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Optimized Placement of Wind Turbines in Large Scale Offshore Wind Farm using Particle Swarm Optimization Algorithm

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Abstract— With the increasing size of wind farm, the impact of the wake effect on wind farm energy yields become more and more evident. The arrangement of the wind turbines' (WT) locations will influence the capital investment and contribute to the wake losses which incur the reduction of energy production. As a consequence, the optimized placement of the wind turbines may be done by considering the wake effect as well as the components cost within the wind farm. In this paper, a mathematical model which includes the variation of both wind direction and wake deficit is proposed. The problem is formulated by using Levelized Production Cost (LPC) as the objective function. The optimization procedure is performed by Particle Swarm Optimization (PSO) algorithm with the purpose of maximizing the energy yields while minimizing the total investment. The simulation results indicate that the proposed method is effective to find the optimized layout, which minimizes the LPC. The optimization procedure is applicable for optimized placement of wind turbines within wind farms and extendible for different wind conditions and capacity of wind farms.

***Index Terms*— Wake effect, energy yields, optimized placement, wake model, Levelized Production Cost (LPC), Particle Swarm Optimization (PSO).**

Nomenclature

V_0 [m/s]	the input wind speed at the first line WT
V_x [m/s]	the wind speed in the wake at a distance x downstream of the upstream WT
R_0 [m]	the radius of the WT's rotor
R_x [m]	the generated wake radius at x distance along the wind direction
$S_{overlap}$ [m^2]	the affect wake region
V_{ij} [m/s]	the wake velocity generated by the WT at ith row, jth column of wind farm
V_{nm} [m/s]	the wind velocity at the WT at row n, column m
N_{row}	the number of WTs in a row
N_{col}	the number of WTs in a column
x_{nm}, y_{nm} [m]	the position of the downstream WT at row n, column m in coordinate system
x_{ij}, y_{ij} [m]	the position of the upstream WT at row i, column j in coordinate system
C	the center of the upstream WT
O_{nm}	the center of the downstream WT at row n, column m
O_{ij}	the center of the wake that developed from the upstream WT at row i, column j
α [°]	the wind deviation angle which is the angle between line C-Oij and x axis
β [°]	the angle between line C-O_{nm} and x axis
β' [°]	the angle between C-O_{nm} and x axis in second case
R_{ij} [m]	the radius of the wake that generated from the upstream WT rotor at row i, column j
S_{ij} [m^2]	the fan shaped area of the wake area generated by upstream WT at row i, column j
S_{nm} [m^2]	the fan shaped area of the sweeping area that generated by the downstream WT rotor at row n, column m
μ [°]	the chord angle corresponding to S_{nm}
γ [°]	the chord angle corresponding to S_{ij}
L_{ij} [m]	the distance between upstream WT at row i, column j and downstream WT at row n, column m
$S_{overlap,ij}$ [m^2]	the overlapped area in Fig.1
$S_{q,ij}$ [m^2]	one temporary variable that is needed in the deviation process.
h_{ji} [m]	the length of diagonal line in green quadrangle
d_{ji} [m]	the distance from O_{ij} to O_{nm}
S_r [m^2]	the sweeping area generated by the rotor downstream WT
β'' [°]	the pitch angle
λ_{opt}	the optimal tip speed ratio for the pitch angle β', at which the power coefficient will be maximum
ρ [kg/m^3]	the air density,
$C_{p,opt}$	the power coefficient at λ_{opt}
$P_{m,ij}$ [MW]	the mechanical power generated by WT at row i, column j
v [m/s]	the injected wind speed
R [m]	the rotor radius
$P_{tol,t}$ [MW]	the total power production during interval t
$P_{tol,loss,t}$ [MW]	the total power losses during interval t

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T_E [day]	duration interval for energy yields calculation
T_t [h]	the duration when the wind farm generating power of $P_{tol,t}$
E_{tol} [MWh]	the energy yields of the wind farm
t [hour]	the energy yields calculation time
$P_{loss,i}$ [MW]	the power losses of cable i
I_i [kA]	the current in cable i
$R_{e,i}$ [ohm/m]	the resistance of cable i
$\rho_{R,i}$ [ohm*m/mm²]	the resistivity of selected cable i
$l_{R,ij}$ [m]	the length of cable i
$S_{R,i}$ [m²]	the sectional area of cable i
d_x [m]	the interval of WTs in x direction or rather the distance between WTs in a row
d_y [m]	the interval of WTs in y direction or rather the distance between each row of WTs
C_i [MDKK/km]	the unit cost of cable i
$S_{n,i}$ [W]	the rated apparent power of cable in line i
N	total number of cables in a wind farm
A_p, B_p, C_p	the coefficient of cable cost model
$I_{i,rated}$ [A]	the rated current of cable in line i
$U_{i,rated}$ [V]	the rated voltage of cable in line i
L_i [km]	the length of cable i
w	the inertia weight
w_{inital}	the initial inertia weight at the start of a given run
w_{final}	the final inertia weight at the end of a given run
n	the nonlinear modulation index
l_1, l_2	learning factors
$rand_1$, $rand_2$	the stochastic numbers which can generate some random numbers within [0, 1]
x_i^k, x_i^{k+1} [m]	the position of particle i at iteration k and k+1 respectively
v_i^k, v_i^{k+1} [m]	the speed of particle i at iteration k and k+1 respectively
$local_i^k$ [m]	the best position of particle i at iteration k
$global^k$ [m]	the best position of all particles at iteration k

I. INTRODUCTION

According to the wind report 2013 of Global Wind Energy Council (GWEC), wind energy has become the second largest renewable energy source and will take up to 25% of total renewable energy by 2035 [1]. Compared with onshore wind farm, offshore wind farm always has higher energy production efficiency and is not limited by land occupation problem; however, the investment is relatively larger. In order to maximize the energy production while getting the minimum investment, more and more researchers are concentrating on solving the Wind Farm Layout Optimization (WFLO) Problem with evolutional algorithms. Since the scale of wind farms in early stage are relatively small, the initial attempts focus on maximizing energy yields or minimizing total losses within the wind farm using evolutional algorithms without taking the wake effect into consideration. In [2], a multi-objective PSO algorithm is used to minimize the layout costs and maximize the energy output without considering the wake effect and the discounted costs of wind farm during life-cycle. The optimization for offshore wind farm electrical system is done in [3], in which the configuration with minimal LPC under required reliability is found via Genetic Algorithm (GA) while similar work is also presented by considering the cost and losses of each main component within wind farm [4].

The wake deficit can be explained as the impact of upstream WT to the downstream ones which incur the reduction of the total energy yields of the wind farm due to the wind speed drop downstream [5]. With the development of wind energy technology, both the capacity of the WT and wind farm increases a lot. Since the size of WT is larger, the wake effect's impact on energy yields becomes evident [6]. Three wake models commonly are the Jensen model, Ainslie model and G.C. Larsen model [7]. In Jensen model, the wakes behind the WTs are assumed to expand linearly and the wind speed within the wake of different heights is regarded to be the same. Ainslie developed a parabolic eddy viscosity model in which the wake turbulent mixing and ambient turbulence on wake are included. Since the results are obtained by solving the differential equations, it needs more time to get the solution and is more suitable for dynamic analysis of WT. The semi-analytic wake model is constructed by Larsen. As reported in [8], the model is recommended for solving wake loading problem. Besides, some works of developing new model to help forecasting the energy yields of wind farm has been done in Risø National Laboratory [9][10]. In [9] an analytical model which divided the wake into 3 regimes and the phenomena of multiple wakes merging, wake expanding and wake hitting ground, etc. are all specified. The developed wake models provide researchers with the basic tool to continue the optimization work within the wind farm considering wake effect. All the models can be used for energy yields calculation, however, most of the wind farm layout design work are using Jensen model [11]-[15]. The main reason is that calculation of energy yields using Jensen model requires the least computation time in comparison with the other models. Moreover, Jensen model shows better performance on the accuracy of energy yields calculation which is demonstrated through a case study in [7] and in [14]. Taking into account the reasons mentioned above, Jensen model is selected in this paper.

As it is known, the wake would recover and expand before encountering the other WTs. The wind direction is of particular importance for deciding the distance for wake to recover, in other words, the placement of WTs should consider the wake effect along with the varying wind speed's influence [16]. In order to reduce the wake losses and make the wind farm more cost-efficient, some works have been done on the planning of wind farm by comparing the energy yields from different layouts by using some commercial software as LENA-tool [16] or MaWind [18]. In [19], Patel proposed that the beneficial distance between WTs in prevailing wind direction is 8 rotor diameter (RD) to 12RD while in the direction perpendicular to prevailing wind direction the distance should be 3RD to 5RD. The placements of WTs are based on this empirical conclusion. In [20], the impact of wind directions on the energy production is studied. The energy yields are calculated by considering the wake effect with varying wind speed, however, the spacing of WT to the neighboring WTs are not in the optimization procedure. In fact, the optimal spacing for WTs is different for various wind farms and even in the same wind farm the optimal spacing for different types of WTs should be different as well. The authors are proposing more advanced method for wake rather than the simple models and we believe that if the spacing of the WTs is obtained as a result of an optimization problem, the annual power production will increase compared to the production of the wind farms whose layouts are designed based on some empirical methods.

In order to get the solution, some evolutional algorithms are also widely used. In [21][22], the layouts are found by GA and the results are also compared with those obtained in commercial software WindFarmer as well as in the work of Mosetti et al in [21] while Net Present Value (NPV) is adopted to evaluate the cost variables in the wind farm and the foundation cost model is proposed that is suitable for wind farm optimization [14]. The optimized locations of WTs and the most economical way to lay the cables within the wind farm is presented in [23], in which the wind direction is considered from northeast – southwest. The optimized layout is found at the maximum energy yields efficiency with given number of WTs and 5 times diameter of WTs' blade's spacing between the WTs in a row and the same distance between the rows. In [24], a developed algorithm, binary PSO, is presented which is more efficient to fulfil the same target compared with GA. As indicated in [25], evolutionary algorithms as GA and PSO have a good performance of finding the near optimal solution for the constrained nonlinear optimization problem. In this project, the PSO algorithm is adopted to implement the simulation since it has higher computation efficiency in solving nonlinear problems with continuous design variables compared with GA [26]. In [27]-[29], the PSO algorithm was adopted to find the near optimal WT positions.

In this paper, there are two main contributions: one is setting up a new wake model based on Jensen model which takes both varying wind velocity and direction into consideration for calculating the wind speed at each WT within the offshore wind farm. The other is to find the optimized distances between WTs in a line and distances between each WT row with minimal LPC. The power losses as well as the wake deficit are considered so that the optimized layout can be found. Since the problem is nonlinear, the heuristic algorithm (PSO) is adopted to get these optimized distances. The parameters, such as the size of particle, iteration times are carefully designed to get the near optimal result while saving the computation time. The FINO3 reference wind farm with 800 MW capacities is chosen to demonstrate the effectiveness of the new method.

The paper is organized as follows. The analytical equations for calculating the wake velocity with varying wind speed are proposed in Section II. The objective function which is based on the LPC is specified in Section III. The theory of non-linearly inertia weight PSO and the optimization framework are discussed in Section IV. The simulation results and analysis are presented in Section V and Conclusions are given in Section VI.

II. WIND FARM MODEL

Firstly, a comprehensive model is set up. Both the wake effect impact from all upstream WTs as well as the impact of the wind speed variation on wake effect itself is included in this model. Then the energy yields calculation model is described in this section.

A. Wake Model

In this paper, the Jensen model is chosen as the baseline to develop a comprehensive wake model. The analytical equations for calculating the wake velocity considering varying wind speed is derived in the following.

1) Jensen Wake Model

In Jensen model, the wind speed of the downstream WT is formulated as [30][31]:

$$V_x = V_0 - V_0\left(1-\sqrt{1-C_t}\right)\left(\frac{R_0}{R_x}\right)^2\left(\frac{S_{overlap}}{S_0}\right) \quad (1)$$

$$R_x = R_0 + kx \quad (2)$$

Where, C_t is the thrust coefficient of the WT and k is the wake decay constant. The recommended value of k is 0.04 for offshore environment [32].

2) Wake Combination

In a large wind farm, the downstream WT would be affected by several upstream WTs. In order to evaluate wake effects of corresponding turbines, Katic et al proposed a method in which the multiple wakes are calculated by using the 'sum of squares of velocity deficits'. Hence, the wind velocity at the WT at row n, column m can be derived as [16]:

$$V_{n,m} = V_0\,[1-\sqrt{\sum_{i=1}^{N\_row}\sum_{j=1}^{N\_col}[1-\left(\frac{V_{ij}}{V_0}\right)]^2}\,] \quad (3)$$

3) Wake Model with Varying Wind Direction

If the wind direction changed, the WT would change its nacelle so that the normal vector to the rotor plane is aligned with the wind direction. The variation of the wind velocity as well as the direction will both influence the wind speed deficit. This change can be described by using a modified model with coordinate system illustrated in Fig. 1. The wind direction is defined as the wind deviation angle to north clockwise.

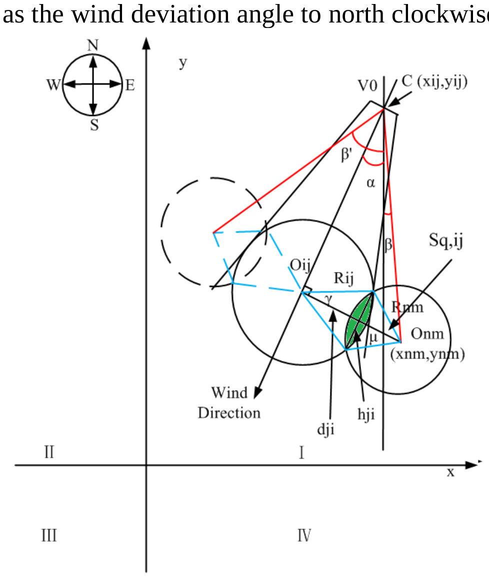


Fig. 1. The wake model with varying wind speed.

As can be seen in Fig.1, the wind can come from four quadrants. In each quadrant, two cases should be considered. The turbine is overlapped with the right half or the left half of the wake plane. The green area is $S_{overlap,ij}$ and the blue quadrangle area is $S_{q,ij}$. The solid line represents the first case and the dotted line corresponding to the second case. The derivation process for the analytical equations of condition one can be seen below.

$$L_{ij}=\sqrt{\left(x_{ij}-x_{nm}\right)^2+\left(y_{ij}-y_{nm}\right)^2} \quad (4)$$

$$d_{ji}=L_{ji}\left|sin(\alpha+\beta)\right| \quad (5)$$

$$R_{ij}=R_0+kL_{ji}\left|cos(\alpha+\beta)\right| \quad (6)$$

$$\mu=2cos^{-1}\frac{R_{nm}^2+d_{ji}^2-R_{ij}^2}{2*R_{nm}*d_{ji}} \quad (7)$$

$$\gamma=2cos^{-1}\frac{R_{ij}^2+d_{ji}^2-R_{nm}^2}{2*R_{ij}*d_{ji}} \quad (8)$$

$$h_{ji}=2R_i\left|sin(\mu/2)\right| \quad (9)$$

$$S_r=\pi R_{nm}{}^2 \quad (10)$$

$$S_{ij}=\frac{\gamma(R_{ij})^2}{2} \quad (11)$$

$$S_{nm}=\frac{\mu R_{nm}{}^2}{2} \quad (12)$$

$$S_{q,ij}=h_{ji}d_{ji} \quad (13)$$

$$S_{overlap,ij}=S_{ij}+S_{nm}-S_q \quad (14)$$

Combining (2) to (14), the wind velocity at the downstream WT at row n, column m with wind speed V_0 and wind angle α in quadrant (I) can be rewritten as:

$$V_{n,m}=V_0\left\{1-\sqrt{\sum_{i=1}^{N\_row}\sum_{j=1}^{N\_col}\left\{1-\left[\left(\frac{V_{ij}}{V_0}\right)\left(\frac{S_{overlap,ij}}{S_r}\right)\right]^2\right\}}\right\} \quad (15)$$

If the wind turbine is in the dotted line circle location, that is the second condition, then the analytical equations should be modified by substitute the $(\alpha+\beta)$ term in the equation (5) and (6) with $(\beta'-\alpha)$ while keeping all the other parts the same.

4) Wake Effect Region Judgment

There are three cases that should be considered in the wake velocity calculation, that is, full wake effect, partial wake effect and non-wake effect as illustrated in Fig. 2.

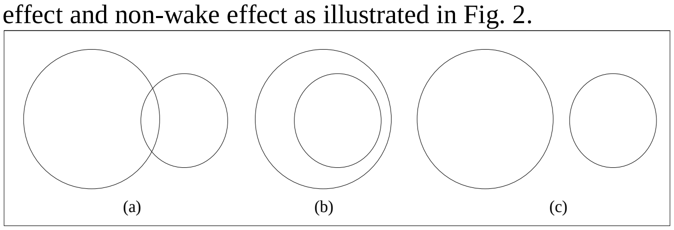


Fig. 2. (a) Partial wake effect. (b) Full wake effect. (c) Non-wake effect.

The judgment process can be summarized in Table I as follow.

TABLE I
WAKE EFFECT REGION JUDGMENT FOR WAKE MODEL WITH VARYING WIND DIRECTION

Case	Condition	Analytical Equations
(a)	$R_j-R_i<d_{ji}<R_j+R_i$	(4) - (15)
(b)	$0\le d_{ji}\le R_j-R_i$	(1) (2) (3)
(c)	$d_{ji}\ge R_j+R_i$	$V_j=V_0$

B. Energy Model

The energy yields calculation concerns three elements: the power production, the power losses and the duration. The analytical equations for calculating energy production are derived step by step in the following.

1) Power Production

The power produced by WT at row i, column j can be calculated using the following equation [33][34]:

$$P_{m,ij}=0.5\rho C_{p,opt}(\beta'',\lambda_{opt})\pi R^2 v^3/10^6 \quad (16)$$

In the simulation, the power production of each WT is found by assuming a maximum power point tracking (MPPT) control strategy, so (16) is valid when the wind speed is between cut-in wind speed and rated wind speed [35]. The relationship between wind speed and power output, C_p and C_t is listed as a lookup table in [36]. So, the total power production that generated by the WTs can be written as:

$$P_{tol}=\sum_{j=1}^{N\_col}\sum_{i=1}^{N\_row}P_{m,ij} \quad (17)$$

2) Power Losses and Energy Yields

The power losses of AC cable can be expressed as:

$$P_{loss,i}=3I_i^2R_{e,i} \quad (18)$$

Where,

$$R_{e,i}=\rho_{R,i}\frac{l_{R,i}}{S_{R,i}} \quad (19)$$

The length of the cable is related to the distance between WTs. As can be seen in Fig. 3, the cable connection layout is illustrated with blue lines. Hence, if the WTs are placed in a large interval the energy yields will be increased, however, longer cables are required. Then, the total losses within the wind farm should be written as:

$$P_{tol,loss}=\sum_{i=1}^{N}P_{loss,i} \quad (20)$$

Considering (16) to (20), the energy yields of the wind farm can be formulated as:

$$E_{tol,av}=\sum_{t=1}^{T_E}\left(P_{tol,t}-P_{tol,loss,t}\right)T_t \quad (21)$$

III. PROBLEM FORMULATION

The investment for an offshore wind farm is large in which the electrical system takes a high proportion. It is beneficial to maximize the energy production while invest as little as possible. The mathematical model is built to evaluate how to optimize the layout of the wind farm and the assumptions are described at the end of this section.

A. Levelized Production Cost

In this simulation, the objective function is constructed using LPC index which takes capital investment, operating and maintenance discounted costs during the life-cycle into account. The mathematical equations for LPC regarding offshore wind farm are formulated in [37]. In this project, the capital cost is calculated by the total cable cost using the model proposed in [38].

$$C_i = A_p + B_p exp\left(\frac{C_p S_{n,i}}{10^8}\right)^2 \quad (22)$$

$$S_{n,i} = \sqrt{3} I_{i,rated} U_{i,rated} \quad (23)$$

$$CAP_t = \sum_i^N C_i L_i Q_i \quad (24)$$

$$C_0 = \sum_{t=1}^{Ny} CAP_t (1+r)^{-t} \quad (25)$$

$$LPC = \left[\frac{C_0 r (1+r)^{Ny}}{(1+r)^{Ny} - 1} + OAM_t\right] \frac{1}{E_{tol,av}} \quad (26)$$

As it can be seen from above equations, LPC is determined by two parts: total discounted costs and the total discounted energy output. The total investment C_0 is assumed to be made in the first year and paid off during the lifetime of the wind farm. The generated energy $E_{tol,av}$ is the average energy yield per year.

B. Objective Function

The wind farm could be divided into a grid of the areas in the center of which a WT is placed. The wind farm layout is assumed to be designed as in Fig. 3.

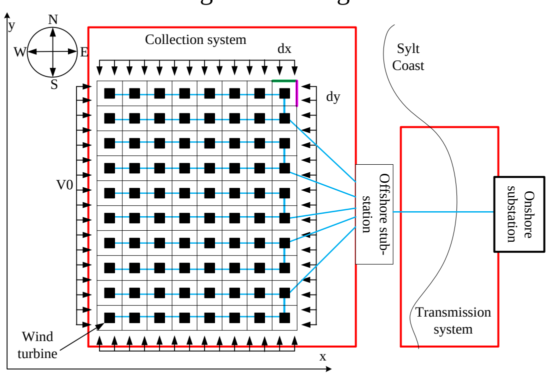


Fig. 3. The proposed wind farm layout for simulation.

In Fig. 3 each solid square represents a WT. The blue lines represent the cable connection. The problem can be expressed as:

Obj: $min\{LPC(d_x, d_y)\} = min$

$$\left\{\left[\frac{C_0(d_x, d_y) r (1+r)^{Ny}}{(1+r)^{Ny} - 1} + OAM\right] \frac{1}{E_{tol,av}(d_x, d_y)}\right\} \quad (27)$$

Constraint: $8R \le d_x \le 40R, 8R \le d_y \le 40R$ (28)

C_0 should be related to the types as well as the length of each cable, so its value it's related to d_x and d_y of the wind farm, E_{tol} will be related to the wake effect as described in Section I and wind speed deficit is highly dependent on d_x and d_y so that the changing of optimization variable d_x and d_y will induce the changing of E_{tol}.

C. Assumptions and Constraints

In this simulation, some assumptions are made as follows:

1) The reference wind farm is assumed to be a regular shaped wind farm with a rectangle or square shape.

2) All cables in the collection system are assumed to be 3-core Cross Linked Polyethylene (XLPE) AC cable, the cables' length is selected according to the geometrical distance without considering detailed practical situations, such as the barriers, restriction in sea, the length from WT foundation to sea bottom, etc. The HVDC light cable is adopted for transmitting power from offshore substation to onshore substation because of the long distance.

3) When the wind direction changes, the WT's nacelle will change its position as well, however, the yaw speed cannot follow the wind direction changing speed. That is so-called yaw misalignment [39]. In this project, the yaw misalignment impacts on the final energy yields are neglected.

4) As mentioned in section Ⅱ, there should be a tradeoff which concerns the energy output as well as the cable investment. However, the costs of the other components within the wind farm are not highly related to this distance. In this simulation, only the costs and losses of cables are considered.

5) The d_x and d_y is restricted in the range of $8R_0$ to $40R_0$ as the lifetime of the turbine will decrease a lot due to turbulence if they are closer than $8R_0$ [14].

IV. Wind Farm Layout Optimization Method

A numerical solution is needed to help the construction of the optimized layout. In this paper, PSO method is adopted as the optimization method. The theory and the optimization procedure are presented in the following.

A. Particle Swarm Optimization (PSO)

Based on the social behavior of fish schooling and bird flocking, Kennedy and Eberhart [40] proposed an evolutional algorithm which has a good performance of solving non-linear optimization problem. In PSO, each possible solution is defined as a particle. The searching space is called particle size and the particle position is updated by giving each particle with a predefined speed. Then, all the particles will tend to move to theirs best positions which are the local optimal solutions. The updating process will not be terminated until it reaches the maximum iteration or an acceptable value. The final value should be stabilized after numbers of iterations. Then, this best value that is found by PSO is called the global optimal solution. The algorithm can be expressed in following equations [41].

$$v_i^{k+1} = wv_i^k + l_1 rand_1 (local_i^k - x_i^k) + l_2 rand_2 (global^k - x_i^k) \quad (29)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (30)$$

Where w is the inertia weight and rand is a function that can generate a random number which is in the range of [0, 1]. A larger w means the algorithm has a stronger global searching ability while smaller w ensures the local searching ability. The parameter control methods for w can be concluded into two categories [42]: the time-varying control strategy [43]-[46] and adaptive parameter control strategy [47]. The first strategy indicate that the PSO performance can be improved by using linear, non-linear or fuzzy adaptive inertia weight while the other introduce evolutionary state estimation (ESE) technique

[48] to further improve the performance of PSO. In this project, the non-linear inertia weight [49] control method is adopted since the optimization variables are only the distances between each WT row and column. The time-varying control strategy could find the optima when the problem is not so complex [43]. The expression of nonlinear inertia weight is as follow:

$$w = w_{final} + (w_{initial} - w_{final})\left(\frac{I_{\max} - t}{I_{\max}}\right)^{n} \tag{31}$$

Where t is the current iteration number and I_{max} is the maximum iteration.

B. Wind Farm Layout Optimization by PSO

As proposed above, the LPC index is used to evaluate the wind farm layout. The simulation procedure to access the wind farm layout by PSO is shown in Fig. 4. The parameters of PSO are initialized in the first step. The LPC will be calculated by a random generated particle position, d_x and d_y. Then the position will be updated to find the minimum LPC. The LPC is calculated in a Fitness function. The function will be run when a new position is loaded. The above procedure would not stop the PSO main function until it is run beyond the maximum iteration time. Finally, the optimized d_x and d_y will be selected which generated the minimum LPC.

Climatological Information: The data is obtained from the work of Norwegian Meteorological Institute [49][51], in which the wind speeds are sampled per 3 hours, for the convenience of calculation, the raw data is formulated into wind rose which is used for the energy production calculation of a year.

Cable Database: In [52], various voltage levels' cables with different conducting sectional areas could be found. In this simulation, the cables in the wind farm are 500 or 630 mm2 XLPE-Cu HVAC cables operated at 66 kV nominal voltage for the collection system and 1000 mm2 Cu 300kV HVDC light cable [53] is selected for the transmission system.

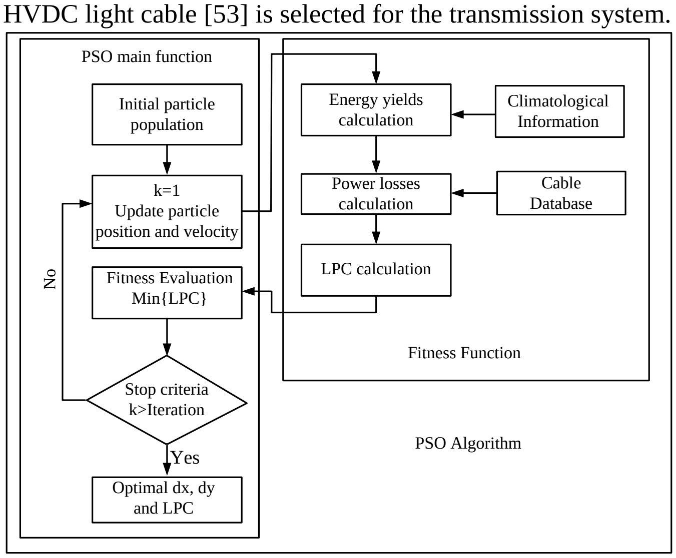


Fig. 4. The optimization procedure of finding optimized wind farm layout.

V. Case Study

In this section, a reference wind farm is firstly introduced and then four study cases are presented. The relations between parameters of PSO and the final results are also discussed to assure the accuracy of the algorithm in this section.

A. FINO3 Reference Wind Farm

The reference wind farm is located in vicinity of FINO3 - 80km west of German island of Sylt. The installed capacity of the wind farm is 800 MW [54][55].

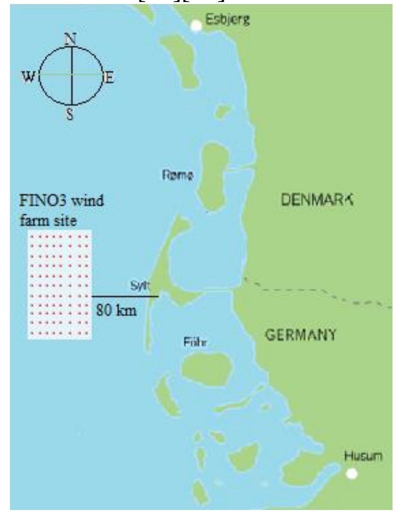


Fig. 5. FINO3 reference wind farm siting.

The site of the reference wind farm can be seen in Fig. 5. The wind farm is assumed to be with a rectangular shape with 8 rows and10 columns layout.

In this simulation, the 10 MW DTU WT is adopted as the reference WT. The specification of which is listed in Table II and the wind velocity and direction is shown as a wind rose in Fig. 6 which is the Climatological Information as described in section IV.

TABLE II
DTU 10MW Wind Turbine Specification [36]

Parameter	10 MW DTU Wind Turbine
Cut-in Wind Speed	4 m/s
Rated Wind Speed	11.4 m/s
Cut-out Wind Speed	25 m/s
Rotor Diameter	178.3 m
Rated Power	10MW

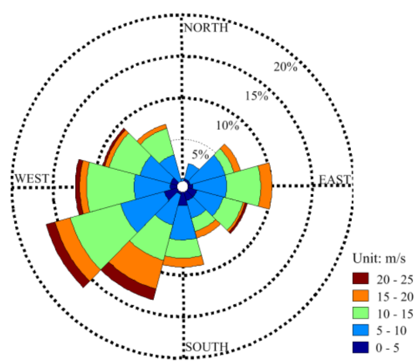


Fig. 6. Wind rose for wind climate in the vicinity of FINO3.

The power production of a wind farm can be estimated by using probabilistic models, such as Weibull distribution function for a number of wind speed ranges which is a stochastic approach. While in this paper, the wind rose is adopted to calculate the wind farm energy yields during optimization process.

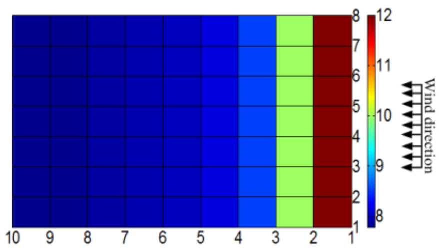
Based on the measured wind data in the vicinity of FINO3, the wind rose is generated by dividing the wind direction into 12 sections with 30 degree per section, furthermore, in each section the wind velocity is divided into 5 ranges with each interval of 5 m/s. So the used wind rose likes the Weibull distribution with a number of wind speed ranges, plus wind direction. Consequently, the uncertainties have been considered. The approach could be able to give more detailed results than Weibull distribution, since it may have a probabilistic distribution model in each direction if more data available.

B. Wake Effect Calculation

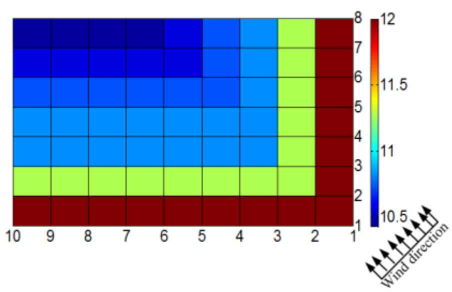
Four samples, which is the wind from northeast, north, east and southwest are selected from wind datasheet to validate the effectiveness of the new wake model. The information of the input parameters is listed in Table III.

TABLE III
SAMPLE DATASHEET

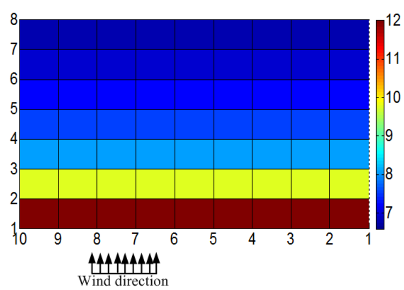
Sample	Wind direction (º)	Wind Velocity (m/s)	X (m)	Y (m)
(a)	0	12	800	1000
(b)	45			
(c)	90			
(d)	135			



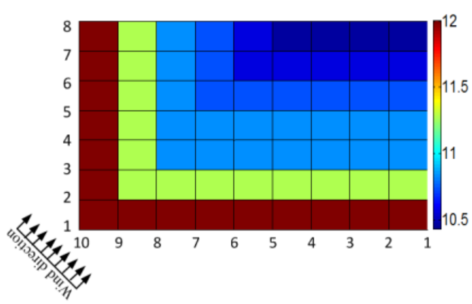
(a)



(b)



(c)



(d)

Fig. 7. Wind speed distribution of wind farm considering wake effect.

The wind speed distributions at WTs considering the wake effect are illustrated in Fig. 7. X and Y indicate the spacing of WTs between rows and columns respectively. The wind distribution is changed with the wind velocity and direction which is corresponding to the expected results, that is, the wake effect will incur the reduction of the wind velocity at the downstream WTs.

C. Case Study

1) Case 1:Optimized layout for constant dx and dy

The relations of the iteration and results (fitness value) are studied and shown in Fig. 8.

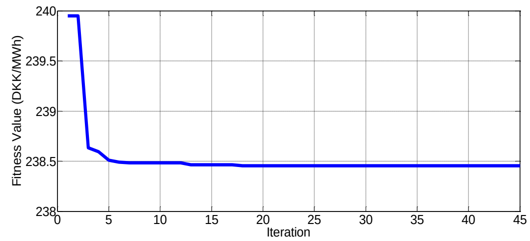


Fig. 8. The fitness value corresponding to each iteration for constant dx and dy layout.

The optimized length and width of the FINO3 reference wind farm is found by PSO. The energy yields and total cable costs for this layout is calculated and listed in Table IV.

TABLE IV
LAYOUT RESULTS FOR CONSTANT D_X AND D_Y

Duration	365 day
d_x	713.2 meter
d_y	981.82 meter
LPC	238.4549 DKK/MWh
Annual Cable Power Losses	45.28 GWh
Annual Energy Yields	3556.46 GWh
Cable Cost	837.01 MDKK
Annual Energy Yields without Considering Wake Effect	4419.36 GWh
Wake losses percentage	19.53%
Iteration	45

The wake losses percentage is 19.53% in this case which demonstrate the necessity of considering the wake effect in energy yields calculation. The best layout for this reference wind farm should be d_x equals to 713.2 meter while d_y is 981.82 meter. The results correspond to the fact that in vicinity of FINO3 the prevailing wind is from southwest which has been shown in Fig. 6 (b). The increase of d_y means to increase the width of the wind farm from north to south by which the energy yields will be increased. Moreover, the number of cables laying on that direction is less than those in x direction. As a consequence, d_x is relatively smaller than d_y.

2) Case 2: Optimized Sparse Layout

In this case, the spacing between WTs in a row and the spacing between each WT column in reference FINO3 wind farm is assumed to be different. In other words, the optimization variable will be changed as:

$$d_x=[d_{x,1}, \ldots, d_{x,i}],\ i\in[1, N\_row-1]$$
$$d_y=[d_{y,1}, \ldots, d_{y,j}],\ j\in[1, N\_col-1]$$

Where N_row is the total number of rows and N_col is the total number of columns. The relations of the iteration and results are shown in Fig. 9 and the results of optimized sparse layout are listed in Table V.

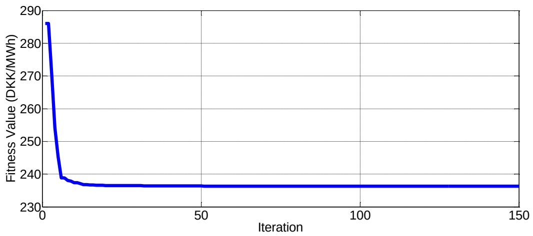


Fig. 9. The Fitness value corresponding to each iteration for optimized sparse layout.

TABLE V
LAYOUT RESULTS FOR OPTIMIZED SPARSE LAYOUT

Duration	365 day
$d_{x,i}$	713.2 meter
$d_{y,j}$	1750.66 meter 1945.90 meter 713.20 meter 1004.81 meter 713.20 meter 1700.96 meter 713.20 meter 1954.65 meter 1950.83 meter
LPC	236.3054 DKK/MWh
Annual Cable Power Losses	46.80 GWh
Annual Energy Yields	3637.96 GWh
Cable Cost	848.36 MDKK
Annual Energy Yields without Considering Wake Effect	4419.36 GWh
Wake losses percentage	17.68%
Iteration	150

For the optimized sparse layout, the wake losses decreased to 17.68%, however, the power losses and the investment on cables are both increased.

The results are also compared with a regular wind farm layout with 7 rotor diameter distance (1248.1 m) between two WTs and 7D spacing for rows which is concluded in Table VI.

TABLE VI
LAYOUT COMPARISONS OF TWO OPTIMIZED LAYOUTS

Name	Optimized layout for constant d_x and d_y	Optimized sparse layout	7D layout
Annual Cable Power Losses	45.28 GWh	46.80 GWh	51.71 GWh
Annual Energy Yields	3556.46 GWh	3637.96 GWh	3839.94 GWh
Cable Cost	837.01 MDKK	848.36 MDKK	959.41 MDKK
LPC	238.4549 DKK/MWh	236.3054 DKK/MWh	253.3376 DKK/MWh
Layout	4.99km*8.84km =44.11 km^2	4.99km*12.45km =62.13 km^2	8.73km*11.23 km=98.04 km^2

As can be seen in Table VI, the cable costs and power losses is reduced by sparse layout and further reduced by constant d_x and d_y layout. The energy yields of optimized layout for constant d_x and d_y is minimal while minimal LPC is obtained by optimized sparse layout. The 7D layout has the largest energy yields and occupies the largest sea area while optimized layout with d_x and d_y is converse. The proposed method is succeeded in finding optimized layouts which improves the LPC with 5.87% for constant d_x and d_y layout while optimized sparse layout reduce the LPC with 6.72% comparing with 7D layout, however, the optimized layout with constant d_x and d_y save 55% area occupation while optimized sparse layout only save 36.63%. The best layout in the simulation should be optimized sparse layout while in practical, the optimized layout for constant d_x and d_y maybe draw more attention since the less area occupation means less installation cost.

VI. CONCLUSIONS

The wind flow within a wind farm would be disturbed by the wake effect. This incurs the reduction of energy production. In large scale wind farms, the wake losses which depend on the spacing of the wind turbines are obvious. In this paper, the wake model for calculating the wake losses has been developed. The effectiveness of the model was well demonstrated by a study case. The results show that the proposed model can be used for wake losses calculation with varying wind direction and velocity. The optimized layouts are found using PSO algorithm. From comparison, it can be concluded that the proposed method may be used for the regular shaped wind farm layout design.

The method proposed in this paper is under the assumption that the wind farm is under MPPT control strategy all the time. If the wind farm is under power regulation mode, then the problem may become a reserve dispatch issue, which may be considered in future work. Actually, the offshore wind farms are mostly running in MPPT, due to being expensive to run in regulation.

This paper focused on the regular shaped wind farm layout, as Horns Rev I, optimization which should be rectangular or square shape. All other shaped wind farm layouts are classified into irregular shaped wind farm. In the future, the optimization of irregular shaped wind farm layout considering wake effect will be addressed. In that case, other optimization variables as the locations of each WT within the wind farm instead of the spacing between each pair of WTs would be introduced. In order to place the wind turbines optimally, binary PSO will be adopted to decide the suitable locations to arrange the WTs. The robustness of PSO will be illustrated for this type of study. Since the energy yields calculation of irregular shaped wind farm layout is more complex compared with regular shaped wind farm layout, the optimization process will be more time consuming.

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