Undergraduate Research on Improving Power Grid Planning Models

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***Abstract*—Electric grids worldwide are changing and evolving as the grids are modernized and new technologies are introduced and adopted. Solar and wind energy are expected to dramatically increase by 2030, consumption of electricity will likely increase with the addition of electric vehicles and large loads such as bitcoin mining. Accordingly, it is helpful to create open-source grid planning models to reflect these transformations. This paper focuses on updates to a network planning for a Texas 2030 synthetic power system model. Transmission lines of an existing Texas 2016 synthetic power grid are modified to operate under future load and renewable generation scenarios for 2030. The process entails modifying a network model with DC power flow then performing AC Reactive Power Planning (RPP) for AC power flow convergence. In this work, various algorithms are utilized in making alterations to the 2016 grid, resulting in a well-functioning synthetic grid for 2030. Contributions are made towards the transition to clean energy and valuable power flow algorithms are added to the power systems community.**

***Index Terms*—grid modernization, synthetic power grids, power flow, reactive power planning**

I. INTRODUCTION

A. Motivation

Network models of the electric grid in the United States were previously available to the public. These models were important to and utilized in power systems research. However, security concerns have limited the availability of the network models of the real world electric transmission system since September 11, 2001. As a result, power systems research dives into using algorithms to create synthetic electric power grids. Synthetic grids depict large scale, realistic representations of power grids [1]. A synthetic grid models the complexity of the real grid but without any confidential data. It is used to perform grid simulations and analysis.

Realistic synthetic electric grids are helpful in analyzing possible scenarios or test cases for the real world power system. For example, testing out the impact of a line contingency is possible on the synthetic grid as opposed to tripping the transmission line in order to test out and plan for this scenario [2]. Accordingly, electric utility companies, Regional Transmission Operators (RTOs), and Independent System Operators (ISOs) rely on realistic synthetic network models of the electric grid for operating and planning the electric power system. Power engineers and students are also able to gain practical experience while operating synthetic grids and addressing challenges of grid modernization [3].

Synthetic models involve mathematical representation of various aspects of the electric transmission system, including generators, transformers, transmission lines, series and shunt devices, and loads [2]. Power system research relies heavily on conducting simulations on realistic network models of the electric grid. Synthetic grids are needed for several reasons, including the lack of information sharing among different utility entities, increased addition of variable renewable energy sources, and a lack of public access to existing power system models since 2001. Furthermore, synthetic electric grids allow for large, realistic, and publicly available power system network models and consequently power system research, daily operation, and short to long term planning.

Cases have been created using methods described in [4] which only considered the peak load scenarios like is done in practice, dynamics in [5], and time series in paper [6] and [7]. However, these cases don't have feasible optimal power flow (OPF) solutions for multiple renewable power scenarios [8] and [9]. As a result, this research is needed to cover multiple renewable generation and load scenarios on a large system.

Network planning for the Texas 2030 grid involves a 7000 bus case. The original Texas 7000 bus model was designed using 2016 wind and solar energy. Modifications were made to the grid for 2030's projected renewables and load. This resulted in numerous overloaded transmission lines. Overloaded meaning more power is flowing through the line based on our simulation of the grid than the actual line capacity. This work updates the overloaded transmission lines of an existing Texas 2016 synthetic grid in order for it to operate under future load and renewable generation scenarios for 2030.

While it is possible to fix overloaded lines manually, it is tedious to do this for multiple scenarios. The best approach for resolving overloaded lines uses mixed integer AC power flow. However, such complexity is not feasible for a 7000 bus system. The current literature does not work on large scale systems of thousands to tens of thousands of buses [10] and [11]. Each method has its advantages, disadvantages, and common utilization [12]. All of this emphasizes the need for this work which provides a systematic way of updating the lines to address the manual task and utilizes the simplified

DC power flow to address the mixed integer complexity. To modify the lines, we calculate DC power flow, then resize the lines which leads to a recalculation of DC power flow. There is a continuous process of computing DC power flow and updating overloaded lines. The goal of this research is to update transmission line capacities using DC power flow and add shunts to the grid for reactive power planning using AC power flow.

B. 7K case

Synthetic electric grids are test cases; they are not constructed from any actual power system due to the private nature of real electric grid models. Nevertheless, synthetic grids contribute significantly to power systems research by spurring innovation, supporting the reproducibility of results, and strengthening peer reviews [13]. As synthetic power grid models are built, a challenge arises concerning whether the created cases are realistic power grids. Furthermore, the electric load on the transmission line is continuously growing, and variable renewable energy sources, including solar and wind energy, are being added to the grid. This work touches on these two points as it focuses on modifying and validating a realistic synthetic grid for the transition toward clean energy. Texas' 2030 synthetic grid needs to reflect the modernization of the grid while maintaining a realistic depiction of the actual electric grid.

A great deal of research has gone into creating and improving synthetic network models in order to make them more realistic and account for a largeness in scale. This research builds on previous work and continues the enhancement of the Texas synthetic grid.

II. METHODS

A. Scenarios selection

One of the important goals of this paper is to prepare Texas' 2030 synthetic grid to be robust against extreme weather events. Since Texas' 2030 grid has a heavy mix of renewable generation, the impact of weather is an important consideration. The weather on any given day will affect the generation from renewable sources and will eventually redistribute power from conventional generation. Thus, the transmission line limits and the conventional generation should be sufficient to cater to these power flow requirements. To be prepared for extreme weather scenarios, the grid parameters like transmission line limits and reactive power availability should be sufficient for normal grid operation for all time points of the year 2030.

One approach is to run power flow on the Texas 2030 synthetic grid for every single time point scenario. Based on the results of these scenarios, the grid parameters are updated. However, this results in a high computational time, and it is unnecessary to run power flow on all time points. It is assumed that if the grid solves the worst-case scenarios, the updated parameters will be sufficient to obtain normal operation of the synthetic grid for all other scenarios.

Thus in this paper, the scenarios are limited to extreme scenarios. The idea is that if the synthetic grid is robust to these extreme events, then it will be able to handle the variation in the weather for the entire year. To do this, the approach is to first plot the renewable generation against the demand for the entire year of 2030. This is shown in Fig. 1.

From this figure, four extreme scenarios are identified. These are four different scenarios with: a. Low Load and High Renewable Generation, b. Low Load and Low Renewable Generation; c. High Load and Low Renewable Generation; d. High Load and High Renewable Generation. The days corresponding to these four scenarios are shown in Table I.

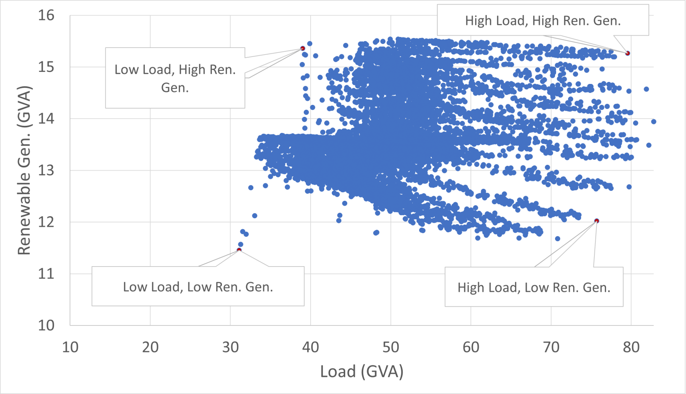

Fig. 1. Renewable Generation versus Load for the year 2030

TABLE I
FOUR SCENARIOS AND THEIR CORRESPONDING TIME POINT (YEAR 2030)

Scenario	Date and Time
Low Load and High Renewable Generation	Feb 27, 1:00 PM
Low Load and Low Renewable Generation	Feb 28, 1:00 AM
High Load and Low Renewable Generation	Aug 06, 6:00 PM
High Load and High Renewable Generation	Aug 06, 1:00 PM

B. Updating line parameters

There are four core input files utilized in this work and seven foundational algorithms for understanding the connections and power flows across the network model. These algorithms play a vital role in modifying the grid. The flow of the input files and algorithms resulting in updates to the grid in the form of output files is shown in Fig. 2.

The input files include data about the buses and branches in the network model, possible conductors for resizing, and load and generation information for multiple scenarios. The buses data has information about each bus and the branches data has information about each transmission line or transformer connecting two buses. The conductor data has possible conductors that can be used in resizing overloaded transmission lines. The load and generation data has real and reactive power for each of the four extreme scenarios for Texas in 2030. Python, PowerWorld Simulator, and CSV files are used throughout this research.

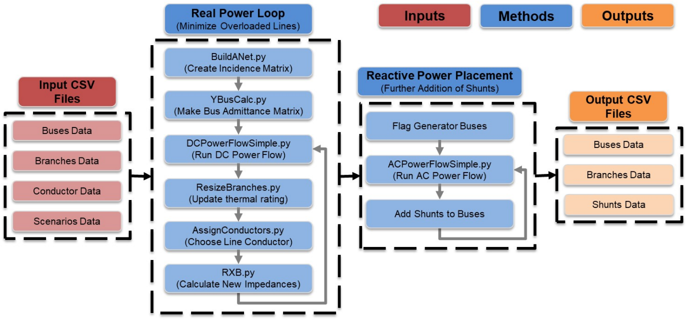

Fig. 2. Flowchart

The network model is established using several functions to calculate its incidence matrix, admittance matrix, and power flow. BuildANet calculates the incidence matrix which depicts the topology of the network, and YBusCalc computes the bus admittance matrix, Ybus, which represents the nodal admittance of the buses in the grid. Power flow determines the power flowing through the branches by evaluating the voltage magnitude and phase angle and the real and reactive power at each bus. The DCPowerFlowSimple and ACPowerFlowSimple functions solve the power flow whereby DC power flow is a simplified form of AC power flow.

$$P_k = V_k \sum_{n=1}^{N} V_n \left[G_{kn} \cos\left(\delta_k - \delta_n\right) + B_{kn} \sin\left(\delta_k - \delta_n\right) \right] \tag{1}$$

$$Q_k = V_k \sum_{n=1}^{N} V_n \left[G_{kn} \sin\left(\delta_k - \delta_n\right) - B_{kn} \cos\left(\delta_k - \delta_n\right) \right] \tag{2}$$

There have been various novel methods for formulating AC power flow equations in recent years within the power systems research community [14]. The AC power flow problem in (1) and (2) is solved using the Newton-Raphson method. The goal is to attain four values: voltage magnitude V, voltage phase angle δ, real power P, and reactive power Q. Once V, δ, P, and Q for every bus in the network is known, complex power line flows are calculated as the maximum complex power between the sending (bus k to bus n) line flow and receiving (bus n to bus k) line flow.

$$-[B][\delta] = [P] \tag{3}$$

DC power flow linearizes (1) and (2) by assuming that voltage magnitudes V = 1, R << X so line admittance G = 0, $\cos(\delta_k\text{-}\delta_n)$ = 1, $\sin(\delta_k\text{-}\delta_n)$ = $(\delta_k\text{-}\delta_n)$ [2]. (2) reduces to a constant and is therefore neglected while (1) reduces to (3) which is used to compute real power line flows [15]. The power flowing through each branch is compared with its thermal limit to determine overloaded lines in the grid.

Overloaded lines endanger power grid stability. Consequently, the following three functions modify overloaded lines by updating the line thermal rating. ResizeBranches increases the thermal rating of an overloaded line to the next higher rating, AssignConductors allots the conductor index for a conductor with the closest thermal rating to the line, and RXB computes new resistance R, reactance X, susceptance B values given the updated thermal rating of the line [2]. New R, X, B values reflect the change in line rating. The capacity of each overloaded transmission line is gradually increased as opposed to drastically raising it.

With the seven functions established, the RealPowerLoop function integrates the BuildANet, YBusCalc, DCPowerFlowSimple, ResizeBranches, AssignConductors, and RXB functions in updating overloaded lines. The function first runs DC power flow, then determines which lines are overloaded by comparing each branch's thermal rating to the simulated power flowing through it as calculated from the DC power flow. Lines are overloaded if the thermal rating is less than the DC power flow, meaning that more real power would flow through the line, based on DC power flow results, than its actual line capacity. While some transformer branches may be overloaded, the focus is on updating overloaded transmission lines, which in turn resolves majority of the few overloaded transformers.

Once overloaded lines are known, the next step is to update the thermal ratings by resizing the transmission lines. This is done by calling the ResizeBranches function to change the size of the line, then the AssignConductors function to designate a conductor index for the resized line, then the RXB function to calculate new resistance, reactance, and susceptance (R, X, B) values for the resized line. The action of updating the R, X, B values modifies the capacity of each transmission line. DC power flow is computed again and used to determine any overloaded lines. This process repeats until there are no overloaded lines or it reaches the seventieth iteration of the loop. The zero overloaded line condition achieves the goal of not having any overloaded transmission line while the iteration limit ensures a finite loop in the case whereby all possible updates have been made to the grid but there are still some overloaded lines. Lastly, the data for the grid is updated to reflect the grid's modifications. Overloaded lines are resolved using DC power flow with the overarching goal of having no overloaded lines on the grid.

C. Reactive power planning

Reactive power is necessary for power system operation and voltage stability. However, reactive power cannot be transmitted over long distances and therefore needs to be locally supplied. After updating overloaded lines using DC power flow, the final step in modifying the grid entails performing AC Reactive Power Planning (RPP) for AC power flow convergence. Reactive Power Planning involves providing reactive power locally by adding shunt capacitors at various buses across the grid. The ReactivePowerPlacement function shown in Fig. 2 flags generator or PV buses with a PV flag, then loops through a number of steps until 80% of temporary PV buses return to PQ buses. In the while loop, the function first calls the ACPowerFlowSimple function. Then, buses with the highest kV in each substation are set as PV buses except if the bus is flagged as a PQ bus, meaning it should remain a PQ bus. Of these buses recently and temporarily changed to PV buses, the smallest 5% when looking at the absolute value of reactive power are set as PQ buses.

A for loop follows for different scenarios to be run. In the loop, AC power flow is run, then temporarily changed PV buses are checked to see if the voltage magnitude at the bus is between 0.96 and 1.06. This shows that the bus's known voltage magnitude from being a PV bus is within an acceptable range. Therefore, it is possible to add a shunt capacitor to that bus, so the bus is flagged with an 'add shunt' flag. The maximum reactive power from running AC power flow for the different scenarios is stored. Shunt capacitors are added to the mid-range, 48-52%, reactive power of buses flagged with 'add shunt' immediately outside the for loop. The value of the shunt is -1.2 times the maximum reactive power stored. The buses with the smallest absolute value of reactive power mentioned above are flagged with the PQ flag.

Lastly, the grid is updated to reflect the changes made to its network topology as a result of adding shunts. Accordingly, the modified grid is without any overloaded transmission lines or voltage violations.

III. RESULTS

This section focuses on the results attained with the methodologies for updating line parameters and reactive power planning.

Utilizing the RealPowerLoop function, 1619 total overloaded transmission lines at various iterations are updated until all overloaded lines except 15 lines are resolved on the Texas 7000 bus synthetic grid with considerations in place for four extreme load and renewable generation scenarios in 2030. The results are shown in Table II for high load and high renewable generation, high load and low renewable generation, low load and high renewable generation, low load and low renewable generation scenarios. Although the 15 lines were modified, they remained overloaded due to the fact that the maximum line capacity of any possible line based on the available conductor data was reached.

TABLE II
UPDATING LINE PARAMETERS

Requirement	Result
<1% overloaded lines	0.93% (1619 to 15 overloaded lines)

The initial specification entailed having no overloaded transmission lines. However, with a large network, having less than 1% remaining overloaded lines was sufficient when factoring in four severe scenarios. As many overloaded lines as possible were resolved using the RealPowerLoop function. Hence, the next step was determining where to place shunt capacitors on the grid to maintain appropriate voltage limits.

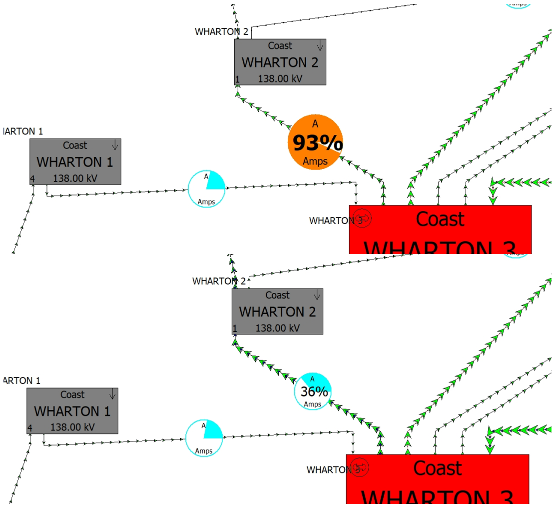

Fig. 3. Transmission line from bus 111363 to bus 110132 (top) before and (bottom) after updates

The ReactivePowerPlanning function modified the network topology by using AC power flow to calculate the most suitable bus locations to add shunts. Changes to the grid, specifically modifications of R, X, B values of lines and addition of shunts, were made in PowerWorld. These changes were reflected in the results obtained after running AC power flow in PowerWorld. The results were checked against two specifications: transmission lines are not overloaded and bus voltage magnitudes remain close to rated values. For there to be zero overloaded lines and voltage violations, the line capacity for all lines in the network needed to be $\leq$ 100% Lim MVA and the per unit voltage magnitude for all buses needed to be between 0.9 and 1.1 p.u. Table III shows the results for five scenarios.

TABLE III
UPDATED LINE PARAMETERS AND REACTIVE POWER PLANNING

Scenario	Update	>100% Lines	Max Line	>100% Xfrmrs	Max Xfrmr	Vmin	Vmax
HL HG	Before	0	95.9%	0	87.2%	0.9478	1.0804
	After	0	91.8%	4	138.4%	0.9310	1.0669
HL LG	Before	0	99.9%	0	90.9%	0.9466	1.0812
	After	0	88.0%	4	139.9%	0.9405	1.0655
LL HG	Before	0	80.3%	0	73.7%	0.9913	1.1014
	After	0	53.0%	0	70.2%	0.9802	1.0593
LL LG	Before	0	70.8%	0	62.1%	0.9939	1.1141
	After	0	47.3%	0	58.9%	0.9850	1.0661
Highest Load	Before	4	111.6%	0	90.8%	0.9443	1.0983
	After	0	97.5%	6	144.1%	0.9304	1.0610

For each scenario, the number of overloaded transmission lines, maximum percentage limit line capacity across all lines, number of overloaded transformers, maximum percentage limit transformer capacity across all transformers, minimum and maximum voltage angles in per unit are contrasted before and after the network was modified. Overloaded transmission lines and voltage violations occur at various time points in 2030. However, the focus of this research was on four extreme scenarios. These four scenarios covering low or high load and generation conditions had no overloaded lines before the grid was updated. However, both low load scenarios had voltage violations which were fixed after the update. Initially, the grid updates were to be tested on only the four extreme scenarios, but these scenarios didn't have overloaded lines. As a result, a highest load scenario was included in the testing and validation to cover a situation whereby there were a few overloaded lines. In the highest load scenario, there were four overloaded lines and all of these lines were resolved after the grid modifications.

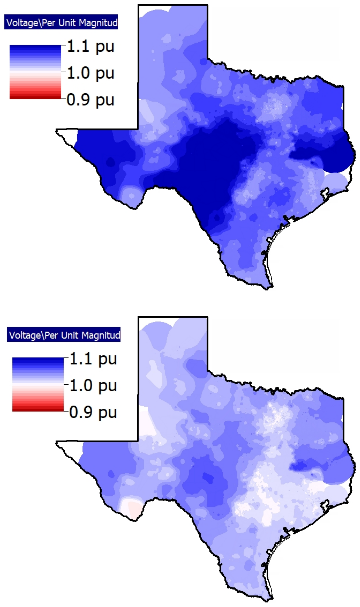

Fig. 4. Voltage contour (top) before and (bottom) after updates

While all overloaded transmission lines were fixed in these scenarios, there was a negative impact on transformers for three out of the five scenarios which had high amounts of load. The maximum percentage limit transformer capacity increased and the number of overloaded transformers increased for all three high load scenarios. Nonetheless, the maximum percentage limit line capacity was reduced across all five scenarios. This demonstrates that the methods of updating line parameters using DC power flow and reactive power planning using AC power flow successfully resolves all overloaded lines so that transmission lines are not overloaded and even have a lower maximum percentage limit line capacity across all lines.

Overall, modifications were made to the Texas grid to make it operable under 2030 load and renewable generation scenarios. There were some negative impacts on transformers in the three high load scenarios selected, but this work centered on updating transmission lines. The algorithms successfully determined the optimal process for resolving overloaded transmission lines and voltage violations.

IV. CONCLUSION

This research focuses on creating algorithms in order to determine the best approach to modify transmission lines and add shunts in the electric grid to account for the addition of wind and solar power to the grid. The existing Texas 7000 bus model was designed using 2016 wind and solar energy. Transmission lines became overloaded with modifications to the grid which factored in projected renewable generation and load for 2030. The algorithms fixed the overloaded transmission lines and voltage violations. Hence, the Texas grid has been modified to operate under future load and renewable generation scenarios for 2030.

A. Future Work

This work concludes with a modified, well-functioning, and realistic Texas synthetic grid for the transition to clean energy. Power flow and reactive power planning algorithms have been established to determine the best way to update the grid for 2030. Still, these algorithms can be further optimized in future works to improve the grid. One such method is to include an algorithm to modify overloaded transformers. Another is to update the reactive power planning algorithm so that it adds steps for shunts in order to factor in the need for discrete shunts to gradually increase in steps. Furthermore, the scope of the 2030 load and renewable generation scenarios can be expanded to a greater number of scenarios, including normal daily scenarios, in order to cover more time points in the year. Once updates to the 7K bus case are solidified, future research can be done on larger cases.

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