Combined Approach Based on ACO with MTSP for Optimal Internal Electrical System Design of Large Offshore Wind Farm

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***Abstract*—The wind turbine (WT) layout and electrical system layout plays a vital role in offshore wind farm (OWF) design. The wake effect has a significant impact on the power production of the OWF. WTs in wake region will not experience healthy wind; hence it affects the power production. The proper placement of WTs can reduce the wake effect in OWF. The optimal design of large OWF is based on combined approach of Ant colony optimization (ACO) with multiple travelling salesmen problem (MTSP) is presented. The objectives of the approach are to improve power production, minimize the length of cable and cable cost. By considering (a) placement of WT with consideration of wake effect, (b) placement of substation, (c) selection of submarine cables with higher reliability and minimal power loss, and (d) minimum length of WT cable routing with zero cross connection. ACO-MTSP approach is applied on large OWF connected with 280 WTs and results are compared with the outcome of reference OWF.**

***Index Terms*—Ant colony optimization, multiple travelling salesman problem, offshore wind farm, wake effect, wind energy.**

PARAMETERS

α	Spacing between the WTs in a row.
β	Spacing between the WTs in a column.
γ_1	Angle between the WT_{11} & WT_{12}.
γ_2	Angle between the WT_{11} & WT_{13}.
γ_3	Angle between the WT_{12} & WT_{13}.
η_{ij}	Visibility.
ρ	Evaporation rate of pheromone (0 to 1).
τ_{ij}	Strength of pheromone path of city i to j.
$\Delta\tau_{ij}^{bs}$	Pheromone value of best-so-for tour.
$\Delta\tau_{ij}^{k}$	Pheromone value of k^{th} ant path of city i to j.
A_{ol}	Area of overlap.
A_r	Area of rotor.
C_C	Cost of MV submarine cable [k$/km].
C_{CT}	Cost of total cable.
C_{EC}	Cost of export cable.
C_{IA}	Cost of inter-array cable.
C_T	Thrust coefficient.
C_S	Cost of HV submarine cable [k$/km].
D	Rotor diameter of WT.
D_{eff}	Effective rotor diameter.
H	Hub height.
I_k	Current flow through the submarine cable.
$L_{HV(s)}$	Length of export cables [km].
L_{ji}	Length of cable connected between the j^{th} WT and i^{th} WT.
L_{bs}	Best-so-for tour length.
L_k	k^{th} ant tour length.
$L_{k(z)}$	Length of m feeders [km].
N_{W_n}	Availability of wind speed at n^{th} column WT.
Q	Amount of raise pheromone coefficient.
$R_{9.5}$	Wake radius at a distance of 9.5 times of D.
T_a	Ambient turbulence intensity.
V_∞	Undisturbed wind speed.
V_{pq}	Wind velocity at the p^{th} row, q^{th} column WT.
V_{ij}	Wind velocity at the i^{th} row, j^{th} column WT.
a_1&a_2	Wind speed constant values from Larsen wake model.
d_{ij}	Distance of city i to j.
e	Weight coefficient given to the best-so-for tour.
m	Number of salesmen.
n	Numbers of cities.
p_{ij}	Probability value to select the next city.
r_w	Wake radius.
s	Number of substations.
u	Pheromone trail constant.
v	Guide investigation constant.

I. INTRODUCTION

The utilization of electrical energy is increased drastically in last two decades. To meet energy demand, conventional and renewable energy sources are utilized. The renewable energy sources are the best solution for enormous power generation, reduction of green gas emission, and limit the usage of conventional energy sources. Now, the share of global wind energy is 3.7% of total energy. The approximate installed wind capacity is 497 GW till 2015 and aimed to install 4,403 GW by 2050 [1]. The installed wind energy till 2015 is helped in reduction of CO_2 gas emission to 0.6 billion tons. The placement of wind turbines (WTs) divides the wind farms into onshore and offshore wind farms (OWFs). The onshore wind farm has the limitation of difficulty in installing higher rating WTs. It has huge tower structure, larger rotor diameter, and lengthy blades. The higher rated onshore wind farms are located in hilly and remote areas because of availability of good wind velocity; hence transportation of WT

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parts is difficult and the social acceptance is a major problem. The OWFs has the higher capacity factor and has got more importance compared to onshore due to the ability to install huge rated WTs, no social acceptance problem, availability of good wind velocity and higher installation capacity [2]. But, OWF has some constraints. Those constraints are (a) requied huge foundations, (b) longer repair time, and (c) rough environmental conditions for transportation and maintenance. OWF includes WTs, offshore platforms, offshore substations, transformers, inter-array cables (medium voltage submarine cables), export cables (high voltage submarine cables), onshore substations and AC-DC converters. The interconnection of cable between the WTs is depended on collector topology. Those are radial, ring, star, double sided ring and etc [3]. The optimal design of OWF leads to minimize the number of (a) offshore platforms, (b) offshore substations, (c) converters, and (d) length of inter-array and export cable. Since the cable size is decreasing, it is intuitive that the power loss and the cost incurred in cable reduces.

The optimal design of OWF was carried out in the literature by applying various techniques for different contexts. The genetic algorithm (GA) is used for optimization of OWF electrical system in terms of levelised production cost (LPC) and reliability [4]. Authors in [5] have employed the improved GA technique to get an optimized model of OWF's electric distribution system. The combination of hybrid GA and immune algorithm optimize the internal electric connection system of OWF [6]. Geometric programming is applied to achieve an optimal design of OWF layout [7]. In [8] authors have proposed modified GA technique to minimize the length of submarine cable and cost of OWF. Optimal design of OWF electrical layout was developed by applying the Bender's decomposition technique whereas; the progressive contingency incorporation algorithm was proposed in [9]. The combination of fuzzy c-means (FCM) and binary integer programming method was applied to accomplish the optimal design of electrical layout [10]. In [11] authors have proposed improved FCM to design optimal electrical collection system for large OWF. Hybrid AC-DC OWF topology with mixed integer nonlinear programming method was used to obtain the minimization of cost and number of AC-DC power converters [12]. The combination of GA with Prim's algorithm was proposed to obtain the optimal radial topology of OWF in [13]. A mixture of Prim's algorithm with minimum spanning tree (MST) method [14] was employed for optimal location of the substation in OWF. In [15] authors have introduced opposition-based ant colony optimization to get an optimum location of wind farms. Clarke and Wright savings heuristic method with vehicle routing [16], ant colony optimization (ACO) [17], mixed integer linear programming [18], and GA [19] were implemented for the optimization of inter-array cable routing between WTs in OWFs. In [20] authors have proposed the mixture of a fuzzy clustering algorithm, GA and multiple travelling salesmen problem (MTSP) to optimize the double sided ring collector topology of OWFs. Authors have implemented the particle swarm optimization (PSO) [21] and dynamic MST [22] methods to optimize the cable layout with minimal LPC. Adaptive PSO with MST method was employed to design optimal cable layout of OWF and substation location [23]. In [24] authors have applied benders decomposition algorithm to optimize the collector system with consideration of multiple substations and cable types.

Some researchers have described the optimization of OWF with consideration of wake effect. Authors have applied improved evolution algorithm [25] to optimize WT layout with the attention of wake effect. Improved GA [26] and intelligently tuned harmony search method [27] have employed to achieve optimal placement of WT in OWF with consideration of micro siting and wake effect. GA-ACO method was proposed to optimize the WT layout [28]. In [29] authors have introduced PSO to optimize placement of WT in a regular shaped wind farm.

Section II explained the optimization method based on ACO and MTSP. Section III discussed the wake model and assessment of wake effect. Section IV explicated the problem formation and objective function. The case study and results are detailed in Section V. Finally, concluding remarks are given in Section VI.

II. Optimization approach

A. Ant colony optimization

ACO is a natural inspiration of ant's food searching process. It is a successive search method and also called as a metaheuristic method. In the process of searching food, ants identify the optimum route between the nest and the source point of food [30]. The process of searching is explained below:

1) Group of ants starts for the food searching in different directions and choose various routes.
2) In this process, they release a chemical (pheromone) on the ground in the route. The strength of pheromone decays fast with time.
3) Once they identify the food, return to the nest. Then they identify the minimum length of the route based on strength of pheromone and probability rule.
4) If the strength of pheromone is high, the length of the route is less and vice versa. Ant army follows the selected route.

B. Multiple travelling salesmen problem

MTSP is the route mapping approach between the specified cities. In this, n numbers of cities are assigned to m number of salesmen. The procedure is as follows: the maximum number of cities to be traveled by each salesman is $((n/m) + 1)$. First, all salesmen start their journey from the random city. The rules are (a) each salesman has to travel city only once in his tour, (b) if one salesman covered a city, others do not have to travel it, (c) every salesman has to start their journey in different routes, and (d) they have to travel every city without fail and satisfy the rule (a) and (b) [30].

C. Combination of ACO and MTSP

In this approach, the number of cities is equal to the number of ants. Each ant starts their travel from a random city and completes the tour at the initial point. Ants select next city to travel by probability rule which is the function of the strength of pheromone and distance between the cities.
Initial value of pheromone $\tau_{ij}(0)$ is little higher than the pheromone released in each iteration.
Visibility $\eta_{ij} = 1/d_{ij}$ is routing the desirable nearest city.
Probability rule is given in below,

$$p_{ij} = \frac{[\tau_{ij}]^u [\eta_{ij}]^v}{\sum_{w \in allowed} [\tau_{ij}]^u [\eta_{ij}]^v} \quad (1)$$

In (1), $\sum_{w \in allowed}$ adds the untouched cities in tour.
Update the pheromone trails using (2),

$$\tau_{ij} = (1-\rho)\tau_{ij} + \sum_{k=1}^{m} \Delta\tau_{ij}^k + e.\Delta\tau_{ij}^{bs} \quad (2)$$

In (2), $\Delta\tau_{ij}^k = \{Q/L_k$ if k^{th}ant tour in (i,j), otherwise 0.
$\Delta\tau_{ij}^{bs} = \{Q/L_{bs}$ if k^{th}ant tour best so far in (i,j), otherwise 0.

The combination of ACO and MTSP algorithm is explained by flow chart as shown in Fig. 1. The number of cities n is equal to sum of WTs and substations. The number of salesmen m is taken as number of feeders.

III. Larsen wake model

Wake effect is the formation of a wake behind the WT. It is the variation of wind speed from weaker to strengthen point behind the WT. The effect of wake in downstream side WTs is more compared to upstream. The wind speed regains behind the WT after some distance. It is ranging from one to several times of rotor diameter. The wake effect is classified into partial, full and non-wake effect. The mathematical wake model was introduced to analysis the wake effect. Wake models are divided into two types. They are kinematic model and field model. The momentum equation is used to model the velocity deficit of the wake behind WT in a kinematic model. Kinematic wake model includes Jensen model, Larsen model, Ainslie model and Farnden model [31]. The assessment of power loss in OWF is explained in [32] by accounting turbulence intensity and atmospheric stability.

The Larsen wake model is a kinematic model and proposed by G.C Larsen [31]. The wake model formulation is based on Prandtl turbulent boundary layer equation. It is nonlinear wake expansion. Larsen wake model can give an explanation in terms of wake width, wake radius, and wind velocity deficit. The assumptions are constant and strong wind flow by ignoring wind distribution. The formulation of wake model is discussed below:

The wake boundary r_w as shown in (3)

$$r_w = 1.7563(c_1^{\frac{2}{5}})(x)^{\frac{1}{3}} \quad (3)$$

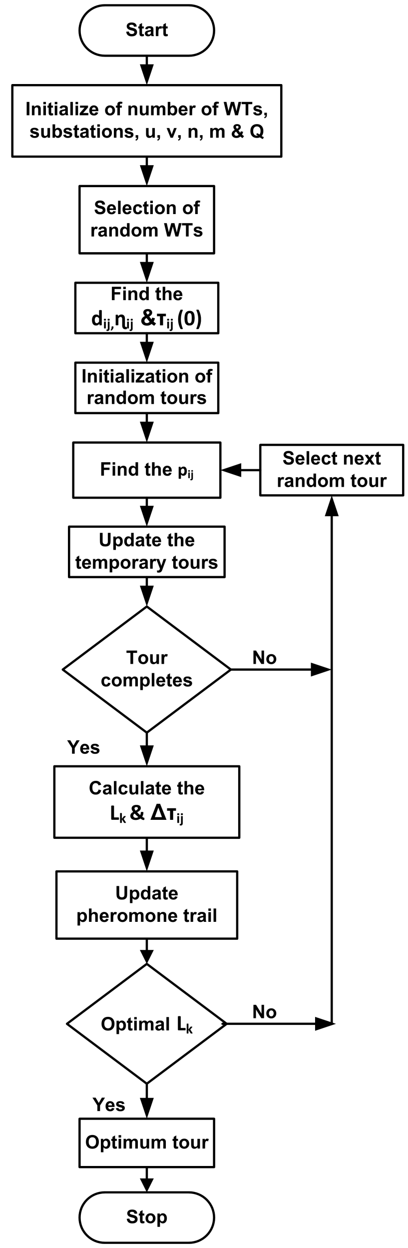

Fig. 1. Flow chart of ACO-MTSP algorithm

Where, $x = C_T \frac{A_{ol}}{A_r}(a + a_0)$.
The axial velocity deficit in the wake ($dV = V_\infty - V$) is given as,

$$dV = -\frac{V_\infty}{9} \frac{x^{\frac{1}{3}}}{(a+a_0)} + [\frac{r^{\frac{3}{2}}}{\sqrt{3c_1^2 x}} + 1.344 c_1^{\frac{-1}{5}}]^2 \quad (4)$$

Where, $a = y * D$ ($0 \leq y \leq 15$) and c_1 is function of Prandtl mixing length and the rotor position with respect to the applied coordinate system. c_1 is given in (5).

$$c_1 = \frac{4.3}{100}[\frac{D_{eff}}{2}]^{\frac{5}{2}}(C_T \frac{A_{ol}}{A_r} a_0)^{\frac{-5}{6}} \quad (5)$$

The value of a_0 depends on D, D_{eff} and $R_{9.5}$. It is indicated in (6)

$$a_0 = \frac{9.5D}{(\frac{2R_{9.5}}{D_{eff}})^3 - 1} \tag{6}$$

The D_{eff} is expressed as,

$$D_{eff} = D\sqrt{\frac{1+\sqrt{1-C_T}}{2\sqrt{1-C_T}}} \tag{7}$$

$$R_{9.5} = 0.5[R_{nb} + min(H, R_{nb})] \tag{8}$$

$$R_{nb} = max(1.08D, (21.7T_a - 0.005)D) \tag{9}$$

$$V_{pq} = V_\infty[1 - \sqrt{\sum_{i=1}^{p}\sum_{j=1}^{q}[1-(\frac{V_{ij}}{V_\infty})]^2}] \tag{10}$$

A. Assessment of wake effect

The wind velocity sharing at each WT due to wake effect is calculated. Wake loss is the value of wind velocity loss in wake region. In OWF, first column WTs can experience full wind speed (1 pu). The remaining column WTs may experience less wind speed which reduces the value of OWF power production. In reference OWF (ROWF) [8], the distance between the WTs in a row and column are 7D and 4D respectively. The wind velocity sharing of ROWF is shown in Fig. 2.

The assessment of wake loss in OWF is given in (11). The average wake loss value of ROWF at a 7D spacing between the WTs is 0.44 pu.

$$N_{W_n} = a_1 N_{W_{(n-1)}} + a_2 N_{W_{(n-2)}} \tag{11}$$

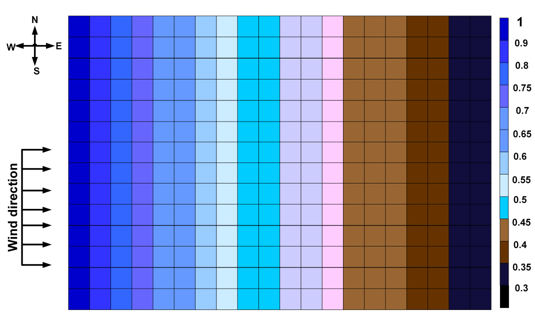

Fig. 2. Wind velocity sharing of ROWF at $7D$ spacing between WTs

IV. Problem Formulation

The problem formulation aims at optimal design of OWF. It includes (a) minimization of the length of inter-array cable and export cable, (b) wind turbine cable routing, (c) placement of WTs and substations, and (d) diminishing the wake effect. The ACO-MTSP approach is applied to optimize OWF. Objective function is stated below:

$$Min \sum_{z=1}^{m} L_{k(z)}$$

$$L_k = \sum_{i=1}^{p}\sum_{j=1}^{q} L_{ji} \tag{12}$$

Subject to,

$$p_{min} \leq p \leq p_{max} \tag{13}$$

$$q_{min} \leq q \leq q_{max} \tag{14}$$

$$L_{min} \leq L_{ji} \leq L_{max} \forall i, j = (1, 2, ...n) \tag{15}$$

$$I_k \leq I_{rated} \tag{16}$$

The C_{IA} is the cost of cable connected between WTs by feeder and it is connected to substation.

$$C_{IA} = \sum_{z=1}^{m} C(L_{k(z)}) = (\sum_{z=1}^{m} L_{k(z)})C_C \tag{17}$$

Where, $L_{k(z)} = (L_{k(1)}, L_{k(2)}, L_{k(3)}, ..., L_{k(m)})$.

The C_{EC} is the cost of cable connected between substation and HV collector hub.

$$C_{EC} = \sum_{z=1}^{s} C(L_{HV(z)}) = (\sum_{z=1}^{s} L_{HV(z)})C_S \tag{18}$$

Where, $L_{HV(z)} = (L_{HV(1)}, L_{HV(2)}, L_{HV(3)}, ..., L_{HV(s)})$.

The C_{CT} is the sum of the inter-array cable cost and export cable cost given in (19)

$$C_{CT} = C_{IA} + C_{EC} \tag{19}$$

V. Case Study and Results

In this paper, the optimal design of large OWF by applying ACO-MTSP approach is carried out. The OWF comprising 280 WTs is planned to erect at yellow sea in east China. The reference OWF has the space between the WTs in a row and column is 4D and 7D respectively [8]. The rated power of WT is 2 MW and rotor diameter is 80 m. The distance between the onshore substation and OWF is 15 km. The inter-array cable connects the WTs in a string. The string of WTs is connected to medium voltage (MV) substation. The export cable interconnects the MV substations to medium voltage (HV) collector hub. Medium voltage AC submarine cable is used as inter- array cable. It is 35 kV Cross-linked polyethylene (XLPE) type AC submarine cable with cross section area of 150 mm^2. The current flow through 35 kV submarine cable from 2 MW WT is 32.99A. The current carrying capacity of the 35 kV submarine cable is 330 A; hence a number of WTs interconnected in the string is 10. So, the limit of interconnection of WTs in a string is 10. The parameters of MV submarine cable are indicated in Table I [24].

High voltage AC submarine cable is used as export cable. It is 150 kV XLPE type AC submarine cable with cross section area of 500 mm^2. It has the current carrying capacity of 655A; hence the cable can connect up to 85 WTs.

TABLE I
35 kV AC SUBMARINE CABLE PARAMETERS

Cross-sectional area mm^2	Conductor resistance Ω/ km	Cable capacitance μF/km	Cable inductance mH/km	Current carrying capacity (A)	Cable cost k$/km
70	0.3420	0.1263	0.3865	215	169.23
120	0.1966	0.1460	0.3637	300	207.69
150	0.1587	0.1563	0.354	335	229.23
185	0.1271	0.1665	0.3456	375	258.46
240	0.0971	0.1805	0.3365	430	272.31

A. Optimal design of OSWF

The optimal design of OWF is prepared with the help of ACO-MTSP approach. Larsen wake model's wind velocity data in wake portion is used for placement of the WTs in wind farm. The distance between the WTs in a row and column are 6D (α) and 4D (β) respectively. To nullify the wake loss in OWF, the placement of WTs with respect to angle is given in Table II. The optimal placement of WTs shown in Fig. 3 and the values of β_1 and β_2 are 0.882D and 2D respectively.

TABLE II
DETAILS OF WT PLACEMENT

Reference WT	Projected WT	Angle
WT_{11}	WT_{12}	$\geq \gamma_1$
WT_{11}	WT_{13}	$\geq \gamma_2$
WT_{12}	WT_{13}	$\equiv \gamma_3$

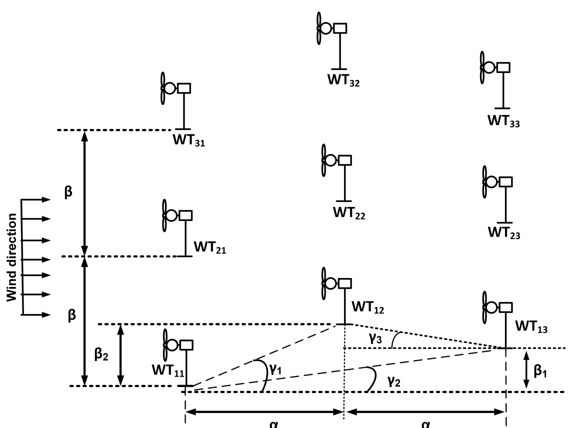

Fig. 3. Optimal design model of WT placement

B. Case1: Placement of substations at a center of WTs layout

The 280 WTs in OWF are connected to 4 Substations. Each substation can connect to 70 WTs and distribute by 7 feeders per substation. The substations are placed at the center of 70 WTs layout. The optimal design of OWF with the placement of substations at a center of WTs layout (COWF) is shown in Fig. 4. The optimal length of inter-array cable and export cable are 206.26 km and 39.715 km respectively. The total length of interconnection cable is 245.975 km.

C. Case2: Placement of substations near to HV collector hub

The optimal design of OWF with the placement of substations near to HV collector hub (NOWF) is shown in Fig. 5. The optimal length of inter-array cable and export cable are 253.14 km and 19.214 km respectively. The total length

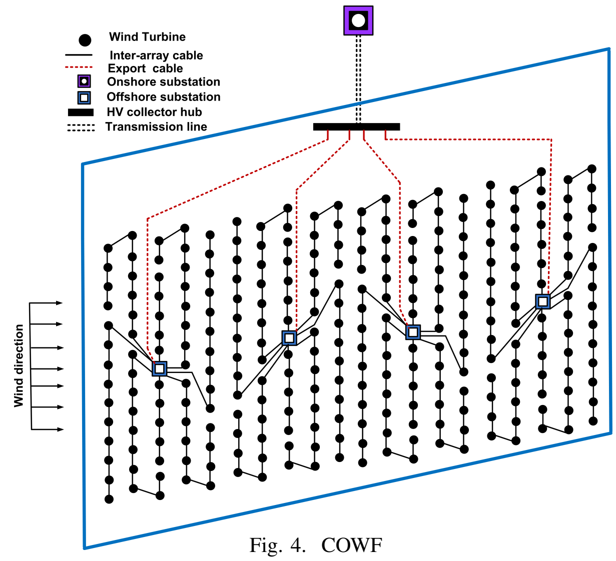

Fig. 4. COWF

of interconnection cable is 272.354 km. The cable cost and interconnecting cable length of COWF, NOWF, and ROWF are given in Table III.

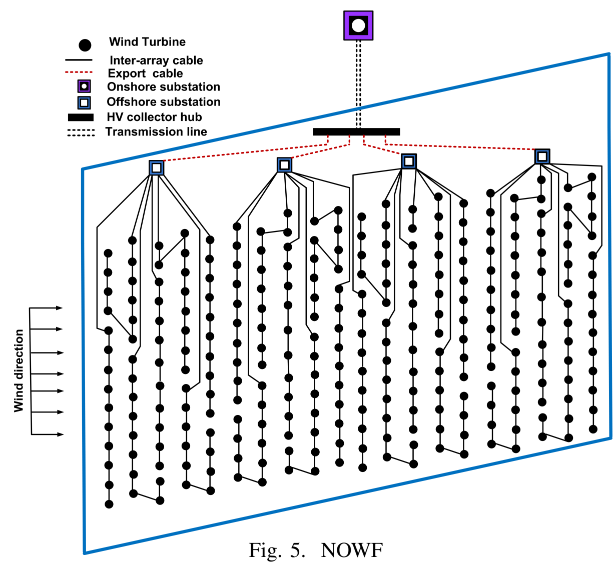

Fig. 5. NOWF

The average wake loss of optimal design of OWFs (COWF and NOWF) reduced to 0.027 pu. The wake loss value of reference OWF with 12D spacing between WTs is approximately equal to wake loss value of COWF and NOWF. The power production of OWF depends on the availability of wind velocity experienced by WT in the entire wind farm. If the WTs experience the 100% rated wind velocity than the OWF can able to produce rated power.

TABLE III
RESULT SUMMARY OF OWF DESIGNS

OWF	Inter-array cable length (km)	Export cable length (km)	Total cable length (km)	Total cable cost (millon$)
ROWF [8]	260.034	38.856	298.890	76.044
COWF	206.260	39.715	245.975	64.080
NOWF	253.140	19.214	272.354	66.154

VI. Conclusion

This paper applied an optimization approach based on ACO and MTSP for optimal design of OWF. It includes the minimization of submarine cable length, improves the power production, and reduces the wake effect. A large OWF consisting of 280 WTs and rated power of 560 MW is used for the study. For the analysis of wake, nonlinear wake expansion model is taken into account. The mathematical implementation of Larsen wake model is discussed. The objective function is stated and formulation of wake loss value of OWF is explained. The wake loss is reduced in the design of COWF and NOWF. The selection of MV and HV submarine cables are clarified with the numerical explanation. The outcomes of optimal OWF are evaluated with reference OWF. The interconnection cable length of COWF and NOWF is 82.3% and 91.12% of ROWF respectively. The cable cost of COWF and NOWF is 84.27% and 87% of ROWF. The interconnection cable length of COWF is less compared to NOWF. So, the placement of substation at a center of WTs layout is given the best outcome. This concludes that COWF is the best optimal design compare to NOWF.

References

[1] G. W. E. Council, "Global wind energy outlook 2014," 2014.

[2] A. Sannino, H. Breder, and E. K. Nielsen, "Reliability of collection grids for large offshore wind parks," in *Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. International Conference on*. IEEE, 2006, pp. 1–6.

[3] R. Srikakulapu and U. Vinatha, "Electrical collector topologies for offshore wind power plants: A survey," in *Industrial and Information Systems (ICIIS), 2015 IEEE 10th International Conference on*. IEEE, 2015, pp. 338–343.

[4] M. Zhao, Z. Chen, and F. Blaabjerg, "Optimization of electrical system for a large dc offshore wind farm by genetic algorithm," in *Nordic workshop on power and industrial electronics*, vol. 37, 2004.

[5] D. D. Li, C. He, and H. Y. Shu, "Optimization of electric distribution system of large offshore wind farm with improved genetic algorithm," in *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*. IEEE, 2008, pp. 1–6.

[6] D. D. Li, C. He, and Y. Fu, "Optimization of internal electric connection system of large offshore wind farm with hybrid genetic and immune algorithm," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*. IEEE, 2008, pp. 2476–2481.

[7] M. Nandigam and S. K. Dhali, "Optimal design of an offshore wind farm layout," in *Power Electronics, Electrical Drives, Automation and Motion, 2008. SPEEDAM 2008. International Symposium on*. IEEE, 2008, pp. 1470–1474.

[8] F. M. González-Longatt, P. Wall, P. Regulski, and V. Terzija, "Optimal electric network design for a large offshore wind farm based on a modified genetic algorithm approach," *IEEE Systems Journal*, vol. 6, no. 1, pp. 164–172, 2012.

[9] S. Lumbreras and A. Ramos, "Optimal design of the electrical layout of an offshore wind farm applying decomposition strategies," *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1434–1441, 2013.

[10] Y. Chen, Z. Dong, K. Meng, F. Luo, W. Yao, and J. Qiu, "A novel technique for the optimal design of offshore wind farm electrical layout," *Journal of Modern Power Systems and Clean Energy*, vol. 1, no. 3, pp. 258–263, 2013.

[11] H. Ling-Ling, C. Ning, Z. Hongyue, and F. Yang, "Optimization of large-scale offshore wind farm electrical collection systems based on improved fcm," pp. 67–67, 2012.

[12] M. De Prada, C. Corchero, O. Gomis-Bellmunt, A. Sumper *et al.*, "Hybrid ac-dc offshore wind power plant topology: Optimal design," *IEEE Transactions on Power Systems*, vol. 30, no. 4, pp. 1868–1876, 2015.

[13] O. Dahmani, S. Bourguet, M. Machmoum, P. Guérin, P. Rhein, and L. Jossé, "Optimization of the connection topology of an offshore wind farm network," *IEEE Systems Journal*, vol. 9, no. 4, pp. 1519–1528, 2015.

[14] P. Hou, W. Hu, and Z. Chen, "Offshore substation locating in wind farms based on prim algorithm," in *Power & Energy Society General Meeting, 2015 IEEE*. IEEE, 2015, pp. 1–5.

[15] F. Pouladi, A. M. Gilani, B. Nikpour, and H. Salehinejad, "Optimum localization of wind turbine sites using opposition based ant colony optimization," in *Developments in eSystems Engineering (DeSE), 2013 Sixth International Conference on*. IEEE, 2013, pp. 21–26.

[16] J. Bauer and J. Lysgaard, "The offshore wind farm array cable layout problem: a planar open vehicle routing problem," *Journal of the Operational Research Society*, vol. 66, no. 3, pp. 360–368, 2015.

[17] B. C. Neagu and G. Georgescu, "Wind farm cable route optimization using a simple approach," in *Electrical and Power Engineering (EPE), 2014 International Conference and Exposition on*. IEEE, 2014, pp. 1004–1009.

[18] M. Fischetti and D. Pisinger, "Inter-array cable routing optimization for big wind parks with obstacles," in *Control Conference (ECC), 2016 European*. IEEE, 2016, pp. 617–622.

[19] A. Jenkins, M. Scutariu, and K. Smith, "Offshore wind farm inter-array cable layout," in *PowerTech (POWERTECH), 2013 IEEE Grenoble*. IEEE, 2013, pp. 1–6.

[20] S. Wei, L. Zhang, Y. Xu, Y. Fu, and F. Li, "Hierarchical optimization for the double-sided ring structure of the collector system planning of large offshore wind farms," *IEEE Transactions on Sustainable Energy*, 2016.

[21] P. Hou, W. Hu, B. Zhang, M. Soltani, C. Chen, and Z. Chen, "Optimised power dispatch strategy for offshore wind farms," *IET Renewable Power Generation*, vol. 10, no. 3, pp. 399–409, 2016.

[22] P. Hou, W. Hu, C. Chen, and Z. Chen, "Optimisation of offshore wind farm cable connection layout considering levelised production cost using dynamic minimum spanning tree algorithm," *IET Renewable Power Generation*, vol. 10, no. 2, pp. 175–183, 2016.

[23] P. Hou, W. Hu, and Z. Chen, "Optimisation for offshore wind farm cable connection layout using adaptive particle swarm optimisation minimum spanning tree method," *IET Renewable Power Generation*, vol. 10, no. 5, pp. 694–702, 2016.

[24] Y. Chen, Z. Y. Dong, K. Meng, F. Luo, Z. Xu, and K. P. Wong, "Collector system layout optimization framework for large-scale offshore wind farms," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1398–1407, 2016.

[25] J. S. Gonzalez, M. B. Payan, and J. M. R. Santos, "An improved evolutive algorithm for large offshore wind farm optimum turbines layout," in *PowerTech, 2011 IEEE Trondheim*. IEEE, 2011, pp. 1–6.

[26] J. S. González, M. B. Payán, and J. R. Santos, "A new and efficient method for optimal design of large offshore wind power plants," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 3075–3084, 2013.

[27] N. P. Prabhu, P. Yadav, B. Prasad, and S. K. Panda, "Optimal placement of off-shore wind turbines and subsequent micro-siting using intelligently tuned harmony search algorithm," in *Power and Energy Society General Meeting (PES), 2013 IEEE*. IEEE, 2013, pp. 1–7.

[28] Y.-K. Wu, C.-Y. Lee, C.-R. Chen, K.-W. Hsu, and H.-T. Tseng, "Optimization of the wind turbine layout and transmission system planning for a large-scale offshore windfarm by ai technology," *IEEE Transactions on Industry Applications*, vol. 50, no. 3, pp. 2071–2080, 2014.

[29] P. Hou, W. Hu, M. Soltani, and Z. Chen, "Optimized placement of wind turbines in large-scale offshore wind farm using particle swarm optimization algorithm," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1272–1282, 2015.

[30] M. Dorigo and S. Thomas, *Ant Colony Optimization*. Cambridge, Massachusetts: The MIT press, 2004.

[31] D. J. Renkema, "Validation of wind turbine wake models," *Master of Science Thesis, Delft University of Technology*, 2007.

[32] R. J. Barthelmie, K. S. Hansen, and S. C. Pryor, "Meteorological controls on wind turbine wakes," *Proceedings of the IEEE*, vol. 101, no. 4, pp. 1010–1019, 2013.