Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Optimization of offshore wind turbines layout considering wake effect

To cite this article: Li-Xia Li and Wen-Bo Liu 2022 *J. Phys.: Conf. Ser.* **2310** 012001

Optimization of offshore wind turbines layout considering wake effect

Li-xia Li[1a], Wen-bo Liu[2a*]

[1]College of Automation, Shenyang Institute of Engineering, Shenyang 110136, China

[2]School of Electric Power, Shenyang Institute of Engineering, Shenyang 110136, China

[2a*]1025712243@qq.com

Abstract: In the actual construction of an offshore wind farm, the layout of wind turbines directly affects the flow characteristics of each wind turbine. When the wind passes through the upstream unit, the work done at the hub of the downstream fan decreases, resulting in the wake effect. Therefore, on the premise of considering the wake flow, it is of great significance to study the optimization of fan arrangement. The research and selection of reasonable wind turbine arrangements have a significant effect on power generation efficiency and power output. In this paper, the improved Gauss model is used to simulate the wake flow, and the cost model that is more close to the actual construction is selected. By taking the number and distance of wind turbines as variables and the cost generated as the objective function, the research is carried out. The research is carried out in the process of automatic optimization through a particle swarm optimization algorithm.

1. Introduction

With the rapid development of wind power in China in recent years, wind power as the main direction of early development, onshore wind power generation technology has been relatively mature, and offshore wind power generation as a new important branch has great potential. Compared with the onshore wind power generation, the offshore wind power generation has the advantages that the onshore wind power generation does not have, that is, the territorial area of China's sea is wide, and the wind resources on the sea are rich. Moreover, offshore wind farms are relatively close to the power load centers of coastal cities, thus reducing the loss of traditional long-distance power transmission and reducing the cost of power grid access. The presence of sea breezes is more stable than that of land, with less wind resistance. However, up to now, wake effect is still one of the main factors affecting wind power efficiency in wind farms, and it is also a difficult problem that has not been completely solved in the domestic wind power industry. Based on the establishment criteria of wind farm, the output of wind turbine can be increased as much as possible in a limited building area, so the wake effect is often a crucial and decisive factor to determine the fan layout.

2. Jensen wake model

Jensen's diagram is shown in Figure 1, where V_T is the wind speed when the front wind turbine passes through the rotor, V_0 is the wind speed of natural incoming flow, V is the wind speed after the rear wind turbine is affected by the wake of the front and rear fans, X is the distance between the front and rear fans, R is the radius length of the impeller of the fan, and R_W is the radius of the influence range of the wake:

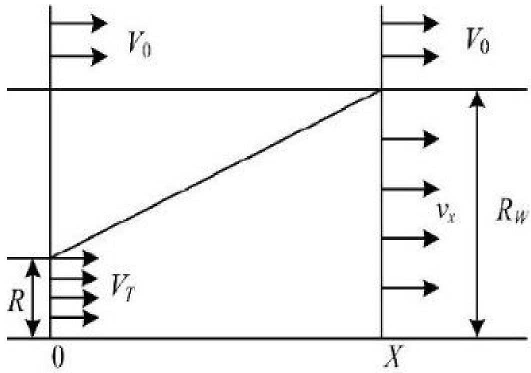

Fig. 1 Schematic diagram of Jensen wake model

3. Gaussian of Jensen wake model

Through the derivation of Jensen's model, it can be seen that the velocity distribution in the wake region is a function of the flow direction distance X, and then the velocity distribution in the cross-section is average, so the center value of the average wind speed is taken as a one-dimensional model. A large number of experiments and numerical simulation results show that the wake velocity on the drafting section assumption and the actual wind farms wake flow field, thus an improved Gaussian wake model is put forward to improve the situation, through the analysis found that the drafting speed at wake cross section appears as Gaussian distribution, the model is more close to the actual flow field, the model is shown in Figure 2.

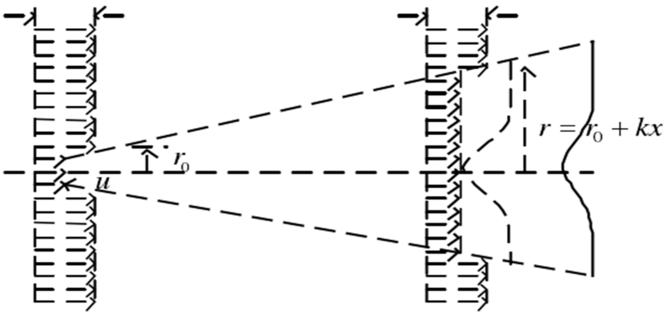

Fig. 2. Gaussian model

Firstly, the following hypotheses are made for the wake field data: (1) the velocity in the wake region is nonlinear; (2) The initial radius of the wake area is the initial radius of the fan; (3) The wake flow at downstream position X of the fan presents a Gaussian distribution.

The Gaussian model of wake flow is shown in Figure 2. It is assumed that the selected target is not affected by viscous shear force in the target flow field, and the results show that it is steady. In the figure, v0 and V respectively represent the wind speed of the incoming flow at an infinite distance and the wake velocity at the position x away from the downstream. r_0 and r represent the wind wheel radius and the initial wake radius at x downstream of the fan, respectively.

Secondly, a three-dimensional coordinate system is established, the x direction represents the direction of wind inflow, the y direction represents the horizontal direction at the cross section of the wake, the z direction represents the vertical direction of the wake cross section, and ΔV represents the velocity loss rate at the cross-section of the wake. And the ratio $\dot{m}(x)$ of the loss value of mass flow to the total air mass flow can be expressed as:

$$m(x)=\int_{-\infty}^{+\infty}\frac{\Delta V}{V_0}(x)dA \tag{1}$$

According to the analysis, the velocity deficit of the cross-section of wake presents a Gaussian distribution, which can be obtained as follows:

$$\frac{\Delta V}{V_0}=C(x)\left\{\frac{1}{\sqrt{2\pi\sigma}}e^{-\frac{(y-\mu)^2}{2\sigma^2}}\right\}\left\{\frac{1}{\sqrt{2\pi\sigma}}e^{-\frac{(z-\mu)^2}{2\sigma^2}}\right\} \tag{2}$$

If $m(x)$ is a linear extension model:

$$m(x)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\Delta V}{V_0}(x)dydz=\pi r^2\frac{\Delta V}{V_0}(x) \tag{3}$$

If $m(x)$ is a model based on Gaussian model distribution:

$$m(x)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\Delta V}{V_0}(x)dydz=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}C(x)\left\{\frac{1}{\sqrt{2\pi\sigma}}e^{-\frac{(y-\mu)^2}{2\sigma^2}}\right\}\left\{\frac{1}{\sqrt{2\pi\sigma}}e^{-\frac{(z-\mu)^2}{2\sigma^2}}\right\}dydz=C(x) \tag{4}$$

According to formula (3) and (4), it can be known that the mass loss in the Gaussian model is equal to the brightness loss in the linear expansion model, and the following equation can be obtained:

$$C(x)=\pi r^2\frac{\Delta V}{V_0}(x) \tag{5}$$

Substituting (1) into (2) can be obtained:

$$\frac{\Delta V}{V_0}=\frac{1}{4}\left(\frac{r}{\pi}\right)^2\left(1-2a\left(\frac{r_0}{r_0+kx}\right)^2\right)e^{-\frac{(y-\mu)^2}{2\sigma^2}}\bullet e^{-\frac{(z-\mu)^2}{2\sigma^2}} \tag{6}$$

According to the formula, it is concluded that if the expected value is displayed symmetrically in the image $\mu=0$,Using the effective distribution range of the $(-2\sigma,2\sigma)$ Gaussian two-dimensional model. Then the actual effective area of Gaussian distribution is 95.446%, so it is concluded that $2\sigma=r$.

$$V=V_0\bullet\left\{1-\frac{1}{4}\left(\frac{r}{\sigma}\right)^2\left(1-2a\left(\frac{r_0}{r_0+kx}\right)^2\right)e^{-\frac{y^2+z^2}{2\sigma^2}}\right\} \tag{7}$$

Without considering the influence of wind shear, the wake velocity within the same radius in the cross-section of the wake should be the same numerically, so it can be converted into a two-dimensional wake model:

$$V=V_0\bullet\left\{1-\frac{1}{4}\left(\frac{r}{\sigma}\right)^2\left(1-2a\left(\frac{r_0}{r_0+kx}\right)^2\right)e^{-\frac{y^2}{2\sigma^2}}\right\} \tag{8}$$

4. Wind farm fan layout and optimization of Gaussian wake model

4.1 Mathematical model of wind farm layout

4.1.1 Calculation of generating Capacity Model

The calculation procedure of the total power generation P_{total} in the wind farm can be carried out as follows:

Make clear the optimization scheme of wind turbines and arrange them in order according to different incoming flow directions. Through the relevant wind turbine power curve given by the merchant, the power of each fan at different wind speeds can be obtained by interpolation method:

(1) Calculate the total generating capacity P_{dir} of all wind turbines under different wind directions

$$P_{dir} = \int_{U_{in}}^{U_{out}} f(u) \left[\sum_{i=1}^{Nt} P(U_i) \right] du \tag{9}$$

Type: $f(u)$ is the distribution function of wind speed probability density, U_{in} is the input wind speed, and U_{out} is the output wind speed.

(2) Calculate the total energy yield under each wind direction according to the above formula and get the total energy yield P_{total}

$$P_{total} = \sum_{j=1}^{j=n} \left[P_{dir} \cdot f_{dir}(j) \right] \tag{10}$$

Type: $f_{dir}(j)$ is the frequency of different wind directions, and n indicates that n is divided into 360° sectors.

4.1.2 Investment cost calculation model

It is clear from Figure 3 that when a sufficient number of wind turbines are installed, the cost of a single wind turbine is almost reduced to one third of the initial cost. It can be seen from Figure3 that when the number of wind turbines increases, the cost recovery increases linearly. When the unit number is less than 20, the generation cost increases rapidly; when the unit number reaches 40, the cost increases slowly; when the unit number is greater than 40, the generation cost increases linearly, as shown in Figure 4.

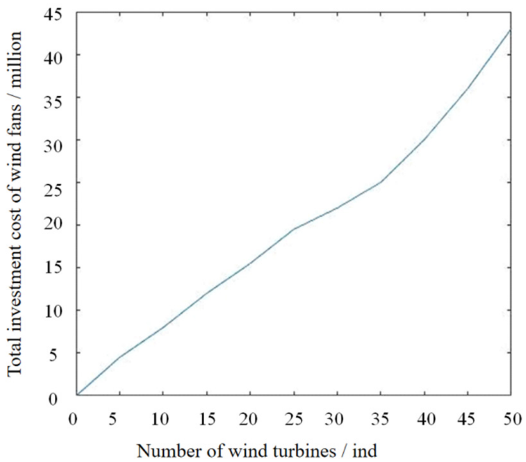

Fig .3. Cost model

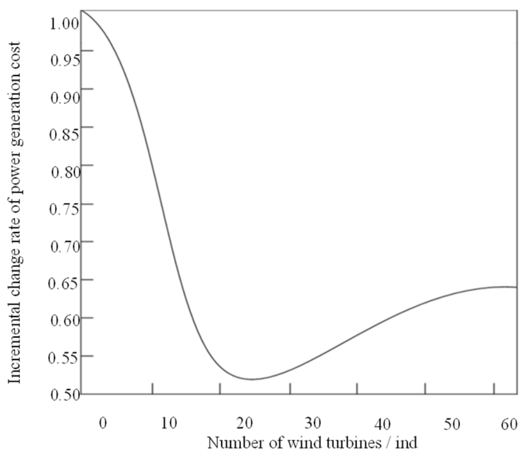

Fig. 4 Change rate of power generation cost per unit

The costs incurred in the process of investment and construction include the late operation and maintenance cost of the fan and the fixed cost of installing the fan. Fixed costs include the unit design, production, transportation and installation costs of a product. The cost of late maintenance mainly refers to the labor cost, management fee and other expenses put into use during the period after the wind farm is completed. Adopt the most commonly used cost model developed by Mosetti. As follows:

$$Cost = N\left(\frac{2}{3}+\frac{1}{3}e^{-0.0017N^2}\right) \quad (11)$$

In the expression: $Cost$ -- is the total cost of the wind farm;

N -- is the number of wind farm stroke generator units;

4.2 Single objective optimization

The results of case optimization show that a basic objective function and independent variables should be set first. To enable it to represent the ratio of wind farm investment cost to power generation, there are two independent variables: installed number of wind farm N , position of wind turbine in wind farm (x_i, y_i), where the objective function is expressed as follows:

$$f_{obj} = \frac{Cost}{P_{total}} \quad (12)$$

4.3 Optimization Scheme

The particle swarm optimization algorithm is put into the optimal layout of wind farm units. The optimization scheme is as follows: take a square wind farm $2000m\times2000m$, divide it into 10×10 square squares, place a fan in the center of the grid, and use "0/1" to indicate whether the fan exists.

The optimization steps are as follows:

(1) initialize the velocity and position of the particle swarm, and each particle contains the information of the wind farm fan cluster and the number of fans.

(2) Get the adaptive values of particle position and velocity.

(3) Through the comparison in the early stage, it is concluded that if the current value is high, the current value should be updated to the best position for replacement.

(4) The current adaptive value of the particle is compared with the global value to obtain the best position.

(5) The velocity and position of each particle are updated through continuous iteration.

(6) If it is the optimal solution, the current operation is ended and the conclusion is drawn; If not, continue iterating.

4.4 Optimization Results

Table 1 Environmental parameters in wind field

Parameter	On behalf of the symbol	Numerical
The wind field size	-	$2000m\times2000m$
Mesh generation	-	$10*10$
Rotor diameter	m	$40m$
Wheel hub height	m	$60m$
thrust coefficient	Ct	0.88
Surface roughness	Z_0	$0.3m$
Power calculation	P	$P=0.3U^2$

Table 2 Wind farm data

Wake model	Number of wind Turbines / ind	Total generating capacity / *kw*	Cost per kilowatt hour / kw^{-1}	The efficiency of wind power / %
Jensen model	31	13570	1.4723×10^{-3}	91.75
Gaussian model	28	12318	1.5984×10^{-3}	85.6

An even flow from four directions; The wind speed is $12m/s$. Gauss model and Jensen wake model were compared, and the wind field data were shown in Table 4.2, as shown in Fig. 5 and Fig. 6 for fan layout:

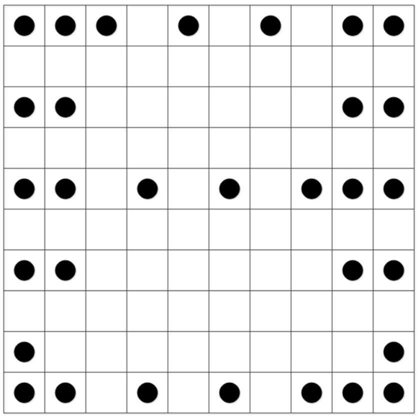

Fig. 5 Jensen model

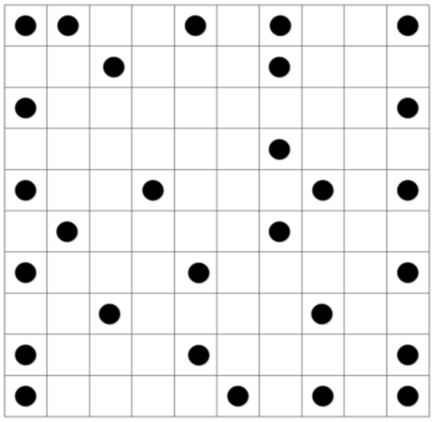

Fig. 6 Gaussian model

5. Conclusion

According to the case analysis, when the offshore wind farm is in the condition of four-way wind, the efficiency of the wind turbine arranged by the improved Gaussian wake model is about 5% higher than that of the Jensen wake model, and the cost of the wind farm arranged by the improved Gaussian wake model is slightly lower than that of the Jensen wake model, about 3.2%. The data show that the Gaussian wake model studied in this paper has a high research value for the construction of offshore wind power plants, and has the feasibility, rationality and correctness of actual application. It can be seen from the scheme that in the optimization process, the number of fans arranged in the center of the wind farm is small, which conforms to the actual construction characteristics and fully conforms to the law of wind turbine discharge layout.

Reference

[1] Fan Xiaochao, Chen Jing, Shi Ruijing, Wang Weiqing. Optimal Control of Wind farm considering wake effect and Load Loss. Hydroelectric Power, 201,47(10):89-94+99.

[2] Liu Yiyuan, Xin Yanli, Tang Wenhu, Salvy Bourguet. Evaluation of Wake Effect and Yaw Optimization of Offshore Wind Farm Based on Gaussian Model. Guangdong Electric Power, 201,34(05):1-10.

[3] Sprite. Wind turbines machine optimization research. Xi 'an university of science and technology, 2020. DOI: 10.27398 /, dc nki. Gxalu. 2020.000627.

[4] xiao-long liu. Offshore wind farm wake effect and micro location optimization. North China electric power university (Beijing), 2019. DOI: 10.27140 /, dc nki. Ghbbu. 2019.001416.

[5] Bingtuan Gao, Zhengyang Hu, Lei Zhang, Zhichao Yang. Considering the wake effect of wind farm lightening output optimization control. Journal of renewable energy, 2018, 4 (01): 117-125. The DOI: 10.13941 / j.carol carroll nki. 21-1469 / tk. 2018.01.018.

[6] Zhang Zhongwei. Research on wind Turbine Layout optimization based on wake effect in wind farm. Xinjiang University, 2017.

[7] Yang Zhichao, Gao Bingtuan, Ye Fei, Bo Xin. Optimal control of maximum output of wind farm based on wake effect. Electric power construction, 2017,38(04):96-102.
[8] Masoudi Seiied Mohsen, Baneshi Mehdi. Layout optimization of a wind farm considering grids of various resolutions, wake effect, and realistic wind speed and wind direction data: A techno-economic assessment. Energy,2022,244(PB).