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Computerized Wind Farm Generation Tie Line Infrastructure Footprint Routing and Subsequent Dynamic Line Rating

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SUMMARY

Transmission lines are the backbone of the U.S. electrical grid. Due to increased penetration of renewable resources, there is an increasing need for connecting the often-remote resources to existing transmission line infrastructure. The exact placement of the wind farm may change many times over the course of the design of projects. Redesigning the wind farm generation-tie line is a tedious process for these changes. The Transmission Route Engineering And Design (TREAD) tool, developed at the Idaho National Laboratory, allows for computerized design of the general route of any transmission line, considering geographic, cartographic and terrain data in the routing process. The tool is applied specifically to the wind farm generation-tie lines. When suitable weather data is available the system can generate a dynamic line rating (DLR) model that can be used to analyze the additional capacity of a gen-tie line from concurrent cooling effects before it has been constructed. The system uses the DLR information to take advantage of rating-boosting effects of the terrain and prevailing wind conditions, thereby providing a maximum DLR rating. After construction the general line ampacity state solver (GLASS) can be integrated into control rooms for real-time and forecast predictions of capacity provided by DLR. In this work, we demonstrate the TREAD software in a case study using proposed wind generation sites and existing transmission infrastructure in the Bonneville Power Administration network. It is shown that the software can efficiently generate preliminary tie-line designs for the proposed location of wind generation sites. In addition, the DLR of these tie-lines is shown and the increased power flow over a static assumption results in increased capacity of up to 25%.

KEYWORDS

Dynamic Line Rating, Shortest Path Algorithm, Transmission line design and construction

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1. INTRODUCTION

The electric grid is considered to be the largest machine in the world. It is an immensely complicated system with the fundamental purpose to provide reliable electricity to consumers. It can be broken into three major groups; generation, transmission, and load centers [1]. The transmission infrastructure connects the power generation to loads and is the backbone of the electric system. The transmission lines have been designed around a historical central generation architecture. It moves power from large fossil-fuel and hydropower plants to the cities where it is needed.

More recently, the power gird has seen a dramatic increase in the penetration of distributed renewable generation units. This has been motivated in an effort to reduce carbon emissions and curtail the increasing frequency of extreme weather events due to climate change. However, the transmission system was not designed to be integrated with increased generation at different points. Transmission lines are limited in the amount of power they can transmit. Therefore, the increase of distributed renewable generation has resulted in an increasing amount of congestion on the network [2]. Furthermore, the stochastic nature of renewable generation, such as wind and solar, make it difficult for transmission line operators to properly dispatch the flow of generation. This leads to curtailments in renewable generation and increased cost to generate the needed power [3].

The transmission line ratings, or amount of power a line can move from generation to load, is generally limited based on the maximum conductor temperature. Several standards have been developed and used in practice to calculate their capacity. They are the International Council on Large Electric Systems [4]-[6], the International Electrochemical Commission [7], and the Institute of Electrical and Electronics Engineers [8], [9]. Transmission line operators use line limits to ensure the safety of the network. When lines are overheated it can result in clearance issues as the conductor sags because of the thermal expansion. This can potentially lead to outages if the line sags excessively and possibly encroaching on minimum clearances possibly compromise public safety. Furthermore, it can result in annealing to the conductor. However, it is well known that the assumptions used in the standards to calculate the static line ratings of conductor are conservative. This leads to ratings that often are underutilizing the transmission capability of the conductor. Research has shown that there is a large benefit in using a dynamic line rating (DLR) which use a real-time or forecasted approach to rate the capacity of the lines. Case studies utilizing weather data in the field has shown potential for DLR to increase ampacity above static throughout several countries [10]-[14].

Renewable energy types of all kinds are becoming more prevalent [15]. They share one commonality, the geographic dependency on specific location where the renewable source is most available. For example, Fig. 1 shows the wind resource map for Idaho, U.S. Here, it can be seen that there is a high variability in wind resources within relatively short distances. This is highly important in the location of wind turbines sites for economic reasons. However, without accommodation of resources due to terrain, it is impossible for these resources to be utilized. The nearest grid interconnection location is often not near the site of a proposed wind generation farm and would requires a gen-tie line to facilitate the addition of the wind generated power to the grid [16], [17].

In addition to the difficulty in integrating renewable sources to the existing grid there is additional difficulty in developing new long-distance transmission line under any circumstance. Public opposition to the routing of new lines, known as not in my backyard, have caused many problems for various infrastructure projects [18]. Even though general support for various renewable technologies is high there is still resistance to exactly where these locations are cited [19]. This will be an ongoing issue for the foreseeable future until public opinion changes significantly.

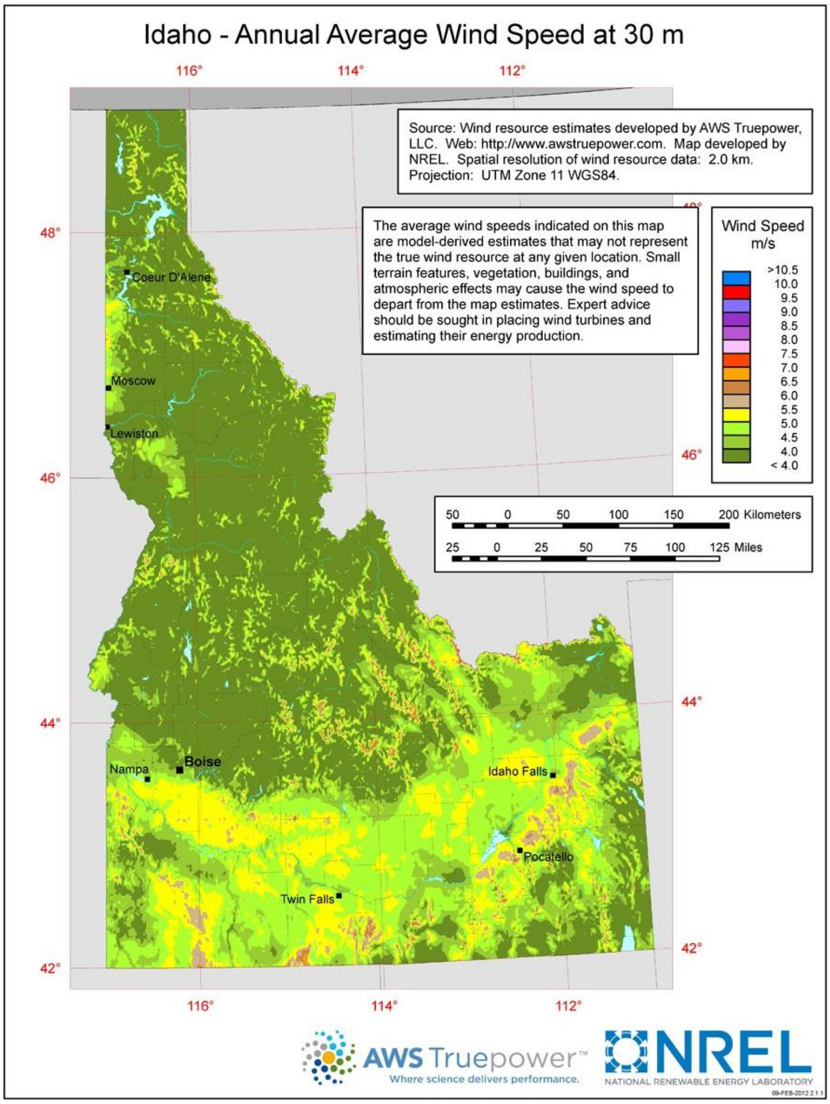


Fig 1. Wind resource map for Idaho [28].

Construction of a new transmission line is a complex process that takes considerable time and effort [20]. The structures that make up transmission lines traverse many different areas, municipalities, and terrain types. The size and varied nature of these lines form many different variables to consider when building a transmission line of any length [21]. These different variables can be encoded into a numeric manner to allow for a computerized system to be able to take much of the repeated design work out of the redesigning of transmission sections due to small adjustments in end location or new available data.

Graphical shortest paths are the shortest points between any two arbitrary vertexes. In a discrete graph there may be many different vertexes. The edges connect different vertexes together. Traversing a graph is following edges from vertex to vertex. This is basic graph theory [22]. Creating the shortest path is the process of progressively building a path by following the smallest edge length and adding the vertex and edge to the currently shortest path, then adding the path to the existing set of paths and repeating the process with the next shortest path. This in its simplest form is Dijkstra's algorithm [23]. The exact structure of how this algorithm changes is different for the exact algorithm implemented for each of the different uses [24].

For transmission lines the main issue with shortest path determination is the construction of the discrete graph in the first place. There are different methods of combining various forms of terrain data but the most common is rasterization of terrain data. This is the simple addition of layers based on geographic rasterization to create a cost surface [25]. The rasterization method then discretizes the cost surface into a grid which then can be used to create vertexes and edges. INL has developed a novel solution for the routing of transmission lines. The solution can design the shortest possible path that will avoid land-owners that do not wish to have the infrastructure in their backyard, as well as land that is off limits due to environmental concerns or other issues. The rest of the paper is formatted as follows; Section 2 introduces the generation tie-line routing software and the considerations it uses to optimize the rout used. A case study using proposed wind generation sites and existing transmission infrastructure is completed in Section 3. A conclusion of this work is done in Section 4 and Section 5 gives thanks to the funding source of this work.

2. TRANSMISSION ROUTE ENGINEERING AND DESIGN

This section details the background of the Transmission Rout Engineering And Design (TREAD) software was developed by Idaho National Laboratory (INL). The software allows for the design of the generation tie lines to be iterated upon significantly more rapidly than what would otherwise be possible. The software completes this by using a routing algorithm to navigate through cartographic data. The route that is generated is then analysed with DLR, during routing and/or after the route has already been completed.

2.1 Transmission Line Routing

Vector based graphical data, or cartographic data, needs to have the geographically dependant data collated with other pieces of data. This data aggregation will be referred as a cost surface for this paper. The data stored within The TREAD software uses a dynamic method to generate the cost surface while also building the discrete grid. The cost surface is created and evaluated at every point while the discrete graph is constructed. The edges between the vertexes are represented as the distance of the span that may eventually be constructed, analogously, the vertexes would be the towers. TREAD mainly uses geographic vector structure data to determine the cost surface, however, this can also be interspaced with point cloud data that may be rasterized data.

The choice of where to add the next vertex is based off the direction to the desired end point. There is an additional temporary cost that increases when the possible angular direction drifts away from direct to the end. The purpose is to prevent the system from seeing routes leading away from the final vertex. There is also a temporary reduction of cost that is inversely proportional to the remaining Euclidian length to the final vertex to encourage the best chance of finishing the route. Neither of the temporary values are used to calculate the cost of the final route that is generated. These temporary values provide bounding to the routing process. Unlike other routing algorithms there is no specific bounded region that is declared before routing begins. A workspace that has not been explicitly defined allows for rapid development and easy to use functionality of the software.

Finally, as the lines are being iterated upon within the software, the lines are valued against each other with cost of materials and construction. The first complete path is then presented as the shortest path. TREAD generates an approximate solution to the shortest path and as such provides a useful tool in the initial stages of developing a new transmission line.

The fundamental connection between reality and the software is the valuation of the routing locations through the data inputs. There are several different kind of data inputs that the system can understand. These take the form of two-dimensional cartographic data, three-dimensional terrain data, and weather data. This data is then utilized when the routing system is developing the hypothetical route through the location where the data is then needed.

2.2 Cartographic Data

The cartographic data usually takes the form of Environmental Systems Research Institute shapefiles that have information contained within which is meaningful for transmission line construction. This may take the form of local map data that defines the migratory or nesting area for a particular animal species.

These different files are assigned a value that represents the cost, difficulty, or desirability of routing a transmission line across the area. This data can represent anything, and multiple layers of data can be overlayed. When overlayed the combination function of the different layers can be decided.

2.3 Terrain Data

Data that indicates the difficulties in the terrain can also be used by the system. The software can take the point data and computing the normal vector of many different points to find the slope on the highest resolution scale possible. The slope of the data is then used to augment the cartographic data present. The routing system valuates level easy to construct land higher than sloped land to connect the start and end points with minimal height climb or declination.

2.4 Utility Integration

The software can integrate with the General Line Ampacity State Solver to provide the dynamic line rating for the generated line. The TREAD software generates all necessary structure data, and if provided weather data and computational fluid dynamic model look up tables for the reason in question then the route can be optimized to take advantage of dynamic line rating boosting effects of dynamic line rating.

The GLASS model that is created by TREAD allows a theoretical line to be incorporated into a control room before it is built. This allows for economic analysis of the line and how it may serve to connect to generation or alleviate congestion while the construction process is underway. The system uses non-proprietary data connection solutions and can integrate with most data management systems.

2.5 Not in My Backyard

The concern of the public cannot be ignored. TREAD can use geographic data that has been marked as inaccessible in the form of a shapefile to prevent any development on that land. This allows for the various stakeholders that do not want any construction in viewable areas to be heard. Possible improvements of this system is to include a dynamic web portal that will allow for people to choose their plot of land or vote on publicly available areas to not be constructed on.

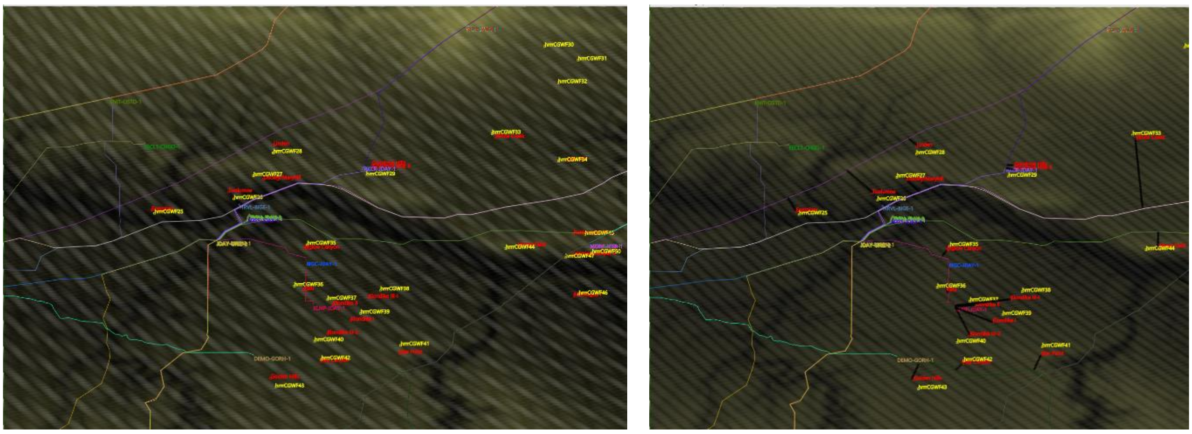
2.6 Dynamic Line Rating

Dynamic line rating is the process of using the heat balance equations for line rating, proposed in IEEE 738 standard or in the CIGRE technical brochure on the subject [4,9]. The heat balance equations are fed with real time weather data allowing for the rating of the line to change with the environmental conditions. Specific environmental differences, such as mountains, that can greatly affect the specific conditions at each of the points are handled through a computational fluid dynamics model of the local terrain that is able to map the weather conditions at measured points to the span that is being calculated. To predict future conditions future weather conditions needs to be used, or at the very least predicted. The most reliable standard for forecasted weather data is the High Resolution Rapid Refresh model operated by the National Oceanic and Atmospheric Administration [26]. This model gives high spatial resolution data at a rate that can be used for forecasting the conditions that a transmission line may route through. This allows any designed location of a transmission line to be dynamically rated.

3. TREAD CASE STUDY

In this work we use a region of the Bonneville Power Administration network in Southern Washington in the U.S. Here, there are several existing and proposed wind generation sites. The location of 25 proposed sites are shown in Fig. 2(a). Here, it can be seen that the proposed sites are not all next to existing transmission lines. Therefore, several different generation tie lines (gen-tie lines) would be needed to construct the proposed generation.

This region's parameters that are discussed in Section 2 are used in the TREAD software. The resulting gen-tie lines created are shown in Fig. 2(b). Due to the region having little complex terrain, the generated lines are generally straight. The only real obstacle is the river, which is not crossed. Next, we look at the coupling of the gen-tie lines DLR and the wind generation they connect to the grid.



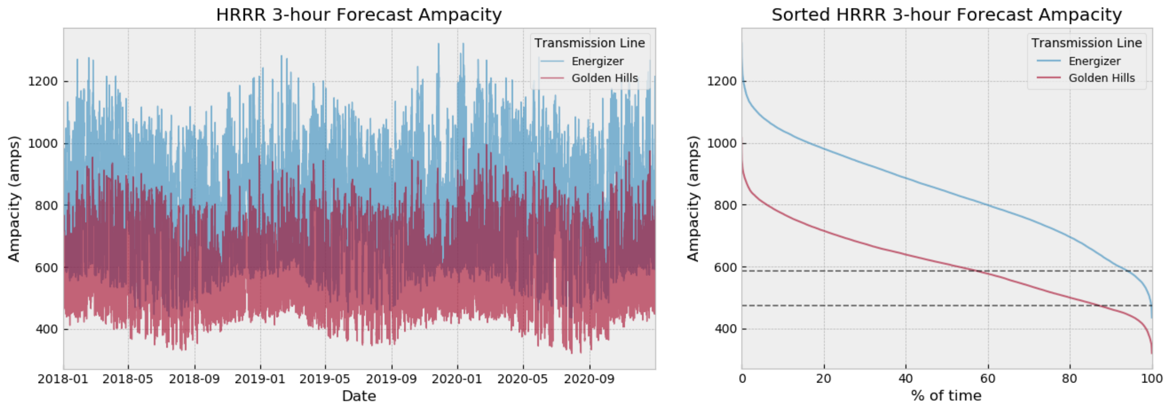
(a) (b)

Fig. 2. The Bonneville Power Administration proposed wind generation location (yellow) and existing transmission line infrastructure in (a). The Resulting gen-tie lines created with the TREAD software shown in (b).

3.1 Wind Generation and DLR Synergy

In this section, we delve into the synergy between the DLR and the wind generation of the gen-tie lines created using TREAD. For this part of the study, we look specifically at two of the gen-tie lines, Energizer and Golden Hills. These lines were selected because they will connect two of the largest wind farms. The Energizer site is a 263 megawatt (MW) project and the Golden Hills is a 200 MW project. Based on the size of these project and a voltage of 161 kilovolts (kV), the needed conductor size based on the static line rating is Partridge and Ibis ACSR. These conductors are rated at 587, and 475 amps, which results in 283, and 229 MW, for the Energizer and Golden Hills line, respectively [27].

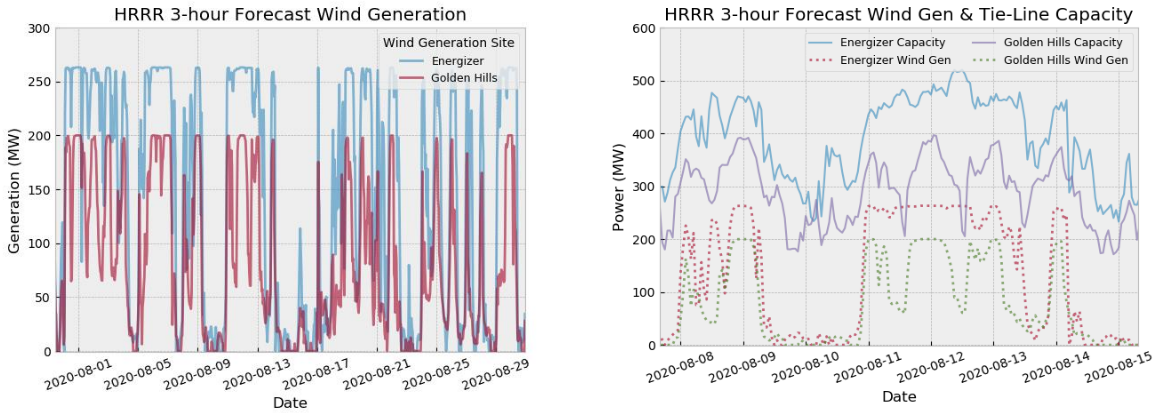
The first analysis is the DLR ampacity of the two lines over a 3-year period using GLASS software and 3-hour HRRR forecast data. The timeseries results are shown in Fig. 3(a) and the sorted values over the period are shown in Fig. 3(b). It can be seen that the DLR ampacity is above the static rating nearly 90% of the time. It is important to note that the DLR is not always above the static rating and even though this may curtail generation during this time, however, the safety of the line should be of upmost importance and grid operators need to know when worst weather scenarios do occur.



(a) (b)

Fig. 3. The 3-hour HRRR forecast DLR of selected large gen-tielines in the BPA region over a 3-year period (a) and the sorted values above the static line rating in (b).

Next, we evaluate the wind generation output using the 3-hour HRRR [26] model and power curve of the generation units in the Energizer and Golden Hills sites. The resulting wind generation of the sites is shown over a month-long period in Fig. 4(a). The natural synergy between the wind generation and the DLR, which TREAD considers when determining the rout, of the line is shown over a week-long period in Fig. 4(b). It is important to note that when there is significant wind generation the DLR of the line is high and there is extra capacity in the line.



(a) (b)

Fig. 4. The 3-hour HRRR forecasted wind generation over a month in (a) and the correlation of wind generation and tie-line DLR over a week period in (b).

4. CONCLUSION

The Transmission Route Engineering And Design (TREAD) software allows rapid initial design and iteration for the purposes of developing transmission lines and gen-tie lines. This is accomplished through using a dynamic cost surface generation technique and variant of Dijkstra’s shortest path algorithm. The data processing and handling allows the system to route through different kinds of terrain while still taking into account the public opinion. When the route is generated it can be tested and iterated rapidly to take advantage of the possible dynamic line rating available for the area. The test case showed in this paper that there was up to a 25% increase in ampacity generally over the static value of the conductor.

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