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Linear State Estimator Deployment for Real-Time Power System Monitoring in AEP's Control Room

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SUMMARY

Power systems in the last decade have seen a significant increase in renewable integration at the transmission and sub-transmission levels of the grid. Presently, power systems are prone to low-damped oscillations due to the increase in renewable generation penetration, especially inverter-based generation. Synchrophasors provide observability into the oscillatory behaviour of the power systems, providing transmission operators the ability to detect and monitor oscillations in real time.

Phasor Measurement Units (PMUs) provide high speed, time synchronized phasor measurements of transmission systems, making them a suitable solution for control room operations, and serving as a back up to SCADA systems. However, the synchrophasor system observability doesn't fully cover the system due to the limited PMU deployments at the transmission level. Linear State Estimation technology provides expanded synchrophasor observability to substations and transmission lines beyond the PMU-equipped substations.

American Electric Power Service Corporation (AEP) deployed the Linear State Estimator (LSE) solution to expand the PMU system coverage and support the existing oscillation monitoring tools by providing reliable data for real-time monitoring and event detection. The objective of AEP's LSE deployment is to provide additional observability and situational awareness capability using Phasor Measurement Unit data for oscillation analysis, and to enhance grid resiliency by providing a backup solution when the traditional Energy Management System (EMS) / State Estimator (SE) system fails. The LSE operates providing estimations for three separate regions under the jurisdiction of the three Regional Transmission Organizations (RTOs) where AEP operates (within PJM, SPP and ERCOT systems). The LSE currently uses measurements from 533 PMUs, with an expected increase in coverage of up to 720 PMUs in the next few years. This paper presents AEP's approach in deploying Linear State Estimation for control room operations. Furthermore, this article shows examples of AEP's use cases and realized benefits to AEP transmission.

KEYWORDS

Power System Operations
Real-time Monitoring
Utility Deployment
Grid Reliability
Control Room
Linear State Estimation
Synchrophasor Data Systems
Situational Awareness

Introduction

American Electric Power Service Corporation (AEP) is currently working with Electric Power Group (EPG) on a project to deploy a synchrophasor data-based Linear State Estimator (LSE) at AEP's Operations control centers. The project was initiated in 2020 and is currently commissioned and operational in three environments: Operator training; testing; and staging. The latter two receive live PMU data at a rate of 30 samples per second from a local Phasor Data Concentrator (PDC) that communicates with a second, remote production PDC at a central location. The PDCs collect synchrophasor data from PMUs in geographically diverse regions under the jurisdiction of the three Regional Transmission Organizations (RTOs) where AEP operates (within PJM, SPP and ERCOT systems). The LSE at AEP currently uses measurements from 533 PMUs, with an expected increase in coverage of up to 720 PMUs in the next few years. Currently, extensive PMU coverage, along with the deployment of the LSE technology, allow AEP to realize many benefits supporting situational awareness in the control rooms.

The LSE solution deployed and commissioned at AEP consists of a robust and mature technology which had been tested and validated to provide estimations with less than 1% variance, the accepted industry standard. [1] The technology is designed to address existing challenges in traditional state estimators by providing a guaranteed solution at a much higher reporting rate, independently from EMS/SE. This allows the LSE to provide accurate information to the control room when EMS/SE is down due to hardware or software failure or physical and cyber-attacks [2]. Additionally, given the nature of its linear algorithms, the LSE always provides an answer. This is opposed to the traditional SE, which relies on the convergence of its iterative algorithm, a process known for failing to converge when the system is under critically stressed conditions. The mathematical advantage of the LSE enables it to solve the estimation problem at the synchrophasor rate (30 samples per second for this deployment), providing situational awareness at high resolution, as compared to the traditional SE which provides one snapshot every minute. Solving state estimation at the synchrophasor rate enables detection of fast power system dynamics, such as power oscillations, which are expected to appear more often with the increase in renewable integration. AEP is planning to supply the LSE output to their real-time oscillation detection tools as part of the next steps after commissioning the production LSE environment.

Another key benefit of the LSE implementation in AEP's situational awareness strategy is increased coverage of the monitored footprints. The LSE expands the real-time observability beyond the existing coverage of physical PMUs deployed in the field [3]. This reduces the investment cost associated with installing physical PMUs, while still providing situational awareness capability. The LSE technology uses a detailed system model, as well as real-time topology information from breakers and switches, received through Inter-Control Center Communications Protocol (ICCP) to determine the current network configuration. This configuration is then used, along with PMU locations and real-time data quality processing, to perform a real-time observability analysis. The analysis is updated each time the network topology or the measurements availability status are changed. As part of the preliminary analysis during early commissioning of the LSE, it was determined that the maximum system observability increased from 47% to 87% in the PJM 765 kV system, from 40% to 55% in the SPP 345 kV system, and from 38% to 56% in the ERCOT 345 kV system. The observability is expected to increase even more in the short term, as more PMUs are enabled to participate in the estimation process before completion of the commissioning stage in the production environment.

The LSE production environment will provide operators in AEP's control rooms with the tools to monitor the power grid independently from EMS/SE. This is achieved through one-line diagram type displays, as well as high speed trend charts and alarming functionalities. The one-line diagram displays integrate both substation topology and voltage-layer based overview diagrams with PMU data and LSE estimations for quick validation and analysis. The alarms functionality can be configured either for individual or sets of signals, providing up to eight levels of criticality, ranging from normal to emergency conditions. In order to avoid false alarms triggered by PMU data quality issues, a separate application is used to detect and correct bad data in real time. The data quality application uses six different validation algorithms for validating data corruption, PMU status and signal-level checks. The outcome of this process is a reliable, and fully independent data source to assist transmission operations and engineers.

Moving forward, AEP will work closely with EPG to train operators on how to use the LSE technology and take advantage of AEP's synchrophasor infrastructure. The training sessions, as well as operator feedback, will provide the basis for developing operational procedures to help transition to the use of synchrophasor applications in the control rooms. By doing this, AEP is gaining more observability, situational awareness, and enhanced grid resiliency — leading the way for others in the industry.

LSE Deployment Characteristics

PMU Data Infrastructure

Since 2018, AEP has deployed 533 PMUs in separate regions under the jurisdiction of the three RTOs where AEP operates (PJM, SPP and ERCOT). Figure 1 shows a simplified diagram of AEP's PMU data infrastructure for the testing and staging environments. The EAST PMUs include 248 PMUs in the coverage of AEP's PJM footprint, collecting synchrophasor data from five voltage levels including 765 kV, 500 kV, 345 kV, 138 kV and 69 kV. The WEST PMUs contain 285 PMUs located in AEP's service areas in ERCOT and SPP, measuring at 500 kV, 345 kV, 230 kV, 161 kV, 138 kV, 69 kV and 12 kV. The EAST and WEST PMUs are installed in the substation field, sending synchrophasor data to a corporate PDC to be collected and distributed to the Linear State Estimator and downstream applications. Note from figure 1 that the PDC system is configured as a highly available and redundant system. Additionally, as a regulated utility, AEP exchanges data with external RTOs (PJM, ERCOT and SPP).

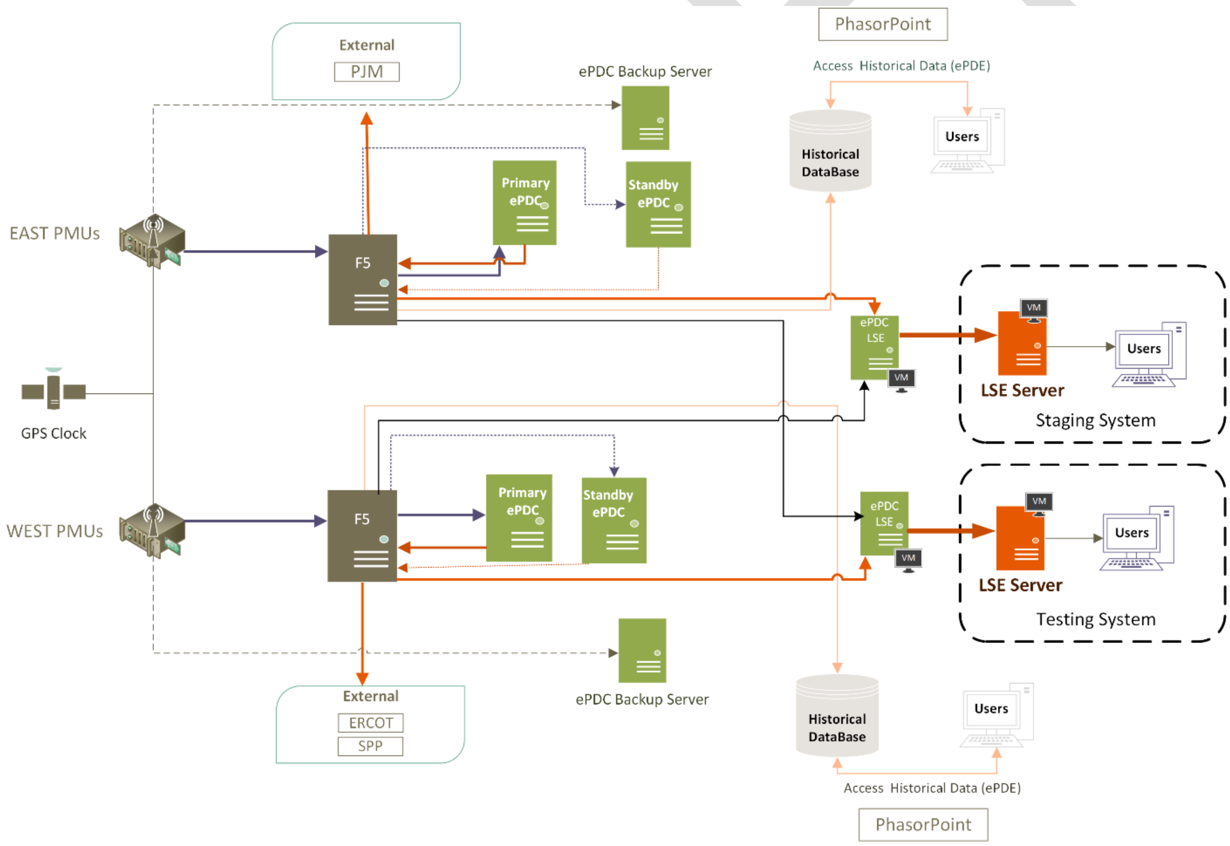

Figure 1: AEP's PMU Infrastructure.

Deployment Architecture and Targeted Functionalities

The LSE platform receives all of AEP's synchrophasor data at 30 samples per second from AEP's Corporate PDC. The PDC (as well as all the software included in the platform) is provided by Electric Power Group (EPG).

Figure 2 shows the LSE architecture diagram with the different input data sources. The first block in the architecture processes the data to maintain PMU and signal names according to the AEP naming convention.

The PMU naming convention is leveraged during the automatic model promotion to maintain the relationship between measurement locations and network elements. The next block corresponds to the "*enhanced* Linear State Estimator (*e*LSE) Host" application, which is responsible for PMU data validation and conditioning. Data validation is the process of checking data for errors related to communication problems, PMU devices, data format, topology, out of range (high and low limits) and time synchronization. The application performs six different validation algorithms in real time to guarantee that the data fed to the estimation engine is appropriate for calculation, providing clean data sets for monitoring and alarming in the control room. Additionally, the validation process assigns data quality flags that can be used for conditioning (i.e., replacing data, and for sending the quality flags to downstream applications for monitoring).

The clean data set is sent to the "*e*LSE service". Along with the real-time synchrophasor data, the *e*LSE service uses the network model information and real-time topology telemetry to provide the best estimate of the power system state. The network model information is automatically created and integrated from the same model used in EMS. This model — provided in CIM format — contains static network information, such as connectivity between substations and substation topology in node-breaker format. The model also contains impedance parameters from transmission lines, transformers and series and shunt compensators. The real-time topology telemetry (digitals) is fed to the *e*LSE directly from EMS through ICCP (as shown in Figure 2). The digitals provide the statuses, of breakers and switches to determine the most accurate representation of the power grid. Note that changes in the breaker/switch statuses, as well as changes in synchrophasor data quality, trigger two internal processes: topology processing, and observability analysis.

Topology processing performs the conversion between node-breaker model in the CIM format to the bus-branch model required to formulate the LSE mathematical equations. In simple terms, topology processing groups substation nodes that are connected through zero-impedance elements (such as breakers and switches). When a breaker or switch changes status, the eLSE determines the new bus-branch model that represents the system topology. Similarly, observability analysis uses the latest set of available PMU measurements to determine the maximum footprint (buses and transmission lines) that can be included in the LSE equations. The buses that are included are considered observed buses, and they consist of those buses which are observed by a PMU in the same substation or observed by a PMU at the other end of a transmission line, providing expanded observability to the bus.

The estimated data, as well as the raw synchrophasor data, is sent to the "Alarm Engine" for alarming and advanced calculations processing. The data and alarms are stored in a centralized database which is accessible through role-based profiles for operators and engineers in the LSE Visualization client. Figure 2 shows a diagram of the data flow in the LSE Deployment.

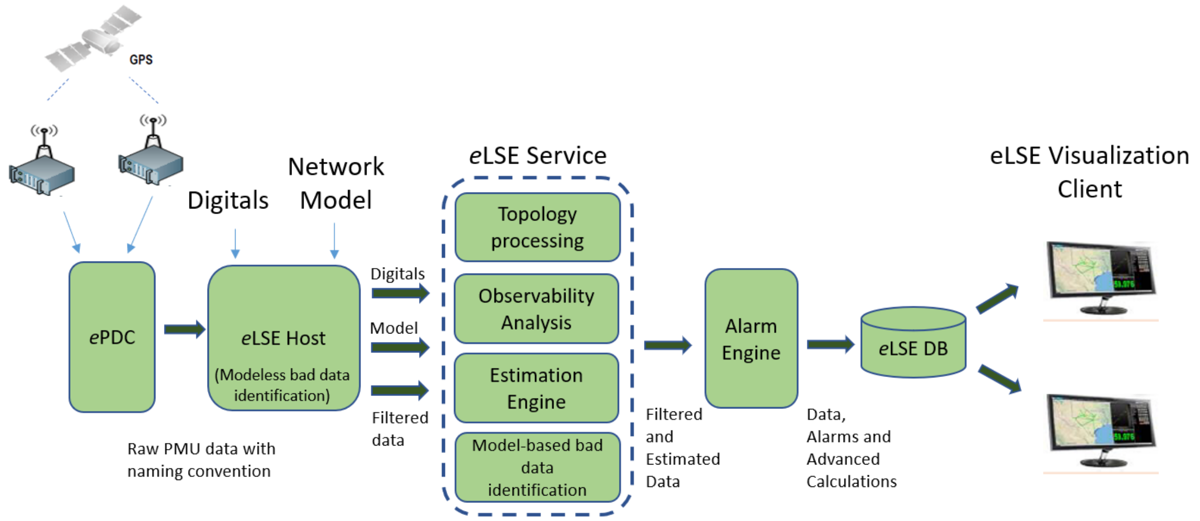

Figure 2: LSE Architecture diagram.

Automatic Model Promotion and Maintenance

AEP's LSE deployment is designed to fully operate as a back-up solution when EMS is down. In order to achieve this, the network model information and the overview single-line diagrams for situational awareness and monitoring should be integrated to always reflect the same information, (while working independently). As part of this integration during the project commissioning, AEP worked with EPG to develop processes that facilitate an automatic model promotion and an automatic single-line overview diagram promotion from the existing EMS.

The automatic system model promotion takes (as input) the CIM file used in EMS, and an automatically generated configuration file with the latest PMU and signal names from the synchrophasor system. The information from both files is then combined in the model builder by leveraging AEP's naming convention to automatically map the measurements to the corresponding network elements. The convention includes station names and KV levels in PMU names, and detailed mapping information, such as device type and node name in signal names. By implementing this convention, AEP avoids the need for maintaining mapping information separately.

The automatic overview single-line diagram promotion uses the latest diagram files promoted in EMS and the PMU configuration associated with the diagrams. The overview diagram files contain in plain text all the transmission lines and stations with relative geospatial coordinates, The conversion tool reads the power system elements and their coordinates and converts the diagram into an appropriate format for display in the LSE visualization client. The tool also identifies topology changes and allows engineers to accept or edit changes, while also adjusting the diagram on top of a geospatial layer.

Control Room Visualizations

Operators in the control room monitor AEP's grid through a set of customized displays in three profiles associated with each service areas in PJM, SPP and ERCOT. For each footprint the main display corresponds to an overview single-line diagram, which provides wide-area monitoring of the entire system. The display is equipped with color-coded elements that change color when there is a violation triggering an alarm. Additionally, pop-up windows located in the region of the violation are designed to help operators to quickly identify the problem and perform drill-down analysis within substations. Inside substation single-line diagrams, operators can visualize side by side estimations and raw measurements in their respective nodes, verify data quality, and verify breaker and switches statuses, which change dynamically in the diagrams. Figure 3 shows an example of a display use in the control room. The left side display shows an overview single-line diagram with the geospatial layer turned off. The top right display shows an incident indicator alerting of different alarm types by regions, the middle right display shows a trend chart of some frequency signals, and the bottom display shows a tabular view with detailed information on alarms.

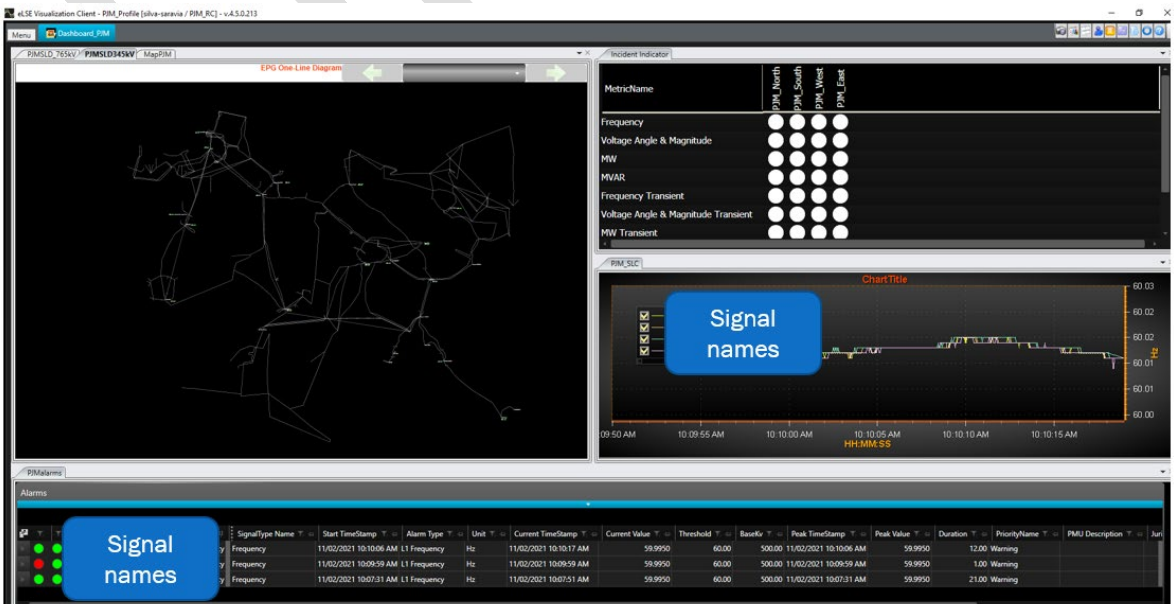

Figure 3: Example of LSE display used in the control room.

Benefits of using a Linear State Estimator at AEP

Independent Grid Situational Awareness (Backup to AEP's EMS)

Utilities have traditionally used the state estimator in the EMS for control room operations. However, the conventional state estimator may not always converge or guarantee a high-quality solution every time. This happens more frequently when the system is in a higher stressed condition or experiencing multiple contingencies. There is a critical need for the state estimator to work during these atypical conditions; a lack of situational awareness will impede the operators who are trying to make a crucial decision for their system. In such a scenario, the operators may lose the system visibility of the system condition in EMS.

AEP has deployed the LSE in their control center environments (operator training, testing and staging), with a goal to achieve an independent system for grid situational awareness. The second goal is to assist operators in assessing and diagnosing the current system conditions for initiating any necessary corrective actions to bring the system back to a more secure state. The LSE solution deployed and commissioned at AEP consists of a robust and mature technology which had been tested and validated to provide estimations with less than 1% variance, the accepted industry standard. The technology is designed to address existing challenges in traditional state estimators by providing a guaranteed solution at a much higher reporting rate, independently from EMS/SE. This allows the LSE to provide accurate information to the control room when EMS/SE is down due to hardware or software failure or physical or cyber-attacks. Additionally, given the nature of its linear algorithms, the LSE always provides an estimate of the system.

Expanded Observability

One of the key benefits of AEP's LSE deployment is the increased coverage of the monitored footprint. The LSE technology expands the real-time observability beyond the existing coverage of physical PMUs deployed in PJM, SPP and ERCOT systems. This is done by taking advantage of the model information and the available measurements to estimate voltage phasors in AEP's stations where PMU devices are not installed. Furthermore, note that the LSE's expanded observability also reduces the cost of having a fully observed bulk power system, by avoiding the high cost associated with installation and commissioning of physical PMU devices.

The expanded observability can be quantified by looking at the number of observed stations by footprint and voltage level. The following list shows an example of the impact of the AEP's LSE deployment in the highest voltage levels studied during early commissioning of the LSE — actual numbers are higher due to the addition of more PMUs before project completion.

- PJM 765 kV System – Observability increased from 47% to 87%
- SPP 345 kV System – Observability increased from 40% to 55%
- ERCOT 345 kV System – Observability increased from 38% to 56%

Similar increments are also observed at other voltage levels across the three systems, including expanded visibility at substations bordering AEP's footprint. Table 1 shows a more detailed description of AEP's observability with PMU measurements and LSE results in the PJM footprint.

Substations/KV Level	345 KV	500 KV	765 KV
Total Number of Substations	90	5	30
Observability with PMUs	19	4	14
Extended Observability with LSE	30 (+12 outside AEP)	0 (+4 outside AEP)	12 (+3 outside AEP)
PJM/AEP PMU coverage	**21.1%**	**80.0%**	**46.7%**
PJM/AEP LSE coverage	**54.4%**	**80.0%**	**86.7%**

Table 1. Observability by voltage level in PJM system.

For the 345 kV system, the observability increases from 21.1% with PMU measurements only, to 54.4% of the total system by using LSE. This represents a 157.8% increase in the observability and situational awareness. Similarly, for the 765 kV system, the observability and situational awareness of the grid increases from 46.7% to 86.6%. This represents an 85.7% increase in observability achieved by the deployment of LSE. Figure 4 shows a graphical representation of the expanded observability added by AEP's LSE deployment in the 765 kV at PJM.

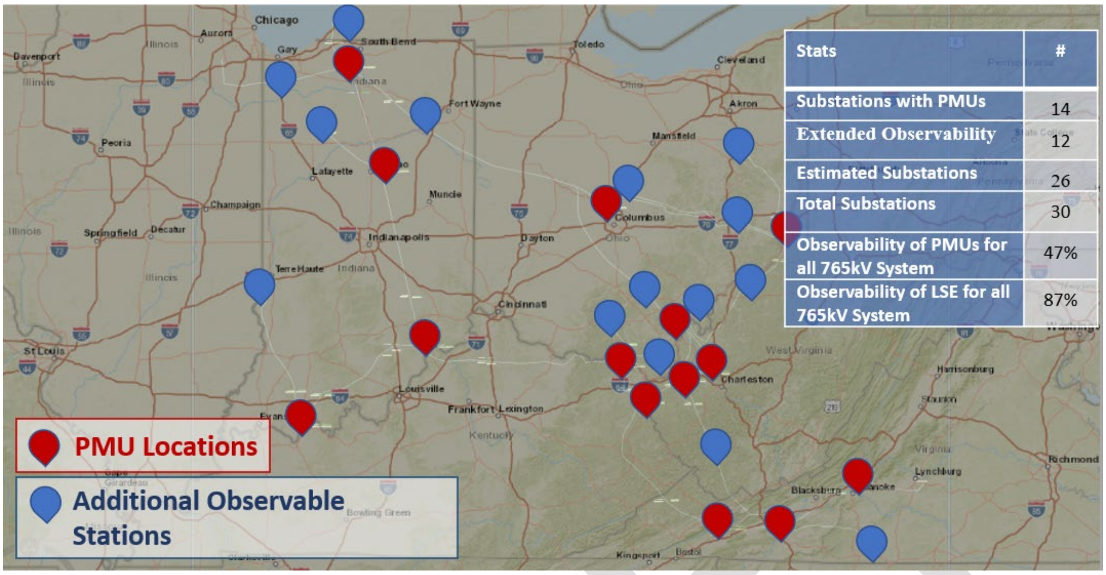

Figure 4: Extended Visibility of 765 kV PJM system with eLSE – 87% Observable.

Reliable High-Resolution Data for Monitoring Grid Dynamics

Today's power system brings new challenges to operations in the control room. Among these challenges is the presence of higher penetration of inverted-based resources (IBR), such as wind and solar generation, which are known to impact the grid dynamic behavior [4, 5]. Fast dynamics associated with IBR related to improper tuning of controllers or malfunctioning devices can induce the appearance of forced and natural power oscillations. These can translate into a wide range of operational problems, from congestion in transmission lines and line trips, to generator trip and (even) power plant damages and system blackouts.

AEP's LSE deployment provides operators with a new tool to monitor fast power system dynamics, such as oscillations, and calculate real-time analytics [6] to alarm and timely perform mitigation action to avoid the problems described above. The monitoring of the power system dynamics is achieved by providing two combined benefits: (a) high resolution data, and a (b) reliable data source.

The high-resolution data provided by LSE comes as a natural result of the mathematical characteristics of its linear equation formulation. This linearity is an advantage compared to the traditional SE, which solves an iterative problem. The linearity of the LSE enables the calculation engine to provide estimations at the synchrophasor sample rate (30 estimations per second), while traditional SE provides estimations every minute, thus making the LSE data an ideal candidate for feeding real-time oscillation analysis tools.

The reliable data source provided by the LSE is one of the main benefits of a state estimator, leveraging measurement redundancy and model information to determine the best estimate of the state of the system. In this sense, the state of the system is characterized by the estimated voltage phasors at each bus in the grid, estimated through a least-squared optimization formulation. The resulting estimations filter out bad data quality problems, including normal measurement noise, abnormal data variations (such as dropouts of angle spikes due to GPS clock problems), communication errors, and malfunctioning potential and current transformers (PTs and CTs). Furthermore, the LSE deployed in AEP's control room has the capability to automatically identify and isolate measurements that are significantly different from the estimated values, impacting the quality of the estimation. Thus, the resultant data has been validated and is trustworthy for its use in operations and for advance analytics applications, including oscillation analysis, which are sensitive to data quality problems. Therefore, the LSE deployment makes the use of synchrophasor data more robust and reliable for operators to monitor the grid and take mitigation actions, when needed.

Conclusions

Linear State Estimation is the core synchrophasor platform to provide control centers with the intelligence required to support the existing oscillation monitoring tools, by providing reliable data for real-time monitoring and event detection. AEP deployed Linear State Estimation to operate and solve for three separate regions under the jurisdiction of the three RTOs (within PJM, SPP and ERCOT systems). Linear State Estimation provides AEP with expanded observability and offers an effective solution for grid resiliency and situational awareness that operators can use when conventional systems are degraded or unavailable. AEP has already deployed the LSE in three environments and is preparing to promote the platform to be deployed in the production environment in 2022.

AEP is currently focusing on increasing the PMU deployment in the transmission system at the three interconnections, with the goal of achieving full observability of the transmission system. The deployment of the Linear State Estimation enables the infrastructure to achieve full observability. When established, it provides the oscillation analysis tools with reliable data for real-time monitoring and analysis, resulting in immediate value and benefit to AEP's transmission organization.

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