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New Optimization Approach Based on Ant Colony Optimization with Travelling Salesmen Problem for Optimal Design of Offshore Wind Farm

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Abstract: The establishment of larger offshore wind farms (OWFs) with higher rating wind turbines (WTs) has emerged by new technology in world wide. Large scale OWFs are experiencing economic challenges as well as wake effect. These issues can be overcome by optimal design (OD) of OWF. In this paper, a new optimization approach for OD of OWF is proposed. The optimization approach is the combination of ant colony optimization and travelling salesmen problem. The OD gives the allocation of WTs with consideration of constraints such as, length of interconnection cable between the WTs and wake effect on WTs. The cost of interconnection cable is the part of cost of OWF. The minimization of length of IC leads to reduction of cable cost and power loss in cable. The proposed approach is applied to North Hoyle OWF with thirty WTs considering OD of ring and radial topologies.

Keywords: Ant Colony optimization, offshore wind farm, Travelling Salesman problem, wake effect, wake loss.

1. INTRODUCTION

Due to rapid change of climate and greenhouse gas emission, keen interest is given towards renewable energy generation. In 21st century the wind energy is gaining more importance of which offshore wind farm (OWF)s are playing vital role. At present the electrical energy demand is more as compared to generation. In case of Indian energy scenario, the energy demand is scaling up at a rate of 2.8% per annum [1]. To fulfill the energy demand, the global wind energy generation is targeted to huge installation. The approximate installed global wind capacity till date is 496.9GW and projected to meet 4,402.5GW by the end of 2050 [1]. The global electricity supplied by the wind energy is 3.7%. The installed wind power generation in India is 25.1GW till 2015. It is expected to reach 83.1GW by the end of 2030 and holds share of 9% in global wind power [2]. Wind energy had reduced 637 million tons of CO_2 emissions in 2015 and 3 billion tons by the end of 2030 globally [1]. The increment in percentage global wind power capacity for each decade up to 2050 is shown in Figure 1 [1], [2], [3].

The global wind power capacity includes onshore and offshore wind power generation. The OWFs are getting more popular compared to onshore wind farm [4] due to following reasons:

- Large scale land requirement,
- Higher rating wind turbine (WT) requirement,
- Availability of strong wind in entire year and
- Huge installation capacity.

The OWF includes WTs, collector hub, offshore substation, transformers, submarine cables, etc. The collector hub connects to all WTs in wind farm. Based on electrical collector topology, the WTs in OWF

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are interconnected and then connected to the hub. The WTs interconnected in ring topology is shown in Figure 2 [5]. The interconnection cable (IC) length and size varies with OWF capacity. The capital cost of OWF includes the cost of WTs, transformers, substation, offshore platform and submarine cable. In addition, OWF have higher maintenance cost and outage cost due to critical operational environment and low accessibility [5].

Genetic algorithm (GA) and geometric programming are applied to get optimal layout in [6], [7]. In [10] authors have used the GA technique to solve the optimal micro siting of WTs. The mixture of improved GA and multiple travelling salesmen problem approach is applied for optimization of OWF in [8], [9]. Authors have used the combination of fuzzy C-mean (FCM) and binary integer programming technique to achieve automatic placement of the WTs to nearest substation [12]. The better computational time for optimal design (OD) was achieved by using benders decomposition technique [11]. In [12], [13] author applied minimum spanning tree method to get OD of electrical layout. A hybrid AC-DC OWF topology was proposed in [14]. Mixed integer nonlinear programming is applied to get the optimal outcomes, like minimal number of AC-DC power converters and minimum cost. Particle swarm optimization (PSO) method is used to allocate the WTs in optimal manner with consideration of wake effect, hence to get OD of OWF [15]. Further, Levelized production cost function was used to find the minimized investment cost of OWF. In [16] a mixed approach of GA and ant colony optimization (ACO) algorithm is applied with consideration of wake effect and various cable ratings to design optimal model. In [17] author proposed a combination of PSO and FCM clustering algorithm for the placement of WTs and substation in OWF.

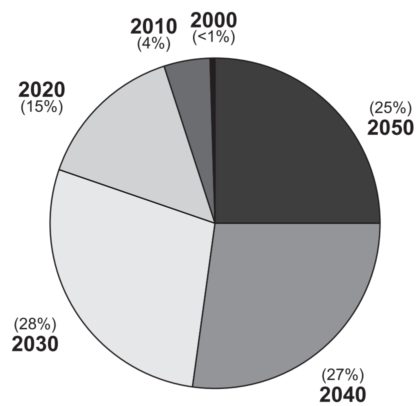

Figure 1: Total global wind power capacity

Wake effect is more prominent in large OWFs. The wake effect is the effect on strength of wind behind the primary WT and the range of disturbed wind speed changes with distance. The distance is measures in several times of WT rotor diameter. The wind speed is classified as upstream and downstream. Downstream side WTs are more affected by the wake, hence, power production of OWF differs. The wake effect on WT can be reduced by placement of WT. If the gap between the consequent WTs is less, the effect of wake on downstream side WTs will be higher and vice versa. The power production of OWF relies on wake effect and availability of wind. The estimation of power loss in OWF was discussed in [18] by accounting turbulence intensity and atmospheric stability. The standard analytical wake models include (a) Larsen model, (b) Jensen model, (c) Ainslie model and (d) Farndsen model [19]. The Larsen model is chosen for analysis and optimization of the OWF because it provides good amount of the regain wind speed behind a WT.

Section II is explains ACO with travelling sales men problem (TSP). Section III models OWF and wake effect. The results are discussed in section IV. Concluding remarks are given in section V.

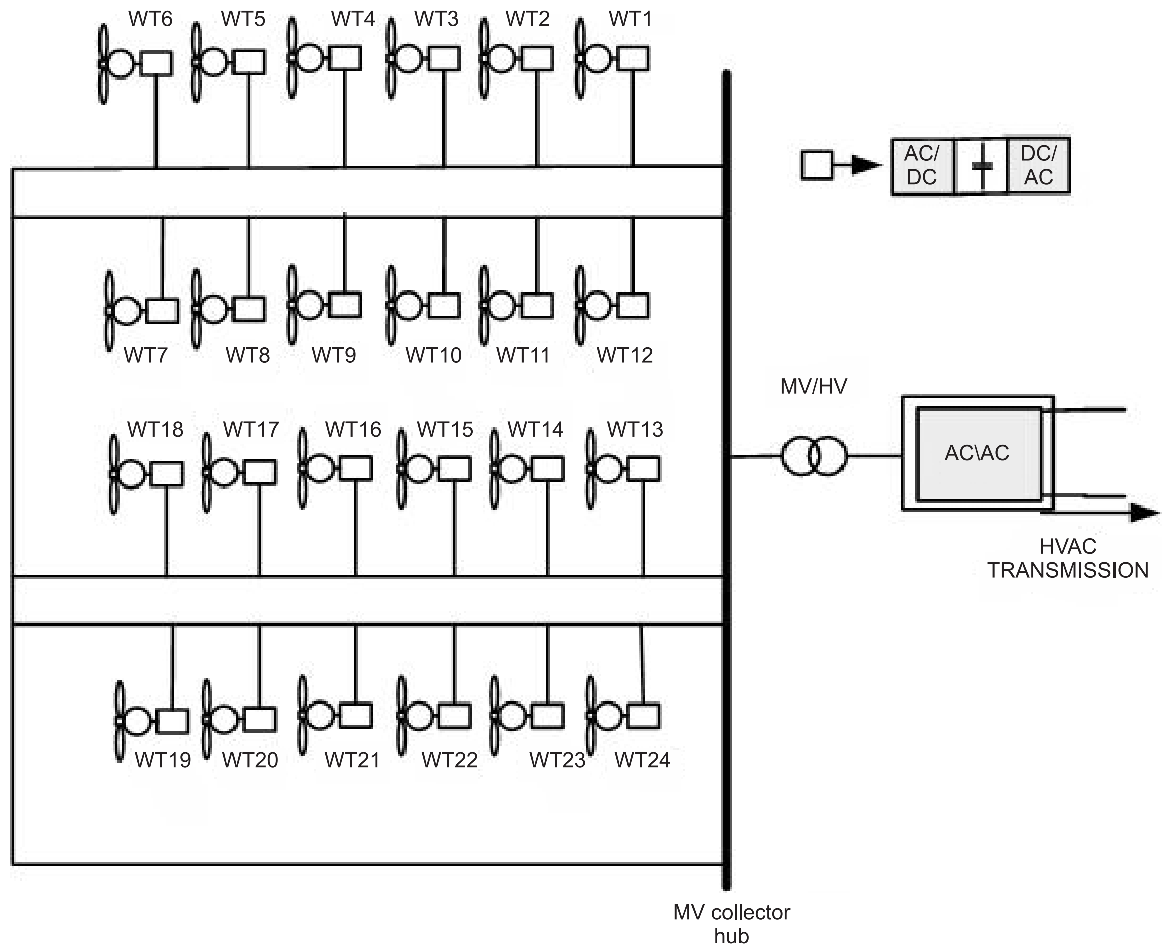

Figure 2: Ring topology of OWF

2. ANT COLONY OPTIMIZATION

ACO is biologically inspired from ants and it is a food search process of ants. It is a population based search method. In general ants find the shortest route from source of food point to nest. In the process of searching food, ants release pheromone on the ground in the route. The pheromone is a chemical and concentration of pheromone which decays fast with time. First different group of ants starts their journey from nest to source of food point in various directions. They finish their random tours in different directions and reach to nest. Then they will give message to the ant army. The ant army decides the shortest path by the probability value which is a function of concentration of pheromone. If the concentration of pheromone is more indicates minimum length of tour. Once the shortest path is decided, the ant army follows the path blindly. Finally the ant army carries the food to the nest [22].

A. Ant Colony Optimization with Travelling Salesmen Problem

In ACO with TSP approach, the number of ants is taken as the number of cities. At starting the ants are randomly selecting the initial city and complete their tours. Based on probability rule, ant or salesmen decide the next city of tour. The probability rule is the function of concentration of pheromone value and the visibility value as given in (2). The mandatory condition here is that, the ants are allowed to travel a particular city once in a tour. Primary value of pheromone τ_{ij} (0) is higher than the pheromone released in each iteration. Visibility value of city i to j is

$$\eta_{ij} = 1/d_{ij} \tag{1}$$

Probability rule is given in below,

$$P_{ij} = \frac{[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{x\varepsilon \text{ allowed}}[\tau_{ij}]^{\alpha}[\eta_{ij}]^{\beta}} \quad (2)$$

In (2), $\sum_{x\varepsilon \text{ allowed}}$ adds the untouched cities in tour.

Update the pheromone trails using (3),

$$\tau_{ij} = (1-\rho)\tau_{ij} + \sum_{k=1}^{m}\Delta\tau_{ij}^{k} + e\cdot\Delta\tau_{ij}^{bs} \quad (3)$$

In (3), $\Delta\tau_{ij}^{k}$ = {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 basic parameters in ACO algorithm are listed below,

m is numbers of ants

d_{ij} is Distance of city i to j

τ_{ij} is concentration of pheromone path of city i to j

p_{ij} is the probability value to select the next city

α is the pheromone trail constant

β is guide investigation constant

ρ is evaporation rate of pheromone (0 to 1)

$d_{\min}$ is minimum distance between cities

k is the total pheromone and kth ant

Q is the amount of raise pheromone coefficient

L_k is the kth ant tour length

$IT_{\max}$ is maximum number of iterations

The realization of ACO with TSP approach is enlightened by flow chart as shown in Figure 3.

3. MODEL OF OFFSHORE WIND FARM

The model of OWF explains the placement of WTs considering wake effect. The power production of OWF is strongly dependent on the wake effect. The wake model provides the healthy wind speed data of wake behind the primary WT and explains the effect. Larsen wake model is considered for OD of OWF based on (a) length of IC, (b) power production profile and (c) cost of cable. The Larsen wake model is explained in detail;

A. Larsen Wake Model

The Larsen wake model is a kinematic far model. It was intended by G.C. Larsen [19]. Prandtl turbulent boundary layer equation is used to formulate the wake model. It can give solution in terms of (a) the width of the wake, (b) the mean velocity profile of wake and (c) radius of wake. The wake formation of WT by Larsen model is shown in Figure 4. The assumptions are constant and strong wind flow by neglect wind sharing. The first order equations of wake model discussed below;

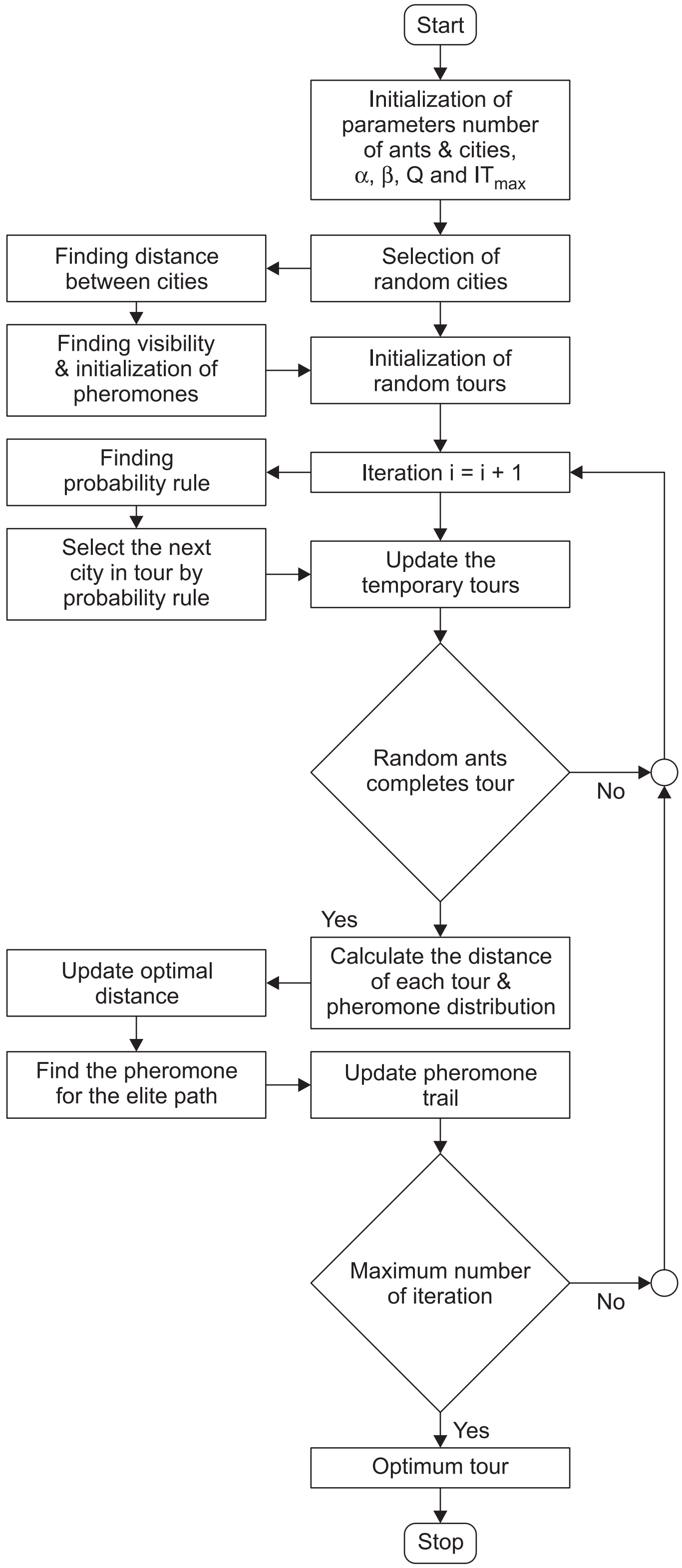

Figure 3: ACO with TSP algorithm flow chart

The rotor wake radius R_w is expressed in (4).

$$R_w = (1.7563(c_1^{2/5})(x)^{1/3}) \tag{4}$$

Where $x = C_T A_r(a + a_0)$, C_T is Thrust coefficient and A_r is area of rotor. The wake boundary as per (4) is shown in Figure 4 by a black line.

The axial velocity deficit in the wake (ΔN) is given as,

$$(\Delta N)(a, r) = \frac{-N_{inf}}{9}(C_T A_r (a + a_0)^{-2})^{1/3} + \frac{r^3}{3c_1^2 x} + 1.344\, c_1^{-1/5} \tag{5}$$

Where N_{inf} is the undisturbed wind speed and c_1 is function of Prandtl mixing length and the rotor position with respect to the applied coordinate system is given in (6)

$$c_1 = \frac{4.3}{100}\left[\frac{D_{eff}}{2}\right]^{5/2}(C_T A_r a_0)^{-5/6} \tag{6}$$

The value of a_0 depends on D, D_{eff} and $R_{9.5}$. It is indicated in (7)

$$a_0 = \frac{9.5D}{\left(\frac{2R_{9.5}}{D_{eff}}\right)^3 - 1} \tag{7}$$

where D is rotor diameter.

The effective rotor diameter D_{eff} is expressed as,

$$D_{eff} = D\sqrt{\frac{1+\sqrt{1-C_T}}{2\sqrt{1-C_T}}} \tag{8}$$

$R_{9.5}$ is the wake radius at a distance of 9.5 times of rotor diameter, given in (8),

$$R_{9.5} = 0.5[R_{nb} + \min(H, R_{nb})] \tag{9}$$

Where H is hub height. R_{nb} is given in (9)

$$R_{nb} = \max(1.08\,D, (21.7\,T_a - 0.005)\,D) \tag{10}$$

Where T_a is ambient turbulence intensity.

The wake formation behind the WT for N_{inf} is 10 m/s and T_a is 0.1 by using Larsen model is shown in Figure 4 [19].

4. CASE STUDY AND RESULTS

In this paper, the optimization approach based on ACO with TSP obtains the OD of North Hoyle OWF considering with and without wake effect. This section discusses the calculation of wake loss value and power production value for OWF.

The NH OWF is located at Prestatyn in Irish Sea, United Kingdom. The 30 WTs are arranged in 6 rows and each row has 5 WTs. The distance between the WTs in row/column is 10 D (800 m)/4.375D (350 m). The capacity of each WT is 2M W and rotor diameter (D) is 80 m. The MVAC/HVAC transmission is used and operating voltage level is 33 kV/132 kV. Two radial inter array cables interconnect the WTs. The IC are 33 kV XLPE type AC submarine cable with a cross section of 185 mm^2 and total length of cable is 18 km [20]. The estimated cost of cable and transformer is given in the Table 1 [21].

A. Estimation of Wake Effect

The calculation of wind sharing at WTs due to wake effect is discussed. The undisturbed wind at 1 p.u. is received by WTs in primary column. The wind flow received by other consequent column WTs is calculated and the spacing between WTs in a row is 10 D. The wind flow sharing of NH OWF is shown in Figure 5. The wake loss value of NH OWF is 7.438%.

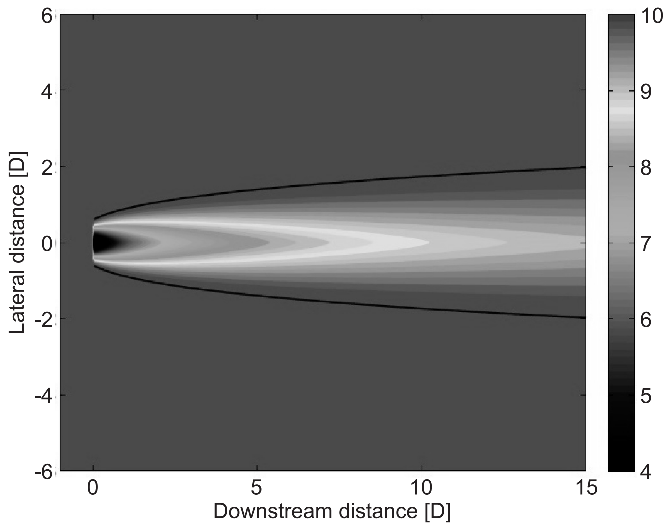

Figure 4: Wake formation of Larsen model

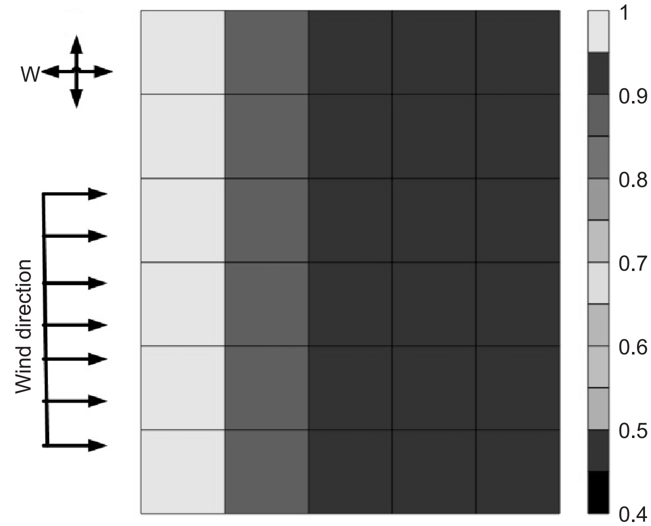

Figure 5: Wind speed sharing in NH OWF at 10D

B. Optimal Design of OWF

The OD of NH OWF is prepared by applying the new combination of optimization techniques. To accomplish the OD, wake effect is taken in account. The aim of OD is to minimize the length of IC. The distance between the WTs in row (A)/column (B) is taken as 6D/4D. Ring and radial topology have taken to prepare the ODs. Each case of topology, with and without accounting wake effect is considered.

1. **Case 1:** OD of NH OWF without wake effect: In case1, the wake effect is not taken into account and OD is made based on length of IC. The OD of NH OWF without wake effect for radial topology (ODRA) and ring topology (ODRI) are shown respectively in Figure 6 and Figure 7. The power production value depends on the wake effect in OWF. When the value of wake loss is low, the WTs in OWF can experience higher undisturbed wind flow and it leads to improve the power production of OWF. In this wake loss value is 20.03% and power production value is 79.97%. The comparison of ODRA and ODRI in terms of IC length and cost are given in Table 2.

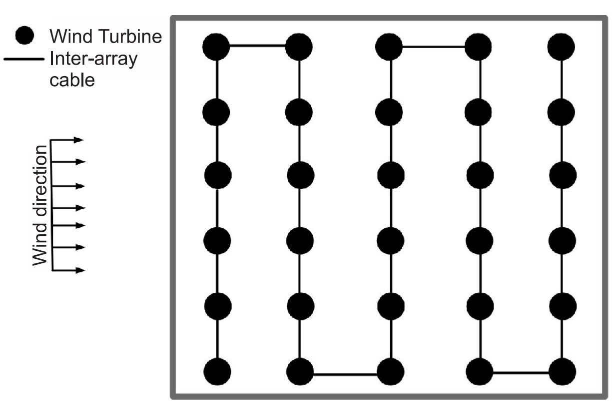

Figure 6: Radial OD of NH OWF without wake effect

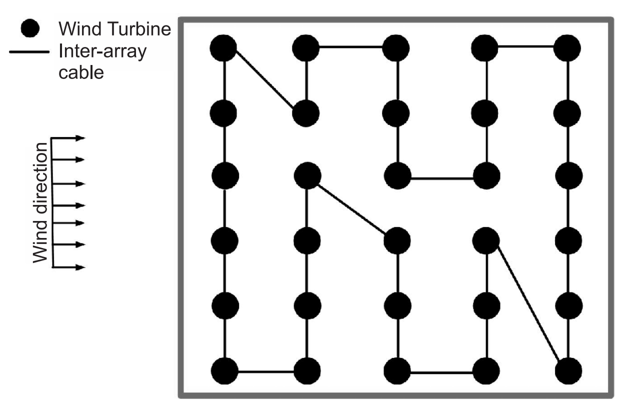

Figure 7: Ring OD of NH OWF without wake effect

2. **Case 2:** OD of NH OWF with wake effect: In case 2, OD is made based on length of IC and wake effect. The allocation of WT and distance between the WTs are decided by Larsen wake formation. The amount of wake effect is nullified, if (a) the WT b_x is placed with an angle (θ_1) of 18.44° with respect to WT a_x and (b) the WT c_x is placed with an angle (θ_2) greater than 4.20° with respect to

WT a_x. This pattern continues for next columns as indicated in Figure 8. The values of B_1 and B_2 are 0.882 D and 2D respectively.

Table 1
Estimated cost of components per unit

Components	*Estimated per unit [£millions]*
Inter array cable	0.50 (per km)
Transformer	0.75

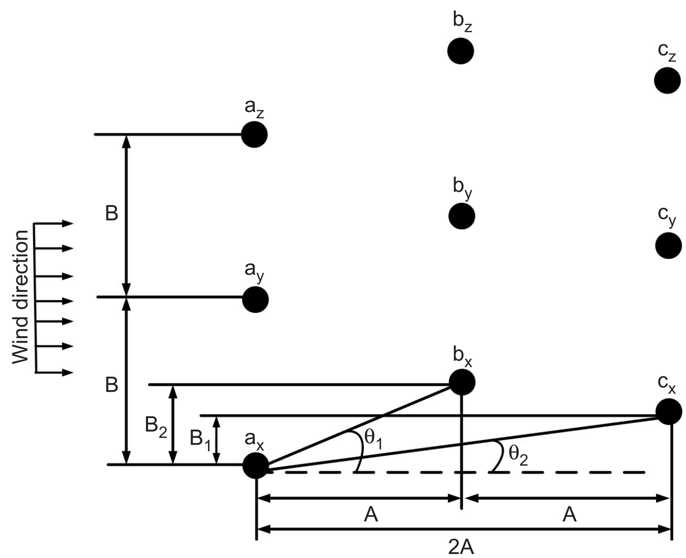

Figure 8: Model for optimal allocation of wind turbine

The OD of NH OWF with wake effect for radial topology (ODWRA) and ring topology (ODWRI) are shown respectively in Figure 9 and Figure 10. In this case the wake loss value is 1.8% and power production value is 98.2%. The comparison of ODWRA and ODWRI in terms of IC length and cost are given in Table 3.

Table 2
Results summary of optimal designs without wake effect

OWF	*Spacing between WTS in Rows/Columns*	*Cable Length [km]*	*Cable cost [£millions]*	*Power production [in percentage]*
NH	10D/4.375D	18.000	9.000	92.56
ODRA	6D/4D	9.920	4.960	79.97
ODRI	6D/4D	11.393	5.696	79.97

Table 3
Results summary of optimal designs with wake effect

OWF	*Spacing between WTS in Rows/Columns*	*Cable Length [km]*	*Cable cost [£millions]*	*Power production [in percentage]*
NH	10D/4.375D	18.000	9.000	92.56
ODWRA	6D/4D	9.988	4.994	98.20
ODWRI	6D/4D	11.545	5.772	98.20

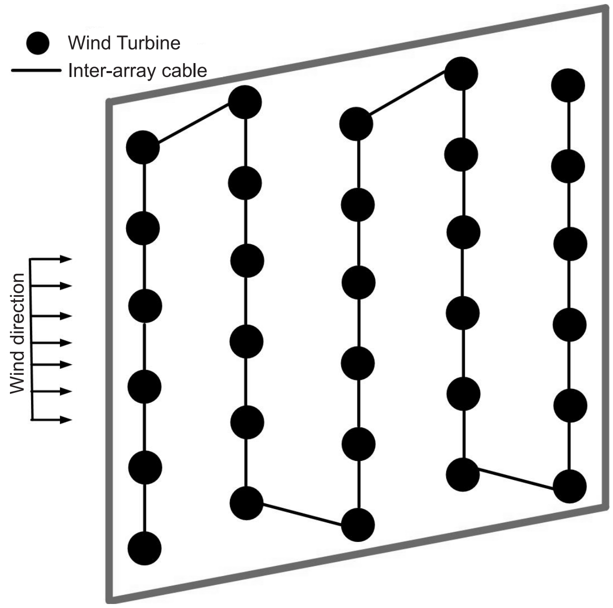

Figure 9: Radial OD of NH OWF with wake effect

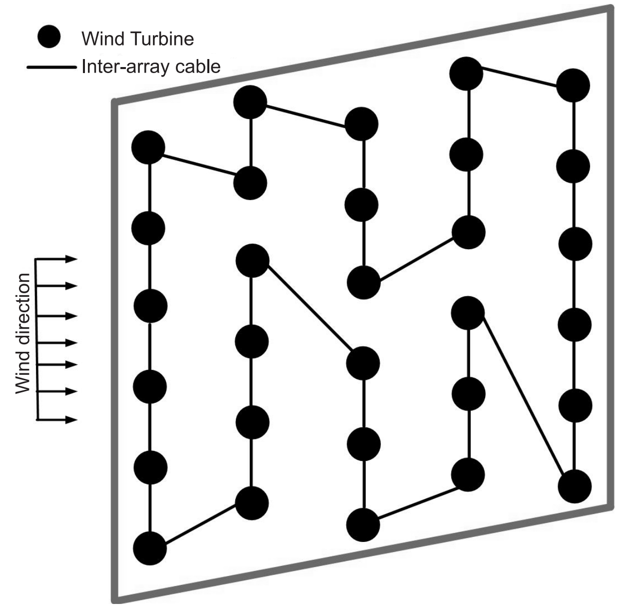

Figure 10: Ring OD of NH OWF with wake effect

5. CONCLUSION

In this paper new combinational approach of optimization techniques is used. The combination of ACO with TSP is applied to design optimal outcome of NH OWF. The radial and ring topologies are used for case study of NH OWF. Wake effect on OWF in terms of wake loss value and power production value is discussed. The ODs of NH OWF are made with consideration of with and without wake effect. The Larsen wake model was discussed in systematically with first order equations and solutions. It is used to allocate the WTs in optimal position with negligible effect of wake. The ODRA and ODWRA are based on radial topology designs. The ODRI and ODWRI are based on ring topology designs. The length of IC was minimized by ODs. It reduces the cost of cable and OWF. The IC cost of ODRA is 55.11% and ODWRA is 55.49% of NH OWF. This paper concludes that (a) ODRA and ODWRA are ODs for minimum length of IC and (b) ODRI and ODWRI are ODs for reliability.

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