2025 Research Portfolio

Project Set – PS39A

Display Title: PS39A: Real-time Operations and Situational Awareness

Objective (The Why)

Operator situational awareness is critical to the reliability and security of the power system and minimizes disruption caused by system disturbances. Although there is an increasing availability of sensor data from power system equipment and resources, system operators generally lack optimized decision support that can be derived from this data. In most cases, operators are overloaded with unnecessary data.

The key research questions that are addressed in this research are: how can the flow of information from critical equipment on the grid to operators in a control center be optimized? How can operators recognize increased risks associated with changes to the state of the system and to react before the system risks become reality? What are the data, software, visualization, hardware, building design and human factors innovations needed to operate the power system of the future?

Approach (The How)

This project focuses on key challenges and approaches that are high priority each year and in alignment with the five-year research action plan. The current state of control center innovations is analyzed so the research team and members are tracking the state of the art.

On other specific high priority topics, the approach is to monitor, develop, and test new designs and software enhancements. The project is broken into four cross cutting workstreams:

- Operational Data and Models
    - This workstream examines the models that are used in operations technology tools such as SCADA/EMS alarms and the models of the system used in power flow calculations. This includes reference guides and technical updates.
- Operational Processes and Applications
- Development of a framework for assessing operational capabilities, processes and tools to be used as a framework for roadmaps, capability uplifts and action plans. Operational Decision Making
    - Enhancements to operator training and decision making with the aim of overall improvements to situational awareness. This includes improvements to visualization and design in real time operations,
- Operational Facilities and Equipment
    - This workstream investigates and researches new and innovative approaches to control center facilities and the use of new visualization techniques for operators.

Within each workstream EPRI researchers produce software, reports, interactive material, and regular topic-focused webcasts. The technology is transferred via case studies or supplemental projects with demonstrations and discussions at face-to-face meetings and webcasts.

Research Value

- **Improve Reliability:** Make alarm and data visualization systems predictive for the operator, make the response proactive not reactive. Enhance the operator's awareness of system implications based on alarm, sensor data with a consequent grid reliability improvement.
- **Improve Efficiency:** Introduce software and analytics to detect root causes of system disturbances and alarm floods. Operator's attention will be efficiently focused on mitigating the issue, increasing the speed of response to loss of load disturbances.
- **Reduce Human Error:** Use the techniques of mental workload monitoring and latest human factors research and training. This should reduce the safety risk for staff, public and limit unnecessary customer outages
- **Control Center of the Future:** The grid is evolving rapidly. The data, processes, software, hardware and human factors needs will have to be defined and developed so that companies can plan for and develop

the capabilities and tools for future system operations and the operators are adequately prepared for control of the grids of the future.

Anticipated Deliverables

Deliverable	Date
Operational Capability and Process Model and Automation Framework *A framework for assessing operational capabilities and processes*	Dec. 2025
Roadmap for Control Center of the Future V2025 *An update on the 2024 roadmap report to include the different functional models for transmission operators and more details on leading edge technology*	Dec. 2025
Standardized Transmission Operator Dashboards V2024 *Continuing the developments in recent years, in 2025 we will continue development of standardized dashboards in the PI tool*	Dec. 2025
AVAT - Alarm Visualization Assessment Tool V2023 *The aim is to continue to develop AVAT in 2024 and include the use of Large Language Models for querying big datasets*	Dec. 2025
Future Training Needs for IBR and Towards an Operational Readiness Centers *A guide to the training needs for operating grids with high penetrations of IBR. And the types of simulators that will be needed in future, towards an operational readiness center*	Dec. 2025
Control Center State Assessment – High Priority Research Gaps *A shot report detailing the current state of transmission operators and what the high priority gaps for research are*	Dec. 2025
Notable Power System Events information *This is a website that captures all power system related events, such as blackout, or extended outages; specifically on the affected transmission systems across the globe.*	Dec. 2025
Human Machine Interface for Transmission and Distribution Control Rooms An interactive computer based training program based on the HMI best practices guide, guiding the user through interactive examples to improve visualisation design	Dec. 2025
Advance Control Center applications	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002026968	Alarm Visualization Assessment Tool (AVAT) v2024	Alarm Management, monitoring and assessment tool for transmission and distribution operations	Dec. 2024
3002029663	Standardized Operation Dashboards V2024	Continuing the developments in recent years, in 2024 we will develop standardized dashboards in the PI tool	Dec. 2024
3002029666	Knowledgebase for Operators to Manage Inverter-based Resources	*An Interactive Technical Tutorial to support Operators in managing inverter-based resources during normal and emergency conditions*	Dec. 2024
3002030318	Notable Power System Events information	This is a website that captures all power system related events, such as blackout, or extended outages; specifically on the affected transmission systems across the globe.	Dec. 2024
3002029659	Operational Capability and Process Model	A framework for assessing operational capabilities and processes	Dec. 2024

Project Set – PS39B

Display Title: PS39B: Volt/Var Management and Power Flow Control

Objective

Voltage and reactive power control are essential for securing the proper operation of a power system during both normal and emergency conditions. Volt/var control in large networks has become very challenging due to significant changes in the system generation mix and other structural changes. These new characteristics have a noticeable impact on the way the system is to be controlled to maintain satisfactory steady-state and dynamic voltage profiles and secure operation. While current processes and methods for Volt/var control have been successfully used for many years, transmission system operators have recognized their major limitations in properly coordinating and implementing Volt/var control under these more stringent operating conditions. This drives the need for adaptations of voltage control approaches that require more complex coordination and interactions among controllers, and for improved processes and methodologies to procure and administrate var resources.

In addition, a suite of new technologies to improve the controllability and utilization of transmission networks has become available in recent years. These technologies, usually referred to as grid-enhancing technologies (GET), include advanced line ratings (Ambient Adjusted Rating, or AAR, and Dynamic Line Rating, or DLR), advanced power flow control, and topology optimization. The extensive use of these technologies may imply the need for complex control and protection schemes, especially in the case of advanced power flow control, and the adaptation of the methodologies and tools used in various operation planning and analysis tasks. The potential benefits of these technologies have been demonstrated in numerous studies and pilot projects, however, the implementation implications of using GETs from the system operation and reliability point of view have yet to be addressed. Because of this, operation engineers need a better understanding of the operation implications of having these technologies deployed in their systems.

Considering these needs, the project set is comprised of two separate but connected efforts:

1. Volt/var management and control
2. Power flow control and grid-enhancing technologies (GETs) in operations

PS39B.1 Volt/Var Management and Control

Objective

The objective of this project set is to develop strategies, methodologies, and software tools to assist utilities in dealing with various volt/var issues encountered in system operations, as well as to aid transmission planners in identifying the most cost-effective reactive power hardware solutions.

Approach

The following work will be performed in 2025:

- **Volt/var optimization**: This will continue the development and implementation of various voltage control and reactive power optimization functionalities implemented in the VCA *Studio* software, which include:
  - Reactive power reserve analysis using the voltage control area concept developed as part of this project.
  - Voltage profile optimization and scheduling of var resources in operations.
  - Optimal control settings of reactive power resources like capacitor/reactor banks, transformer taps, dynamic compensators.
  - Decision support for Volt/var issues encountered in operations to identify optimal mitigation actions for voltage violations and voltage stability risks.
  - Optimal location and sizing of reactive power resources - Help planners identify the most appropriate location, type, size/capacity, and characteristics of var resources to be installed in the system to comply with reliability standards.

The work in 2025 will expand the VCA *Studio* software capabilities by adding additional optimization functions, improved user interface, and data handling, as well as additional functionalities that may be requested by members. The work will also include additional case studies with utility members to test and prove the developed methodologies, and document results and lessons learned.

- **Impact of large loads (data centers, electrolyzers) on Volt/var control and stability**:
In recent years, there has been a significant influx of large loads interface with power electronics, mainly massive data centers, data mining farms, and, more recently, electrolyzers. Unlike traditional loads, these modern loads, driven by power electronics, might not endure disturbances as effectively. The response of these loads to system disturbance is not well understood and may impose important challenges to system operation security. Certainly, some of these new loads can draw substantial power, reaching hundreds of MW. Consequently, abrupt disconnection of these loads during disturbances can lead to significant voltage and frequency fluctuations. This task is intended to assess the impact of large new loads on voltage control and stability, identify the challenges, and devise methods and approaches to mitigate potential risks. This work was initiated in 2024 and will continue in 2025.

- **Reference Guide on Industry Practices and Tools for Voltage/Reactive Power Planning and Management (VVPM)**: The VVPM Reference Guide documents the variety of voltage and var planning and management practices and tools used by transmission planners and operators globally across the industry and identifies factors/circumstances for which certain practices may be more suited. A new version of the VVPM reference guide will be delivered in 2025.
- **Reference Guide on Reactive Power Compensation for Transmission Systems**: This reference guide presents a technical and economic assessment of various technologies for reactive power compensation and voltage control. It is intended to help planners and engineers to identify the most cost-effective reactive power compensation devices and to operate them in a more efficient manner. An updated and expanded version of this reference guide will be delivered in 2025.
- **Substation Level Active and Reactive Power Forecasting (Short-term)**: Forecasting active and reactive load at the substation level is essential for performing short-term operation studies. As the penetration of DER and new types of load increases, the conventional methods of modeling substation loads based on the regional load forecast may not be accurate, resulting in incorrect line flows and bus voltages calculated in the day ahead or RTCA analysis. This task will explore new approaches and tools to provide short-term real and reactive load forecasts on the substation bases as they are represented in the EMS system.

Research Value

This project set will deliver value to members in several ways:

- Better strategies, methodologies, and software tools to assist a) operators and operation engineers to evaluate risks of Volt/var control issues and associated security threats and help design and implement the most efficient mitigation plans, and b) planners to design optimal investment plans for new Volt/var resources.
- Optimized use of reactive power resources including reactive power capability of renewable generation
- Handy and practical technical information on existing and emerging var compensation technologies and their capabilities and use.
- Improved planning and operational processes by evaluating existing methods relative to approaches documented in the reference guides.
- Practical knowledge about emerging Volt/var control challenges derived from changes in the power system, such as the widespread deployment of large loads, and operation measures to mitigate possible negative impacts.

Anticipated Deliverables

Deliverable	Date
Voltage Control Areas and Reactive Power Optimization Software (VCA Studio) V5.2. Update of the software tool to perform various voltage and reactive power optimization functions in power systems operations and planning	Dec. 2025
Voltage and Reactive Power Optimization in Transmission Systems - Use of VCA Studio Software - 2025 Release Technical update describing the Volt/var optimization methodologies and techniques developed in this project, including optimal actions for mitigating voltage control and reactive power issues in operations and planning.	Dec. 2025
Voltage Control and Stability in System with Emerging Large Loads – *Tools and Methods for Impact Assessment and Decision Support* Analysis and characterization of the impact of emerging large loads (data centers, H2 electrolyzers) on voltage control and stability	Dec. 2025
Voltage Control and Reactive Power Management (VVPM) Reference Guide - 2025 Edition This reference guide is a compendium of state-of-the-art VVPM tools and practices used by transmission planning and operations staff for planning and operating the bulk power system	Dec. 2025
Substation Level Active and Reactive Power Forecasting (Short-term) Practical tool and process for accurate short term real and reactive load forecasts on the substation bases	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002029671	Voltage Control Areas and Reactive Power Optimization Software (VCA Studio) V5.1	Software tool to perform various voltage and reactive power optimization functions in power systems operations and planning	Dec. 2024
3002029673	Voltage and Reactive Power Optimization in Transmission Systems - Use of VCA Studio Software - 2024 Release	Document and illustrate the use and performance of the VCA Studio tool through description of comprehensive application studies	Dec. 2024
3002029676	Voltage Control and Reactive Power Management (VVPM) Reference Guide - 2024 Edition	This reference guide is a compendium of state-of-the-art VVPM tools and practices used by transmission planning and operations staff for planning and operating the bulk power system	Dec. 2024
3002029677	Voltage Stability Assessment in Systems	Tools and practical guidelines for planning and operation engineers to use voltage stability assessment methods and tools to more	Dec. 2024

Product ID	Title	Description	Published Date
	with Large Integration of IBR and DER	accurately represent and capture the effects of IBR	
3002026912	Voltage and Reactive Power Optimization in Transmission Systems - Use of VCA Studio Software	Document and illustrate the use and performance of the VCA Studio tool through the description of comprehensive application studies	Dec. 2023
3002026910	Operational Challenges in Voltage Control for Future Power Systems	Analysis and characterization of Volt/var challenges encountered in transmission operations and effective measures to mitigate them	Dec. 2023
3002026907	Voltage Control Areas and Reactive Power Optimization Software (VCA Studio) V5	A software tool to perform various voltage and reactive power optimization functions in power systems operations and planning	Dec. 2023
3002026914	Voltage Control and Reactive Power Management (VVPM) Reference Guide - 2023 Edition	A compendium of state-of-the-art VVPM tools and practices used by transmission planning and operations staff for planning and operating the bulk power system	Dec. 2023
3002026975	Reactive Power Compensation for Transmission Systems - Technical and Economic Assessment of Technologies - 2nd Edition	Reference material to identify cost-effective reactive power compensation devices and to operate them in a more efficient manner	Dec. 2023

Related Research

The work being done in this project set is closely coordinated with and designed to complement the work being done in the Integration of Distributed Energy Resources (P174), Transmission Planning (P40), and Integration of Bulk Renewable Generation (P173).

PS39B.2 Power flow control and grid-enhancing technologies (GETs) in operations

Objective

The project analyzes the operation aspects of GETS to identify potential challenges and the need for new methodologies and tools to maximize their benefits and mitigate reliability risks.

Approach

The following work will be performed in 2025:

- **Implementation issues of advanced line rating (AAR and DLR)**: FERC Order 881 requires transmission owners/providers to implement AARs in real- time operation and forecasting 10 days into the future, and to use emergency ratings for contingency analysis in the operational horizon and in post-contingency constraints. Order No. 881 does not mandate the implementation of dynamic line rating (DLR) but this technology is part of a new docket, and it is expected to be regulated in the near future. This task will analyze the implications of using AAR and DLR in real-time operations and operation planning of transmission systems, including the impact of forecast inaccuracies and the corresponding reliability risks. The impact analysis will include various operation functions and operational studies in different time frames. This work was initiated in 2024 where an industry survey and comprehensive literature review were performed to characterize the implications of using DLR in different operation and operation planning activities. The work in 2025 will focus quantification of those impacts based on statistical rating assessment and power system analysis.
- **Integration of Advanced Power Flow Control (APFC) in transmission operation:** APFC technologies are electronic-based devices that can actively change the way power flows through the transmission system without changing generator dispatch or the network's topology. These devices can divert power flow from congested lines to other circuits with spare capacity, making more efficient use of transmission assets. From the operation perspective, there is a need to develop strategies and approaches to control and operate multiple APFCs when they are used in a meshed power network to manage wide-area power flows. This task will analyze control scheme and strategies to coordinate the operation of multiple APFCs to maximize control efficacy and avoid potential adverse interactions among them. The impact consequences to the system of AFPC control scheme misoperation or failure will also be studied.

Research Value

This project set will deliver value to members in several ways:

- Practical knowledge about the implications of the widespread use of advanced line ratings in operations, and potential measures to mitigate adverse effects.
- Practical knowledge about and strategies to coordinate the operation of power flow controllers to maximize benefits to the system and avoid operating security issues.

Anticipated Deliverables

Deliverable	Date
Integration of Advanced Power Flow Controllers in transmission operation Analyze the operation and control of multiple power flow control devices and develop guidelines for system operators	Dec. 2025
Transmission operation with advanced line rating (AAR /DLR) Technical update analyzing various issues and challenges for transmission system operations derived from the widespread use of advanced line ratings.	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002029679	Impact Assessment of AAR and DLR on Operational Processes and Functions	Analyze the challenges and opportunities of using advanced line rating technologies across the operational domain, including impacts on internal/external ratings coordination, impacts on operational security practices, impacts on operational engineering support	Dec. 2024

Related Research

The work being done in this project set is closely coordinated with and designed to complement the work being done in the Integration of Distributed Energy Resources (P174), Transmission Planning (P40), and Integration of Bulk Renewable Generation (P173).

Project Set – PS39C

Display Title: PS39C: System Restoration and Emergency Operations

Objective

Ensuring that the power system is resilient to outages due to extreme events such as: severe terrestrial and solar weather, cyber-attacks, malicious actors, and others has received increased attention in recent years. Transmission system planners and operators need improved tools and methods that minimize impact under extreme events and aid in faster recovery following major outages or blackouts. Federal and state governments are working jointly with the power industry to address resiliency by focusing on approaches such as redundancy in restoration strategies and hardening of assets. Additional efforts are needed to make prudent planning and investment decisions and provide support to operators making decisions during events that test the resiliency of the system. The ultimate goals of this multi-year R&D effort are to:

- Assess role of emerging and alternate technologies such as renewable resources, energy storage, nuclear power plants, distributed energy resources, etc. in system restoration
- Develop tools that can help restoration planning and operations staff in developing, validating, testing and implementing system restoration plans
- Develop tools that can help restoration planning staff in identifying blackstart capable generating resource needs
- Develop methods and processes to improve transmission system resiliency under extreme events such as Geomagnetic Disturbances (GMD), Electromagnetic Pulse (EMP), extreme weather, loss of normal communications, etc.
- Develop advance training to prepare operators for complex system operation with increased impact from power electronics devices

Approach

In recognition of the research needs and objectives mentioned above, the 2024 work will be focused on the following:

- **Further development of restoration tools:** Over the years, EPRI has developed and advanced two tools to support the development and execution of restoration plans: 1) System Restoration Navigator (SRN); and 2) Optimal Blackstart Capability (OBC) for developing restoration plans and to better assess restoration plans and processes. In 2025, the tools will be further enhanced to account for cold-load pick phenomena during early restoration and modeling of inverter-based resources to support integration of these resources in restoration strategies. In addition, a probabilistic framework to account for viability of early restoration cranking plans following various types of extreme events (wildfires, storms, drought, etc.). The framework will be used to identify and quantify the risks, common mode (single point of) failures, etc.
- **Advancing research related to role of bulk and distribution-connected inverter-based resources in restoration**: Current EPRI research is focused on assessment of potential viability of blackstart and system restoration using inverter-based resources (IBRs). The technologies and approaches in this area are still in the development stages. The EPRI research intends to develop:
    - Analytical framework for studying the use of IBRs for blackstart and restoration support to bulk power system.
    - Planning and operation guidelines to integrate emerging technologies (wind, solar, battery) in restoration strategies.
- **Development of tools to improve situational awareness tools during extreme events:** Power Control Center (PCC) functionalities (SCADA, EMS, and AGC) are critical for reliable operation of the

grid. All credible failure modes of individual components and systems are diligently analyzed and addressed in design and maintenance practices; however, low probability events can occur which could impact EMS and/or control center functionality. To maintain operations during these events, EPRI has been working in development of tools to address partial or complete loss of SCADA. In 2025, focus will be on further development of an algorithm and process to identify, detect and isolate portion of the network that is unobservable due to missing SCADA measurements, provides reliable State Estimator solution for the remaining observable portion of the system, as well as develop functional level of situational awareness for the unobservable region.

- **Development of Grid Modeled Intrusion Detection System (GMIDS):** Recently data intrusion has become a credible threat to data integrity. In case of cyber-attacks, manipulation or disruption of SCADA can trigger a cascading impact on the grid, potentially affecting its reliability and safety. Timely identification of data anomalies, assessment of their threat level, and alerting the security team are critical to ensuring secure operation of the grid. Therefore, efforts are ongoing to develop a grid-modeled intrusion detection system that can identify anomalies, replace them with estimated values, analyze the anomalies to determine their cause, and if the analysis indicates malicious cyber cause determine its threat level. In 2025, the algorithms will be further refined to analyze SCADA measurements, characterize and classify the patterns of anomalies due to cyber-attacks and utilize the information to identify data intrusion and alert cyber security teams
- **Role of nuclear power plant in system restoration:** Traditionally, with a few exceptions, the nuclear power plants do not actively participate during the power system restoration process. Whilst this approach was relatively uncomplicated when there was an abundance of conventional power station with blackstart capability, many power systems are starting to see their restoration strategies becoming eroded following the fast shift in the generation mix. For utilities where the generation mix is dominated by inverter-based resources and nuclear power plants, the restoration process becomes more complex and demanding and the requirement to provide offsite power to nuclear facilities within a short period of time may present an additional burden. In 2024 and continuing in 2025, the focus will be in reviewing technical and regulatory challenges and investigate ways to mitigate them to allow integration of existing and future designs of nuclear power plants in power system restoration strategies.
- **Blackstart testing:** With reduction in blackstart resources, it is necessary to confirm depleted resources can still deliver a successful outcome. A robust and rigorous live blackstart testing regime must complement simulation studies. The goal of this effort is to document challenges raised by significant recent events when blackstart units failed to deliver as expected and how field testing could have avoided the failures, and provide members insights into best practices for blackstart testing.
- **System defense plans:** System defense plans are defined as technical and organizational measures undertaken to prevent localized disturbances or deterioration in the performance of the transmission system operation from escalating into a widespread disturbance or blackout. These measures generally rely on automatic response, sometimes manual, to limit the propagation of abnormal system conditions. In 2025, a framework to understand the adequacy of well-established components of System Defense Plans under fast-changing characteristics of power systems and identify new methods for increasing the reliability of the defense plans will be developed.
- **Operator Training:** One of the risks emerging in real-time environment is brittleness of the power systems with limited indication of stability limits and reduced indicators of correlation between cause and effect which impairs the ability of the operators to construct mental models, recognize patterns and draw from their extensive range of previous experiences to implement remedial actions. To manage the risk of pushing the 'human operator out of the loop', the operator training must be adapted to align with the changes and challenges introduced by power electronic devices to avoid experienced operators operating at novice level**.** The focus of this task will be developing advance and novel training methods and scenarios to prepare operators for complex system operation with increased impact from power electronics devices

Research Value

By accomplishing the ultimate goals of this multi-year project, the project funders should expect to:

- Improve reliability and resiliency through improved decision support tools for operators to address system emergencies and restoration
- Improve blackstart resource placement and investment decisions,
- Support development of emergency operations and restoration plans.
- Gain insights on integration of inverter-based variable generation, DER, energy storage in restoration plans and strategies.
- Increase operational experience in managing inverter-based resources.

Anticipated Deliverables

Deliverable	Date
System Restoration Navigator (SRN) v2025 (Pre -software) *Stand-alone tool to be used primarily by restoration planners to develop, validate, and update restoration plans.*	Dec. 2025
System Restoration Navigator (SRN) v2025 (Pre -software) *Stand-alone tool to be used primarily by restoration planners to develop, validate, and update restoration plans.*	Dec. 2025
Integrate IBRs in Blackstart and Restoration: Case Studies (Technical Update; Joint with 173A) *Provides results of case studies and demonstration conducted to assess role of wind, solar, battery storage and DER in-system restoration.*	Dec. 2025
Grid Modeled Intrusion Detection System: Algorithm and Case Studies (Technical Update; Joint with P183) *Analytical framework to identify anomalies in SCADA and estimate the missing data*	Dec. 2025
Resilient State Estimator (Technical Update) *Provides algorithm used to develop a resilient state estimator which can avoid total divergence under extreme conditions*	Dec. 2025
Role of DER in Restoration (Technical Update) *Further development of the research identifying key challenges and enhancement opportunities concerning DERs and bulk power system restoration.*	Dec. 2025
Role of Nuclear Power Plant in Restoration (Technical Update) *Summarizes technical and regulatory challenges that must be overcome to allow integration of existing and future designs of nuclear power plants in power system restoration strategies*	Dec. 2025
Blueprint for Blackstart Testing: Global System Practices, Lesson Learned and Recommendations (Technical Update) *Provide members with insights into best practices for live blackstart testing and challenges raised by significant recent events when blackstart units failed to deliver as expected*	Dec. 2025

Deliverable	Date
Framework to Review System Defense Plans (Technical Update; Joint with P40B) *Provide members with insights into the topic of System Defense Plans on when, why and how to review and improve.*	Dec. 2025
Future Training Needs for IBR and Towards an Operational Readiness Centers (Technical Update; Joint with 39A) *A guide to the training needs for operating grids with high penetrations of IBR. And the types of simulators that will be needed in future, towards an operational readiness center*	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Short Description	Published Date
3002029694	System Restoration Navigator (SRN) v13	Operation support tool to develop, validate and update restoration plans	Dec. 2024
3002029696	Role of Nuclear Power Plant in Power System Restoration	Improve understanding of technical, licensing and regulatory challenges in using nuclear power plant in restoration strategies	Dec. 2024
3002029698	Grid Modeled Intrusion Detection System (GMIDS) : Algorithms and Case Studies	Analytical framework to automatically identify and remove anomalies (due to a cyber-attack) in SCADA measurements and develop estimation techniques to fill the missing or bad data	Dec. 2024
3002029699	Role of Inverter-based Resouces in Restoration	Provide recommendations based on outcome of case studies and demonstration conducted to assess role of wind, solar, battery storage and DER in-system restoration	Dec. 2024
3002024642	Resilient State Estimation: A Non-divergent State Estimation Method	An algorithm to detect, identify and isolate the region/buses containing the cause of divergence of state estimator.	Dec. 2023
3002024703	Human Remote Terminal Unit (RTU) Identification Tool v3.0	This tool provides location and quantity of human RTUs to develop situational awareness under complete loss of control center data.	Dec. 2022
3002026984	Integration of IBR in Restoration Strategies: Case Studies Summary	Provides improved understanding of integration of emerging technologies in restoration strategies	Dec. 2023
3002026981	Small-Signal Stability of 100% IBR Dominated Power Systems During Blackstart	Overview of need and methods of evaluating small signal stability during each stage of restoration	Dec. 2023

Product ID	Title	Short Description	Published Date
3002026978	Grid Modeled Intrusion Detection System (GMIDS)	Analytical framework to automatically identify and remove anomalies (due to a cyber-attack) in SCADA data from gird point of view and develop estimation techniques to fill the missing or bad data	Dec. 2023
3002024543	Power System Restoration Reference Guide	This report summarizes principles and practices followed globally in developing and implementing plans for restoring a power system following a widespread blackout. (2020 Update)	Dec, 2022
3002024543	System Restoration Navigator v12.0	SRN is a stand-alone tool and is meant to be used primarily by restoration planners to develop, validate and update restoration plans. (2020 Update)	Nov, 2023
3002026918	Optimal Blackstart Capability Tool v10.0	The tool can be used to assess the effectiveness of existing blackstart units, or to identify potential locations to install new blackstart capability. (2020 Update)	Dec, 2023
3002024621	Geomagnetic Disturbance Operating Reference Guide	Discusses preparation actions, real-time actions and long-term action to mitigate impacts of a GMD event.	Nov, 2022
3002026981	Small Signal Stability During Restoration with Inverter Based Resources	This document provides an overview of need and methods of evaluating small signal stability during each stage of restoration	Dec, 2023

Project Set - PS39D

Display Title: PS39D: Operations Planning & Engineering Support Studies

Objective

The objective is to address challenges associated with the increasing diversity of operational conditions needed to assess risk more completely in the operations planning environment while reducing the engineering time to allow staff to spend more time analyzing results. Improving risk management in operations planning is driven by the growth in the operational uncertainty associated with renewable generation, changing generation mix and increasingly active distribution resources. This effort focuses on supporting operations planners with that challenge by substantially increasing the level of automation in the grid analysis process for tasks such as outage screening, optimal scheduling, and practical scenario creation, with expected benefits in terms of both the identification and mitigation of conditions that pose an operational challenge.

Applying existing operational planning practices to this emerging paradigm will become increasingly labor intensive and may not identify operational risks with the same accuracy. This project focuses on leveraging continuously improving decision support and automation to address such challenges while maintaining system reliability.

Approach

The focus of this project is to develop and integrate advanced solution methodologies and tools for power system analysis that supports the needs of operations planning grid. There are multiple workstreams being addressed in this project set and the approach taken to address them are described below:

- **Optimal Outage Scheduling**: This is focused on improving the coordination of scheduled outages to minimize reliability issues and costly repositioning by implementing more proactive rather than reactive processes. It looks at optimization and Artificial Intelligence (AI) methods to improve the scheduling of outages to be more optimal and improve coordination between asset owners and schedulers while performing efficient, automated studies. In 2025, the current first come first serve methods will be compared to optimal methods in case studies and prototype software.
- **Case Selection and Building**: This is focused on developing processes to identify scenarios that are feasible and pose the most risk to the system that need to be studied in operations planning – including outage scheduling. To study these scenarios efficiently, this work also focuses on developing automated processes to build the cases to perform the studies and allows engineers to spend more time studying results. In 2025, methods to create realistic generation dispatch profiles will be explored.
- **Operational Performance Analysis**: Currently, there is rarely a study of inadequacies in operational cases unless there is a postmortem on an event. This workstream focuses on developing metrics and systematic methods to evaluate the performance of operational cases to predict and encompass the risk realized in real-time operations. Metrics for evaluation are being developed and how to calculate them and then use them to drive changes to improve the cases are explored. In 2025, case studies to refine metrics and iterate on performance analysis methods will be performed.
- **Operations Models**: With higher penetration of renewable generation, increasing electrification and larger power electronics-based loads, system loads and generation patters as well its dynamic characteristics can drastically change in a relatively short time. This necessitates reevaluation of system modeling needs as well as security assessment needs for reliable operation of the electrical power system. This workstream will investigate types of system simulations needed for the assessments, scenarios and types of disturbances and contingencies to be studied. It will also investigate system, generation and load models needed for those simulations. It will also be important to address need for periodicity of such assessments, computational efficiencies needed for timely assessments of reliability threats and evaluations of mitigation measures needed for secured operation of the grid.
- **Contingency Generation and Screening:** While NERC requirements mandate N-1 contingency analysis in the real-time operations environment, frequent system updates and evolving technologies have made contingency modeling a burdensome and time-consuming task. Incorporating the Advanced Reliability Toolset (ARTS) platform into the operations planning horizon aims to simplify the process.

Screening of these contingencies can also pinpoint facility outages that may be especially problematic, leading to dynamic or cascading outage scenarios.

Research Value

By successfully applying and automating probabilistic study tools needed to address the operational uncertainty challenge, the following benefits are sought:

- Reductions in the engineering time needed to study individual planned outage request scenarios with high resolution of detail by more than 80%,
- Earlier detection of outage conflicts and reliability issues increasing cancellation risk, leading to greater efficiency in the use of outage windows and maintenance crews,
- Improved assurance of the probability and impact associated with forced outages of grid assets, leading to reduced operating costs and reliability in variable periods,
- Incorporating good practices from other utilities and ISOs around the world on operational planning processes and practices, and
- The ability to apply the tools and methods in practice through engagement with vendors and the open-source community.

Anticipated Deliverables

Deliverable	Date
ARTS in Operations Planning: A white paper to explore use of the Advanced Reliability Toolset (ARTS) platform to perform automatic contingency generation for operations models and contingency screening to identify the most significant, potential reliability impacts. (Joint Deliverable with P40E)	Dec. 2025
Automated Outage Coordinator (AOC) v2.3: A tool to automate outage studies that generates scenarios, executes studies and visualizes outcomes. Improvements in 2025 will focus on more modularization of the scheduling, screening and scenario creation portions of the tool for easier use.	Dec. 2025
Optimal Outage Scheduling: Applications of AI and Case Study: Build on 2023 methodology by looking at how AI methods might be able to improve schedules and speed up the optimization process. Apply the methods to case studies.	Dec. 2025
Benchmarking Operational Forecasts: Update and Large Load Impacts on Performance: Annual update on operational load forecasting performance benchmarks and focus on investigating performance in areas that are seeing large load interconnections impact the forecasting performance	Dec. 2025
Operational Models: Data and Validation Needs in Operations: The models used in operations - particularly for dynamics/EMT - can be different than planning models and more accurate if using operational data. This effort will focus on what are the data, modeling assumptions, and validation needed for operational models to improve studies. (Joint with all P39 & P173B)	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002029701	Automated Outage Coordination (AOC) v.2.2	Continue development of platform to test automation of outage scheduling case building, scenario generation and outage screening.	Dec. 2024
3002029703	Methodologies for Optimal Outage Scheduling	Develop a process and methodology for a proactive optimal or reserve outage scheduling system.	Dec. 2024
3002029704	Benchmarking Operational Forecasts: Performance During Extreme Events	Continue and expand on providing benchmark performance of publicly available operational forecasts. (Joint with P173B)	Dec. 2024
3002026925	Automated Outage Coordinator (AOC) v2.1	Adds important new capability for snapshot (planning) studies, improvements to the options for building study scenarios, providing a Single-Line Diagram (SLD) to review results, improvements for creating contingencies, and improvements to ease of installation and application start for Windows.	Dec. 2023
3002026990	Benchmarking Operational Forecasts	This research seeks to establish benchmarks for load forecasts by examining the performance of forecasts across the United States and Europe for the years of 2017-2023	Dec. 2024
3002026993	Scenario Development and Case Study	In this report, the potential to automate the outage scheduling process is investigated while applying a clustering approach to study the outage approval process under additional data-driven scenarios of varying load and renewables levels.	Dec. 2023
3002026927	Planned Outage Grouping Case Study	In this report, the potential to automate the outage scheduling process is demonstrated while applying a machine learning-based screening approach to study the outage approval process, with grouping and reprioritization of outages based on their predicted statuses.	Jan. 2024
3002027326	Performance Assessment of Ops Planning & RT Ops (TI Project)	This effort is an initial step to create a methodology for assessing the operations planning study cases built compared to the real-time conditions to try and identify areas for improvement in the case building process	Dec. 2023
3002027329	ML & AI for Prioritization of Outage Scheduling (TI Project)	In this research effort, a literature review of optimal scheduling practices is provided to evaluate practicality and ability for machine-learning techniques and heuristics to be applied. In addition, current research efforts for applying machine-learning techniques to screening outages are detailed.	Dec. 2023
3002027327	Algorithms and Tools for PCM to Feasible ACPF (TI Project)	Details the development of scripts and methodologies using EPRI internal tools to derive AC feasible cases for reliability studies from cases produced by production cost modeling (PCM) or capacity expansion modeling (CEM).	

Related Research

Load Forecasting Initiative: This project intends to advance the state-of-the-art in load forecasting across system planning and operations. These advancements are planned to be tool-agnostic and be made available to be applied by utilities, ISOs/RTOs, and load forecast providers, with case studies demonstrating their effectiveness. Additionally, this project intends to expand EPRI's capabilities for load forecasting research, while integrating existing knowledge from related EPRI work, e.g., Climate READi. Key objectives of the project include:

1. Develop EPRI's forecasting research roadmap and business strategy.

2. Develop and demonstrate a holistic framework for creating long-term/planning forecasts.

3. Assess current short-term forecasting methodologies and develop targeted improvements for prioritized gaps, e.g., extreme weather.

4. Provide guidance on data inputs, covering both data availability and the impacts of data choice based on case studies.

Project Set – PS39E

Display Title: PS39E: Monitoring, Analysis, and Control Using Synchrophasors

Objective

Today's state-of-the art in grid monitoring and control is based on the Supervisory Control and Data Acquisition (SCADA) system as well as the Energy Management System (EMS). Significant changes in the characteristics and utilization of the grid driven by changes in generation mix, integration of renewable resources and demand variability, as well as communication network and sensor technology advancements (e.g. synchrophasor technology), necessitate the need for advanced grid monitoring, analysis and control functionalities.

A grid monitoring, analysis and control infrastructure is envisioned that will leverage recent technology advancements in sensors and communications to enable use of high-resolution measurements and will leverage the advanced control capabilities of inverter-based resources (IBR) interconnected to the grid for provision of grid services. It is expected that synchrophasor technology will be a major component of this infrastructure. The deployment of Phasor Measurement Units (PMUs) and other devices that provide high-resolution synchronized measurements in transmission grids is continuously increasing, and along with this, numerous synchrophasor-based applications have been and continue to be developed, both for offline and online environment. Wide area monitoring systems (WAMS) are being deployed in transmission control rooms to complement EMS and provide to the grid operators advanced applications for situational awareness and security assessment.

The goal of this multi-year R&D effort is to facilitate adoption and application of synchrophasor technology in transmission control center operations through the development of advanced techniques and tools that enable the envisioned grid monitoring, analysis and control infrastructure. Topics covered in this project include:

- Synchrophasor applications that facilitate reliable and efficient grid integration of renewables.
- Synchrophasor applications for automated closed-loop grid control.
- Adoption of WAMS and integration with EMS.
- Integration of distribution PMU measurements and synchronized waveform measurements into transmission control center applications.
- Use cases of real-time (RT) simulators and hardware-in-the-loop (HIL) experiments for implementation and testing of wide-area monitoring protection and control (WAMPAC) systems.

Approach

The following work is planned to be performed in 2025:

1. **Oscillations Monitoring, Analysis and Control:** Due to emerging grid transformations, more frequent and severe oscillation events are being experienced in power grids around the world. This work focuses on the development of tools for mitigation of natural and forced oscillations, including IBR-induced sub-synchronous oscillations. Power oscillation damping (POD) controls for IBR are also investigated in this work.
2. **Synchrophasor Based Inertia Monitoring**: Increasing grid integration of IBR may result in system inertia reduction. Low levels of system inertia might jeopardize the dynamic stability performance of the grid. An emerging PMU application is real-time estimation and monitoring of system inertia which is expected to be valuable for low inertia systems and help evaluate requirements for the use of fast-frequency response (FFR) and sufficient amount of reserves to prevent triggering of under-frequency load shedding (UFLS) protection schemes.
3. **Synchrophasor Measurement and Machine Learning Based EMS/WAMS Applications**: The application of artificial intelligence (AI) and machine learning (ML) techniques using synchrophasor data for providing situational awareness and security assessment to the system operators, is of growing

interest. This work focuses on the use of PMU measurements in combination with ML for novel implementation of EMS/WAMS applications such as state estimation and dynamic security assessment (DSA) and explores the benefits of using those complementary to conventional applications in transmission control centers.

4. **Integration of Distribution PMU and Synchronized Waveform Measurements in EMS/WAMS**: Integration of distributed energy resources (DER) in the distribution systems is resulting in interactions of the distribution and transmission grids. The use of distribution-level PMUs to capture distribution grid dynamics and interactions with the transmission system is emerging. This work investigates the use cases of distribution PMU measurements and their integration in EMS/WAMS applications. In addition, synchrophasor measurements provided by PMUs have limitations in monitoring high-frequency dynamics associated with IBRs. This work investigates the use cases of synchronized waveform measurement data and their integration in EMS/WAMS applications.
5. **Adoption of WAMS and WAMPAC**: Adoption of synchrophasor technology into transmission control centers is achieved through WAMS. While WAMS systems are typically deployed as independent systems, integration with EMS is desired to support control room operators. In addition, utilities are establishing advanced laboratory facilities to create, model and test new technologies for power systems including WAMPAC systems. Real-time simulators are a critical component of these facilities and are expected to benefit and accelerate the advancement and deployment of WAMPAC systems. The project investigates use cases and the value of RT-HIL simulations in advancing and deployment of WAMPAC systems.

Research Value (

By conducting the R&D efforts and accomplishing the goals described above, project funders should expect to derive the following potential benefits:

1. Advanced real-time situational awareness, security assessment and resilience through advanced monitoring and analytics
2. Securely and efficient integration of increased levels of renewable resources
3. Enhanced system reliability and security through faster, optimized and robust control of the grid

The R&D results are expected to provide value to both ISOs and utilities (either vertically integrated or member of an ISO).

Anticipated Deliverables

Deliverable	Date
Forced Oscillation Localization Tool (FOLT) (Software): *Identifies the source of forced oscillations using PMU measurements.*	Dec. 2025
IBR Induced Oscillations Source Location (Tech Brief; Joint with 173A): *Investigates algorithms for identifying the IBR responsible for sub-synchronous oscillations*	Dec. 2025
Inertia Estimation Toolbox (IET) (Software; Joint with 173B): *Estimates system inertia using PMU measurements*	Dec. 2025
Inertia and Frequency Nadir Estimation in IBR Dominated Grids (Tech Brief;Joint with 173B): *Documents methods to estimate system inertia and frequency nadir using PMU measurements in IBR dominated grids*	Dec. 2025

Deliverable	Date
Machine Learning & PMU Based Transmission Control Room Applications (Tech Brief): *Documents machine learning methods that use PMU measurements for various transmission control room applications*	Dec. 2025
Integration of Distribution PMU Data in Transmission Control Room Applications (Tech Brief): *Discusses the value of integrating distribution PMU data in transmission control room applications*	Dec. 2025
Integration of Synchronized Waveform Measurements in Transmission Control Room Applications (Tech Brief): *Discusses the value of integrating synchronized waveform measurement data in transmission control room applications*	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002029706	Forced Oscillation Localization Tool Case Studies	Summarizes case study results using FOLT	Dec. 2024
3002029707	Machine Learning Based Dynamic Security Assessment Using PMU Measurements	Summarizes machine learning algorithms and models for security assessment using PMU measurements	Dec. 2024
3002029708	Machine Learning Based State Estimation Using PMU Measurements	Summarizes machine learning algorithms and models for state estimation using PMU measurements	Dec. 2024
3002029709	Distribution PMUs - Technology Review and Use Cases	Summarizes uses cases of distribution PMUs	Dec. 2024
3002029710	Synchronized Waveform Measurements - Technology Review	Summarizes latest developments in synchronized waveform measurement technology	Dec. 2024
3002026930	Forced Oscillation Localization (FOL) Tool - Offline v3.0	Software tool to identify the source of forced oscillations using PMU measurements. Offline version	Dec. 2023
3002026931	Forced Oscillation Localization (FOL) Tool - Online v1.0	Software tool to identify the source of forced oscillations using PMU measurements. Online version	Dec. 2023
3002026932	Graph Neural Network Based Grid Health Index Tool (GNN-GridHI) v1.0	Tool that performs security assessment of a transmission grid using PMU measurements and machine learning	Dec. 2023
3002026940	Security Assessment with PMU Measurements and Machine Learning	Investigates machine learning algorithms and models to conduct security assessment using PMU measurements	Dec. 2023

Product ID	Title	Description	Published Date
3002026996	Integration of EMS/SCADA with WAMS	Summarizes techniques, protocols and architectures for integration of EMS/SCADA with WAMS	Dec. 2023
3002027270	Inertia Estimation Toolbox (IET) v3.0	Estimates system inertia using PMU measurements	Dec. 2023
3002027272	Inertia Estimation and Monitoring: Algorithm and Case Studies	Documents analytical framework for inertia regionalization, estimation and monitoring	Dec. 2023