Educational Applications of Large Synthetic Power Grids

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***Abstract*—This paper describes the use of large electric grids in university electric power system courses. Since much actual power system information is not publicly available, the application of public domain synthetic grids developed by the authors is presented including a 2000-bus grid. Discussion of the educational applications utilized in a senior level class are given for power flow analysis and sensitivity, economic dispatch, contingency analysis, optimal power flow (OPF), security-constrained OPF, transient stability, and real-time dynamic operations. In each of these, the application of the large synthetic grids give students insights and experience with cases closer to actual power systems in complexity and size.**

***Index Terms*—Contingency analysis, dynamic interactive simulation, economic dispatch, optimal power flow, power system education, power system simulation, power flow problem, power flow sensitivity, security constrained optimal power flow, synthetic power grids, transient stability.**

I. Introduction

GRADUATES of an engineering program who go to work in the electric utility industry should be ready to study large power systems. Though very small examples are useful for teaching the analysis principles and modeling basics, there are natural benefits to additionally exposing students to power systems that are realistic in size and complexity. A key reason undergraduate power systems courses often do not utilize large grids is that such data sets can be hard to obtain with the appropriate permission for classroom usage. Though there are some existing test cases such as [1], [2], much actual power grid information is not fully public due to legitimate security concerns.

This paper discusses how synthetic power grids can fill this gap by providing publicly available test cases that match the size and complexity of actual grids. These fictional systems are designed using automated techniques and validated for statistical similarity to real systems, while including no confidential data [3], [4]. Synthetic power grids can additionally include generator cost curves [5], geographic coordinates, single-line diagrams, and transient stability models [6]. These features, the case size and complexity, and the key ability to be shared without restriction open up new opportunities in power engineering education.

The large system assignments described by this paper have been implemented in a undergraduate class, titled "Power System Operation and Control," at Texas A&M University. To date they have been used in Fall 2017 and Spring 2018, both times with an class of 70 primarily undergraduates divided into six 12 student lab sections. The lab portion of this class now includes, in addition to exercises with physical equipment and small system models, assignments that analyze a 2000-bus synthetic power grid in the commercial software package PowerWorld Simulator. A variety of planning and operations studies using the 2000-bus synthetic case are assigned throughout the term, as described in this paper. Topics include power flow sensitivity, contingency analysis, optimal power flow, and transient stability. All of the cases and instructions associated with these lab assignments are freely available online in a variety of formats [7].

II. Background

A. Simulation Assignments in Power Engineering Education

Computer simulations have formed a part of power systems education for over four decades [8], [9]. Since analyzing practical systems quickly becomes difficult for hand calculations, over the years software tools have been created and used for teaching power engineering. An early example is [10], which dedicated a course to computer applications in power system control centers. By the late 1980s many universities were balancing hardware lab assignments with computer simulations in power systems courses [11]. New and more feature-rich software tools and their educational applications were developed in the following decade, as engineering education could integrate analysis for security, transients, and control [12]–[15]. Advances in computer graphics made tools more user-friendly and interactive [16], [17], and towards the turn of the century educational software for power systems was becoming more general and widely used [18]–[20]. Reference [21] is an example of the use of simulation in training industry professionals. In the context of power system simulation, [22], [23] highlight the importance of targeting industry needs in university education.

In the last decade, simulation in power systems education has advanced to envelop new grid technologies [24]–[27], and to integrate with common programming interfaces and open

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source platforms [28]–[30]. With increased computing capability, power systems labs now greatly benefit from exercises using state-of-the-art software [31]. Recent publications have shown that new lab assignments are including hardware, software, and real-time simulations such as hardware-in-the-loop [32], [33]. Software simulations are broadening in topic also to cyber infrastructure [34] and the applications extend even to secondary education [35].

Throughout this extensive literature documenting power system simulation in education, the test cases consistently tend to be small, usually on the order of ten buses or fewer. Building on a long tradition of power systems education, the paper shows how teaching modeling, analysis, and control concepts can be supplemented with demonstration and assignments that involve large power systems. The main motivation for using large systems in undergraduate education is that when they enter the power industry students will be dealing with large systems. In addition, there are unique aspects to studying large systems, which include a system diagram that cannot be displayed on the whole screen at once, multiple areas that involve aggregating hundreds of generators, and inter-area oscillations in frequency response characteristics.

B. Synthetic Power Grids

The need for fully-public, high-quality power system datasets to encourage innovation in power systems has driven work to study the characteristics of power grids, with a goal of replicating these properties in fictitious networks. In [36]–[39] power systems are studied as complex networks and analyzed for graph theory properties such as node degree distribution, average shortest path length, diameter, and clustering coefficient. In applying these methods to building synthetic grids, several approaches have been used, including a small-world model for building realistic topologies [40], spatial embedding [41], clustering [42], and graph generation [43].

The 2000-bus synthetic grid utilized here was developed using the approach of [3]. This approaches combines public geographic, generator and load data with algorithms for the creation of a fictitious transmission system. The resultant grid mimics the characteristics of actual grids, though this becomes more challenging as the system size grows. A reactive power planning algorithm puts voltage control devices and obtains an ac power flow solution [4]. The whole method yields fully public datasets representing geographically-embedded fictitious systems which are similar to actual grids and useful for research. Additional work has augmented these cases with generator cost curves [5] and transient stability models [6].

III. Learning Objectives and Methodology for Power Systems Course with Large Grids

A. Course Topics and Lab Assignments

The objectives of this fifteen-week semester course, which included mostly senior-level undergraduate students and a few first-year graduate students, is to teach how power systems are modeled, analyzed, and managed. Prerequisites for the course include circuit theory and linear signals and systems. Table I gives the lecture topics and associated lab assignments for each of the fifteen weeks of the course. The assignments shown in boldface type use a large synthetic grid model.

TABLE I
Course Outline and Lab Assignments

Wk.	Lecture Topics	Lab Assignment
1	Introduction, complex power, 3-phase, per-unit	No lab
2	Power system structure, history, operations	No lab
3	Modeling of transmission lines and transformers	Power calculations (Matlab)
4	Loads and generators	Three-phase circuits (PowerWorld)
5	Y-bus matrix	Power system operations
6	Power flow problem	No lab (Exam #1)
7	Numerical solutions	Synchronous generator parameters
8	Sensitivity, large systems	Synchronous generator operation
9	Economic dispatch	**Power flow analysis, sensitivity**
10	OPF, SCOPF	**Economic dispatch, contingencies**
11	Power system stability	**OPF, SCOPF**
12	Power system stability	No lab (Exam #2)
13	Power system controls	Power markets
14	Distribution systems	**Transient stability, dynamics**
15	Emerging topics	No lab

The weekly lab assignment component demonstrates the planning and analysis concepts taught with exercises using a combination of software and hardware tools. The first three labs use very small systems, first in a Matlab toolbox to show active and reactive power, phasors, and imbalance; then in PowerWorld Simulator, with an introduction to single line diagrams, power flow solutions, maximum loading, and area control error (ACE). The fourth and fifth labs demonstrate calculation of synchronous generator parameters and the equivalent circuit for simulation modeling using hardware exercises. Students do open-circuit and short-circuit tests, and observe the effect of excitation control on voltage and power when a generator is operated under variable load.

Starting in the second half of the semester, labs begin to integrate both small and large power system simulation, as Sections III.C and IV will detail. The first of these covers fixing overloaded branches with sensitivity analysis, volt-var control, capacitors, tap coordination, and phase-shifting transformers. Then the following labs introduce the economic operation of power systems and system dynamics.

B. Integrating a Large System Into the Lab Exercises

The synthetic 2000-bus case (Fig. 1, [3], [4]) is a natural fit for engaging student interest in large power systems at Texas A&M, since its geographic footprint follows the Electric Reliability Council of Texas (ERCOT), which serves the majority of the U.S. state of Texas. While at first glance the grid looks real, it contains no actual lines since it was built with a synthetic methodology. As Fig. 1 shows, four levels of high-voltage networks connect eight areas and 1250 substations. The case's 544 generators roughly correspond to public information about actual plants, with fuel types including coal, hydro, natural gas, nuclear, solar, and wind.

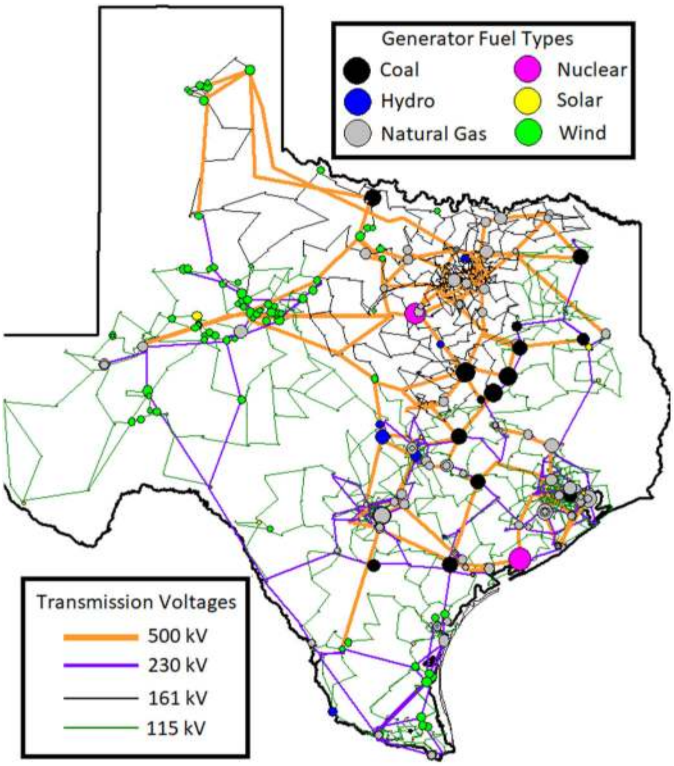

Fig. 1. Synthetic 2000-bus test case oneline diagram [3], [4]. Transmission voltages are shown, as well as circles representing the generators, with color indicating fuel type and size indicating the relative MW capacity. This grid is fictitious and does not represent the actual Texas grid.

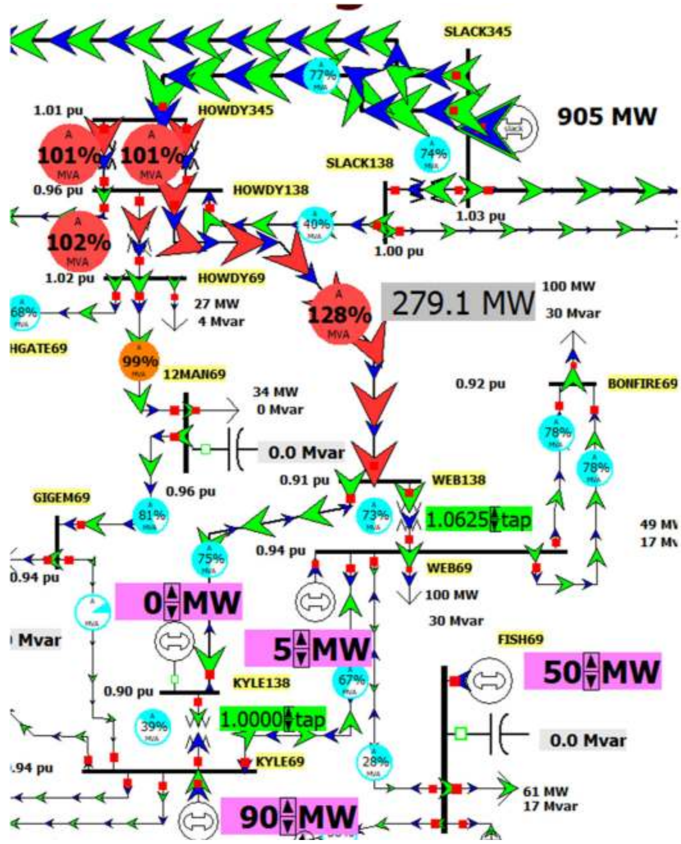

Fig. 2. A portion of the small power system (37-bus) used for the first part of each of the lab assignments. For the power flow lab, several lines are overloaded (red pie charts [44]) following a generator failure (the magenta label showing 0 MW). The other magenta rectangles show controllable generators, which can be re-dispatched to fix the violations. The arrows show real power flow (green), real power flow on violating lines (red), and reactive power flow (blue).

In addition to power flow data and the single line diagram, the synthetic data associated with this case includes quadratic cost curves for each of the generators and transient stability models. Synchronous machine models, excitation systems, governors, and system stabilizers are all specified. While this course only introduces some of these models, the principles of transient stability can be shown in the effect on 2000-bus system frequency response.

Analyzing a power system of this scale in a two-hour lab session is challenging, especially as students are still learning the software and the underlying modeling concepts. One key to making the cases accessible is that each lab instruction guide is detailed and shows with specific steps how to use the software to perform the studies under consideration. In addition, specially tailored single line diagrams with prominent labels and controls, which are highlighted later in the paper, aid students in visually comprehending what is happening across the system and focuses their attention on the concept at hand.

IV. Lab Assignments With the 2000-Bus Synthetic Grid

A. Power Flow Analysis Lab

The first introduction to operating a larger power system comes in the sixth lab, which focuses on power flow analysis studies. The objectives of this lab are for students to gain insight and experience with the power flow solution, sensitivities, the effects of various controls, and how to mitigate line overloads and excessive losses. There are two parts: one with a 37-bus case and the other with the 2000-bus synthetic Texas grid. A key objective in adding the 2000-bus grid to this exercise is to present students with a large system and allow them to learn by doing that they could apply techniques presented in lecture to solve problems with the larger grids they will encounter in industry.

For the first portion of this lab, the instruction guide acts as a tutorial that describes the starting situation in the 37-bus case for the fictional utility, part of which is shown in Fig. 2. The starting situation is that a 175 MW generator in the center of the system has failed. This causes several overloaded lines as the lost power is supplied by the slack bus, which represents an external intertie. The oneline diagram is configured to show these overloads prominently, with MW fields for two particular lines given in large gray boxes. The other controllable generators are shown with magenta fields that can be edited to change their dispatch value. There are also control options for load tap changing transformers (LTCs), switched shunts, and a phase angle regulating (PAR) transformer. There are additional fields giving bus voltages, substation names, and the total system load and losses.

The students' assignment for this first portion is to develop, justify, and implement a strategy to fix the line overload violations and minimize the system losses. They start by collecting

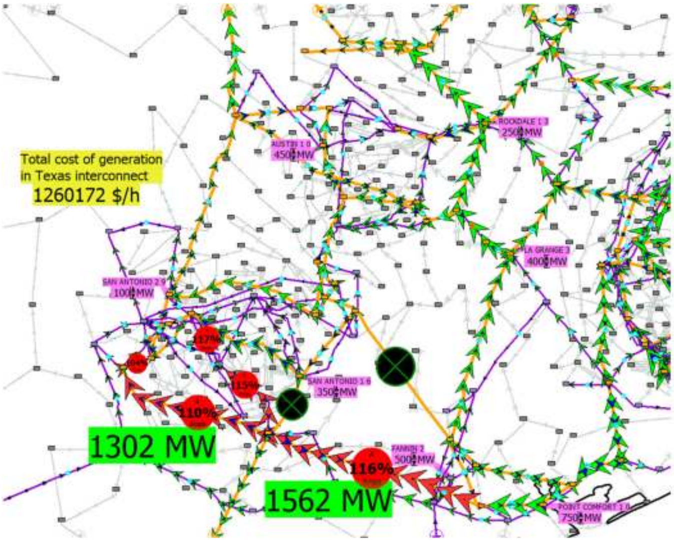

Fig. 3. Zoomed-in display of the 2000-bus case used for the power flow analysis lab. The green fields show the power flow through two 500 kV lines which are overloaded (red pie charts [44]) following a double outage contingency (black circles). The magenta rectangles show controllable generators, which can be re-dispatched to fix the violations.

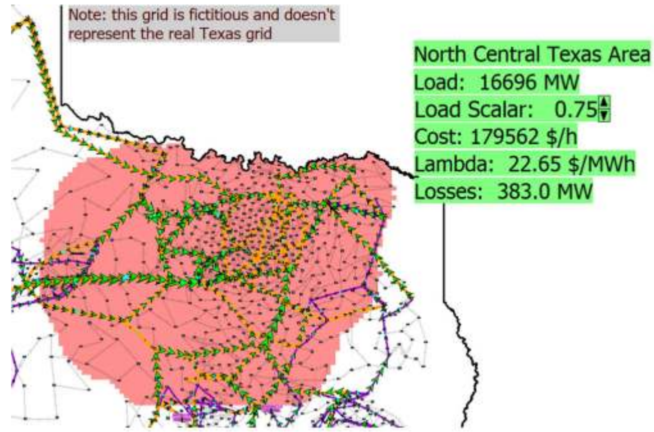

Fig. 4. Synthetic 2000-bus Texas case, with the North Central area highlighted in red and the green fields giving data relevant to the economic dispatch solution.

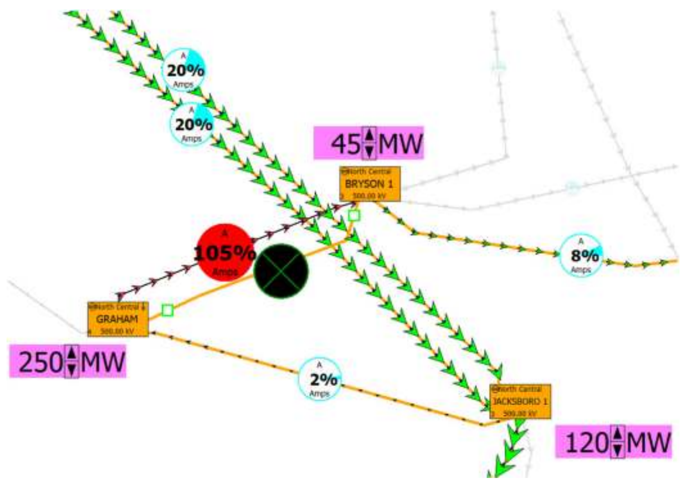

Fig. 5. Zoomed-in view of a contingency violation in the 2000-bus case.

data on the sensitivity of two line overloads to a change in selected generators' dispatch setting and the change in the PAR setting. (For example, if the 5 MW generator is increased to 10 MW and the line flow reduces from 279.1 MW to 277.1 MW, the sensitivity will be -0.40.) This analysis will show which controls are most useful for correcting the violations, and how much they should be changed. Once the changes are implemented, the directions point out circulating reactive power flows that are contributing to a higher than necessary level of active power losses. By coordinating the LTCs and switching in capacitors, the losses can be reduced to an empirical minimum.

Next, the students are directed to the 2000-bus system representing the fictitious Synthetic Texas Grid Company, which has an analogous situation in which a double line outage has caused overloads in the transmission system. It is a much larger case, but the customized diagram presented in Fig. 3 shows the overloads similarly to the 37-bus case just completed, and highlights some controllable generators with magenta fields. Just as before, the students calculate the sensitivities and develop an action plan to resolve the emergency situation. Though cost is not a crucial concern in this exercise, students observe how the system cost of operation has increased with these remedial actions.

B. Economic Dispatch and Contingency Analysis Lab

The next lab exercise introduces the economic operation of power systems, and contingency analysis. Again the assignment starts with the 37-bus case and moves to the 2000-bus case with assignments that are similar but have important distinctions unique to the large system.

In this lab, students focus on the North Central area of the system, highlighted in red in Fig. 4. They explore the effects of changing the load by a constant scalar from 70% of peak in 5% increments to full peak. The software adjusts the generation with an economic dispatch solution, leading to a system marginal cost (lambda) value and a new power flow solution. In learning about economic dispatch, the students quantify and explain how the total cost, losses, and lambda have changed with the load.

For the contingency analysis portion of the lab, students run ac power flow solutions on 77 single-element outage conditions using the automatic contingency analysis software tool. In the 70% peak condition, there is one violation, and in the 100% peak condition there are two violations. Students sort the list of contingency results and report the outaged lines and the corresponding overloaded lines.

Next students are assigned to investigate both of these contingency conditions and restore the system to secure operation. They find each of the violating areas and reproduce the contingent situation. Then they observe the overload and determine what control actions can be taken to mitigate the violation. Fig. 5 shows one of these as an example, where the outaged 500-kV line, indicated with the black circle, causes the neighboring 161-kV line to overload at 105%. It turns out that in reducing the generation at one substation and increasing it at the neighbor (against the economic dispatch), this overload can be eliminated.

The connection visible here between economic dispatch and secure operation of the power system sets the stage for the security constrained optimal power flow analysis of the next lab.

C. Optimal Power Flow Lab

The eighth lab of the semester aims to familiarize students with optimal power flow (OPF), security constrained OPF (SCOPF), and locational marginal prices (LMPs) on both power systems. For the 37-bus case, the manageable size allows investigation of each individual generator to verify its profit and LMP. A few binding constraints appear as the load is increased, so that the solution moves from what is essentially an economic dispatch to a LMP-based constrained solution. Students are instructed to isolate a single generator and plot its profit as a function of its bid offer. With a low enough bid, the generator is the marginal unit and profit increases with the bid, until another generator becomes more profitable. Finding this maximum, and possibly multiple local maximums, introduces the operational decisions generator owners make when bidding into a LMP-based market.

The 2000-bus system gives the added benefit that locational marginal prices are associated with system areas and a geographic span. In this portion of the lab, the situation is that several lines are out along an east-west corridor, leading to the potential for congestion as load varies throughout a summer day. The diagram shown in Fig. 6 gives students control of the simulated load scalar for each of seven areas in the system, which are initialized to 80% of peak. The OPF solution for this case yields near-uniform LMPs, as in the 37-bus case, and again as the load changes congestion is introduced. Students investigate which areas have the most significant impact on LMPs and which combinations of load scalars are particularly troublesome. The typical results are that the prices are higher in the east since the cheaper wind generation in the west cannot be fully transmitted to the load centers.

Some conditions of load near peak lead to extremely high LMPs and even unenforceable constraints in the OPF solution. Recognizing that load shedding is a last resort, the next part of this lab assigns students the task of determining which loads, under emergency conditions, would have the most favorable effect on LMPs if shed. This data indicates the loads' appropriateness for relieving the excessive congestion.

The final step in this analysis is to run an SCOPF solution, considering 349 single element outage contingencies. This number was selected to capture the high voltage network contingencies, since including all N-1 events, as would be done in an actual analysis, would take too long for the lab period. But with these contingencies considered the results show the change in LMPs across the system due to binding security constraints.

D. Transient Stability Lab

Having small and large systems provides the opportunity to teach different aspects of power system transient stability analysis in the lab setting. This lab has two parts for each case: one in which students run planning studies and the other which simulates a real-time operations scenario.

The 37-bus case transient stability runs very fast and has a nearly-uniform frequency response due to its small size. Thus it is well suited to calculating critical clearing time. Students are assigned the task of simulating the transient stability response to a line fault and opening, adjusting the clearing time and observing the range in which the response is stable. This process is repeated for two different contingencies, and two different loading conditions. In addition, the impact of the generator inertia constant H is investigated. When H is increased, the critical clearing time is longer, since the increased inertia improves stability in the system.

These insights carry well into the analysis of the 2000-bus system, for which the transient stability simulations take longer to run and frequency varies noticeably among parts of the systems. In this lab, students investigate the frequency and voltage response of the system to a contingency corresponding to the loss of a large amount of generation. The plots in Fig. 7 show the overall behavior of the system, as the frequency drops quickly and settles below 60 Hz due to the governor droop. Students first investigate the difference between the loss of 1350 MW and 2700 MW, showing that a larger disturbance has a more severe frequency response.

The next task, illustrated by Fig. 7, is to compare two contingencies that both correspond to the loss of 2700 MW of generation. The first involves the loss of all 2700 MW at the same location on the eastern side of the case, whereas the second contingency involves the simultaneous loss of 1350 MW in that spot and another 1350 MW far to the west. While both contingencies are stable and settle to a frequency of about 59.9 Hz, the response is noticeably different. The second condition has a lower nadir frequency and shows different and more intense inter-area oscillation.

Then the transient simulation is rerun, with 2000 MW of coal generation removed from the system. This study connects the class material to a current event facing the actual ERCOT system [46]. This reduction in system inertia can be observed in the impact on frequency response, analogously to the changing of the H constant in the 37-bus case.

Finally, this lab includes a portion which involves simulated real-time operation, where transient stability simulations are run in an interactive environment and students attempt to maintain system stability throughout the scenario. In both the 37-bus case and the 2000-bus case, the scenario is that a tornado is assumed to move through the system, taking out three lines in rapid succession. These changes induce oscillations in system voltage and frequency, and cause other lines to be overloaded. If overload, under-frequency, or over-excitation violations are not fixed quickly enough, the modeled protection schemes will trip those lines or generators, exacerbating the problem. The task is to stabilize the system with minimum load shedding, and avoid a blackout, where the system has deteriorated to the point that the simulation can no longer solve.

The controls provided in these scenarios are load shedding, generator set points, and line switching. The interface diagram for the 2000-bus case is shown in Fig. 8. Line flows arrows show how power is being transferred in the system, and pie charts indicate line loading levels [44]. Black circles show lines

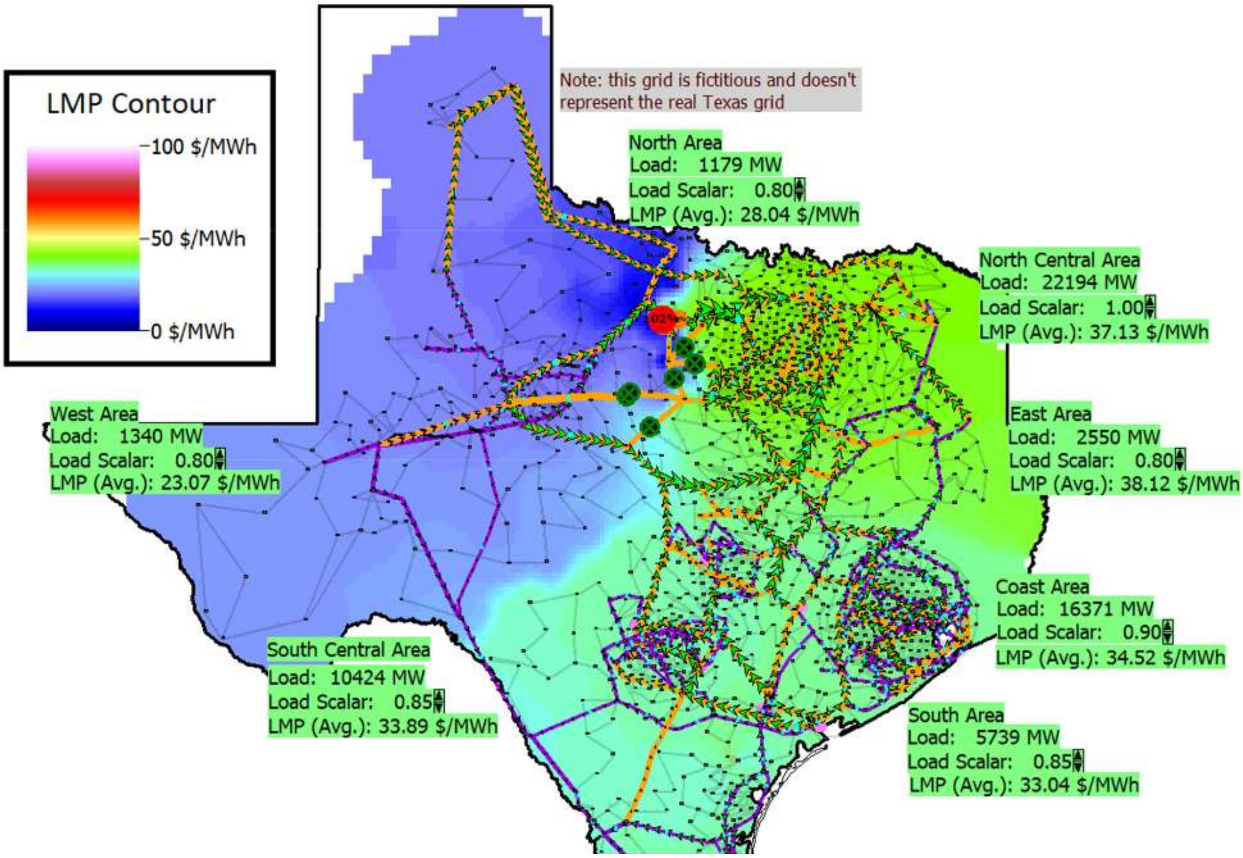

Fig. 6. Diagram display for optimal power flow lab on the fictitious synthetic 2000-bus system. Green fields provide controls for the load scalar in seven of the system areas, and report the average LMP for these areas. The background contour [45] shows that the locational marginal prices.

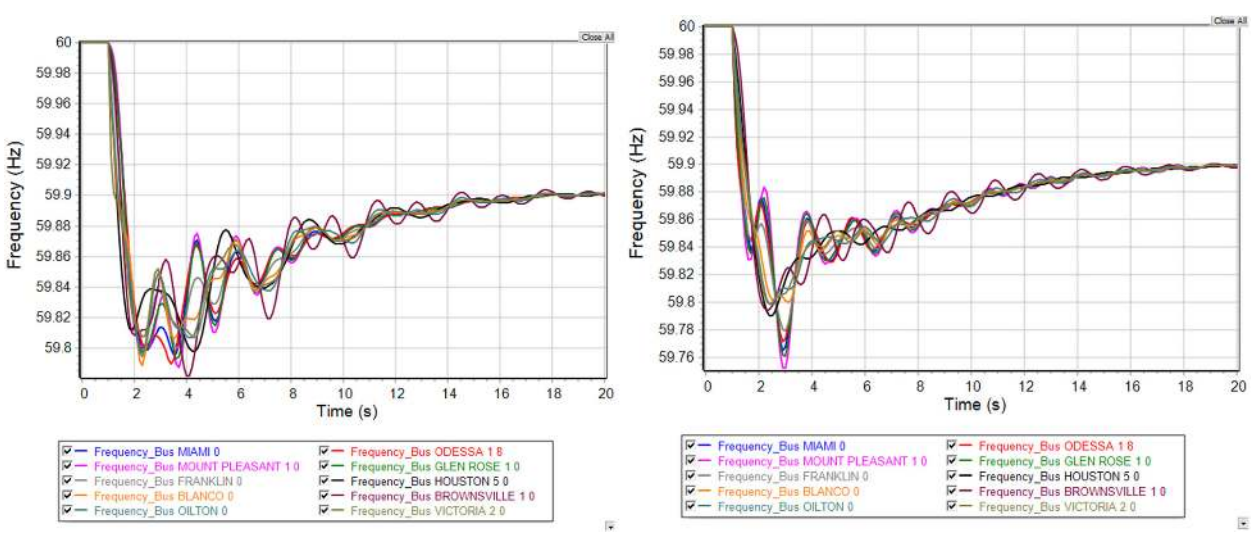

Fig. 7. Frequency response plot for transient stability simulations on the 2000-bus synthetic case. Ten selected bus frequencies are shown. The left plot is the contingency of the loss of 2700 MW of generation at the same location near eastern side of the system, and the right plot shows the loss of 2700 MW of generation, with half in the east and the other half in the far west.

which are already opened, and red circles indicate overloaded lines that will open if further intervention is not done. The background contour shows where voltage issues are occurring [45]. System frequency is indicated by a strip chart in the upper left corner. The gray boxes, mainly to the right, represent loads that can be shed, and the magenta fields correspond to controllable generators.

With a large 2000-bus case, there are many generating units and loads, so this exercise helps to develop an intuitive insight into how power is flowing across the system and what changes

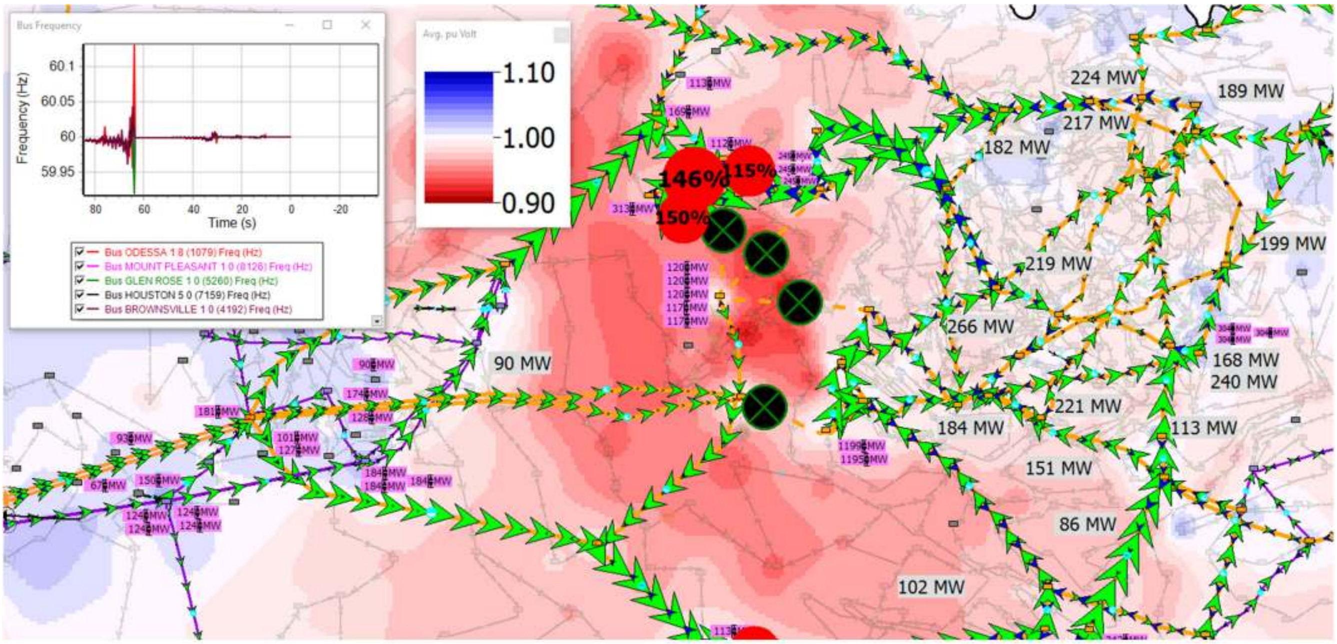

Fig. 8. Interface diagram for the dynamic simulation of the 2000-bus case, halfway through without any intervention. This is a zoomed-in view that shows four opened lines (black circles), and three severely overloaded lines (red circles). The gray boxes show loads that could be shed, and the magenta boxes show generators which can be opened or adjusted. The contour shows voltage magnitude [44]. The strip chart in the upper left plots the frequency at five buses as the simulation plays out in real time.

can be made to improve the system state. This exercise integrates what has been learned throughout the course, in power flow sensitivity, contingency analysis, and transient stability. Most students were able eventually to avoid the Fig. 8 voltage collapse by changing generation and load, albeit it took most several iterations.

V. Student Perception and Extension

The course was highly rated in student end-of-semester assessments, and students found the additional challenge and realism of large-system lab exercises to be valuable. One student commented that the lab "has allowed me to work with big systems that are similar to what industry power engineers use. The case is laid out geographically, so it is beneficial to see how an outage at a substation in one area can affect neighboring substations' reliability." Another student said the labs helped her "appreciate how complex a full-sized grid can be."

After becoming familiar with the synthetic 2000-bus system through half a semester in class, four students also used the case for a senior thesis project. The project looked at planning for the future of the synthetic Texas grid under additional load and renewable generation, and making the system more resilient to severe weather and geomagnetic disturbances. These students presented their work in a poster at the *2018 IEEE Texas Power and Energy Conference (TPEC).*

VI. Conclusion

Synthetic power grids open up opportunities in power system education by providing test cases that are realistic, large, and complex, and are publicly available for sharing. In integrating a synthetic 2000-bus test case into lab assignments, students gain insights and experience in studying and operating practical transmission systems. Exercises which involve a large synthetic case supplement a course with an extension that bridges the gap between textbook examples and actual system analysis. The instructions and cases presented here are available online [7].

Acknowledgment

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