Reduced transmission grid representation using the St. Clair curve applied to the electric reliability council of Texas

Conference Paper · June 2017

DOI: 10.1109/EEM.2017.7981961

4 authors, including:


Henry Martin
ETH Zurich


Thomas Deetjen
University of Texas at Austin


Michael E Webber
University of Texas at Austin

Reduced Transmission Grid Representation using the St. Clair Curve applied to the Electric Reliability Council of Texas

Henry Martin
Thomas Hamacher
Department of Electrical and Computer Engineering
Technical University of Munich
Munich, Germany
Email: henry.martin@tum.de

Thomas A. Deetjen
Michael E. Webber
Department of Mechanical Engineering
The University of Texas at Austin
Austin, Texas, United States
Email: tdeetjen@utexas.edu

***Abstract*—This paper applies a grid reduction method that is based on the St. Clair curve to create a transmission approximation of the Electric Reliability Council of Texas (ERCOT, the grid operator of the state of Texas, US) for use in a unit commitment and dispatch UC&D model. Comparison with known transmission limitations suggests that the approximation error might be too great for the approximation method to be used in an UC&D model. This paper discusses the method, its advantages compared to existing work in the field, its limitations and possible improvements for future usage.**

I. Introduction

A. Background and Motivation

The Electric Reliability Council of Texas (ERCOT) is the main Transmission System Operator (TSO) wholly contained within the state of Texas. ERCOT covers about 75% of the geographical area and 90% of the electricity load. ERCOT maintains relatively weak ties with other grids in North America, thus ERCOT must produce the vast majority of electricity that it consumes. ERCOT generates most of its electricity from fossil fuels but has increased its renewable generation drastically over the past decade. In 2015, over 11% of electricity generation in ERCOT came from onshore wind and at times (for example during the Autumn) wind power can supply 40% or more of total demand. [1].

Most of Texas' best RES are located in the western part of the state (see 1), but the vast majority of load is in the central and eastern part of the state. To enable the use of renewable energy resources from rural west Texas, significant electricity transmission infrastructure is required. For this purpose, the Competitive Renewable Energy Zones (CREZ) project was launched in 2007. The CREZ project defined 5 regions, the so-called CREZ regions, that are particularly suitable for wind generation. From 2007 until early 2014, a total of almost 5800 km of new transmission lines were built to connect the CREZ regions (located in the western part of the state) to the east [2].

The integration of high percentages of renewable energy generation is complex. Researchers attempt to find the optimal

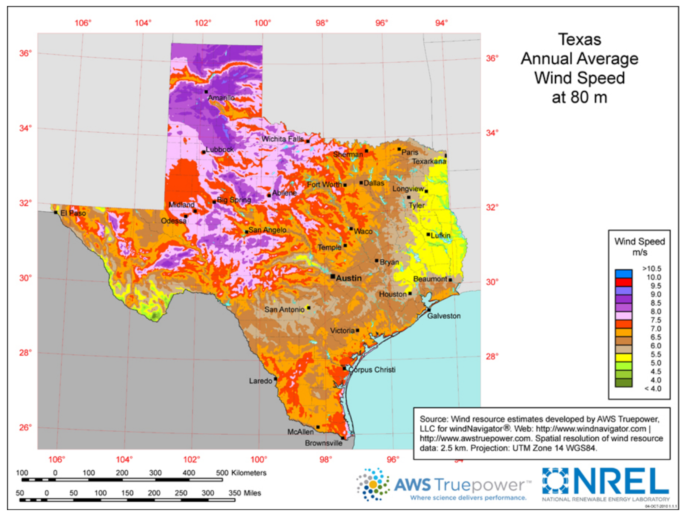

Fig. 1. Annual average wind speed at 80m in Texas [3]. Texas wind resources tend to be best in the northwest part of the state.

amount and placement of renewable generation that minimizes the overall social cost while maximizing other parameters like carbon reduction and energy output or peak-load reduction, while ensuring the stability of the grid. These questions are often answered using fundamental unit commitment and dispatch models, which contain detailed information about market participants (consumer behavior, power plants, merit order based auction prices, weather data, etc.). These models seek to emulate the economic dispatch behavior of the actual market. Even though transmission constraints can have a great impact on these questions, they are often not included in these models. Transmission is often omitted because full representation of the grid can increase the complexity of the model leading to excessive computational constraints. This paper attempts to solve this issue by developing an approximate transmission

978-1-5090-5499-2/17/$31.00 ©2017 IEEE

model of the ERCOT power grid to be used in a unit commitment and dispatch model. Stolle, et. al., [4] presents an approach that uses publicly available data and the St. Clair curve to create a reduced representation of the grid that can be used with unit commitment models. We apply this method to create a reduced representation of the ERCOT transmission grid and compared the results against known transmission capacities published by ERCOT

B. Network reduction practice

In the European electricity market modeling approach, it is common to assume that transmission lines are lossless and possess an infinite transmission capacity. This so called "copper-plate" assumption can be applied to the whole grid [5] [6] or to single regions interconnected with equivalent transmission lines [7] [8]. This assumption is closely linked to the European market design which is organized in a similar way. The European electricity market is divided in different market areas or bidding areas within which market participants are able to exchange energy without capacity allocation [9]. While the internal trade is unlimited, the power trading in between the different market areas is limited by capacities that are defined by the TSOs. Studies with an economic focus, that are performed in such a context, do not necessarily need a full representation of the grid but only a reduced model consisting of zones with restricted interconnections.

The case for the Texan electricity market is different, as it is organized as a nodal market using locational marginal prices. In a nodal market, well connected generation and load units are clustered in nodes, where each node has a unique market price. A nodal market will also have zones of equal prices but they can change dynamically depending on the distribution of load and generation and the congestion of transmission lines.

A very common approach to create a reduced transmission model is to use a zonal DC power flow approximation [10]. In this approximation two types of information are needed; information about how the power flow is distributed in between the zones and information about the maximum transmission capacity in between the zones. The first information is described in the Power Transfer Distribution Factor matrix (PTDF) which describes the active power flows in transmission lines caused by an power imbalance in one of the nodes [10]. The PTDF matrix can be constructed using 1 where $\mathbf{B}_d$ is the matrix of susceptances calculated assuming that the line resistances are negligible compared to the line reactances [10] and $\mathbf{A}$ is the incidence matrix of the full network. Eq 1 shows the PTDF calculation.

$$\mathbf{PTDF} \times \mathbf{N} = (\mathbf{B}_d \cdot \mathbf{A}) \cdot (\mathbf{A}^T \cdot \mathbf{B}_d \cdot \mathbf{A})^{-1} \qquad (1)$$

After the $\mathbf{PTDF}$ matrix has been constructed for the full grid, all nodes of the network that are within one zone are aggregated, resulting in a single node for each of the desired zones, as shown in Fig 2. This step requires using generation shift keys that account for the topology of generation and consumption within a zone. The calculation of these factors requires understanding of the grid being modeled, and is often supported by expert feedback on how the power grid will behave in specific situations or regions [11] [12].

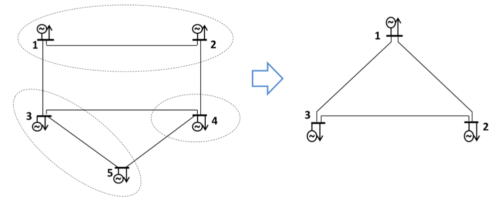

Fig. 2. Schematic representation of the reduction from a DC to a zonal load flow from [10]

When the zonal $\mathbf{PTDF}$ matrix is constructed, information about the maximum transmission capacity of the inter-zonal connections must be gathered. This information is usually compiled by reducing the physical capacity limits of the inter-zonal transmission lines by experience-based factors. These factors account for example for intra-zonal congestions that would limit the inter-zonal transmission capacity [11].

C. Added value of our paper

Even though there are existing methods to create reduced representations of the transmission grid that can be used in unit commitment and dispatch models, these methods often require detailed electrical and spatial information of all elements in the power system, power system simulation tools, and a detailed knowledge of the grid. Acquiring this information can be a considerable obstacle for studying the electric grid at this depth. This paper evaluates a less complex approach to creating a reduced representation of the transmission grid that is based on the St. Clair curve [13] [14].

II. Transmission grid approximation

A. Region design

The first step of this transmission approximation method is to choose appropriate regions for the overall energy system. Choosing the shape of the regions has significant impact on the resulting equivalent transmission model. The following design principles were used to help minimize errors in the approximation.

- Regions should be well-interconnected within themselves.
- The region borders should cut as few transmission lines as possible to reveal possible congestion bottlenecks.
- There should be as few regions as possible to keep the result succinct and to reduce the effort necessary to create the equivalent transmission model.

Even when following those basic design principles there are still many degrees of freedom for the actual size and shape of each region. To avoid designing the regions arbitrarily, we looked for existing region definitions that could be modified to fit our needs. We decided against using political borders, such as county lines, as they are not necessarily a good indicator for transmission bottlenecks[7], but began with a set of predefined weather zones used by ERCOT. To address questions concerning the optimal integration of renewable energy in Texas, the ERCOT weather regions were modified as follows:

- A higher spatial resolution in west and south-west Texas (where Texas renewable resources are greatest).
- Isolation of the CREZ regions.
- Modification of the borders to minimize the transmission lines between regions and to avoid double cutting of transmission lines.

The final region design can be seen in Fig 3.

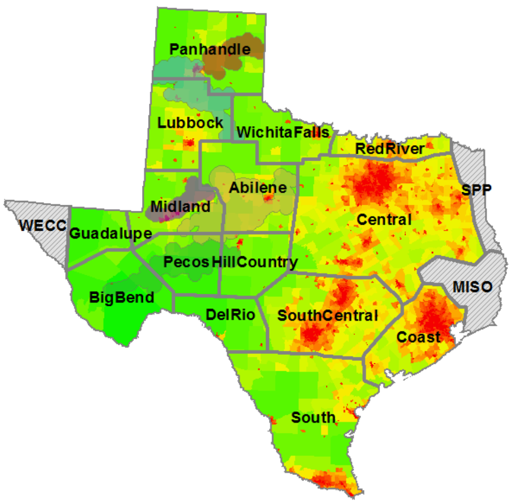

Fig. 3. The result of the region design step is a map of Texas divided into 18 regions. The regions have a higher spatial resolution in the west, where Texas' strongest renewable resources are located. The five CREZ regions, also located in the west, are drawn as clouds. The background is a population density map where green values represent areas with few inhabitants and red values represent highly populated areas. The population density can be used to approximate the major load centers which are primarily located in east Texas, where the spatial resolution of the designed regions is lower. Note that ERCOT does not cover the entire state of Texas, but is wholly contained within. Regions which are not served by ERCOT are colored in gray.

B. Identify crossing lines

After the region design step, it was necessary to identify the lines that interconnect pairs of regions and retrieve their electrical information. We started by superimposing the region boundaries with a map of the ERCOT grid that was provided by ERCOT and is dated to October 2016. The map shows transmission lines, electric bus positions and the bus names. The map was superposed with the regions designed in II-A using ArcGIS[1], allowing manual fine-tuning of region boundaries (to reduce the number of cross-regional transmission lines), and identification of the bus numbers that define the cross-regional transmission lines.

In the next step we retrieve the electric information of all inter-regional transmission lines from an input file for a power system simulation tool that was provided by ERCOT and that holds electric information about all transmission lines in the ERCOT area. Bus numbers are used to identify the transmission lines and extract the values of the shunt susceptance and the reactance necessary for calculating 3 and 4 for each of the lines, as well as the number of circuits per line. Transmission lines with several circuits will be treated as individual lines for each circuit. The data we use and detailed data about the transmission system in general are not publicly available but it would be possible to use typical line characteristics from a textbook instead.

[1] www.arcgis.com/

C. Equivalent transmission lines

Transmission lines in between two adjacent regions are modeled as a parallel circuit with two voltage levels as shown in Fig 4. Each transmission line is defined by its impedance and its maximum transmission capacity. To calculate the equivalent impedance for the parallel circuit, the 138kV impedances must be transformed to equivalent 345kV impedances. This information is done using Eq 2, which can be derived from the equations for the ideal transformer. X is defined as the impedance for the 345kV circuit and X is the original 138kV impedance. The total impedance for the equivalent transmission line is found using Eq 3.

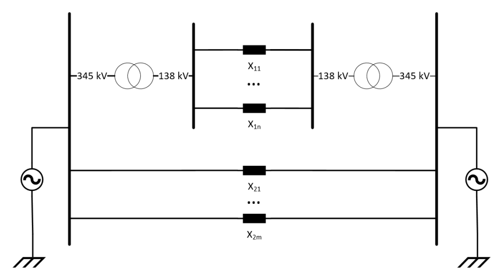

Fig. 4. Schematic circuit representation of the transmission lines in between two adjacent regions. The interconnection of regions is modeled as a parallel circuit with n 138kV transmission lines and m 345kV transmission lines.

$$X = X \cdot a^2 \; with \; a = \frac{345kv}{138kv} \tag{2}$$

$$\frac{1}{X_{total}} = \sum_{i=1}^{n} \frac{1}{a^2 \cdot X_i} + \sum_{j=1}^{m} \frac{1}{X_j} \tag{3}$$

D. The St. Clair Curve

In 1953 H.P. St. Clair introduced a set of curves which describe the relationship between the maximum transmission loadability per unit and the length of the line [13]. These loadability curves, which are known as St. Clair curves, meant as a help for practitioners to quickly access the performance of transmission lines at various voltages and distances. This work was later extended and generalized by [14]. Fig 5 shows the universal loadability curve for overhead uncompensated transmission lines applicable to all voltage levels from [15]. In this context, uncompensated means that there are no stability supporting measures, like capacitor banks, taken for the line. The St.Clair curve from Fig 5 allows the estimation of a transmission line's capacity as a function of its surge impedance loading (SIL) and the length of the line. The SIL is calculated using Eq 4 where V is the voltage level of the line, X is the original impedance of the line and B^{sh} is the shunt susceptance.

$$SIL = V^2 \frac{V^2}{\sqrt{\frac{X}{B^{sh}}}} \tag{4}$$

The maximum transmission capacity is then calculated by multiplying the SIL with the St. Clair coefficient as shown in Eq 5. The St. Clair Coefficient $c(l)$ depends only on the length of the line and can be retrieved from the St. Clair Curve shown in Fig 5.

$$P_{line} = c(l) \cdot SIL \tag{5}$$

$$P_{tot} = \sum_{i=1}^{n} SIL_i \cdot c(l_i) + \sum_{j=1}^{m} SIL_j \cdot c(l_j) \tag{6}$$

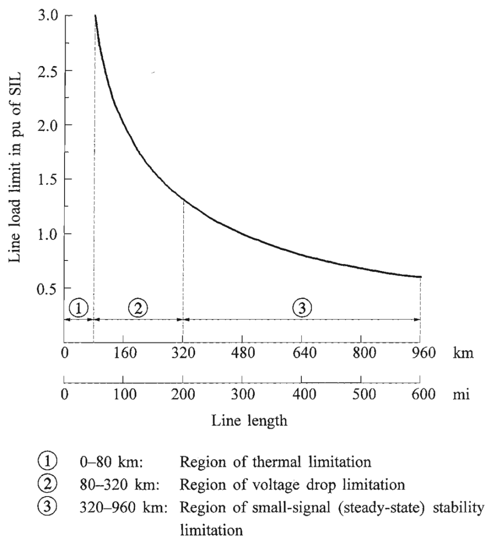

Fig. 5. The St. Clair curve as based on the results of [14] retrieved from [15] is used to estimate the maximum loadability of a transmission line. It combines three major causes for transmission limitations (thermal limitations, voltage drop limitations and steady-state stability limitations) in a single, simple relationship. This relationship allows a transmission line's maximum capacity to be estimated as a function of the line's length alone.

The total transmission capacity in-between two regions is obtained by summing up the estimated transmission capacities of the parallel lines of the different voltage levels.

E. Length of the equivalent transmission line

The actual length of a transmission line is often difficult to tell without having detailed access to grid information. The length of the transmission lines in-between two regions is therefore estimated. There are different approaches for estimating the length of transmission lines in between two regions. The simplest approximation uses the distance in between the two geographical centers of the regions. Another, more accurate method, uses the distance in between the two

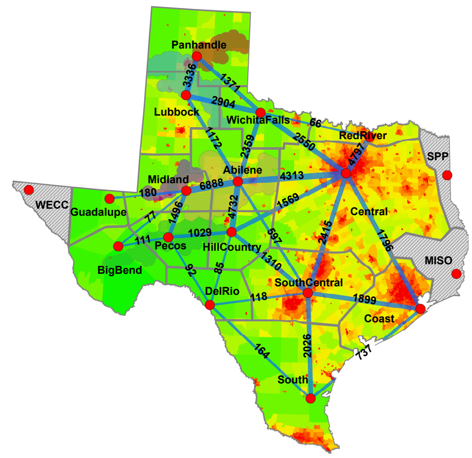

Fig. 6. The result of the ERCOT transmission approximation. A total of 28 approximated transmission lines connect the 15 ERCOT regions with capacities ranging from 70 to 6900 MW.

electrical centers of the regions [4]. The electrical center of a region is the place where most of the electricity is flowing to or from. Examples would be big cities, industrial centers or big power plants. In practice, a region can have several cities and more than one power plant. In this case the electrical center is in the center of those points with more important loads or generations having a higher influence on the location of the electric center.

III. Results

The result, as shown in Fig 6, is a list of 28 transmission lines that connect the 15 ERCOT regions, one line for each pair of adjacent regions. This approximation can, theoretically, be used as an input for a UC&D model. The maximum transmission capacity varies between 70 and about 6900 MW, which is within the expected order of magnitude. Our model had two transmission lines that have strong geographic correlation with two existing ERCOT transmission lines with well-documented capacities. Using these comparisons, our 1,796 MW approximated Coast-to-Central transmission line was under-estimated by 2,400 MW (a 42% error), and our 5,447 MW approximated Lubbock-Abilene + Lubbock-Wichita Falls + Panhandle-Wichita Falls lines were over-estimated by 2,447 MW (a 81% percent error).

These results show that, while these approximation methods can be used to gain a general understanding of the order-of-magnitude of the transmission connections between regions in a transmission network, their error might be too high to be used in a unit commitment and dispatch model, especially because there is no general trend of over- or underestimation which might allow the interpretation of the results as upper or lower transmission boundaries.

One possible reason for the under- and overestimation is that the transmission capacity between two regions is very sensitive to the estimated length of the equivalent transmission line. We observed that the transmission capacities where overestimated in the west, where we chose to design small regions and underestimated in the east, where we chose to design large regions.

For further usage of the St. Clair curve for transmission approximation, it might be better to design uniformly sized regions rather than using a variety of regions sizes meant to emphasize the focus of a particular study. This improvement might create a general trend in over- or under-estimation. Additionally, regions could be created to maximize the correlation between the location of the approximated transmission lines and actual transmission corridors with known capacities. This improvement could provide more validation opportunities, which would help to quantify the approximation error.

Another possible reason for the high estimation error is that transmission between two regions also relies on stability factors that are not captured in the St. Clair curve approximation. For instance, many of the ERCOT regions have large amounts of renewable energy generation with negligible demand. The transmission capacities of the lines out of these regions is constrained by ERCOT's ability to maintain frequency stability in those regions. The St. Clair curve might be a good foundation for transmission approximation, but further developments should be considered before it can be utilized effectively for unit commitment and dispatch modeling for the purpose of renewable capacity planning.

Acknowledgment

This work was sponsored by funding from the Electric Reliability Council of Texas with additional funding from ExxonMobil.

We gratefully acknowledge the contributions of Laura Stolle and Matthias Huber who lay the groundwork for this study.

References

[1] Electric Reliability Council of Texas, Inc., ERCOT Quick Facts, Feb. 2016.

[2] Lasher, Warren, "The Competitive Renewable Energy Zones Process," ERCOT (2014).

[3] National Renewable Energy Laboratory, Texas Wind and Solar Resource Maps," Available from http://www.nrel.gov/gis/mapsearch/, Accessed on Dec. 2016.

[4] Stolle, Laura, Huber, Matthias, "Model-based Analysis of HVDC-Grid Extensions Planned in Germany", Msc Thesis, Chair of Renewable and Sustainable Energy Systems, Technical University of Munich, 2015

[5] Schmid, Eva, and Brigitte Knopf. "Quantifying the long-term economic benefits of European electricity system integration." Energy Policy 87 (2015): 260-269.

[6] Heide, Dominik, et al. "Seasonal optimal mix of wind and solar power in a future, highly renewable Europe." Renewable Energy 35.11 (2010): 2483-2489.

[7] Steinke, Florian, Philipp Wolfrum, and Clemens Hoffmann. "Grid vs. storage in a 100% renewable Europe." Renewable Energy 50 (2013): 826-832.

[8] Bove, Roberto, Matthias Bucher, and Fabio Ferretti. "Integrating large shares of wind energy in macro-economical cost-effective way." Energy 43.1 (2012): 438-447.

[9] ENTSOE, Bidding Zones Review Process. Technical report, 2014. Available from https://www.entsoe.eu/Documents/MC%20documents/140123_Technical_Report_-_Bidding_Zones_Review__Process.pdf ,Accessed on Dec. 2016.

[10] Van den Bergh, Kenneth, Erik Delarue, and William Dhaeseleer. "DC power flow in unit commitment models." no. May (2014).

[11] REM, CWE. CWE enhanced Flow-Based MC feasibility report. Technical report, 2011. Available from http://www.amprion.net/cwe-market-coupling ,Accessed on Dec. 2016.

[12] Van den Bergh, Kenneth, Jonas Boury, and Erik Delarue. "The flow-based market coupling in central western europe: Concepts and definitions." The Electricity Journal 29.1 (2016): 24-29.

[13] H. P. St. Clair, Practical concepts in capability and performance of transmission lines, A.I.E.E. Transactions Part III. Power Apparatus and Systems, Vol. 72, No.2, pp. 1152-1157, Jan. 1953.

[14] Gutman, Richard, P. P. Marchenko, and R. D. Dunlop. "Analytical development of loadability characteristics for EHV and UHV transmission lines." IEEE Transactions on Power Apparatus and Systems 2 (1979): 606-617.

[15] Kundur, Prabha. Power system stability and control. Eds. Neal J. Balu, and Mark G. Lauby. Vol. 7. New York: McGraw-hill, 1994.