Large-Scale Synthetic Grids in Classroom Planning Studies

Ashly L. Bornsheuer, *Student Member*, *IEEE*, Brandon Allison, *Student Member*, *IEEE*, Keegan Flaherty, *Student Member*, *IEEE*,
Thomas Overbye, *Fellow*, *IEEE*, Kate Davis, *Fellow*, *IEEE*
Electrical and Computer Engineering
Texas A&M University
College Station, USA
brandona@tamu.edu, overbye@tamu.edu

***Abstract*— A senior capstone transmission expansion planning project is presented for a large-scale synthetic grid. Parameters such as generation, load, and contingencies are incorporated in the case to create summer peak load cases over a period of seven years. The methodologies to create the load case, containing the seven year load growth projection, and the solution case, containing the proposed upgrades for each year, are presented.**

Keywords*— *transmission planning, capstone, senior design, education, synthetic grid

I. INTRODUCTION

Transmission planning is performed by members within the electric power industry on large-scale power flow cases to ensure long-term grid reliability. Some characteristics of large-scale cases include “topology-variance”, “geographic dispersion”, probable line limits, realistic unit capacities and commitment, nominal voltage variation, varying ratios of transmission lines to substations, and “large dimension[s]” that may contain 10,000 or more buses [1],[2]. In comparison to smaller cases, large cases require more complex cost and reliability analysis, have larger computation times, and have more potential points of failure. Students who prepare to enter the electric power industry need to have exposure to power flow cases of equivalent magnitude so they can address the design and complexity of these large cases.

According to [3], university courses within North America are adapting to address both growing student interest and challenges within the power industry. Recent courses in have introduced large-scale power systems to students [4]; however, literature suggests that most students are working with cases in the order of tens of buses and only incorporate minor topology developments [5],[6]. For example, the widely used power systems analysis and design textbook, [5], uses power flow cases with less than 40 buses. This paper builds upon previous work in [7],[8] to expand the access of larger power systems to students.

Capstone courses provide opportunities for students to develop a project that reflects relevant work similar to that of industry and will go into further detail than what students will typically receive within classroom laboratory exercises. The Accreditation Board for Engineering and Technology’s (ABET) accreditation standards require that students should have the “ability to design a system, component, or process to meet desired needs within realistic constraints” [9]. Students who enter the electric power industry need to understand how to improve large-scale power systems that include constraints such as generation retirements, load variation, cost, and violation limits.

A methodology and case study are presented to demonstrate the design and implementation of a 7-year planning study for a capstone course. The case is based Texas’s ERCOT (Electric Reliability Council of Texas) system’s summer peak load over a 7-year period. A large-scale synthetic case of 2000 buses is used as the power flow model footprint for the design case [10],[11]. This case is designed to be similar in complexity to ERCOT’s grid. Synthetic grids are power flow cases that have sufficient system size and complexity to represent realistic grids without containing Critical Energy Infrastructure Information (CEII), and hence are fully public. Case parameters, including load profiles and decommissioned generation, are inserted each year to model the constraints of the design case. The team then addresses all reliability issues that arise from contingency analysis with modifications or upgrades to the system. This paper presents a methodology for creating a transmission expansion planning capstone design project that addresses considerations of reliability and economic constraints seen within industry.

II. METHODOLOGY

A. Solution Requirements for Power Flow Cases

A power flow case is created to represent the summer peak load for each year from 2014-2021.When each year’s case is solved, realistic reliability and economic constraints are followed.

1) Reliability

As in industry, the resulting design case should meet voltage and line limit constraints as defined from the North American Electric Reliability Corporation’s (NERC) TPL requirements [12]. NERC requires that “system steady state voltages and post-Contingency voltage deviations shall be within acceptable limits as established by the Planning Coordinator and the Transmission Planner” [13]. The design case is based on the Texas footprint, so ERCOT’s regulations are used to create the allowable voltage thresholds shown in TABLE I.

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TABLE I
ERCOT VOLTAGE OPERATING STANDARDS

ERCOT Voltage Regulations		
	Upper Limit	Lower Limit
Pre-Contingency	1.05 pu	.95 pu
Post-Contingency	1.05 pu	.90 pu

NERC also requires that "applicable facility ratings shall not be exceeded"; lines and transformers must be operated within their MVA and current limitations. These NERC regulations apply both pre- and post-contingency, thus base case limit monitoring and post-contingency violations indicate the problems that must be solved. Other NERC requirements were not considered for this design case.

In accordance with NERC's Reliability concepts [13], in the pre- and post-contingency states, the resulting case shall "operate within facility capabilities by utilizing Normal and Emergency (short-term) Ratings, as applicable, within their associated time parameters". During the post-contingency state for the design case, the normal rating is used to determine the loading on system facilities. Only single contingencies and tower contingencies are considered in the design case.

2) *Economic Considerations*

To emulate realistic budget restrictions within industry, the cost of upgrades within the design case is minimized. The students consider multiple upgrades to the system and choose the cheapest, most reliable option. To implement this, a parameter estimation method is used to determine device characteristics and their respective costs for lines, generators, capacitor banks, and transformers. According to [14], Texas power companies spent $2.1 billion in system upgrades in 2016. This number is the basis of the yearly budget for the design case.

B. *Load for Power Flow Cases*

1) *Load Forecast*

To predict the load change over time, ERCOT's long-term summer peak forecast [15] is used in combination with projected population census data [16]. The summer peak is modeled to exhibit the system's response under the most constraining circumstances. However, since public ERCOT load records are only published as an aggregate for the state, the load is distributed among the 2000 buses according to county-level projected populations as in [16].

TABLE II

Symbol	Quantity
$Cpop_i$	County X Population for year i
$Tpop_i$	Texas Population for year i
$E.MW_i$	ERCOT forecasted peak load for year i
MW_i	County X load in year i

$$\Delta\text{MW} = \left(\frac{Cpop_{i+1}-Cpop_i}{Tpop_{i+1}-Tpop_i}\right) * (E.MW_{i+1} - E.MW_i) \quad (1)$$

$$MW_{i+1} = MW_i + \Delta\text{MW} \quad (2)$$

The design case's load spans each year from 2014 through 2021, with bus-level load projections for each year. The 2000 bus base case has a similar load to ERCOT in 2014, thus 2014 is chosen as the starting year for load projections. Formulae (1) and (2) are applied to all counties in Texas for years 2015-2021. County population growth predictions from the census provide a reasonable way to distribute the total load growth as predicted by ERCOT. This method of using population to assign load is used in the creation of the 2000-bus case in [10]. Fig. 1 displays a contour of percent load increase for year 2021 from the initial year 2014. It has an aggregate load of 77,125 MW, which is equivalent to ERCOT's projection for 2021 in Fig. 1 below. Fig. 1 also displays its highest percent increase of load within the main urban hubs of Texas, namely Dallas, Houston, Austin, and San Antonio.

2) *Bus Load Allocation*

Once the load is divided into the 254 counties of Texas, it is linearly portioned to the 2000 buses from the 254 counties based on the closest county. Distributed power factors are also considered. In the original 2000-bus case in [10] every load has a preset power factor of 0.96. Power factors are determined based from an exponential probability distribution, maintaining an average power factor of 0.96. This creates a realistic representation of power factors, resulting in realistic reactive power usage at each bus.

3) *Generation Retirement*

Decommissioned generators within ERCOT's Capacity, Demand, and Reserve Reports for years 2015-2018 [17]-[20] are removed within the design case for generators of similar size and location. While the synthetic grid in [10] does not precisely replicate the real grid, they do share relevant characteristics. Decommissioned generation within the design case results in almost 4,000 MW of generation retirement from 2016 through 2018.

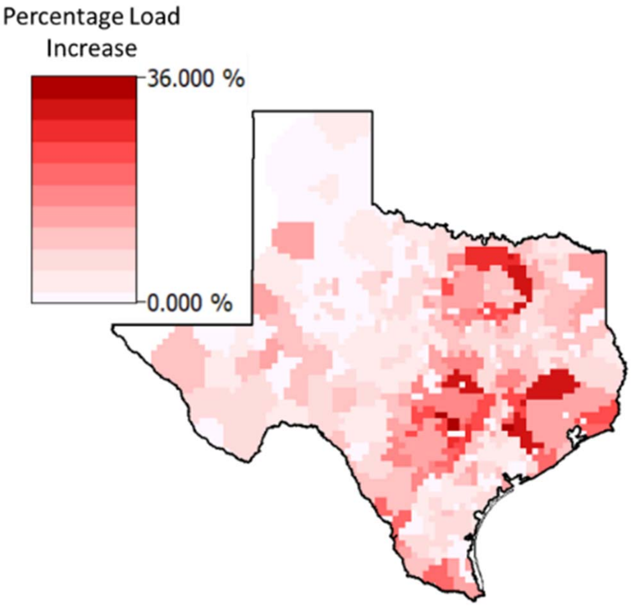

Fig. 1. Year 2021 Load vs Year 2014 Load

C. *Creation of Power Flow Cases*

Following the creation of the load predictions, the load within the original design case is linearly incremented to the predicted load for each respective year. Much like realistic grids, the case, at its starting point, is operating near its capacity with many constraints under peak load. Thus, when the peak load increases, the number of constraints grow significantly, and the system begins to suffer from voltage decline. Without any topology modifications to the design case, it is not possible to solve the case for years 2018 – 2021.

1) *Contingency Analysis*

As stated above, a contingency analysis is necessary to qualify the case as reliable. Contingency analysis allows a user to quickly determine results from many "what if" scenarios by flagging which scenarios would result in the worst consequences. Mitigating potential threats by adjusting generation or making system upgrades reduces potential risk to the grid through a redundant system that allows any single element to fail. The reduced risk aligns with NERC's goal of grid integrity and damage prevention [21]. PowerWorld has a tool to perform this analysis automatically from an input contingency file.

Credible contingencies that are both plausible and likely as defined in NERC's Reliability Concepts are included. It is typical to test all single contingencies, including generators, branches and transformers within a system, which are present in the design case. Tower contingencies present in ERCOT's planning standards are also included. These are a specific set of contingencies for 2 circuits that share a segment of right of way and therefore a single point of failure [14].

As tower configurations are not defined in the original case in [10], it is assumed that any 2 lines connected between the same two substations that are longer than 0.5 miles share the same towers; they are considered as a tower contingency. Substations groups with 3 or more lines between them will have $\lfloor B/2 \rfloor$ tower contingencies, where B is the number of branches connected between the two substations.

2) *Creation of Yearly Power Flow Cases*

Upon completion of the yearly loads, the yearly cases are be created and upgrades to the system can begin. The process for creating and upgrading the cases is presented in [10]. Essentially, the load is incremented for each year and the resulting violations are split among the students in separate case files; when upgrades are completed, the cases are combined back into a single case representative of that year. Upgrades are proposed for each year based on the violations presented within the contingency analysis. The limit thresholds for violations are based on the NERC requirements presented above. System upgrades are selected based upon the equipment availability and economic feasibility.

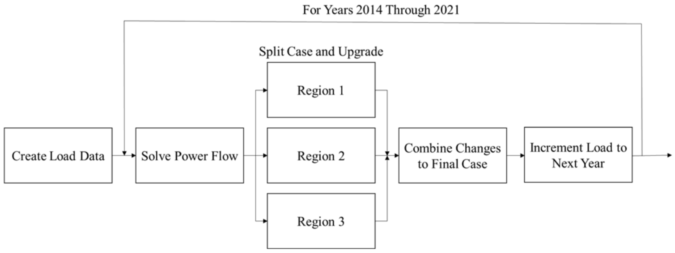

Fig. 2. The Case Regional Split and Combination Process

Throughout the 7 years of load growth, more than 5000 limit violations occur. To split the workload, ERCOT's 8 weather regions are partitioned into a power flow case for each student. It is assumed that a change made in one area will not affect other areas given that they are a sufficient distance from each other. This allows the students to make improvements in their areas without considering outside areas. While this is not a perfect assumption, it is accurate enough to require little mitigation after combining the cases. In each of the cases, the entire Texas power flow is solved, however only violations within each case's assigned weather regions are reported and solved. Changes are tracked and made until no violations remain within the case's responsible area; however, violations in other areas will remain. Following the completion of the separate regional cases, all tracked changes from each region are applied to the base case. With the assumption that changes to the system have an insignificant effect on buses far away, violations mitigated in each area should also be mitigated in the combined case. The process is shown in Fig. 2.

When a year's changes are combined into a single case, the load is incremented to create the consecutive year's base case. Potentially, large changes in load between years can cause an error in power flow convergence. To prevent this situation, the Time Step Simulation tool in PowerWorld is utilized to linearly step and solve each bus's load for 30 time points. It is assumed that the system will converge with smaller increments in load. 30 time points are chosen to represent a month of increasing load; contours at each time point can be utilized to understand the gradual changes in the system from year to year.

D. *Solution for Power Flow Cases*

1) *Parameter Estimation*

To make topology changes to the system, realistic parameters are required for all devices. A method for parameter estimation is followed to make realistic changes to the system. The method provides prices and parameters for market-available generators, branches, transformers, and shunts. The methodology is used when making any change or addition to the design case. Several sources are used to ensure that the devices created have accurate specifications and prices that are readily available on the market. The capacitors, generators, branches, and transformers are priced based on [22].

To calculate branch parameters, inputs of line substations, line voltage, line size, and line bundling configuration are used. Available cable sizes and prices are pulled from industry vendor [23] to calculate a line's inductance, resistance, and shunt admittance from its diameter and length (which is derived from the substation locations). These calculations are well known in industry and are derived in [5].

Conductor type, line type, to and from substations, and bundling amount are used to calculate the parameters and cost of the line. The bundling number options used are unbundled, 2-bundled, 3-bundled, and 4-bundled.

The available tower configurations and their associated costs are based on the voltage and per unit length of the wire. The tower costs are subtracted from the estimated total costs given in [22]. Parameters are also calculated for transformers; the inputs of MVA limit and nominal voltages determine the installation cost, resistance per unit, and reactance per unit. Prices are given by [24].

2) *Remedial Action Schemes*

Remedial action schemes (RAS) are included within the design case and are automatically implemented during contingency analysis. As explained in [25], a RAS is an "automatic protection system [that takes] corrective actions to maintain system reliability [in response to] abnormal or predetermined system conditions". Within the design case, these actions are implemented for situations when a capacitor bank or generator contributes to a large portion of the violation and the original power flow solution does not converge within the desired voltage or thermal thresholds.

This project does not consider NERC's protocol for contingency category P1 in [12] to not change generation dispatch for single contingencies. It is assumed that generation can be changed to solve a violation, so a RAS can be input to the case if a violation is the direct result of the generation dispatch. The prevalence of RASs in industry presents a discrepancy between the design case and industry power flow cases. Industry planners typically do not plan on requiring a RAS as part of their multi-year plan. However, RAS's are often used in real-time when future planned system conditions differ from actual conditions. For capacitors, if a capacitor causes a line to exceed its MVA limit by a large margin post-contingency, it is considered acceptable to implement a RAS to switch it out of service even though the capacitors regulated may no longer be at its optimal voltage level.

3) *Reporting Methodology*

To properly keep track of system topology changes and upgrade costs, an organized reporting methodology is used. Mitigations are listed per violation and include information such as violation limits, contingency names, contingency locations, violation locations, and associated projects. A project is defined by the student and multiple violations can adopt it as a viable solution. Projects include figures such as costs, new system elements, impedances, and limits. Before and after pictures of the project are also referenced for reporting purposes.

TABLE III

STATISTICS FOR YEAR 2018

Description	Value
Number of Initial Violations	67
Total Upgrade Cost	$ 3,346,000,000
Number of Branches Added	27
Number of Branches Reconductored	36
Number of Generators Added	4
Number of Other Changes (inc: Switched Shunt and Transformer Upgrades)	29

III. CASE STUDY

Using the methodology presented above, design cases are created with a 7-year load prediction and upgrade plan from years 2014 - 2021. For each of the 7 years in the upgrade plan, a completed case is saved, and a detailed change log is provided with associated device parameters and costs.

A. *Statistics for Year 2018*

Table III displays statistics about year 2018. The total upgrade cost is of the same order as referenced in the system requirements. Overall, when compared to ERCOT's system upgrade budget, the upgrades performed in the case study over all seven years are reasonable. The total number of changes required to resolve all initial violations is 43% larger than the number of violations, which implies that a violation may require changes to multiple system elements. Statistics are shown in Table III.

B. *Common Upgrades and Solution Examples*

Within the design case, common topology upgrades are considered for most violations. System upgrades include switched shunts, branches, transformers, and generators.

1) *Switched Shunts*

Switched shunts are added to the design case to address voltage violations that are not addressable by generation or switched shunts that are already present. Typically, in a peak summer case only low voltage violations will be present. The added switched shunts are initialized as automatically-controlled blocks to respond to different load scenarios.

2) *Branches*

Typically, when a line experiences a current violation, that branch is either reconductored or a new branch is installed to alleviate that path. In Fig. 3, Brownsville 1, Mission 1, and San Juan are all 230 kV substations that provide support to the 115 kV San Juan area. A tower contingency from San Juan to Mission 1 causes a large loss of support from the 230 kV to 115 kV system, resulting in the power flow solution to not converge. A 230 kV line from Brownsville to Mission 1 is added to provide support to the 115 kV system; the case converges with no violations.

3) *Generators*

Generation is added to the design case when the student determines an area is sufficiently lacking in generation support. For example, many violations within the area may be resolved by the addition of generation as opposed to upgrading all the lines. Following the addition of a generator at substation Spring 7, the voltage contours in Fig. 4, display raised local voltages that are closer to 1.0 p.u. [26]. The addition resolves 6 violations that are identified during contingency analysis. The addition of generation is considered a long-term solution, as opposed to simply upgrading the lines that are the symptoms of a lack of generation.

4) *Transformers*

In general, the design case's step-down transformers are replaced when they are overloaded and can no longer support the lower-voltage system. A new transformer is added to lessen the constraints on the substation and resolve the thermal violation.

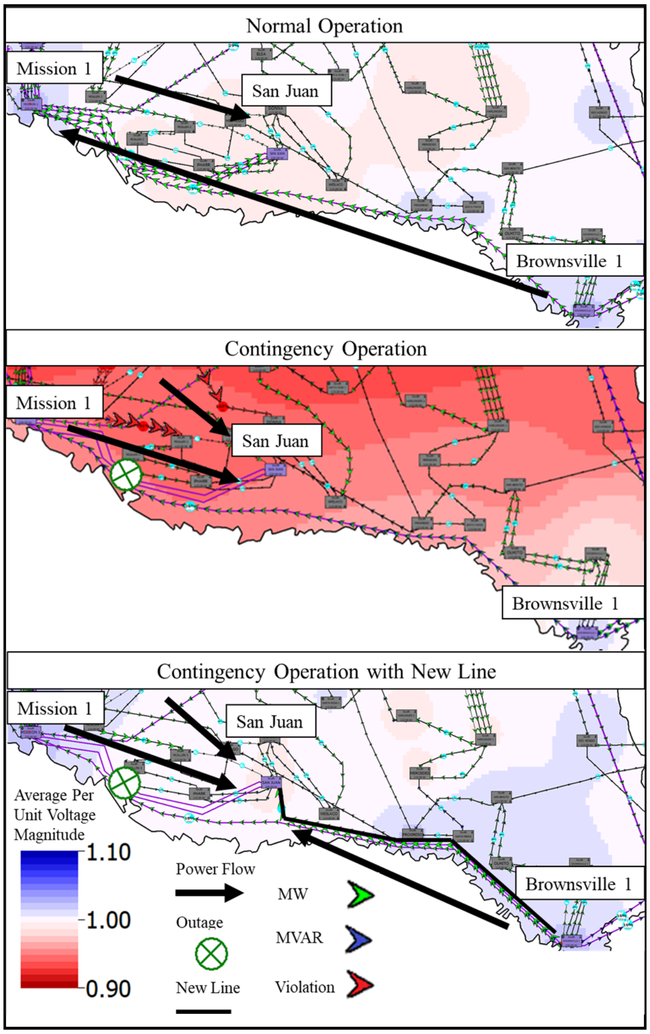

Fig. 3. Branch Addition. A new branch is added between substations Brownsville 1 and San Juan to mitigate branch MVA and voltage problems from contingency Mission 1 to San Juan

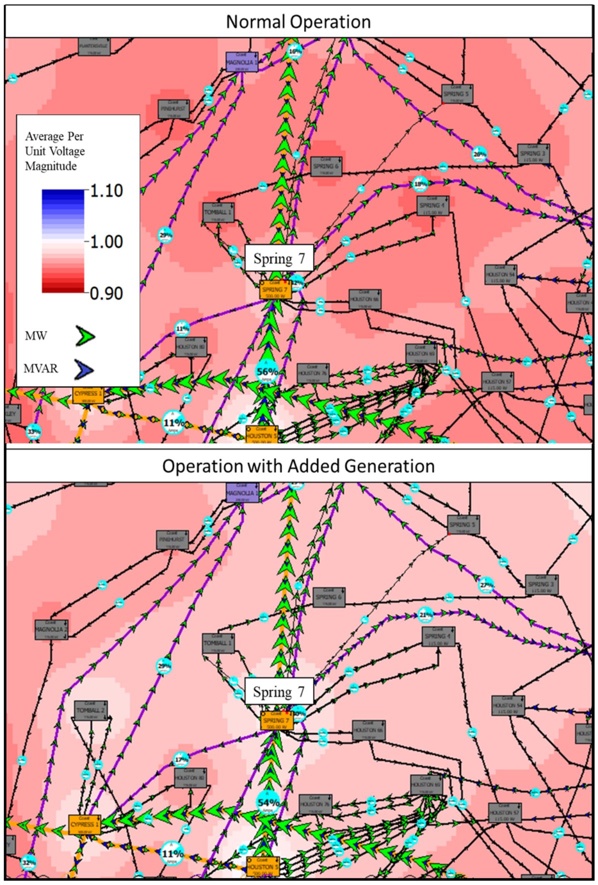

Fig. 4. Generation Addition. Generation is added at substation Spring 7 to assist with voltage issue due to large import of power

C. *Challenges*

Although the original case is not designed to support the load predicted for future years, the predicted load increases relatively uniformly across all regions. Consequently, regional device flows increase uniformly and do not cause quick large changes on any of the devices. However, urban areas of the system have large concentrated loads, buses, and lines, so more violations are present in these areas. The short lines that are present within densely-populated areas have higher sensitivity to system changes due to their lower impedances and limits. For example, as a significant urbanized area in Texas, the Houston area experiences a high sensitivity to increased load and generation variation. Since the substations in this area are dense, a lot of time is required to address the resulting violation errors.

As the load increases, new generation must eventually be installed in the system. The initial base case system has a respectable amount of generation reserve, so generation additions are not critically necessary until year 2018. Generation additions occur in discrete sizeable units and have a considerable direct impact on local branch flows. Generation additions that are not initially planned for in the base case creation algorithm [27] have the potential to create both pre- and post-contingency violations.

Finally, the original case is not designed for resilience to tower contingencies. The year 2014 base case contains a significant number of post tower contingency violations that require either reconductoring the lines or adding additional parallel transmission lines.

D. Combination

Combining the cases into a single case can cause creation conflicts because there could be multiple changes to the same system element. As there are tens of changes between each student's case, it is also difficult to verify that all changes are present within the final case. Additionally, new violations may occur that were not previously present in each student's power flow case.

IV. CONCLUSION

This paper demonstrates that realistic topology changes can be inserted to Texas 2000 bus synthetic grid to meet ERCOT's anticipated summer peak load from 2014-2021. Specifically, the system modifications resolve voltage and thermal violations both pre- and post-contingency to meet specified reliability requirements. Expanding the use of large-scale systems into a capstone course allows for complex analysis and modeling for systems similar to those seen in industry. Semester to year-long studies better replicate the scope of expansion planning projects within industry.

Power systems senior design projects are rare in general, especially those focusing on transmission system expansion. This design case attempts to take as few assumptions as possible to create a problem needing realistic solutions that incorporates federal and state guidelines for the reliability of a system. The solution process is performed over several years to allow for practice and repetition. This case has a wide scope and provides room for students to develop analytical skills that reflect work an engineer would perform in industry.

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