ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

EXTENDING CURRENT TECHNIQUES FOR ELECTRICAL LAYOUT OPTIMIZATION OF ONSHORE WIND FARMS CONSIDERING 3D MODEL OF THE TERRAIN

M.Sc. THESIS

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Thesis Advisor: Dr. Lecturer Burak BARUTÇU

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

KARA TİPİ RÜZGAR ENERJİSİ SANTRALLARININ 3 BOYUTLU ARAZİ MODELİ KULLANARAK ELEKTRİK TEK HAT OPTİMİZASYONU

YÜKSEK LİSANS TEZİ

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HAZİRAN 2018

Kaan Deveci, a M.Sc. student in Energy Institute of ITU with student ID 301151043, successfully defended the thesis entitled “Electrical Layout Optimization of Onshore Wind Farms Considering 3D Model of the Terrain”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Dr. Lecturer Burak Barutçu** ....
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Yıldız Technical University ....

Date of Submission : 4 May 2018
Date of Defense : 6 June 2018

To my family,

FOREWORD

Your truly has a bachelors degree in Energy Systems Engineering and a double major in Mechatronics engineering from Bahcesehir University. When I was a sophomore, I have discovered the need of this kind of a research for onshore wind farms during my summer training in Demirer Enerji. I am greatly thankful to Erol Demirer, Emre Demirer and Cem Sokullu for their kind attention in my summer training. I am also thankful to Burak Derinpınar for his suggestions in operational issues related with electrical layout of onshore wind farms. I am also thankful to Board of Fina Enerji for giving permission to study on Ziyaret RES.

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Thank you all for your unwavering support.

May 2018

Kaan DEVECİ
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ABBREVIATIONS

2D : Two dimensional
3D : Three dimensional
CF : Capacity factor
C_l : Capital investment value for cable Type-*l*
C_{ij} : Cost of i^{th} cable at line *j*
E_{loss} : Energy loss due to internal cable resistance
EP_t : Energy price at year *t*
i_{max} : Maximum current can a wind turbine produce
iCF : A problem dependent variable for cable selection process
L : Electrical line between wind turbines
L_i : The length of i^{th} line
L_k : Total trenching length for modified clustering based configuration
L_R : Total trenching length for radial clustering configuration
MPT : Minimum path tree
MST : Minimum spanning tree
n : Number of nodes
N : Number of clusters
NP-hard : Non-deterministic Polynomial-time hard
NPV : Total trenching length for radial clustering configuration
NSGA-II : Non-dominated Sorting Genetic Algorithm 2
PL : Parallel line
PSO : Particle Swarm Optimizer
QT : Quality Threshold Algorithm
Rate : Discount rate
RCC1 : Radial clustering first case
RCC2 : Radial clustering second case
RCC3 : Radial clustering third case
RCCM : Radial clustering main case
RES : Wind energy power plant
R_i : Internal cable resistance of cable Type-*l*
ST : Sub-tree
std() : Standard deviation function in MATLAB
T : Wind turbine
T_{max} : Maximum number of wind turbines for a single radial cluster
UTM : Universal transverse mercator
w_e : Cost matrix between nodes

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EXTENDING CURRENT TECHNIQUES FOR ELECTRICAL LAYOUT OPTIMIZATION OF ONSHORE WIND FARMS CONSIDERING 3D MODEL OF THE TERRAIN

SUMMARY

The optimization problem of the internal electrical layout of onshore wind farms are very complex due to its NP-Hard nature and constitutes the second biggest expense in onshore wind farm projects. This study aims to solve the electrical layout problem using predefined paths. It is shown that the determination of optimum cable thicknesses in terms of net present value (NPV) and investment costs over a layout can be done a priori, and it does not have to be included in the optimization analysis as design parameters. Second, a new problem for predefined paths which considers parallel cables and their optimum order of connection is defined and solved by using well known metaheuristics Particle Swarm Optimizer (PSO) and Non-dominated Sorting Genetic Algorithm 2 (NSGA-II). Third, a strategy for radial clustering of wind turbines over a substation is given in order to automize the clustering procedure. In this strategy, substation is taken as the origin and imaginary lines starting from the origin pass between wind turbines and create radial clusters. The angles of each imaginary line in the clockwise direction are selected as variables and the objective function is chosen as the standard deviation of the distribution of wind turbines in each cluster. A node based optimization strategy for electrical layout problem is introduced for the first time which takes the effects of altitude change into account using 1 arc-second high resolution satellite images. Using this strategy, it is possible to predict objective function values more accurately and it gives a route for electrical cables on digital elevation model (DEM). The last but not the least, trenching constraints are also considered for 3D analysis. It has been shown that the proposed strategy can handle trenching constraints for wind farms. The proposed strategies are applied on a real onshore wind farm in Hatay/Samandağ (Ziyaret RES) using radial and string configurations.

3 BOYUTLU ARAZİ MODELİ KULLANARAK KARA TİPİ RÜZGAR ENERJİSİ SANTRALLARININ TEK HAT OPTİMİZASYONU

ÖZET

Rüzgar enerjisi santrallarında tek hat optimizasyonu çalışması, türbin sayısı arttıkça karmaşıklığı artan bir problemdir. Cayley'in ağaç formülünü kullanarak, N^{N-2} tane özgün tek hat bağlantısı kurmanın mümkün olduğu bilinmektedir (burada N rüzgar türbinleri ve şalt sayısının toplamıdır). Tipik bir kara tipi rüzgar enerjisi santralında elektriksel bağlantılar toplam proje bütçesinin yaklaşık %8'ini oluşturmaktadır. Bu pay, kara tipi rüzgar enerjisi santrallerinde rüzgar türbinlerinden sonraki en yüksek giderli ikinci kalemdir. Bu sebeple araştırmacılar, mikrokonuşlandırma çalışmalarından sonra en çok bu alana yönelmişlerdir.

Literatürde rüzgar enerjisi santralları için birçok çalışma mevcuttur. Bunlar tek hat optimizasyonu için 2 boyutlu yaklaşımlarla gerçekleştirilmiştir. Deniz tipi rüzgar enerjisi santrallarında zemin nispeten daha düz olsa da, kara tipi rüzgar enerjisi santrallarında arazinin topoğrafik yapısında sert değişiklikler olabilmektedir. Bu çalışma göstermiştir ki 3. boyut ihmal edilirse türbinler arasındaki en yakın mesafeler belli oranlarda hatalı bulunmaktadır. Bu hatanın telafi edilebilmesi için belli oranlarda proje gider kaleminde pay bırakılması gerekmektedir. Ayrıca, bazı durumlarda 2 boyutlu yaklaşımla belirlenen askeri tarama ağacı bağlantılarının, 3 boyutlu yaklaşım kullanıldığı zaman değiştiği de görülmüştür. Bunun sebebi arazinin karmaşık yapısıdır. Önerdiğimiz optimizasyon yöntemi arazinin engebeli yapısını dikkate alarak en kısa yollarla rüzgar türbinlerini bağlamaktadır.

Bu çalışma iki adımda tamamlanmıştır. İlk adımda rüzgar türbini santrallarında altyükleniciler tarafından belirlenen yollar N tane noktadan geçen en kısa mesafe olarak hesaplandığı varsayımı üzerinden belirlenmiş olup, daha sonra belirlenen en uygun kablolar ile 25 yıllık elektriksel kayıpların net bugünkü değerleri ile yatırım değerleri toplanarak analiz edilmiştir.

Literatürdeki çalışmaların çoğunda kablo verisi elektrik tek hat optimizasyonu çalışmalarında değişken olarak kullanılmıştır. Bu çalışmada optimizasyon aracına kabloların değişken olarak tanımlanması gerekmediği; bir hattan geçen yıllık enerji üretimi hesaplanarak en uygun kablonun önceden belirlenebileceği açıklanmıştır. Böylece optimizasyon algoritmasının değerlendirmesi gereken değişken sayısı azaltılmış; onun yerine probleme yeni değişkenler getirerek döşeneceği hat yolu önceden belirlenmiş birden fazla paralel kablonun hangi türbinlerden akım çekerse sistemin optimizasyonunun sağlanacağı araştırılmıştır. Önceden belirlenen yolların kullanımı tek hat optimizasyonu çalışması için uygulamada sıkça rastlanan bir durumdur. Yatırımcılar altyüklenici inşaat firmasının santral içinde hazırladığı araç yoluna paralel olarak elektrik kablolarını döşemektedir. Böylece herhangi bir arıza olması durumunda gerekli müdahale araçlar ile hızlıca yapılabilmektedir. Aynı zamanda iş makinaları araç yolu yaparken ona paralel kablo hattını da kolayca çekebilmektedir.

Çalışmada elektrik tek hat optimizasyonu radyal gruplandırma ve dizi gruplandırma ile modifiye edilmiş kümeleme yaklaşımı ile değerlendirilmiştir. Bu bağlantı yöntemleri içinden radyal gruplandırma en iyi sonuçları vermiştir. Rüzgar türbinlerinin ve şalt koordinatlarının önceden belirlendiği ve orta gerilim trafo kullanıldığı kabulu yapılmıştır. Çalışmada yapılan yatırım hesaplarına kablo masrafları ile birlikte transe işleri dahil edilmiştir. Bunun dışındaki nakliye giderleri, bakım, bağlantı ekipmanları giderleri, kompanzasyon maliyeti vb. değerler çalışmaya dahil edilmemiştir.

Modifiye edilmiş kümeleme yöntemi, geliştiricilerinin sunduğu kümeleme yöntemi değiştirilerek çalışmaya uyarlanmıştır. Modifiye edilen yöntemde grupların temsilci noktaları birbirine en yakın rüzgar türbinleri olarak seçmek yerine imajiner noktalar olduğu kabul edilmiş ve optimizasyon algoritması ile koordinatları bulunmuştur. Kümeleme yönteminin geliştiricileri yöntemin avantajı olarak tek hat üzerinde yaşanabilecek herhangi bir arıza durumunda daha az sayıda rüzgar türbininde enerji üretiminin duracağını belirtmişlerdir. Bu sebeple modifiye edilmiş kümeleme yöntemi ile radyal ve dizi yöntemlerinin sonuçlarını sağlıklı bir şekilde kıyaslayabilmek için, kablo arızasını simule edebilecek bir yöntem geliştirilmiştir. Bu yöntemin ilgili parametreleri için uzman görüşlerine başvurulmuştur.

Sunulan yöntem ile tek hat optimizasyonu arazinin 3 boyutlu yapısını değerlendirerek gerçekleştirilmektedir. Sadece en kısa mesafeler bulunmamakta; ayrıca arazi üzerinde kablonun izleyeceği güzergah da belirtilmektedir. Sunulan yöntemin pratikliği sayesinde kazılamayacak herhangi bir alan varsa, en kısa mesafeler hesaplanırken 3 boyutlu arazi modelinde kazılamayacak alanın yükseklik değerlerinin sonsuz yapılması yeterlidir. Algoritma, izlediği yolu uzatmamak için alternatif güzergahlara yönelmektedir.

Literatürde rüzgar türbinlerinin radyal gruplandırması için herhangi bir yöntem kullanılmamakta; muhtemelen radyal gruplandırma elle yapılmaktadır. Bu çalışmada radyal gruplandırma işleminin bilgisayar ortamında en iyileştirilerek yapılması için genetik algoritma ile bir yöntem sunulmuştur. Bu yöntemde sanal çizgiler ile radyal grupların ayrıştırıldığı varsayılmış olup, çizgilerin orijin ile yaptığı açılar de problemin değişkenleri olarak kabul edilmiştir. Amaç fonksiyonu her yadyal kümede bulunan rüzgar türbini sayısının standart sapması olarak alınmıştır. Böylece rüzgar türbinleri mümkün olduğunca eşit dağıtılacak olup hat üzerinde yaşanabilecek herhangi bir teknik arıza kaynaklı üretim kesintisi minimize edilmek istenmiştir.

Çalışmada kesin ve metasezgisel algoritmalar kullanılmıştır. Metasezgisel algoritmaların dezavantajı global optimum çözüme ulaşma garantisi sunmamalarıdır. Öte yandan, kesin algoritmalara göre kabul edilebilir bir başarı oranını tutturarak çok daha hızlı çözüm üretebilmektedirler. Çalışmada 2 boyutlu yaklaşımla askeri tarama ağacı (MST) bulunabilmesi için parçacık sürü algoritması kullanılmıştır. 2 boyutlu yaklaşım için maliyet matrisi öklidyen mesafe yöntemiyle hesaplanmıştır. 3 boyutlu yaklaşımla askeri yol ağacı (MPT) bulunabilmesi için yine parçacık sürü algoritması kullanılmış olup; maliyet matrisinin hesaplanması sırasında Dijkstra'nın algoritması kullanılmıştır. 3 boyutlu yaklaşımda maliyet matrisinin oluşturulması için topografyanın enlem boylam ve yükseklik değerleri düğümler kullanılarak sanal ortama aktarılmıştır. Oluşturulan sanal topografya modeli üzerinde sadece komşu düğümlerin birbiri ile bağlantısına izin verilmiş olup, her iki düğüm arasındaki mesafe Öklidyen yaklaşımla hesaplanarak bulunmuştur.

Bu çalışma Hatay Samandağ'da bulunan Ziyaret RES üzerinde uygulanmıştır. Santralın arazi modeli, 1 ark-saniye çözünürlüğe sahip uydu görüntülerinin bilineer interpolasyon teknikleri ile zenginleştirilmesi ile oluşturulmuştur. Google Earth kullanılarak Samandağ'daki rüzgar türbinlerinin yüksekliği, bilineer interpolasyon yöntemi ile bulunan yükseklik değerleri ile kıyaslanmış olup ortalama hata %0,6 olarak elde edilmiştir.

Ziyaret RES için en uygun bağlantı yöntemi radyal yöntem olarak bulunsa da, radyal kümeleme yöntemlerinin de dezavantajları vardır. Radyal kümeleme yöntemlerinde her bir radyal küme içinde bulunabilecek maksimum rüzgar türbini sayısı belirlenmesi gerekmektedir ve bu değer kümeleme işlemi esnasında bir kısıt olarak uygulanmaktadır. Bu kısıtın uygulanma nedeni, kabloların maksimum akım taşıma kapasitesidir. Kümelenen rüzgar türbinleri, komşu kümeden herhangi bir rüzgar türbini ile bağlantı kuramamaktadır. Bu sebeple, olası bir global optimum çözüm kaybedilebilmektedir. Çalışmada önerilen paralel kablolar yaklaşımı ile bu kısıt ortadan kaldırılabilir veya esnetilebilirdir.

Gelecek çalışmalarda global optimum çözümün bulunabilmesi için yeni bir algoritma geliştirilecek olup açık kaynak olarak araştırmacılara sunulacaktır. Ayrıca uygulanan 3 boyutlu yöntem, deniz tipi rüzgar enerjisi santrallarında da kullanılabileceği gibi, güç iletim hatlarını içeren bütün uygulamalar için uyarlanabilirdir.

1. INTRODUCTION

There is a growing interest in the utilization of wind energy, around the world due to an increasing trend in renewable and alternative energy sources. Nowadays, large scale wind farms are being built with hundreds of wind turbines. Typically, the required distance between each wind turbine might lead to the use of several kilometers of electrical cables depending on the number of wind turbines and topographical conditions of the terrain. Due to this reason, the cost of internal power transmission systems has a significant share in wind farm budgets; typically 8% for onshore and 18% for offshore power plants [1].

The optimization of electrical layout problem for wind farms is very complex due to its NP-Hard nature [2] and this complexity increases as the number of wind turbines increase. Using Cayley's formula, the number of unique electrical layout configurations will be N^{N-2} where N is the number of wind turbines and only one of these configurations will be the optimum solution. Due to this complexity and its significant share in the project budgets, the problem has grabbed the attention of researchers over the last decade. In the literature, Zhao et al. proposed a single objective optimization study for electrical system for offshore wind farms by using genetic algorithm [3]. Their goals were optimizing the electrical system design and its reliability. But they did not include the effect of cable thicknesses, connections on electric cable losses in their study. Wu et al. proposed a study for both micrositing of wind turbines and optimizing their electrical layout for offshore wind farms in [4]. They have first microsited wind turbines on a grid and then optimized their electrical layout connections in their study. Since they did not search for a minimum spanning tree for electrical layout, their study ended up with larger trenching lines than the global optimum. Also they did not vary the string dimensions for optimal connection. Dutta and Overbye contributed wind farm layout optimization problem with 3 studies [5-7]. In [7], they compared the effects of different configuration types on the electrical layout optimization by considering the total trenching length. In [5], they proposed a new design strategy for wind farms including the trenching constraints by using a convex hull based bypassing algorithm. In [6], they proposed a new method to connect wind turbines by using levelized clustering representative points. In that study, authors claimed that the proposed clustering based approach yielded better results in a period of 25 years. Another study proposed by Fischetti and Pisinger used Steiner points in optimally connecting wind turbines can be found in [8]. They have used mixed integer linear programming and heuristic based hybridized approach (matheuristics) in order to optimize the electrical layout. Even though the use of Steiner points is not fully exploited within the study, as described in [9], use of Steiner points in offshore wind farms are not feasible in economic point of view. Wedzik et al. in [10] prepared an integrated linear algorithm for simultaneous optimization of electrical layout using mixed integer linear programming. Pemberton et al. [11] proposed a methodology for optimizing electrical layout of onshore wind farms in terms of minimized cost, losses and maximum reliability.

In most of the modern wind farms, radial feeders or string configurations are used for electrical layout design. Especially when a string configuration is preferred, the current flow in the string may exceed the maximum current capacity. At this point, the use of parallel cables is required. However, dividing wind turbines into groups and connecting each group with substation by using the same predefined path may not satisfy the optimality. Also in some cases, instead of using a cable with the bigger cross section, using 2 cables with smaller cross sections could be more beneficial in terms of investment return. And in most of the onshore wind farms, a cheapest electrical cable within the feasible product range is chosen for electrical layouts. Here, two important questions arise: First, *"is it feasible to use cheapest electrical cable for ensuring the optimality?"* Second, *"if a predefined path must be followed and the maximum current flow limit is exceeded for a given group of wind turbines, what is the optimum layout of parallel cables and order of connection with wind turbines?"* This study proposes two new design strategies to give answers to the questions above. First, a strategy for optimal cable selection considering the investment costs and net present value of electrical losses is given. It has shown that optimum cable selection is a *priori* and does not require an optimizer. Second, a new problem is defined for predefined paths with parallel cables in order to find their optimum order of connections with each wind turbines. Two novel strategies for radial clustering and cable failure analysis are also introduced in this thesis.

To the best of our knowledge, all of the studies in the literature neglect the effects of altitude change and suggest two dimensional approaches for the solution of the problem. However, the effects of altitude change become a very crucial factor, especially for onshore wind farms. Neglecting the third dimension may result with prediction errors for calculating the total length of electrical cables, trenching, and so the budget. It is also possible to obtain an electrical layout configuration which is not even close to the optimum if the simplified two dimensional approaches are used. In this study, a novel 3D approach is also proposed for the first time in order to estimate the total trenching and cable length more accurately. The proposed method calculates objective functions more accurately, finds a route for cables on a digital elevation model, and can consider the trenching constraints. All techniques are applied on a real onshore wind farm in Hatay/Samandağ (Ziyaret RES). Both radial feeder and string topologies, as well as a modified version of clustering based technique given in [6] are used in the analysis.

The remainder of this thesis proceeds as follows. In the second part, the Ziyaret RES is introduced, optimization problems are defined, and the suggested 3D strategy is given. In the third part, results are analyzed by using 2D and 3D approaches. In the last part, conclusions are given.

2. METHODOLOGY

In this section, the most common methods used in wind farm layout optimization is compared first. For this purpose, obtained layouts after radial clustering and string configurations are used with the modified version of the method in [6]. In the first part, the effects of the elevation over electrical layout are neglected and the effects of altitude change on electrical layout problem briefly examined in the second part.

In wind energy power plants, there are two types of electrical cables for use in power transmission: underground or overhead. Underground cables are being selected in most of the cases due to operational and efficiency reasons. Overhead cables are more likely to be exposed to harsh weather conditions than underground ones, and their electrical loss is higher than the underground cables. Overhead cables are still used when digging ground for underground cables is not allowed (i.e. when there is a cultivated field between two wind turbines). Here, underground cables are chosen to analyze the electrical layout of Ziyaret RES. This plant has 75 MW capacity with 30 wind turbines and located in Hatay/Turkey. The 2D representative image for the Ziyaret RES is given in Figure 2.1. The voltage of internal transmission system in Ziyaret RES is assumed to be 34.5 kV as in most of the commercial wind farms. We assumed that the coordinates of wind turbines and substation are predefined.

In this study, daisy chain connections for wind farm layout optimization problem is considered. With this connection type, wind turbines are connected to each other from furthest to closest through the substation in daisy chains. For obtaining a daisy chain configuration, one must find the minimum spanning tree (MST) over the area of interest. Obtaining MSTs are good for reducing trenching length. In daisy chain type of connection, the project planner must take current flow limitations into account and determine the wind turbines which will be connected to the same feeder along with the minimum spanning tree.

One of the common electrical layout configuration techniques is the radial clustering. In this technique, wind turbines are radially clustered around a substation and optimized by finding the MSTs of each cluster. The second most common technique is string configuration. In this technique, MST of all wind turbines along with the substation is found without using any clustering techniques. Generally speaking, trenching length for radial clustering is more than the string configurations which uses global MST, but losses and cost of initial investment for cables will be lowered. On the other hand, string configuration provides lower trenching costs together with higher electrical losses and higher investment costs for cables. Typically, there is no best technique in internal power system optimization, therefore, radial clustering, minimum spanning trees or hybridized solutions could all be the best technique for any onshore wind farms.

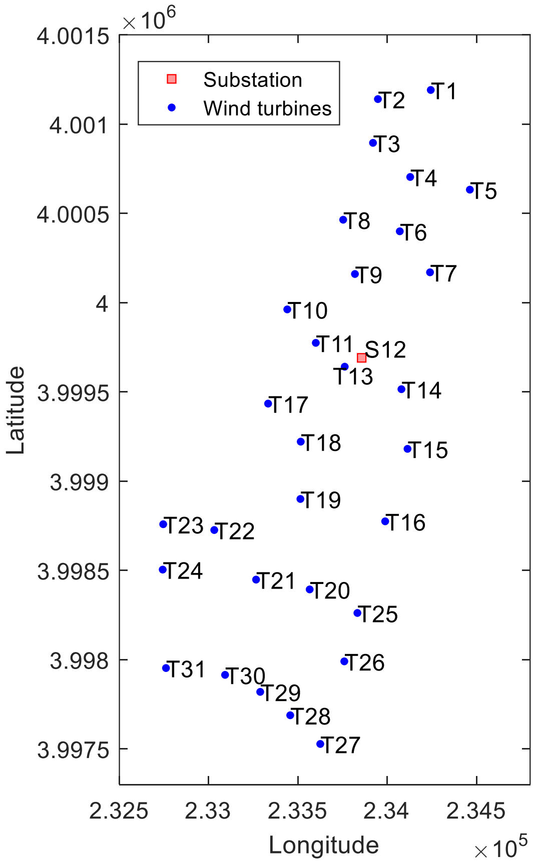


Figure 2.1 : 2D representation of Ziyaret RES.

Together with these techniques mentioned above, a modified version of the clustering based method proposed in [6] is also evaluated. In this method, wind turbines are clustered into subgroups. Then the turbines closest to each of the clusters are assigned as cluster representative points and the wind turbines within a cluster are connected with their representative points. Finally, the representative points which carry all the produced power within their clusters are connected to each other through the substation. When an electrical cable failure occurs on a feeder, turbines which are behind the location of failure will not provide electricity unless a loop connection is used. By using this proposed clustering based technique [6], energy production is less likely to be interrupted in great amounts in case of a cable failure. In order to apply this method for Ziyaret RES, k-means clustering is used instead of Quality Threshold clustering algorithm is used and the reasons for this will be explained in the following sections.

In this study, the data for electrical cables and trenching cost are taken from [7] and given in Table 2.1. From this table, one can see that as the cross section of the cable is increased, the internal resistance is decreased and the cost is increased. Therefore, for internal power system optimization, one must minimize two objectives simultaneously: the initial investment costs and the internal electrical losses along the lifetime of the power plants (which is assumed as 25 years for this study). Therefore, the main goal is to minimize the trenching length and to select the best cable types with considering 25 years of cable losses and overnight investment costs.

Table 2.1: Cable data used in the study.

Cable	Al Strand Conductor Size	Continuous Ampacity with Medium Voltage (Amps)	AC Resistance at 25℃ (Ω/m)	Cost ($/m)
Type-1	1/0	150	0.00054820	28
Type-2	4/0	211	0.00027410	35
Type-3	500 kcmil	332	0.00011844	42
Type-4	750 kcmil	405	0.00008130	85
Type-5	1000 kcmil	462	0.00006330	125
Trenching	-	-	-	50

2.1 Minimum Spanning Tree Problem

A minimum spanning tree is a tree that covers all nodes with the minimum cost. Since it provides the minimum cost, there is no cycle formation within an MST configuration. The MST problem is a very old and well-studied problem in the literature. It provides the first step for many engineering problems such as transportation, distribution, network design, etc. The minimum spanning tree problem is formulized in the following set of equations (2.1-2.6).

$$Min.\ \ f(x) = \sum_{e \in E} w_e x_e \tag{2.1}$$

$$Subject\ to\colon \sum_{e \in E} x_e = n - 1 \tag{2.2}$$

$$\sum_{e \in E(S)} x_e \leq |S| - 1 \tag{2.3}$$

$$\forall S \subset N \tag{2.4}$$

$$S \neq \emptyset \tag{2.5}$$

$$x_e = \{0,1\} \tag{2.6}$$

In the MST formulation, x_e is the binary decision variable and takes the value of 1 if the edge e is selected and 0 otherwise. w_e represents the weight of the edge *e*, *n* represents the total number of nodes and equal to |N|, and *S* represents a set of nodes in *N*. Every edge (*e*), is associated with a cost w_e (distance between nodes). The first group of constraints is true for all minimum spanning trees, a tree with *n* nodes must exactly have *n-1* edges. The second group of constraints imply that the set of chosen edges contain no cycles.

In most of the modern onshore wind farms, the layout of electrical cables coincides with the paths inside of the wind farm. Those paths are created by construction companies considering the factors such as total cost, operations (i.e. ease of transportation of turbine blades), etc. In this study, MST of the Ziyaret RES is assumed to be the predefined paths determined by the construction company either by using radial clustering or string configuration.

2.2 Analysis of Cables

The first step of this problem starts with the determination of the output currents from each wind turbine. With an average lagging factor of 0.85, the current produced from a wind turbine at its rated output power can be calculated using (2.7).

$$i_{max} = \frac{2.5\ \times 10^6}{3 \times \left(34.5 \times 10^3 \times \frac{1}{\sqrt{3}}\right) \times 0.85} \cong 49.22 \frac{Amps}{turbine} \tag{2.7}$$

The value obtained from (2.7) is the maximum current a wind turbine can produce and current flow limitations over electrical cables will be arranged based on these values. Please note that all wind turbines within the Ziyaret RES are identical.

The internal resistance of electrical cables will result in electrical losses along the transmission line. Due to *today's cost of a future value,* the economic effect of power losses will reduce with years. On the other hand, cables with lower electrical resistance will have higher investment costs in *today's value*. Then, the best cable to hold current of *M* turbines will be chosen by using (2.8).

$$Max.\ \ f = -C_l - \sum_{t=1}^{25} \frac{E_{loss} \times EP_t}{(1 + rate)^t} \tag{2.8}$$

Where E_{loss} is yearly electrical losses due to internal cable resistance in kWh. EP_t is the energy price at year *t*, *rate* represents the discount rate, *t* represents the time as year, and C_l represents the capital investment value for cable Type-*l*. Here, *f* can be defined as the decision making criterion for electrical cables. The first and second terms of *f* represents the first and second objectives of the problem. Since the investment cost and losses are defined with a negative sign, it is more desired to use a cable with higher values of *f*. The annual energy loss formula over electrical cables is given in (2.9).

$$E_{loss} = \frac{3 \times 8766 \times (i_{max} \times CF)^2 \times R_l}{1000} \tag{2.9}$$

Here, *CF* represents capacity factor, R_l represents the internal resistance of cable Type-*l*, and i_{max} is the maximum current produced by the wind turbines. The current produced by each wind turbine varies with time, therefore, the value of i_{max} in (2.9) should be multiplied with a capacity factor, *CF*. One can see that the parameters of the formula are current flow, the capacity factor, and the resistance of the cable. In (2.9), the only term related with the length of the cable appears in R_l. It is obvious that the relation between cable length and electrical losses is linear. Also, the relation between the length of the cable and term C_l is also linear.

In the studies including [7, 17], researchers mentioned that for electrical layout optimization it is possible to omit time series and use a constant capacity factor of the wind farm for calculating annual energy produced. In Ziyaret RES, all wind turbines are identical and it is assumed that all wind turbines produce energy with a constant capacity factor. Hence, if we calculate the matrix of *f* for all type of cables under operation with a different number of wind turbines, cables with highest values of *f* will be the optimal choice. Hence, determination of the optimum cross section of cables will become available *a priori* and does not require any optimizer. Because of the linearity of the relations explained above, it will be sufficient to calculate the matrix of *f* for 1 m of cable Type-l with different combinations of electrical currents. Also due to the homogeneity assumption in produced power by each wind turbine, the procedure will be relatively simple.

2.3 A Strategy for Predefined Paths

In application, electrical cables are buried parallel to predefined paths. In most of the cases, those paths coincide with the highways inside of the windfarm which is created by construction companies. Using predefined paths provides ease of access to cables in case of any failure over the layout. Also it is easier and cheaper to dig ground when the highways are constructed around the area of interest using dozers (no need to bring machines on different locations). Therefore, the next step is to analyze layouts with predefined paths.

While predefined paths are considered for layout optimization, the current carrying capacity of the cable with the biggest cross section may be exceeded by a subbranch. At this point, a secondary or maybe tertiary cable should be buried in parallel to the first one. Burying down parallel cables will result in a decrease in trenching cost. In this study, the use of parallel cables is limited to two at most. Assume that there are N different paths $L_1, L_2, L_3, \ldots, L_N$ on the MST configuration. Then, the problem should be formulated as in (2.10-2.15).

$$Min.\ \ f_1 = \sum_{i=1}^{N}\left(CT_1 L_i + CT_2 L_i T + \sum_{j=1}^{2} L_i C_{i,j} \right) \tag{2.10}$$

$$Min.\ f_2 = NPV_{25}\left(EP \times 8766 \times 3 \times \left(CF \times X_{i,j} \times I_{max} \right)^2 \times R_{i,j} \times \frac{L_i}{1000} \right) \tag{2.11}$$

$$Subject\ to\colon \sum_{j=1}^{2} X_{i,j} = LineCurrent_{max}\ , where\ i = \{1,2,3,..,N\} \tag{2.12}$$

$$X_{i,1} \leq X_{i+1,1} \tag{2.13}$$

$$X_{i,2} \leq X_{i+1,2} \tag{2.14}$$

where

$$T = \begin{cases} 0, & if\ x_{i,1} \vee x_{i,2} = 0 \\ 1, & otherwise \end{cases} \tag{2.15}$$

Here, first objective function represents the investment costs related with cables and earthworks. $C_{i,j}$ represents the cost of i^{th} cable at line l where $i = \{1,2\}$ and L_i represents the length of each line in the predefined path. CT_1 and CT_2 represent the cost of trenching with single and double cables which are taken as 50$ and 25$, respectively. In order to add an additional trenching cost for secondary cable, T takes a value of 0 or 1 depending on the use of a secondary cable. The second objective represents the net present value of energy loss due to electrical resistance of the cables for 25 years. EP represents the price of electricity, CF represents the capacity factor, X are the variables of the problem, $R_{i,j}$ is the internal electrical resistance of i^{th} electrical cable buried into line l, and I_{max} represents the current produced at the rated power. First group of constraints represents operational limits of the layout. As an example, if a line L carries current from 2 wind turbines, $X_{L,1} + X_{L,2}$ must be equal to $98.44A$ in order to carry the required amount of current over the line. First group of constraints is enough to satisfy the capacity needs over a line. But there must be another group of constraints to avoid optimizer from selecting physically impossible layouts which are given by the second group of constraints. Assume that a line carries current from 7 wind turbines and will be connected with an 8th turbine. Let the variables of the problem be {147.66,196.88} at the line i and {98.44, 295.32} at the line $i+1$. In this situation, even though the first group of constraints are satisfied, secondary group of constraints are not. Because this is physically unacceptable, the current cannot pass between separate cables. The correction of this physically unacceptable situation should be {147.66, 196.88} at the line i and {196.88, 196.88} or {147.99, 246.1} at the line $i+1$. For the rest of the study, the values of $C_{i,j}$ and $R_{i,j}$ will be selected based on the results of cable analysis.

2.4 A Strategy for Radial Clustering

Use of radial clustering technique in internal power transmission optimization consists of two steps: clustering wind turbines radially and finding MST for each cluster along with the substation. To the best of our knowledge, there is no study which proposes an optimization method for the use of radial clustering technique in wind farms. Therefore, a new method for automizing the radial clustering process is proposed. With this method, imaginary lines are assumed to be passing between wind turbines and separate clusters based on the objectives and constraints given by the user.

Here, a simple genetic algorithm is used for optimization. For details of the genetic algorithms, readers may refer to [18]. The coordinate of the substation is chosen as the origin and the coordinates of the wind turbines are updated accordingly. Then, the angle between vector [0,1] and position vectors of wind turbines are calculated. Variables of the problem are selected as the angles of these imaginary lines in the clockwise direction. The problem is described in (2.16-2.17).

$$Min. \quad f(Cluster) = std([Cluster]) \tag{2.16}$$

$$Subject\ to\ Cluster_i < T_{max} \tag{2.17}$$

Where *Cluster* represent the array which holds the number of elements in each *N* clusters and has a dimension [1xN]. T_{max} represents the maximum number of wind turbines that a single cable can operate under the rated power conditions. Note that when the wind turbines within the wind farm are not identical, one must use T_{max} as a limiter to current flow between the last turbine of the cluster and the substation. Using the proposed strategy for predefined paths, one can prefer not to use any constraint for radial clustering. Initially, *N* is assumed as 4 with T_{max} = 9. Obtained results are compared with a case where *N* = 3 and constraint of T_{max} is not used.

2.5 A Method for Simulating Cable Failures

In the next step, a simulation method for analyzing the claim given for clustering based configuration in [6] is proposed. In this part, cable failure is simulated and applied to the different configurations. Firstly, all cable lines are concatenated to each other in a logical order and the length of each line is normalized between [0,1]. By generating *m* random numbers between [0,1] and assuming that all random numbers correspond to the location of a cable failure, it will be possible to estimate the operational effects of cable failure through the lifetime of a power plant. In order to do this, these random numbers will be denormalized based on the total lengths of each configuration and the cable that is going to fail together with the number of wind turbines which will stop feeding the substation will be determined. Based on expert opinions given for Turkey, it is assumed that 1 cable failure occurs per 2 years within a wind farm and it is also assumed that the cable failure problem will be solved in 3 hours under normal conditions (i.e. all required electrical materials are assumed to be available within the wind farm). Therefore, 13 cable failures over the lifetime of the power plant will be simulated.

2.6 Extending Current Techniques for 3D Analysis

In this section, the research question is: *"Is it admissible to neglect the third dimension? If not, how does the third dimension affect the problem of electrical layout optimization?"*. In order to further analyze this research question, initially, the required topographical information is gathered from 1 arc-second high-resolution Shuttle Radar Topography Mission-1 (SRTM1) image which covers the location of Samandağ. The SRTM1 data includes *Xx* and *Yy* coordinates and their altitudes. Using bilinear interpolation, the number of nodes around the area of interest is increased and given in Figure 2.2. In this figure, X, Y and Z coordinates represent the longitude, latitude, and altitude data of each node which is given with the Universal Transverse Mercator (UTM) coordinate system.

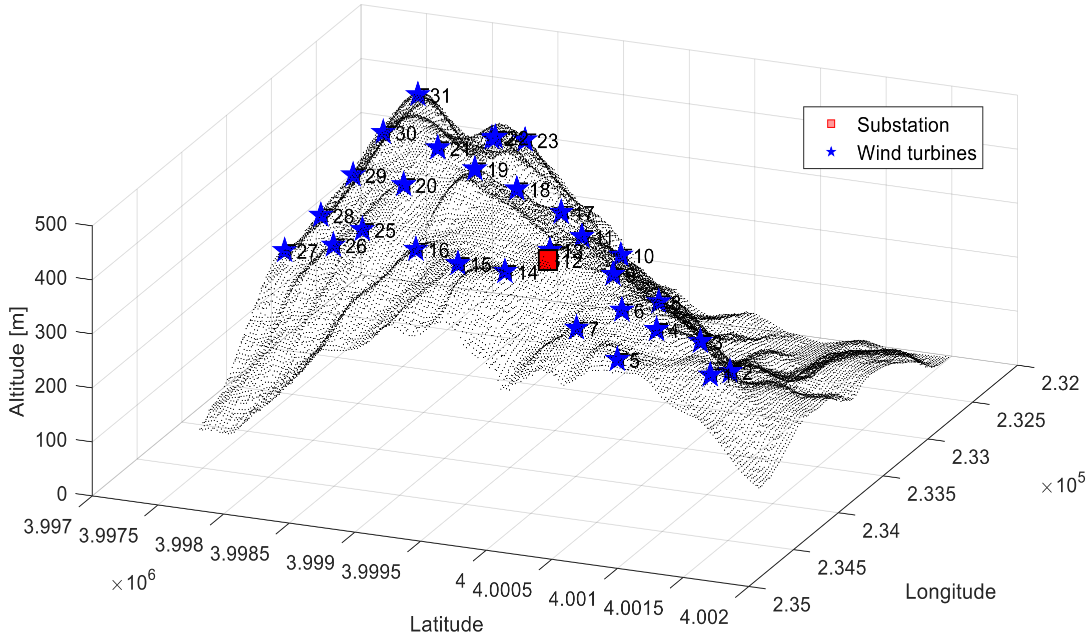


Figure 2.2 : 3D representation of Ziyaret RES.

As one can see from the Figure 2.2, topographical changes are very dramatic for Ziyaret RES as in most of the other onshore farms. Consider a case with 2 wind turbines which are sited close to each other in the Euclidean distance. When the underground cables are preferred for electrical layout, the path of electrical cable will sweep the ground in real life applications instead of using the shortest distance between two points. If the area of interest has sharp altitude changes, using 2D approach for obtaining minimum spanning trees (MST) may mislead the project planner in loss and investment cost predictions. Therefore, considering the effects of altitude change in the internal electrical layout of a wind farm would give more accurate results.

Let *D* be a directed graph, with nonnegative edge lengths. The length of a path in *D* between two vertices (say it *v* and *w*) is the sum of its edge lengths. The real distance between two vertices is the minimum length of a path from two vertices. A minimum length path from *v* to *w* is called the shortest path [19]. In this case, minimum path three (MPT) can be defined as a tree that connects all vertices with using their shortest possible paths. By modifying the MST formulation, one can obtain the mathematical formula for MPT problem as given in (2.18-2.21).

$$Min\ Z(x) = \sum_{e \in E} w_e x_e \tag{2.18}$$

$$Subject\ to: \sum_{e \in E} x_e = n - 1 \tag{2.19}$$

$$\sum_{e \in E(S)} x_e \leq |S| - 1, \qquad \forall S \subset N, \qquad S \neq \emptyset \tag{2.20}$$

$$x_e = \{0,1\} \tag{2.21}$$

As in the problem definition of MST, the value of x_e will be 1 if the edge is selected in the tree and 0 otherwise. *n* represents the number of nodes and equal to |*N*|, and *S* represents a set of nodes in *N*. Every edge (*e*) is associated with a cost *w*. Unlike in MST formulation, instead of using Euclidean distances between source and target nodes, the cost matrix *w* is obtained by measuring the shortest paths between vertices by using Dijkstra's algorithm.

2.7 Dijkstra's Algorithm

Dijkstra's algorithm builds up the required shortest paths by starting from a source node to a target node. In Dijkstra's algorithm, 3 sets of branches are defined:

I) The branches definitely assigned to the tree under construction (they will form a subtree).

II) The branches from which the next branch to be added to Set-I will be selected.

III) The rest of the branches (which are rejected or not yet considered).

The nodes are subdivided into two sets:

A) The nodes which are connected by the branches of Set-I.

B) The remaining nodes (one and only one branch from Set-II will lead to each of these nodes).

Dijkstra's algorithm starts by picking an arbitrary node as the only member of Set-A and by placing all branches that end in this node Set-II. Initially, Set-I is empty. After, following steps are repeated:

Step 1. One node is transferred from Set-B to Set-A by removing the shortest branch of Set-II and adding to Set-I.

Step 2. Consider the branches leading from the node and transferred to Set-A to the nodes still in Set-B. If the branch under consideration is longer than the corresponding branch in Set-II, it is rejected. Otherwise, replace the corresponding branch in Set-II, and the latter is rejected.

These steps are repeated until the Set-II and Set-B are empty. In the end, the branches in the Set-I will include the desired tree [20]. For the rest of the study, the shortest paths between target and source nodes are obtained by using Dijkstra's algorithm. The algorithm is restricted to connect 2 adjacent nodes in design space (Samandağ) and cannot jump over any node. Then, the cost of a path is calculated as the sum of the Euclidean distances of each adjacent node which are used to connect the source and target nodes.

3. RESULTS & DISCUSSION

3.1 Cable Analysis

Wind turbines will not produce their rated power all the time. Here, we assumed that all wind turbines produce same annual electrical energy (same electric current) which is equal to an acceptable value of capacity factor times rated power value. Please note that the sign of *f* is negative because it represents the value of electrical energy lost and the investment costs in \$. Therefore, the maximum value of *f* for each case will be used for selecting the optimum cross sections of cables. The value of EP_t is assumed to be constant because of energy bids and to be equal to 0.05 \$/kWh, *CF* is assumed to be 0.3, and the discount rate is taken as 0.04. The calculated electrical losses in kW and the NPVs of feasible electrical cables in \$ for 25 years and for 1 meter of cable Type-l are given by Table 3.1 and Table 3.2. The negative sign in NPV in Table 3.2 corresponds to the outflow of cash due to cable investment and internal electrical resistance of cables over 25 years of the operational period. As it is clear, greater values of NPVs given by Table 3.2 is more preferable.

Table 3.1: Yearly electrical losses for 1m of each cable in kWh.

Cable	1T	2T	3T	4T	5T	6T	7T	8T	9T
Type-1	0.157166	0.628662	1.41449	-	-	-	-	-	-
Type-2	0.078583	0.314331	0.707245	1.257325	-	-	-	-	-
Type-3	0.033956	0.135824	0.305604	0.543296	0.848901	1.222417	-	-	-
Type-4	0.023308	0.093233	0.209774	0.372931	0.582705	0.839096	1.142102	1.491726	-
Type-5	**0.018148**	**0.072591**	**0.16333**	**0.290364**	**0.453693**	**0.653318**	**0.889238**	**1.161454**	**1.469966**

Table 3.2: Calculated matrix of function *f*.

Cable	1T	2T	3T	4T	5T	6T	7T	8T	9T
Type-1	**-30.4553**	**-37.821**	-50.0973	-	-	-	-	-	-
Type-2	-36.2276	-39.9105	**-46.0486**	-54.642	-	-	-	-	-
Type-3	-42.5305	-44.1219	-46.7742	**-50.4874**	**-55.2616**	**-61.0967**	-	-	-
Type-4	-85.3641	-86.4565	-88.2771	-90.826	-94.1031	-98.1084	**-102.842**	**-108.304**	-
Type-5	-125.284	-126.134	-127.552	-129.536	-132.088	-135.206	-138.892	-143.144	**-147.964**

For instance, for a line which carries current from 3 wind turbines to any location (can be a wind turbine or substation), the best cable type is Type-2 in terms of *f* explained in (2.8) for 25 years. In other words, when we compare financial losses due to energy loss on cables for 25 years in addition to their initial investment values, the best type of feeder for 3 wind turbines is Type-2. The lowest electrical losses are observed with Type-5 cables but its investment cost is higher than the others and therefore it will not be considered by project planners unless it is the only feasible choice. Note that all these results are taken with an assumption of homogeneous annual energy production for the sake of simplicity and cost of trenching is not included in *f* matrix. For more detailed analysis with different CF values, or when wind turbines with different rated powers are considered, an extended approach will be given in the following section.

The aim was to find the best solution in terms of investment return from this trade-off. Many investors in wind energy prefer to choose cables by looking up their maximum power capacities and pick the cheapest feasible solution. When the electrical loss is analyzed 25 years of the period (Table 3.3), its seen that the cheapest solution is not the best fit for all cases. In this case, the cheapest feasible cable type for carrying current from 3 wind turbines is Type-1. But when we consider both the investment and NPV of losses together, the best choice becomes Type-2.

Table 3.3: List of the cheapest and the optimum cables

Number of Turbines	Cheapest Solution	Best Solution
1	Type-1	Type-1
2	Type-1	Type-1
3	**Type-1**	**Type-2**
4	**Type-2**	**Type-3**
5	Type-3	Type-3
6	Type-3	Type-3
7	Type-4	Type-4
8	Type-4	Type-4
9	Type-5	Type-5

The next step is to analyze the case with 2 parallel cables instead of one. By doing so, with a small amount of increase in trenching costs, the objective function values with 2 cables whose diameters are less than the single case will be analyzed. Also, in case of 10 or more turbines are connected within a branch, the product range used in this study will not be able to carry all current with a single cable, because of the current flow limitations. Due to this reason, the objective values of cables per 1 meter with additional (assumed as 50%) increase in the trenching cost is also calculated and are given in Table 3.4.

Table 3.4: Calculated NPV and investment costs for each case with additional trenching cost.

	Number of Wind Turbines								
Cable	1T	2T	3T	4T	5T	6T	7T	8T	9T
Type-1	-55.46 ₺	-62.82 ₺	-75.10 ₺	-	-	-	-	-	-
Type-2	-61.23 ₺	-64.91 ₺	-71.05 ₺	-79.64 ₺	-	-	-	-	-
Type-3	-67.53 ₺	-69.12 ₺	-71.77 ₺	-75.49 ₺	-80.26 ₺	-86.10 ₺	-	-	-
Type-4	-110.36 ₺	-111.46 ₺	-113.28 ₺	-115.83 ₺	-119.10 ₺	-123.11 ₺	-127.84 ₺	-133.30 ₺	-
Type-5	-150.28 ₺	-151.13 ₺	-152.55 ₺	-154.54 ₺	-157.09 ₺	-160.21 ₺	-163.89 ₺	-168.14 ₺	-172.96 ₺

For the rest of the study, electrical cables will be selected by using the “best solution” column of Table 3.3 and Table 3.4 (Table 3.4 will be used if and only if the secondary cable is activated by the optimizer).

3.2 More Effort on Cable Analysis

When an onshore wind farm includes non-identical wind turbines, or when the project planner prefers to use exact CF values of each wind turbine for more accurate results, a special attention must be given to values f matrix. Instead of simplifying the procedure as described above, another method for determination of the best cable thicknesses is suggested.

Let’s determine the cross section of cables considering different rated power and CF values of wind turbines which are connected in series as represented by the single line diagram given in Figure 3.1. If all wind turbines are assumed to be identical and have maximum current and capacity factor values of 49.22A and 0.3, respectively, then the best cables for C_1 and C_2 will be the Type-1 cable. If their annual energy generation would be nonidentical, using (2.7) one can determine the amount of i_{max} for each wind turbines. Rearranging (2.9) and multiplying with EP will give (3.1).

$$E_{loss} = -\frac{3 \times 8766 \times \left(\sum_{m=1}^{M} i_m \times CF_m\right)^2 \times R_l}{1000} \times EP \tag{3.1}$$

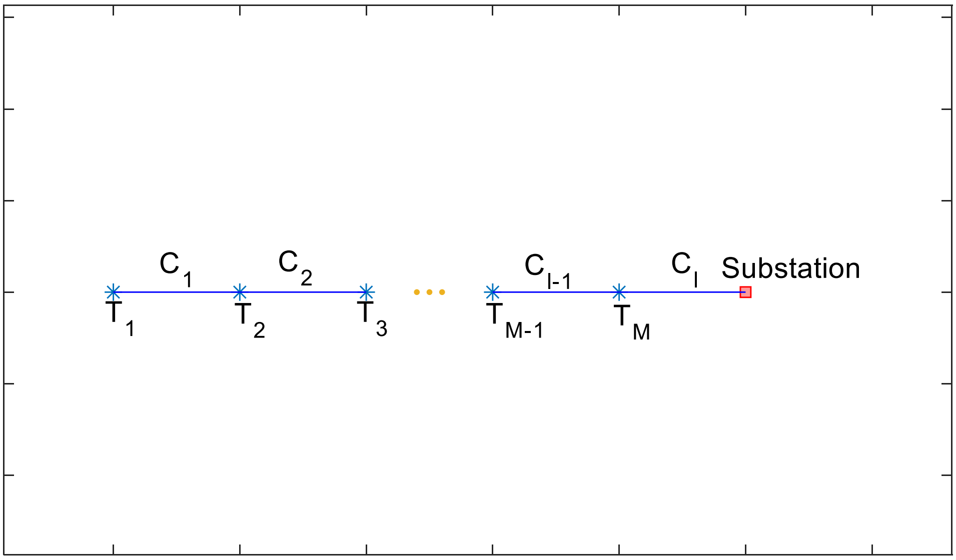


Figure 3.1: A representation of single line diagram

Here, the problem dependent part, $\sum_{m=1}^{M} i_m \times CF_m$, will be named as *iCF*. Using (3.1), one can find the values of *iCF* to determine the best values of *f* described in (2.8) for each type of cable. Let's consider 2 cables, Type-1 and Type-2 for C_1 of the figure. If *iCF* versus *f* is plotted for unit length, the following two curves given in Figure 3.2 will be obtained.

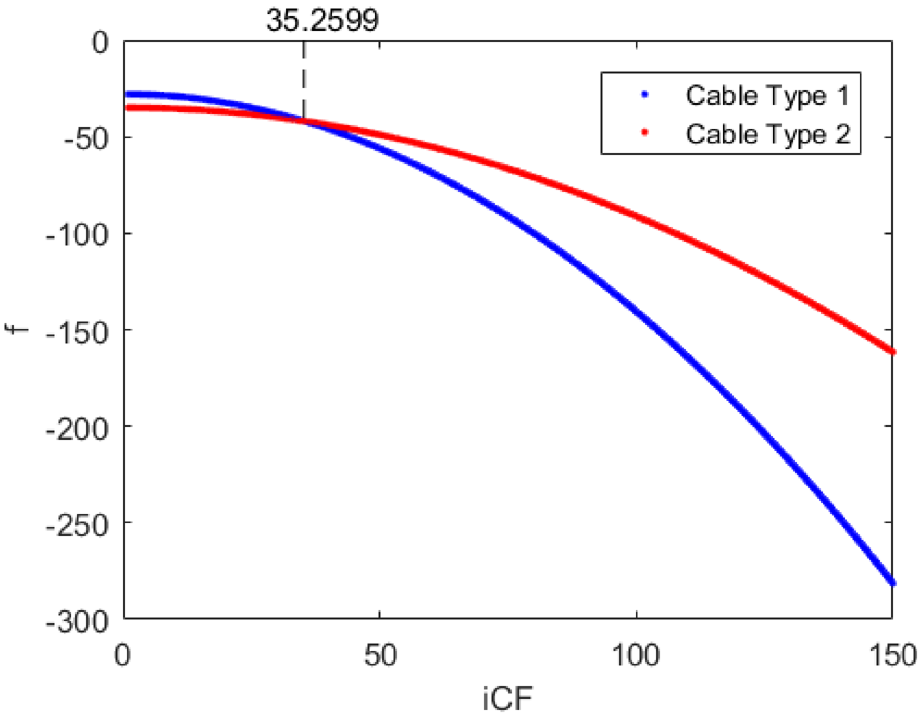


Figure 3.2: *iCF* versus *f* for C1

The intersection point of two curves, the break-even point, separates the best cable for line C_1 at iCF = 35.2599. This plot points out that for lower values of *iCF* with 35.2599 the best type of cable will be Type-1 and for higher values the best selection will be Type-2. Recall the homogeneous production assumption for each wind turbine with i_{max} = 49.22A and CF = 0.3, *iCF* will be equal to 14.766 for a single wind turbine. Combining the breakeven point with maximum power capacity of Type-1 cable, one can say that up to 2 homogenous wind turbines with 2.5MW rated power and a CF of 0.3, Type-1 cable is the best option in terms of *f*. This shows that our approach is extendable for wind turbines with nonidentical annual energy generation. Together with the value of *iCF*, one must also consider the current carrying capacity of each cable in determination phase. The determination of the best type of cable is important because knowing the best cross section in advance will result in a significant reduction of convergence speed. Also, this will allow researchers to use different variables with different approaches for reaching the global optimum solution of onshore wind farm electrical layout problem. For heterogeneous cases, best cross sections are given by Table 3.5 in terms of *iCF* and I_{max}.

Table 3.5: The list of *iCF* values for determination of cable cross sections.

Cable	iCF (rounded)	$A = \sum_{m=1}^{M} i_{max,m}$
Type-1	$iCF \leq 35.26$	$A \leq 150$
Type-2	$35.26 \leq iCF \leq 46.79$	$A \leq 211$
Type-3	$46.79 \leq iCF \leq 237.41$	$A \leq 332$
Type-4	$237.41 \leq iCF \leq 328.91$	$A \leq 405$
Type-5	$iCF \geq 328.91$	$A \leq 462$

In Ziyaret RES, all of the wind turbine will produce 49.22 Amp. at rated power. If the CF for each of the wind turbine is taken as 0.3, the value of 1 *iCF* will be equal to 14.766 Amp. Considering the maximum current carrying capacities and *iCF* intervals in Table 3.5, Type-1 cable will be the best selection in terms of *f* up to 2 wind turbines whereas Type-2 cable will be the optimum for 3 wind turbines, and so on. These results coincide with the results in Table 3.3 and can be generalized for all cases with nonidential *iCF* values. For the rest of the study, it is assumed that all wind turbines generate electricity homogeneously as described above.

3.3 Studies with 2D Approach

3.3.1 Radial clustering

Since the value of T_{max} is 9, initially N is assumed as 4 (for N = 3, the constraint of T_{max} is exceeded: 10-10-10). The representation of the optimized clusters with N = 4 is given in Figure 3.3. The results have 8 wind turbines in 2 clusters and 7 wind turbines in the remaining clusters. Red dashed lines in Figure 3.3 represents the imaginary separators which are used as variables of the radial clustering problem. Each clusters obtained by the proposed technique and their associated wind turbines are given in Table 3.6.

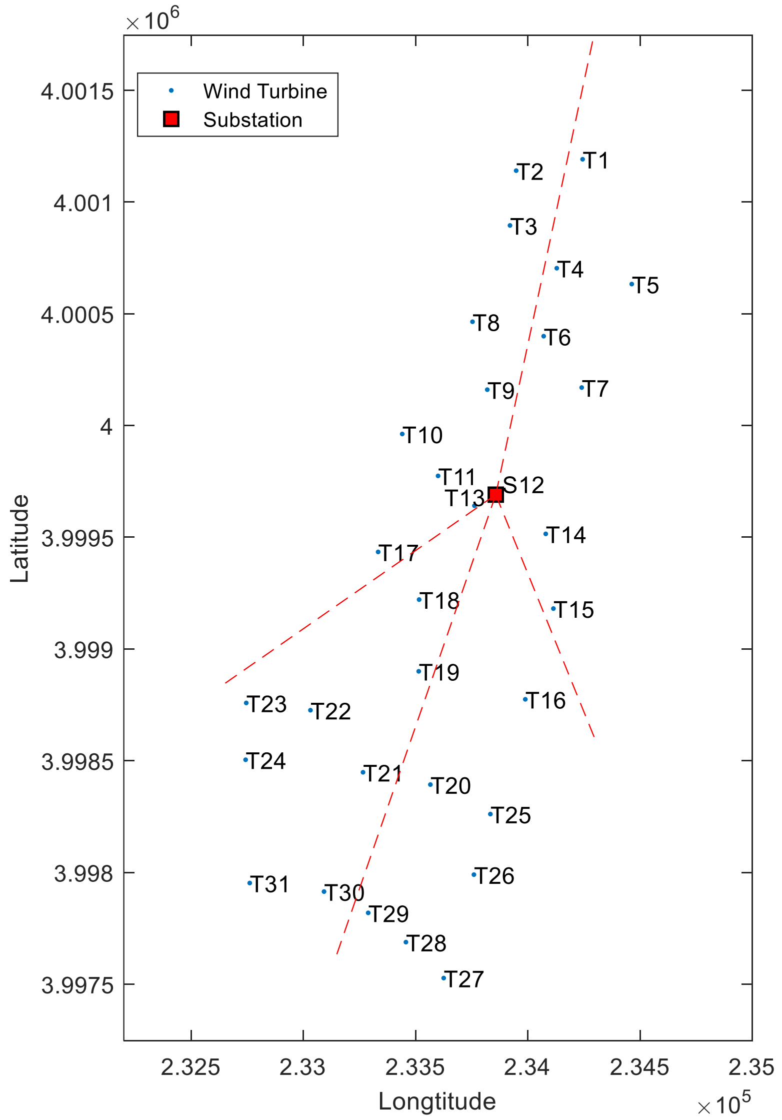


Figure 3.3: Representation of radial clusters over wind farm with N = 4

Table 3.6: List of clusters and their associated wind turbines.

Cluster No	Associated Wind Turbines
Cluster 1	T1, T4, T5, T6, T7, T14, T15
Cluster 2	T16, T20, T25, T26, T27, T28, T29
Cluster 3	T18, T19, T21, T22, T23, T24, T31, T30
Cluster 4	T2, T3, T8, T9, T10, T11, T13, T17

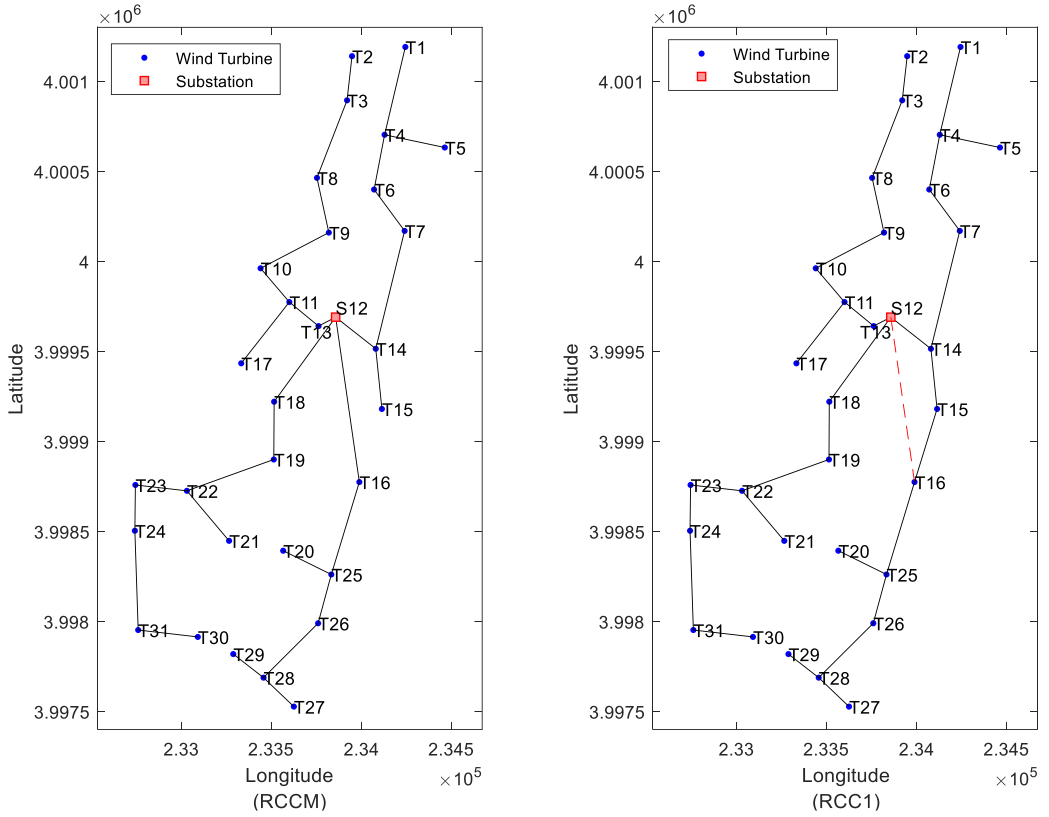
In order to obtain MSTs for each cluster, wind turbines are combined with substation (S12). By using a particle swarm optimizer (PSO) MSTs for each clusters are obtained. For details of the PSO, readers may refer to [21]. The obtained solution has 11292.59m total trenching length and represented by RCCM part of Figure 3.4.

After MSTs are obtained within each cluster, possible bypass lines to reduce trenching lengths are determined and 3 new cases are additionally analyzed. In the first case (will be called as RCC1) T16 is connected with T15 instead of directly connecting to the substation. In the second (RCC2) and third (RCC3) cases, T18 in Cluster 3 is connected with T17 and T13 respectively instead of directly connecting with the substation. Each of these cases are displayed in Figure 3.4 and Figure 3.5. The idea is to check whether shortening the trenching length by using already trenched routes fits better in terms of objective function value and to check if radial clustering configuration can be further developed. For this evaluation, special attention is paid to lines in which 2 cables are buried (trenching cost is increased 50%).

Numerical experiments showed that in RCC3, the objective function value is greater than all the other cases. While the gain from trenching is more than the extra investment due to increased cable lengths and increased electrical losses, the objective function value is increased as in the case of RCMC3. In RCC1 and RCC2 there is no net gain due to the negative change in the objective function, the reduction of trenching length increased the total cable costs and electrical losses. The results of the cheapest, the most expensive, and the optimum cable selection cases for RCCM, RCC1, RCC2, and RCC3 are given by Table 3.7.

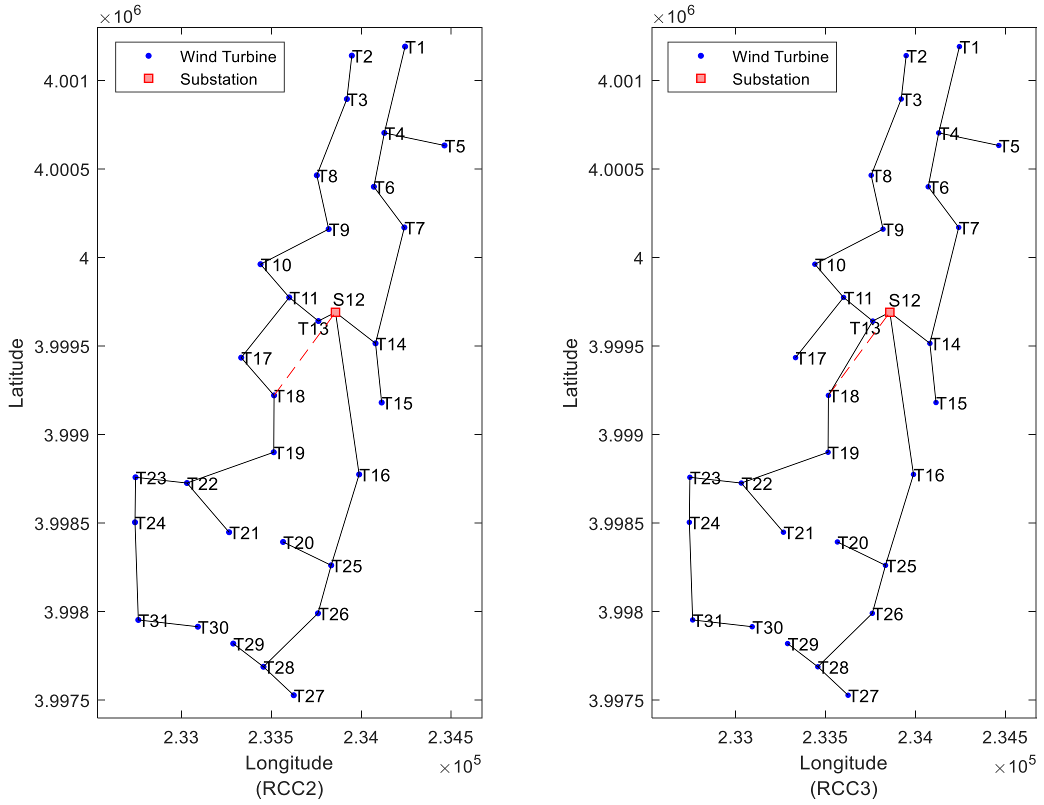
Table 3.7: Results of the cheapest, expensive, and optimum cases on RCCM, RCC1, RCC2, and RCC3.

Connection	The Cheapest[$]	The Most Expensive[$]	Optimum[$]
RCCM	-1207025.1	-2041297.6	-1196426.8
RCC1	-1209749.2	-2048316.3	-1199151.0
RCC2	-1259522.9	-2109475.0	-1248924.7
RCC3	-1206496.8	-2041242.7	**-1195898.6**



(RCCM) (RCC1)

Figure 3.4: Obtained electrical layouts with radial clustering (RCCM and RCC1)



(RCC2) (RCC3)

Figure 3.5: Obtained electrical layouts with radial clustering (RCC2 and RCC3)

The best solution found so far by using radial clustering technique is -1195898.6$ with RCC3. This value includes the amount of money spent or electrical loss due to cable investments or electrical losses throughout the lifetime of the wind energy power plant. Please note that only electrical losses, trenching amount, and cable investments are included in the objective value. Other equipment such as panel, relay, transformer, breaker, etc. or maintenance/repair fees are not included. Modified results showed that constraints of a maximum number of wind turbines defined for radial clustering technique preclude the optimizer to reach a global optimum.

3.3.2 String configuration

In the string configuration, assuming that the subcontractors prefer to construct paths for vehicles by using global MST of the wind farm, which includes all wind turbines and the substation, the electrical cables will be buried parallel to these roads. By doing so, technicians can instantly fix any cable failure when any issue related with power transmission system occurs. The obtained global MST is displayed in Figure 3.6. The total trenching length is calculated as 9194.4 m.

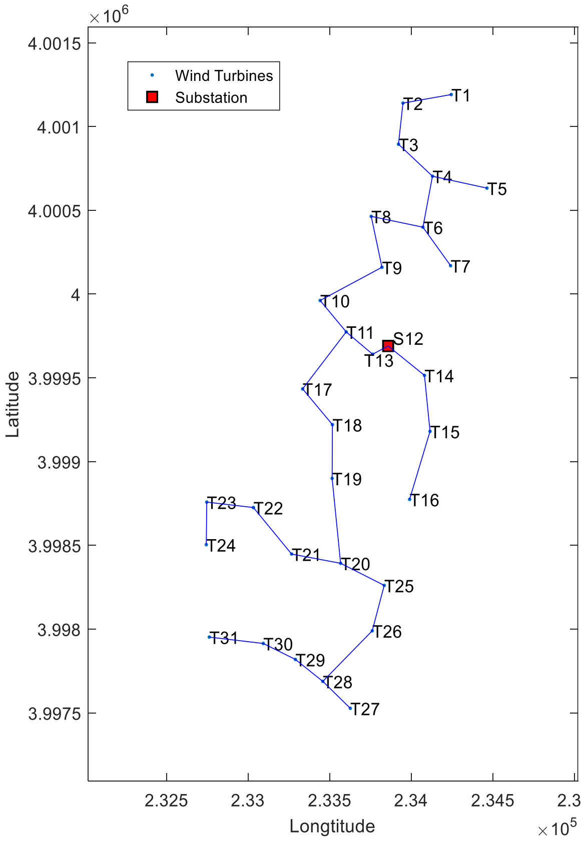


Figure 3.6: Simple tree layout obtained for Ziyaret RES

A thorough search of the relevant literature yielded that the case when the number of wind turbines coming over a line exceeds the maximum current capacity of cables is not explored. Up to here, radial clusters which include 7 or 8 wind turbines are analyzed. Hence, this limit was not exceeded. However, in the remaining parts a brief analysis will be given for cases with the maximum current carrying capacity is exceeded.

By using Figure 3.6, one can see that the northern part of the obtained MST representation includes 11 turbines. But the feeders used in this study can carry maximum 9 of them. The research question is, "*is it good to pick 9 turbines from northern side in order to decrease the electrical resistance from the farthest point and pick last 2 turbines separately? Or is there any better composition that can reduce both investment and losses over 25 years?*".

For this problem, a metaheuristic method in order to reduce the computational time of such a complex multi-constraint and multi-objective optimization problem is preferred. Here, a well-known multiobjective optimization algorithm, Non-dominated Sorting Genetic Algorithm 2 (NSGA-2) developed by Deb et al. is chosen. [22].

The current is not allowed to flow over unnecessary paths in the simulations, i.e. electrical cable left from T17 cannot flow through the T10, all cables carry electrical current through the substation by using the shortest path. Numerical experiments showed that obtaining a feasible set of solutions within a few seconds is not possible with the whole wind farm. Therefore, instead of increasing the number of generations of the genetic algorithm, sub-tree representations which are separated by the substation have been further analyzed. The subtrees (ST) are selected as:

$$ST1 = [T16, T15, T14, S12]$$

$$ST2 = [T17, T18, T19, T20, T21, T22, T23, T24, T25, T26, T27, T28, T29, T30, T31, S12]$$

$$ST3 = [T1, T2, T3, T4, T5, T6, T7, T8, T9, T10, T11, T13, S12]$$

Given 3 subtrees, the ST1 includes 3 turbines, ST2 includes 15 turbines, and ST3 includes 12 turbines. As the number of wind turbines increases in a subtree, the complexity of the problem also increases. Therefore, NSGA-2 is ran with 100 population/300 generations for ST1, 100 population/1000 generations for ST2 and ST3. ST1 have no connection with ST2 and ST3 until lines meet at S12. Special attention is paid to the joint path which is partially used by ST2 and ST3 [T11-T13-

S12]. Only at this part, more than 2 parallel cables (4) are allowed to carry current through the substation. Besides, it is assumed that cables from different subtrees are buried in different trenched zones (2 x 75$ in trenching fees per 1 meter). Readers may note that until T18, 2 lines in parallel must already be used in order to hold the rest of the turbines (14). In other words, one or more turbine current from ST3 cannot join cables of ST2, since this would require a third cable in parallel which is not allowed. This shows that dividing MST into 3 subtrees are acceptable in terms of optimization strategy under given restrictions.

This methodology allows the optimizer to pick any kind of cables until the maximum current constraint is ensured. Regardless of whether the largest or smallest cable cross section provides the optimum solution for the first turbine connected in daisy chain style, the optimizer finds the optimum cables by searching all possible configurations. Therefore, the proposed method will still work with wind turbines with different rated power or different capacity factor values. The convergence speed of the algorithm may be increased by adjusting the box constraints of the integer variables. Since creating subtrees does not have any negative effect on the global optimal solution, we leave improving the algorithm performance as a future task.

After optimization is completed, a point from the Pareto front with a simple multi-criteria decision making process is chosen. Here, a solution with the maximum value of f for which is equal to the sum of objectives f_1+f_2 is chosen. The problem is multi-objective in its nature, but in terms of economic point of view, the project planners would select a feasible solution with maximum economic benefits using f. But note that this assumption may not be followed by project planners in any case and they would choose to use different criterion which is greatly affected by operational limits (i.e instead of using pretty different cable sizes, planners would stick at one type with greater cross section).

The obtained solution from the NSGA-2 optimizer are given in Table 3.8, Table 3.9, and Table 3.10 for ST1, ST2, and ST3, respectively. A brief representation for each of the line is given in Figure 3.7.

Table 3.8: Optimum solution found for ST1.

Parallel Lines	L13	L14	L15
ST1/PL1	0	0	0
ST1/PL2	3	2	1

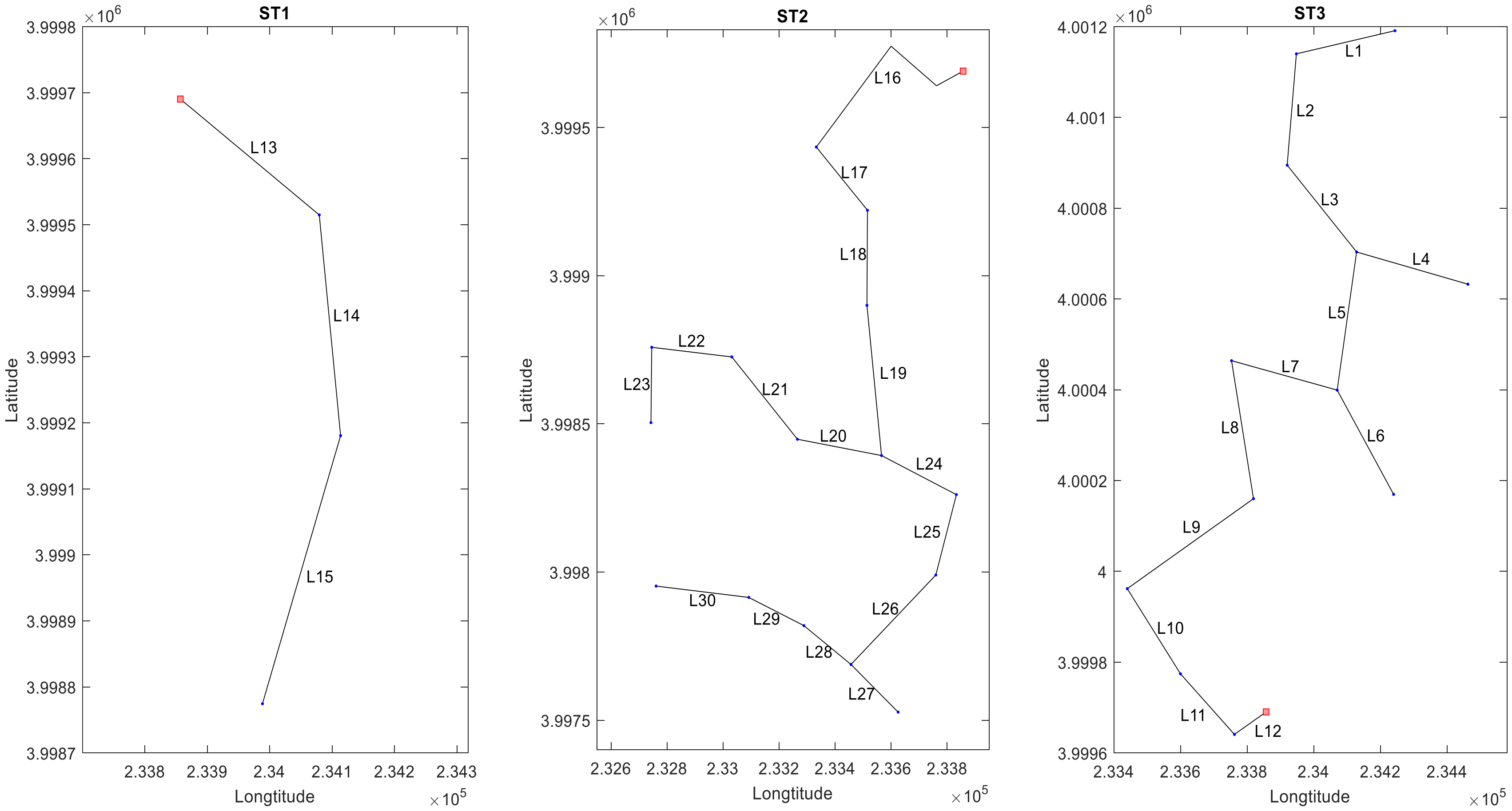


Figure 3.7: Line representation for subtrees

Table 3.9: Optimum solution found for ST2.

Parallel Lines	L16	L17	L18	L19	L20	L21	L22	L23
ST2/PL1	9	8	8	7	0	0	0	0
ST2/PL2	6	6	5	5	4	3	2	1
	L24	L25	L26	L27	L28	L29	L30	
ST2/PL1	7	6	5	1	3	2	1	
ST2/PL2	0	0	0	0	0	0	0	

Table 3.10: Optimum solution found for ST3.

Parallel Lines	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
ST3/PL1	1	2	3	1	5	1	6	6	6	6	6	6
ST3/PL2	0	0	0	0	0	0	1	2	3	4	5	6

As expected, up to a point the optimization algorithm does not tend to use the second parallel line to burry electrical cables, and that point pretty much depends on 2 subjects: Configuration of the rest of the tree through the substation and the relation between additional trenching and cable costs. The values of the variables are given in Table 3.8, Table 3.9, Table 3.10 represent the number of wind turbines carried by the given line. For example, the algorithm simply connected ST1 by using 1 electrical cable only. But for ST2, the configuration was much more complicated. The optimizer chose to pick single line until the line includes 7 wind turbines (T31, T30, T29, T28, T27, T26, T25). When the NPV values of each cable per 1 turbine are analyzed by dividing the values given in Table 3 into a number of wind turbines M, the highest ratio will be obtained with cable Type-3 with 6 turbines (by using data in Table 3, -61.0967/6 ≅ -10.18). This means that the algorithm may tend to build layouts with 6 turbines connected in series in earlier phases. But due to the changes in length and number of wind turbines at the rest of the line, algorithm tend to go for [7 5] in the buried zone instead of [6 6]. On the other hand, optimizer built a layout with reaching 6 turbines in the early phase of collection, and finished up with [6 6] in the last group ST3. For this problem, there are two trade-offs. First one is simple, the trade-off between cable investment cost and the cost of losses over 25 years of plant lifetime. And the second one is the connections with parallel cables: early maturity (reaching the value of *Tmax* with a greedy approach) with single cable reduces the additional trenching amount (when the second cable is not used) but increases the cable prices especially when 7 turbines or more are connected, or vice versa. For a fair comparison, k-means clustering is applied to the string configuration and 3 clusters excluding the wind turbines T14, T15, and T16 are created. By using same lines over MST, wind turbines are allowed to connect with only their cluster members. The turbines selected to connect with each other are given for k-means clustering in Table 3.11.

Table 3.11: Configuration of wind turbines obtained by k-means clustering.

Clustering	Group	Turbines
K-means	Group 1	T1, T2, T3, T4, T5, T6, T7, T8
	Group 2	T9, T10, T11, T13
	Group 3	T14, T15, T16
	Group 4	T17, T18, T19, T20, T21, T22, T23, T24
	Group 5	T25, T26, T27, T28, T29, T30, T31

Obtained values for the initial investment, NPV of losses, and the decision-making criterion *f* are given in the Table 3.12. Values given as *f* is one of the strongest criteria for project planners. Naturally, investors are willing to obtain the maximum earnings from a minimal investment. Since the energy will be produced based on the micrositing performance characteristics of the project and wind characteristics, the project planners' needs will be satisfied if the losses are reduced (we hereby define losses with a negative sign, so for our case it is an increase) with minimum layout investments. As it is expected, the best solution to MST layout problem is obtained by the proposed methodology. Results indicate that it requires the lowest investment cost for cables and trenching.

Table 3.12: Comparison for k-means clustering and proposed method in use of MST configuration.

Expense	K-means clustering with Optimum case	 The cheapest case	 The most expensive case	Proposed Method
Cables/trenching	-1208629.7 $	-1196276.8 $	-2092297.3 $	**-1165957.9 $**
Losses	-163080.9 $	-182622.0 $	**-98166.2 $**	-169257.5 $
Value of f	-1371710.5 $	-1378898.8 $	-2190463.4 $	**-1335215.5 $**

3.3.3 Modified clustering based method

Getting inspired by the study in [6], the proposed clustering based approach is modified. Instead of assigning clustering representative points, imaginary points that connect all turbines within a cluster to substation are assigned. By doing so, instead of manually assigning a representative point, an optimizer will be able to pick optimum imaginary point that will connect clusters and substation (if the best location for representative point is on the exact position of any wind turbine, algorithm will still be able to find a solution close to that wind turbine). For this study, k-means clustering algorithm is used instead of using QT clustering. An advantage of k-means clustering is that it is computationally more efficient compared to QT clustering. Even though the researchers in [6] mentioned that they chose QT clustering due to the fact that there is no need to specify the number of clusters, one has to define a different parameter in QT clustering: the radius of a cluster. Also with QT clustering, it is not guaranteed that all wind turbines will be in a cluster created by the QT algorithm. Initially 3 clusters (north, middle, and south clusters) are created for this problem by using k-means clustering algorithm. The turbines within each cluster are summarized in Table 3.13.

Table 3.13: Clusters obtained by k-means clustering.

Cluster Name	Assigned Wind Turbines
North	T1 T2 T3 T4 T5 T6 T7 T8 T9
Middle	T10 T11 T13 T 14 T15 T16 T17 T18 T19
South	T20 T21 T22 T23 T24 T25 T26 T27 T28 T29 T30 T31

Encoding of this problem is simple: 4 variables for northern and southern clusters that represent the *Xx* and *Yy* coordinates of the cluster representative points'. For the remaining cluster in the middle, all wind turbines are connected to the substation. The objective functions are chosen as the same: minimum investment cost and minimum losses. From the obtained Pareto front, a solution is selected by using the same decision making criterion, *f*. Based on the results, the initial investment value for electrical layout is obtained as -1525867.2 $ and the NPV of losses over 25 years are calculated as -109524.7 $ which is -1635391.9 $ in total. The *Xx* and *Yy* coordinates of the representative points for northern and southern clusters are obtained as 234049.7, 4000416.2 and 233323.4, 3998333.4, respectively and shown in the Figure 3.8. Compared to radial clustering and string configuration (global MST) this value is the worst. Even though the authors in [6] explains that the clustering based approach is expensive initially but provides more benefits over time, we failed to see such promising results in this study. Another statement in [6] was that the proposed clustering based technique is operationally more preferable due to one by one connections of wind turbines with their cluster representative points. In any possible failure on cables, wind turbines behind the failed line will not be able to feed the grid and therefore produced electricity will be lost unless a loop configuration is used. In order to verify this statement, a simulation model for cable failure is developed and the results will be explained in the following section.

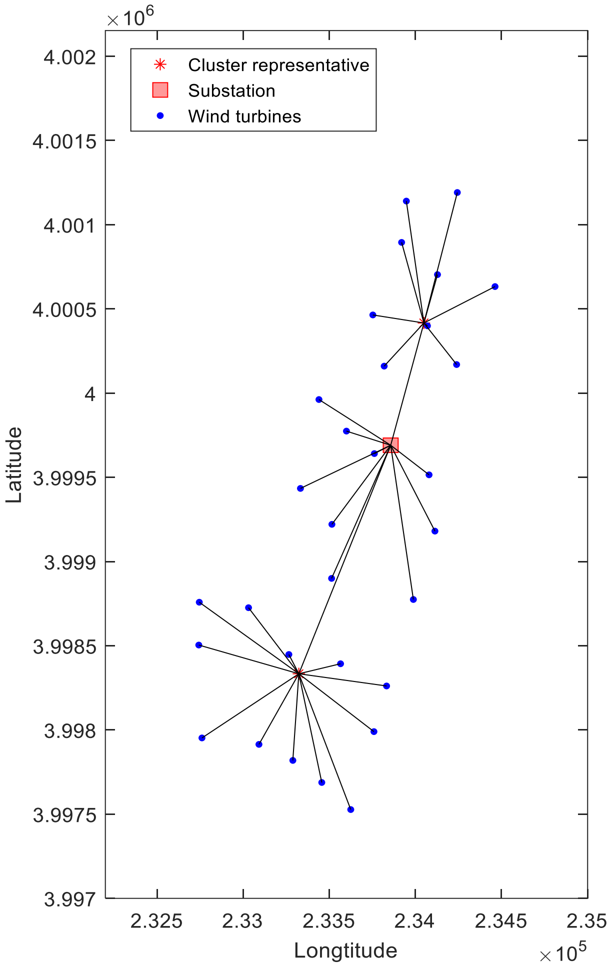


Figure 3.8: Representation of clustering based configuration

3.3.4 Simulation results for cable failure

In this part of the study, the modified clustering based strategy is compared with the best configuration found so far, radial configuration. Assume that total trenching length for radial and k-means cases are L_R and L_k. In order to simulate the system behavior in any cable failure, all cable lines are concatenated in a logical order and total trenching length is normalized between 0 and 1. Cable failure is simulated by generating 1 random number per 2 years between 0 and 1 for Turkey's conditions. Each random number represents the position of cable failure and will result with loss of connection between wind turbines which are behind the point of disconnection.

Starting from Cluster1 to Cluster4 of RCC3 the line is concatenated and total length of the trenched zone is obtained as 11199 m. For modified clustering based configuration, total length is found as 14755 m. By using MATLAB's uniform random number generation function *rand()*, 13 random numbers are created and denormalized using total length of each configuration. After lines with failure are determined, the number of wind turbines which are going to stop feeding the substation are counted for each year and found as in Table 3.14.

Table 3.14: Number of wind turbines stopped feeding the substation at year *t*.

	Number of turbines stopped feeding substation												
Year	1	3	5	7	9	11	13	15	17	19	21	23	25
New System	1	1	1	1	1	1	1	12	1	1	1	1	1
Radial Configuration	3	6	4	6	6	3	2	3	7	7	5	7	7

As it is proposed in [6] numerical experiments showed that the number of wind turbines which are going to stop feeding the substation with modified clustering based approach is less than the radial configuration. Based on the simulated conditions, total of 24 wind turbines will stop producing electricity for 3 hours with the modified clustering based approach. On the other hand, 66 wind turbines will stop feeding the substation for 3 hours with the radial configuration. Here, a scenario analysis to see the effects of capacity factor at failure instant of the wind farm is performed. It is assumed that the best, average, and the worst case scenarios have capacity factors of 0.1, 0.3, and 0.8 respectively. Then, the NPV of energy lost in $ are calculated for each scenario and given in Table 3.15.

Table 3.15: Scenario analysis for cable failure over 25 years with NPV in dollars.

Scenario	New System	Radial Configuration
Best Case	-534.6 $	-1487.745 $
Average	-1603.8 $	-4463.2 $
Worst Case	-4276.8 $	-11901.96 $

It is obvious that in all scenarios under given conditions (assuming all electrical equipment and technicians are ready at the wind farm to solve the issue on time) new method proposed by [6] cannot catch up the radial clustering design in 25 years. The difference between both design methodologies in terms of *f* is 439493 $. Generally speaking, instead of having 1 cable failure over 2 years, 57 cable failures per 2 years under worst case scenario should have taken place in order to compensate the difference with radial configuration which is almost impossible. Numerical results with QT clustering do not change the difference between two configurations and therefore the simulating cable failure is ended without using QT clustering.

3.4 Studies with 3D Approach

3.4.1 Radial clustering

Initially, the clustering procedure is completed using the genetic algorithm as it is explained in the “Radial Clustering” part. 2 cases for 3D radial clustering are prepared: One with 4 clusters and the other with 3 clusters. The obtained groups for both cases are given in Table 3.16 and Table 3.17. The maximum current capacity of the cable with the highest cross section is exceeded in the case with 3 clusters, therefore, the proposed strategy with 2 parallel cables in the “A Strategy for Predefined Paths” is applied for a case with 3 clusters. Referring to the *f* matrices obtained for the single and secondary type of cables in the previous study, the use of a secondary parallel cable becomes economically feasible when the number of turbines connected in series to the same feeder becomes 9 or more. The same strategy is also applied to the case with 4 clusters in order to analyze the correctness of this claim.

Table 3.16: Radial clusters with $N = 4$.

Cluster Name	Wind Turbines
4C/A	T1, T4, T5, T6, T7, T14, T15
4C/B	T16, T20, T25, T26, T27, T28, T29
4C/C	T18, T19, T21, T22, T23, T24, T31, T30
4C/D	T2, T3, T8, T9, T10, T11, T13, T17

Table 3.17: Radial clusters with $N = 3$.

Cluster Name	Wind Turbines
3C/A	T1, T2, T3, T4, T5, T6, T7, T8, T9, T14
3C/B	T15, T16, T19, T20, T25, T26, T27, T28, T29, T30
3C/C	T10, T11, T13, T17, T18, T21, T22, T23, T24, T31

Secondly, cost matrices for wind turbines are obtained with both 2D and 3D approaches. For 3D and 2D approaches, *nxn* matrices are created by using all possible connections of nodes with Djkstra’s algorithm and with a simple Euclidean distance calculator, respectively. Obtained 3D and 2D cost matrices are used in Particle Swarm Optimizer (PSO) in order to obtain MPT and MST configurations. The 2D representations of 4 cluster and 3 cluster cases are given in Figure 3.9 and Figure 3.10, respectively. When the 3D approach is considered, connection parts that have changed in the tree representations are given with red lines. These are due to topological changes of the Samandağ, PSO optimizer preferred to connect different nodes to find the shortest route. Details of the changes for 3 cluster and 4 cluster cases can be seen in Figure 3.11 and Figure 3.12, respectively. The obtained results with 3 and 4 clusters are given in the Table 3.18. From Table 3.18, one can see that the difference in total costs which includes NPV of electrical losses and overnight investment costs reduced when the number of clusters increased. This is because of increased length of cable use with smaller cross sections in 4 cluster case. As it is expected, in 4 cluster case algorithm did not choose a secondary parallel cable whereas in 3 cluster case a secondary cable is used. The total trenching length is increased from 3 clusters to 4 clusters with both 2D and 3D approaches.

From Table 3.18 one can see that the best solution is obtained with 3 clusters using 2D approach. However, when the altitude changes are considered with the 3D approach, the best solution becomes the case with 4 clusters. These results show that due to the effect of altitude change around the terrain, 2D approaches may mislead the project planner in terms of both the objective function values (*f*) and type of configuration.

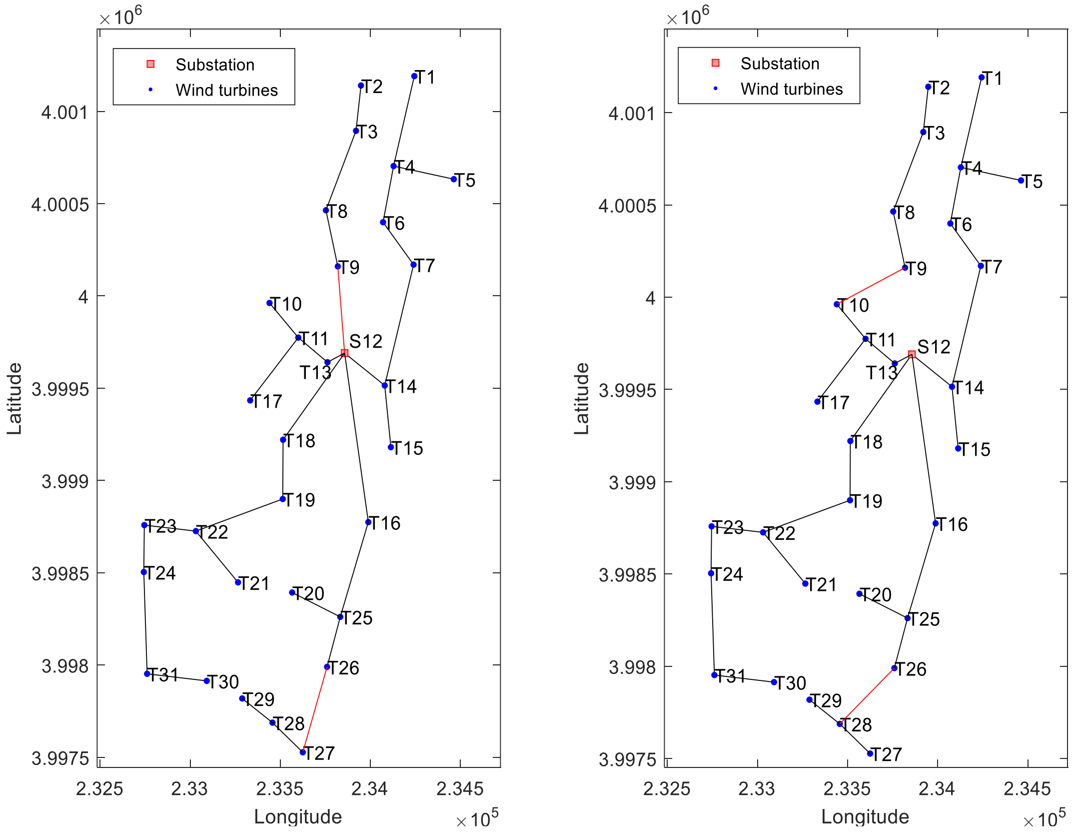


Figure 3.9: Obtained MST with 4 clusters (3D case on the left and 2D case on right)

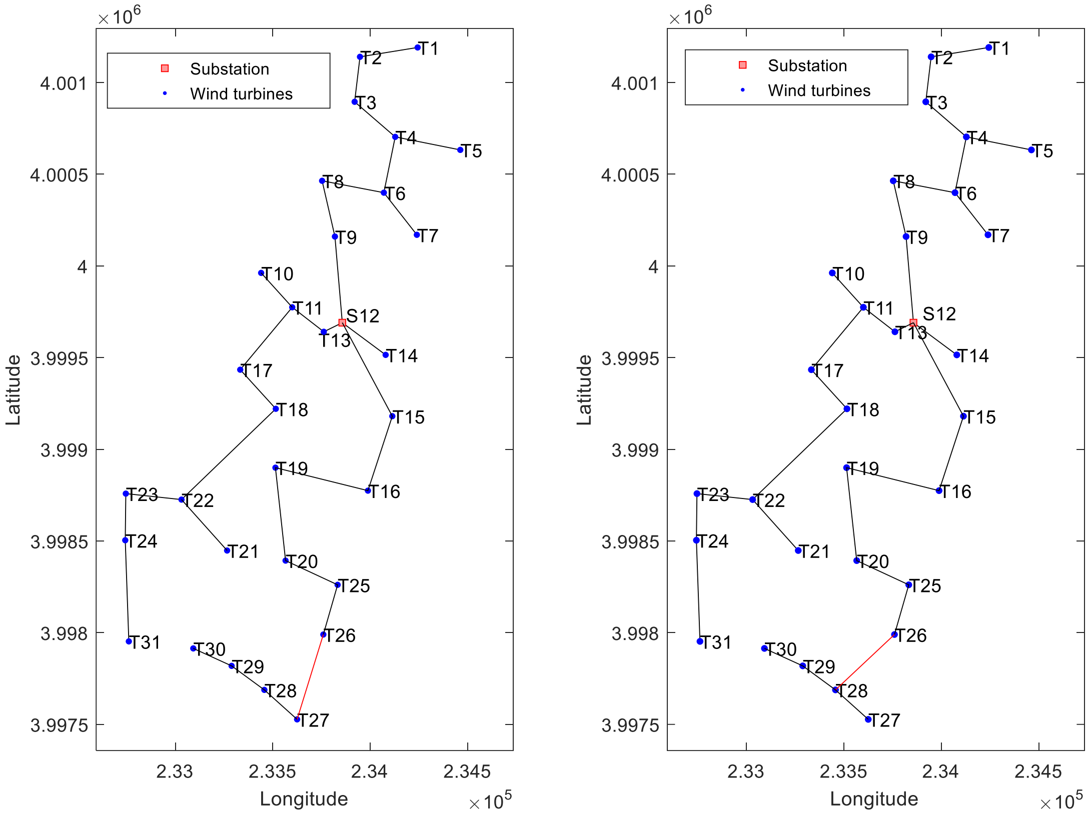


Figure 3.10: Obtained MST with 3 clusters (3D case on the left and 2D case on right)

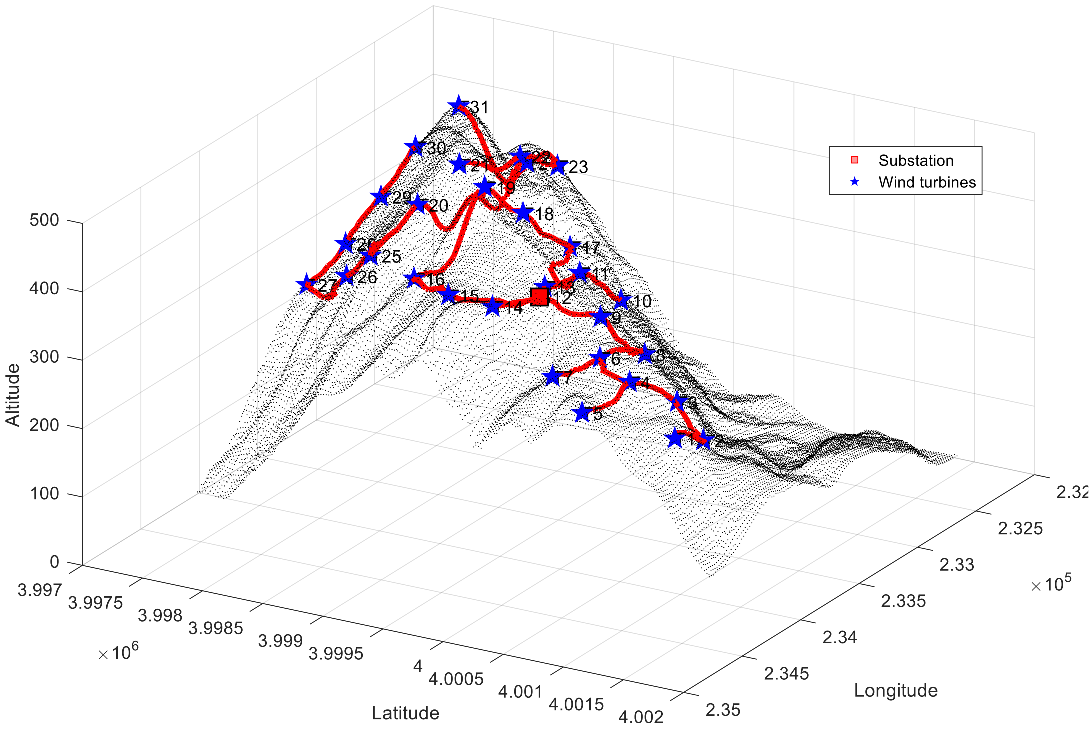


Figure 3.11: 3D representation of 3 cluster case

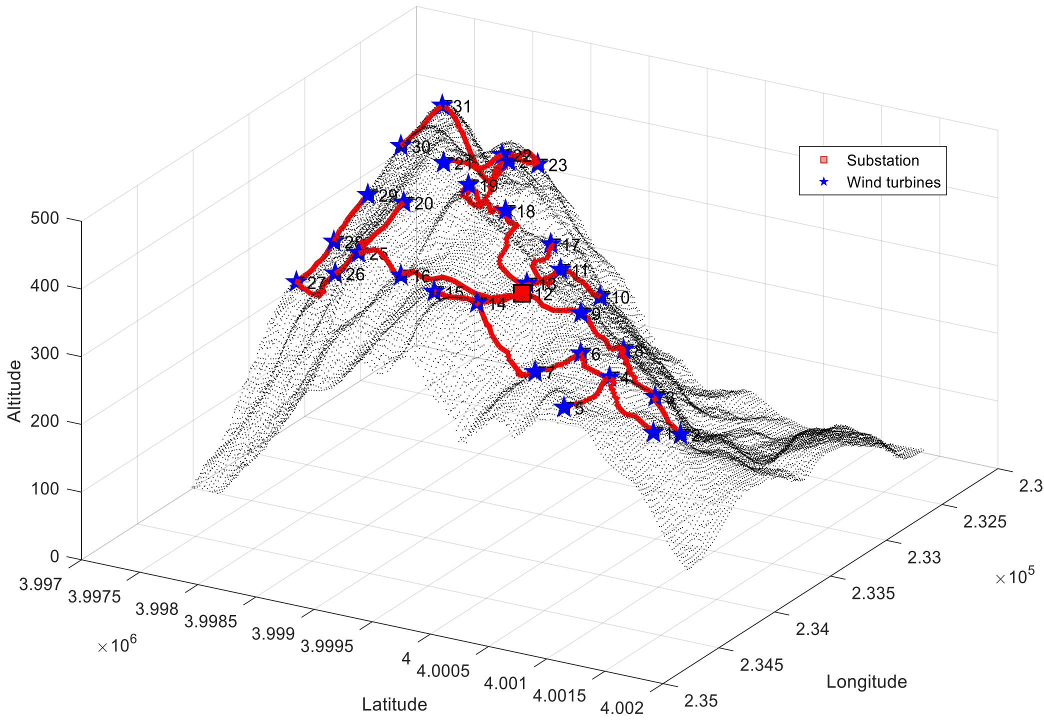


Figure 3.12: 3D representation of 4 cluster case

Table 3.18: Obtained results for radial clustering configuration.

Number of Clusters	Approach	NPV of Losses	Overnight Costs	f	% Difference	Trenching Length	% Difference
3	3D	168252.9	1272900.1	1441153.1	11.2	11654.5	12.1
	2D	152299.8	1127141.2	1279441.0		10249.2	
4	3D	142491.1	1261844.6	1404335.6	6.1	13499.5	16.3
	2D	122627.1	1196426.8	1319054.0		11292.6	

3.4.2 String configuration

Note that electrical cables are buried parallel to predefined paths. It is assumed that the predefined path of Ziyaret RES has exactly same routes with MPT. Therefore, 3D costs obtained with Dijkstra's algorithm are used to obtain MPT for obtaining a predefined route. Using 3D costs in MPT calculations affect the connection of nodes significantly. The PSO does not tend to connect wind turbines over rugged terrain. Instead, it tries to find smoother paths which will result in shorter path lengths. A comparison for 2D views of MPT and MST is represented in Figure 3.13. The red lines are given in Figure 3.13. correspond to changes in connection of nodes from MST to MPT. 3D view of the string configuration is given in Figure 3.14.

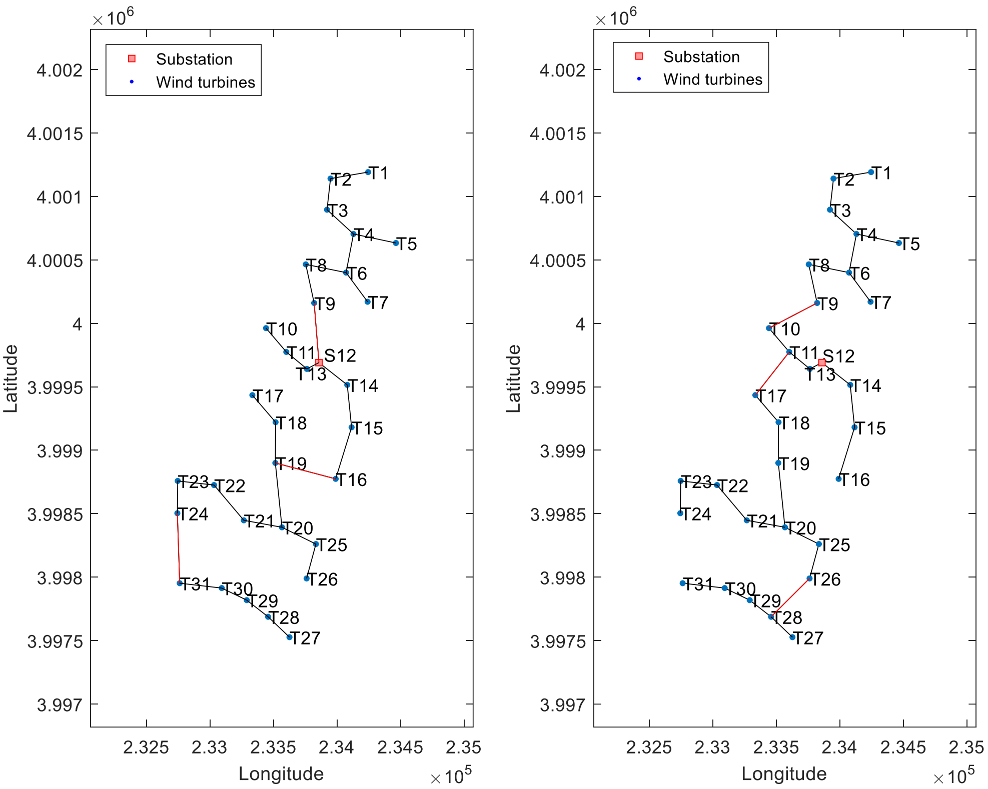


Figure 3.13: 2D representation of obtained MPT (on the left) and MST (on the right) for Ziyaret RES.

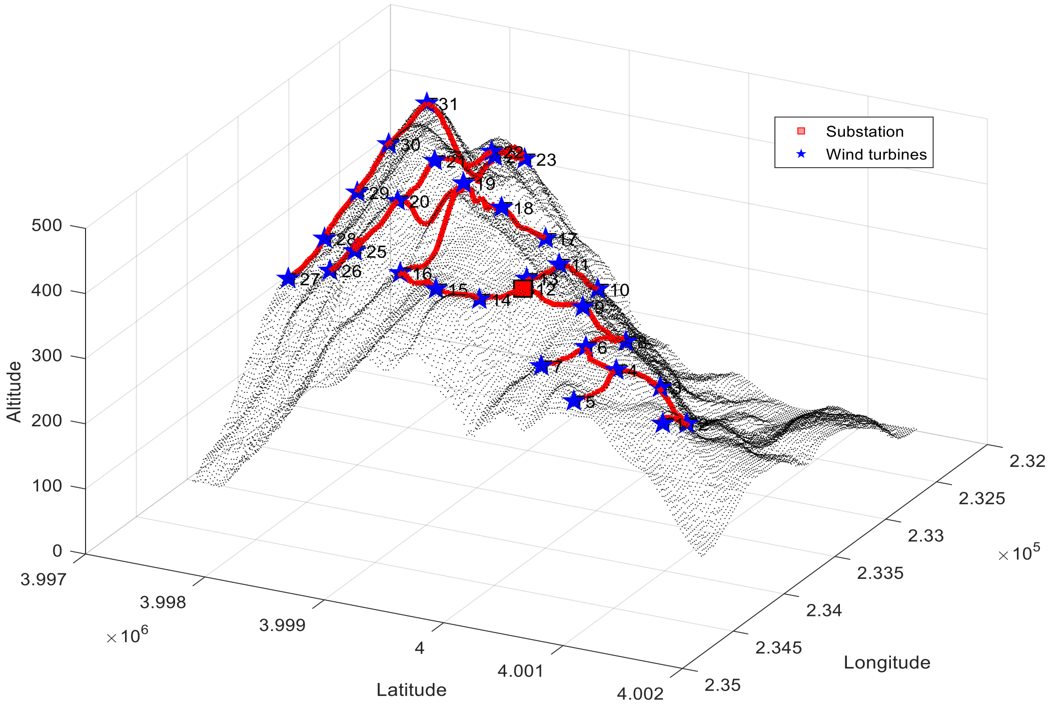


Figure 3.14: 3D representation of string configuration for Ziyaret RES.

Using the same procedure with 2D analysis, MPT is divided into 3 subtrees. The wind turbines included by each branch are selected as:

$$ST1 = [T1, T2, T3, T4, T5, T6, T7, T8, T9]$$

$$ST2 = [T10, T11, T13]$$

$$ST3 = [T14, T15, T16, T17, T18, T19, T20, T21, T22, T23, T24, T25, ..$$

$$.., T26, T27, T28, T29, T30, T31]$$

Using the formula given in (2.10) and (2.11), the NPV of losses and overnight investment costs are optimized and compared with the 2D approach in Table 3.19.

Table 3.19: Comparing the effects of MST and MPT on the electrical layout problem.

Approach	NPV of Losses	Overnight Costs	*f*	% Difference	Trenching Length	% Difference
2D	169257.5	1165957.9	-1335215.5	13.8	9194.4	10.2
3D	197378.9	1351537	-1548916		10239.2	

The comparison given in Table 3.19 includes results from 2D approach using MST and 3D approach using MPT. The results show that there is more than 10% difference in the values of *f* for string configuration which cannot be neglected during the project phase. Because of altitude effects, instead of connections T17-T11/T9-T10/T26-T28, connections of T9-S12/T19-T16/T24-T31 are used in MPT. As the roughness of the terrain increases, the difference and the number of changed connections in 2D and 3D approaches will also increase for any onshore wind farms.

3.4.3 Applying trenching constraints for electrical layout optimization

Generally, wind farms are constructed at rural areas. In some cases, there may be a cultivated field which is passing the borders of the wind farm. Or there may be an area that is very hard to dig and burry electrical cables. At that point, one must apply trenching constraints into electrical layout optimization. The proposed 3D strategy does not require any additional algorithms or optimization methods for taking trenching constraints into account. If there is a constraint on the area of interest, it is suggested to change the altitude data of the zone with trenching constraint into infinity. A very basic example is given in Figure 3.15 with using top view of nodes. In that figure, an area with trenching constraint is shown with blue color. As one can see, the shortest path found by Dijkstra's algorithm is adaptable to new conditions and did not visit the blue nodes.

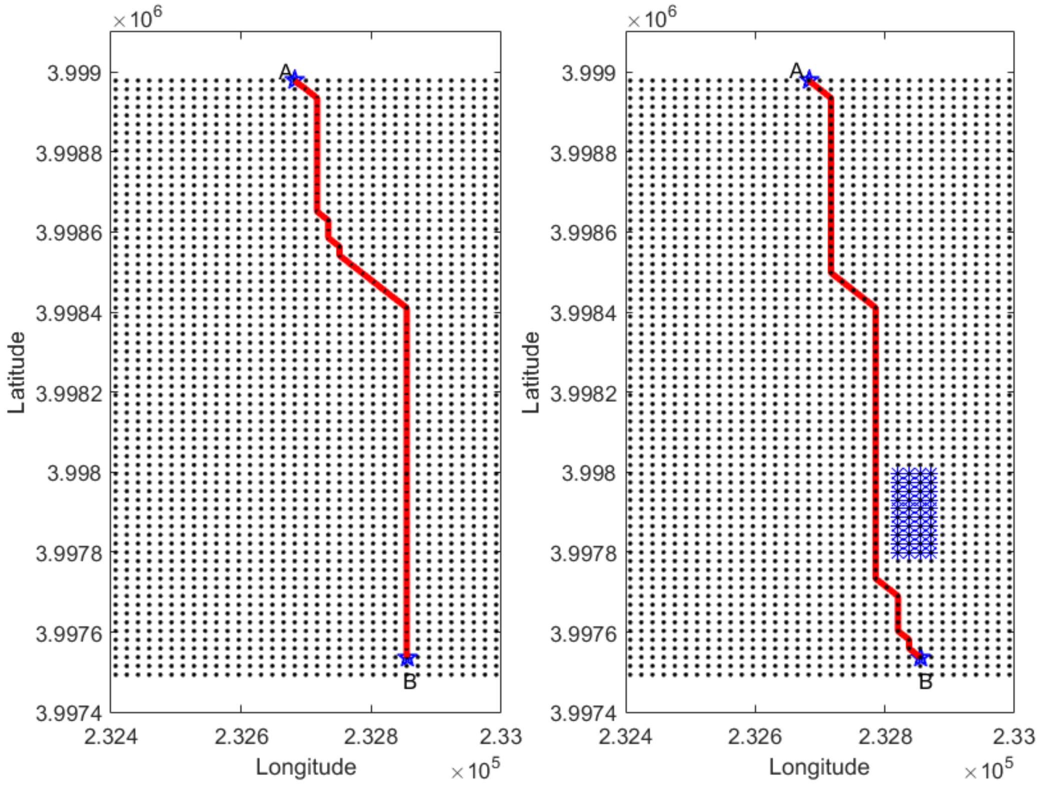


Figure 3.15: Top view of the shortest path between point A and B. On the left, the constraint is not included and on the right, trenching constraint is considered for the blue area.

4. CONCLUSION

In this study, the electrical layout for onshore wind farms was analyzed in three steps. In the first step, the best electrical cables were determined for different values of annual energy production. It was shown that the optimum cable selection procedure is a priori and does not require any optimizer. In the second step, predefined paths were assumed to be determined by construction companies as the MST & MPT of the nodes in Ziyaret RES. Reducing the number of variables in electrical layout problem created additional space for new variables. This available space was then used for finding the optimum connection points of the parallel cables for predefined paths. The proposed optimization strategy for predefined paths can be applied to string configurations as well as radial configurations. This methodology has been tested with a metaheuristic and therefore cannot guarantee a global optimum solution. The results of the new problem are compared with another solution obtained by using k-means clustering strategy. Even though the net gain for string configuration in objectives by using proposed strategy was 36500 \$ (considering 2D approach), when the trenching costs were excluded, averagely %5 improvement in the selection criterion (*f*) was obtained. Note that at this part, project planners may give predefined paths manually instead of defining new paths by using MSTs or MPTs. In the last step, optimal cables were assigned to each lines.

Next, a 3D strategy was proposed for the first time using digital elevation model of the terrain. By using this strategy on Ziyaret RES, 13.8% difference in the value of *f* and 10.2% difference in the total trenching length is observed in the string configuration comparing to the traditional 2D approach. In the radial clustering with 3 clusters, 11.2% and 12.1% difference is observed in the values of *f* and total trenching length respectively whereas 6.1% and 16.3% difference in the values of *f* and total trenching length is observed with 4 cluster case. Note that as the unevenness of the area increases, the difference between the objective function values of 2D and 3D approaches will be increased. Also, it was shown that using 2D approach may mislead the project planners in terms of optimal configuration. Regarding this reason, the effect of third dimension should not be neglected. Using the proposed method also shows the optimum route of feeders which may guide the construction companies in advance. The proposed methodology also provides ease of use when constraints are considered for trenching.

In the future studies, reliability of the electrical layouts should be analyzed. Also the proposed 3D strategy can be applied to offshore wind farms.

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