Design Considerations for Operational Power System Simulation Scenarios

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***Abstract*—This paper describes the design of power grid operational scenarios that can enable students or professionals to experience operating the grid. The scenarios are created using complex and realistic grid systems of varying sizes, and range from normal daily operations to extreme events. They can involve one or multiple participants based on the objectives of the training exercise, complexity of the system and tasks, etc. The main objective is to use these scenarios towards effective grid operations training, and research applications. The scenarios created include, 1) a voltage control scenario to simulate normal operations, 2) a geomagnetic disturbance (GMD) simulation to experience operating a simple grid model under a GMD, and 3) a multi-user scenario to simulate normal operations while communicating with a team. The paper introduces the simulation environment used, and describes the scenario design process including the learning objective, system variation, and the user interface and controls.**

***Index Terms*—power grid simulation, operations, control, interactive, scenario design, geomagnetic disturbance**

I. Introduction

In addition to grid planning and operations, power system simulations can play an important role in formal engineering education, on-the-job training, and power system research. These simulations are well established, continuously evolving, and can impact the future of smart grid development [1]. Industry has long used operator training simulators (OTSs) and dispatcher training simulators (DTSs) to train their personnel [2]. Numerous tools exist for demonstrating the operation of the electric grid [3–9]. These simulators can emulate real-world systems and historical data can be used to design them to optimally train employees, on the system they will be operating. However, due to the sensitive nature of our power system infrastructure, students and researchers often never get the opportunity to experience one of these simulations.

Recent developments in phasor measurement unit (PMU) time-frame interactive simulation environments [9, 10], such as the Dynamic Simulator (DS), as well as the accompanying creation of large-scale, realistic synthetic grid systems [11–14] have made these simulations accessible to students and researchers alike. Given these sophisticated tools and models, the challenge becomes how to use them effectively for purposes of training and education, for a variety of audiences. Short duration, steady-state or single contingency scenarios can be a good place to start. Examples include the textbook type of exercises in [15]. These help teach concepts such as contingency and sensitivity analysis, and other basic power system principles. This paper, however, focuses on the development of longer, more complicated, real-time, interactive simulation scenarios which are meant to mimic the role an operator would play in a control center.

Scenario design has been a key part of power systems operations training, associated with DTS's [16] and OTS's [17]. A scenario can be described in simple words as "the running of an event group with a base case" [16]. In [18], the instructor is responsible for applying and changing the scenarios at certain intervals, which may include load changes, faults, change in generator voltage setpoints, etc. In [17], a heuristic method was developed to automate the creation of scenarios to match the training goals along with trainee experience, adopting methods from artificial intelligence. However, this is computationally intensive and relies on the collection of a large amount of actual, power system operational data and is more suited for industry applications, where the data is usually proprietary. This paper aims to address some of these gaps by creating these scenarios based on publicly available grid models, so that the scenarios are not proprietary or confidential. In addition, not only are all these scenarios pre-programmed but the DS simulating them runs a full transient stability simulation in real-time, as opposed to the above examples.

Longer, more "realistic" simulation scenarios could be of immense value to both students and researchers. Students can gain a feel for what it is like to operate a power system during both normal and emergency situations, in real-time. Researchers can use these simulations to evaluate the effectiveness of new visualizations, interfaces, operator tools, or training techniques. They can measure the impact of human factors on different aspects of power grid operations.

While the value of these operational scenarios is clear, the design possibilities are virtually endless. This paper describes the design of real-time, interactive, operational scenarios of realistic grid system, with three scenarios detailed. The first is a single-user voltage control simulation of a large system, with a dynamic load profile. The second is a multi-user simulation, designed to mimic a typical control room, in which users are controlling a medium sized sub-set of a larger system, also with a dynamic load profile. The final scenario is a single-user simulation of a small system during a geomagnetic disturbance event (GMD). Section II describes the development and features of all the scenarios, while Section III summarizes the paper with directions for future work.

II. Scenario Development

Developing these dynamic operational scenarios offers a unique challenge. As mentioned earlier, these scenarios are built on top of existing synthetic power system models. These underlying systems include machine models, governors, exciters, stabilizers, excitation limiters, load models, relays, etc. These models were designed to use a simulation time step in the range of a half cycle. More details about the creation and validation of these synthetic models can be found in [11–14]. Along with these snapshot base cases containing power flow and dynamic model data, time-varying characteristics were also added to them to enable time-step steady state studies such as optimal power flow (OPF) [19]. This includes hourly data for 1) load variation, 2) renewable generation variation, such as wind, and 3) outages. Such "steady-state scenarios" can be leveraged in the creation of the dynamic scenarios of paper, especially for normal operations. For more challenging conditions, events such as large faults, fast-changing load ramps, etc. can be included.

There are certain key steps involved in developing each simulation scenario, which have also been briefly discussed in [16–18]. The steps here build on those and describe specific considerations for the design of these scenarios for particular user experiences. These parameters include: duration, system size, operator roles, user interfaces/tools and operator training/objectives. In general, the scenario development consists of five design stages shown in Fig. 1. This general framework was used to design the scenarios described in this paper.

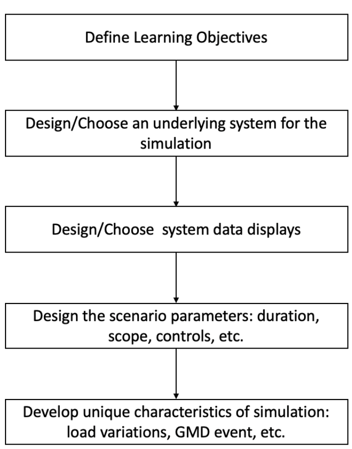


Fig. 1. Diagram Describing Simulation Development

A. Single-User Voltage Control Scenario

This scenario is designed to give users a realistic experience in operating the grid during normal, day-to-day operations as a voltage control operator. Load ramping causes changes to the voltages throughout the system over a period of time and the operator is tasked to use the reactive power devices available to them, to keep the voltages within an acceptable range.

a) Learning Objectives: From an education and research perspective, there is generally more interest in simulating contingencies or major events such as natural disasters, to study operator response. While these simulations are helpful in training students for disaster scenarios, most day-to-day operations are not so dramatic. Therefore, to allow for more realistic operational experiences, it is important to include more "mundane" scenarios for students and researchers to use for training. The voltage control scenario simulation allows the user to experience a load ramping and adapt the system in a longer term scenario. After completing this scenario the participant should have a more intuitive feel for:

- how to effectively use generators to control voltage and keep transmission lines within their limits while still serving system load
- how adjusting shunt status can affect bus voltages
- how load tap changers (LTC) use affects reactive power and voltage across the system

b) Underlying System: The 2000-bus system based geographically over the footprint of the US state of Texas, and described in [12] was created using the approach in [11]. The reactive power planning of this system was done during one of the latter stages of the synthetic grid creation process, using an algorithm [20] that places voltage control devices and solves the ac power flow. This approach combines public geographic, generator and load data with design algorithms to create a fictional version of the transmission system. The resulting grid mimics the characteristics of actual grids, allowing for more useful testing to be done without the need for confidential data. For use in a real-time dynamic study, as is the case for this operator scenario, generator models were added to the case to allow for more accurate transient stability data during operation, and the larger shunts in the base case (i.e. those above 100 Mvar) were split into smaller shunts, to give the operator more control over the reactive power at specific buses.

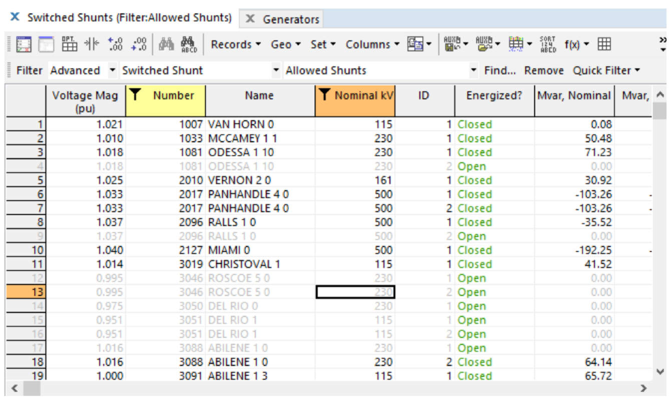
c) Applied Voltage Scenario: The scenario the operators engage with is a 30-minute long, load changing event across the entirety of the Texas 2000-bus system, in real-time. Using DS described in [9], a load variation time series is created and applied to push the bus voltages beyond their limits. The user is then tasked with keeping the voltages within, or returning them to, their limits for the duration of the simulation. The goal in this scenario is to control the bus voltages throughout the system, keeping them within a range of 0.94 - 1.1 pu, with a warning range of 0.97 - 1.07 pu [20]. This warning range is a safety buffer as the general agreed upon ranges allowable for voltages in a system are between 0.94 and 1.1 pu. The narrower range creates a more engaging scenario for the operator, as well as allowing for some bus voltages to go beyond the bounds set without endangering the system, since the goal is for the operator to treat the training as if it were on a real grid.

d) User Interface: The base DS offers tabular displays that allow the user to control elements in the system. For this simulation, the scenario was setup to allow the user access to the following controls:

- generator voltage set-point control

- generator status
- shunt status
- load tap changer (LTC) status, tap or phase value

These are the main controls used in real-world operational procedures for reactive power control across a system. In the DS, the user is able to make changes to the system using the tabular displays such as the list of switched shunts in the system shown in Fig. 2. By right clicking on one of these shunts in the window shown in Fig. 2, the user can access the shunt's control display shown in Fig. 3 and make changes. The user can also monitor the system using the load and voltage displays in Figs. 4 and 5, which were developed after user testing and feedback, described below.


Switched Shunts (Filter:Allowed Shunts) | Generators
Filter Advanced | Switched Shunt | Allowed Shunts | Find... Remove Quick Filter

	Voltage Mag (pu)	Number	Name	Nominal kV	ID	Energized?	Mvar, Nominal	Mvar,
1	1.021	1007	VAN HORN 0	115	1	Closed	0.08	
2	1.010	1033	MCCAMEY 1 1	230	1	Closed	50.48	
3	1.018	1081	ODESSA 1 10	230	1	Closed	71.23	
4	1.018	1081	ODESSA 1 10	230	2	Open	0.00	
5	1.025	2010	VERNON 2 0	161	1	Closed	30.92	
6	1.033	2017	PANHANDLE 4 0	500	1	Closed	-103.26	-
7	1.033	2017	PANHANDLE 4 0	500	2	Closed	-103.26	-
8	1.037	2096	RALLS 1 0	500	1	Closed	-35.52	
9	1.037	2096	RALLS 1 0	500	2	Open	0.00	
10	1.040	2127	MIAMI 0	500	1	Closed	-192.25	-
11	1.014	3019	CHRISTOVAL 1	115	1	Closed	41.52	
12	0.995	3046	ROSCOE 5 0	230	1	Open	0.00	
13	0.995	3046	ROSCOE 5 0	230	2	Open	0.00	
14	0.975	3050	DEL RIO 0	230	1	Open	0.00	
15	0.951	3051	DEL RIO 1	115	1	Open	0.00	
16	0.951	3051	DEL RIO 1	115	2	Open	0.00	
17	1.016	3088	ABILENE 1 0	230	1	Open	0.00	
18	1.016	3088	ABILENE 1 0	230	2	Closed	64.14	
19	1.000	3091	ABILENE 1 3	115	1	Closed	65.72	

Fig. 2. Single-user Voltage Scenario: User Control Elements

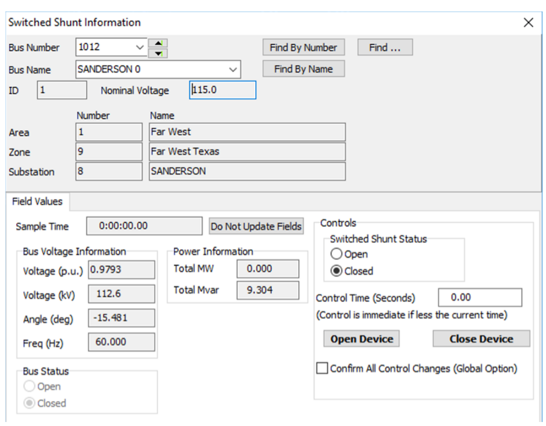


Fig. 3. Single-user Voltage Scenario: Switched Shunt Control Dialog

Considering the large scale of the system, the display scheme from Fig. 2 can be overwhelming to someone who is unfamiliar with the tabular displays, so additional displays were added to improve usability. Using feedback from repeated user testing, visual displays were designed to work in conjunction with the system voltage contour [21] and the tabular displays. The main display page used for this scenario is the voltage magnitude overview screen shown in Fig. 4, which provides users with the locations of the buses with the highest and lowest values in the system. The page also shows the user a listing of the generators and shunts closest to the unbalanced buses. This was implemented due to the large size of the system, the entire state of Texas, which made it difficult

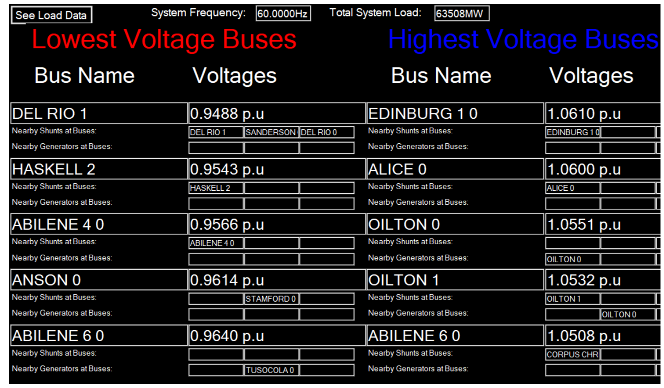
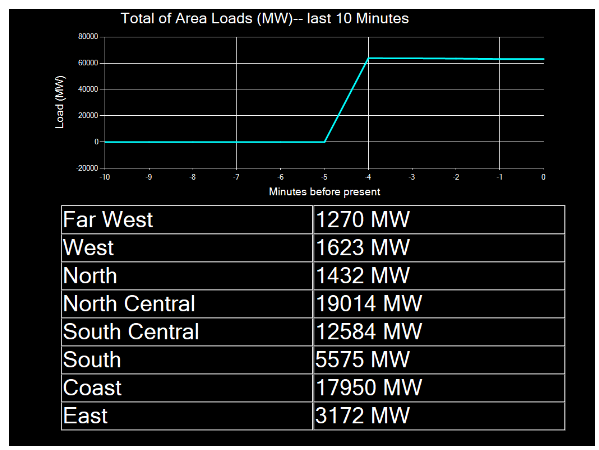


Fig. 4. Single-user Voltage Scenario: Main Display



Far West	1270 MW
West	1623 MW
North	1432 MW
North Central	19014 MW
South Central	12584 MW
South	5575 MW
Coast	17950 MW
East	3172 MW

Fig. 5. Single-user Voltage Scenario: Load Display

for an inexperienced operator to find nearby control actions to utilize in solving voltage instability using only the system oneline and tabular values.

After the preliminary testing was completed with power systems graduate students, another display, shown in Fig. 5, was added to allow operators to track the loads throughout the system to better anticipate where voltage control measures would be needed. The total loads for the eight regions of Texas are shown in a tabular display and above is a graph of the total system load shown in real-time.

B. Multi-User Operational Scenario

The second scenario is designed to give multiple users the unique experience of operating a power system during normal, day-to-day operations, as a team. In order to achieve this experience, the W4ips [14] was built, which utilizes a lightweight message broker for data transfer and an installation-free web-based user interface, and thus has the capability to have multiple users operating the power grid with the shared real-time data stream synchronously. The architecture of the system, its user interface, whose extensive dashboard is shown partly in Fig. 6, and its communication implementation are out of scope of this paper and have been explained in detail in [14]. This subsection will mainly explain the underlying power system model and the scenario, as well as the learning objectives.

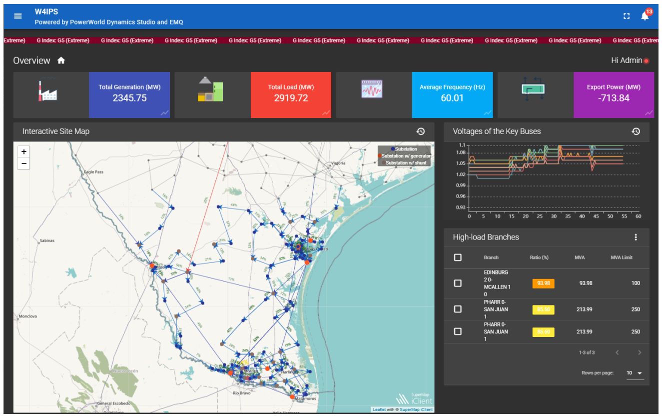


Fig. 6. Transmission operator's dashboard

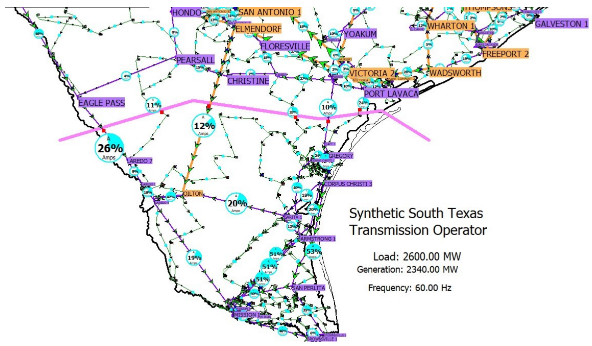


Fig. 7. The target area (i.e. Southern Texas) in the synthetic Texas grid

a) Underlying System and Scenario: In this scenario, users work in team(s) of three to control the South Texas area of the 2000-bus synthetic Texas grid, as shown in Fig. 7. The scenario runs for ten minutes at 60 times real-time, simulating peak load on a hot Texas summer day from 10 AM to 8 PM. Each user interacts with a web-based client application to control the transmission network, generation fleet, and shunt capacitor banks, respectively. Throughout the simulated day, the client reports both the cost of operation in dollars and a reliability score. The user team is required to work collaboratively to operate the target area as reliably and cost-effectively as possible. Normally the test operators are asked to switch roles for each run, and three different roles are provided in this scenario:

- Transmission operator: To prevent or mitigate transmission line overloads, as well as coordinate generator operator and reactive power operator by providing system-wise information and high-level insight.
- Generator operator: To decide which generators to have in-service and what their MW dispatch should be, to optimize the total operational cost subject to system reliability needs. The generator operator is also responsible to work with the transmission operator to better distribute the load to avoid the transmission line overloads.
- Reactive power operator: To maintain the bus voltage magnitudes inside the ideal per-unit range of 0.9 to 1.1. Normally the reactive power operator keeps the voltage stable by switching the shunt capacitors, but when need the operator is also allowed to communicate with the generator operator to have additional generator units committed for reactive power support.

Fig. 8. Control Center Laboratory at Texas A&M University

b) Learning Objectives: Users in the multi-user environment are expected to gain experience and insights on large power system operations by exploring the inter-related, major, operational tasks of transmission, generation, and voltage control. Such simulations are ideal for use in a control room type environment, such as the one shown in Fig. 8, which is actually a control center laboratory at Texas A&M University used for research and education.

C. Single-User GMD Scenario

This scenario is designed to give users the experience of operating a grid system during a GMD, which can induce quasi-dc currents, known as geomagnetically induced currents (GICs), in the grid. GICs may impact transformers by causing excessive heating, and half-cycle core saturation which can increase reactive losses and lead to voltage collapse [22, 23]. Some utilities have procedural documents describing preemptive measures to take in the event of a GMD warning but very few people have experience in operating a power system in real-time during a strong or even a moderate GMD event. This is the experience hopefully provided with this scenario, for educational, training, and research purposes.

a) Learning Objectives: Significant GMD events, while rare, are unlike anything else that a power system operator would typically experience or train for. Students and researchers learn the theory behind GMDs and their interaction with power systems, but without hands-on experience it is difficult to get an accurate perception for the operational challenges these events can incur. Specifically, GMD-induced electric fields cause GICs to flow in the transmission system through the windings of grounded transformers. Understanding how these GICs flow in the system and how to manage their effects are critical.

This scenario was designed to give users an intuitive feel for:

- the speed and dynamic nature of a GMD event

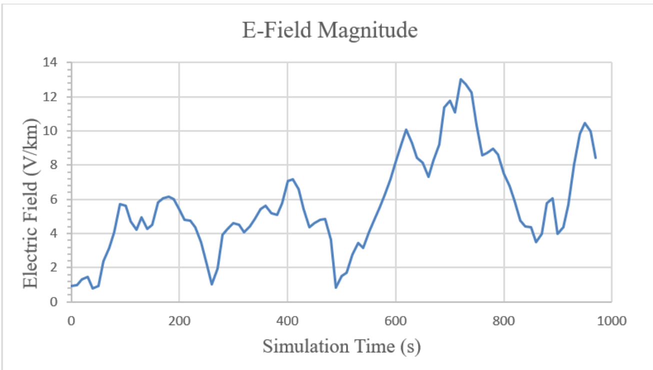


Fig. 9. GMD Electric Field Magnitude (Volts/km)

- how GICs flow through a system
- control methods to limit GICs
- GIC related Mvar losses
- the creation of additional Mvar reserves
- voltage control during a GMD event

b) Underlying System and Applied GMD Event: The underlying system used for this scenario is much smaller than the previous systems and consists of 39 buses. This allows the user to see every component in the system on a single one-line diagram, allowing them to more easily see 1) how the GMD affects the system variables, and 2) the impact of their control actions, without getting lost in the system itself.

A uniform, time-varying electric field, that is a scaled portion of the North American Electric Reliability Council (NERC) benchmark electric field waveform [24], was then applied as the input GMD event. The total simulation is approximately 16 minutes long and includes the most severe portion of the benchmark event. To create a moderately challenging scenario for an improved learning experience, the event was intensified by scaling the electric field magnitudes from the benchmark's 8 V/km peak to 13 V/km. Fig. 9 shows this magnitude profile. It is notable how quickly the magnitude changes whereas the direction of the electric field (not shown here) changes even more drastically. The speed with which these fields fluctuated came as a surprise, making a scenario like this valuable to the user experience.

c) User Interface: For this scenario, the user has full control of all of the elements in this power system, which are typically controllable in the real-world by one or more users/entities. This flexibility allows the user to learn about GMD mitigation by themselves through practice, by testing a range of actions. The control actions available to them include:

- Open/Close Transmission Lines/Transformers
- Open/Close Shunts
- Startup/Shutdown Generators
- Adjust Transformer Tap Ratios
- Adjust Generator Voltage Set-point, MW Set-point

Since the system is relatively small, all of the controls can be accessed directly from the oneline without opening any additional dialogue boxes or tables. This is especially important in this case because of the speed with which the system changes during the GMD event. Even the generator

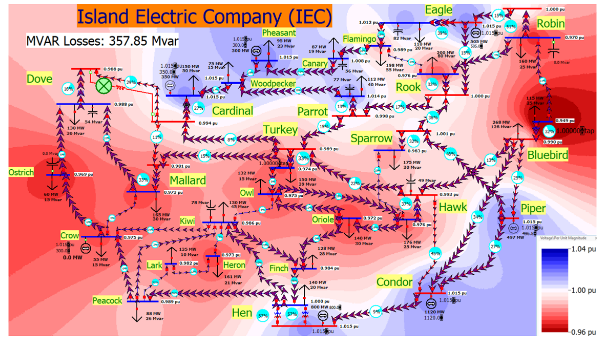


Fig. 10. Single-user GMD Scenario One-line

set-points can be adjusted directly from the one-line display. These easily accessible controls prevent visual disruptions and mitigate the effects of change blindness [25]. This make it easiest for the user to see the immediate effect of their control action and adjust their technique accordingly.

Fig. 10 shows a contour of the bus voltages for this system captured during the simulation, with a voltage key (range 0.96 - 1.04 pu) shown in the bottom right corner. As mentioned earlier such contours have been used in other scenarios, especially to visualize voltages. In addition, the display for this scenario includes fields such as "Mvar Losses" shown prominently in the upper left corner. These are only counting transformer losses due to GICs flowing through them. This value helps the user determine if a particular action helped reduce the GIC-related Mvar loading on the system. GICs flowing through the system are indicated with animated arrows, with the size proportional to the GIC magnitude. This provides the user with an overall view of the GIC flow in a system, and an understanding of the control actions, if needed, to mitigate the GICs. A final key element of this display is a strip chart of the bus voltages, where the line thickness of each bus voltage is weighted by the load at that bus. This is more critical in a GMD event, because the Mvar loading can create large voltage differentials on transformers. This weighting helps the user identity which buses are just connecting substations and which are actually serving customers that might be more adversely affected by low voltage conditions.

d) Special Training: Since GMD analysis is not a very commonly studied subject in the power systems area yet, before attempting this operational scenario, it is important to provide to the user (as needed) a background on GMD causes and effects, GIC modeling in the power flow [23], and an overview of the control actions available to them. Various entities have suggested certain preemptive measures to take in the event of a GMD warning. These act as an emergency operating procedure and could substantially improve the users performance. For instance, [26] includes the following on their list of "Operator Actions with the onset of a GMD":

- restoring out-of-service transmission lines
- reducing loading on critical system components
- reducing loading on generators operating at full load
- dispatching generation to manage system voltage, tie line loading, and distribute operating reserve
- bringing equipment capable of synchronous condenser

operation online to provide reactive power reserve

The case is initialized with some shunts and generators offline. This is intentional as they are not needed for voltage and reactive power support during normal operations. However, if the user takes action early on to bring these resources online, it can help reduce the strain on the system significantly when the storm is peaking in severity.

III. Summary and Future Work

This paper presented design considerations for real-time, dynamic, power system operation simulations. Three proposed simulation scenarios were detailed that allow users to operate realistic power systems in both normal and contingency situations. The multi-user scenario allows users to experience a more realistic control room environment where communication and coordination are critical. The time-series results and logs of these dynamics simulations can then be analyzed to provide insight into user performance. These performance characteristics can be used to evaluate new user interfaces and tools, as well as learning curves and the impact of training courses on user performance during certain off nominal scenarios. Future work will delve deeper into the analysis of human factors in such environments, along with developing more scenarios for a variety of unusual, extreme, and normal situations, with systems of varying complexity and user roles.

Acknowledgment

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References

[1] R. Podmore and M. R. Robinson, "The role of simulators for smart grid development," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 205–212, 2010.
[2] S. Gissinger, P. Chaumes, J . Antoine, A. Bihain, and M. Stubbe, "Advanced dispatcher training simulator," *IEEE Computer Applications in Power*, vol. 13, no. 2, pp. 25–30, 2000.
[3] T. J. Overbye, P. W. Sauer, C. M. Marzinzik, and G. Gross, "A user-friendly simulation program for teaching power system operations," *IEEE Transactions on Power Systems*, vol. 10, no. 4, pp. 31 725 – 1733, 1995.
[4] M. Foley, A. Bose, W. Mitchell, and A. Faustini, "An object based graphical user interface for power systems," *IEEE Transactions on Power Systems*, vol. 8, no. 1, pp. 97–104, 1993.
[5] R. Podmore, J. C. Giri, M. P. Gorenberg, J. P. Britton, and N. M. Peterson, "An advanced dispatcher training simulator," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-101, no. 1, pp. 17–25, 1982.
[6] J. E. Tate, T. J. Overbye, J. Sebestik, and G. C. Reese, "Interactive lessons for pre-university power education," *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 824–830, 2008.
[7] T. Strasser, M. Stifter, F. Andrén, and P. Palensky, "Co-simulation training platform for smart grids," *IEEE Transactions on Power Systems*, vol. 29, no. 4, pp. 1989–1997, 2014.
[8] A. Chakrabortty and A. Bose, "Smart grid simulations and their supporting implementation methods," *Proceedings of the IEEE*, vol. 105, no. 11, pp. 2220–2243, 2017.
[9] T. J. Overbye, Z. Mao, A. Birchfield, J. D. Weber, and M. Davis, "An interactive, stand-alone and multi-user power system simulator for the pmu time frame," in *2019 IEEE Texas Power and Energy Conference (TPEC)*, 2019, pp. 1–6.
[10] T. J. Overbye, Z. Mao, K. S. Shetye, and J. D. Weber, "An interactive, extensible environment for power system simulation on the pmu time frame with a cyber security application," in *2017 IEEE Texas Power and Energy Conference (TPEC)*, 2017, pp. 1–6.
[11] A. B. Birchfield, T. Xu, K. M. Gegner, K. S. Shetye, and T. J. Overbye, "Grid structural characteristics as validation criteria for synthetic networks," *IEEE Transactions on power systems*, vol. 32, no. 4, pp. 3258–3265, 2016.
[12] A. B. Birchfield, T. J. Overbye, and K. R. Davis, "Educational applications of large synthetic power grids," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 765–772, 2018.
[13] T. Xu, A. B. Birchfield, and T. J. Overbye, "Modeling, tuning, and validating system dynamics in synthetic electric grids," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6501–6509, 2018.
[14] Z. Mao, H. Huang, and K. Davis, "W4ips: A web-based interactive power system simulation environment for power system security analysis," *Proceedings of the 53rd Hawaii International Conference on System Sciences*, 2020.
[15] P. W. Sauer, M. A. Pai, and J. H. Chow, *Power system dynamics and stability: with synchrophasor measurement and Power System Toolbox*. IEEE Press, 2018.
[16] D. L. Fletcher and J. G. Coleman, "The dispatcher training simulator at peco energy company," *IEEE Transactions on Power Systems*, vol. 13, no. 3, pp. 1150–1155, 1998.
[17] G. D. Irisarri, M. Rafian, B. N. Miller, and E. J. Dobrowolski, "Heuristic scenario builder for power system operator training," *Proceedings of the IEEE*, vol. 80, no. 5, pp. 698–711, 1992.
[18] C. Y. Teo, H. B. Gooi, and T. W. Chan, "An innovative pc based simulator for power system studies," *Electric Power Systems Research*, vol. 38, no. 1, pp. 33–42, 1996.
[19] H. Li, J. H. Yeo, J. L. Wert, and T. J. Overbye, "Steady-state scenario development for synthetic transmission systems," in *2020 IEEE Texas Power and Energy Conference (TPEC)*, 2020, pp. 1–6.
[20] A. B. Birchfield, T. Xu, and T. J. Overbye, "Power flow convergence and reactive power planning in the creation of large synthetic power grids," *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 6667–6674, 2018.
[21] J. D. Weber and T. J. Overbye, "Voltage contours for power system visualization," *IEEE Transactions on Power Systems*, vol. 15, no. 1, pp. 404–409, 2000.
[22] V. D. Albertson, J. M. Thorson, R. E. Clayton, and S. C. Tripathy, "Solar-induced-currents in power systems: Cause and effects," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-92, no. 2, pp. 471–477, 1973.
[23] T. J. Overbye, T. R. Hutchins, K. Shetye, J. Weber, and S. Dahman, "Integration of geomagnetic disturbance modeling into the power flow: A methodology for large-scale system studies," in *2012 North American Power Symposium (NAPS)*, 2012, pp. 1–7.
[24] "Tpl-007-1r." [Online]. Available: https://www.nerc.com/pa/Stand/Pages/TPL0071RI.aspx
[25] D. J. Simons and D. T. Levin, "Change blindness," *Trends in Cognitive Science*, vol. 1, no. 7, pp. 261–267, 1997.
[26] "Procedures for geomagnetic disturbances which affect electric power systems," Mar 2016. [Online]. Available: https://www.npcc.org/Standards/Procedures/C-15_Procedures_for_Geomagnetic_Disturbances_Which_Affect_Electric_Power_Systems_Final_TFCO_approved_03-18-2016.pdf