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OPTIMAL DESIGN OF ONSHORE WIND FARM COLLECTOR SYSTEM USING PARTICLE SWARM OPTIMIZATION AND PRIM'S ALGORITHM

ALI ZANGENEH[1]

Key words: Onshore wind farm, Collector system, Particle swarm optimization (PSO), Prim's algorithm, Radial clustering.

Designing of wind farm collector system (WFCS) which aggregates and transmits generated electric power by wind turbines (WTs) into the main grid has become more important with increasing size and capacity of wind farms. This paper presents a heuristic algorithm based on the combination of radial clustering algorithm and Prim's algorithm to design the optimal collector system for an onshore wind farm. The objective of the proposed method is to minimize the total relative cost of the collector system branches, including the internal electric distribution network and the connecting sub-transmission/transmission line to the main grid. Applying this objective leads to a lower installation cost. The contribution of the paper is first proposing an approach to find the best location of the onshore wind farm's substation and second presenting a heuristic algorithm to determine the best radial configuration of the WFCS. In the latter case, a combination of the proposed heuristic radial clustering method and the Prim's algorithm is applied. A wind farm in southeast Iran, Khaf, is used in three scenarios to assess the effectiveness and performance of the proposed approach.

1. INTRODUCTION

Nowadays renewable energy sources (RES) have attracted much attention to generate electric power because of the factors such as global environmental concerns, technology development, and rising prices of the conventional fossil energy [1]. The wind turbine is one of the RES technologies that is emerging rapidly either as individual rural units or wind farms. Cost and efficiency of a wind farm are determined based on a variety of factors including wind speed, geographical conditions, type and size of wind turbines, reliability, the total length of the branches and its configuration in the collector system [2]. In large wind farms, optimal designing of the collector system has become more important due to the economic and technical issues. Wind farms can be installed in two types: offshore and onshore. In [3], the notable differences between these projects are assessed.

Design and construction of a wind farm include optimizing the layout and configuration of the internal electrical network which has the responsibility of aggregating generated power. This problem can be divided into three main stages: The first stage is to design the layout of wind farms to determine the location and sitting of the WTs [4, 5]. Sitting and designing of the wind farm's substation to transmit the energy to the main grid is performed in the second stage and finally, the optimal design of the distribution collector system to aggregate the generated power by WTs is in the last stage. The scope of this paper is to determine the best location of the wind farm's substation and optimal radial configuration for the distribution collector system of the wind farm.

One of the main difficulties of the optimal collector system design problem is the numerous feasible configurations from which to choose the best one. There are several approaches proposed for the collector system design, based on different mathematical models and solving methods. In [6, 7], the different configurations of the wind farm are compared from the efficiency viewpoint. Zhao *et al.* [8] apply a genetic algorithm in the electrical network optimization of a wind farm. The optimization model includes the reliability and levelized production cost of the wind farm. Lundberg, in his thesis [9] investigates the various layouts of wind farms, including both ac and dc electric networks. In the study, energy loss modeling of the wind farm as well as energy capture of wind turbines are calculated for various possible configurations. Also, the impact of power quality on different configurations is assessed in the point of common coupling (PCC). Authors of [10, 11] present a Benders' decomposition technique to design the optimal electric layout of an offshore wind farm. Their proposed approach based on the mixed-integer programming (MIP) results in a substantial time-saving. A stochastic optimization model that covers the three main factors of the collector system design, including investment cost, efficiency, and reliability are proposed in [12]. Dutta and Overbye [13], present a graph-theoretic approach, finding the minimum spanning tree with considering the maximum number of turbines in each cable route.

This paper proposes a heuristic algorithm based on the radial clustering as well as Prim's algorithm to determine the optimal substation site and collector system design for an onshore wind farm in southeast Iran, Khaf. In the proposed approach, the best location of the wind farm's substation is determined in three possible scenarios. Besides, the optimal onshore collector system corresponding to each scenario is obtained and compared. The optimal configuration of the collector system is determined so that the total relative cost of the branches is minimized. This purpose will lead to the minimum installation cost due to reducing the equipment cost. The assumptions which are considered in the proposed decision-making model are:

a) The placement, type, and capacity of the wind turbines are assumed known in this study. They have already been determined in a previous study

[1] Department of Electrical Engineering, Shahid Rajaee Teacher Training University, P. O. Box 1678815811, Tehran, Iran.
E-mail: a.zangeneh@srttu.edu

based on some factors like wind speed and direction profile, type and characteristics of the selected wind turbines, wake effects, and so on.

b) The region of the onshore wind farm, Khaf, has no terrain geographical constraint to install the collector system as an overhead distribution system.

c) According to the capacity of Khaf wind farm, it is assumed that only one substation is required for a wind farm to transmit the generated power into the main grid.

Also, the content and contribution of the paper can be organized as follows:

a) Propose a heuristic algorithm and apply it to optimally design the collector system of a real onshore wind farm in Khaf.

b) Propose a radial clustering algorithm to find the wind turbines which have to be connected to the same feeder in the radial configuration of the distribution system.

c) Siting the wind farm's substation by considering the total length of the collector system and the sub-transmission branch connecting to the main grid.

This paper is organized as follows: the problem definition, including determination of the onshore wind farm's substation and collector system design is presented in Section 2. Section 3 describes the Prim's algorithm as one of the well-known methods in graph theory to determine the minimum spanning tree (MST). The numerical results of a practical case study in Khaf, southeastern Iran, is presented in Section 4 for three scenarios. Finally, the conclusion has been presented in Section 5.

2. PROBLEM DEFINITION

The proposed model of designing an optimal collector system for an onshore wind farm consists of three main steps. The first step is to find the best location for the onshore wind farm's substation, which is responsible to aggregate the generated power of all wind turbines and to transmit it to the main electric network. The substation has to be installed in the wind farm territory, either on the border or inside the wind farm. In the next step, the optimal number and configuration of the feeders for the wind farm collector system are determined based on a proposed heuristic radial clustering. The optimal number of the feeders depends on the nominal ampacity of the selected feeders and capacity of wind turbines. In this step, each wind turbine is assigned to a defined cluster. Since all the wind turbines have to be connected through radial feeders (clusters) to the wind farm's substation, a heuristic radial clustering is applied in this step. Unlike the conventional clustering approaches, which are just based on the nearest distance between vertices (nodes), the proposed heuristic approach sets the vertices (wind turbines in this study) in the same cluster based on the proximity angle and distance between them. The last step determines how the wind turbines in each cluster are connected so that the minimum total length is obtained. Prim's algorithm is used to determine the best configuration of the radial feeder in each cluster.

2.1. WIND FARM SUBSTATION PLACEMENT

The optimal siting of the onshore wind farm's substation is similar to the substation placement in a distribution network planning, which is usually found using load gravity point of the distribution networks. In other words, the substation placement is usually determined using the minimum distance between load points and substation in both problems. Wind turbines are considered as negative load points in the wind farm designing so that the generated power direction is reversed and power flows from the wind turbines to the substation and then, to the transmission network. Another difference is that all wind turbines in the wind farm usually have equal capacity while the load distribution may be heterogeneous and non-uniform throughout the distribution network. Thus the gravity point of the wind farm can be an appropriate choice to install the substation, especially in the case that the density of wind turbines is high. In [14], the authors applied (1) to determine the wind farm's substation.

$$\min \sum_{i=1}^{n_T} \left[\left(X_i - C_x \right)^2 + \left(Y_i - C_y \right)^2 \right]^{1/2} , \qquad (1)$$

where X_i and Y_i are longitude and latitude of the i^{th} wind turbine respectively. C_x, C_y are respectively the longitude and latitude of the wind farm's substation which should be determined and n_T is the total number of wind turbines.

Although the gravity center obtained by (1) provides the minimum total length of connections of all wind turbines, the length of the overhead sub-transmission line that connects the wind farm's substation to the main grid is not considered in (1).

This line has a significant portion of the total cost in the collector system design. In Khaf project, the installation cost of the overhead sub-transmission line (132 kV) is approximately four times of the collector system feeders (20 kV). Therefore, Eq. (2) is proposed by adding the distance between wind farm substation and main grid into (1) as follow.

$$\min_{C_x, C_y} w_1 \sum_{i=1}^{n_T} \left[\left(X_i - C_x \right)^2 + \left(Y_i - C_y \right)^2 \right]^{1/2} + w_2 \sum_{i=1}^{n_T} \left[\left(X_{mg} - C_x \right)^2 + \left(Y_{mg} - C_y \right)^2 \right]^{1/2} , \qquad (2)$$

where X_{mg}, Y_{mg} are respectively the longitude and latitude of the nearest main grid substation, which is connected to the wind farm substation and w_1, w_2 are the coefficients regarding the relative cost of distribution and sub-transmission overhead lines. By optimizing (2) using a PSO algorithm, the substation of the wind farm is placed somewhere on a straight line between the gravity point of the wind farm and the substation of the main grid depending on the values of the relative weight factors. It should be noted that the total length that is calculated in (1) and the first term of (2) is the total length between the wind farm substation and each wind turbine individually. However, in the practical design, a cluster of wind turbines is connected to the substation with the same feeder. Therefore the total calculated length of the distribution lines of the collector system is greater than its real value. This

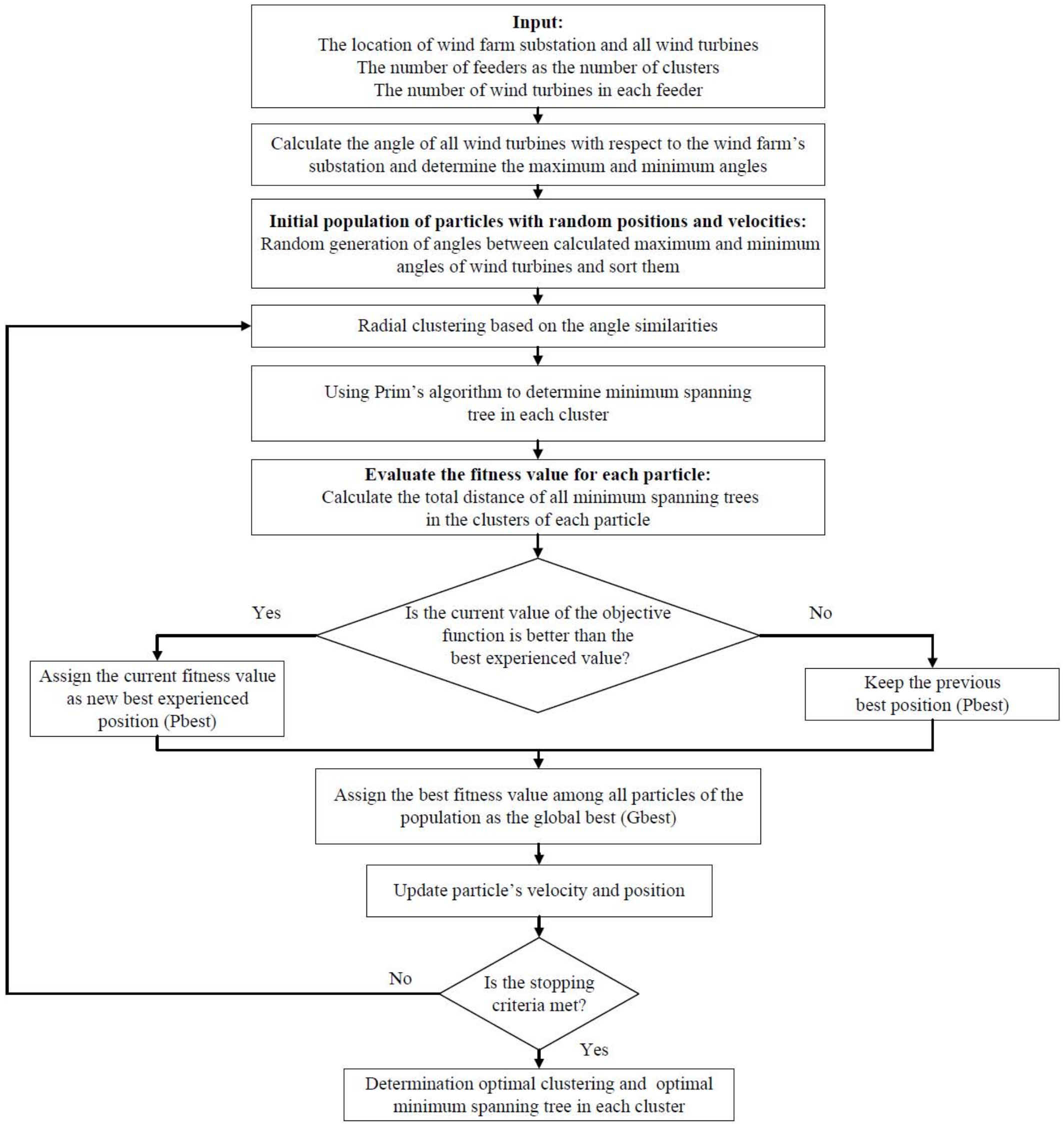


Fig. 1 – The proposed design algorithm of the wind farm collector system.

deviation is important in (2) that causes to enlarge the effects of the first term with respect to the second term and makes a significant error. As previously mentioned the second weight factor (w_2) is approximately four times of w_1, because of the ratio 4:1 of installation cost.

2.2. OPTIMAL DESIGN OF WIND FARM COLLECTOR SYSTEM

The algorithm shown in Fig. 1 demonstrates the second and third steps of the proposed approach in which a particle swarm optimization (PSO) method [15, 16], combined with the Prim's algorithm is applied to find the best clusters with a minimum spanning tree. The clustering is performed based on a proposed heuristic radial approach. At the beginning of the algorithm, the angle of all the wind turbines is determined concerning their geographical positions and the specified wind farm substation. In this approach, the substation of the wind farm is set as the origin of the Cartesian coordinate system, and the geographical angle of each wind turbine is calculated in this system. Afterward, the maximum and minimum angles are specified as the marginal borders of the wind farm. To start the PSO algorithm, some particles are initialized as the random angles (θ_j) between the calculated minimum and maximum angle values. These random angles are sort in ascending order to make angular sectors as initial clusters shown in Fig. 2. Radial clustering is made by assigning the calculated angle of each WT into formed clusters based on the concept of the angle similarity. After that, the minimum spanning tree (MST) is determined in each cluster. The sum of the total distances obtained with the Prim's algorithm is considered as the fitness function for PSO. This process is repeated until the best clusters and MST are obtained through the particle swarm optimization included in the algorithm of Fig. 1.

2.2.1. A HEURISTIC RADIAL CLUSTERING ALGORITHM

K-means is one of the popular clustering algorithms. It is assumed that the clusters are formed based on the minimum distance of the points to their cluster centers. The aim of this algorithm is to find the k mean vectors $\{\mathbf{c}_1, \ldots, \mathbf{c}_k\}$ on an interleaving approach according to (3). The cluster assignments $y_i \in \{1,\ldots,k\}$ are established given the centers and the centers are computed given the assignments [17].

$$\min_{y_1,\dots,y_k,c_1,\dots,c_k} \sum_{j=1}^{k}\sum_{y_i=j}\left\|x_i - c_j\right\|^2 , \qquad (3)$$

where $\|\cdot\|$ represents the Euclidian norm.

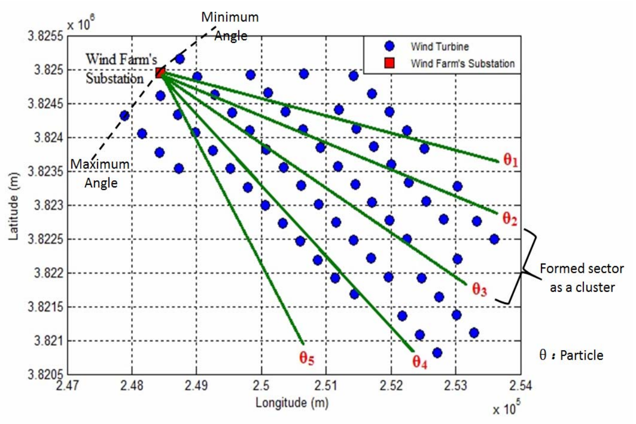


Fig. 2 – Radial clustering in a typical wind farm.

Due to the radial nature of the distribution WFCS, the *K*-means clustering algorithm is not useful and appropriate to find the best configuration of the feeders. Thus a heuristic radial clustering algorithm is proposed in this paper based on the concept of the *K*-means clustering algorithm. The main idea behind the algorithm is to find *k*-sectors shown in Fig 2 instead of the *k* mean centers and determine the minimum spanning tree (MST) of the all assigned points in each sector so that the total length of all MSTs is minimized (4).

$$\min_{\theta_1,\dots,\theta_k} \sum_{j=1}^{k+1} \text{Lenght}\Big(\text{PRIM}\big(S(\theta_j,\theta_{j+1})\big)\Big) , \qquad (4)$$

where $S(\theta_j,\theta_{j+1})$ is the set of points (here WTs) in the sector between angles θ_j and θ_{j+1}. PRIM is the function of the Prim's algorithm to form the MST and Length is the function to calculate the total length of the MST.

2.2.2. PSO ALGORITHM

The PSO algorithm consists of three main steps, which are repeated until the stopping condition is met:

a) Evaluate the fitness of each particle: in this paper, the fitness function is the total length of the cables in the collector system, which is obtained as the sum of the all minimum spanning trees.
b) Update individual and global best fitness and positions: as shown in Fig. 2, the positions of the PSO algorithm are angles, which form the radial clusters.
c) Update velocity and position of each particle according to (5) and (6) respectively.

$$v_i(t+1) = \omega v_i(t) + c_1 r_1\left[\hat{x}_i(t) - x_i(t)\right] + c_2 r_2\left[g(t) - x_i(t)\right] , \qquad (5)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) , \qquad (6)$$

where $x_i(t)$ and $v_i(t)$ are the position and velocity of the i^{th} particle at iteration t, the parameters ω, c_1 and c_2 are user-supplied coefficients, The values r_1 and r_2 are respectively random values which are regenerated for each velocity update. The value $\hat{x}_i(t)$ is the individual best solution for particle *i* at iteration *t* and g(*t*) is the swarm's global best solution at iteration *t*.

3. MINIMUM SPANNING TREE-PRIM'S ALGORITHM

A spanning tree of an undirected graph is just a subgraph that contains all the vertices without forming any loops between them. Therefore, it is possible to find a lot of spanning trees for a graph. If the edges of the graph have weight, the minimum spanning tree (MST) is defined as a spanning tree with minimum total weight [18, 19]. Many various algorithms have been proposed so far to find the MST of a graph. Among them, Prim's algorithm is a greedy algorithm to find the MST of a graph. In this paper, Prim's algorithm [18] is used to determine the best configuration of a feeder with a minimum total length in each cluster. The pseudocode of the algorithm is presented as follows [20]. In this algorithm, it is assumed that V and E is the set of vertices and edges respectively, w is the weight of the edge, *r* is an arbitrary vertex as the root of MST, V_T is the set of vertices during MST construction and d[v] holds the weight of the edge with the least weight from any vertex in V_T to vertex v.

```
procedure PRIM_MST(V, E, w, r)
begin
  V_T := {r};
  d[r] := 0;
  for all v ϵ (V-V_T) do
     if edge (r, v) exists, set d[v] := w(r,v);
     else set d[v] := ∞;
  end
  while V_T ≠ V do
     find a vertex u such that
        d[u] := min {d[v] | v (V - V_T) };
     V_T := V_T ⋃ {u}
     for all v ϵ (V-V_T) do
        d[v] := min {d[v] , w(r,v)};
 end while
   end PRIM_MST
```

4. NUMERICAL RESULTS

Iran has suitable potential to develop the construction and operation of wind turbine due to the windy areas. One of the large wind investments is going to be carried out in Khaf, an area in southeastern Iran with a good wind speed almost throughout the whole year [21]. It has been determined as an interesting place to install wind farms. Figure 3 shows the first phase of the project, including 63 WTs of 1.5 MW with a total capacity of about 100 MW.

The numbers and layout of the wind turbines in the wind farm have been determined based on a previous study considering the speed and direction of the wind, wake effect and terrain conditions. The position of the wind farm, the 132 kV overhead line and substation of Khaf are also depicted in Fig. 3. The voltage of the collector system is selected 20 kV according to the standard voltage level of the distribution system in Iran and the voltage of the wind farm substation is 132/20 kV to connect to the main grid.

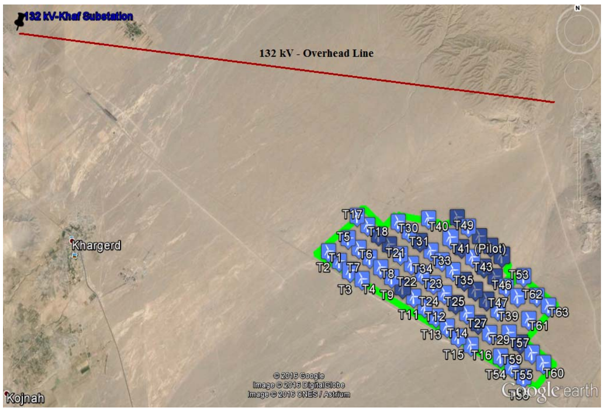


Fig. 3 – The position of Khaf wind farm, the 132 kV-overhead line and Khaf substation.

There are three scenarios for locating the wind farm substation: (a) the gravity point of the wind farm, (b) a point on the line between the wind farm's gravity point and Khaf substation, and (c) a point on the shortest path between the gravity point and the 132 kV-overhead line in north of the wind farm.

The gravity point of the wind farm, which has the minimum total length from all the wind turbines, is calculated using (1) and shown in Fig. 4. By considering the length of the 132 kV overhead line which connects the wind farm into the main grid, the best location of the wind farm substation will change. Scenarios (b) and (c) consider the length of the sub-transmission overhead line connecting the wind farm to the main grid to determine the wind farm substation. Figure 5 shows how choosing the weight factor in (2) can move the location of the substation in the line between the wind farm's gravity point and the 132 kV Khaf substation in scenario b. In Fig. 5a, an equal weight factor is applied in (2) while Fig. 5b shows the case in which the weight factor of the 132 kV line (w_2) is fourfold of the weight factor for 20 kV collector system branches (w_1) due to their relative installation costs.

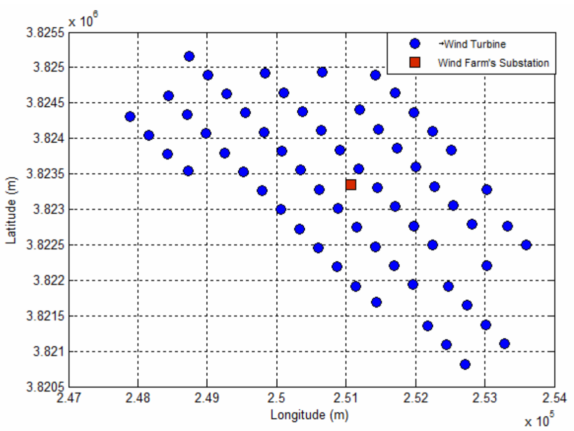
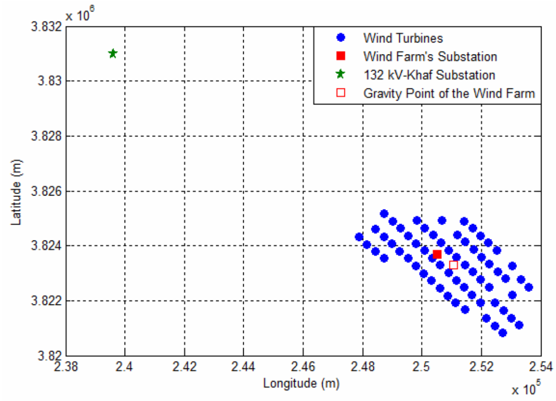
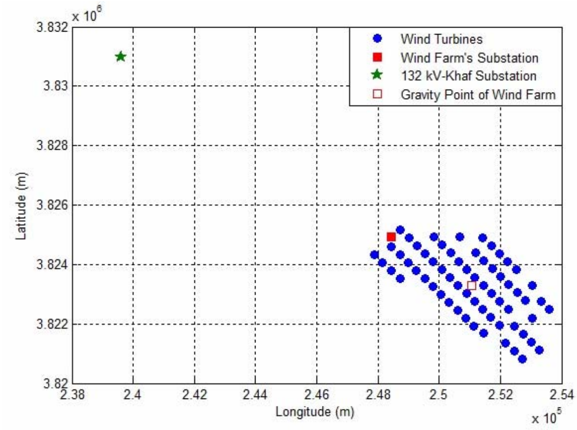


Fig. 4 – The gravity point of the wind farm as a potential point to install the wind farm's substation.



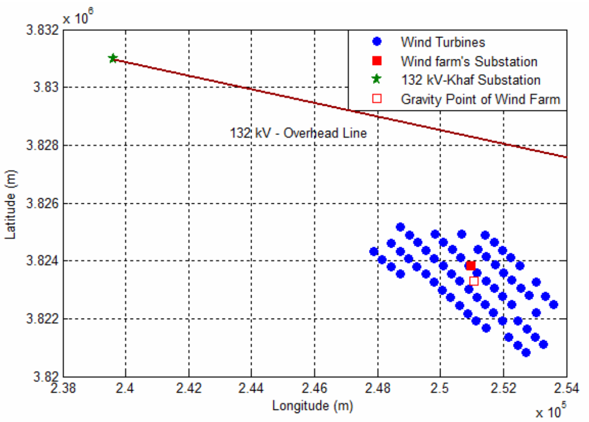
(a) weighting factors: $w_1 = w_2 = 0.5$



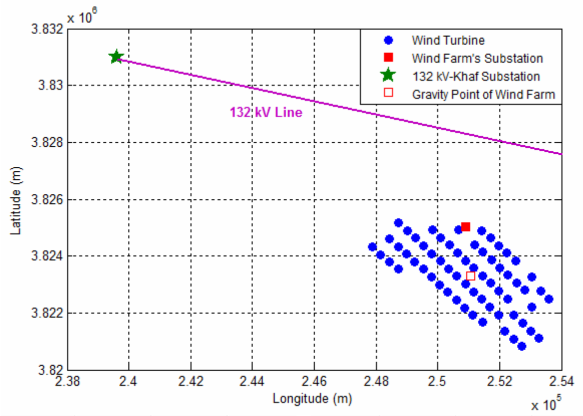
(b) weighting factors: $w_1 = 0.2$ and $w_2 = 0.8$

Fig. 5 – The position of the wind farm's substation regarding the gravity point of the wind farm and Khaf substation (scenario b).

Figure 6 shows the position of the wind farm substation with respect to the gravity point, as the nearest point to all the WTs, and the 132 kV overhead lines in the north wind farm. The location of the wind farms substation is not along the vertical line to the 132 kV overhead transmission line due to the terrain barriers in the north wind farm. In this case, besides wind farm substation, an additional substation needs to be constructed on the route of the sub-transmission line.



(a) weighting factors: $w_1 = w_2 = 0.5$



(b) weighting factors: w_1= 0.2 and w_2=0.8

Fig. 6 – The position of the wind farm's substation regarding the gravity point of the wind farm and 132 kV- overhead line (scenario c).

After determining the location of the wind farm substation in three scenarios, the second and third steps of the collector system design is performed according to the algorithm shown in Fig. 1 to determine the optimal clusters of WTs, optimal configuration and MST in each cluster. The proposed algorithm is run for different locations of wind farm substation determined in the three scenarios.
The parameters setting of PSO algorithm has a crucial influence in finding the final solution. Especially choosing an appropriate inertia weight w is an important duty and various works have been done to select it. The initial values of the ω, c_1 and c_2 are assumed equal to 0.7298, 1.4962 and 1.4962 respectively and they are considered constant, $\varphi_1=2.05$, $\varphi_2=2.05$ and $\varphi=\varphi_1+\varphi_2=4.1$,

$$\omega=2\Big/\left(\varphi-2+\sqrt{\varphi^2-4\varphi}\right)=0.7298 ,$$

$$c_1=\omega\times\varphi_1=1.4962 \text{ and } c_2=\omega\times\varphi_2=1.4962 .$$

The minimum and maximum values of velocities are set as follows. First, the maximum (VarMax) and minimum (VarMin) angles of the position wind turbines are determined with respect to the location of the substation. Then the maximum velocity is set based on the 0.1*(VarMax-VarMin), which is equal to 12.62°. The minimum velocity is defined as the minus of maximum velocity equal to –12.62. The particles are initialized using a uniform random function in the MATLAB, which generates numbers between maximum and minimum angles. The velocities are initialized as zero values and are limited between maximum and minimum velocities during iterations. If the position of the particles is violated from the allowable range, it is fixed on the maximum or minimum values of the variable. As well, the number of populations is assumed constant during iterations.

Figure 7 shows the convergence of the PSO algorithm to determine the best radial configuration of the collector system in scenario a. The number of population and iteration in the PSO algorithm is equal to 100.

Figure 8 shows two optimal configurations for 8 clusters and a maximum of 10 WTs in each cluster (8a) and 6 clusters with a maximum of 12 WTs in each cluster (8b) respectively. The total length of the 20 kV distribution collector system in Fig 8a and 8b are equal to 27674.2 m and 29160.7 m, respectively. Therefore, the configuration of the collector system is selected as 7 feeders of double circuit 20 kV overhead lines in this scenario.

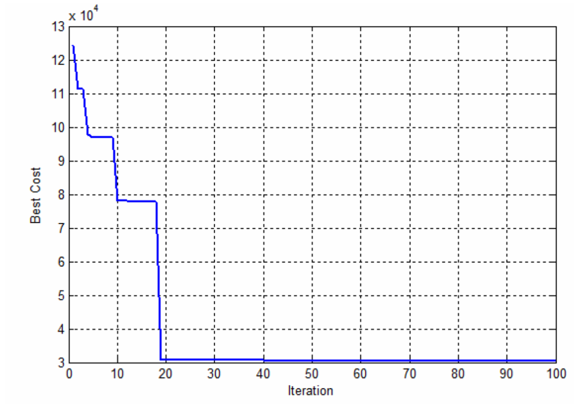
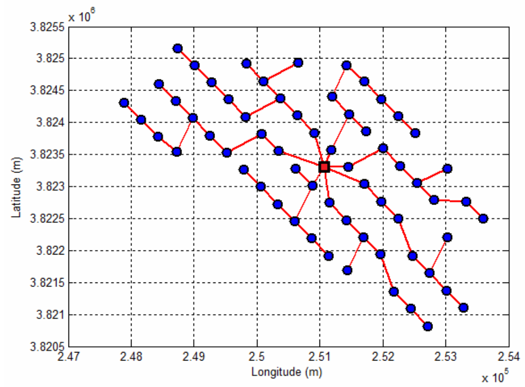
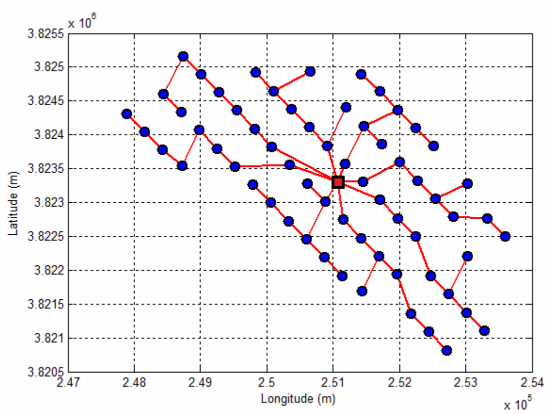


Fig. 7. Convergence curve of PSO algorithm

Figure 9 shows the optimal configuration of the collector system in the scenario (b). In this scenario, the substation is located northwest in the nearest point of the wind farm to the 132 kV Khaf substation. Various configurations based on the number of feeders and maximum WT in each feeder is scrutinized and two configurations with a total length of 33876 m and 29968 m are depicted in Fig. 9a and 9b respectively.



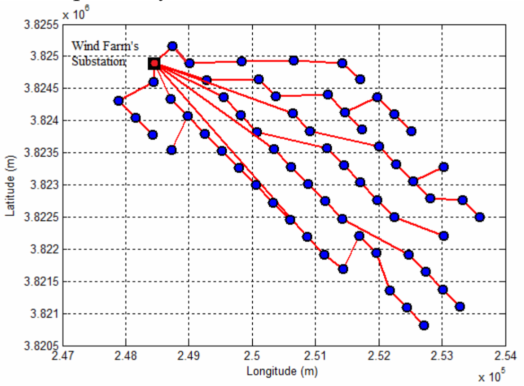
(a) Number of feeders or clusters: 7 and maximum number of WTs in each cluster: 12



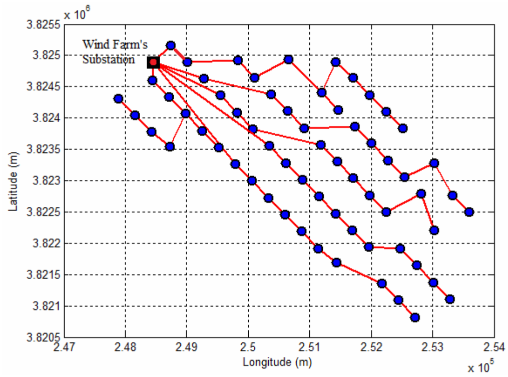
(b) Number of feeders or clusters: 8 and maximum number of WTs in each cluster: 10

Fig. 8. Optimal configuration of WFCS in the scenario a.

In scenario (c), the substation of the wind farm is in the nearest point to the 132 kV overhead line in the north of the wind farm, but it is necessary to install an additional 20/132 kV substation to connect the wind farm to the main grid. Fig 10a and 10b show two optimal configurations in this scenario for a different number of feeders and maximum WTs in each feeder with a total length of 30369 m and 33719 m respectively.

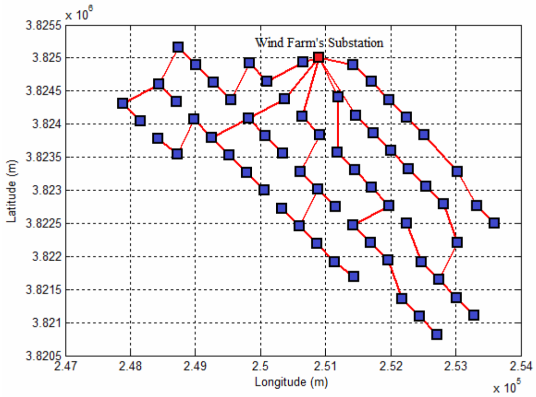


(a) Number of feeders or clusters:8 and maximum number of WTs in each cluster: 10

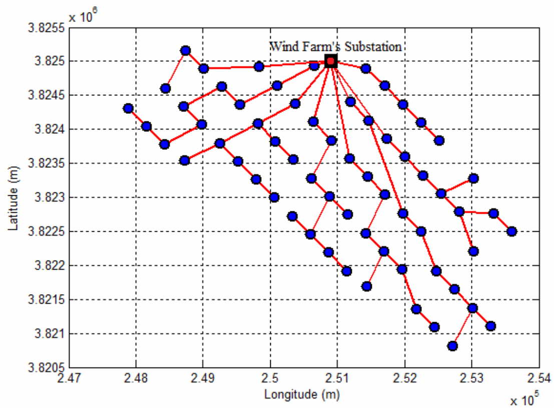


(b) Number of feeders or clusters:6 and maximum number of WTs in each cluster: 12

Fig. 9. Optimal configuration of WFCS in the scenario b.



(a) Number of feeders or clusters: 6 and maximum number of WTs in each cluster: 12



(b) Number of feeders or clusters:8 and maximum number of WTs in each cluster: 10

Fig. 10. Optimal configuration of WFCS in the scenario c

Table 1 summarizes the information about the best configuration in each scenario to compare the obtained results. As it can be observed, the 132 kV lines have a significant role in the total cost and consequently, the shorter 132 kV line will lead to the lower total cost. Although the scenario (c) has the minimum total length of 132 kV line, the required additional substation, make it an inappropriate option for Khaf wind farm. Thus the configuration of the collector system obtained in scenario (b) is the best option to choose.

To assess the effects of various weight factors on the location of the wind farm substation and the collector system, five case studies with different weight factors are defined in table 2 for scenario b with 8 clusters and maximum of 10 WTs in each cluster. The case studies and their results in the siting of the wind farm substation according to the objective function (2) are presented in table 2. The total installation cost of each case study, including the installation cost of 132 kV overhead-line as well as 20 kV collector system are presented in table 3.

Table 1

Approximate cost of the WFCS design

		Scenario (a)	Scenario (b)	Scenario (c)
20 kV Overhead lines	Total length (km)	27.674	29.968	30.369
	Total cost (M$)	0.83	0.9	0.911
132 kV Overhead lines	Total length (km)	13.82	10.75	3.54
	Total cost (M$)	1.65	1.29	0.425
Cost of additional 20/132 kV substation (M$)		–	–	2
Total cost of collector system (M$)		2.48	2.19	3.34

In Table 2, $f = (w_1f_1+w_2f_2)$ is the objective function (2), f_1 and f_2 denote to the first and second summation in (2) respectively. Based on the current data regarding the relative costs between 20 and 132 kV overhead lines in Iran, the ratio of w_1:w_2 is 1:4. The obtained results illustrate that by increasing (or decreasing) the w_2 with respect to the current state, the optimal location of the wind farm's substation tends to move toward Khaf substation (or the gravity point of the wind farm) to decrease total costs. This issue is shown in Table 3 that includes the variations of the total length and cost of the 20 kV and 132 kV overhead lines as well as the total cost of the collector system in different case studies of scenario b.

5. CONCLUSIONS

This paper proposes a heuristic algorithm to optimally design the collector system of a wind farm. The algorithm is based on the combination of the two methods: radial clustering based on angles similarities with included simultaneously finding of the minimum spanning tree in each cluster.

The radial based clustering approach clusters the wind turbines using the similarity of the angles between WTs and substation and performs the minimum spanning tree between WTs of a cluster with the PSO heuristic algorithm.

Table 2

The sensitivity of the substation location with respect to the weight factors

Case	w_1	w_2	f_1 (m)	f_2 (m)	f	The distance of the wind farm's substation to the Khaf substation (m)	The distance of the wind farm's substation to the gravity point (m)
1	0.1	0.9	108555	7280	17408	7280	6535
2	0.15	0.85	60683	9391	17084	9391	4424
3	0.2	0.8	41768	10750	16954	10750	3096
4	0.25	0.75	34255	11674	17319	11674	2141
5	0.3	0.7	29879	12390	17637	12390	1425

This approach can be very useful and effective in designing the radial distribution network compared to the conventional clustering approaches. The Prim's algorithm finds the best minimum spanning tree with a minimum total length in each cluster. The proposed approach is applied in the practical wind farm in southeast Iran, Khaf, in different scenarios.

Table 3

Total cost of collector systems in various case studies

		Case #1	Case #2	Case #3	Case #4	Case #5
20 kV Overhead lines	Total length (km)	53.103	41.771	29.968	27.025	25.268
	Total Cost (M$)	1.595	1.254	0.9	0.812	0.759
132 kV Overhead lines	Total length (km)	7.280	9.391	10.750	11.674	12.390
	Total Cost (M$)	0.874	1.127	1.29	1.401	1.487
Cost of Additional 20/132 kV Substation (M$)		-	-	-	-	-
Total Cost of Collector System (M$)		2.469	2.381	2.19	2.213	2.246

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REFERENCES

1. Y. Eroglu, S. U. Seçkiner, *Wind farm layout optimization using particle filtering approach*, Renewable Energy, **58**, pp. 95-107 (2013).
2. M. De Prada Gil, J.L. Domínguez-García, F. Díaz-Gonz_alez, M. Aragües-Penalba, O. Gomis-Bellmunt, *Feasibility analysis of offshore wind power plants with dc, collection grid*, Renewable Energy, **78**, pp. 467-477 (2015).
3. P. Enevoldsen, S.V. Valentine, *Do onshore and offshore wind farm development patterns differ?*, Energy for Sustainable Development, **35**, pp. 41–51 (2016).
4. L. Wang, A. Tan, Y. Gu, *A novel control strategy approach to optimally design a wind farm layout*, Renewable Energy, **95**, pp. 10-21 (2016).
5. D. Christie, M. Bradley, *Optimising land use for wind farms*, Energy for Sustainable Development, **16**, pp. 471–475 (2012).
6. A. Demean, V. Topa, C. Munteanu, R. Rizzo, *Comparative study in terms of efficiency of different wind farms structures*. Int Conf Clean Electrical Power (ICCEP), Ischia, Italy, pp. 517-520 (2011).
7. Z. Li, M. Zhao, Z. Chen, *Efficiency Evaluation for Offshore Wind Farms, Int Conf Power System Technology*, Chongqing, China, pp. 1-6, (2006).
8. M. Zhao, Z. Chen, J. Hjerrild, *Analysis of the Behavior of Genetic Algorithm Applied in Optimization of Electrical System Design for Offshore Wind Farms,* 32nd Annual Conf Industrial Electronics, Paris, France, pp. 2335–2340 (2006).
9. S. Lundberg, *Configuration study of larger wind parks*, Ph.D. thesis Chalmers University of technology, Gutenberg, Sweden 2003, ISSN 1651-4998.
10. S. Lumbreras, A. Ramos, *A Benders' decomposition approach for optimizing the electric system of offshore wind farms*, IEEE Conf PowerTech, Trondheim, Norway, pp. 1-8 (2011).
11. S. Lumbreras, A. Ramos, *Optimal Design of the Electrical Layout of an Offshore Wind Farm Applying Decomposition Strategies,* IEEE Trans. Power Systems, **28**, *2*, pp. 1434-1441 (2013).
12. M. Banzo, A. Ramos, *Stochastic Optimization Model for Electric Power System Planning of Offshore Wind Farms*, IEEE Trans. Power Systems, **26**, *3*, pp. 1338-1348 (2011).
13. S. Dutta, T.J. Overbye, *Optimal Wind Farm Collector System Topology Design Considering Total Trenching Length*, IEEE Trans. Sustainable Energy, **3**, *3*, pp. 339-348 (2012).
14. P.D. Hopewell, F. Castro-Sayas, D.I. Bailey, *Optimizing the design of offshore wind farm collection networks*, Proceedings of the 41st International Universities Power Engineering Conference (UPEC), Newcastle, UK. pp. 84-88 (2006).
15. P. Hou, W. Hu, M. Soltani, Z. Chen, *Optimized Placement of Wind Turbines in Large-Scale Offshore Wind Farm Using Particle Swarm Optimization Algorithm*, IEEE Trans. Sustainable Energy, **6**, *4*, pp. 1272 – 1282 (2015).
16. P. Hou, W. Hu, Z. Chen, *Optimisation for offshore wind farm cable connection layout using adaptive particle swarm optimisation minimum spanning tree method*, IET Renew. Power Gener., **10**, *5*, pp. 694–702 (2016).
17. www.cs.huji.ac.il/~shashua/papers/class9-clustering.pdf
18. P. Hou, W. Hu, Z. Chen, *Offshore substation locating in wind farms based on Prim algorithm*, IEEE Power & Energy Society General Meeting, Denver, CO, USA, pp. 1–5 (2015).
19. R. Sedgewick, P. Flajolet, *An introduction to the analysis of algorithms (2nd Ed.),* Addison-Wesley Professional, Boston, 2013, pp. 319-336.
20. http://parallelcomp.uw.hu/ch10lev1sec2.html
21. http://www.thewindpower.net/report_en_136-iran-wind-energy-outlook.php.