simulations are performed in a digital twin platform based on Unity 3D, where wind speed and direction are used as inputs for the digital twin. Furthermore, Jensen's wake model is implemented to model the dynamic behaviour of the wind. To find an optimal position for all individual wind turbines, two methods are proposed. The first method is based on reactive control, while the second method is based on optimal control. The possible energy gains of dynamic repositioning with real-life scenarios are assessed to show the feasibility of the proposed method.

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Keywords: Digital-twin; Floating wind farm; Dynamic repositioning

1. Introduction

With the industrial revolution, fossil fuels have become the main source of energy. However, fossil fuels will be severely depleted approximately in 50 years [1]. Therefore, more sustainable energy resources are needed in the following decades. Wind energy has become an alternative solution for sustainable energy production. The first known study of electricity production from wind was made by James Blyth in the late 19th century. In the consequent year, Charles F. Brush built the first automatically operating wind turbine for electricity production. The rotors of the wind turbines were 17 meters in diameter [2]. Today, the blades' diameters can reach up to 222 meters (SG 14-222 DD). Due to the colossal sizes, a vast area of land is required. Not only the wind farm area but also the surrounding fields are crucial for efficiency. Therefore, only some dedicated areas can be used for onshore applications. In recent years, advances in technology have led to the development of offshore wind farms. Compared to onshore, wind speed is much more abundant and steadier at offshore. Furthermore, noise, aesthetic pollution, and other environmental footprints can be minimized.

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1.1. Motivation

There are two possible offshore wind turbine design solutions. For shallow water, the pylons can be mounted into the seabed. However, this method is not preferred in deeper water due to the installation cost. Floating wind turbine can be seen as a solution for deep water installation. Some possible designs include tension leg, semi-submersible, and spar with mooring line system [3]. With some additional equipment such as thrusters/propellers, each of the individual wind turbine can be repositioned to minimize the wake effect, and hence increasing the total energy production. Since dynamic repositioning is a new concept and has never been demonstrated in the actual wind farm, quantifying the effectiveness of this concept in simulation using digital twin technology could be beneficial. A digital twin can be defined as a digital representation of a physical asset. It usually consists of a visualization of the asset based on a computer aided design (CAD) model and a set of mathematical models describing the behaviour of the asset. There are several types of digital twins defined in the literature [4]. A digital twin that exists before the physical asset is called a digital twin prototype. This type of digital twin can be used in the design phase to create a high-quality product. A digital twin instance is a type of digital twin of each individual instance of an asset once it is manufactured. This type of digital twin can be connected with the physical twin by utilizing measurement from sensor data.

This paper proposes a novel approach to increase the energy production of floating offshore wind farms based on dynamic repositioning and digital twin technology. The type of digital twin technology used in this paper is digital twin prototype, but later can be extended to digital twin instance and digital twin aggregate using communication standard such as OPC Unified Architecture (UA). To this end, a 3 × 5 wind farm is used as a case example.

1.2. Literature review

In any wind farms, wind speed would experience wake effect which is defined as the wind speed decrease caused by upstream turbines. To maximize the energy production and to make full use of the machines' working ability, it is essential to reduce such effect [5]. Different methods have been studied to accomplish this task. For example, Chen et al. proposed that changing the height of hubs can improve the output of wind farms [6], while Souma et al. chose to change the rotor radius to boost the electricity output [7]. Although these methods can reach a considerable improvement, these parameters would be fixed after the wind farm was built. Once the terrain or wind conditions are changed, it is hard to adapt and keep the efficiency. Thus, more studies need to be conducted to analyse the application of dynamic layout design. A more universal solution was provided by Ju Feng and Wenzhong Shen [8]. They developed a toolbox that can provide solutions for wind farm designers or other potential users. Before any calculation, users can define the terrain and parameters of wind turbines (number, yaw height, and rotor radius). Then a genetic algorithm is applied to find the optimal layout. This is more intuitive than the former studies and can be used as a tool that can be used in industry.

1.3. Contribution of this paper

Through literature review and market investigation, a visualization tool is still needed for wind farm designers. Current studies mainly focus on evaluating the wake effect precisely and giving numerical results. This can be useful for pure research. But for universal usages, a more intuitive platform would be more applicable. This shortcoming motivates us to considering digital twin as the visualization and simulation tool. Compared to traditional experiments, it costs less, runs faster, and provides a more intuitive results that can be used for decision making and other research and non-research purpose. Therefore, the contributions of this project will be the following points:

- Development of a digital twin platform for floating offshore wind farm. The platform is created using Unity 3D (written in C#).
- Development of dynamic repositioning algorithms based on reactive and optimal control algorithms. Based on these algorithms, the digital twin platform can provide optimal solutions for users once the area and wind turbine parameters are defined.

1.4. Organization of this paper

This paper is organized as follow. Section 2 presents the wake model. The concept of dynamic repositioning and repositioning algorithm are presented in Section 3. Section 4 discusses the development of the digital twin platform based on Unity 3D. Section 5 contains results and discussion. Finally, conclusion and further development are presented in Section 6.

2. Wake model

Jensen's wake model is one of the most widely used wake models, which assumes a linearly expanding wake with a velocity decrease depending on the distance. This method only considers the far wake region since the vortex shedding contribution is ignored. Similarly, the tip vortices effect is not considered. Furthermore, the Jansen's wake model is derived from momentum conservation downstream of the wind turbine. The wake velocity is a function of the downstream distance where the wake expansion is linear. The Jensen's wake model was derived for a single wind turbine; however, it can be extended to wind farm application [9].

Jensen's single wake model

Jensen's wake model uses conservation of momentum across control volume in the wake region. From the conservation of momentum, the following equation is obtained:

$$\pi r_0^2 v + \pi \left(r^2 - r_0^2\right) v_0 = \pi r^2 v_1 \tag{1}$$

Here, r_0 is the radius of the wind turbine, v_0 is the freestream velocity, v is the wind speed behind the turbine, r is the wake radius, and v_1 is the wind velocity downstream after the desired distance. The wind speed behind the turbine can be obtained from the freestream velocity as follow:

$$v = (1 - 2\alpha)\, v_0 \tag{2}$$

where α is the axial flow induction coefficient. This coefficient determines the speed of expansion. Atmospheric conditions are one of the parameters which determine the coefficient. For this application, the coefficient is selected as 0.04 [9]. The wind velocity at the wake area can be described with the below equation:

$$v_1 = v_0 + v_0 \left(\sqrt{1 - C_T} - 1\right) \left(\frac{r_d}{r}\right)^2 \tag{3}$$

where C_T is the thrust coefficient and is a function of velocity. This coefficient is normally provided by the turbine manufacturers. After combining all these equations, the final velocity equation in the wake region becomes:

$$v_1 = v_0 \left[1 - \frac{1 - \sqrt{1 - C_T}}{(1 + 2\alpha s)^2}\right] \pi r^2 \tag{4}$$

Eq. (4) enables to express velocity at the wake area as a function of freestream velocity, thrust coefficient, induction factor, and distance behind the rotor ($s = D/2s$). Furthermore, as seen in the Eq. (4), the thrust factor should be less than one. The manufacturers usually provide a curve for the thrust factor as a velocity function. For simplicity, C_T is selected as 8/9, which is the maximum value that can be achieved theoretically [10].

Jensen's multiple wake model

The significance of the wake effect increases in the wind farms because, for efficiency, the wind turbines need to be packed as close as they can. However, as it is also shown in the previous section, closer the wind turbines are subversive the wake effect is. In a wind farm, the wakes of many turbines may impact one turbine. The Eq. (5) can be used to calculate the wake effect of multiple wind turbines. It is an extension of the single turbine model to multiple turbines. This equation needs to be solved for each wind turbine recursively to find the energy deficit at the desired location.

$$v_i = v_0 \left[1 - \sqrt{\sum_{i=1}^{N_t} \left(1 - \left(\frac{v_i}{v_0}\right)^2\right)}\right] \tag{5}$$

The multiple turbine wake effects can be extended into more advanced models which consider three-dimensional effects. Those models provide more accurate results; however, most of them are computationally costly.

3. Dynamic repositioning method

Dynamic repositioning is a relocation procedure to optimize the wind farm layout. This paper investigates the feasibility of dynamic repositioning to increase the power production on floating wind turbines by minimizing the wake effects due to the turbine interaction. We propose two methods: reactive control and optimal control.

3.1. Reactive control

The first proposed solution for dynamic repositioning is by using reactive control. The inputs of this method are the wind speed and the wind direction. The method relies on sensor system such as spinner anemometer and nacelle LiDAR system to monitor the incoming wind flow. Once the sensor detects wakes, each of the individual wind turbine will reposition itself to minimize the effect of the wake. Reactive control is the simplest feedback control method and is easy to implement. The main drawback is that the method does not consider the energy needed to move the wind turbine from one position to another as a constraint. Hence, the energy gained from the dynamic repositioning can be negative. Furthermore, the method does not consider optimality (see Fig. 1).

Fig. 1. Reactive control strategy.

3.2. Optimal control

The second proposed solution is based on optimal control. In this method, data from sensor system is used as inputs for an optimization algorithm to obtain a set of optimal position of wind turbine. The advantage of using this method is that the solution is (sub) optimal and we can consider the energy for moving the wind farm in the calculation. Hence, we can guarantee that the solution is feasible, i.e., the energy gained from dynamic repositioning is positive. In this case, the optimization problem can be written as:

$$\min_{p} -E\left(p, \vec{v}, e\right) \tag{6}$$

Here, the total energy E of the wind farm is dependent on the position of the individual wind turbine p, the velocity vector $\vec{v}$, and the energy required to move the wind turbines e. To ensure the solution is feasible, e can be considered as a constrain. The constrained optimization problem can be solved using direct and indirect methods. In the direct method, both the state and the control are approximated using polynomial or piecewise constant parameterization. In the indirect method, calculus of variation is used to obtain the first-order optimality conditions. Both methods have been successfully implemented, however, the former is often used recently due to advances in computational science (see Fig. 2).

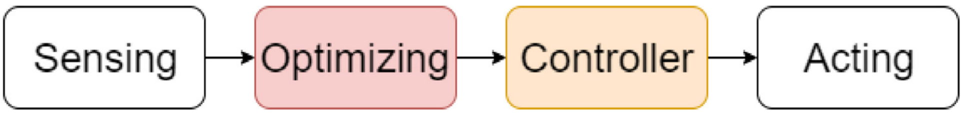

Fig. 2. Optimal control strategy.

4. Development of digital twin platform

Fig. 3 shows an interface of a digital twin prototype for wind farm application. The platform was developed at the Norwegian University of Science and Technology and has been used for teaching and research. It was developed using Unity 3D. Static and dynamic data for simulation can be transferred through OPC-UA communication protocol.

Fig. 3. Digital twin platform developed at the Norwegian University of Science and Technology.

The schematic engine in the digital twin is designed based on the working flow in Fig. 4. Data obtained from the sensor system is transferred into an OPC UA server. OPC UA is a standard communication protocol that has been used in many industries. From here, the data can either be used directly in the digital twin visualization interface or transferred first to Node-RED to quickly create a live data dashboard. The optimization algorithms are embedded in the digital twin platform. Users can then choose one of two solutions. If the reactive control solution is chosen, the program will detect the wind parameters and rotate the wind turbines accordingly. The method searches an optimum solution if the wake is detected. Then the wind turbines will dynamically reposition. If the optimal control method is chosen, the solution is obtained by solving an optimization problem.

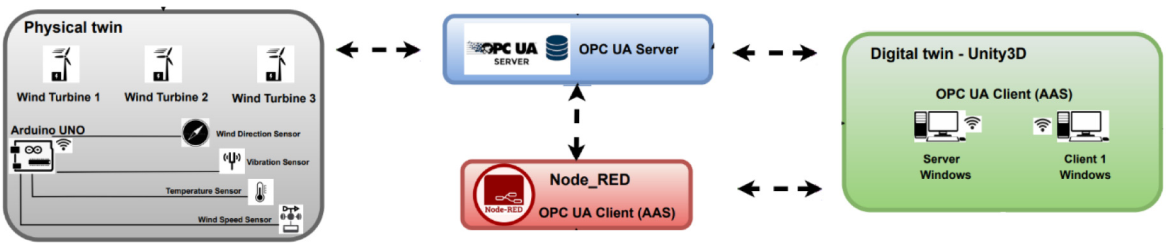

Fig. 4. Schematic diagram of the digital twin platform.

5. Result and discussion

The dynamic repositioning algorithms presented in Section 3 are implemented in the digital twin platform described in Section 4. The case study is a wind farm with 15 turbines arranged in a 3 × 5 layout. Each turbine can produce up to 8.6 MW of electrical energy. As the base case, the turbines are arranged in rows. To minimize the effect of the wake, we can reposition the wind turbines in the middle row either to the left or to the right using thrusters. Fig. 5 illustrates the concept.

In this simulation, the diameter of each blade is 167 m; thus, each turbine will have a swept area of 21,900 m^2. The distance between each turbine in a row is six times the diameter of the blade. We assume the propulsion system incorporates a 2,4 MWh battery energy and can travel at 2 m/s. The energy gained from each turbine is presented in the left hand side of Fig. 6. As a base case, the turbines are stand still and the total energy gained is 22,98 MW. In the reactive control case, the turbines in the middle row are moved to the left side for about 500 m. This causes a significant loss in the total energy gain. On the other hand, the optimal control provides a moderate reposition distance by moving the turbines for only 103 m to the left. Thus, the total energy gain is slightly higher. In the optimal control case, we constrained the energy needed to move the platform. This is to ensure the energy gained using this method is above the feasibility threshold.

Fig. 5. Configuration of the wind farm in a row (left) and zigzag (right).

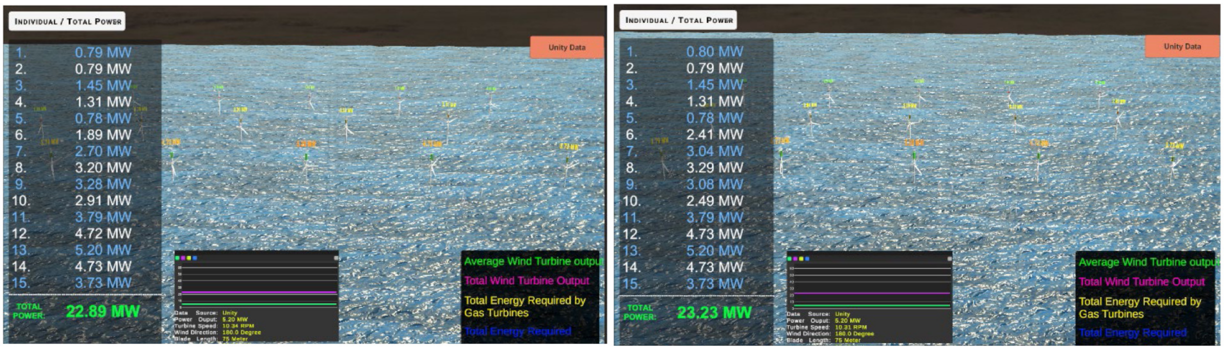

Fig. 6. Reactive control (left) and optimal control (right) solution.

6. Conclusion and further development

This paper presents a feasibility study to evaluate dynamic repositioning for floating wind farm application. The study is based on digital twin technology, where Jensen's wake model is used to calculate the wake effect. Two control methods are proposed and evaluated: reactive and optimal control. Based on numerical simulation, control method based on optimal control theory provides feasible solution since it guarantee the energy gain is positive. Results from our simulations show dynamic repositioning can be considered as a solution to increase the energy production in the future. The wake model is very simple and cannot capture the dynamic behaviours of the wind accurately. Furthermore, both the reactive and optimal control are solved using a naive approach. Future works include behaviour modelling the dynamic of floating wind turbine, improving the wake model, and more robust optimal control numerical solution schemes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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