NASPI North American SynchroPhasor Initiative

NASPI Work Group Meeting and Vendor Show
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Abstracts

Session 1 – Power System Dynamics and Contingency Analysis

Utilization of Synchrophasors for Monitoring System Disturbances at CAISO

David Daigle
California ISO

In 2023 to 2024, CAISO monitored several significant system oscillations, and, through coordination with multiple transmission operators (TOPs) and generation owners, has compiled a robust catalog of event data and root cause analysis from recent disturbances. In part due to these recent observations we have made significant strides in fine tuning our oscillation detection and monitoring tools, and have refined our event analysis capabilities. Through this process we have improved our communication between the various TOPs in our reliability coordinator (RC) and balancing authority (BA) footprints for understanding the sequence of events that lead to these disturbances.

We will share newly-cleared data and analysis from these disturbances. In particular, we will go into detail on one unique oscillation event involving conventional generation that occurred during the latter half of 2024. We will convey the challenges and successes of maintaining infrastructure for large numbers of Synchrophasor measurements as our adoption continues to grow. We will share how we're using Synchrophasor data and other data sources to monitor oscillations in our footprint. Within the last year, CAISO has developed several new tools to help improve oscillation detection and analysis, and we will present the progress and benefits of these new approaches.

Field Deployment and Demonstration of an Adaptive Wide-Area Oscillation Damping Controller at the Italian Power Grid

Lin Zhu[1], Evangelos Farantatos[1], Silverio Casulli, Guido Coletta[2], Salvatore Tessitore[2], Cosimo Pisani[2], Giorgio Giannuzzi[2], Haozong Wang[3], Xinlan Jia[3], Yi Zhao[3], Wenpeng Yu[3], Yilu Liu[3,4], Ritchie Carroll[5], Christoph Lackner[5],

[1]Electric Power Research Institute, [2]Terna, [3]University of Tennessee, [4]Oak Ridge National Laboratory, [5]Grid Protection Alliance

Oscillations are a major concern for the European Continental synchronous area system since they can compromise the security of the power grid. One of the inter-area oscillation modes is the North-South (N-S) mode shown in Figure 1. On December 3rd 2017, the Italian grid was operating under an unusual low-loading condition, and two consecutive generation disconnections due to market operation excited the N-S mode, resulting in a sustained 0.293 Hz oscillation which lasted for more than 10 minutes.

EPRI and UTK are collaborating with Terna, the Italian TSO, on developing an adaptive wide-area oscillation damping controller (WADC) to mitigate the N-S oscillation mode. The scope of the multi-year project comprises offline simulations of the replicated December 3rd 2017 oscillation event, controller hardware-in-the-loop implementation and testing, and field deployment and demonstration. Presently, the WADC is developed on the openPDC platform as a user-defined action and is deployed at the Terna control center. As shown in Figure 2, the WADC collects PMU measurements and generates the control command to damp the N-S oscillation mode. Frequency measurements from two PMUs are selected as the primary and backup input signals respectively, and one synchronous condenser is selected as the actuator. More actuators including synchronous condensers, HVDC links, FACTS devices, and inverter-based resources can be added in future. IEEE C37.118 is used as the communication protocol for both frequency measurements and control commands. An enhanced PMU device is deployed at the substation to parse the control commands and interface to the synchronous condenser. A separate GUI is also developed by GPA to visualized PMU measurements, control commands, and WADC status, etc.

The field testing results demonstrate that the WADC, in the next steps of the project, will contribute to control damping for the Italian side of Continental Europe N-S oscillation mode to ensure grid security and reliability under various field test scenarios typical of the energy transition. Currently, the WADC is operating as a novel automated wide-area monitoring protection and control (WAMPAC) tool in Terna's routine grid operation.

Scalable Implementation and Deployment of RTLSE and RTLSE-based Contingency Analysis for Transmission Systems

Dulip Madurasinghe, Mohammadreza Maddipour Farrokhifard, Aravindhan Vadivel, Vijay Sukhavasi, Saurabh Sahasrabuddhe

GE Vernova

State estimation (SE) and contingency analysis (CA) are crucial security assessment tools for the power system, ensuring its stability and reliability. Modern electric power systems have become increasingly dynamic, requiring efficient monitoring to adapt to changing conditions. The linear state estimator (LSE) plays a crucial role in providing accurate and real-time system assessments. Real-time LSE (RTLSE) is a tool in the Wide Area Management System (WAMS) suit of the GE Vernova GridOS, which provides linear and guaranteed estimation of the voltage phasors of nodes in the observable network. Utilizing RTLSE results, a base case for real-time CA (RTCA) can be created. GE Vernova has developed an RTCA tool that leverages Line Outage Distribution Factors (LODF) for efficient contingency analysis and system reliability assessment. LODF estimates the power flow redistribution across the network when a transmission line or transformer goes out of service. By incorporating LODF into RTCA, operators can identify weak links in real-time and take corrective actions. Integrating RTCA with RTLSE enhances situational awareness by providing real-time analysis of branch contingencies.

With the growing number of deployed PMUs, we recognized the industry's need for a horizontally scalable solution that can be deployed both on-premises and in cloud environments. In this presentation, in addition to the implemented algorithms for RTLSE and RTCA, we will showcase these unique capabilities of RTLSE and RTCA, enabled by the GridOS foundation and architecture. We will demonstrate how RTLSE and RTCA are adopted in terms of modeling and integration with EMS systems. We will present results and metrics that show the performance of both RTLSE and RTCA.

Session 2 – Synchro-Waveform Applications

Investigating Power System Oscillations Using Waveform (POW)

Wilsun Xu

University of Alberta

Power system oscillations are a significant concern for system operators, a problem that has grown due to the interconnection of inverter-based resources (IBRs). Traditionally, oscillation events are investigated using voltage and current phasor data. This presentation takes a different approach by examining the actual voltage and current waveforms underlying the phasors. It is found that oscillation is the appearance of a beating waveform in the phasor domain. The beating waveform, in turn, is caused by a few spectral components interacting with the fundamental frequency wave. These spectral components have frequencies that reside between the harmonic frequencies, and they are called interharmonics according to IEC 61000-4-30. The implication of this finding is the following: the generation and propagation of interharmonics are the real cause of power system oscillation phenomenon.

This presentation will explain why the presence of interharmonic components is a necessary and sufficient condition for phasor oscillations. It will also use the interharmonic concept to establish a more intuitive understanding of synchronous generator oscillations. Multiple field measurement cases will be used to support these findings. Building on the new insights, the limitations of phasors for oscillation monitoring and characterization will be discussed.

Next-level WAMS Based on Synchro-waveform to Address Emerging Stability Issues

Sungyun Choi, Yeunggurl Yoon, Hyeon Woo

Korea University

Recently, as massive converters and DC-based devices increasingly infiltrate the grid, newly emerging resonance and converter stability issues have necessitated upgrades to the existing wide-area monitoring system (WAMS). These upgrades require a high-resolution measurement unit utilizing synchro-waveform technology, known as the waveform measurement unit (WMU). Specifically, sub- or super-synchronous oscillations and converter-induced harmonics cannot be fully captured by legacy SCADA systems or PMUs. This limitation necessitates the use of WMUs, which can directly sample waveforms with GPS-synchronized time tagging. The time synchronization capability of WMUs enhances wide-area situational awareness beyond local applications.

In this context, a project aimed at designing, developing, and demonstrating the WMU-based WAMS has been planned and is set to launch in Korea in 2025. As part of the project, the presentation covers four major aspects: (1) the development of WMUs and waveform data concentrators (WDCs), (2) the creation of a high-resolution wide-area stability monitoring system featuring hybrid state estimation and playback, (3) the HILS validation of the devices and systems under development, and (4) the development of WMU-based online wide-area situational awareness applications—including oscillation source location, stability monitoring in converter-intensive areas, and advanced monitoring using big data and artificial intelligence. Additionally, the presentation addresses the technological and practical challenges associated with implementing the project.

Advancing Power Quality Awareness with High-Resolution Continuous Waveform Recording

Clifford Galli, Richard Kirby, Jared Bestebreur

Schweitzer Engineering Laboratories

Data centers, industrials and manufacturing facilities rely on electricity supply of satisfactory power quality. AI training algorithms, arc furnaces, EV charging, power electronics, and other non-linear loads are driving a growing need to better understand power systems within facilities with the goal of optimizing performance, detecting equipment failure earlier, and mitigating their impact on the larger smart grid.

This presentation shares recent observations from high-resolution (14.4 ksps) timestamped voltage and current waveform measurements (Continuous Point-on-Wave). Post-analysis of the continuously recorded waveform data provides additional troubleshooting information allowing analysis of any disturbance that occurs on the power system. Observations are primarily obtained from a three-phase manufacturing facility electric service. The presentation demonstrates how power quality metrics, software calculated incremental quantities signals, software derived PMU, and load profile data (LDP) can be derived in real-time (calculated) directly from the 14.4 ksps continuous waveform measurements.

The purpose of the presentation is to demonstrate the value of continuous waveform recording for power quality monitoring and analysis.

Session 3 – Inertia Estimation

Real-time Inertia Estimation in Kauai Island Using Probing-based Method: Field Implementation and Demonstration

Xinlan Jia[1], Yi Zhao[1], Yilu Liu[1,2], Jiangkai Peng[3], Andy Hoke[3], Jin Tan[3], Ezequiel Hernandez[4], Kelsey Horowitz[5], Richard Vetter[6], Brad Rockwell[6], Cameron Kruse[6]

[1]University of Tennessee, Knoxville, [2]Oak Ridge National Laboratory, [3]National Renewable Energy Laboratory, [4]Green Power Technologies, [5]The AES Corporation, [6]Kauai Island Utility Cooperative

Power system inertia is a key factor in evaluating grid frequency stability. The rapid deployment of inverter-based resources (IBRs) and the retirement of synchronous generators (SGs) have significantly reduced the power system inertia level and frequency recovery capability under frequency disturbances. Additionally, the increasing number of IBRs that provide fast frequency responses in the form of virtual inertia and P-f droop, poses new challenges to the real-time monitoring of system inertia. To assist grid operators with more reliable and secure operations, a real-time inertia estimation tool that utilizes synchrophasor measurements for high-accuracy system inertia estimation is highly needed.

In previous study, a real-time inertia estimation software using controllable probing signal injections and corresponding synchrophasor measurements for accurate system inertia estimation is developed by UTK. This software is capable of controlling a battery inverter for injecting probing signals into the power grid, using active power measurements and frequency measurements as inputs, going through system identification process to identify system dynamic model, and then output the estimates droop constant Dp and system inertia HGen. Its estimation accuracy has been validated through extensive PHIL testing at the NREL Flatirons campus.

As a continuation work, this software was deployed and tested at the Kauai Island power grid with the help from KIUC last summer. This field demonstration leverages the one of the solar power plants that is located in the center of the KIUC grid to inject active power probing pulses for inertia estimation. Various field test scenarios have been designed to investigate how system inertia level changes during different operation dispatches, quantify the virtual inertia contribution from the gird-forming IBRs through disconnection and reconnection, and track how inertia level changes during a 24-hour period. The key findings from this field demonstration will be presented in the presentation.

Active and Localized Measurement of Grid Inertia

Alexandra von Meier[1], Antonio Enas[2], Duncan Burt[2]

[1]Independent Consultant, [2]Reactive Technologies

This presentation will make the case for direct, continuous, and active measurement of grid inertia on a local or regional basis. We will present Reactive Technologies' approach to performing precise synchronized measurements of a.c. waveform with a distributed fleet of eXtensible Measurement Units (XMUs) in response to active probing (modulation) at frequencies in the 0.1-0.5 Hz range with a megawatt-scale Energy Storage System (ESS). XMUs sample voltage at 48 kHz directly and conveniently from low-voltage sockets, and upload data for cloud-based analysis. The presentation will outline the methodology used for determining actual inertia in terms of measured ROCOF versus known load change over a precise, synchronized interval. Measurement and signal processing are conducted in quasi-real-time, and reported at convenient intervals (e.g., 5 min).

Sample measurement data will illustrate several important findings. First, we identify the significant variability in the contribution of load to system inertia, showing the insufficiency of conventional algorithms that may over- or underestimate inertia (e.g., when the contribution from load is incorrectly assumed to be proportional to total demand). Second, we highlight the importance of considering ROCOF in spatially disaggregated terms. Specifically, the conventional approximation that a.c. frequency is the same across a synchronous network is not apt in the context of assessing inertia resources. As is no surprise to the NASPI audience, oscillations and propagating transients can have operationally significant impact, such as tripping relays due to an excursion of local, not systemwide, frequency or ROCOF.

Complementary to existing WAMS, analytics based on distributed XMU data can capture the spatial characteristics of grid inertial response and the spatially divergent ROCOF measurements. We will illustrate such phenomena with real measurements from the power grids of Great Britain, mainland Europe and Australia, showcasing how power imbalances occurring in lower inertia regions induce much larger regional ROCOF than that experienced by the rest of the system.

Session 5 - Task Team Breakout Sessions

Dominion Energy's WAMS Deployment for Operations

Samantha Whalen[1], Horacio Silva Saravia[1], Emmanuel Oleka[2], Abigail Till[2], Scott Adams[2]

[1]Electric Power Group, [2]Dominion Energy

Dominion Energy (DE) has partnered with Electric Power Group (EPG) to deploy a real-time, synchrophasor-based WAMS solution for operations. The goal of this deployment is to get this real-time WAMS Solution, called Real-Time Dynamics Monitoring System (RTDMS), into the control room and in front of operators, enabling them to manage dynamics of grid with addition of Data Center loads, IBRs and growing incidence of oscillations. This solution allows operators to see the Wide-Area health of the grid at a glance with the Dashboard display (Figure 1), which alerts operators to any alarms in the system using both alarm views and a multi-layer geographical map. RTDMS provides operators with high-resolution (30 fps), time-synchronized data from PMUs which allows for detecting oscillations. This high-resolution data is also critical for monitoring the dynamics of IBRs and data centers. Dominion has a large share of data centers located in a small radius. One finding that has come from the Dominion WAMS deployment has been the discovery of a steady, 1Hz forced oscillation that occurs at PMUs near the data centers. This discovery has prompted investigation into what could cause this oscillation and why it is only seen at/near data centers.

One of the most important parts of the WAMS deployment at Dominion is training for operators. EPG had a series of hands-on training sessions with a small test group of experienced operators, each session incorporating operator feedback from the previous. These sessions served two purposes: to familiarize the operators with the tool and to provide EPG with feedback

to help make the tool more used and useful for operators in the control room. Operators want to see actionable alarms, as any alarm that is seen by an operator should come with a procedure to remediate that alarm. However, engineers and others may be interested in seeing alarms that are more for investigation and analysis purposes. RTDMS allows for separate profiles which means that an operator profile can be set up to only show alarms which have associated actions (contact plant operators, redispatch generation, etc.). On the other hand, an engineer profile may see all the alarms that come in, which may include some less severe or non-actionable alarms such as small, local oscillations.

A major finding of the Dominion WAMS deployment has been how important data quality is for reliable information and alarms. Dominion has encountered several different data quality issues through the course of the WAMS deployment, which were brought to attention using EPG's daily reporting system, called GridSmarts. This prompted the creation of a Data Quality Troubleshooting Guide to help determine the root cause of these issues based on PMU status flags from the C37.118 standard. PMU status flags come not only from the PMU itself but can be changed by a Phasor Data Concentrator (PDC) in the dataflow as well. This was an important distinction as in some cases the PMU reports bad data while in other cases, the PDC labels the data as bad due to data drops, lost packets, etc. To determine the root cause of the data quality issues, it is important to know whether the issue is coming from the PMU level or the PDC level.

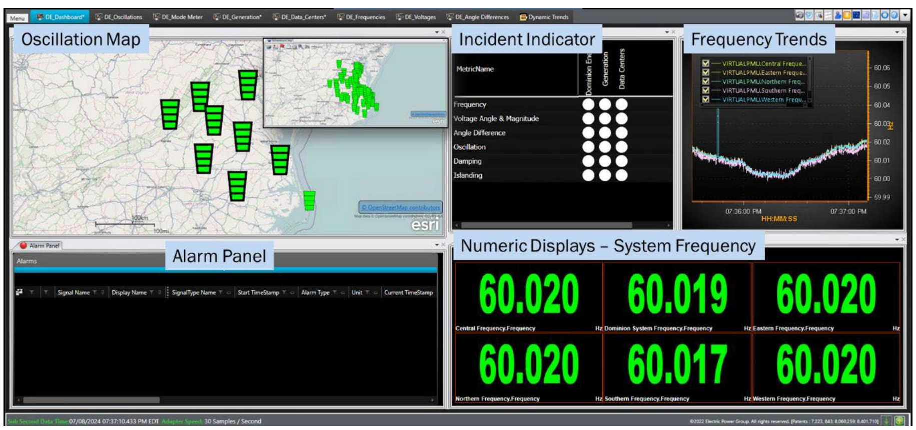

Figure 1: RTDMS Dashboard Display for Dominion

STTP integration for synchrophasor stream processing applications in Apache Flink

Daniel Villegas, Athula Rajapakse

University of Manitoba

Stream Telemetry Transport Protocol (STTP) was recently introduced to overcome some of the limitations in IEEE Std C37.117-2011 protocol such as lack of network fragmentation management, encryption and compression. STTP has the potential to drive the development of novel synchrophasor data applications and enable the use of alternative technologies such as the cellular networks and cloud technologies for synchrophasor data communication and processing.

In this work, we focus on integrating STTP with Apache Flink, a widely adopted stream processing framework. This will provide a scalable interface to create stream processing applications for synchrophasors. This integration is developed in two layers, a standalone Java library for STTP and a customer source that can subscribe to STTP streams.

The presentation is organized in the following way. First it introduces the high-level components of the system and overall system architecture to give the audience a clear idea of the setup. Next, it walks the audience through the implementation of the STTP library for Apache Flink. This is followed by an example of a stream processing application created using the library is presented to the audience. To conclude, the learned lessons and highlights of our experience implementing the STTP library are shared.

Computer Scientist's Critique of MPLS, IEC 61850, and STTP

Dave Bakken[1], Dan Brancaccio[2]

[1]Washington State University, [2]Quanta Technology

Many general purpose technologies are used in power grid settings despite not being designed for mission critical use. Others were designed by people without a reasonable prerequisite background.

In this presentation, I will give examples of 3 technologies that have such significant problems. MPLS was not intended to do anything like it is now being used for: it was designed for very coarse-grained quality of service (QoS) between sites over long periods of time (say 30 minutes), not for QoS for a given critical sensor update stream. IEC 61850 has huge benefits in replacing point-to-point wires in substations, a benefit which is virtually impossible to overstate, and its substation configuration language (SCL) is elegant. However, it has many severe issues. Its applications must detect missing and duplicated packets. GOOSE authentication uses RSA signatures, which is far too expensive for many older and smaller substation devices, and they assume that a WAN transport can be used the same way as one for a LAN. Finally, STTP will be evaluated.

This presentation will explain the above, plus other issues involved with using these technologies which were not designed for mission-critical settings. It will also give an overview of how many of these issues are handled in every other industry but the power sector.

Setting Thresholds for the RMS-Energy Oscillation Detector

Jim Follum

Pacific Northwest National Laboratory

Detection is the critical first step in addressing the reliability concerns posed by forced oscillations. The RMS-energy detector is available in commercial tools and widely used by industry, but the current practice for setting thresholds is labor intensive and provides few details about expected performance. In this presentation, a thresholding method is proposed that is based in statistics, supports automation, and can be readily implemented alongside or within commercial tools. The method produces thresholds that provide predictable performance for oscillations of interest while avoiding nuisance alarms from low-level oscillations. Results based on field-measured PMU data will be used to validate the approach and summarize lessons learned that will be useful to organizations interested in oscillation detection.

Session 8 – Utility Success Stories

Inverter-Induced Forced Oscillation Source Location Estimation Using Synchrophasors: SRP Case Study

Lin Zhu[1], Matthew Rhodes[2], Evangelos Farantatos[1]

[1]Electric Power Research Institute, [2]Salt River Project

With the increasing integration of Inverter-Based Renewable Resources (IBRs) into power grids, a growing number of severe oscillation events induced by IBRs have been observed and reported in the US and worldwide. A few such oscillation events have recently occurred in Salt River Project (SRP) territory due to control loop issues of newly installed Battery Energy Storage Systems (BESSs). Accurate and fast oscillation source locating is becoming more critical to assist system operators to mitigate oscillations and maintain reliable grid operations.

The proposed presentation will introduce EPRI's Forced Oscillation Localization Tool (FOLT) and its application with SRP's PMU measurements collected during two actual oscillation events. FOLT utilizes three different methods: dissipating potential, oscillation magnitude, and oscillation mode angle to estimate source location, without requiring real-time grid topology. Additionally, the tool can estimate the source type of the forced oscillations and identify whether the source is inside or outside utility/ISO's territory.

In this case study, FOLT successfully and accurately indicated for both events the correct BESS plants as the oscillation source location, and BESS active power control as the source type. This work contributed to SRP's assessment of the potential value derived from application of PMU-based oscillation detection and monitoring tools at SRP's control center.

Beyond Oscillations: Atypical Responses from a Real-World Solar PV Plant

Chetan Mishra[1], Luigi Vanfretti[2], Jaime de la Ree[1], Kevin D. Jones[1]

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There has been a recent increase in abnormal oscillations in Dominion Energy's power system stemming from unstable PV plant voltage controllers during outage season. While the conventional oscillation location problems are certainly a challenge and of great benefit, being able to go beyond localization and to infer the root cause of this phenomena is crucial to prevent them and other similar occurrences. In scenarios where there are multiple entities involved (e.g., multiple privately-owned generation facilities, equipment manufacturers and transmission facilities), being able to pinpoint the problem's culprit can help to speed up the resolution by prioritizing working with the right entities as a utility.

This work presents an analysis of an atypical response from a transmission-level photovoltaic (PV) solar power plant triggered by a local line outage in Dominion Energy's power system, shown in Fig. 1. The uniqueness of this response resides in the fact that its characteristic response is square wave-like, and unlike typical dynamic response scenarios, it does not stem from conventional nonlinearities. It is demonstrated how careful and systematic analysis of synchrophasor measurements in the plant, through time-series analysis techniques, can help illuminate the underlying mechanism leading to the atypical response observed. The findings are also demonstrated by a simulation of the mechanism.

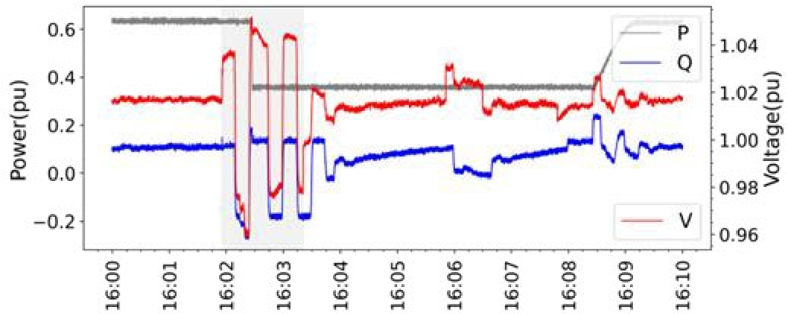

Fig 1. Atypical PV solar power plant response during an outage

Power system monitoring status of Korea based on PMU data and application

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[1]Korea Electric Corporation, [2]Kwangwoon University

The number of PMUs installed in Korea is a total of 73, and they have been utilized for various post-fault analyses. PMUs have been used for post-fault analysis on various faults. In particular, they have shown excellent performance in faults related to oscillations. The oscillation detection application applies an algorithm that detects oscillations by sensing trajectories. In addition to oscillation detection, various other applications have been developed. Accurate analysis results for vibrations below approximately 30Hz are shown, and real-time operation is also possible. Furthermore, a tool for estimating RoCoF based on system faults data and mathematically estimating the inertia excluding generator inertia has been developed and validated through joint research with EPRI. Lastly, a tool for estimating voltage stability using Thevenin equivalent circuits has also been developed.

Session 9 – Timing, Protocols, and Data Management

Low Earth Orbit Time Sourcing- Resilient alternative to GPS for critical timing

Daniel B. Burch

Adtran Oscilloquartz

GPS jamming & spoofing events continue unabated worldwide, wreaking havoc in communications and Phase Measuring Units (PMUs) that use GNSS/GPS as sole time reference. Low Earth Orbit (LEO) time services can supplement or supplant GPS for time referencing, with encrypted, higher power signals that are not rendered useless by GPS interference devices. Employing LEO time references eliminates the requirement for costly external (sky-view) antenna systems, as LEO signals can penetrate many structures, greatly reducing the installation costs at every site. Miniature LEO receivers can also be embedded in PMU's themselves, reducing the cost for accurate PMU time referencing.

Power companies across Noth America, Europe and Asia have successfully tested LEO reception in may structure types with exceptional results to serve as supplement or replacement of traditional

GNSS/GPS time references. This presentation describes how LEO time referencing can be implemented in core and edge power utility facilities.

Overview of the IEEE Standard 2664: "IEEE Standard for Streaming Telemetry Transport Protocol (STTP)"

Ritchie Carroll[1], Ken Martin[2]

[1]Grid Protection Alliance, [2]Electric Power Group

The new IEEE Standard 2664 covers the Streaming Telemetry Transfer Protocol (STTP) that has been developed over the last decade. It is a descendant of the protocol developed for SIEGate, originally conceived as an implementation of the NASPI sponsored NASPInet data network. STTP has gone through several cycles of development to become the product it is now.

IEEE 2664 is a messaging protocol that uses a publish-subscribe architecture. It can be sent over any suitable wire protocol, though the standard specifies IP. It operates with a command channel using TCP/IP to manage the connection and a subscription channel for data transfer. Subscriptions are set up using standard SQL type selection and filtering methods for meta-data management. All communications can be secured with standard methods.

IEEE 2664 is designed to handle any kind of streaming data including both phasor and point on wave data. Measurement values are packaged with an identifier, timestamp, and quality flag as an individual unit. Units can be sent together to reduce overhead but are size managed to reduce loss due to fragmentation. The basic timestamp system uses the 8-byte, 100 ns resolution time scale popularized by Microsoft. However, the standard includes methods to extend this to finer resolution into the ps range. The protocol supports continuous, real-time data exchange as well as historical and intermittent burst data transfer.

Complementary Timing in a Transmission Utility Environment

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[1]Pacific Northwest National Laboratory, [2]Bonneville Power Administration

The Bulk Electric System (BES) is a key critical infrastructure element necessary for the operation of nearly every industry in the United States. Precise Time-of-Day (ToD) via Global Positioning System (GPS) signals from Global Navigation Satellite Systems (GNSS) are currently relied on for control, protection, and disturbance analysis of this critical system. Reliance on GPS as the sole precision timing source for the US electric grid is under increasing scrutiny. Bonneville Power Administration (BPA), a federal Power Marketing Administration operating much of the BES in the Pacific Northwest, has embarked on a multi-phase test program, supported by the Pacific Northwest National Laboratory and funded by the Department of Energy, to reduce dependence on GPS-based timing for their high voltage transmission system. The primary goal of this work is to determine the best path for distributing precise time-of-day (ToD) over their electric utility communications system with an accuracy that meets the stringent transmission timing requirements of ±1 μs for synchrophasors/phasor-measurement units (PMUs), line differential relaying, and traveling wave fault location. A related goal is to demonstrate detection and alarming on timing errors.

Phases 1 and 2 of the testing have been successfully completed, meeting the ±1 μs timing requirement. Phase 1 lab testing used direct connections between IEEE 1588 compliant/Precision

Time Protocol (PTP) Enhanced Primary Reference Timing Clock (ePRTC) timing equipment, monitoring and test equipment, and IEC 87L current differential relays. Phase 2, synthetic network testing, simulated a basic transmission system composed of control center to substation and substation to substation communications carrying PTP traffic over both fiber optic cable and radios, using both packet and non-packet technologies, to a PMU representing end devices.

This presentation will describe the timing threat to the US BES, how BPA identified the weakness of GPS as a single timing source several years ago, added it to their protection roadmap, and are completing their first two test and evaluation phases, with the next phase to be at-scale testing on their transmission system. The final goal is implementation to BPA's standard timing operations.

Third-Party Sensor Data as a Service

Bruce Warmack, Ali Boyaci, Aaron Wilson

Oak Ridge National Laboratory

Power grid operations, stability and reliability depend on accurate, real-time monitoring. To date, almost all sensing of the grid is performed by devices and systems specified, owned, operated and maintained by the utility or controlling entity. Increasing grid dynamics and the grid's criticality to society among other factors is driving a need for increasing levels of observability: at finer spatial and temporal resolutions, across more dimensions, and with higher confidence. At the same time, the number of non-utility sources of sensor data, from co-located infrastructures, increasingly sophisticated Behind-The-Meter (BTM) assets, and sensors owned and operated by third parties for their own purposes, presents an opportunity for detailed observability without owning, operating or maintaining a sensor, or even its attendant communications systems.

Because utilities have been responsible for almost every aspect of sensing to date, there has never been a need to deconstruct sensing services such that they could systematically defined and then provided by an external party, i.e., Sensor Data as a Service (SDaaS). In many cases, utility sensor data, once produced, is carried across communications networks specified, owned, operated and maintained by the utility performing the sensing, which is to say the utility is providing SDaaS and data transport. Aspects of SDaaS or attributes will likely include sensing, integrity, location, time, event detection, analysis, backhaul transport, and delivery of valuable information to augment PMU, DFR and other utility data.

This presentation will provide real examples of how low-voltage data from points across distribution grids can provide real-time awareness and historic insights of frequency, harmonics, phase shifts, faults, arcing, equipment misbehavior, etc. We will highlight data from two data providers across the footprint of Vermont Electric Co-Op. To become of value to utility customers, providers must ensure the reliability, accuracy, and security of the data, as well as analytics to support operational decision-making and planning. Aggregation, curation, compliance, validation, compatible data formats, interoperability, and scalability are all important for utility adoption.

Session 10 – IBR Analysis

Bayesian Optimization Approach for DER Dynamic Model Calibration

Pavel Etingov, Shuchismita Biswas, Jim Follum, Tianzhixi Yin, Tawsif Ahmad, Kaustav Chatterjee, Antos Cheeramban Varghese, Syed Ahsan Raza Naqvi

Pacific Northwest National Laboratory

The proposed presentation explores the application of Bayesian Optimization to calibrate parameters of the DER_A model used to represent the aggregated behavior of distributed energy resources (DERs)like solar photovoltaics and battery energy storage systems in transmission planning studies. This study utilizes publicly available phasor measurement unit (PMU) data from the Grid Event Signature Library (GESL) to assess the effectiveness of the DER_A model in capturing the dynamic behavior of diverse DER fleets. It is found that the DER_A model can reproduce the behavior of different DERs, including solar photovoltaic and battery energy storage systems. However, default model parameters may not always be suitable. A closer match to real-world behavior can be achieved with optimally calibrated model parameters. By employing an iterative Bayesian Optimization methodology, the approach systematically reduces discrepancies between observed and simulated data, thereby enhancing model accuracy. The presentation will detail the methodologies employed and the model calibration testbed developed, including the iterative Bayesian Optimization approach for parameter calibration and the measurement play-in method for model verification. By leveraging data from the GESL, the study highlights observed DER responses and demonstrates the improved performance of the calibrated model. This work underscores the critical need to systematically verify and calibrate model parameters to reflect specific system conditions, there by improving the accuracy of dynamic studies and supporting the reliable operation of the electric grid.

Real-Time Inertia and System Strength Measurement and Intelligence for Improving Control Room Operations and Grid Reliability

Neeraj Nayak, Krish Narendra, Hemant Goklani, Song Xue

Electric Power Group

The increasing penetration of inverter-based resources (IBRs) in power grids worldwide has led to significant challenges related to declining system inertia and system strength, both critical for maintaining grid stability and reliability. Traditional grid operations rely on high levels of rotational inertia and robust system strength to absorb disturbances and support frequency control. However, with the rapid shift toward renewable energy integration, grid operators face challenges in managing inertia and system strength.

Synchrophasor technology offers a powerful solution for real-time measurement, monitoring and assessment of system inertia and strength, enabling grid operators to make informed decisions to maintain grid stability and reliability. Synchrophasor based solution incorporates the effect of synchronous generation, critical data center loads, IBR response, controllers and other system dynamics to provide estimation of effective inertia and system strength in real-time, as well as provide a day ahead forecast using ML/AI capabilities. Electric Power Group (EPG) has developed Real-Time Inertia and System Strength Monitoring solutions that provide actionable intelligence for managing modern power grids. These solutions are designed to enhance situational awareness and

support proactive control strategies, ensuring reliable and resilient grid operations. Deployments of EPG's Inertia and System Strength solutions are underway in diverse regions, including ElectraNet in South Australia, OETC in the Middle East, TPC in Taiwan, IESO in Canada, Red Sea Project in Saudi Arabia, and various grid operators and utilities across North America.

This presentation will showcase leveraging of WAMS synchrophasor technology with advanced applications for system strength and inertia measurement, monitoring, visualization and forecasting. These synchrophasor-based solutions offer enhanced situational awareness, allowing operators to take timely actions to mitigate risks and ensure grid stability under high renewable penetration conditions. Presentation will provide an update on real-world deployments of EPG solutions – this will allow attendees to gain a better understanding of how these tools enable utilities and grid operators to enhance their control room operations, prepare for extreme contingencies, and ensure grid stability in the evolving energy landscape.

Experience of REGS-PPC Testing and Performance Analysis using PMU Data

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Grid Controller of India Limited

The Integration of Renewable Energy Sources (RES) such as solar and wind is continuously increasing in the Indian power systems grid and globally. In Renewable Energy Generating Station (REGS) plant, Power Plant Controller (PPC) is a device which controls the active and reactive power output generated by the Inverter Based Resource (IBR) units. PPC takes inputs from Power Quality (PQ) meter installed at point of interconnection (POI) as actual values. This input is compared with the reference value input provided by the grid operator and command is sent to IBR units and additional equipment installed if any for compliance of connectivity standards as shown in Figure 1.

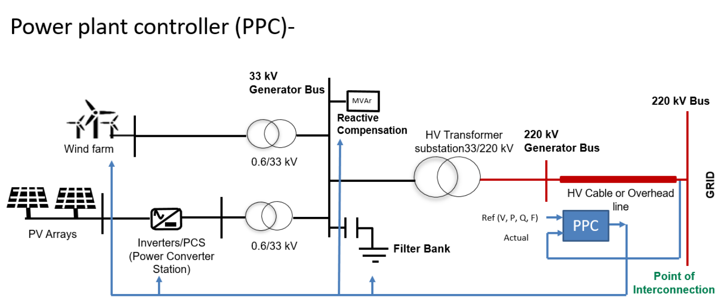

Figure 1 REGS control operation using PPC

Different functional control modes are implemented in PPC to comply with requirements of Indian grid connectivity standards and grid code. Testing of each control mode is done to analyze, whether REGS PPC operates as per Indian grid code. After testing, the results of each test are verified from the data received from Phasor Measurement Unit (PMU).

Operation, testing and performance of each control modes are summarized below:

1. Active power control mode testing: In this control mode, active power response of plant is based on active power set point given to PPC. While ramping up/down, REGS should adhere

to the ramp rate implemented. It should achieve the provided set point without inducing oscillations/fluctuations.

Test is performed by providing different active power set points to PPC and response of the plant is observed using PMU data.

Following issues are being generally observed during the testing of active power control mode:

- Oscillations or Fluctuations in active power response while ramping up as depicted in Figure 2.
- Inability to operate at the ramp rate implemented in PPC, as per grid requirements.
- Large overshoot followed by transients while reaching the set point.

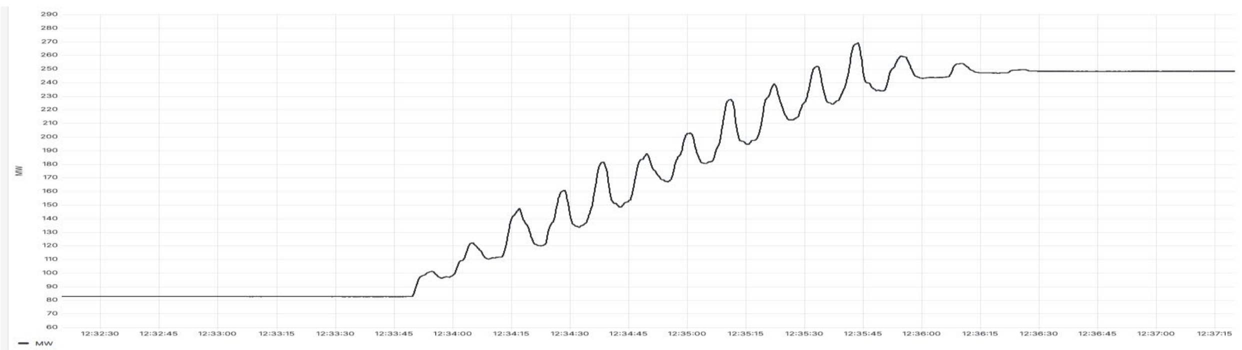

Figure 2: Oscillations in Active Power (MW) when set point of Active power is changed.

2. Reactive Power Control Mode Testing: Reactive Power control mode is implemented using three different sub-control modes:-
    - Voltage Control Mode in which reactive power provided by the plant is based on the voltage conditions at point of interconnection. If voltage at POI is higher than threshold voltage, plant absorbs reactive power and if voltage at POI is lower than threshold voltage, REGS injects reactive power.
    - Reactive power set point control mode in which reactive power provided by the REGS is based on the set point input to PPC.
    - Power factor control mode in which reactive power provided by the REGS is based on the PF set point input to PPC.

    Testing of each mode is done separately so that entire reactive power capability from maximum absorption to maximum injection of REGS is accessed.

    Following issues are being generally observed during the testing of reactive power control mode:-

    - Oscillations in reactive power around certain set points as shown in Figure 3
    - Sudden spikes in reactive power when set point of PPC is changed.
    - Loss of generation/Tripping of IBRs on over voltage or under voltage while providing reactive power response as shown in Figure 4

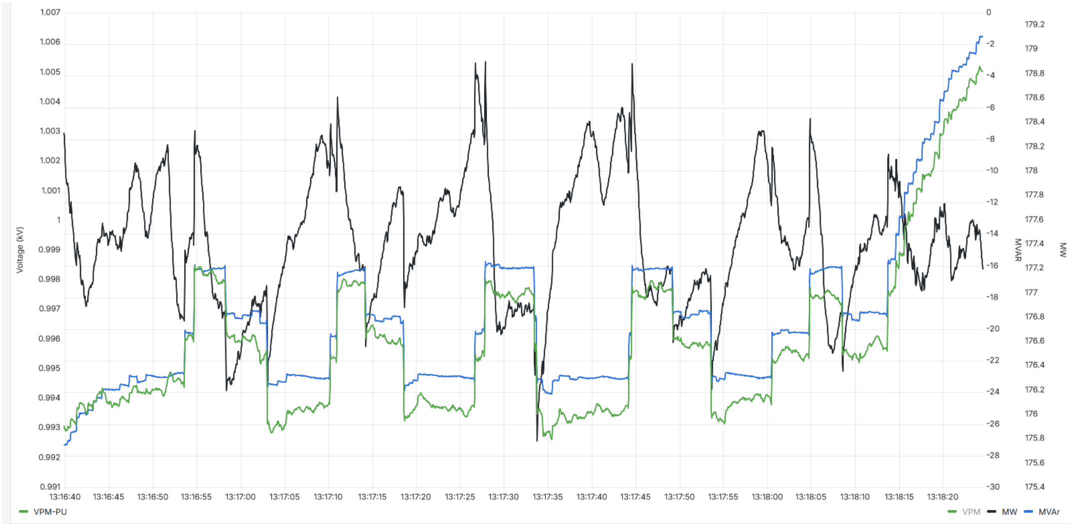

Figure 3 Oscillations in Reactive Power (MVAr) when set point of 20 MVAr was provided.

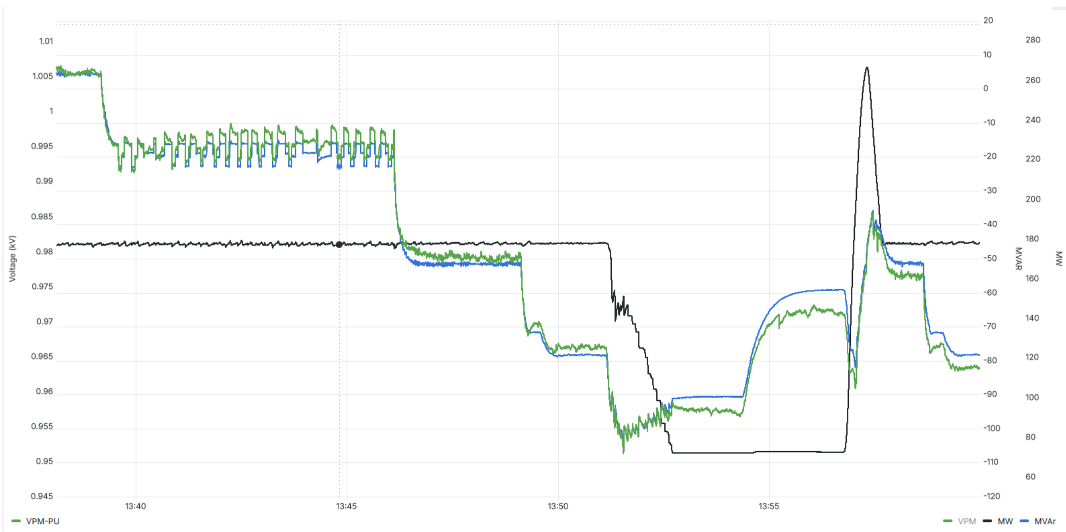

Figure 4 Loss of Active power (MW) generation due to under voltage

3. Frequency Control Mode Testing: In this mode of operation, plant is required to regulate the output of the generating unit as per frequency response requirement using frequency controllers having droop of 3 to 6% and a dead band not exceeding ±0.03 Hz as per Indian grid code.

   Test is performed using simulated frequency as input to the PPC and active power response provided by REGS is observed.

   Following issues are being generally observed during the testing of active power control mode:

   - Inability of plant to provide active power response within the required time.
   - Presence of overshoots, transients and oscillations in active power and reactive power as shown in Figure 5.

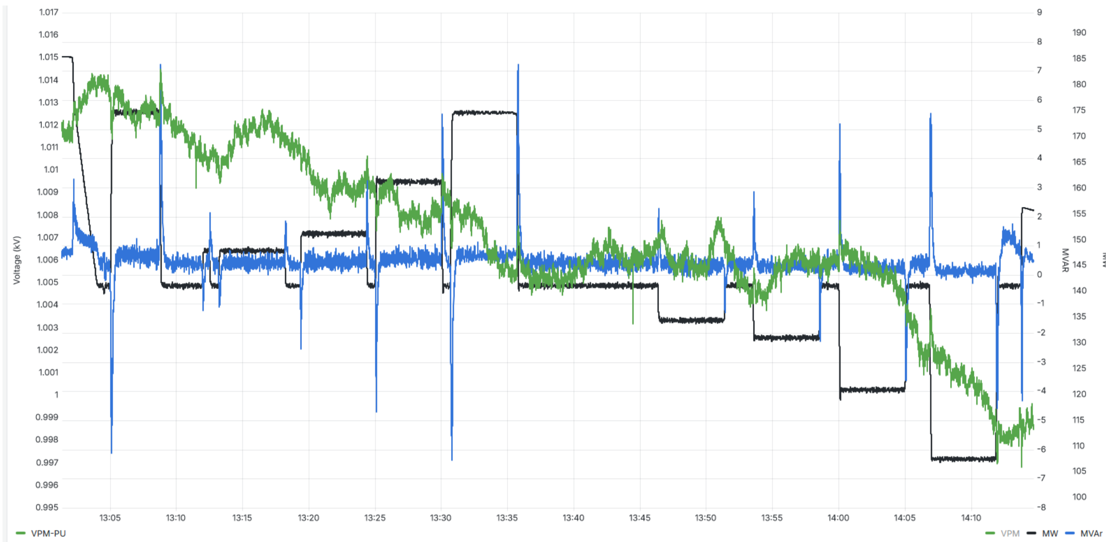

Figure 5 Spikes in Reactive power (MVAr) while testing frequency control mode

The shortcomings identified during the PPC testing are being taken up with REGS and corrective actions are implementing by REGS. This results in smoother integration of IBR with grid.

Session 11 – Advanced Applications

Protecting and Monitoring Transmission Lines with Enhanced Power Flow

Daniel L. Ransom, Wayne Hartmann

GE Vernova

Traditionally, wide-area monitoring, protection, and control systems (WAMPACS) are used for reacting (tripping) to prevent cascading outages from problems such as system stability (angular and voltage), frequency, and other system alert, emergency, and extreme events. A recent application of WAMPACS for controlling, monitoring and protecting transmission lines with enhanced power flow: dynamic system rating (DSR). DSR combines thermal dynamic line ratings (DLR) that raise the power transfer for line and bus loading, dynamic power rating (DPR) monitoring voltage and angular stability, and optimal power-flow controllers (OPFC) for line flow-management control.

As line power transfer and bus loading increase, voltage and angular stability margins decrease. Compounding the issue is the penetration of inverter-based resources (IBRs), which produce variable voltage and current outputs and provide less power-system inertia. Using traditional transient-stability determinations, these factors introduce errors and unnecessarily conservative margins. Synchrophasors (PMU data) yield precise and real time determination of transient stability in line and bus locations where exists congestion and large penetration of variable IBR renewable sources. This PMU data provides precise, transient-stability, power-flow limit determination, with contingency analysis. Thus, maximum safe power flow occurs on lines and load buses in the PMU-monitored area.

This paper explores the fundamentals of grid congestion and its negative impacts, DSR functional building blocks, DSR calculation methods, power angle, equal-area contingency analysis, voltage stability curves, and power-flow redirecting and redispatch tactics to improve transient stability. Also presented is a detailed simulation of applying the method.

Synchrophasor-based Power Flow and Contingency Analysis for Dominion Energy Power Grid

Sebastian Martinez-Lizana[1], Utkal Kapadia[1], Horacio Silva-Saravia[1], Angel Gonzalez Vera[2], Abigail Till[2], Emmanuel Oleka[2], Bharath Ravulapati[2], Kiamran Radjabli[3]

[1]Electric Power Group, [2]Dominion Energy, [3]Utilicast

Dominion Energy (DE), as part of its vision to enhance real-time decision-making and system visibility through PMU data, has partnered with Electric Power Group to develop the first and largest real-time Synchrophasor-based Power Flow and Contingency Analysis Applications. This technology improves upon the functionalities of traditional EMS by utilizing high-speed, time-synchronized PMU data for real-time assessments, enhancing situational awareness and accuracy, and equipping operators with tools to evaluate the effects of fast system changes induced by the growth of data centers and renewable energy penetration. The core functions of real-time assessment are achieved by continuously updating a comprehensive grid model using synchrophasor data and Linear State Estimation (LSE) for real-time voltage profile calculations. The synchrophasor voltage profile serves as the basis for real-time power flow and Contingency Analysis (CA), leveraging a novel methodology known as Synchrophasor Power Flow (SPF).

SPF builds upon the capabilities of LSE by integrating high-speed estimations with slow-speed data to create a complete real-time power flow case. This case is used to identify real-time violations and serves as a foundation for performing real-time CA. The SPF methodology adjusts the base case voltage profile by incorporating LSE estimates through fictitious reactive power injections. V-Q sensitivities are then used to rank optimal locations for these injections.

CA is developed from the SPF solution by using it as a base case to simulate "what-if" scenarios involving potential grid events. By incorporating MVAr adjustments imposed by synchrophasor data, the methodology effectively utilizes PMU data to provide operators with a reliable tool for evaluating potential scenarios under the latest and most accurate system conditions. This approach minimizes over-tuning and false-positive violations, enhancing the reliability of CA for operational decision-making. These adjustments seamlessly integrate with remedial action schemes, area interchange control, and islanding, which are critical components of real-time assessments.

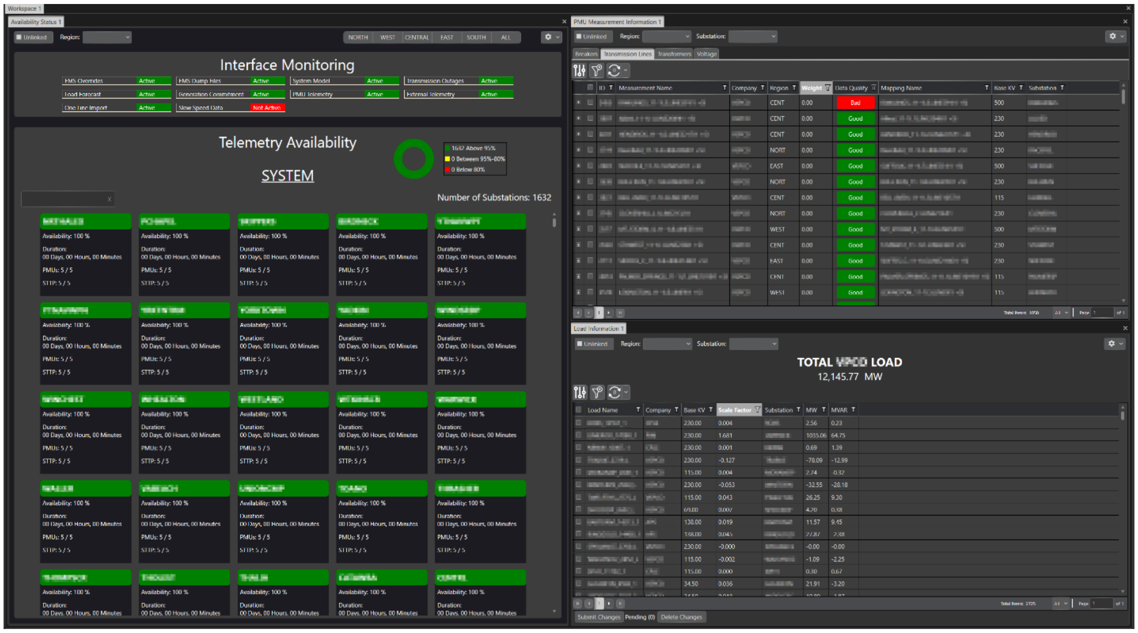

Figure 1: Combined Workspace: Availability Status PMU, PMU Measurement Information, and Load Information. (Names in the figure have been intentionally blurred for confidentiality purposes.)

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