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Multi-Period Optimization of Floating Wind Farm for Open Sea Nature Gas Hydrates Exploitation

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Natural gas hydrates are a kind of new energy resource that attract widely research interests. The open sea exploitation of hydrates consumes large amount of energy, it is not economic by directly using the exploited natural gas. Open sea floating wind farm is applied in this study to provide energy to the offshore platform for hydrogen production by reforming of methane. Floating wind farm is not studied widely and most works have been done to optimize the layout of turbines in different types and diameters, but less consideration is given to the layout design of wind farms in multi-period situation. Wind resource varies with seasons significantly and the location of wind turbines (WTs) can be changed in different time. This work proposes a new methodology to optimize the multi-period layout of wind farm based on Genetic Algorithm (GA) and Geosteiner algorithm. The objective is to obtain the largest annual economic benefit (AEB), including the annual production benefit (APB) and the cost of energy (COE). Finally, the optimal layout scheme is determined to help solving the layout problem of open sea wind farms. A 4.1 km × 4.1 km wind farm is applied in this study, it is indicated that under the condition of 12 periods layout, 1.7986×10^9 ¥/y of AEB can be achieved. Compared with single period optimization, AEB is increased by 6.3289×10^6 ¥/y by using multiple period optimization.

1. Introduction

Facing the current situation of energy shortage, seeking clean and efficient new energy has become an important issue today. Global gas hydrate reserves are large, with the advantages of clean combustion and large reserves, and it is an unconventional gas resource with significant resource potential. The majority of hydrates exist in the seabed sediments, of which the natural gas hydrates has bright prospects for mining (Martinez et al., 2016). In addition, natural gas hydrates have many other applications, such as energy transmission, gas separation, storage, water purification and so on.

In hydrates exploitation, CO_2 is injected into seabed to extract gas hydrates. Due to the low added value of methane and the requirement of CO_2, directly producing hydrogen through methane reforming on offshore platforms is considered. In this way hydrogen with higher added value can be obtained, and at the same time the generated CO_2 can be injected seafloor to replace natural gas hydrate. However, large amount of energy has to be provided for reforming reaction, and providing energy by burning methane is not that economic. Offshore wind energy is considered to provide energy. Compared with wind speed for onshore and offshore, the wind speed on the open sea is higher and the wind resource distribution is more balanced (Esteban and Leary, 2012). For open sea offshore floating wind farms, most of the related studies aimed at optimizing the layout of wind farms with different diameters and different types of turbines. For example, Feng and Shen (2017) carried out wind farm layout for Danish Horns Rev I wind farm by using multiple types of wind turbines as optimization variables. The study found that the design of manifold types of WTs in wind farms is more suitable for larger size WTs.

Among the factors that affect the layout optimization of wind farms, wake effects, wind speed, and wind density can affect power generated by WTs, and the layout of cables will also affect the construction costs. Based on the principle of energy conservation, when wind energy is captured by the upstream wind turbine, the wind

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speed will decrease accordingly, wind speed captured by the downstream WTs will be smaller than the upstream, which called wake effect. The wake effect can result in a 10 % - 20 % loss of the total power generation in a wind farm (Wilson et al., 2015). When studying the wake effect of wind turbines, the models used are Jensen model (Jensen,1983), Frandsen model (Frandsen et al., 2006), Lissaman model (Lissaman, 1979) and so on. The construction of a wind farm on open sea can provide the energy supply for natural gas hydrate reforming hydrogen production without using methane combustion to provide energy requirements. Compared to a wind farm without a divided period, multi-period offshore wind farm design can be well adjusted for wind resources in order to achieve optimal energy supply. The statistical planning of offshore wind energy in multi-period can be estimated more accurately for the power generation and economic benefits of the wind farm layout. This study proposed a theory based on Genetic algorithm (GA) and Geosteiner algorithm to optimize the layout of wind farms under multi-period conditions. Based on the wind conditions in a certain area, the operating period of the wind farm is subdivided into twelve by month. And objective function is annual economic benefit (AEB).

2. Problem formulation

Jensen model is mainly used to calculate the wake effect when researching the smooth topography or offshore wind turbines at present.

2.1 Wake loss model

Jensen model is used to calculate the wake effect of wind farms on open sea. It ignores the effect of turbulence, which approximates that the wake region changes linearly and expands linearly along the axial direction (Zhang et al., 2018). Jensen model for the wake loss calculation is illustrated in Figure 1. The wind speed probability distribution model of a wind farm is expressed by Weibull distribution, it can reflect the basic situation of wind speed distribution more realistically (Gong et al., 2011).

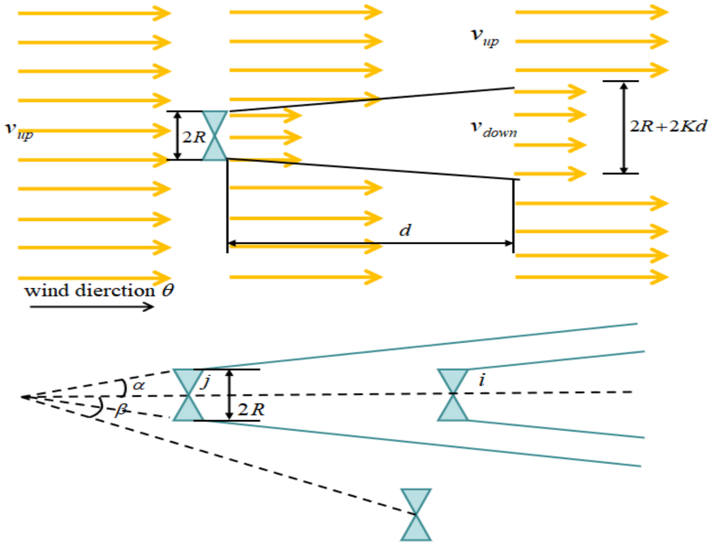

Figure 1: Wake model of wind turbines

Figure 1 shows an example of the wake effect after parallel wind passes a single wind turbine. For Weibull distribution, the wake effect only affects the scale parameter $c_i(\theta,x_i,y_i)$, which can be described by Eq(1) (Lackner and Elkinton, 2007), where θ is wind direction, i and j are index of wind turbines, v_{up} is upstream wind speed and v_{down} is downstream wind speed. The turbine is placed in a direction perpendicular to the wind direction θ.

$$c_i(\theta,x_i,y_i)=c(\theta)\times(1-Vel\_def_i)(\forall i=1,2,3...N_{WT}) \tag{1}$$

Wake loss is a major factor in optimizing the position of WTs. It is the percentage reduction in wind speed due to wake effects after passing a wind turbine. Vel_def is the total wind speed deficit at wind turbine i, it can be calculated through Eq(2). N_{WT} is the number of wind turbines. After the wind passes a WT, the wind speed changes linearly and decrease from v_{up} to v_{down} due to wake effect.

$$Vel\_def_{ij} = 1 - v_{down} / v_{up} = \frac{1-(1-c_T)^{1/2}}{(1+Kd_{ij}/R)^2} \tag{2}$$

$$d_{ij} = \left|(x_i - x_j)\cos\theta + (y_i - y_j)\sin\theta\right| \tag{3}$$

Where c_T is the thrust coefficient of the wind turbine, K is wake spreading constant and d_{ij} is the distance between the wind turbine i and wind turbine j following the wind direction θ. R is rotor radius of a WT. Eq(2) only indicates the wake effect caused by one WT, so the sum of wake effects caused by all WTs on the wind turbine i can be expressed as Eq(4).

$$Vel\_def = \Big(\sum_{j=1, j\neq i, \beta_{ij}<\alpha}^{N} Vel\_def_{ij}^{2}\Big)^{1/2} \tag{4}$$

As shown in Figure 1, for a given wind direction α, when β is greater than α, the wind turbine is not affected by the wake effect. Conversely, if β is less than α, the wind turbine is within the influence range of other wind turbines' wake effect, which can be expressed as Eq(5).

$$\beta_{ij} = \cos^{-1}\left\{\frac{(x_i - x_j)\cos\theta + (y_i - y_j)\sin\theta + \frac{R}{K}}{\left[(x_i - x_j + \frac{R}{K}\cos\theta)^2 + (y_i - y_j + \frac{R}{K}\sin\theta)^2\right]^{1/2}}\right\} \tag{5}$$

2.2 Power model

As for the power model, a linear model is used in this paper and it can be described as follow (Bansal and Farswan, 2017).

$$P_i(v) = \begin{cases} 0, v < v_{in} \quad or \quad v > v_{out} \\ \lambda v + \eta, v_{in} \le v < v_{out} \quad (\forall i = 1,2,3...N_{WT}) \\ P_{rated}, v_{rated} \le v \le v_{out} \end{cases} \tag{6}$$

Where $P_i(v)$ is the output power of a single wind turbine, P_{rated} is the rated power, v is the wind speed at the rotor height of wind turbines is fixed, v_{in} is the cut-in speed, v_{out} is the cut-out speed, and v_{rated} is the rated speed. When the wind speed is less than v_{in}, the output power of wind turbine is zero, because the wind is too small to run the turbine; on the contrary, when the wind speed is too large (greater than v_{out}), the turbine will stop working to ensure the safe operation. λ is the slope and η is the intercept.

2.3 Cost model

In the process of optimizing wind farms, the economic indicators considered include COE, Levelized Production Cost (LPC) and so on. Many researchers have made relevant predictions and estimates for the costs of offshore wind farms.

2.3.1 Objective function

There must be a proper distance between two wind turbines to keep wake effect smaller. However, increasing turbines spacing also results in increasing the cable cost (Wang, 2016) and occupied land. The blades of turbines will disturb the wind after the wind passing through the turbines, which results in increasing the air turbulence. By increasing the distance between the turbines, wake effect can be reduced. Conversely, if the arrangement of turbines is too close, the wind speed will be too late to recover to the downstream turbines after the wind passes the upstream turbines, which can affect the operation of the downstream wind turbines. Considering the actual wind farm area and line cost, proper wind turbine spacing should be established, about 3 - 5D of the column spacing and 5 - 9D of the row spacing set is suitable.
The distance between the turbines set in this article is 5D, D is the diameter of the turbine, and $(x_j - x_i)^2 + (y_j - y_i)^2 \geqq 25\ D^2$ should be ensured in this work. (x_i, y_i) and (x_j, y_j) are the positions of any two WTs. All of them must be installed within the range of the wind farm. The objective function applied in this paper is to maximize annual economic benefit (AEB), as shown below (Wu et al., 2020).

$$obj = \min(-(APB - TAC)) \quad (7)$$

AEB is the largest annual economic benefit, including the sum of the economic benefits of twelve periods; APB is the annual production benefit, which is the sum of the twelve periods' power production benefits. TAC stands for the total annual cost, which includes cost of energy (COE) and cost of cable (COC), and equations are as follows (Wu et al., 2020). Where Eq(8) is for calculating production benefits at each period and Eq(9) represents the annual production benefits.

$$PB_h = 730 \times C_{electricity} \times E(P) \quad (h = 1,2,3...12) \quad (8)$$

$$APB = \sum_{h=1}^{12} PB_h \quad (9)$$

$$COE = N_{WT}(C_{WT} \times ES + C_{om}) \times \frac{r}{1-(1+r)^{-N_{year}}} \quad (10)$$

$$COC = C_{cable} \sum_{m}^{N_{edge}} L_m \times \frac{r}{1-\left(1+r\right)^{-N_{year}}} \quad \left(\forall m = 1,2,3 \cdots N_{edge}\right) \quad (11)$$

Where $C_{electricity}$ is the electricity price, E(P) is the expected power production of all turbines, h represents the periods. C_{WT} is costs of single wind turbine, C_{om} is the cost of operation and maintenance of each wind turbine, r is the annual interest rate, N_{year} is the life span of the wind farm, which generally set to 20 y. C_{cable} is the cost of cable investment, installation and maintenance, L_m represents the length of m^{th} edge, N_{edge} is the number of edges in EMST. ES is the economic scale and is calculated as follow.

$$ES = \frac{2}{3} + \frac{1}{3} e^{-0.00174 N_{WT}^2} \quad (12)$$

2.3.2 Objective function and discretization

The wind speed distribution in a wind farm varies with the wind direction. There are different wind speed distributions for different wind directions. The wind speed distribution follows the Weibull distribution, and it can be described as follow.

$$P_{velocity}(v, k(\theta), c_i(\theta, x_i, y_i)) = \frac{k(\theta)}{c_i(\theta, x_i, y_i)} \left[\frac{v}{c_i(\theta, x_i, y_i)}\right]^{k(\theta)-1} e^{-\left[\frac{v}{c_i(\theta, x_i, y_i)}\right]^{k(\theta)}} \quad (\forall i = 1,2,3...N_{WT}) \quad (13)$$

Where $P_{velocity}(v, k(\theta), c_i(\theta, x_i, y_i))$ is the probability density function of the wind speed distribution, $k(\theta)$ is the shape parameter function, which is related to the wind direction; $c_i(\theta, x_i, y_i)$ is the scale parameters related to wind direction and turbines' position. After considering the wake effect, the power production of a single turbine can be expressed as follow.

$$E(P) = \sum_{i=1}^{N_{WT}} \int_0^{360} p_\theta(\theta) d\theta \int_0^{\infty} P_i(v) p_{velocity}(v, k(\theta), c_i(\theta, x_i, y_i)) dv \quad (\forall i = 1,2,3...N_{WT}) \quad (14)$$

As shown in Eq(14), where $p_\theta(\theta)$ is the probability density function of the wind direction distribution. In this work, the power production E(P) is discretized to simplify the calculation process.

3. Case study

The scale of offshore wind farm given in this paper is 4.1 km × 4.1 km, which is divided into 10 × 10 grids. 28 turbines are set with the diameter of 82 m and the height of the hub is 70 m. The objective function is the largest AEB, which can be expressed as obj = min(-AEB). Selected wind speed distribution is divided into 12 periods by month, and the economic benefits of each period are optimized to ensure final result. AEB is determined based on optimized data of each period. The power curve of a WT is displayed in Figure 2. The economic benefits of the wind farm under the condition that the period is not divided are calculated. Wind direction frequency is calculated on the basis of the year-round data and compared the AEB with the divided period. In this paper, GA and Geosteiner algorithm are used to solve the wind farm layout problem in a certain area.

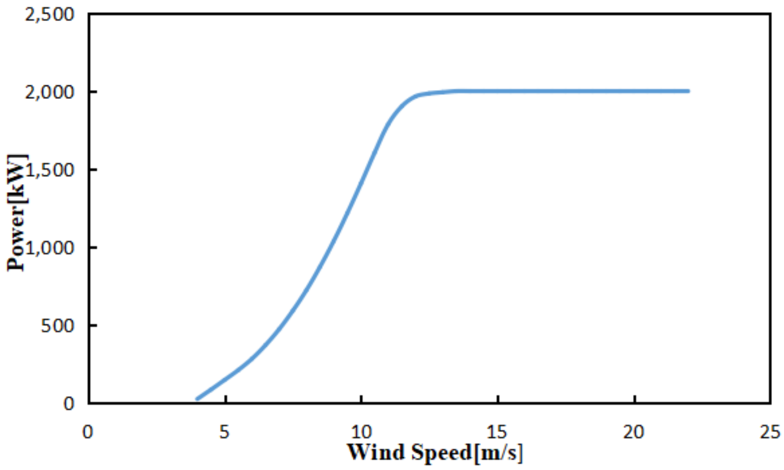

Figure 2: The power curve of a wind turbine

4. Result analysis

The arrangement of wind turbines and the corresponding economic benefits are obtained in each period by optimization and calculation as shown in Table 1, and the AEB can also be determined. It can be seen that the economic benefit in Dec was the largest at 1.4705 × 10^8 ¥/y, and the economic benefit was the smallest in Jul at 1.3295 × 10^8 ¥/y. Under different wind direction frequency distributions, it is more accurate to calculate the economic benefits of the wind turbines arrangement according to the periodic distribution. In the case of periods, AEB is the sum of twelve months of economic benefits with 1.7986 × 10^9 ¥/y; As for single period, AEB obtained by optimization is 1.7923 × 10^9 ¥/y, which can be seen that AEB is increased by 6.3289 × 10^6 ¥/y by using multiple period optimization.

Table 1: Economic benefits of 12 periods

Periods	Jan	Feb	Mar	Apr	May	Jun
EB/¥	1.4542×10^8	1.3989×10^8	1.4490×10^8	1.4120×10^8	1.3463×10^8	1.3794×10^8
Periods	Jul	Aug	Sept	Oct	Nov	Dec
EB/¥	1.3295×10^8	1.4265×10^8	1.3470×10^8	1.3895×10^8	1.4703×10^8	1.4705×10^8

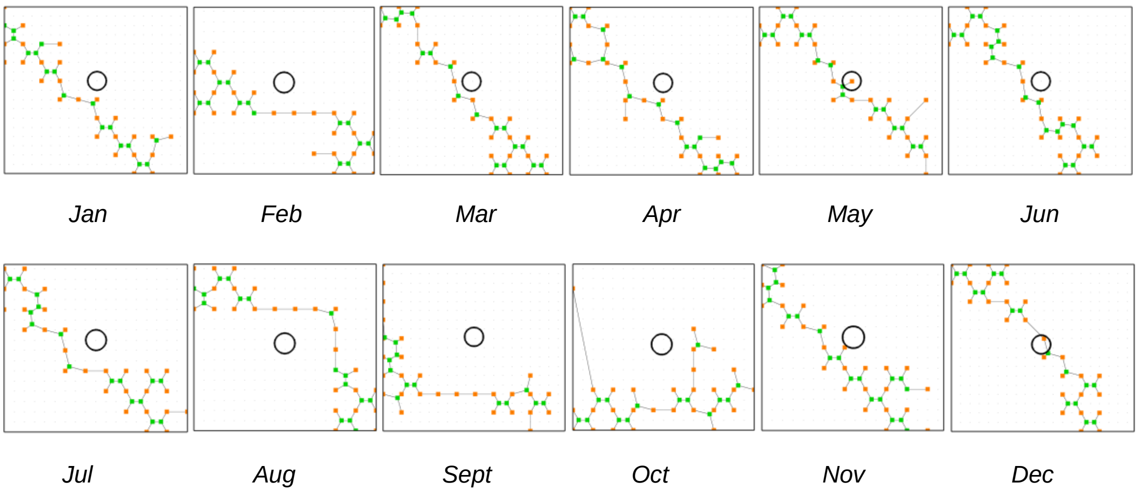

Figure 3: The optimal WTs layout for each periods

The layout of the wind turbines in each period is given in Figure 3, orange dots represent the arrangement of the WTs and green dots represent the Steiner point, the black circles represent the location of the offshore platform. The wind turbines in each period are arranged correspondingly according to the wind frequency and the main wind direction of the period. The layout of WTs in different periods can well transform and utilize wind resources based on wind data. Due to the change of wind direction frequency in each period, there will be some changes in the overall layout of wind turbines. The main wind direction showed similarity for most periods, so the layout tends of WTs do not change so much. And the layout of wind turbines is diagonally distributed.

5. Conclusions

This paper used Genetic Algorithm to optimize the layout of a certain area wind farm by dividing 12 periods. The results showed that the objective function AEB can reach 1.7986×10^9 ¥/y for a given area when the offshore turbines are arranged in a periodic manner, which is increased by 6.3289×10^6 ¥/y compared with AEB of not dividing period; the economic benefits obtained higher and more in line with reality, which have a great reference value after dividing the period. The wind direction and the location of the best wind resource on open sea change over time, so the layout of the wind turbines is accordingly adjusted to get the best AEB. The longest cable length in the optimization results is selected as the cable length in design of the wind farm, which can solve the problem of insufficient cable length when adjusting the layout of the WT in wind farms.

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