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State-of-the-art of data collection, analytics, and future needs of transmission utilities worldwide to account for the continuous growth of sensing data

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ABSTRACT

Nowadays, transmission system operators require higher degree of observability in real-time to gain situational awareness and improve the decision-making process to guarantee a safe and reliable operation. Digitalization of energy systems allows utilities to monitor the system dynamic performance in real-time at fast time scales. The use of such technologies has unlocked new opportunities to introduce new data driven algorithms for improving the stability assessment and control of the system. Motivated by these challenges, a group of experts have worked together to highlight and establish a baseline set of these common concerns, which can be used as motivation to propose innovative analytics and data-driven solutions. In this document, the results of a survey on 10 transmission system operators around the world are presented and it aims to understand the current practices of the participating companies, in terms of data acquisition, handling, storage, modelling and analytics. The overall objective of this document is to capture the actual needs from the interviewed utilities, thereby laying the groundwork for setting valid assumptions for the development of advanced algorithms in this field.

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Nomenclature

AGC	Automatic Generation Control
BESS	Battery Energy Storage System
CE	Continental Europe
CIP	Critical Infrastructure Protection
COMTRADE	Common format for Transient Data Exchange for power systems
CVT	Capacitor Voltage Transformer
DFR	Digital Fault Recorder
DME	Disturbance Monitoring Equipment
DSO	Distribution System Operator
e-DNA	Data processing server
ENTSO-E	European Network of Transmission System Operators for Electricity
EMS	Energy Management System
FACTS	Flexible AC Transmission Systems
FFR	Fast Frequency Reserve
GPA	Grid Protection Alliance
HVDC	High-Voltage Direct Current
IED	Intelligent Electronic Devices
ISO	Independent System Operator
NERC	North American Electric Reliability Corporation
PDC	Phasor Data Concentrator
PMU	Phasor Measurement System
PPA	Power Purchase Agreement
PQ	Power Quality
ROCOF	Rate of Change of Frequency
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator
WAMS	Wide-Area Monitoring System

1. Introduction

Power system operators worldwide are looking to integrate increasing levels of variable renewable energy resources to meet their economic, clean energy, and resilience goals. In doing so, utilities and grid operators are facing significant challenges in their grid operation and management due to the inherent variability, uncertainty, and the lack of inherent inertia against abrupt changes or electrical transients to enhance stability during disturbances. Consequently, system operators require higher degree of observability in real-time to gain situational awareness and improve the decision-making process to guarantee safe and reliable operations. The proliferation of advanced sensing infrastructures, such as phasor measurement units (PMUs) and faster communications media allows system operators to monitor the system dynamic performance over a wide area of a system at faster time scales from remote locations [1]. At the same time, the integration of such units has unlocked new opportunities to introduce advance analytics algorithms for improving the stability assessment and control of the system. However, significant challenges are arising because of the growing amount of data and the need to store and use the data in real-time for operations, modelling and planning. These demanding tasks have inspired a group of researchers across the world to create the IEEE task force "Application of Big Data Analytic on Transmission Systems for Dynamic Security Assessment" to joint know-how and work together to highlight the existing data challenges in the operation and control of the extra high voltage networks and to lay the foundations for common concerns within the power system community, which will be used as motivations to propose innovative analytics and data-driven solutions in future efforts.

In this document, we present the results of a survey on 10 different transmission system operators around the world to understand the current practices in terms of data acquisition, handling, storage, modelling and analytics. As result, we have jointly created an official report, which describes the ongoing activities by different utilities and what their future needs are for control room integration. In this brief, the synthetized version of the report is presented, where the most relevant points of the full report are expressed.

In contrast to existing works in the literature [2,3], where extensive reviews of methodologies for a particular direction such as dynamic security assessment have been proposed, the originality of this document is capturing tangible details explained directly from the participating companies. Moreover, this survey highlights the geographical locations and individual characteristics of the different power systems surveyed, emphasizing the level of development and maturity of the available sensing and analytics technology.

Key aspects highlighted in the document comprise the current data infrastructure, processing and storing of their data and the applications available today for offline and online operation. Moreover, the participating utilities describe in detail where they stand with regards to artificial intelligence and machine learning applications and how advanced are their data analytic solutions. The companies describe the type of current approaches they use to perform data analytics, which span from commercial cloud base to in-house developed software platforms. The amount and type of metering infrastructure available to acquire data is explicitly described, which differs among utilities according to their geographical, political, and economic situation. In most cases, it is stressed the role of the personal training, know-how and skills to move forward in the transition to a more digital power system and to assess the dynamic security of the system in real-time. In addition, the current needs in control rooms, in terms of lack of solutions that transmission system operators (TSOs) would like to have in operation, are described.

The document is organized as follows, the results of the interviewed electric companies are arranged by geographical locations. First, four utilities from North America namely Tennessee Valley Authority (TVA), Dominion Energy and Southern Company Services in the USA and the Mexican Interconnected System, are introduced. Then, two electrical companies in South America such as XM Colombia and The National Electric Coordinator (CEN) in Chile are presented. Finally, four transmission operators in Europe namely Swissgrid from Switzerland, TenneT from Netherlands, Svenska kraftnät from Sweden and National Grid from Britain are also documented. Each operator has three subsections, in the first subsection a description of the transmission system is provided where the topology and its main features are highlighted. In the following subsection, the participating utilities describe the current practices and situation with regards to how the high-resolution sensing data is handled in their respective country. In the last subsection, challenges, needs and future directions identified by the system operators, are described. Finally, a conclusion summarizing the document is provided.

2. North American power systems

2.1. Tennessee Valley Authority-USA

Established in 1933, the Tennessee Valley Authority (TVA) is the nation's largest public power provider and a corporation of the U.S. government. TVA's power service territory includes most of Tennessee and parts of Alabama, Georgia, Kentucky, Mississippi, North Carolina and Virginia, covering 80,000 square miles and serving more than 10 million people (Fig. 1). TVA sells electricity to 153 local distribution power companies, 56 directly served industries and federal facilities. TVA owns and operates more than 16,200 miles of transmission lines and 500 substations. TVA's generation portfolio is 39% nuclear, 19% coal, 26% natural gas, 11% hydro, 3% solar + wind (1215 MW contracted wind) and 1% energy efficiency programs with a total capacity of 33,727 MW. TVA recently announced plans to install a 40MWh Battery Energy Storage System (BESS) project. Under Power Purchase Agreement (PPA) arrangements, 50 MW/200MWh of storage will be installed with a solar plant in Mississippi.

The main characteristics of the power transmission system, including approximate number of assets are 103,798 transmission structures, 513 power stations and switchyards, 482 power transformers, 2923 power circuit breakers, 15,263 instrument transformers, 2165 revenue meters, 18,013 transmission relays, 625 power quality monitors, 232 digital fault recorders, 3400 miles of high-density optical fiber.

The transmission voltage levels are: 115 kV, 161 kV (most prevalent), 230 kV (Northern Georgia), 345 kV (a few inter-ties in Kentucky), 500 kV (most prevalent). Distribution and sub transmission voltage levels are: 13, 26, 46, and 69 kV, respectively. In terms of generation, there are three nuclear sites, 17 natural gas and/or oil-fired sites, five coal-fired sites, 29 conventional hydroelectric sites, one pumped-storage hydroelectric site, one diesel generator site, and 14 solar energy sites. Currently, synchronous generation is predominant, but there is an increasing number of utility scale solar PV plants, with ~1200 MW on contract (PPA) and expected to come online in 2021–2023, with 484 MW announced in 2020. TVA operates 14 solar energy sites, with a total net summer capability of approximately 1 MW. Inside the Tennessee Valley, the combined participation for all renewable solutions is 490 MW of installed operating capacity through both TVA-owned sites (1 MW) and PPAs. Outside the Tennessee Valley, TVA contracts for approximately 1215 MW of operating wind capacity through PPAs. Storage: Raccoon Mountain Pumped-Storage Plant [4], a hydroelectric facility with four generating units (500 MW of capacity per unit) with a summer net dependable capacity of 1616 MW. This is the only existing storage facility in TVA.

2.1.1. *TVA data infrastructure*

The measurement devices providing synchrophasor data for monitoring, operation, control, and protection of TVA's territory was evolving as explained next. The first generation of installed PMUs were standalone units near protection delays because TVA engineers believed that protective relays should be exclusively dedicated to protection functions. As the PMU technology matured, TVA stated to enable the PMU functionality in the protective relays, mostly in transmission line protective relays. PMUs are currently part of TVA's digital fault recorder (DFR) standard, following NERC standard PRC-002-2 — Disturbance Monitoring and Reporting Requirements. TVA is considering the possibility of installing merging units in the future to guard against the risks from human and natural electromagnetic pulse sources. The challenge, however, lies in teaching/training the workforce. PMU functionality can be turned on in any transmission line protective relay all the way down to the 69 kV voltage level on in an as needed basis. DFRs with PMU functionality is a requirement for any new substation and any major upgrade. All substations of 161 kV and above in TVA's system have DFRs. The number of measurement channels in each device will depend on the location where the device is installed.

All the measurement devices are connected to ethernet switches, which are linked to a wide-area communications network infrastructure owned by TVA, called PowerWAN. Data is transmitted all the way back to the control centre. TVA engineers process part of the data using software made available by grid protection alliance [5]. There is an in-house developed, data processing server called e-DNA that is located at the control centre. This server is intended to centralize all condition monitoring at TVA's system. TVA is investing to bring local indications to e-DNA. By local indications, it is meant the monitoring information that is only available at the substation level.

There is a big effort to install appropriate communications links to bring all this monitoring information to the control centre. Moreover, it is current standard in TVA to have all newly installed circuit breakers, transformers, substation battery banks, and capacitor banks monitoring systems sending information to e-DNA. Basically, the information acquired from these devices' monitoring systems is collected by an ethernet switch, connected to PowerWAN. The e-DNA server then collects and stores the information from PowerWAN. Asset/equipment condition monitoring has been the primary use of real-time analytics. The granular data available in e-DNA enables near real-time situational awareness of equipment in substations. The analytics of equipment data has allowed TVA to perform predictive maintenance, instead of preventive maintenance, and hence to eliminate timed routines on equipment. Although not yet a proven technology (according to TVA's experience), preventive equipment maintenance based on data analytics is promising and might lead to maintenance cost savings and provides improved situational awareness.

2.1.2. *TVA data challenges*

Equipment condition monitoring based on data analytics is an ongoing experiment in TVA and its engineers are dedicating a lot of effort on this and expect to have a better understanding of what this technology can do in a couple of years from now. Substations battery bank is a primary example of equipment that requires periodic condition monitoring, including periodic inspections of the float voltage of each cell and the bank float voltage. Some of the activities for substation battery bank condition monitoring require visual inspections as per NERC regulations. These activities require maintenance crews to go onsite, but the installation of cameras is being considered by TVA technical leadership. The full inspection of a battery bank might take a full day and requires the presence of two technicians.

Conversely, a remote inspection aided by data analytics is expected

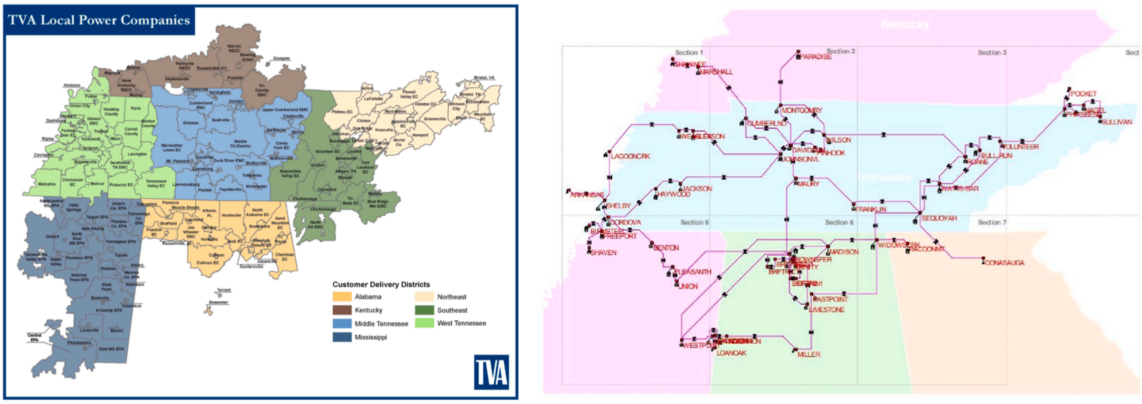

Fig. 1. TVA service territory and its 500 kV system.

to take no more than a couple of minutes. Circuit breakers' performance/health monitoring is another application example. In breakers of recent technology, it is possible to monitor: the wear of the insulation nozzle inside the switching chamber of the circuit breaker, the velocity of the circuit breaker in switching on/off the circuit, trip coil current, number of circuit breaker operations. Circuit breakers' manufacturers and grid solutions companies provide solutions for a detailed monitoring of circuit breakers [6–9]. Detailed data of circuit breakers can be used to determine, for example, if the circuit breaker is slowing down and the trip coil is going bad. Another application example is the health monitoring of capacitor voltage transformers (CVT). Some data acquired from the CVTs, e.g., voltage magnitudes, are already available from the SCADA system and it is imported into e-DNA. The goal is to predict failures by performing image processing, for example. TVA has developed visualization tools, most of which are available at the GPA [5] dashboard. According to TVA engineers, the development of data analytics applications is at its infancy in the company. Data analytics tools have been geared toward addressing localized problems at the substation/equipment level. These tools/applications are mostly used on a planning mode, i.e., they are executed offline. Also, PMU data has been used to identify undesirable dynamics/issues with generation equipment.

TVA is planning to build a so-called asset performance control centre, where operators and engineers will be responsible for monitoring all equipment in the network in real-time. This control centre is going to be fully dedicated to equipment monitoring and separate from the existing control centre, which performs real-time monitoring and operation of system. While the current focus is on addressing localized problems using PMU data for situational awareness at the substation/equipment level, future early-stage R&D will focus on the impact these local problems might cause elsewhere. TVA engineers are interested in trends using PMU data, wide area monitoring and related applications.

2.2. Dominion Energy-USA

Dominion Energy supplies electricity in parts of Virginia, North Carolina, and South Carolina and supplies natural gas to parts of Utah, West Virginia, Ohio, Pennsylvania, North Carolina, South Carolina, and Georgia (Fig. 2). The company also has generation facilities in Indiana, Illinois, Connecticut, and Rhode Island, offering clean, safe, reliable, and affordable energy to more than 7.5 million customers. The company's asset portfolio includes 31,000 MW of power generation, 10,200 miles of electric transmission lines, and 84,800 electric distribution lines.

2.2.1. Dominion energy data infrastructure

In Dominion Energy's system, the synchrophasor data come primarily from DFRs, which are used as PMU devices. Another significant portion comes from intelligent electronic devices (IEDs) or protection relays. Some additional data come from PMUs. Note that all generation substations are covered with DFRs, but these devices provide sampled values (also called "point-on-wave") and synchrophasors at a rate of 4800 Hz. This data set is currently available from the substation local storage only. The DFR uses an embedded low pass filter to down sample the original data. Synchrophasors are estimated from the sampled values and streamed to the data cloud, which can be accessed remotely. The reporting rate is configurable as either 60 or 30 Hz. The data analytics team uses 30 Hz resolution more often.

Although the DFRs devices have the capability to transmit sampled values, there are two key limiting factors: i) the communication network is not ready to transmit data at the kilohertz rate and ii) data storage is expensive. PMUs have on average 26 channels, while DFRs have on average of 85 channels. In Dominion Energy, there is an established practice to select the number of measurement channels for newly installed devices. The most popular PMUs and DFRs vendors are: Standalone PMU (SEL-487E) and dual-use PMU (SEL-421, and SEL-487E), EMAX and USI DFRs. At the transmission control enclosure locations, a single PDC on the communications panel is installed connected to the substation SCADA and control (aka critical) network. Where available, the distribution and generation systems are connected to the same PDC for streaming data.

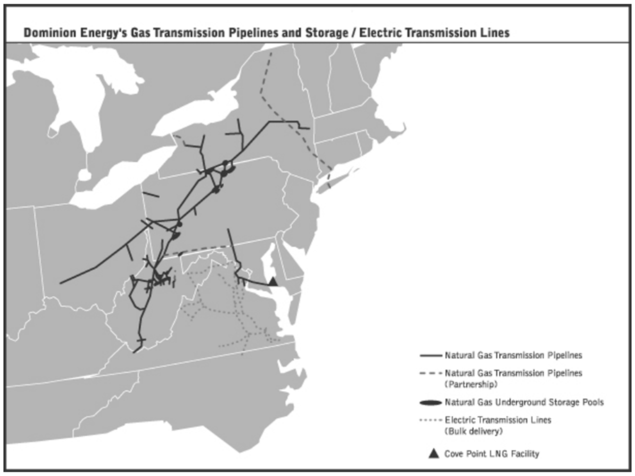

Fig. 2. Dominion Gas and electric transmission Lines.

This network, called the Substation Automation Network, is separated from the enterprise network and is only accessible through the Centralized Services portals and the same security that is used in the traditional SCADA and alarming data is followed by the PDCs. Cybersecurity is an important factor to consider during the design and planning of the infrastructure that requires network communications. Generated sampled data is stored on a rolling 14-day basis in local storage in the substations, while synchrophasor data is cloud stored using Amazon Web Services (AWS). This choice was motivated by the fact that moving data is time-consuming and, thus, expensive.

The information is accessible to engineers and data analytics developers with clearance to data stored locally in substations upon request and synchrophasors data are readily available from the PingThings PredictiveGrid platform via the user interface and also used for data analytics [10]. Engineers and data analytics developers with clearance simply access the data platform using a personal login. The data size varies with respect to triggering levels for various conditions. For example, many devices ramp up the sampling rates when conditions are detected such as high harmonics, or an electrical short circuit occurs.

The database with the existing system is approximately of 172.8 TB/day flowing to the historian. However, is not clear if these data are or not compressed and to what extent. The PredictiveGrid platform makes things easier as all the data is stored in the cloud and is readily accessible via a python terminal (Jupyter notebook). It cuts down the development time for data analytics. The length of the communication network latency varies according to the platform and applications. Each site with a different communication medium and different network speed and traffic queueing has a different response which can vary throughout the day. Dominion uses speeds from 207 ms to 315 ms.

2.2.2. Dominion energy data challenges

The data analytics group at Dominion Energy was created to use "data to drive planning decisions." They are completely independent of the control room and operate more like in a "planning mode". The group was created around 2019 and since then, the focus has been on offline data analytics. To connect other software such as MATLAB/Simulink or PSS/E to this platform is possible, for more analysis and research, although the data analytics team currently does not see a need to do it. Since the main focus of the data analytics team from the very beginning has been offline studies, at the moment no means of visualization tools such as graphs or nomograms have been developed.

Consequently, there is no data analytics continuously running and the typical procedure is to offline look for interesting dynamics that deserve further investigation. Several issues using the current data analytics practices have been detected, one example is the identification of electromechanical oscillations in a nuclear and combined cycle power plants. In terms of identification of dynamic phenomena, the data analytic group has focused on spectral analysis of ambient data, which falls into the small-signal analysis domain. Other dynamic phenomena such as frequency or resonance stability have not yet been investigated. Due to the relatively new developing of this group, analysis of collected data is at its early stage. Some work has been done on voltage stability, particularly focused on estimating the Q-V Jacobian matrix directly from the data.

Some of the techniques currently in use or intended to be used for dynamic security assessment include: classification-based methods (fuzzy logic, decision trees), trajectory-based methods (trajectory sensitivities), machine learning-based methods (neural networks), spectral analysis (data-driven) small-signal stability analysis, (data-driven) modal analysis. In the future, Dominon Energy has the intention to include the following data in the PredictiveAnalytics platform on an as-needed basis: SCADA/EMS data that is currently available at the control center, weather sensing data, shaft speed of synchronous generators, state of charge of energy storage systems, any other sort of time series data that might give support to future developments.

Additionally, there is a plan to develop an observer for synchronous generation plants, which could be classified as a dynamic state estimation problem. Currently, there are no immediate plans to incorporate developed analytic tools in the control center and the main reason is that these tools would require a well-established plan that would require training operators for adopting these technologies.

2.3. Southern Company Services-USA

Headquartered in Atlanta, GA, Southern Company (NYSE: SO) is a leading energy company serving 9 million customers through its subsidiaries. Southern Company provides clean, safe, reliable, and affordable energy through electric operating companies in three states, natural gas distribution companies in four states, a competitive generation company serving wholesale customers across America, a leading distributed energy infrastructure company, a fiber-optic network, and telecommunications services. Southern Company Generation is a business unit of Southern Company that manages the operation of 77 fossil and hydro plants for Southern Company's more than 4.68 million retail customers in a territory spanning most of Alabama and Georgia, and southeastern Mississippi (Fig. 3).

Southern Company Operations has responsibility for more than 27,000 miles of transmission lines, 3700 substations and 300,000 acres of right of way. The generation company manages production, fleet operations, planning, engineering and fuel procurement for Southern Company's coal, oil, gas and hydro generating units at 103 power plants.

2.3.1. Southern company services data infrastructure

Southern Company's Transmission PMU fleet is currently comprised of 135 PMU devices. These include stand-alone PMU devices as well as DFRs with PMU functionality, with 30 Hz as the standard reporting rate for all units. The number of measurement channels varies with the different PMU monitoring devices. Though configurable, in general, DFRs tend to have more measurement channels available. Also, large substations with more transmission lines typically have more measurements than smaller substations with fewer connected lines.

The practice is to incorporate as many measurements as are available and can be accommodated at a given site. On average, about 45 unique phasor measurements are taken at each substation. The PMUs stream data to centralized PDCs. The data is stored in centralized historians fed from the PDCs that are hosted on the company's servers. Synchrophasor data is not used by Southern Company's control centers for real-time decision-making so the data is considered out of scope for the NERC CIP standards.

The company generates approximately 0.14 TB of synchrophasors per day. The data is made available to internal personnel via a web portal connected to the data historian. Southern Company synchrophasor communication network has an average latency of 72 ms. The R&D organization manages the Schatz Grid Visualization and Analytics

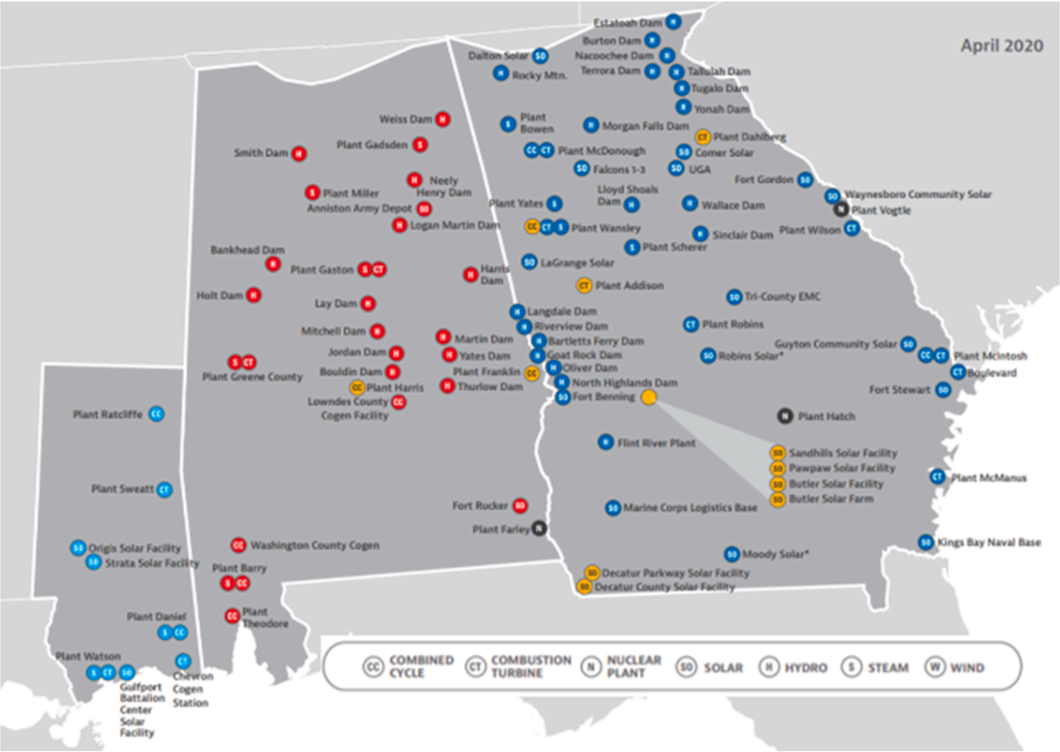

Fig. 3. Southern Company Generation.

Center (SGVAC). The SGVAC is an innovation center that facilitates the research, pre-operational development and assessment and demonstration of situational awareness technologies for Transmission and Distribution.

Both simulated and real grid data feeds are leveraged in a secure environment for analysis and testing. One of the areas of focus is synchrophasor technology. In-house and commercially developed software platforms are used for data analytics and visualization. This includes some real-time analytics that run 24/7 and have detected grid events such as oscillations in the past. Some of these tools can be connected to external software platforms such as MATLAB/Simulink and PSS/E for further analysis.

2.3.2. *Southern company services data challenges*

Southern Company is currently evaluating advanced applications based on artificial intelligence for the detection and prediction of grid events as well as to detect insipient equipment failure. There is also interest in leveraging similar algorithms for dynamic security assessment. While synchrophasor data is routinely used in planning for model validation and other offline studies, the performance of the various operations-centric tools continues to be evaluated to ensure that the results are consistently credible and well understood. This will allow operations personnel to assess their value proposition and appropriateness for use. When such a determination is made, the necessary steps for integration will be taken.

2.4. *Mexican Interconnected System-Mexico*

The Mexican Electric Power System (MEPS) comprises nine control areas (Central, Eastern, Western, Northwestern, Northern, Northeastern, Peninsular, Baja California, and Baja California Sur areas), plus an additional subsystem (Mulege) as depicted on Fig. 4. Among these nine areas, the first seven listed are interconnected and form the Mexican Interconnected System (MIS). They share resources and reserves because of the diversity of demands and operational situations. The Baja California system operates interconnected to the US Western Electricity Coordinating Council, while the Baja California Sur and Mulege systems are electrically isolated from the MIS. Mexico is connected to neighboring countries through 13 cross-border lines (11 lines to USA, including 2 emergency links and 1 generation central located in USA interconnected to MIS; 1 line to Guatemala; and 1 line to Belize). This network comprises more than 108,000 km of transmission lines from 69 kV and up to 400 kV), connecting 3359 substations.

The operation of the MIS is under the responsibility of 9 regional control centers, one national control center (CENACE) and one national backup center (CENALTE) [11]. The CENACE, in Mexico City, coordinates the wholesale electricity market and the reliable operation of the MIS and in the case of an extraordinary event, the role of the CENALTE is to take over in real-time the functions of the CENACE. Some of the main characteristics of the MIS are its operation from a single company named Federal Electricity Commission (CFE), the National Transmission Grid (NTG) with voltages >69 kV, the General Distribution Networks (GDN) with voltages < 35 kV, and private-owned networks. It has + 940 generation centrals, + 52,900 km of transmission lines at 161 kV, 230 kV and 400 kV, respectively and the effective installed generation capacity >70,000 MW [12].

Its integrated peak demand is 47,903 MWh/h and the generation mix at the begin of 2019 was composed of combined cycle turbines (36.5%), conventional thermal (17%), hydropower (18%), wind power (6.8%), turbogas (4.6%), coal (7.7%), and other alternative sources (9.4%) such as PV, biogas, geothermic power, nuclear energy, cogeneration and internal combustion [11]. In order to secure reliable measurements for the participants of the wholesale electricity market, the MIS requires to measure the energy balance in the exchange points of the so-called load zones, as well as the energy exchange between zones (69 exchange points). Because of this, the development plan for the MIS lists as a

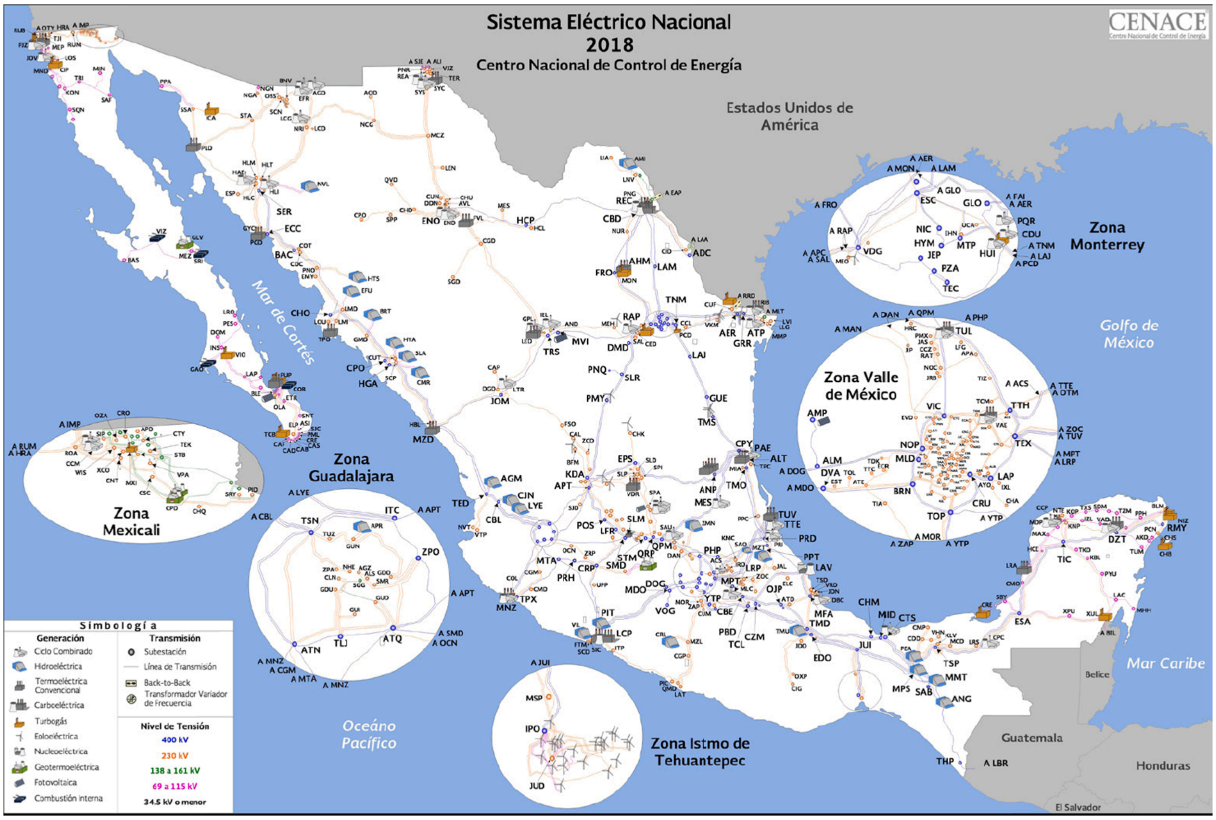

Fig. 4. The Mexican Interconnected System.

necessity to develop both infrastructure and software to perform such measurements [12]. This plan includes the following actions: 1) conditioning 1207 measurement points in distribution circuits and 2) conditioning 14,153 measuring points inside power substations.

The MIS Smart Grid Initiative (SGI) seeks to improve the efficiency, reliability, quality, and safety of the MIS GDN, ensuring open access to the grid through the use of advanced measurement, monitoring communications and operation technologies. The initiative also comprises the evaluation of the advanced distribution management system, performing field surveys of geospatial data and develops applications to streamline operational decision making and installation of 121 advance metering infrastructure devices. The development of the infrastructure required to exploit the functionalities of these systems is also part of the initiative.

2.4.1. *MIS data infrastructure*

The MIS is equipped with approximately 300 PMU devices, different levels of reservoirs in the hydroelectric plants, weather information (ambient temperature) and meteorological data (irradiance and wind speed) from photovoltaic and wind farms, respectively, state of the protections (activation of schemes or certain protection systems), SCADA system data, such as voltage, active and reactive power, frequency, position of switches and blades (open, closed), and temperature in transformer windings and in some thermal power plants. The sampling rate differs from 100 ms up to minutes depending on the monitoring system. For instance, the SCADA system collects information at a sampling rate of 3 s, PMUs at sampling rates of 30 Hz, and diverse sensors for weather and meteorological every 15 min. All these interconnections are managed using pre-established communication protocols. Note that the MIS at Western and Northeaster collect information to assess system with different granularity.

To process and analyse these data, the control room collects these multivariate data (time series, images, audio recordings), using the PMUs and SCADA systems at the substations (topology data, protection device output/alarms and fault recordings). Telecommunication links supported on optical fibre are used for the communication. To optimize the storage of these files, the missing samples of data are first replaced by interpolated data (clean the time series) and finally the files are compressed. The historical data is stored from two to up to five years using commercial hard discs drives. Special attention is given to data collected from 400 kV network by SCADA system, dynamic events identified by PMU and fault recorded events. Some current applications include state estimation, automatic generation control (AGC), dispatch load flow (DLF) and voltage stability assessment (VSA).

2.4.2. *MIS data challenges*

One of the main challenges for handling data in most of the different areas comprising the MIS, is the limited federal budget to upgrade and expand the currently available infrastructure. A particular example is the limited amount of historical data available from the SCADA system, which has been operating for over 23 years now. Furthermore, challenges related to data handling include the modernization of the SCADA system itself, the need of specialized training of staff, the development of know-how on data analytics to perform more advanced analysis to the PMU data and the enhancement of the professional software used for power system's simulations. Moreover, administrative constraints such as lack or limited data exchange among departments are also important challenges that need to be addressed. Up to now, the real-time monitoring system does only steady state applications and there are no plans, in the near future, for introducing operations such as applications related to distance protection relays. The Northeaster area with 30 PMUs installed is the only exception, where wide-area applications based on PMU measurements are in the development stage with the aim to be use for real-time monitoring and visualization.

Thanks to the use of PMU devices, access to high precision data from different geographical areas of the transmission system has evidenced the lack and need of new and more applications in the regional control centres. Some examples of missing applications include voltage and frequency restoration, monitoring of power system oscillations, monitoring of the electricity market and identification of important parameters of the frequency response.

3. South American power systems

3.1. *XM Colombia*

XM is the transmission system operator in Colombia and is in charge of operating the Colombian National Interconnected System (STN) through the National Dispatch Center (CND) and its energy market. XM manages the international energy transactions with Ecuador and coordinates the interconnection with the Venezuelan electricity system. XM commands the planning, coordination, supervision and control of the generation and transmission resources of the National Interconnected System, complying with the operating regulations (Fig. 5).

The system is composed by approximated 1400 buses, 364 synchronous generators of different technology (mostly hydraulic) and capacity, 900 transmission lines and has a maximum generation capacity of 17.6 GW and a maximum power demand of 10.6 GW. The generation mix corresponds to 68% of hydro power plants, 31% of coal and gas power plants and the remaining 1% is a mixture of wind and solar generation. The main challenges that the Colombian system is facing, are related to the high probability of experiencing climate change exacerbating natural hazards such as El Niño phenomenon and its relation to the high generation capacity of the country. In addition, in relation to reliability and security associated to the massive integration of power electronic interface technologies at transmission, and distribution levels, new operational and planning challenges are expected.

3.1.1. *XM data infrastructure*

In the XM Colombian system, there are approximately 100 PMUs

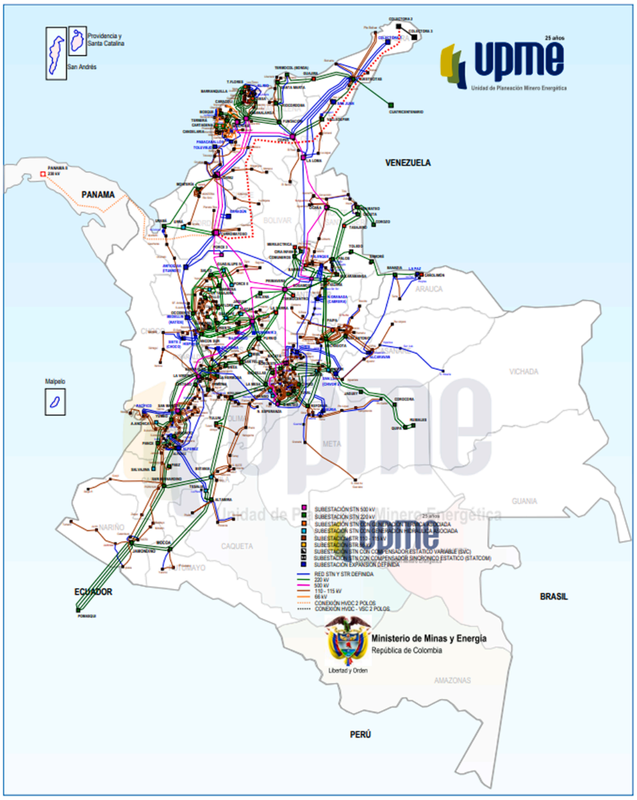

Fig. 5. XM electrical grid from 66 kV to 500 kV.

installed in the transmission system, and there is no Advanced Metering Infrastructure (AMI) for distribution level. However, in November 2020 the regulator entity in Colombia published the first regulation about it, for which, an important growth of such infrastructures is expected. Also, the PMUs are expected to grow with the upcoming generation projects. In the control room the PMU measurements are displayed via a videowall with graphs and indicators of the measured data.

There are two videowalls, one with the remote terminal units (RTUs) information and one with the PMUs. The benefits are that these PMUs represent another source of data to the operators with more advanced metering and indications, such as information about oscillations. The drawbacks are that the optimal way to incorporate this data in real-time operation is still missing. Currently, in XM the following data is collected for use of the system operator: analog signals such as voltages, currents, active and reactive power, flags of status such as switches and protection statuses. The data is collected mainly using RTUs, which are available at each substation in the Colombian system. Additionally, there are also several PMUs installed, from which only 100 are currently in operation. The RTUs with IEC-101 and/or IEC 60870-6/TASE.2 protocol are still the main source of measured data.

The data is first transmitted from the substations to the regional transmission organizations (RTOs) control centers via IEC-101 protocol, and from there it is transmitted to the National Dispatch Center via IEC 60870-6/TASE.2 protocol. The data finally reaches XM SCADA servers where it is organized and displayed to operators in one-line diagrams. Current applications of collected data include state estimation, network analysis tools such as short circuit calculation, post-operative internal applications and planning tools.

Operators use these data online and the planning and the post-operative analysis are done in offline analysis. The collected data is stored using OSIsoft PI servers [13], which is a real-time data storage, normalization, analytics, and notification engine that is maintained by the team in charge of the SCADA system and is updated automatically by the RTUs or PMUs. Current data challenges include missing standards or guides for big data and/or AI based applications. Today, the use of data for real-time monitoring is fully functional with the RTU data. However, changes are expected to come and, also, the need for upgrading the real-time monitoring system.

3.1.2. XM data challenges

In terms of future predictions, trust and accuracy are the main concern in XM and is working on solving this constraint. In particular, lack of personal know-how and training to handle the databases are also a current challenge. Additionally, data related foreseen issues include the utilization of data in the analysis when the dispatch changes 5 min ahead. This distinctive problem will require advanced training and development to suddenly change the dispatch and keep the security and reliability of the system. At XM there is a team dedicated to developing data analytic solutions.

Also, the company is providing courses about AI techniques to employees so all these challenges can be addressed properly. For XM as the Colombian system operator the top priority is the reliability. The society has come to expect, and require, uninterrupted power. These expectations do not change even as the grid transitions to high variable renewable energy. With increased variability and uncertainty, adequacy analysis is the only way to guarantee that the electricity customers always have the power they need.

A form of grid planning that allows grid operators to have the resources available to balance supply and demand, taking into account uncertainties like unexpected generator outages, fluctuating load, and changes in the weather, is needed. The statistical evaluation of all these uncertainties could allow grid planners to reach an acceptable low level of risk of capacity shortages.

3.2. The National Electric Coordinator-Chile

The Chilean power system is of particularly interest, as its renewable penetration is increasing rapidly, reaching 20% by 2020. Its islanding natural condition makes it complex to operate (Fig. 6). Therefore, observability of the system to improve operability is fundamental. The National Electric Coordinator (CEN), as a public, autonomous organization must ensure a safe and economical operation of the set of electrical system facilities that operate interconnected, allowing the country and its inhabitants to be supplied with electric energy.

Since 2016, the coordinator has functions associated with research, development and innovation, within the scope of his responsibilities for coordinating and improving the performance of the electrical system, in an environment of rapid technological changes from the point of view of production and energy transport. Currently, the coordinator has created a specific function on its energy management system (EMS) modelling and applications department in order to conduct descriptive, diagnostic, predictive and prescriptive analysis from using the data produced by the multiple monitoring and information systems available.

The system counts 638 generating units, 1068 substations (96 GVA in total) and 939 power lines. In terms of reactive compensation, there are 571 condensed bank reactive compensators, 30 capacitor series compensators, 2 synchronous condenser and 21 FACTS. The generation fleet is composed by 6′765 MW of Hydro power, 13′514 MW of thermal power, 2′530 MW of wind power, 3′266 MW of solar power and 45 MW of geothermal power, accounting for 26′151 MW of generation. The highest voltage level is 500 kV, with 35′919 km of power lines.

The maximum demand of the system is 10′900 MW, with a total annual energy production of 70′828 GWh/year. The renewable energy production is 15′322 GWh/year, accounting for a penetration level of 21% [14]. The Chilean power system delivers power to the 98,5% of Chile population, covering 3′100 km of the 4′200 km of Chile. The south of the country is powered by small to micro grids of diverse nature.

3.2.1. CEN data infrastructure

At the moment there are 57 PMU units from the company ELPROS along the power system and 64 are expected to deploy in 2022. Alternatively, there is a remote protection reading system from SIEMENS that captures common format for transient data exchange (COMTRADE) from 10 MVA and above substations, operative since 2016. Currently, available data for system operator use is collected through SCADA system are voltages, active and reactive powers, at a sampling rate of 4 sec with 1100 measuring points. Three-phase voltages, currents, frequency and ROCOF, at a sampling rate of 50 times per second from PMUs.

Disturbance records from COMTRADE files, at least 800 Hz, pre and post failure data and additionally, data from demand, solar and wind forecast are also collected. In order to unify the availability of data, the software PI OSIsoft has been implemented recently. For data analytics, the software Qlik Sence is used along with Python. The SCADA data is used by the control room operators to make real time decisions (online) by running a dynamic simulation tool that gives fast assessments of the dynamic response of the system to diverse real time operative actions (short circuits, generator contingencies, etc). This operation depends on the state estimator results, performed by the SCADA software.

Similarly, real time data is used for load following. The control room operator then dispatches units assisted by an economic dispatch simulation to make a choice of the least cost units to operate with. Also, real time data is used to estimate primary frequency control needs. Other online applications are angular difference monitoring, low frequency oscillation detection, islanding detection, voltage stability margin violations, dynamic line rating. There is also a real time, 1-minute latency data need for the wind forecast provider (AWS True Power).

The main offline applications are related with oscillation origin assessments, and fault origin by COMTRADE data and Siemens application (SIMEAS SAFIR). To store data, provide maintenance and perform updates, there are three data servers for the SCADA system. 2-second

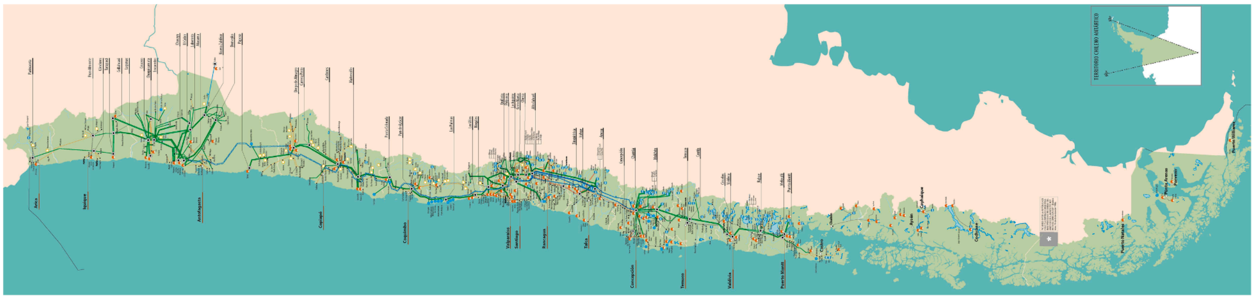

Fig. 6. The Chilean transmission system.

sampled data has a 40-day moving storage window. 1-hour data has a window of 1 year. A historical server maintains 2-s data since 2015. PMU data has 30-day storage.

3.2.2. CEN data challenges

In general, the existence of large volumes of data has arisen various concerns within CEN. An initial concern is the existence of professional capabilities of current engineers in charge of the real time operation in the context of data analytics. CEN has initiated a process to include the Big Data paradigm to its entire organization.

The main foreseen challenges are to align data and analytical processes with the business strategy and organizational vision in order to meet the following targets: 1) centralize data, have affordable repositories, and reduce silos of dispersed data, 2) enhance the organization's ability to analyze and respond to facts, trends or predictions in a timely manner, 3) identify and relate business initiatives to Big Data and analytics needs, prioritizing data needs to outline an implementation roadmap, 4) implement a couple of high-value, high-impact Big Data and analytics use cases that deliver rapid business results for its implementation, under the concept of Pilots, 5) implement the necessary technological components to enable the infrastructure and software that support the initiatives in a progressive and evolutionary way, 6) have quality and standardized data to identify the necessary resources to carry out the defined plan (strategy, people, processes, technologies), 7) have an organizational structure and roles necessary to support the roadmap outlined, be this in the form internal and/or external and 8) initiate a process within the organization to enhance and promote data management supporting a process of change management and communication plan.

Cyber security is one topic considered as priority and challenging. In October 2020, CEN adopted the recommendations from NERC and its Critical Infrastructure Standards (CIP). Through this cooperation, it is sought that the standard to be implemented is convergent with the other standards and processes of the different sectors of the country, in order to have a common language that allows a coordinated response to be given to the different threats and computer incidents. As a result of this joint work, it has been defined the adoption of an internationally recognized standard whose strategic objective is to protect the critical infrastructure of the national electricity system, against threats and cyber attacks, guaranteeing a reliable and safe operation of its facilities. Currently, data-driven models are in process of research. A real time simulation laboratory in the CEN is exploring this trend and it is expected to provide some insights of this new type of model.

Dynamic security assessments are mostly those performed in the SCADA software. There is no particular assessment on what other features may be of interests so far in this sense. An additional challenge related to data handling in CEN is the standardization of data availability by creating a data lake. Similarly, the penetration of renewables is increasing in the system. Significant dynamic parameter predictions, such as inertia, nadir and ROCOF, will be also needed. There is an ongoing initiative at the highest organizational level on assessing the usefulness and the development areas associated with the large volumes of data that are currently not used.

There are also initiatives with universities on how to predict fault causes only with COMTRADE data as input, machine learning to improve simulation representativeness among others. The main need is to increase the situational awareness in control room to make real time decisions. Current SCADA tools are being of great help, and future more comprehensive PMU-based information is expected to improve the real time desertion-making process. Other needs are to improve the interoperability of the PI software with the SCADA and PMU platforms and improve the accuracy of demand and generation forecast to better deploy short-term flexibility in real time situations. An inertia forecasting system would be a very valuable element in the control room to assess primary frequency control needs. Although there are some commercial applications, a lack in knowledge of the professional staff is the challenge; some of the more related engineers are improving their understanding of data analytics to better interpret and operate these applications.

4. European power systems

4.1. Swissgrid-Switzerland

The Swiss electrical system is part of the Central European (CE) electric grid. It involves more than 30 countries and around 530 million customers. As a member of the European Network of Transmission System Operators for Electricity (ENTSO-E) [15], Switzerland is connected to neighboring countries through 41 cross-border lines and plays a crucial role in the international electricity trading (Fig. 7).

The Swiss transmission grid comprises more than 6′700 km of transmission lines with rated voltage levels of 380 kV and 220 kV, and 141 substations. Furthermore, around 40′000 metering points (recording and processing measured values within seconds) are used to map the grid. The Swiss transmission power system is operated and owned by Swissgrid [16], it has + 650 synchronous generators installed [24], + 6700 km of transmission lines at 220 kV and 380 kV, the peak generation capacity >20 GW and peak power demand of approximately 8 GW. The generation mix by 2020 is composed of hydropower (59.9%), nuclear energy (33.5%), conventional thermal power (2.3%) and alternative sources (4.3%) such as solar power, waste incineration, biogas and wind power.

The grid of Switzerland is facing several challenges due to the transformation of the entire electricity economy. In this regard, although the development of the transmission grid has significantly slowed down in the last 40 years, new energy sources and power plants have been connected to the grid and the electricity consumption has increased [17]. Furthermore, the geographical location of Switzerland within Europe and its vast natural water resources make it to represent an important electricity hub for the region and play a key role in supporting the grid performance and dynamics of neighboring countries [18].

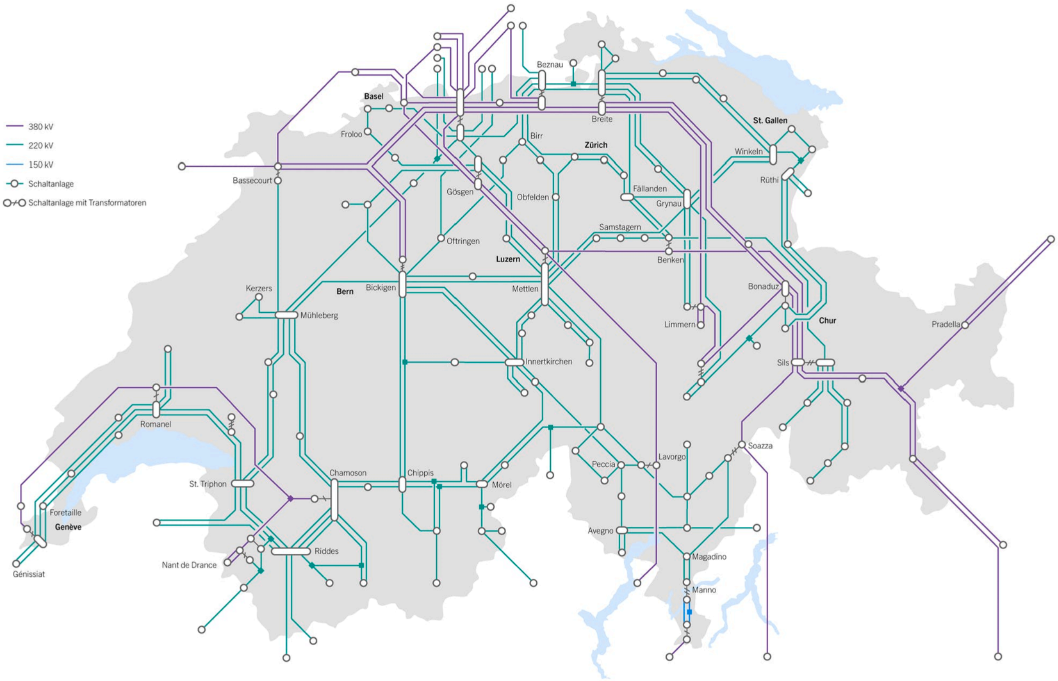

Fig. 7. Overview of the Swissgrid extra-high-voltage grid.

4.1.1. *Swissgrid data infrastructure*

In Swissgrid, the data is recorded or collected though process dependent RTUs, PMUs and meteorological data. As the Swiss power system is embedded in the middle of the CE power system and Swissgrid also fulfills the role of coordination center south (half of CE power system), there are several thousands of data points collected via an extremely complex telecommunication system. The sampling rate varies from 100 ms up to minutes depending on the application.

Several massive databases are permanently filled and stored with decreasing granularity over decades. The interconnection is managed using standardized procedures for online data acquisition, forecast data sharing and calculation results transparent exchange ahead and in real-time are implemented. The type of collected data includes: 1) Topology data such as system element/parameter data (forecast) at least in 1-hour granularity for 24 h ahead. 2) Online measurements of parameters such as frequencies, power flows, voltages, circuit breaker status and tap changer position. 3) Calculated values such as area control error (ACE). 4) Protection device output/alarms and 5) local SCADA output/alarms.

For measuring and communication, standard protocols such as ICCP/TASE.2, TCP-IP, fiber optic located in the transmission line ground wire, dedicated telecommunication links, emergency communication over back-up channels up to satellite communication channels are used. The collected data is processed and collected using large number of proprietary and standard databases and IT-solutions from different vendors tailored for special needs. Current applications include state estimation, load flow calculation, short circuit calculation, wide area monitoring and processing tools, optimal power flow for calculation of voltage setpoints for the day ahead, tools for supporting redispatch activities and tools for supporting the operation of complex ancillary service deployment.

4.1.2. *Swissgrid data chellenges*

The aforementioned applications use a mix of online and offline calculations. However, the day ahead activities and efforts are growing in importance same as tools for intra-day decision support. The collection and storage of the collected data in Swissgrid is crucial as there is always a kind of transient within the data structure itself based on planned outages, new links, and high interdependency with other shareholder such as distribution system operators, generating companies and neighboring transmission operators.

At the same time, availability and reliability of the data are a prerequisite for a stable and sustainable system operation and therefore the whole security of supply. Last but not least, the information needs to be functional in a high secure environment composed by hundreds of interacting servers. Current data-handling challenges in Swissgrid are to restrict the number of invalid or corrupted data to an absolute minimum level to overcome the challenge in being interconnected and secure at the same time. An automatic plausibility check to always rely on would be needed as the amount of data is increasing, the resources for skilled experts are restricted and only short intervention time is available.

Other challenges include synchronized updating of several parameters over different applications, which use same or almost the same data, e.g. dynamic line rating, handling of weather dependent limits in several tools over a certain forecast time horizon. Additionally, it is always hard to distinguish between data failure, tools failure or faults into the data handling process.

Finally, intelligent synchronization of data over company borders fulfilling all required confidentiality requests is a foreseen challenge in Swissgrid. Ongoing activities in Swissgrid to address the aforementioned challenges include projects and activities related to several data hubs and enterprise data.

An example of missing application in the control room of Swissgrid is a consistent handling of multiple equipment limits (line thermal monitoring). No standard manufacturer is fully aware about this request; however, this make only sense on a wider extend if those variable limits are used in the same way in all interconnected calculation tools – operational planning and foreign TSOs. A potential reason of the lack of such application is the absence of a database and data access structure coupled with standard calculation functions.

4.2. *TenneT-Netherlands*

TenneT manages the high-voltage grid in the Netherlands and large parts of Germany (see Fig. 8). This transmission system operator transmits electricity at 110 kV and higher. With around 23,500 km of high-voltage lines, cross borders and connect countries. TenneT seeks to be a key player in the North West European energy market. It works closely with its European partners to further integrate the electricity market, thereby assuring a reliable and secure electricity supply at competitive prices.

Connecting countries and regions creates an international chain of high-voltage grids that makes it easier, cheaper and more efficient to transmit electricity across borders and to more effectively balance international supply and demand. To make sure TenneT can deliver a continuous power supply during the switch to renewable energy, TenneT needs to invest heavily in developing, reinforcing and expanding their grid in the Netherlands and Germany over the next ten years. Upgrading the grid will provide the extra capacity and flexibility needed to prevent it from being overloaded on days when there is a lot of wind for example and to be able to transport energy over increasingly long distances.

This is a particular challenge with wind energy, which is generated far offshore in the German North Sea and used by high concentrations of end users hundreds of kilometres away in the south of Germany. In the Netherlands, TenneT is preparing for the construction of a high voltage grid near the Dutch North Sea coast, which will need to be supported by a strengthened grid onshore. This construction will increase TenneT's grid capacity, as well as strengthen the connections to North West European countries guaranteeing a reliable supply of sustainable electricity in the Netherlands and abroad. Investing in the grid will also contribute to stable price levels and provide a secure, reliable supply of electricity in the long term. TenneT cannot do this important work in isolation, so throughout all the planning stages and during construction work views of everyone involved – e.g. local communities, politicians, NGOs and all other stakeholders are considered and discussed. Looking ahead, TenneT will also invest in digital technologies, including a central "data hub" that can help to manage the many different ways we need to source electricity. This will also help to make sure that all parties taking part in the energy supply business, including private people will have the same opportunities.

4.2.1. *TenneT data infrastructure*

There are currently 6 PMUs from Siemens installed in the TenneT Netherlands grid, measuring voltage, current and frequency. This number will be increased to >100 in the coming years. At the moment the data is not used in the control room yet, but only for offline applications. The protocol used for the communication is the standard PMU protocol C37.118. These metering devices are used for online and offline applications and as wide-area monitoring system.

In terms of storing and maintenance of data, this is still work in progress, the policy has not been fixed yet, because TenneT is in the middle of a EMS-SCADA replacement project for which OSI (Minnesota) has won the provisional award of the European tender. Major challenges for use data for real-time monitoring applications include the collection of data from the IEDs available in the substations by the IEC 61850 protocol and making this wider available for further analysis.

Thus, creating a parallel data path to this data, apart from the SCADA system, in a secure and reliable way. High security constraints are making it difficult to combine data from different data sources in an easy way. This has also an effect on how easy innovative data handling techniques can be used in the system operation environment.

4.2.2. *TenneT data challenges*

Congestion management, balancing and the big grid investment portfolio are TenneT's major challenges. Next to using the existing grid to its limits, improved forecasting of the operational state of the grid and

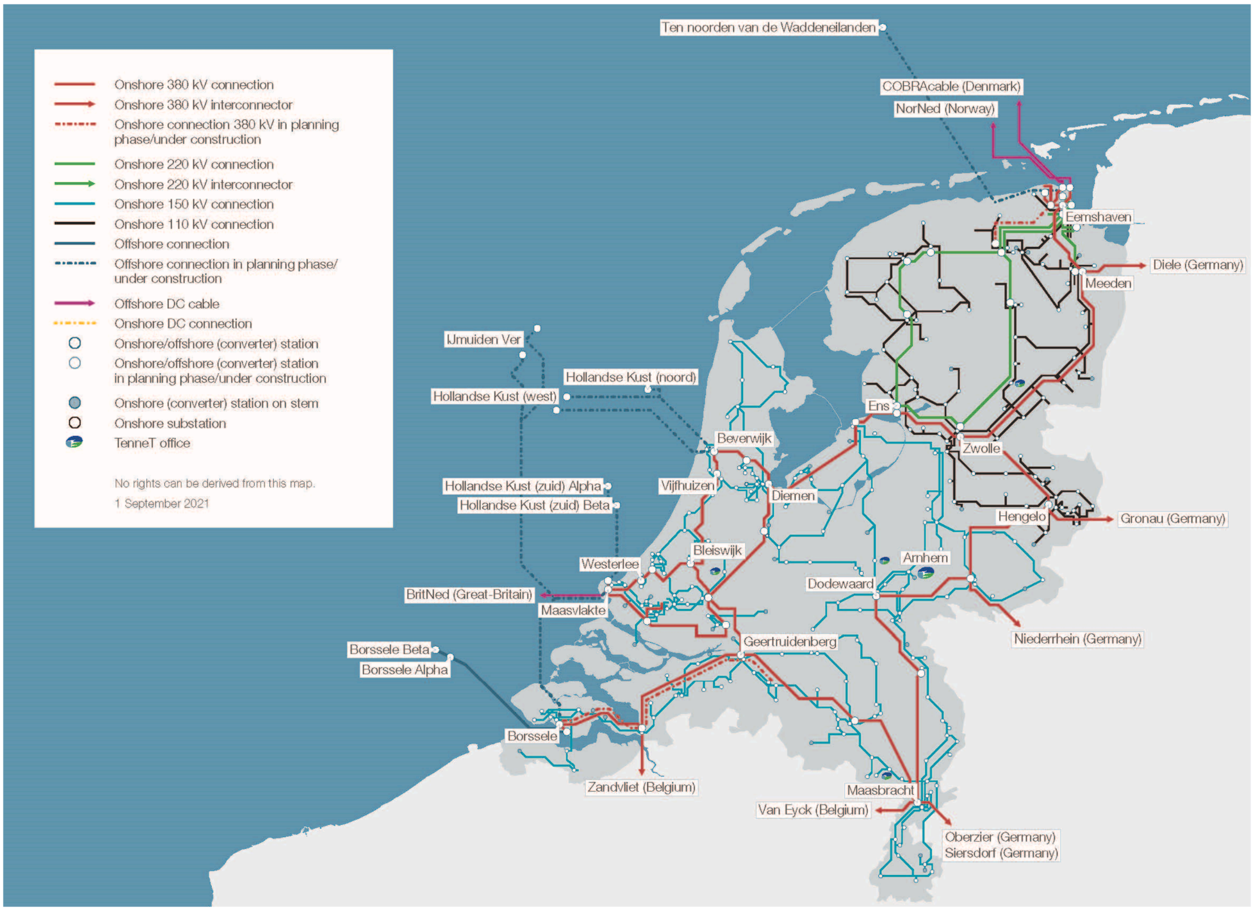

Fig. 8. Gridmap Tennet Netherlands.

decreasing inertia are other challenges. Resilience is another important topic, the energy transition towards a sustainable society is the leading driving force introducing many distributed and via power electronics connected resources in the power system.

Getting a better view and understanding on which new dynamic phenomena are introduced in the power system is a big challenge as well. New operational concepts are needed for the future. In general the target is to have a reliable, affordable and sustainable power system [16]. Using data for future predictions is not only a technical challenge, but also means something for the organisation. System operations are conservative and do not opt for solutions involving integrating innovations with high risk factor. Building a reliable scenario-based model of the future not only in the stable state domain but also the real-time fast phenomena domain is challenging. It is about a so-called digital twin where operators can go through simulated scenarios for the future, experiencing future power system situations which include new grid investments or new power plants (assets in general).

Similarly, data quality is crucial. Currently several versions of the model representing the actual system are available. Data maturity needs to grow to handle this. Assessing model quality needs to be in place. If the outcome of models is trusted, continuous evaluation of the quality of the outcomes in predictions to real life needs to be in place. In this form, inaccuracy of models can be traced back to data quality, model imperfections etc. In this way also trust in models can grow. In order to trust the data to perform real-time dynamic security assessment, the following question needs to be answered: how far should you model the real world (boundaries) for the use of security assessment to have a reliable result? Which (replacement/substitute) strategy to have in case data is not available?

Additionally, data constraints involve cyber security and how to share data from other TSOs and from DSOs to project partners like the Technical University of Delft. Sometimes a non-disclosure agreement is needed to take care of confidentiality. Doing common research and development projects with help of technical universities and manufacturers is quite beneficial and create mutual awareness, trust and good results. Some examples of activities within TenneT to overcome some of the aforementioned challenges are for instance, the program control room of the future. The goal of this activity is to identify the challenges that the energy transition will create for utilities in the future. Similarly, development of technology/platforms to support data gathering and model developments are now considered.

Additionally, a new EMS-SCADA project is in progress, which is also related to the "Control centre of the future" topic. Furthermore a "Resilient Synchrophasor measurement based Grid Protection Platform" project led by the Technical University of Delft is running with involvement of manufacturers, DSOs and TenneT TSO B.V. Topics like disturbance detection, classification as well as power system vulnerability analysis supported by suitable real-time based algorithms are being addressed. An example of an application currently missing at TenneT is more decision support tools for the operators to cope with the described challenges. Moreover, dynamic security assessment is a new area which is under investigation.

4.3. Svenska kraftnät-Sweden

The Swedish transmission grid has about 15,500 km of transmission lines, 160 substations and 16 cross-border interconnectors, see Fig. 9. The annual consumption is about 140 TWh. The annual export amounts to about 10–22 TWh. The Swedish power system is part of the Nordic synchronous region together with Norway, Finland and Eastern Denmark. The production mix has been dominated by hydro and nuclear power, but wind power has expanded in the past few years to also become a major production source.

Fig. 9. The Swedish transmission system.

Wind power will continue to expand heavily, both on- and offshore. Roughly, in 2020, 40% of the yearly production comes from hydropower, 40% from nuclear, 10% from wind power and 10% from combined heat and power plants (either in industrial processes or as part of district heating networks). Most of the consumption is located in one of the three major cities: Stockholm in the eastern, Gothenburg in the western, and Malmö in the south-west of Sweden. A major part of the production is located north, and three nuclear power stations are located south. The result of this uneven distribution, with a large production capacity north and most of the demand south, is a large need of long-distance transmission capacity from north to south. This translates in practice to voltage stability being one of the key stability aspects in Sweden.

4.3.1. Svenska krafnät data infrastructure

Several sources of operational data are collected to monitor and operate the system such as RTU data and breaker positions. About 70 PMUs are installed in Sweden and in the Nordic system there are around 200 PMUs. The Nordic TSOs share measurement streams amongst them in real time and a dedicated electronic highway is used to exchange data. A Nordic WAMS group has been established and assigned to coordinate development initiatives within the Nordics. The PMU data is collected and stored for a year with full resolution (50 Hz) and after a year the PMU data is sampled down to 10 Hz and stored in the long-term archive. Moreover, several power quality analysers with a sampling rate of several kHz are installed to monitor the impact on the power quality from power electronics (e.g. wind power) and its interaction with the grid. In the SCADA environment state estimation is run every three minutes. Based on this result an online load flow and steady-state voltage collapse application performs a security check (N-1) every three minutes. It also includes N-1 overload analysis.

Furthermore, the same application can be fed with look ahead forecasts to perform security checks on future forecast snapshots (this feature is today under development). The same tool is used to calculate NTC (net transfer capacities) to the market by combining historical snapshots and current information about the expected system state and topology. Rotational energy is monitored through breaker positions where close to all generators are included. Frequency stability (N-1 event) is assessed in real time and the instantaneous frequency minimum is monitored in the event of the online reference incident. A forecast of the needed volumes of Fast Frequency Reserve, based on machine learning, is used to procure the right amount of the Fast Frequency Reserve for each operational period to ensure an instantaneous frequency minimum (N-1 event) above 49.0 Hz [19,20].

Real-time imbalance forecasts have been developed in a project called Impala which is a collaboration project between Statnett and Svenska kraftnät. Impala provides a continuous two-hour prediction with 5-minutes resolution. The prediction window is refreshed every 5 min as new data is made available. It is envisioned that these predictions will be used in the future to proactively activate manual frequency restoration reserve bids on the power regulating market. The application is trained with machine learning which makes it achieve better performance than the current methodology [21].

In order to better monitor dynamic phenomena in the control room a highly developed WAMS will be deployed. Applications of this WAMS include pre-processing and data quality check, logging and interpolation to ensure reliable and high data quality, categorisation, classification and root cause analysis, event detection, root cause and incident classification and automatic reporting, just to mention some.

4.3.2. Svenska krafnät data challenges

One important challenge is to validate and ensure sufficient data quality and to pre-processed this data performing data quality checks. Currently the PMU data quality is monitored manually by creating data quality reports on a monthly basis. An upgrade of the PDC/PMU system is currently being planned to ensure a high availability environment. IT issues are constant threats and in a few occasions the collection of PMU data has unintentionally stopped. Ongoing activities are upgraded to ensure a reliable system and availability, as the current PMU installation is a test environment. To mitigate challenges towards effective data infrastructure, Svenska kraftnät is currently implementing a data warehouse that collects operational data from various sources.

The warehouse has a short term and long-term storage. The short-term storage integrates with the IT platforms and performs basic calculations and analytics. The long-term storage is equipped with advanced data analytics tools and data from various sources can be easily combined. Other challenges of using data for real-time monitoring are related to the drawbacks of SCADA data. For example, non-time synchronized measurements and inaccurate measurements limit the applications.

Inaccurate measurements due to e.g. lack of maintenance, possibility to detect inaccurate meters or corrupted measurement values, can also be an issue. Inaccurate measurements are particularly of concern when they are fed into computations. An example is temperature measurements to compute the capacity of transmission lines. An overall challenge when it comes to implementing new data-driven models for applications in the control room is the need of a concerted effort to test new models to show that (1) they bring value, (2) they can be trusted and (3) they can be understood.

Operators must be involved throughout the work to identify needs, design and revise specifications and test new models. These three criteria are of particular importance for real-time applications because decisions taken in the control room are often the last ones in a long chain of decision-making stages (all the way from planning to operations). Hence, some of these decisions cannot be recalled or adjusted and the decision-making support systems in place must fulfil these three criteria. Applications that are currently missing in the control room and under development are for instance the prediction of imbalances close to real-time for a look-ahead horizon of a few hours, real-time computation of line capacity based on current temperature and topology data. An initiative with dynamic line rating is currently running to increase the line capacity at important lines.

In general, the tools above have not been implemented before because there was no actual need for them. Two trends that are pushing towards the development of new tools are: 1) changes in the production mix and the demand entail new challenges. An example is the decommissioning of nuclear power plants and the fast expansion of wind power. This entails lower levels of inertia, which was not an issue before. It also represents faster frequency changes and a need to forecast the system imbalance more accurately, which was also not a problem in the past. 2) New needs are emerging due to recent European regulations and directives. For example, some services previously run by the TSOs themselves, such as capacity calculations, have been centralised at regional security coordinators. This has entailed the need to create new applications and to work with data in a different way. Data quality and standardization have become more important since more data is now exchanged with other parties, not only for information purposes but also as the basis for further.

4.4. National Grid-UK

The system consists out of high voltage transmission wires that extend across Britain and nearby offshore waters. It is owned and maintained by regional transmission companies, while the system as a whole is operated by a single entity. This operating role is performed by National Grid Electricity System Operator (NGESO). NGESO is responsible for ensuring the secure operation of the national electricity transmission system. There are currently three TSOs permitted to develop, operate and maintain a high voltage system within their own distinct onshore transmission areas. These are National Grid Electricity Transmission plc (NGET) for England and Wales, Scottish Power Transmission (SPT) Limited for southern Scotland and Scottish Hydro Electric (SHE) Transmission plc for northern Scotland and the Scottish islands groups.

NGET is part of National Grid, which owns the electricity transmission system in England and Wales (NETS). The NETS consists of approximately 7200 km of overhead line, 1500 km of underground cable and 342 substations. National Grid is at the heart of the energy transition investing around £1.3bn each year to adapt and develop the transmission network to connect new sources of low carbon and green energy to homes and businesses (see Fig. 10). In 2019, for the first time since the industrial revolution, most of the electricity was generated from low carbon resources with 37% renewables and 17% from nuclear [22].

Scottish Power Transmission (SPT) is part of Scottish Power Energy Networks (SPEN). SPT and SPEN own and maintain a large network of cables and overhead power through which they operate three regulated electricity businesses: (1) SP Manweb plc (SPM) serves 1.5 million customers in Merseyside, Cheshire, North Wales and North Shropshire, (2) SP Distribution plc (SPD) serves 2 million customers in Central and Southern Scotland and (3) SP Transmission plc (SPT) owns and operates the transmission of electricity in central and southern Scotland. The transmission network of SPT consists of approximately 4000 km of overhead lines, 360 km of underground cables and 140 substations in central and southern Scotland. In 2016 the system maximum demand was 3.4GW and over 8.7GW of generation was connected to their network. In 2017, SPT, supported by other transmission licensees and the University of Manchester, developed the first GB-wide Wide Area Monitoring System (WAMS) infrastructure (VISOR Project [23,24]) to improve the visibility of the dynamic behavior of the system and enhance the network resilience. The foundation infrastructure for the GB WAMS consists of time synchronized measurement devices, communication channels and data centers. This sensor and communication infrastructure, the WAMS and the VISOR project particularly contributed to the system situational awareness more specifically to power system hybrid state-estimation, monitoring of sub-synchronous oscillations, model validation and the validation of new concepts. Such concepts were tested with hardware in the loop testing facilities at Manchester and showcasing new achievements in the real GB network [23,25,26].

Finally, SHE is part of Scottish and Southern Electricity Networks (SSEN). SHE and SSEN own and maintain the 132 kV, 275 kV and 400 kV electricity transmission network in the north of Scotland. Their network comprises underground cables, overhead wooden poles, steel towers and

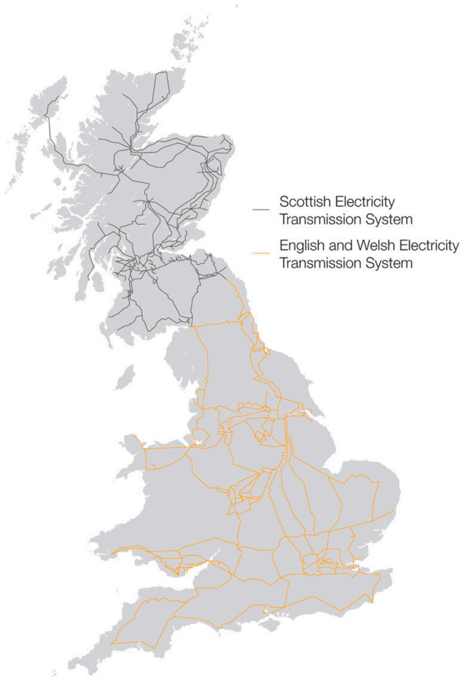

Fig. 10. The GB electricity transmission system.

electricity substations

4.4.1. National grid data infrastructure

The National Grid data infrastructure involves the infrastructure for monitoring and communications and the storage and applications of data. For monitoring and communications the SPEN policy is to install multi-function monitors on every transmission feeder end. These devices are all time synchronised using e.g. GPS and function as fault recorders, PMUs, power quality recorders, etc. The following measurements are collected as of 2018 [22]: (1) synchronized phasor measurements from PMUs, transmitted via the IEEE C37.118 protocol at up to 50 frames per second, (2) synchronized point-on-wave measurements of both voltage and current from Waveform Monitoring Units WMU, transmitted via the IEEE C37.118 protocol at up to at 200 frames per second, (3) phasor data provided by a fleet of PMUs, most of which are multi-functional DFRs, which have been upgraded to include PMU functionality, such as the Qualitrol IDM or Ametek TR-2000 and finally, (4) triggered and power quality PQ data. SPT currently uses a multiprotocol label switching optical fiber network to transfer the large amounts of PMU and WMU data acquired to the TSO. The bandwidth utilized is 4 Mb/s to satisfy the data archiving and backup needs of the existing WAMS system. Although there is resilience within the cloud, each site has one customer edge router, so there is currently a single point of failure at each end [27].

The applications of data and storage involves a PDC aggregating and processing WAMS data streams for bandwidth efficient onward transmission. There, triggered data and PQ data are processed in a combination of manufacturer’s software and SPEN software and permanently stored in corporate network infrastructure. Under the VISOR project, an e-terraphasorpoint has been deployed for the first time in GB. The phasorpoint platform was developed by Psymetrix, who were acquired by Alstom Grid, and subsequently acquired by GE, and is now GE Grid Solutions. E-terraphasorpoint receives conventional PMU data via IEEE C37.118 at 50 Hz, and also accommodates the new 200 Hz WMU devices. The main applications of the e-terraphasorpoint platform are: 1) detection of oscillations across different frequency ranges, 2) detection, location and characterization of system disturbances for real-time operation, 3) post-event analysis (protection performance, fault location, circuit breaker health), connection planning, long-term historical review and statistical analysis of system behavior, 4) estimation of line parameters for network model validation and for addressing measurement noise and systematic errors and 5) new situational awareness displays by combining WAMS information and traditional SCADA/EMS information.

4.4.2. National grid data challenges

The current system with the integration of the WAMS infrastructure is nowadays more effective for the real-time monitoring, however some day to day conventional challenges still exist.

- Substation hardware and network capacity issues for data collection and storage.
- Low identification performance of oscillation events. A full exploitation of the value of the new data collected is necessary. Low tolerance of WAMS systems of real-world data.
- Low data quality and low performance of the communication infrastructure.
- Complex link between increased visibility of real-time behavior and direct business case. One of the primary business drivers is risk mitigation and preventive action to avoid system outages and asset damage, but without first-hand experience of major system disturbances in GB it is difficult to assert financial benefit.
- Costly maintenance, monitoring, security and support of such complex communications and processing architecture.
- Internal training and recruitment of WAMS specialists to achieving the benefits of WAMS implementation in daily operations.
- Need for monitoring policy to define the nature around PMU derived data and the level of service and resilience required by the SO.
- Consistency between SO and TOs when data is shared for cybersecurity reasons. Bandwidth requirements are proportional to the number of monitoring devices, and overloading systems will have negative effects on application performance. A key challenge of the Energy Data Taskforce commissioned by Government, Ofgem, and Innovate UK, is to enable operational data to be layered across the assets to facilitate the participation and coordination of multiple actors at all levels across the system [28].

5. Summary and Conclusions

Power systems are not only transmitting electricity but also information from sensing technology, which are increasingly infiltrating in the network, resulting in an opportunity to realize further optimizations of these complex networks [29]. Data analytics are enhancing the use and value of electrical systems, which is now addressed as business model [30]. Given the relevance of this topic, the results of a survey on different transmission system operators from around the world on their current data handling procedures have been presented. The document highlights the number of practices undertaken, which vary with respect to their geographical location and particular circumstances such as climatic conditions, topography, public policies, and economic restrictions. The information presented here, which was provided and approved by the participating utilities, outlines the following factors that need to be considered in order to improve the development of analysis in transmission systems:

- Utilities collect multivariate data of different time and space granularity, depending on the acquisition technology such as SCADA systems, PMU devices or meteorological information.
- The availability and reliability of the collected data is a prerequisite for a stable and sustainable system operation.
- Without faster protocols and communications media, wide-area situational awareness is no possible to implement and, in some cases, the current state of the communication infrastructure is the main limitation.

- Collected data present high interdependency with other shareholders such as distribution system operators, generating companies and neighboring transmission system operators. Information exchange between the different actors is compulsory to profit from these sources of data.
- Currently, data is processed using standard and proprietary IT-solutions from different vendors tailored to their needs. Standardization of some of these tools is required to develop solutions that can be adopted among companies.
- In some places such as in Europe, tools, servers and applications are shared among other transmission operators, whereas in other regions such as in north and south America, information exchange is restricted even when some of these systems are interconnected.
- One of the main challenges to use data for online applications is to restrict the number of invalid or corrupted data to an absolute minimum, which is a non-trivial problem.
- Given the current data acquisition process, it is difficult in the analysis of system performance to distinguish among data failure, application failure or asset failure.
- Most of the interviewed companies agree on a current lack of data analytic applications currently operating in their control rooms. However, the use of these advanced tools would make only sense if the information excahange among these tools is standarized.
- The results of the survey also confirm that training and development of personnel skills and know-how on data analysis is a common and important constraint among utilities, to give a step forward and implement advance analytical tools in control rooms.

From the wide overview presented on the results of this survey it can be concluded that enhancing data handling and advance algorithms in control rooms are a current need. The new solutions should be straightforward to interpret for the system operators to minimize acquisition of additional personal skills and ideally be accompanied with suggestions to ameliorate the constraints. In this form, without specialized personnel, system operators can take immediate actions and utilities can avoid additional costs caused by the supervision of skilled data handling experts that would only participate for short periods of time in events that are not very frequent in robust systems such as in continental Europe. However, these events are more likely to occur in the near future due to climate change exacerbating natural hazards such as storms, cold and heat waves, flooding, earthquakes, etc and thus, development of advanced analytic tools are required.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Phadke AG, Bi T. Phasor measurement units, WAMS, and their applications in protection and control of power systems. J Mod Power Syst Clean Energy 2018;6(4):619–29. https://doi.org/10.1007/s40565-018-0423-3.
[2] Gholami M, Sanjari MJ, Safari M, Akbari M, Kamali MR. Static security assessment of power systems: A review. Int Trans Electr Energy Syst 2020;30(9):1–23. https://doi.org/10.1002/2050-7038.12432.
[3] Alimi OA, Ouahada K, Abu-Mahfouz AM. A Review of Machine Learning Approaches to Power System Security and Stability. IEEE Access 2020;8:113512–31. https://doi.org/10.1109/ACCESS.2020.3003568.
[4] "Raccoon Mountain." https://www.tva.com/energy/our-power-system/hydroelectric/raccoon-mountain.
[5] "Grid Protection Alliance." https://www.gridprotectionalliance.org/.
[6] "Hitachi-ABB Power Grids." https://www.hitachiabb-powergrids.com/offering/product-and-system/high-voltage-switchgear-and-breakers/monitoring-and-controlled-switching/circuit-breaker-sentinel.
[7] "GE Grid Solutions." https://www.gegridsolutions.com/md/catalog/cbwatch3.htm.
[8] "Siemens Energy," [Online]. Available: https://www.siemens-energy.com/global/en/offerings/power-transmission/transmission-products/circuit-breakers/accessories.html.
[9] "Franklin Electric." https://franklingrid.com/utility-grid-monitors/incon_optimizer3/features/.
[10] "PingThings PredictiveGrid." https://www.pingthings.io/.
[11] CENACE, "Programa de Ampliación y Modernización de la Red Nacional de Transmisión y Redes Generales de Distribución del Mercado Electro Mayorista. PRODESEN 2019-2033," *Cent. Nac. Control Energía*, p. 576, 2019, [Online]. Available: https://www.cenace.gob.mx/Docs/Planeacion/ProgramaRNT/Programa de Ampliación y Modernización de la RNT y RGD 2019 - 2033.pdf.
[12] Mexican Minsitry of Energy, "Programa de Desarrollo del Sistema Eléctrico Nacional 2018-2032,"; 2018.
[13] "OSIsoft PI Server." https://www.osisoft.com/pi-system/pi-core/pi-server.
[14] "Coordinador electrico nacional." https://infotecnica.coordinador.cl.
[15] ENTSO-E, "ENSO-E at a glance."; 2015.
[16] Swissgrid, "Power grid: Swiss transmission grid.".
[17] Swissgrid, "Strategic Grid 2025."; 2015.
[18] Axpo, "Electricity market facts and figures: The Swiss electricity market,"; 2020.
[19] Erik Ørum KENM, Kuivaniemi Mikko, Laasonen Minna, Jansson Alf Ivar Bruseth Erik Alexander, Danell Anders. Nordic Report: Future System Inertia. *Nord Rep*; 2015. p. 1–58, [Online]. Available: https://www.entsoe.eu/Documents/Publications/SOC/Nordic/Nordic_report_Future_System_Inertia.pdf.
[20] Svenska Kraftnät, "Läget I Kraftsystemet,"; 2019.
[21] Salem TS, Kathuria K, Ramampiaro H, Langseth H. Forecasting intra-hour imbalances in electric power systems. *33rd AAAI Conf. Artif. Intell. AAAI 2019, 31st Innov. Appl. Artif. Intell. Conf. IAAI 2019 9th AAAI Symp. Educ. Adv. Artif. Intell. EAAI 2019*; 2019. p. 9595–600, doi: 10.1609/aaai.v33i01.33019595.
[22] BEIS, "UK Energy In Brief," *Resilience*; 2020. p. 1–22, [Online]. Available: https://www.resilience.org/stories/2020-01-14/can-state-of-the-art-batteries-fuel-a-clean-renewable-energy-and-transport-future/.
[23] Wall P, et al. Deployment and demonstration of wide area monitoring system in power system of Great Britain. J Mod Power Syst Clean Energy 2016;4(3):506–18. https://doi.org/10.1007/s40565-016-0218-3.
[24] "VISOR project,"; 2017. https://www.spenergynetworks.co.uk/pages/visor.aspx.
[25] Nechifor A, Albu M, Hair R, Terzija V. An enterprise platform for wide area monitoring of load dynamics using Synchronized Measurement Technology. IFAC-PapersOnLine 2016;49(27):85–90. https://doi.org/10.1016/j.ifacol.2016.10.724.

[26] Clark S, et al. Addressing emerging network management needs with enhanced WAMS in the GB VISOR project. 19th Power Syst Comput ConfPSCC 2016;2016. https://doi.org/10.1109/PSCC.2016.7540948.

[27] Transmission E et al. Visualisation of Real Time System Dynamics using Enhanced Monitoring (VISOR) 2015;0044(215841):4–5.

[28] Sandys L. A strategy for a Modern Digitalised Energy System Energy Data Taskforce report.

[29] Zinaman O, et al. Power systems of the future. Electr J 2015;28(2):113–26. https://doi.org/10.1016/j.tej.2015.02.006.

[30] Conboy K, Mikalef P, Dennehy D, Krogstie J. Using business analytics to enhance dynamic capabilities in operations research: A case analysis and research agenda. Eur J Oper Res 2020;281(3):656–72. https://doi.org/10.1016/j.ejor.2019.06.051.