Large-Scale Electric System Research Center at Texas A&M – Description & Associated Research Activites

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Abstract- **This paper discusses the Large-Scale Electric System Research Center at Texas A&M ("Center"). The Center has been configured to provide deep insights into performance of the entire electric system, from the retail customer interface to the operation of the three main interconnections in North America. The Center has three main missions – 1) support research into electric system planning, operations and performance, 2) serve as an education platform to support university courses and industry short courses, and 3) provide a comprehensive platform for the industry to perform commissioned studies and analysis. The paper describes the systems and equipment at the Center used to support on-going research. The paper also describes select recent research to better inform the reader of the Center's overall capabilities in grid modernization, grid resiliency, sustainability, GMD impacts, human factors, visualization and synthetic grids.**

Index Terms: Testbeds, Transmission, Distribution, Resiliency, Storm Hardening, Renewables, Electric Vehicles, Sustainability, Cyber Security, Coupled Infrastructure

I. INTRODUCTION

To meet the needs of the 21st century, the nation's electricity infrastructure needs to be re-imagined to satisfy the changing requirements on the electric system due to renewable resources, electrification of transportation, distributed energy resources, energy storage, enhanced control technologies enabled by deploying new sensor types, smart distribution systems, increasingly sophisticated energy markets and other similar developments. As noted in a 2016 DOE funded U.S. National Academies report titled, "Analytic Research Foundations for the Next-Generation Electric Grid" [1] the industry needs to "future-proof the grid so that regardless of how the grid evolves the United States is prepared." The electric grid is also part of a wide variety of coupled infrastructures, including natural gas, water, oil, telecommunications, transportation and emergency services. Without a reliable electric grid, many of these infrastructures would rapidly degrade, and at the same time the grid if vitally dependent upon them. Finally, there is also a growing recognition that the grid is vulnerable to what the North American Electric Reliability Council (NERC) calls high impact, low frequency (HILF) events or sometimes-black sky events. These rare, but still plausible events could result in long-term grid outages for millions. Examples include cyber and/or physical attacks, geomagnetic storms, and high-altitude electromagnetic pulses.

To address these growing challenges, several testbeds have been created in different research and academic centers. A cyber-security assessment testbed for SCADA communications is described in [2]. Reference [3] shows examples of three testbeds at different US universities and their features such as real-time hardware-in-the-loop simulation, and co-simulation in a cyber-physical security testbed. A large-scale testbed as a virtual power grid is described in [4] that has integrated tools to test control algorithms. The co-simulation of federated testbeds for high fidelity at scale is detailed in [5], with a focus on resiliency. While these testbeds have enabled great strides in research, there are still areas such as HILF events, human factors, and coupled infrastructure that need more resources.

Texas A&M University (TAMU) has developed the Large-Scale Electric System Research Center ("Center") to address this need. The vision for the Center is to provide an environment in which grid participants can experience and experiment with a host of different future electric grid scenarios. The Center provides a venue to test equipment and software in a manner that could provide convincing evidence that a design or configuration, when deployed, will perform satisfactorily under not just existing grid conditions, but also in a host of future scenarios, including black sky events, electrification of transportation, and sustainable systems of inter-dependent infrastructures.

This paper is organized as follows. Section II discusses the Center's mission and associated objectives, Section III highlights select research activities conducted at the Center, illustrating the flexibility of the Center.

II. THE CENTER'S MISSION

The Center has three main missions – 1) support research into electric system operation and performance, 2) serve as an immersive education environment to support university courses and industry short courses, and 3) provide a comprehensive platform for the electric utility industry to perform commissioned studies and analysis. For example, manufacturers could use the center to demonstrate proof-of-concept for their equipment, validate meeting performance specifications or reliability organizations could assess the implications of changes to policies impacting equipment or control methodologies (e.g., remedial action schemes). Armed with this mission, the Center has the following goals:

- Provide a detailed, realistic emulation of the full electric power system, from local distribution networks up to and

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including a full interconnection (i.e, ERCOT, the Eastern Interconnection or the Western Interconnection).

- Ensure a high level of flexibility to support a variety of configurations to investigate system performance at multiple levels and views.
- Include a realistic utility control center environment to supplement the traditional engineering/planning view of the system with an operational view to holistically study system performance.
- Support hardware-in-the-loop configurations to integrate equipment such as relays, remedial action schemes, etc. into the power system simulations.
- Collect historical data from the US electric system to provide researchers and students in real system performance. Such data is collected from the following sources installed in various locations around ERCOT and, in some cases, other portions of the US including magnetometers, Distribution Fault Anticipators (DFAs) [6] and Phasor Measurement Units.
- Provide an immersive environment to perform university and industry training, allowing for monitored interactions with power systems.

III. SUPPORTED RESEARCH

The existing and future research capabilities of the Center have been broadly classified into five major constituent areas which in turn independently integrate into a core testbed platform. Figure 1 is an overview of the environment which illustrates the constituent research branches integrated to the principal power system testbed. In the figure, elements in each circular object represent the integrative components. The arrows represent initiative supported and highlights the high-level system interaction between the testbed and research area. To illustrate the configurability, flexibility and configurability of the Center, this section describes three research leveraging the center's capabilities.

Figure 1. High-level Research Interaction

A. *Power System Testbed and Synthetic Grids*

Much of the research at the Center has been made possible due to the creation and availability of high quality, realistic, large-scale test systems known as synthetic grids [7]-[9]. By bearing resemblance to real grids, their key purpose is to test out new algorithms and enable reproducible research results since actual power grid data is considered confidential or critical energy infrastructure information (CEII). They contain data (including in-built dynamic power system component models) for a wide range of power system applications and studies, such as optimal power flow (OPF), transient stability, dynamics, geomagnetic disturbance (GMD), generation control, dispatch and economics, and more recently transmission and distribution simulations. Contrary to confidential true datasets, synthetic power systems cases (covering different geographical footprints) deployed in the Center are publicly available on [9]. They include the 200- and 500-bus systems of Illinois and South Carolina respectively, and much larger 2K-, 10K- and 70K- systems covering Texas, west and east United States. A more detailed 24K node-breaker full topology system for Texas and an 80K system synchronously combining the western and eastern United States are also available.

Most of the research at the Center leverages these large and realistic synthetic grid models which in turn offers the testbed with the unique opportunity of emulating real utility control center experience [10], [11]. This ability is hinged on two major capabilities: first, to design power system scenarios as single- or multi-user test cases and user simulations on these synthetic grids, and secondly, execute these scenarios in an interactive simulation environment. For these purposes, the Center leverages the industry-wide software tool of PowerWorld Simulator and Dynamic Studio (DS), which are respectively able to model grid system components and emulate day-to-day operating grids through the provision of interactive simulation capabilities [12] – [14]. The design of operational scenarios, such as normal daily operations, power system component outages, device malfunctions and impacts of extreme weather and non-weather related events on the power grid, provides the benefit of performing effective grid operations training, and research applications.

Figure 2 is a more detailed architecture highlighting user interaction and different components that enable the integration capabilities of the Center.

Core to these simulations is the DS which provides continuous, interactive and real-time simulation capabilities to emulate a typical operational power system. Here, scenario definitions (e.g. effects of high impact, low frequency (HILF) events such as tornado, or ground-induced currents (GICs) on the power system, cascading device trips and outages) are set in the complex and interconnected synthetic power grids. Further realism into the operating power system is performed by incorporating models of field sensor data and the effects of distribution system simulations. By performing an array of switching and control actions, users working from work-area console stations are then able to remotely manage the grid by

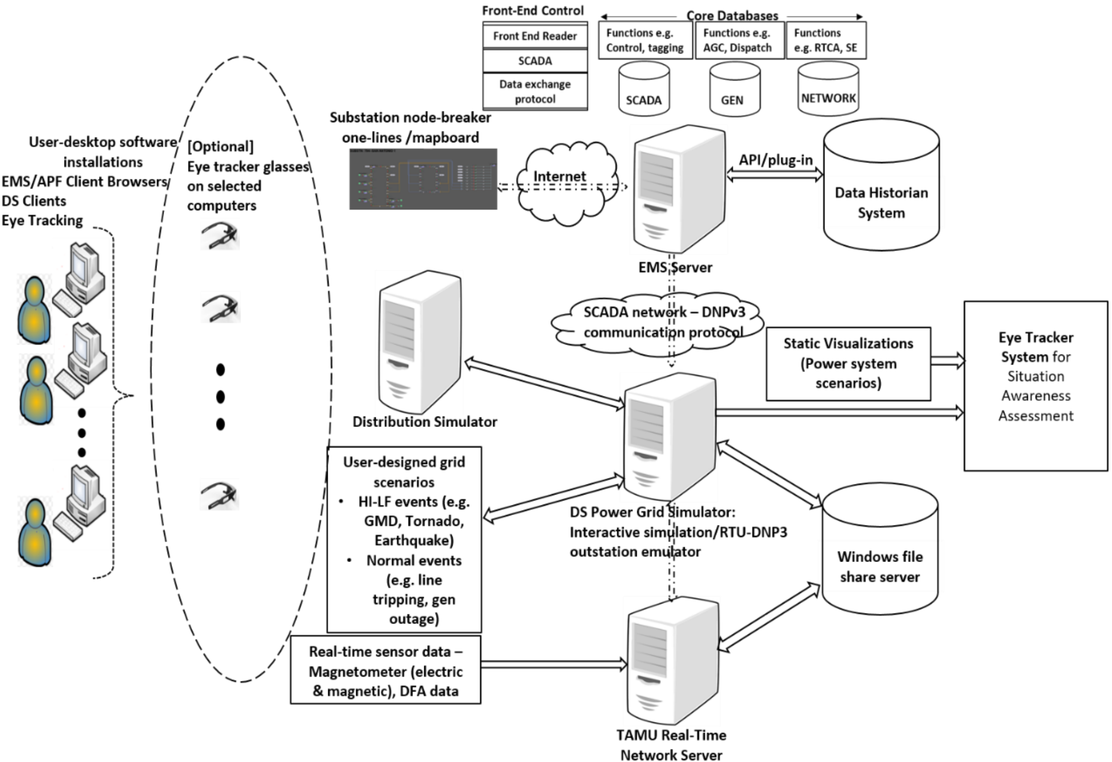

Figure 2. User Interaction and Component Integration

using an energy management system (EMS) browser or other designed client visual interfaces to optimally control different grid states, such as frequency and voltages. For the purpose of future data analysis, experimental actions and results are captured in adaptable file formats in longer-term disk storage devices. Integration of an eye tracking system shown in Figures 1 and 2 expands the capability of the Center by creating the ability to perform detailed situation awareness and human factor experimenting research on visualizations used in conveying information in complex power grids to engineers and research personnel. The system has the ability to be deployed in real-time dynamic simulations to assess user awareness, and can be easily fitted to work with any power system application being used. In another section, the use of the system in assessing static grid visualization is discussed.

The research interaction in Fig.1 and the setup in Fig. 2 summarize the interconnections among the research platforms in the Center. However, the availability and adaptability of our large, interconnected synthetic power system power cases have also afforded more opportunities for joint research with other departments, such as water resources and transportation networks [15],[16].

B. Remote Grid Management and Control (Integrative Component: Energy Management System)

A critical task of utility control centers is to ensure the optimal operation and control of the power system with the aid of remote grid management, monitoring and control [17]. As shown in Fig. 2, the Center currently provides an environment for performing research activities on an electric power system energy management platform (EMP) for the purpose of remote grid management. It incorporates several power system applications, such as state estimation, automatic generation control (AGC) and real time contingency analysis to carry out research activities in optimal grid management. It leverages the DS to serve as a power system data source by performing real-time, interactive, dynamic simulation of a specified scenario of a synthetic grid. Here, it utilizes the integration of supervisory control and data acquisition (SCADA) infrastructure telemetry over a distributed network protocol version 3 (DNP3) communication protocol with an EMS [18], [19].

Figure 3 shows the EMS-SCADA communication architecture in the research-based energy management platform currently being developed in the Center's testbed. The simulator is used to configure a test synthetic system on which transient stability is performed on the interactive DS. The DS serves as a tool to emulate the operation of multiple remote terminal units (RTUs) or outstations in DNP3 terminology. SCADA-type measurements reported by DS in the form of analog or binary data are transmitted as DNP3 input points to the front-end processing (FEP) interface in the platform. A set of core programs in the FEP serve as the SCADA server application from which telemetry commands are issued to and from outstations in the test system. A data

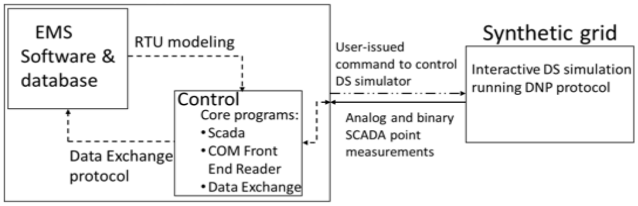

Figure 3. EMS-SCADA Communication Architecture in the Energy Management Platform

exchange protocol performs an intra-control center communication by replicating data from the FEP to the EMS sub blocks.

Application - Remote Device Switching

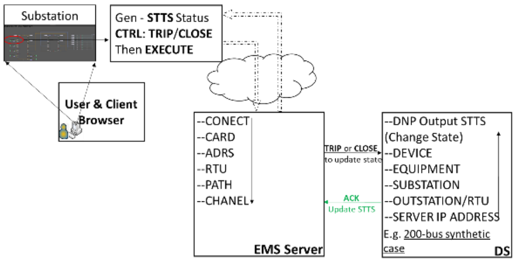

Figure 4. Remote Switching in the Energy Management Platform

Figure 4 demonstrates a generator action that is performed on the DS emulating an operational 200-bus synthetic power grid when remote switching commands are sent from an EMS location. With the aid of EMS visual boards and an operator console, the user is able to monitor, and furthermore, change the state of a substation generator. A TRIP/CLOSE control command issued from the device control interface is transmitted to the server end through a hierarchical data structure that identifies the target equipment. In DNP3 format, the command is then transmitted through SCADA telemetry as a binary output point to the DS. Here, a receiving DNP3 binary output point configured on the target generator alters the operational mode of the device once the destination RTU and substation are established. Depending on a configured time interval, an acknowledgement (ACK) signal is communicated back to the generator display on the EMS to update the status (STTS) field. In addition to switching of generators, switching of other devices such as capacitor shunts, lines and loads have also been established on the testbed. These activities were successfully tested on an industry-wide 60-bus case and different synthetic power cases being used in the Center, including a much more complex and detailed Texas full topology 24K node-breaker model.

C. *Human Factors Experimenting and Visualization*

Given emerging techniques used to relay power system information, it is becoming imperative to assess these methods for their effectiveness in conveying information that adequately captures the state of the power grid. The creation of a true mental abstraction of the status of the grid will in turn enable engineers in their bid to adequately plan and control the power system. Human factors research being carried out in the Center aims to assess situational awareness among users (known as respondents) by utilizing eye-tracking biosensors and stimuli to monitor and record user actions during power system simulations [20], [21]. An outcome of this research is to provide metrics for scoring how well displays convey information, display improvements as well as other aspects associated with the operational tasks such as instructions and environment. Eye tracking hardware and software have been setup in the Control Room to create an integrated analysis platform, to get a finer understanding of user comprehension and develop insights to enhance situational awareness and improve decision-making. Figures 5 and 6 show the architecture of the platform and its usage to quantify the user's awareness while operating a simulated power grid.

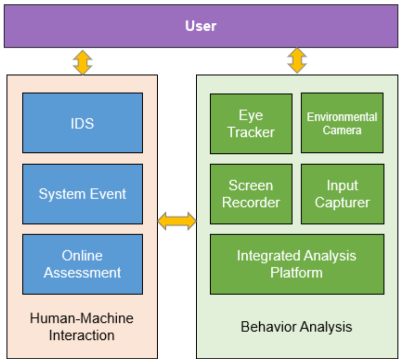

Figure 5. Architecture for the behavior analysis platform designed on top of an interactive power system dynamic simulation environment [13]. System events, measurements and online assessment metrics are transmitted to the integrated analysis platform, where they are merged with physiological data from biosensors (gaze movement, mouse movement, keyboard events, etc.)

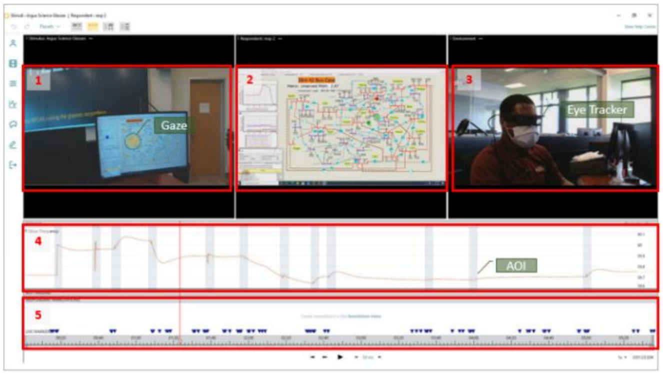

Figure 6. The interface for the integrated analysis platform demonstrates the usage of multiple biosensors and data sources. By incorporating eye tracker (1), environment camera (3), grid measurements (4) and user events (5), area of interest (AOI) can be quickly identified and metrics indicating awareness level can be calculated during the operation of a power system (2).

A required step is to create interactive simulation scenarios [10], including use of representative static or dynamic displays and visualizations that show the user a changing electric system state. Furthermore, the integration of bio sensing eye tracking systems and multiple data sources enables the Center to investigate the use of physiological data to quantify the effectiveness of these visualization and analysis techniques on power system situational awareness.

Application - Uncovering Error in a Power Transfer Distribution Factor (PTDF) Visualization

A human factors experiment that was performed aimed at assessing the awareness of a respondent when a static visualization, containing a design error, was presented. The image showed power flow distribution across major transmission lines in an 80K-bus synthetic network when a power transaction was executed between a bus location in Maine (northeast, US) and Washington (northwest, US). Here, a pre-requisite knowledge of the concept of PTDF [22] by the respondent was assumed so that one could assess the effectiveness of the image in conveying wide-area PTDF information across the grid, eye gaze patterns and, hopefully, if the respondent located the design error. Figure *7* shows the setup used for the experiment.

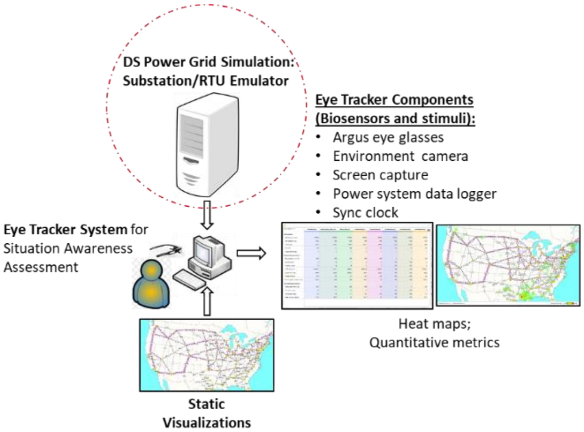

Figure 7. Architecture for Tracking PTDF Design Error in Visualization

The dotted region has been included to show the capability of using the eye tracking system to assess users in real-time, dynamic simulation. A pair of Argus-type eyeglasses (fitted with infra-red sensors) [23] provided recorded eye tracking data obtained during the experiment to a data analysis software. In turn, this tool performed data integration with information from the computer screen and a stimulus synchronous clock that were also simultaneously recorded during the experiment. Preliminary results on the right side of Figure 7 is a static heat map showing the gaze concentration of the respondent during the entire simulation. The red gradient in east Texas is the point of maximum gaze where the respondent identified the substation with non-zero PTDF balance indicating an incomplete nodal flow distribution, hence the site of the design error. Dynamic heat maps, showing sequence of respondent eye gaze and quantitative metrics (such as the time duration in observing different AOIs or time taken to first investigate an AOI), were other results that elicited useful questions and insights into how well the visualization conveyed wide-area PTDF to the respondent.

D. GMD and Magnetometer Network

The TAMU research team has been at the forefront of research in modeling GMDs in the power grid. This has led to several developments in GMD simulations in large-scale power systems. GMDs arise from solar storms, disrupt the earth's magnetic field which induces an electric field at the surface and drive GICs in the power grid. These GICs have the potential to disrupt grid operations and even cause long-lasting blackouts. To mitigate this, it is important to understand and model all the parts of this complex, multi-stage process properly in grid simulations. To this end, the Center recently deployed a network of six magnetometers around the state of Texas to measure the ground magnetic field [24]. The TAMU Magnetometer Network (TAMUMUN) is being used for research in model validation of GMD events, GIC estimation [25],[26], and in setting up a real-time GMD monitoring and control framework for the grid [27].

Figure 8 shows the overall architecture of the network, combined with the analysis and visualization applications at the Center testbed. The network consists of six ground magnetometers measuring the local earth magnetic field, around the state of Texas. At each site of the TAMUMN is a

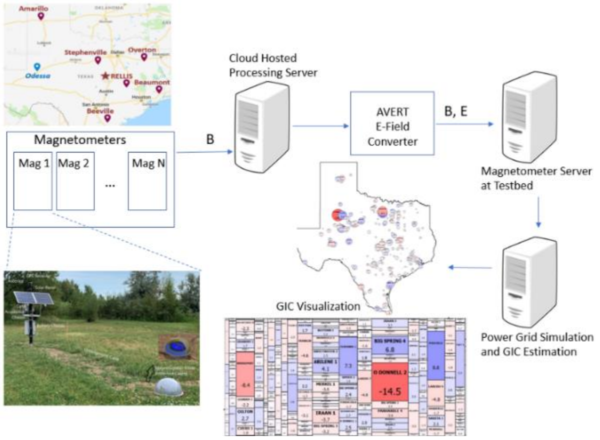

Figure 8. TAMU Magnetometer Network Architecture and Applications

(Space Hazard Monitor) SHM™ real-time magnetometer system, which runs autonomously with hardware and software system monitoring to support continuous data transmission. The station is solar powered and operates without human interaction except for routine service or repair. Each station consists of two major parts - the sensor, and a data acquisition unit (DAQ). The magnetic field sensor is a Bartington Mag-13 triaxial fluxgate magnetometer [29], which is a low-noise sensor that produces a set of voltages proportional to the observed magnetic field strength. The DAQ produces a 1-Hz 3-component vector sample of the geomagnetic field (B_x, B_y, and B_z), time stamped with the UTC second, which is transmitted in real-time (< 1 second latency) to a database archive hosted on a cloud-based virtual machine. The x, y, and z axes orthogonal components represent field directions with positive values for geographic northward, eastward, and vertical into the earth, respectively, and negative values for their opposite directions.

At the cloud-hosted processing server, the data is cleaned, corrected for temperature, and processed through computations to yield derivative quantities such as electric fields (E), useful for calculating GICs. A virtual machine instance set up at the Center consists of data acquisition modules through a time series database, and receives data from the cloud-based server. The data is converted to JSON format prior to being fed to the database. The database is setup to save the real-time data stream efficiently, also providing a RESTful API for queries.

From here, both the magnetic and electric field data can be used for a number of applications. One of them is real-time GIC monitoring and visualization wherein the electric field data is fed into a synthetic grid model of Texas to calculate GICs throughout the system. Since transformer GICs are of most concern in the system, we can visualize these on the display wall board using techniques such as geographic data views (GDVs). The goal of this is to provide real-time situational awareness on GICs to operators and engineers on a relatively infrequent and hence not well-experienced phenomenon of GMDs. Another application and area of research is GIC estimation, wherein different types of measurements such as magnetic fields, and transformer neutral

GICs (which are forthcoming) are used to estimate GIC related states such as electric fields and GICs in the rest of the system.

IV. CONCLUDING REMARKS

This paper describes the Large-Scale Electric System Research Center at Texas A&M (“Center”) which supports critical research into electric system operation and performance, serves as an education platform to support university courses and industry short courses, and provides a comprehensive platform for the industry to perform commissioned studies and analysis. As discussed within, the Center has the necessary software, systems and equipment to support critical research necessary to “future-proof” the electric system however it evolves, including the ability to address known issues such as DER penetration, electrification of transportation, energy storage, resiliency, cyber-security, expanding energy markets and other similar issues.

V. ACKNOWLEDGMENT

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