A Clustering based Wind Farm Collector System Cable Layout Design

S. Dutta, *Student Member, IEEE*, and T. J. Overbye, *Fellow, IEEE*

Abstract— **The goal of achieving 20% wind power penetration by 2030 in the US has stimulated the installation of large scale wind farms in recent years, both on-shore and off-shore. Collector systems consolidate the power generated by turbine units distributed over the geographical area of the wind farm to a substation from where the generated power is transmitted to the electric grid. Design of a wind farm collector system must take into consideration the economics and reliability of operation. Most modern day large scale wind farms consist of hundreds of wind turbines and are generally electrically connected in a radial feeder cable configuration or daisy chains. While these configurations are generally accepted as convention, not much research has been done to analyze other cable layout configurations.**

This paper proposes a clustering based algorithm for cable layout of a large scale wind power plant. Comparison of the proposed method with the radial feeder cable configuration shows that real power losses in collector system are lowered and greater reliability is achieved with the proposed design. An economic analysis has also been done to compare the cost of generated energy associated with the proposed design and the conventional configuration.

Index Terms— **cable layout, clustering algorithm, power loss, quality threshold clustering, wind farm collector system.**

I. INTRODUCTION

UNLIKE traditional power generating plants which are built around a few high rating generating units within a single location, wind farms aggregate the power generated by a multiplicity of small wind powered generators spread out over a large area. The energy generated by each unit is collected and channeled to a substation by means of a network of medium-voltage cables called a collector system. Due to the large separation between the wind turbines and the large area of wind farms, typical cable collector systems can measure over a hundred three-phase circuit miles. Hence, the reliability of the entire wind farm is strongly impacted by the reliability of the collector system. The large expanse and medium voltage of the collector system also results in the collector system representing the largest portion of the total wind farm losses. This paper proposes a cable layout design methodology that reduces active power losses in the collector system significantly compared to the conventional radial system configuration while improving the reliability of the system.

Wind turbine locations and point of interconnection to the electric grid are the primary factors in the design and layout of feeder topology. Other factors include terrain, reliability, landowner requirements, power losses, economics, and climate of the location [1]. Since the point of interconnection is typically located at the wind farm substation, for this work, only the feeder topology from turbine locations to the substation has been considered.

Collector system electrical power losses impact the economic evaluation of wind farm operation. Investments for loss reduction can generate substantial returns in the long-term [2]. Intuitively, to lower power losses, the conductor lengths should be shorter and area of cross-section should be larger. However, shortening conductor lengths may not always be possible due to constraints of land owners, terrain, access roads, and point of interconnection. In addition, the cable sizing is typically dictated by the costs, thermal resistivity of the soil, ampacity requirements, short-circuit withstand requirements, and conductor arrangement in the trench.

Collector systems can be structured in different configurations with varying levels of collector system reliability. Typical collector system configurations are:

- Loop system- This system provides a redundant path for the generator output for each turbine by establishing a looped circuit between the wind turbines. In the event of cable failure, the loop can be opened and the full output of the wind farm can be maintained.
- Single string- This system places all of the wind turbines on a single series circuit. In the event of a cable failure, the wind turbines located beyond the faulted cable would not be available until the cable is repaired.
- Multiple string- This system distributes the wind turbines over several series circuits and permits the use of lower rated equipment. Similar to the single string configuration, in the event of cable failure the wind turbines beyond the faulted cable will not be available until the cable is repaired.

Radial feeder or string configurations are commonly used in the US. However, these configurations compromise system reliability since a fault in a given collector circuit cable will result in an outage of all wind turbines connected to that particular circuit.

Feeder strings may be underground or overhead. The number of wind turbines on a feeder string is limited by conductor ampacity. Underground feeders are generally limited to 25 to 30 MW per string due to soil thermal

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The authors are with the Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801 USA (e-mail: dutta4@illinois.edu; overbye@illinois.edu).

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conditions and available cable sizes. Overhead conductors can carry 40 to 50 MW per string but have higher losses associated.

Most wind farms today connect the wind turbines in a radial feeder configuration or daisy chains. While these configurations are generally accepted as convention, not much research has been done to analyze other cable layout configurations. Although available literature documents work done on layouts of large scale wind farms such as evaluation of AC and/or DC collection systems in varying voltage levels [3], most of these works assume turbines connected in a daisy chain. The present paper proposes a clustering based cable layout configuration. Clustering analysis has been used in earlier research works on wind turbines, but has not been used for collector system design. Most clustering algorithms were used to group wind turbines based on power output for controller system design and development of power forecasting algorithms [4].

The remaining paper is organized as follows: Section II discusses some of the mathematical considerations of the addressed problem. Section III presents the proposed methodology. Section IV describes the quality threshold clustering algorithm. Section V describes the sizes and properties of available cables for the collector system in this paper. Section VI focuses on the procedure for cost analysis. Section VII presents the results and discussions. Finally, conclusions have been made in Section VIII.

II. Mathematical Considerations

The problem of cable layout design for a wind farm collector system can be considered as finding a tree to meet required design characteristics in a graph G = (V, E), where V represents the set of vertices or locations of wind turbines and the substation, and E represents the set of edges connecting the vertices. Given the set of vertices, there can be numerous possible trees satisfying specific design constraints. Hence, finding an optimal tree can be extremely difficult especially if the problem allows the addition of intermediate vertices and edges to the graph in order to improve the value of the objective function. For instance, given a large number of wind turbine locations, the problem of minimizing the total length of cables is NP-hard [5]. Hence, in this work, instead of addressing the optimality of the proposed cable layout, an effort has been made to develop a cable layout algorithm that improves the collector system by lowering power losses and improving the reliability compared to the conventional configuration.

III. Methodology

This method assumes that locations for the wind turbines considering local wind pattern, wake effect, etc are already available. The cable layout method presented here is based on applying quality-threshold clustering on wind turbine locations in multiple levels.

At the first level, the wind turbine locations are clustered into a number of groups. The turbine location in each group that is closest in distance to the substation is called the first level cluster representative point for that group. Cables are laid out from each of the turbine locations of that group to the first level cluster representative point. The cable size is selected from the ampacity required for the cable to carry power from the turbine at medium level collector system voltage.

In the next level, the first level cluster representative points are clustered to compute second level cluster groups and second level cluster representative points similar to the first level. This process is followed till the number of points to be clustered reaches a prespecified tolerance level or the cable ampacity warranted to carry the power exceeds current carrying capabilities of available cable sizes.

In this work, three different cable layout configurations have been compared. These are (i) a pure clustering based method, (ii) a conventional radial system, and (iii) a mixed system which combines clustering and radial systems. The comparison in between the three different systems has been made from the perspectives of overall cost, system reliability, and system real power losses. It has been assumed that Aluminum strand conductors of a few sizes are available as described in section V. Approximate cost and ac resistance values used for this work are also mentioned.

IV. Quality Threshold Clustering

The QT (Quality Threshold) Clustering algorithm [6] was developed to group genes into high quality clusters. Quality is ensured by finding clusters whose diameters do not exceed a given user-defined diameter threshold. This method prevents dissimilar genes (wind turbine locations in this work) from being forced under the same cluster and ensures that only good quality clusters will be formed. The goal of QT clustering is to form large clusters with similar expression pattern, and to ensure a quality guarantee for each cluster. Quality is defined by the cluster diameter and the minimum number of points contained in each cluster. Compared to K-means, another popular clustering algorithm, Quality-Threshold clustering has been used in this work since in QT clustering there is no need to specify the number of clusters, as required in K-means. Also, it is not necessary that all points need to be clustered and returns the same result when run several times. So although QT is computationally more expensive than K-means, this was selected as a clustering algorithm.

The QT algorithm is as follows [7]:

1. A random point is chosen from the list of points to be clustered.
2. The algorithm determines which point has the greatest similarity (closest Euclidean distance) to this point. If the distance is less than the quality threshold distance which is pre-specified, then these two points are clustered together.
3. Other points are similarly added to this cluster. This process continues until no point can be added to this first candidate cluster without surpassing the diameter threshold.
4. A second candidate point is chosen.
5. The algorithm determines which point has the greatest similarity (closest) to this second point. All points in the list of points are available for consideration to the second candidate cluster.

6. Other points from the list of points that minimize the increase in cluster diameter are iteratively added to the second candidate cluster. The process continues until no point can be added to this second candidate cluster without surpassing the diameter threshold.
7. The algorithm iterates through all points on the selected list of points and forms a candidate cluster with reference to each point. In other words, there will be as many candidate clusters as there are points in the list. Once a candidate cluster is formed for each point, all candidate clusters below the user specified minimum size are removed from consideration.
8. The largest remaining candidate cluster, with the user-specified minimal number of points, is selected and retained as a QT cluster. The points within this cluster are now removed from consideration. All remaining points will be used for the next round of QT cluster formation.
9. The entire process (step 1 to 9) is repeated until the largest remaining candidate cluster has fewer than the user-specified number of points.
10. The result is a set of non-overlapping QT clusters that meet quality threshold for both size, with respect to number of points, and similarity, with respect to maximum allowable diameter.
11. Points that do not belong in any clusters will be grouped under the "unclassified" group.

V. Available Conductor Sizes and Properties

It is assumed that ACSR (Aluminum Conductor Steel Reinforced) cables are used for the collector system cable layout. Further, it is assumed that only the cable sizes mentioned in Table I are available.

The cable ampacity is based on conditions [8] that cables are installed in sand with minimum cover of 36 inches, load factor is 100%, and maximum ambient earth temperature is 20 deg C. The dc resistances of the different conductors were obtained from [8], [9]. The ac resistance of a conductor is the dc resistance increased by a skin effect factor and a proximity factor: $R_{ac} = R_{dc}\left(1 + \gamma_{cs} + \gamma_{cp}\right)$, where R_{dc} is dc resistance at desired operating temperature, γ_{cs} is the skin effect factor, and γ_{cp} is the proximity effect factor. The ac resistances are computed from the dc resistances according to the method described in [10] and are tabulated below.

TABLE I
ACSR Cable Sizes and Properties

Al Strand Conductor Size	Continuous Ampacity (Amps)	DC Resistance at 25 deg C (ohms/1000 ft) [9]	AC Resistance at 25 deg C (ohms/1000ft)
1/0	150	0.1672	0.1672
4/0	211	0.0836	0.0836
500 kcmil	332	0.0354	0.0361
750 kcmil	405	0.0236	0.0248
1000 kcmil	462	0.0176	0.0193

VI. Analysis of Costs

A levelized cost estimate for energy delivered by the wind farm has been found by computing the ratio of annual costs and the annual energy produced. The annual cost incurred is the sum of annual loan payments, annual return on equity and operation and maintenance costs. The annual energy generated is found by the product of the nameplate capacity of the wind farm reduced by the collector system losses, number of hours in a year, and the capacity factor of the wind farm. The capital cost of the wind farm project is computed by adding the cost of the turbine units ($1million/1MW turbine), trenching costs ($15/ft), and cable costs and then multiplying with a factor of 1.05 to take into account other components of the capital cost such as site preparation, grid connections, project development, and feasibility study. Some cost figures for different cable sizes for this analysis are as follows:

TABLE II
ACSR Cable Costs

Al Strand Conductor Size	Cost ($/ft)
1/0	5
4/0	10
500 kcmil	12
750 kcmil	26
1000 kcmil	38

The capital cost is spread out over the projected lifetime using a capital recovery factor (CRF) and adding an estimate of annual operation and maintenance costs. It is assumed that the wind project is financed by a loan of 75% of the capital cost with interest rate of 7% and loan term of 20years. The annual payment on the loan is given by [11]:

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] = P.\,CRF(i,n) \qquad (1)$$

Where A is the annual payment in $/yr, P is the principal borrowed in $, i is the interest rate, n is the loan term in years. The operation and maintenance costs are assumed to be 3% of the capital cost and include parts and labor, insurance, contingencies, land lease, property taxes, transmission line maintenance, general and miscellaneous costs. Furthermore, a 15% return on equity is taken.

VII. Results and Discussions

For this study, a 22MW wind farm with twenty two 1MW wind turbine units has been considered. Underground cables interconnect turbines and the substation in the 34.5kV medium voltage collector system. Assuming the units generate power at a lagging power factor of 0.8, the current is projected to be a maximum of $\frac{1\times10^6}{3\times(34.5\times\frac{10^3}{\sqrt{3}})\times0.8} = 20.92$ A per unit at 34.5kV. Optimal wind turbine placement considering effects of local wind patterns, land topography, wind turbine wake effects is a widely researched area. Therefore, for the purpose of this work, it has been assumed that optimal turbine locations in the wind farm are already available. This assumption is justified by the availability of abundant literature in this area. This work does not consider issues of laying cables such as land unavailability within the wind farm area or trenching restrictions.

It has been assumed that the average wind speed at the wind farm location is 8.5m/s. Assuming Rayleigh distributed wind speeds, capacity factor of the turbines can be computed using the following relation [11]:

$$\mathrm{CF} = 0.087\overline{\mathrm{V}} - \frac{\mathrm{P_R}}{\mathrm{D}^2} \quad (2)$$

Where, $\overline{\mathrm{V}}$ is the average wind speed in m/s, $\mathrm{P_R}$ is the rated power in KW of a wind turbine, D is rotor diameter in m. With rated power of each turbine unit taken as 1MW, rotor diameter 52m, and average wind speeds of 8.5m/s, the capacity factor is approximately 37%. In figure 1, the locations of the 22 wind turbines and the substation are shown. The wind turbines are shown as dots and the substation location is indicated by a filled square. The figures in this paper have been scaled so that each unit on X and Y axes correspond to 1000ft. Thus, the minimum distance between any two turbine locations is 1000ft.

The locations of the wind turbine units are given by the following set of points in cartesian coordinates:
{(0,0), (1,0), (2,0), (0,1), (1,1), (2,1), (0,2), (1,2), (2,2), (3,2), (0,3), (1,3), (3,3), (1,4), (5,5), (6,4), (6,6), (7,5), (7,6), (7,7), (8,6), (8,7)}

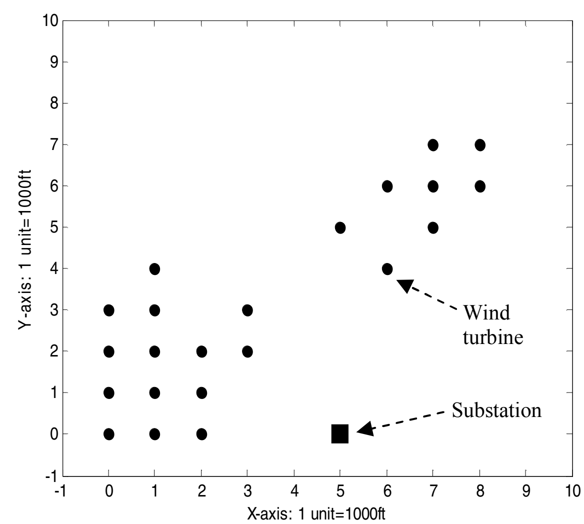

Fig. 1. Locations of 22 wind turbines (dots) and one collector substation (square)

The collector system has been studied for three different cable layout systems. The first method studied is the proposed quality threshold based clustering method, the second method considered is the conventional radial method, and the third is a combined clustering-radial method.

A. Cluster based method

The proposed cluster based method is used to lay out cables in the wind farm. At the first level of clustering, a quality threshold distance of 2.5units = 2500ft is used. The choice of quality threshold distance for each stage of clustering is by trial and error. A good initial guess for the first stage clustering can be 2 to 3 times the minimum distance in between turbines. For every subsequent stage the initial guess can be double the quality threshold distance for the previous stage. The initial guess for the threshold distance is modified to achieve specific design targets and meet constraints such as maximum number of turbines in a cluster.

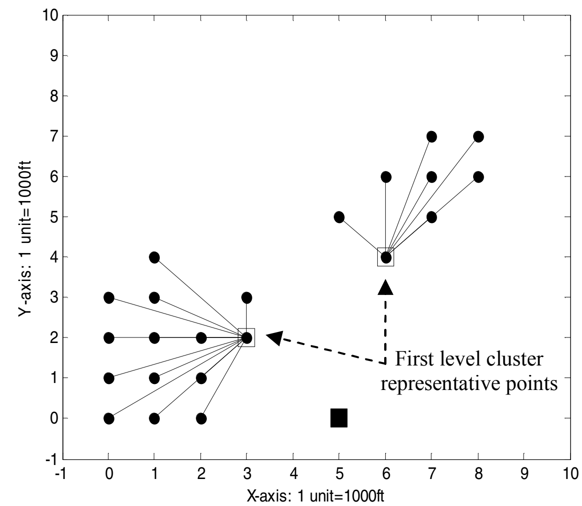

Fig. 2. First level clustering

Figure 2 shows the two clusters formed containing respectively 14 and 8 wind turbines. The first level cluster representative points, shown by squared dots in each cluster are the wind turbine locations in each cluster which are closest to the substation. Cables are laid out from turbine locations in a cluster to the cluster representative point. Since each of these first level cluster cables must carry a maximum of 20.92A, 1/0 conductor sized cables can be used from the available conductor sizes. The total length of 1/0 conductor sized cables is 47.3701units = 47370.1ft.

Maximum losses associated with the 1/0 conductor sized cables is 10398.8W.

In the second level, the quality threshold distance is taken as 4units = 4000ft. Figure 3 shows the cable layouts after the second level clusters are formed. After the second level clustering, the two cluster representative points from the previous level get clustered. The second level cluster representative point is marked as a diamond around a black dot.

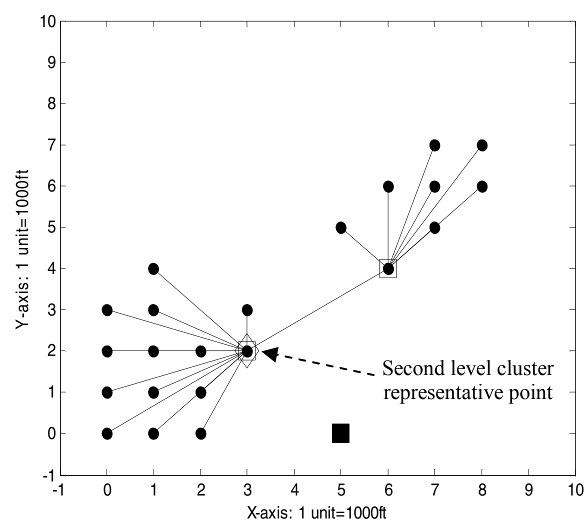

Fig. 3. Second level clustering

Only a single cable is laid out in this level which carries the power from the eight-turbine cluster and hence a total maximum current of 167.36A. Thus a 4/0 conductor sized cable can be used. Length of the required cable is 3.6056units = 3605.6ft. The power losses associated with this cable is 25328.4W.

In the last level, a cable carries power from the second level cluster representative point to the substation. This cable carries power from all the turbines in the wind farm and carries a maximum current of 460.24A. The cable used for this is one with 1000kcmil sized conductors. The length of the required cable is 2.8284units = 2828.4ft and losses associated equal 34688.7W. Figure 4 shows the cables laid out at the end of the third and final level of quality threshold clustering.

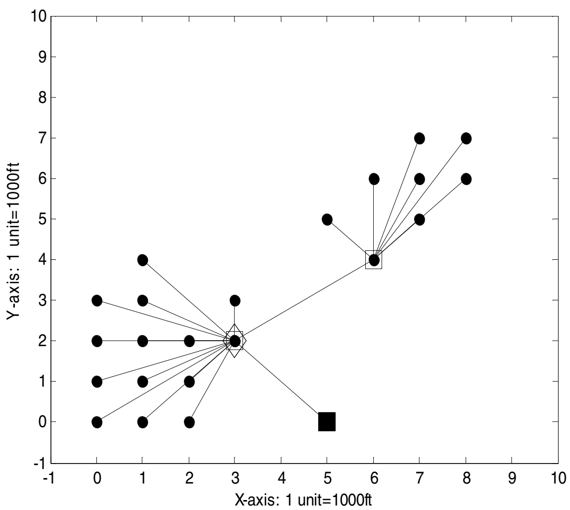

Fig. 4. Third and final level clustering

The total cable length required in this method is 161412.3ft.

The total loss in the cables is 70415.97W=70.42kW.
This is 0.32% of the installed wind farm capacity.
Total cable costs = $380,385.7
Trenching costs = $807,061.5
Turbine costs = $22,000,000
Capital costs = $23,187,447.2 * 1.05 = $24,346,819.56
Cost of electricity = 4.741cents/KWh

B. Radial System method

A conventional method of connecting wind turbines in a wind farm is the radial system or the daisy chain system. The radial system can be single or multiple string system. Each string carries power from one or more wind turbine units to a higher rating feeder cable which carries the power to the substation. Figure 5 shows a possible radial system cable layout configuration for the wind farm considered in this work.

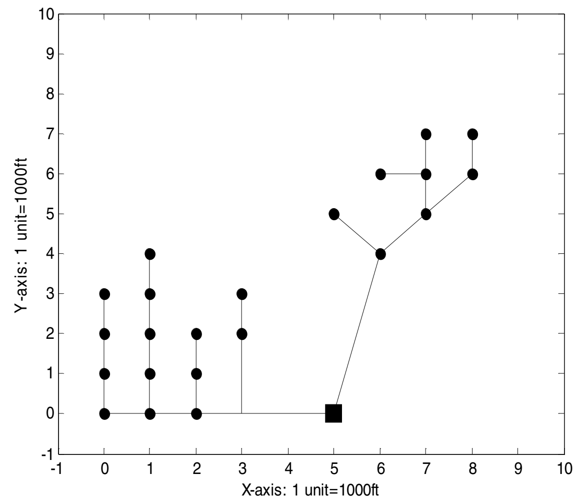

Fig. 5. Radial system cable layout

Assuming all the wind turbine units generate their rated power and the currents are all in phase, an equivalencing process described in [12] is used to compute the currents in each cable.

The cables required in this method are 24376ft of 1/0 conductor sized cables, 1000ft of 4/0 conductor sized cables, and 3000ft of 500kcmil conductor sized cables.

The total loss in the cables is 123.9kW.
This is 0.56% of the installed wind farm capacity.
Total cable costs = $167880
Total trenching costs = $425640
Turbine costs = $22,000,000
Capital costs = $22,593,520 * 1.05 = $23,723,196
Cost of electricity = 4.753cents/KWh

C. Combined Cluster-Radial system

This method uses a combined quality threshold clustering and radial system for the collector system. The cable layout is shown in figure 6. The first level uses the proposed method for clustering the wind turbines. This is followed by a radial interconnection.

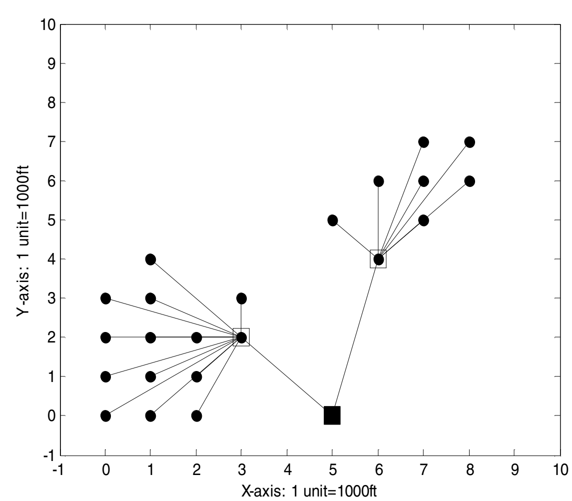

Fig. 6. Mixed layout configuration

The total cable length required in this method is 47370ft of 1/0 conductor sized cables, and 6943ft of 4/0 conductor sized cables.

The total loss in the cables is 99.9kW.
This is 0.46% of the installed wind farm capacity.
Total cable costs = $306,280
Total trenching costs = $814,695
Turbine costs = $22,000,000
Capital costs = $23,120,975 * 1.05 = $24,277,023.75
Cost of electricity = 4.748cents/KWh

To summarize the results, the cable layout with the proposed cluster based algorithm yielded lower power losses compared to the pure radial cable layout configuration. Power loss in the combined cluster-radial system was in between the pure cluster based system and the pure radial system.

From Figure 4, it can be seen that apart from the cables laid out in the second and third level clustering, all the first level cables carry power from one turbine each. This reduces the expected number of turbines lost in the event of a cable fault in the pure cluster based system. Figure 5 shows that in the pure radial system there is a probability of losing greater number of turbines in case of a fault since a greater number of cables carry power from multiple turbine units. This indicates that the pure cluster based system has higher reliability compared to the pure radial system. The figure 6 shows that the combined cluster-radial system replaces the cable laid out in the final level of the clustering algorithm carrying power from all the 22 turbines with two cables carrying power from 14 and 8 turbines each. Hence it provides even greater reliability compared to the pure cluster based system.

The costs of generated electricity from all three systems are comparable, with highest costs for the radial system and lowest for the proposed cluster based system. Because of the lower power losses in the cluster system layout, the annual energy generated by it exceeds the same for the radial configuration. In addition, although the capital costs are higher for the proposed cluster based system compared to the radial system due to higher cable costs and trenching costs, when spread out over the lifetime of the turbines, the annual costs do not vary significantly. This results in slightly lower cost of generated energy in $/KWh for the proposed cluster based system compared to the radial configuration. However, with lower losses, there is greater amount of energy available for transmission to the grid and therefore higher profits for the wind farm.

VIII. Conclusions

This work presented a cluster algorithm based cable layout design for a large scale wind farm. The proposed design method yielded lower collector system real power losses compared to a conventional radial or daisy chain cable layout method. Although the capital costs with the proposed system are much higher than conventional radial layout system, the costs of energy generation in $/KWh from the wind farm do not vary significantly. In the event of cable failure, in a daisy chain layout all turbine units beyond the faulted cable go offline, however, in the proposed pure cluster based method, and the combined cluster-radial method, cable failure results in a smaller number of turbines going offline. This indicates that the proposed method also improves the reliability of the wind farm collector system.

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