2025 Research Portfolio

P40 – Transmission Planning

Program Description/Overview

Traditional power system planning methods and tools are increasingly challenged in today's power system environment as utilities embark on de-carbonization pathways while ensuring system reliability is not only maintained but improved with more emphasis on electrification. This is further compounded by necessity to make system more resilient against extreme events related to extreme weather, cyber-physical security, and other causes. Transmission owners and operators not only need to plan for future demand growth and increasingly uncertain generation portfolios, but also to provide transmission services for scenarios with vast amount of renewable generation sources that are often remote from load centers and have significantly different behavior from synchronous generation. The challenge of meeting reliability and resilience requirements with the changing landscape and increasing levels of uncertainty may necessitate adjusting and enhancing transmission planning criteria and methods requiring new tools and models for transmission planners. Some of the areas for significant research that will help planners to deal with challenges moving forward are:

- Generic, easy to use models of emerging generation, load, and transmission technologies that can be validated periodically for planning studies
- Efficient approaches to generate and screen contingencies for stability concerns to reduce resource and time burden
- Practical framework to plan the system to withstand extreme events such as the impacts of geomagnetic disturbances, electromagnetic pulses, natural events, and various physical security attacks on system resilience
- Consideration of impact of extreme weather events on transmission resilience
- Consideration of impact of climate change along with other policy goals on long-term planning
- Application of risk-based reliability approaches for optimal investment decision for long-term transmission reliability
- Use of high-performance computing (HPC) architecture along with machine learning (ML) and artificial intelligence (AI) for planning studies
- Use of node-breaker models for reliability studies
- Integration of power electronic-interfaced transmission assets such as HVDC, FACTS, grid enhancing technologies (GETs), energy storage, and distributed resources in transmission planning
- Voltage and reactive power management with higher integration of inverter-based resources (IBR)
- Study methods and tools for more specialized topics like sub-synchronous resonance, control interactions, transmission power quality, electromagnetic studies (EMT) etc.
- Protection consideration to keep up with the changing grid specifically including efficient tools to check protection settings for changing system conditions, tools for proactively identifying protection mis-operations and near-misses from a large data repository, validating short-circuit models based on event data, and incorporating protection models in planning studies for higher accuracy in certain cases.
- Integrated planning framework that places transmission planning in the broader context of power system planning ranging from resource planning, T&D deliverability planning, and end-use assessments. Many utilities are embarking on such a comprehensive planning framework and the research in this program plays a pivotal role along with other research programs at EPRI.

Research Value

The mission of EPRI's Transmission Planning research program is to help planners to navigate through the transformative changes in the power system to plan for a grid that is safe, reliable, resilient and economical to operate. The research topics in the program provide the following benefits:

- Innovative methods and tools for reliable and economic integration of new energy resources and end-use loads
- Tools, methods, key insights to transmission planners to save time, mitigate risks, and reduce costs while maintaining reliability and resilience
- Engagement with various stakeholders including regulatory agencies, industry standard groups, and government agencies to advance state-of-the-art transmission planning to benefit public at large and reduce risk for grid operators
- Forum for members to collaborate among each other, expert researchers, and technology providers to solve near-term issues as well as identify and prioritize long-term research needs that collaborative research should address.

Approach

EPRI's Transmission Planning research program delivers value by using the shared experiences and understanding of its utility and ISO members, in conjunction with the expertise of EPRI's staff and network of expert consultants. The program conducts research projects that lead to innovative insights, methods and tools used by system planners. The program also engages with external industry standards groups, regulatory agencies, and other research efforts to ensure that it is building upon and leveraging broader stakeholder efforts and advancing the state-of-the-art. For research areas where the developed deliverables are of value to EPRI members only if embraced by the larger stakeholder community, for example as with the development of new models that need to be adopted in commercial analysis packages, EPRI works to engage in stakeholder efforts and share research publicly to inform society and all stakeholders. The EPRI research program also strives to provide near-term, mid-term, and long-term value from each research project. For example, the 2025 Transmission Planning research program will continue to deliver guidelines on different topics which transmission planners can find useful for their day-to-day work. On the other hand, many projects have multi-year objectives where incremental work is being performed for past 2-3 years with long-term objectives in mind. The research in the Transmission Planning program addresses five primary areas:

- Model Development, Validation, and Management
- Protection Methods, Tools, and Guides
- Methods and Framework for Advancing Transmission Planning
- Special Assessments Supporting Transmission Planning
- Analytics for Emerging Transmission Planning Needs

The research in this program is coordinated with other TO&P programs as well as other EPRI programs such as Energy Storage, Energy Systems and Climate Analysis, Integration of DER, Distribution Planning, Integrated Resource Planning, Electric Transportation, and initiatives such as Climate READi, Grid Enhancing Technologies, Load Forecasting, and Low Carbon Resources Initiative (LCRI). Externally, the program participates in research areas funded by organizations like U.S. Department of Energy (DOE), national labs, New York State Energy Research & Development Authority (NYSERDA) and international organizations such as Global Power System Transformation Consortium (G-PST). The research is carried out by EPRI subject matter experts in close collaboration with industry consultants, academia and industry organizations to ensure high-quality research is always delivered.

Accomplishments

The Transmission Planning program delivers valuable information that helps its members, other electric power stakeholders, and society in numerous ways. Some examples include the following:

- ***Power Plant Parameter Derivation (PPPD) Version 15.0 (3002025588):*** The PPPD software tool is a simulation program that can be used for validating and parameter estimation of models for synchronous generator power plant, wind and PV power plants, and static var systems. The tool uses measured generation equipment responses to system disturbances to validate the generator, excitation system, and governor control system transient stability models. This tool allows generation owners to perform ongoing model validation as system disturbances occur to support system reliability and to comply with emerging North American Electric Reliability Corp. (NERC) requirements to periodically validate the generator models.
- ***Load Component Export Tool (LCET) 5.0 (3002025588):*** The LCET simplifies the process of calculating composite load model parameters and exporting them to file formats used by simulation tools Siemens PTI PSS®E and GE PSLF™. Users can export load model parameters for multiple areas/zones in a planning case.
- ***Load Model Data Processing and Parameter Derivation – Python V1.0 Beta (3002027013):*** Allows transmission planners to parameterize their load models based on event data measurement.
- ***Protection Settings Evaluation Tool (PSET) (3002025028, 3002025029):*** These deliverables provide macros that integrate into commercial short circuit analysis software tools to allow the user to configure aspects of a system-wide short circuit study and then execute the simulations and report on the results. Based on the configuration from the user, the tool identifies protection systems which may mis-operate allowing the user to identify potentially incorrect relay settings prior to mis-operation occurring.
- ***Protection in Planning Studies Tool (PIPS), Version 4.0 Beta (3002024988):*** The purpose of this tool is to create appropriate protection relay models on particular grid equipment and populate the device models with conservative setting assumptions. The tool can then be tested on real grids to assess if these generic protection relay models can successfully identify credible protection issues.
- ***Protection Relay Settings Peer Review Tool/OneLiner, PSS-CAPE (3002027551):*** Automatically perform and document peer-reviews of protection relay settings.
- ***Short-Circuit Model Validation and Error-Identifying Tool for OneLiner (3002027550):*** A tool to simplify the process of short circuit model validation against fault event records.
- ***High Level Screening (HiLS) Tool:*** Analyzes complex dispatch data to select a subset of operating snapshots that can be studied for future system reliability.
- ***Adaptive Coordinated Expansion Planning (ACEP)***: Is a computational tool for identifying generation, transmission, and emerging technologies (e.g., storage) investments over long horizons of time (e.g., 10–40 years) .
- ***Resilience System Investment Framework (RSIF):*** The Resilient System Investment Framework (RSIF) and its associated tool are developed to help transmission planners assess the impacts and consequences resulting from the application of High Impact Low Probability (HILP) contingency events on their systems. RSIF evaluates the resulting impacts to determine possible paths of cascading failures and the associated consequences, using customized power flow approaches to minimize the likelihood of a divergent power flow solution.
- ***GICharm (3002027071):*** This tool is designed to study GMD-related harmonics
- ***Transient Recovery Voltage (TRV) Screening Tool (3002027047):*** This tool is developed on EMTP-RV platform to perform simulations to screen TRV results against available circuit breaker capability. The tool performs breaker TRV analysis with predefined circuit configurations for easy setup and quick initial assessment. Planners can use this tool to determine if a detailed TRV analysis is needed.
- ***Positive Sequence Impedance Scan Tool (ZSCAN V1.2) (3002027064):*** Enables impedance scans in positive sequence domains (PSSE) with active devices near the scanned bus.
- ***ZSCAN-EMT V1.0 Beta (3002027059):*** PSCAD based impedance scan module enables users to assess impedance and stability of a system for a range of various frequencies.
- ***Advanced Reliability Toolset (ARTS) (3002027108):*** A methodology for constructing node-breaker planning models to automate contingency generation.

- ***Controlled Transmission Expansion Planning (CPLANET) (3002027092):*** CPLANET explores various mathematical modeling and numerical optimization approaches for transmission expansion planning considering power flow control devices such as phase-shifting transformers (PSTs)
- ***HVDC Planning Guide: 2023 Update (3002027098):*** Summary of the HVDC planning process, including studies to perform and modeling guidelines.

Key Activities

In 2025, EPRI's Transmission Planning research program will focus research on the following objectives:

- **Model Development, Validation, and Management**
  - Modeling of emerging loads such as EV charging stations, data centers, hydrogen electrolyzers
  - Improvements to the composite load model and help utilities with development and adoption of the composite load model
  - Measurement-based load modeling approach and data collection
  - Aggregated DER model adoption, data aggregation approaches to develop the model, DER representation in transmission system in the context of FERC O2222 (jointly with P173A)
  - Modeling of HVDC controls for off-shore wind connection
  - Grid forming controls for HVDC
  - Refinements to generic models for FACTS and HVDC as needed
  - Guidance on capabilities and limitations of models, simulation platforms
  - Industry collaboration through NERC and WECC working groups
- **Protection Methods, Tools, and Guides**
  - Knowledge transfer through topical webcasts and workshops
  - Protection tools and algorithms
    - Short-circuit model validation tool (SHOVAL) to automate the process of short-circuit model validation and identification of root cause of discrepancies in models and field data
    - Protection Settings Peer Review Tool for comprehensive analysis of relay settings and coordination
    - CIM import/export tool for ASPEN OneLiner and Siemens PSS-CAPE
  - Protection considerations under extreme weather
  - Roadmap to adopt Centralized Protection Schemes (CPS) for transmission protection
  - Protection considerations for grid enhancing technologies
- **Methods and Framework for Advancing Transmission Planning**
  - Support technical aspects related to latest FERC Orders (O896, O1920) and associated NERC efforts
  - Improvements to the Resilient System Investment Framework (RSIF)
  - Assess impact of extreme weather and climate on transmission resilience
  - Develop a framework to assess impact of physical security vulnerabilities on transmission resilience
  - Develop a framework to incorporate the impact of cyber security vulnerabilities on transmission resilience
  - Improvements to the statistical analysis framework in High Level Screening (HiLS) tool to cluster hourly production cost runs
  - Data analytics and outage statistics for transmission planning reliability studies
  - Support transmission planning as part of the comprehensive integrated planning analysis for assessing reliability of decarbonization pathways
  - Update coordinated expansion planning tools - Johns Hopkins Stochastic Multi-Stage Integrated Network Expansion (JHSMINE) and Adaptive Coordinated Expansion Planning (ACEP) tools for co-optimization generation and transmission expansion plans
  - Topical webcasts, quick insights on existing issues.

- **Special Assessments for Transmission Planning**
  - Refine and maintain GICHarm tool for harmonic compliance studies for TPL-007
  - Refine and maintain B2E tool for easy conversion magnetic fields to electric fields
  - Updates to GMD planning and operations guides
  - Refine IBR harmonic models
  - Update IBR harmonic modeling and study guide
  - Guide on flicker analysis in presence of IBR
  - Guide on TRV studies
  - Tool to analyze lightning and switching transients
  - Guide on temporary overvoltage studies
  - Refinement to E-Energize tool for analyzing transients for transformer switching
  - Assess impedance-based and eigenvalue-based methods for assessing small signal stability
  - Refine screening methods for SSO analysis
  - Guidelines for performing SSO analysis in EMT
- **Analytics for Emerging Transmission Needs**
  - Refinement to Advanced Reliability Toolset (ARTS)
    - An approach to develop node-breaker models in planning cases using EMS data by using topology mapping
    - Refine the approach to improve contingency screening algorithms in systems with high penetration of IBR
  - Explore use of High Performance Computing (HPC) for reliability assessments
  - Guidelines on assessing impact of increasing HVDC links in transmission system
  - Consideration of Multi Terminal dc (MTDC) grids in transmission planning
  - Assess use of HVDC to provide ancillary services
  - Updates to the HVDC planning guide
  - Refine Controlled Planning Framework (CPLANET) tool for integrating Grid Enhancing Technologies (GET) in transmission systems
  - Updates to GET reference guide
- Close collaboration with industry stakeholders – WECC, NERC, IEEE, software providers, and equipment providers on modeling and model validation for transmission planning
- Guidance and technical insights through brief technical updates, detailed guidelines, timely webcasts on relevant topics
- Conduct workshops on various topics as needed or based on member feedback
- Support EPRI initiatives related to integrated planning (ISSP), Climate READi, Low Carbon Resource Initiative (LCRI), Data Centers, Load Flexibility among others.

Estimated 2025 Program Funding

$6.5M

Program Manager

Anish Gaikwad

Project Set – PS40A

Display Title PS40A: Model Development, Validation, and Management

Objective

Development, parameterization, and validation of models suitable for bulk power system studies is a critical aspect in assessing system reliability in transmission planning. While significant progress has been made over the years, advent of new technologies across generation and transmission assets, and new end-use loads due to digitization and decarbonization of society has created the need to provide practical, easy to use models that are available in commercial tools used in transmission planning. Transmission planners also need guidance on model parameterization, validation, and overall, a better understanding of the models to be able to use them for right application and trust the results to make judicious investment decisions. The objective of this research project is to fulfill this need and provide a collaborative platform by bringing planning entities, software and hardware vendor communities, reliability organizations, various industry forums, academia, and other research organizations together to advance the state-of-the-art and provide an unbiased platform to facilitate exchange of information.

At present, the research topics addressed in this project set are as follows:

1. **Load Modeling**
   Continue to advance load modeling research for bulk power system studies by refining the existing load models and creating ones for new load types (EV chargers, data centers, cryptomining, and electrolyzers among others), and assisting utilities with the adoption of these models.
2. **Distributed Energy Resource (DER) Modeling**
   Help utilities with modeling of DERs for transmission stability studies including assessment of interconnection requirements such as the IEEE Std 1547-2018.
3. **Modeling of Inverter-Based Transmission Technologies**
   Develop and benchmark new, or refine existing generic models related to HVDC, FACTS, GETs components across major software platforms used by utilities in North America and around the world

Approach

This is a multi-year research effort that is designed to be flexible to address both short- and long-term challenges. The research portfolio is executed on an annual basis with the long-term objective in mind.

The 2025 research work focuses on:

1. Development of models for emerging loads like data centers, hydrogen electrolysis plants, electric vehicle supply equipment (EVSE). Model development will span across both phasor/positive sequence and electromagnetic transient (EMT) simulation platform.
2. Identifying and characterizing any reliability risks posed by these new emerging loads and providing guidance on the assessments needed as these new large loads interconnect to the grid. These assessments span across impact of load ride-thru to high frequency interactions like sub-synchronous resonance. This part of the research will be coordinated with project sets P40D and P173A respectively
3. Identify improvements needed for heat pump modeling as electrification of space heating becomes more pervasive.
4. Laboratory testing of EVSE to characterize response of EV chargers (level 1, 2, and dc fast charging) during grid-to-vehicle as well as vehicle-to-grid mode
5. Conduct industry workshops to disseminate important guidance on usage of positive sequence and EMT modeling, modeling of emerging load, transmission, and generation technologies.

This research project leverages multidisciplinary subject matter expertise within EPRI as well as well-known experts from the industry to develop, refine, and benchmark various generic models as needed by the transmission planners. EPRI's tried and tested vendor engagement is pivotal in working closely with software vendors so that they implement the generic models developed as standard library models in their respective platforms. To demonstrate efficacy of the developed models, pilot studies are performed through this project. Additionally, the project team collaborates with utility members to perform case studies via supplemental projects for widespread usage of the models and research performed in the project. Lastly, the project team is actively

engaged with industry groups like WECC and NERC Load Modeling Working Group, WECC Modeling and Validation Sub-Committee, and NERC System Planning Impacts of DER (SPIDER). Research approach for each one of the areas is summarized as follows:

1. **Load Modeling**
    a. Development of models for emerging loads like data centers, hydrogen electrolysis plants, electric vehicle supply equipment (EVSE). Model development will span across both phasor/positive sequence and electromagnetic transient (EMT) simulation platform.
    b. Identifying and characterizing any reliability risks posed by these new emerging loads and providing guidance on the assessments needed as these new large loads interconnect to the grid. These assessments span across impact of load ride-thru to high frequency interactions like sub-synchronous resonance. This part of the research will be coordinated with project sets P40D and P173A respectively.
    c. Identify improvements needed for heat pump modeling as electrification of space heating becomes more pervasive.
    d. Laboratory testing of EVSE to characterize response of EV chargers (level 1, 2, and dc fast charging) during grid-to-vehicle as well as vehicle-to-grid mode.
    e. Conduct industry workshops to disseminate important guidance on usage of positive sequence and EMT modeling, modeling of emerging load, transmission, and generation technologies.
2. **Modeling of Inverter-Based Transmission Technologies**
    a. Development of models for point-to-point VSC-HVDC systems as well as MTDC systems (EMT and phasor/positive sequence) capable of representing embedded HVDC links, for offshore wind/remote renewable interconnection, as well as meshed dc systems.
    b. Developing dynamic models for grid enhancing technologies like power flow controllers and evaluating their impact on system dynamics.
    c. Conduct industry workshops to disseminate important guidance on usage of positive sequence and EMT modeling, modeling of emerging load, transmission, and generation technologies.
    d. Demonstrating the application of these generic models through collaborative projects with utility members

Research Value

The core value of this research lies in developing better representation of power system components that will help transmission system planners make judicious planning decisions, in particular:

1. Help transmission planners with more accurate representation of loads, DERs, transmission devices, and generation plants in bulk power system studies to assess their impact on system stability and identify any reinforcement options.
2. Comprehensive, reliable, easily accessible one-stop repository of state-of-the-art research on power system dynamic modeling to help members to develop skillsets internally.
3. Industry collaboration with WECC, NERC, and other industry groups providing a platform for sharing information.
4. Overall improvement in system reliability as well as insights on where additional system investment might help.

Anticipated Deliverables

Deliverable	Date
Modeling of Large Electronic Loads for Power System Studies: Data Centers, Hydrogen Electrolyzers, and Fleet EV charging Infrastructure	Dec. 2025
Grid Impact Assessments for Large Load Integration: Impact of Large Electronic Loads	Dec. 2025
Special Assessments on Interaction of Large Electronic Loads with Inverter Based Generation	Dec. 2025
Load Model Data Processing and Parameter Derivation - Python (LMDPPD-P) v1.0 Beta	Dec. 2025
Modeling of HVDC systems: Point to point HVDC, Multiterminal HVDC, and Grid Supporting Functionalities	Dec. 2025
Modeling and Assessment of Grid Enhancing Technologies	Dec. 2025
Modeling of Combined Synchronous Generation and Battery Energy Storage Systems	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002029717	Modeling of Emerging Loads for Transmission Planning Studies	This technical update documents the development of dynamic models for emerging power electronic dominated loads like data centers, hydrogen electrolyzers, and EVSEs.	Dec. 2024
3002029829	Impedance Characterization of Power-electronic Interfaced Large Load Devices	Assessing stability impact of large PE loads on power system using impedance characteristics	Dec. 2024
3002029730	VSC HVDC Positive Sequence Modeling and Model Refinement	This technical update documents the development of positive sequence dynamic model for VSC HVDC links for on shore and offshore applications	Dec. 2024

Related Research

Through the P40A research EPRI actively participates in providing technical leadership to various industry forums and conducts technology transfer with our members. Some notable activities are as follows:

- Providing technical guidance on load modeling related topics to the NERC Load Modeling Working Group and the WECC model validation subcommittee
- Providing technical guidance to the upcoming NERC large load task force and EV task force.
- Testing of EV chargers is being collaborated with Electric Transportation program (P18)
- Jointly working with P173A to characterize the impact of large electronic loads on nearby inverter-based resources and synchronous machines.

P40A.002: Distributed Energy Resources (DER) Modeling

Objective

Help utilities with modeling of DERs for transmission stability studies including assessment of interconnection requirements such as the IEEE Std 1547-2018.

Research Value

1. Help transmission planners with more accurate representation of DERs in bulk power system studies to assess impacts of DERs as well as analyze services provided for bulk system reliability.
2. Comprehensive, reliable, easily accessible one-stop repository of state-of-the-art research on load modeling helping members to develop skillsets internally.
3. Industry collaboration with WECC, NERC, and other industry groups providing a platform for sharing information.
4. Overall improvement in system reliability as well as insights on where additional system investment might help.

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002030173	Modeling of IBR and Load Interactions and Impact of DER Frequency Response on BPS	A Technical Update summarizing the latest research and findings from modeling of inverter-based resources and load interactions along with preliminary results from modeling the impact of distributed energy resources' frequency response on bulk power system performance.	Dec. 2024

P40A.003: Modeling of Inverter-Based Transmission Technologies

Objective

Develop and benchmark new, or refine existing generic models related to HVDC, FACTS, GETs components across major software platforms used by utilities in North America and around the world.

Approach

1. Development of models for point-to-point VSC-HVDC systems as well as MTDC systems (EMT and phasor/positive sequence) capable of representing embedded HVDC links, for offshore wind/remote renewable interconnection, as well as meshed dc systems.
2. Developing dynamic models for grid enhancing technologies like power flow controllers and evaluating their impact on system dynamics.
3. Conduct industry workshops to disseminate important guidance on usage of positive sequence and EMT modeling, modeling of emerging load, transmission, and generation technologies.
4. Demonstrating the application of these generic models through collaborative projects with utility members

Research Value

1. Help transmission planners with more accurate representation of various power electronics-based transmission in bulk power system studies to assess their impacts as well as analyze services provided for bulk system reliability.
2. Comprehensive, reliable, easily accessible one-stop repository of state-of-the-art research on load modeling helping members to develop skillsets internally.
3. Industry collaboration with WECC, NERC, and other industry groups providing a platform for sharing information.
4. Overall improvement in system reliability as well as insights on where additional system investment might help.

Anticipated Deliverables

Deliverable	Date
Advances in Heat Pump Technology (White Paper): Conduct an evaluation of emerging heat pump technology, including examination of xyz technology as well as vendor activity.	Dec. 2025
Technical Update: Modeling of HVDC systems: Point to point HVDC, Multiterminal HVDC, and Grid Supporting Functionalities	Dec. 2025
Technical update: Modeling and Assessment of Grid Enhancing Technologies	Dec. 2025
Technical update: Modeling of Combined Synchronous Generation and Battery Energy Storage Systems	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002027019	Technical Update on HVDC, FACTs, and Synchronous Machine Modeling	This document summarizes the research conducted in the area of HVDC, FACTS and Generator modeling in 2023	Dec. 2023

Related Research

Through the research conducted on the HVDC and FACTs modeling:

1. EPRI has led the development of a generic model for point-to-point VSC HVDC in positive sequence as well as EMT that can be used for off shore wind integration studies. The positive sequence model has been presented to the WECC MVS for consideration to be included as a generic model in the commercial software packages.
2. EPRI HVDC modeling work has been supporting the NYSERDA project on offshore wind integration.

Project Set – PS40B

Display Title PS40B: Transmission Protection Methods, Tools, Guides

Objective

The goal of this multi-year R&D research is to develop protection tools, analytical methods, and guidelines for transmission protection engineers as well as for transmission planners and operators to address challenges posed by changing supply mix, new transmission infrastructure, and increasing threat of extreme weather events. The project aims to advance the state-of-the-art by providing innovative yet simple to use tools, succinct guidelines on new topics, and providing a one stop resource for the members to use EPRI's expertise for addressing their short-term as well as long-term challenges. A key focus of this project is to help utilities develop skillsets for next generation of protection engineers by providing practical topical information.

The ultimate goals of this multi-year R&D project are the following:

1. Improve grid reliability by reducing protection misoperations and effective risk mitigation.
2. Reduce protection engineer effort using automation and software tools.
3. Provide practical guidance for protecting new grid technologies and applying new protection technologies.
4. Develop knowledge and skills of the next generation of protection engineers.

Approach

The research approach includes grid modeling, protection coordination analyses, transient stability and electromagnetic transient studies with explicit protection representation, industry surveys, sharing utility experience, lab-testing protection devices; sensors and technologies, and liaising with commercial vendors and industry forums. The research project provides a platform to share knowledge and experience for the utility members.

1. Knowledge transfer is a key component of the project:
2. 9-12 R&D Webcasts to discuss Project Research Tasks
3. Next Generation Protection Engineer Workshops: 8-10 online workshops across the year

2.5 day In-Person Protection Meeting to discuss Utility Experience and Research Results

4. One-to-one webcasts with individual members

For 2025, the research portfolio focuses on the following:

1) Protection Tools and Algorithms

Over the years, the research in this project has developed a number of tools for automating wide-area protection coordination studies (PSET), modeling protection in planning studies (PIPS), and considering protection in outage scheduling (GridCOPS). These tools are fairly mature at this point and are part of the user's group. However, there are other tools that are still under development and will continue to be refined in 2025. These include:

a) Protection Settings Peer Review Tool for ASPEN OneLiner and Siemens PSS-CAPE
Utilities have well-established practices and systems for calculating and verifying protection settings. The objective of this tool is to complement these existing utility processes by providing a way to perform a set of standardized, utility-specific tests and visualize the results in an intuitive and interactive manner. Engineers performing peer-reviews can use the tool to quickly assess the performance of the relay settings and identify potential misoperations and other protection issues. The tool automates studies in ASPEN OneLiner and Siemens PSS-CAPE considering different fault types, fault locations, and contingencies to stress-test each relay function. The results are shown in a local webpage using a tabular set of tests, test values, and pass/fail evaluation alongside a second page with an interactive single-line diagram showing the reach of overcurrent and impedance protection functions under different faults, fault locations, and contingencies. The engineer can easily use the advanced sorting, filtering, and commenting capabilities to identifying test results and document issues, explanations, or solutions.

b) CIM Import/Export Tool for ASPEN OneLiner and Siemens PSS-CAPE
Many entities have a need to integrate or update short circuit models from external sources. This might be an individual utility updating their model of their neighbor's grid or an ISO updating a single short circuit model from all of the grids across their region. This can be challenging both due to inconsistencies

in how different software tools model and identify grid components, but also in the update process itself. The purpose of this work is to significantly improve the methods and tools for integrating short circuit model data from multiple sources. A set of tools are being coded to provide a powerful method of integrating short circuit models. This will include the use of the non-proprietary CIM short circuit modeling file format as well as the ability to compare and map grid models so the user can very selectively update their model. Example use-cases include:

- Compare two grid models and update one model with user-selected changes in the other. List new components and removed components (busbars, lines etc). Areas, zones, voltage levels, or bus-sets can be included or excluded from the comparison.
- Updating short circuit model information from another tool such as ASPEN OneLiner, Siemens PSS-CAPE, Siemens PSS/e or GE PSLF.
- Integrating new data from external tools with different bus-numbering/naming or identification conventions. Examples of this would include loads, generator dispatches, or relay settings

2) Protection Considerations for Changing Grid

In 2025, the focus will be on addressing the following evolving challenges related to transmission protection:

Protection and extreme weather

i) Detection of broken conductor to prevent wildfire events
ii) Critical and extreme contingencies for short circuit and protection studies
iii) Protection settings and coordination under extreme weather events

b) Wide-area protection schemes evaluation methods
c) Protection consideration for sub-synchronous oscillation events
d) Protection considerations for grid-enhancing technologies

3) Knowledge Base for Practicing Protection Engineers

In 2025, the project set will continue to provide key insights, lessons learned and latest industry developments on a myriad of topics as determined by the utility project advisors. A few topics being considered are:

a) State-of-the-art on centralized and virtual protection
b) System integrity protection scheme (SIPS) applications, design practices and experience
c) Grid protection during system restoration
d) Protection of Power Transformers; Protection of Underground Cables
e) Lessons learned from recent blackouts and major system disturbances
f) Training knowledge, methods, and tools for the next generation of protection engineers

Research Value

1. Methods and practices for protecting the modern and future grid with evolving technologies and challenges. Tools for automating protection studies, identifying potential protection misoperations, and visualizing results in an easy-to-use manner.
2. Material and methods for training and preparing the next generation of protection engineers.

Anticipated Deliverables

Deliverable	Date
Transmission Grid Protection and Wildfires: Broken Conductor Detection	Dec. 2025
Extreme Weather: Protection settings considering extreme contingencies	Dec. 2025
Current Experience with Centralized Protection and Virtual Protection	Dec. 2025
Wide-Area Protection Schemes Evaluation Methods	Dec. 2025
Protection Settings Peer Review Tool for ASPEN OneLiner and Siemens PSS-CAPE	Dec. 2025
Protection solutions to SSR and Low Frequency Oscillations	Dec. 2025
Short circuit model CIM import/export tool for ASPEN OneLiner and Siemens PSS-CAPE	Dec. 2025
System Integrity Protection Scheme (SIPS) Applications, Design Practices, and Experience	Dec. 2025
Grid protection during system restoration	Dec. 2025
ShoVal – the short circuit model validation and fault event analysis tool	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002029735	Using the CIM standard for exchanging short circuit models between ASPEN OneLiner and Siemens PSS-CAPE	This technical brief describes how the CIM standard can be used for storing and exchanging short circuit models including support for new models such as IBR and protection settings.	Dec. 2024
3002029737	Protection and Grid-Enhancing Technologies	This technical brief describes Grid-Enhancing Technologies, how they can fail, how they respond to external faults, their internal protection, their impact on protection performance, how they are modeled and studied.	Dec. 2024
3002030934	Impacts of Extreme Weather on Short Circuit Faults and Protection Performance	This comprehensive technical update describes past extreme weather events and how protection systems responded. This ranges from short circuit faults, abnormal frequency, reduced short circuit levels, and extreme contingencies.	Dec. 2024

Project Set - PS40C

Display Title PS40C: Methods and Framework for Advancing Transmission Planning

Objective

The ultimate goals of this multi-year R&D efforts are to:

- Address the transmission planning needs driven by the increasing uncertainty and variability of generation, loads, and weather impacts on power systems. Align research and development tools and methods with recent FERC Orders and NERC standards that will driv planning needs to include more probabilistic approaches.
- Address the roadblocks in wide-spread adaptation of risk-based approaches in transmission planning by developing practical methods and supporting tools, performing case studies, and knowledge transfer to transmission planners.
- Continue to develop an analytical investment framework for long-term reliability as well as resilience (for high-impact low frequency events) using risk-based concepts that can more rigorously address increasing uncertainties and provide better insights to planners than the existing deterministic approaches.
- Develop methods to incorporate climate resilience analysis into transmission planning.
- Further improvement to the coordinated expansion planning framework.
- Support integrated planning research from transmission planning perspective.
- Work closely with industry forums such as NERC, WECC, IEEE, and CIGRE to disseminate the research to advance the state-of-the-art.

Approach

This research project leverages multidisciplinary subject matter expertise within EPRI as well as recognized experts from the industry to conduct research on various tasks. The project team engages members through annual workshops, periodic webcasts, and participation in relevant industry forums. The project comprises of the following workstreams:

1. **Machine Learning Inspired Methods for Representative Case Selection in Transmission Reliability Analysis**
    a. The increased variability and uncertainty in operating conditions stemming from both the adoption of renewable resources as well as increased electrification initiatives has necessitated the adoption of machine learning methods and concepts for long-term transmission planning, to derive insights from large sets of time-series data across a range of scenarios. Adoption of these methods allows transmission planners to effectively identify the best reinforcement options needed to ensure system reliability in the face of uncertainty. High Level Screening (HiLS) is a research grade tool developed to implement machine learning based concepts. The work in 2025 will focus on further enhancing this framework as follows:
        i. Further refine the algorithms used for dimensionality reduction, clustering, and the metrics used for clustering to investigate how they impact on the choice of clusters chosen by the tool.
    b. In addition to modifying the framework itself, use case of HiLS will be explored. Some potential case studies to consider are:
        i. Using HiLS framework to choose representative snapshots for extreme temperature analysis to potentially support NERC TPL-008-1 standard in future.
        ii. Using HiLS framework to develop snapshots for power flow analysis that consider variability and uncertainty in resource as well as load:
            1. Consideration of multi-year generation dispatch (either coming out of production costing runs or some other input) considering variability in renewable generation, fossil plant retirements as well derates and unavailability due to extreme weather conditions.

2. Consideration of large loads such as data centers, cryptocurrency mining, increased electric vehicle adoption, electrification of space heating, behind the meter generation, storage in developing.

2. Transmission Reliability Assessment Framework

Continue to refine the framework that helps transmission planners adopt risk assessment and risk-based techniques as part of their transmission planning processes. This includes:

a. Using the HiLS based framework to identify the critical snapshots.
b. Extending the existing deterministic planning process by accounting for the probabilities of the contingencies defined in the NERC TPL-001-5 standard using forced outage statistics.
c. Cost-benefit analysis to compare different system reinforcement options including use of non-wires alternatives.

As part of this framework, the research also focuses on helping utilities with analysis of outage data statistics.

3. Automated Contingency Cascade Sweep

This task is aimed at developing robust methods and metrics to evaluate transmission system resilience. As extreme events impacting the transmission system increase in frequency and severity driven by external threats and climate change, there is a significant need to assess cascading, uncontrolled islanding, and voltage instability, and prioritize potential mitigation to reduce the likelihood of adverse impact. By developing consistent methods and metrics, investment options can be evaluated allowing planners to identify adequate solutions from a cost-benefit perspective.

The Resilient System Investment Framework (RSIF) is a research-grade framework to quantify the impact of different projects on the transmission system resilience. RSIF allows planners to evaluate the impact of contingencies during extreme events in the steady-state through a probabilistic cascading assessment that quantifies risk of load and generation loss, risk of uncontrolled islanding and potential risk of voltage instability.

In 2025, the maintenance and development of the RSIF will continue as more and more utilities are seeing the need of the tool. To evaluate the likelihood of cascading during extreme heat and extreme cold weather events, RSIF development focus lies on the implementation of an automated AC contingency calculation which allows the planner to specify single or multiple contingency events for each of which the risk of cascading is quantified. Metrics will be developed to compare the impact adversity of contingency events and support the identification of mitigations improving the transmission system resilience during extreme weather events.

4. Enhancements to the Coordinated Expansion Planning Framework

The coordinated expansion planning (CEP) framework are used to identify generation, transmission, and emerging technologies (e.g., storage) investments over long horizons of time (e.g., 10–40 years), considering the various tradeoffs among them. This framework accounts for various modeling enhancements that allow for more accurate representation of typical network size, uncertainties, chronology, energy limited resources among other features. By explicitly modeling long-term and short-term uncertainties, the model produces robust expansion alternatives that will remain close to optimal for any materialization of the uncertain variable over time.

Recently, efforts have been focused on extending the framework to explicitly model climate-driven hazards and events, as well as the associated changes in expansion decisions, retrofits, winterization, and hardening investments to increase system robustness against these events, and mitigate the impacts to power system integrity if any of these events materializes.

In 2025 the coordinated expansion planning framework will continue to be extended to account for resiliency design considerations and improvements. This with the objective to support planners and

power system stake holders in complying with specific design objectives and considerations and scenarios (e.g., FERC 1920).

Research Value

The value proposition of this project set is to provide cutting edge, yet practical methods for long-term transmission planning which go beyond deterministic thinking and can capture multi-dimensional variability in system conditions experienced by bulk systems in the twenty-first century. The research in this project set can potentially help planners in making optimum long-term planning decisions to balance cost, resilience, and reliability of the system. The key research values of this project set are as follows:

- Provide a unique framework to compare how various transmission reinforcement options impact system reliability as well as address the question - Can options proposed for long-term reliability also help to hedge risk against extreme events and vice-a-versa?
- Overall, help planners extend their deterministic transmission planning process to progressively include probabilistic concepts to better quantify the impact of uncertainties especially as utilities consider de-carbonization pathways
- A practical framework to look at potential benefits of coordinated G&T expansion planning in making optimal economic, reliability as well as resilience decisions
- Provide a unique framework to use climate hazard analysis for transmission system reliability and resiliency evaluations
- Support the integrated planning framework by supporting the transmission planning related aspect and linkages with other planning domains.
- Provide industry leadership on various transmission planning topics through collaborative research.

Anticipated Deliverables

Deliverable	Date
Resilient Coordinated Expansion Planning with Increased Modeling Fidelity	Dec. 2025
Technical Update on Machine Learning Inspired Methods for Representative Case Selection in Transmission Reliability Analysis	Dec. 2025
Scenario Based Multi-Value Transmission	Dec. 2025
Automated Contingency Cascade Sweep	Dec. 2025
Machine Learning Inspired Methods for Representative Case Selection in Transmission Reliability Analysis	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002027035	Resiliency-Aware Expansion Planning with High-Temporal Fidelity and Chronology	Modern power system planning must model resiliency requirements to produce expansion plans capable of withstanding hazards and events derived from the climate change (e.g., heat waves, wildfires, cold snaps, tornados, etc.). Developing resiliency-aware expansion plans requires reformulating the basic CEP problem to consume climate- derived data and expected hazards, and to explore expansion alternatives that go beyond meeting capacity and transmission requirements, but also harden the expansion alternatives to produce robust systems	Dec. 2023
3002027040	Assessment of Long-Duration Storage Resources in Expansion Planning	CEP models need to represent the emerging technology of long-duration energy storage to realize their full benefit in system expansion and to address the variability of renewable energy resources. Power systems will benefit from long-duration energy storage units as the amount of renewables on the system increases and storage is increasingly called upon to meet load for longer durations of time.	Jun. 2024
3002029739	Transmission Resilience Analysis Overview	This technical update provides a summary of 2024 research on transmission resilience assessment.	Dec. 2024
3002029740	Probabilistic Methods for Transmission Reliability Analysis	This technical update provides summary of 2024 research on risk-based reliability assessment with a focus on the application of machine learning methods for scenario selection	Dec. 2024

Project Set - PS40D

Display Title PS40D: Special Assessments for Transmission Planning

Objective

Given the unprecedented changes in power systems driven by ascendance of inverter-based resources, power electronics-based transmission technologies, as well as increased vulnerabilities due to extreme events, transmission planners need to increasingly perform studies that are beyond traditional power flow and stability analyses. These studies, broadly referred to as "special studies", require tools, models and methods that are not commonly used by planners, and there is in general a lack of expertise in the industry. However, there is a growing need for performing these studies to ensure system reliability as well as ability to withstand extreme events. The objective of this research is to provide solutions to the needs today while performing the research to identify and supply the needs for tomorrow.

This project set consists of four sub-projects as follows:

- High-Impact, Low-Frequency Analysis (HILF)
- Transmission Harmonics Analysis
- Electromagnetic Transient (EMT) Analysis
- Sub-Synchronous Oscillations (SSO) Analysis

Approach (The How)

This is a multi-year research effort that is designed to be flexible to address both short- and long-term challenges. The research portfolio is executed on an annual basis with the long-term objective in mind. This research project leverages multidisciplinary subject matter expertise within EPRI and well-known experts from the industry to conduct research. The project team engages members through annual workshops, periodic webcasts, and participation in relevant industry forums. The workstreams for the four topics for 2024 are summarized as follows:

1) High-Impact, Low-Frequency (HILF) Analysis

Develop analytical tools and methods related to GMD vulnerability assessments to help transmission planners and operators to provide background knowledge and insights.

- Refine and maintain the EPRI-developed the GICharm tool which is used in harmonic compliance studies for TPL-007.
- Refine and maintain the EPRI-developed B2E tool which is used to allow for the easy conversion of B-fields to E-fields using the latest earth models (e.g., 1D, 3D). This is used to perform GIC comparison studies.
- Expand the GMD Planning Guide to include the latest findings of GMD-related research.
- Refine and expand the GMD Operating Guide to include corrective action plan (CAP) design for a GMD event.

2) Transmission Harmonic Analysis

The aim of this research is to increase efficiency in modeling, analysis, and interpretation of transmission harmonic analysis.

- Development of a PQ roadmap for utilities for changing resource and load mix. This includes how utilities can go about identifying PQ issues, identifying baseline background distortion, analytics, mitigation options, etc.
- Development of IBR harmonic models with the use of a real-world test case for use to validate harmonic analysis techniques applying the principles in IEEE 2800.
- Development and maintain a repository of harmonic modeling characterization of different transmission-connected loads, i.e., data centers, hydrogen electrolyzers etc.
- Provide planners with guidance on harmonic distortions under various inverter-based conditions.
- Provide recommend planning solutions at the grid and inverter-based generation levels. This will be in the form of examples using various harmonic mitigation techniques for transmission systems.
- Provide research which aims to investigate how to develop accurate models of common transmission equipment and devices for performing harmonic studies.

- Other Transmission Power Quality Analysis
    - In addition to harmonics, other power quality issues in the context of increasing IBR penetration will be addressed. The specific focus will be on flicker analysis, but potentially other topics can be covered as needed.

3) Electromagnetic Transient (EMT) Analysis

Develop practical guidelines, models, and methods to help planners with modeling of components, tuning of models to match measurements, analyses to perform, default parameters to use, and develop mitigation options in commercially available tools used by utilities. Refinements to some of the guidelines developed previously (based on member feedback). These include:

- Performing circuit breaker transient recovery voltage (TRV) studies and performing temporary overvoltage studies.
- Development of EMT screening tools to provide more efficiency with the use of default parameters and pre-defined models.
- Develop a tool to support simulating and analyzing power system transients for lightning and switching events.
- Refine and develop a tool to support simulating and analyzing power system transients for transformer switching including inrush and sympathetic inrush.
- Further develop the tool to support simulating and analyzing EMT studies.

4) Sub-Synchronous Oscillations (SSO) Analysis

Evaluate adequacy of traditional tools and study methods in systems with high penetration of inverter interfaced devices, identify aspects that need to be reconsidered and propose modifications to study tools and methods as needed.

- Investigate use of small-signal stability analysis techniques, e.g., impedance-based and eigenvalue-based stability methods, and need for tools to study and evaluate controller interaction driven and resonance interaction driven stability aspects for grids with increasing levels of IBRs and other power-electronic based devices.
- Develop and maintain impedance scanning tool ZSCAN-positive sequence which can scan for system impedance over different operating conditions, contingencies etc in positive sequence domain such as PSSE, PSLF etc.
- Develop and maintain ZSCAN online, which will enable system operators to continuously monitor system changes with intermittent impedance scans from a network of monitored buses.
- Develop and maintain impedance scanning tool ZSCAN-EMT which can scan for system impedance over different operating conditions, contingencies etc in EMT domain such as PSCAD. The developed module can scan impedances of system with black-box user-defined models (UDM), to study different types of control interactions.
- Develop and maintain Signal Damping Analysis Tool (SDAT) which enables a transmission planner, planning coordinator, and operators to analyze whether oscillations resulting from real or simulated grid events. The software reads the signal input in the form of csv, txt, xls or xlsx format and provides a summary of the damping factors, damping ratios and a complete modal analysis of the signals.
- Develop and maintain a repository of impedance characterization of different PE based loads such as data centers, hydrogen electrolyzers etc.
- Perform case studies to evaluate risk for control interactions. These case studies will be used to test the tools on actual system models and provide insight to screening methods.
- Establish an integrated risk assessment process to assess and mitigate risks for control interactions. This will provide transmission planners guidance on applying screening methods and screening metrics to make informed decisions on when detailed EMT domain simulations are required.

Research Value

The overarching research value of this project set is to reduce engineering efforts and costs associated with developing models, mitigation solutions, and at the same time maintain/improve reliability through timely

identification and mitigation of issues. This project delivers value to members by providing one stop resource for knowledge base and practical guidance related to the four topics.

- The GMD research aims to provide the guidance necessary to meet emerging reliability requirements necessitated by standards; particularly NERC TPL-007 in North America to ensure utilities/ISOs can perform required assessments in a reasonable time, have confidence in the results, and make the best investment decisions.
- Timely updated guidelines on a multitude of engineering topics thus providing a single repository of information on topics that planners may not be familiar or may not know enough
- Develop planning processes with the members' organizations for the special topics and provide subject matter expertise to transmission planners for practical use.
- Provide methods and tools to screen for potential adverse control interactions and instabilities with increasing connections of IBRs and power electronic based devices. This will help the transmission planner identify risk of adverse control interactions and when detailed analysis is necessary.
- This research will ultimately result in the enhanced reliability of the Bulk Power System.

Anticipated Deliverables

Deliverable	Date
Geomagnetic Disturbance Planning Guide (Tech Update): Provide guidance to ensure utilities/ISOs can perform required TPL-007 assessments in a reasonable time, have confidence in the results, and make the best investment decisions.	Dec. 2025
EPRI GMD Operating Guidelines Reference (Tech Update): Application of GMD planning to GMD operations.	Dec. 2025
EPRI GICHarm (Software): Providing the planner with the necessary tool to conduct the GIC-harmonic analysis needed to consider removal of equipment that may be susceptible to harmonics.	Dec. 2025
EPRI Earth Model (Software): Providing the planner with the necessary tool to conduct GIC Model Validation.	Dec. 2025
GMD Benchmark case: Work with the commercial software platforms to study the use of modeling of GMD events from various sources.	Dec. 2025
Planning for Harmonic Analysis of Inverter Based Generation on Transmission Systems (Tech Update)	Dec. 2025
Hybrid IBR Harmonic Tool (Software): IBR harmonic tool to increase efficiency in modeling, analysis and interpretation of transmission harmonic analysis.	Dec. 2025
Application Guide to Transmission System Modeling for Harmonic Analysis (Tech Update): This report presents a methodology for developing harmonic models for common transmission equipment.	Dec. 2025
E-Cap Tool (Software): Screening tool for performing capacitor switching analysis.	Dec. 2025
Guide to Performing Transient Overvoltages Studies at 100kV and Above (Tech Update): Provides application guidelines and investigative reports to support practical approaches to modeling, statistical switching, simulating and analyzing power system switching transients.	Dec. 2025

Deliverable	Date
E-Energize Tool (Software): Screening tool to with perform transformer EMT switching studies.	Dec. 2025
EPRI TRV (ETRV) Screening Tool: Screening tool to conduct TRV studies and assess the results against applicable industry standards	Dec. 2025
EPRI E-Switching Screening Tool: Screening tool to support simulating and analyzing power system transients for lightning and switching events.	Dec. 2025
EPRI Guide for Performing EMT Studies	Dec. 2025
ZSCAN – positive sequence	Dec. 2025
ZSCAN – EMT	Dec. 2025
ZSCAN-online	Dec. 2025
Signal Damping Analysis Tool (SDAT)	Dec. 2025
Load characterization repository	Dec. 2025
Small-signal analysis of sub-synchronous oscillations	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002027240	Geomagnetic Disturbance Vulnerability Assessment and Planning Guide	Application guide for conducting geomagnetic disturbance (GMD) vulnerability assessments per TPL-007.	Dec. 2023
3002027071	PRE-SW: GICharm	GIC harmonic tool to conduct the analysis needed to consider removal of equipment that may be susceptible to harmonics.	Dec. 2023
3002027083	Planning for Harmonic Analysis of Utility-Scale Inverter Based Resources	The goal of the work was to provide guidance necessary to analyze harmonic distortions produced by inverter-based generation in weak grid connections. This report presents further development of modeling inverter-based generation resources and their applications to perform harmonic studies.	Dec. 2023
3002027286	Geomagnetic Disturbance Operating Reference Guide: Guidelines for Operations During a Geomagnetic Disturbance (GMD) Event	A reference for creating geomagnetic disturbance (GMD) operating guidelines.	Dec. 2023
3002027073	PRE-SW: B2ECalc	Tool to compute magnetic field to electric field using various earth models.	Dec. 2023
3002027089	Guidelines for Modeling Transmission Equipment for Harmonics Studies	This report presents a methodology for developing harmonic models for common transmission equipment.	Dec. 2023
3002027044	Pre- SW: EMT-Based Inverter Harmonic Model	This is a tool needed by the industry to perform an adequate assessment of GMD-related distortion impacts	Dec. 2023
3002027047	Pre-SW: EPRI Transient Recovery Voltage (ETRV) Screening Tool	This screening tool was developed in an EMTP environment which performs breaker Transient Recovery Voltage (TRV) analysis	Dec. 2023

Product ID	Title	Description	Published Date
		with predefined circuit configurations for easy setup and quick initial assessment.	
3002027053	PRE-SW: EPRI Energize (E-Energize) Screening Tool	This screening tool was developed in an EMTP environment which performs the inrush analysis with predefined circuit configurations for easy setup and quick initial assessment.	Dec. 2023
3002027054	PRE-SW: E-Switching Tool Screening Tool	The E-Switching tool performs switching studies with an easy-to-use GUI which minimizes user interventions to allow for a more efficient insulation coordination study. The tool is a step-by-step solver using the methodology from IEC 60071-2.	Dec. 2023
3002027238	Application Guide to Performing Circuit Breaker TRV Studies	A guide on performing studies on how to create a suitable network model using their preferred electromagnetic transients (EMT) simulation tool, carrying out the simulations and assess the results against applicable industry standards.	Dec. 2023
3002027242	Inverter-Based Resource Impact on Fluctuating Loads: Impact of Grid Strength on Voltage Variations and Flicker Levels with Highly Fluctuating Loads by Evaluating the Effects of Replacing Synchronous Generators with Inverter-Based Resources	This report analyzed the impact of grid weakening resulting from the integration of renewable resources with limited inertial connection and the retirement of traditional synchronous generators. The report presented how these changes affect voltage quality and flicker levels in the transmission system, particularly in areas already affected by	Dec. 2023

Product ID	Title	Description	Published Date
		non-linear highly varying loads.	
3002024877	Evaluation of High IBR Penetration on Synchronous Generation: A Study of Sub-synchronous Torsional Interactions	This technical update investigates using a case study adapted from a real-world utility case the SSTI risk between inverter-based resources and conventional synchronous generating units.	Jan. 2023
3002027059	ZSCAN-EMT (Impedance scanning tool in PSCAD)	Pre-software	Oct. 2023
3002027064	ZSCAN-PSSE (Pos Seq Impedance scanning tool incorporating active devices)	Pre-software	Oct. 2023

Related Research

- The GMD operating guideline research is coordinated with the Grid Operations Decision Support Tools for System Restoration and Emergency Operations project P39.13 as well as with Transmission and Substation Sector.
- The work on EMT models for inverter-based resources is coordinated with Modeling and Analytics for Emerging Technologies (P173A). Sub-synchronous oscillations work is coordinated with Steam Turbines and Auxiliary System (P219) and Generators and Auxiliary Systems (P220).
- Transmission power quality works is coordinated in general with P1 – Power Quality Program.
- Load characterization work is coordinated with P40A – Load modeling.
- ZSCAN-online is coordinated with P39.
- Small-signal analysis studies/system studies with SSO is coordinated with P173A.

Project Set - PS40E

Display Title PS40E: Analytics for Emerging Transmission Planning Needs

Objective

Significant changes occurring in the power industry due to retirement of fossil generation, increasing levels of renewable generation and energy storage, greater interest in using HVDC for connecting offshore wind and remotely connected renewables, emergence of grid enhancing technologies (GET) as part of transmission infrastructure to support integration of renewables, and changing nature of end-use load pose challenges to develop optimum transmission plans for future. Conventional approaches and tools used thus far may not be enough for future planning needs and there is a need to develop new planning paradigms as well as look at efficacy of using newer power-electronics based technologies as part of holistic transmission planning to improve (or at the very least maintain) existing level of reliability while ensuring economic operation. This research project aims to develop methods, practical tools and analytics for transmission planners to equip them to face the challenges in twenty-first century. The outcome of the research is anticipated to save resource-hours and costs as well as provide insights to make judicious investment decisions and ensure system reliability. At present, the research in this project aims to fulfill this need and focuses on the following separate topics:

1. **Advanced Reliability Assessment Tools**

   Annual reliability assessments are labor-intensive analyses across planning entities. Manual validation and set up of thousands of contingency events and simulations are required. This burden will increase as planners are asked to evaluate the reliability and stability of more initial conditions (power flow scenarios) as variability and uncertainty of generation and load both increases. Creating automated platforms to create node-breaker topologies, define contingency events, run simulations in various commercial software, and evaluate stability impacts will create massive savings in engineering time and allow planners to efficiently evaluate the stability impacts across many cases. This work aims to further develop the existing Advanced Reliability Toolset (ARTS) framework to facilitate this process.

2. **HVDC Planning**

   HVDC systems are playing an increasingly significant role in power systems due to their technical and economic advantages over AC systems, especially for long-distance bulk power delivery. In recent years, HVDC has become a superior solution for integrating large amounts of offshore wind generation, as well as remote variable renewable in inland applications. Global adoption of this technology is expected to rise quite significantly in the next decade. In North America for example, there are several ongoing HVDC projects and many others in study phases across the four interconnections. As HVDC becomes more prevalent, there is the need to furnish transmission planners and operation engineers with relevant and handy information about the technical principles of the technology, the benefits, industry and application trends, implementation considerations, and operation challenges. It is also necessary to provide systematic approaches, tools, and guidelines for planning and assessment of HVDC systems.

3. **Methods and Tools for Integration of Grid-Enhancing Technologies (GETs) and energy storage**

   The advent of grid-enhancing technologies (GETs) has now offered transmission planners alternate options to traditional transmission reinforcements that can increase the flexibility and adaptability of the transmission network, thus improving the response to system rapid changes, and reducing the risks for stranded assets. While many studies have been performed to assess the technical and economic benefits of GETs, implementation implications of the widespread use of these technologies from the system control and reliability point of view are yet to be addressed. Therefore, a comprehensive process to compare the benefits, costs and integration aspects of GETs with traditional reinforcement options is still lacking and has slowed the widespread adoption of the technology. This project is intended to provide insights into the technical, operational, and economic characteristics of traditional and emerging grid-enhancing technologies, their potential uses, and operation practices. It also develops a framework and software tool to evaluate and design cost-effective solutions for transmission reinforcement that considers GETs along with traditional expansion projects such as new/upgraded lines and substations.

Approach

This is a multi-year research effort that is designed to be flexible to address both short- and long-term challenges. The research portfolio is executed on an annual basis with the long-term objective in mind. In 2025, the project will continue to develop and improve each one of the three areas as follows.

1. **Advanced Reliability Toolset (ARTS)**
    a. Continued development of the Automated Contingency Generation Tool API and the Protection Control Group Engine API to leverage the node-breaker model and automate the creation of contingency definitions.
    b. Develop node-breaker topologies in bus-branch planning cases directly from EMS data using automated topology mapping.
    c. Continued development of the two modules that constitute the Contingency Screening and Ranking Tool, (1) Dynamic Voltage Module and (2) Transient Stability Module
        i. For transient stability, develop new capabilities to evaluate impacts of IBR and work to develop a new module in ARTS.
        ii. For voltage stability, begin to evaluate methods and approaches to assess screening for contingencies that may lead to Fault Induced Delayed Voltage Recovery (FIDVR) using short-term time-domain simulations.
    d. Development and implementation of a high-performance computing (HPC) platform to parallelize simulations to assess stability and security of a power system more effectively.
2. **HVDC Planning**
    a. Continue with the research about the impact on operational security and reliability of an increasing number of HVDC links incorporated in the transmission system considering control capability and dynamic response of HVDC converters This includes evaluation of reliability metrics for system impact studies of multi-terminal HVDC and DC networks.
    b. Continue evaluating performance standards and study requirements for HVDC interconnections. A comprehensive set of recommendations for planning criteria and performance metrics for HVDC projects has been delivered in 2024. The work in 2025 will review and expand the analysis to multi-terminal (MTDC) and DC grids and additional technical aspects.
    c. Use of HVDC installation for providing ancillary services: HVDC and MTDC transmission can provide and facilitate the provision of ancillary services to the grid, depending on the type of interconnection (embedded, gen tie, connection of asynchronous systems, integration of remote generation, etc.). This task will analyze the capability of different HVDC configurations to provide various types of ancillary services. The characteristics, conditions for which the services can be provided, and expected performance will be analyzed.
    d. Review and update the HVDC planning reference guide
3. **Grid Enhancing Technologies (GETs)**
    a. Expand the software tool CPLANET (Controlled Planning Network) to further refine the algorithm related to identifying optimal solutions for mitigating thermal overloads in a power system over a range of operating scenarios. The solutions considered include traditional power flow controllers such as phase-shifting transformers and fixed series reactors, advanced power flow controllers such as SSSC devices (FACTS), battery energy storage, as well as traditional expansion projects such as new and/or upgraded transmission lines and substations. The work in 2025 will continue to improve the algorithm to analyze the benefits of re-deployable and mobile power flow control devices and energy storage.
    b. Expand reference guide on integration of Grid-Enhancing Technologies delivered in 2024 to:
        i. Describe and provide information on other technologies used to increase transmission system utilization, including newer developments on mobile and re-deployable devices
        ii. Revise and expand the framework for cost-benefit analysis
        iii. Application of CPLANET and results of case studies
    c. Continue with the assessment of the use and considerations of advanced line ratings (AAR and DLR) in long-term transmission planning.

Research Value

The project set will deliver value to members in several aspects as follows.

1. **Advanced Reliability Toolset (ARTS)**

   The ARTS suite of tools can significantly reduce the engineering labor-hours required across various categories of contingencies and at the same time more accurately capture any changes in network topology which may be missed when manually defining contingencies. These tools can facilitate generation of EMS contingencies using existing state of the system and can potentially help in operations planning as well as real-time contingency analysis.

   a. Automatically building node-breaker models for planning cases using EMS data enhances the accuracy of generated contingency definitions. With node-breaker models in planning cases, TPL contingencies can be easily generated for various substation topologies.
   b. The Automated Contingency Generation Tool (ACGT) is a unique tool that can leverage node breaker models to automatically generate contingency categories defined by planning standards or grid code. The tool can have explicit relay representation as part of the contingency definition explicitly capturing protection actions. This process is replicable and more accurate than manual validation and can save hundreds or even thousands of engineering hours that are current required by this process.
   c. Contingency Screening and Ranking Tool (CSRT) provides an approximate but fast approach to scan through hundreds of contingencies to identify system-critical contingencies instead of running full dynamic simulations. This tool can potentially save engineering-hours and computational resources and at the same time comprehensively assess security, stability, and reliability of the power system.
   d. Automation will also allow planners to complete full network analysis (i.e., all contingency events across the entire system) rather than existing approaches that sectionalize the system or look at only a limited set of contingencies. The full network analysis can be completed on a yearly basis using the tools in this project.
   e. Integrating advanced analytic methods can help planners efficiently identify critical contingency events and develop mitigations to maintain system stability and security.

2. **HVDC Planning**

   This project provides a single, concise, and practical resource on the topics related to HVDC planning which will help planners to understand HVDC alternatives (compared to AC alternatives) to make judicious planning decisions. The key highlights of this project are:

   a. Technical and economic evaluation and operational considerations of HVDC alternatives
   b. Comprehensive guidelines to analyze and evaluate HVDC projects.
   c. Succinct and practical reference material on newer HVDC developments and technology trends
   d. Support industry-wide efforts to develop and implement a consistent set of performance standards and requirements for the evaluation of HVDC systems.
   e. Facilitate research on new research ideas related to HVDC.

3. **Grid Enhancing Technologies (GETs)**

   This project provides transmission planners with information, methods, and tools to help them consider, analyze, and design transmission solutions using grid-enhancing technologies, as follows:

   a. The software tool (CPLANET) provides insights to planners in making judicious planning decisions by analyzing various transmission system reinforcements which may include an optimal combination of advanced transmission technologies, energy storage, and conventional expansion projects.
   b. One-stop repository of reference material to help planners make risk-informed decisions on the use of grid-enhancing technologies as a complement to traditional transmission expansion, by enabling higher utilization of the existing network infrastructure.
   c. Advancing state-of-the-art by developing new methods and tools to improve power grid adaptability, flexibility, and responsiveness through optimal use of modular, scalable and re-deployable transmission devices.
   d. Identify gaps, R&D needs, and solutions for seamless use and considerations of advanced line ratings across planning activities.

Anticipated Deliverables

Deliverable	Date
Advanced Reliability Toolset (ARTS) V2025 Improve Node-Breaker creation capability for planning cases and update contingency screening tool to include FIDVR screening and IBR instability screening methodology	Dec. 2025
Advanced Reliability Toolset (ARTS) A summary of the overall process of contingency generation and screening process. Present case studies with FIDVR and IBR instability and the usage of ARTS tool to identify critical contingencies. Technical guide on using high performance computing to run steady-state and dynamic analysis on PSSE using contingencies generated from ACGT tool	Dec. 2025
Contingency Analysis using HPC Develop guidelines on running TPL contingencies in High-Performing Computing platforms (HPC) and commercial software with cloud computing capabilities.	Dec. 2025
High Voltage Direct Current (HVDC) Planning Guide - 2025 Update A summary of the overall process of planning for HVDC, the type of studies to perform, and guidelines on modeling and simulation tools	Dec. 2025
HVDC Links in Transmission Operations Provides insight into system reliability implication of HVDC links, and identifies mitigation options, including advanced use of a converter.	Dec. 2025
Recommended Planning Criteria and Performance Standards for HVDC - 2025 Update Propose grid code performance and planning standards for HVDC systems, including various types of configurations	Dec. 2025
Controlled Transmission Expansion Planning (CPLANET) v3.2 Enhanced and expanded version of the software tool for optimized transmission solutions that combined advanced transmission technologies, energy storage and conventional projects	Dec. 2025
Grid-Enhancing Technologies - Reference Guide – 2025 Edition Improved and expanded version of reference guide with updated information on the economic, reliability and environmental aspects GETS, and results of case studies and implementation projects	Dec. 2025
Consideration and Representation of Grid-enhancing technologies in Long-term Transmission Planning Analyze how the effect of Grid-enhancing on system operations should be considered in the evaluation and design of long-term transmission expansions	Dec. 2025
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.	Dec. 2025

Past EPRI Research on Topic

Product ID	Title	Description	Published Date
3002029834	Advanced Reliability Toolset (ARTS) V2024	This version of the tool includes Node-Breaker creation capability for planning cases, a new GUI to improve user experience, and an improved structure for easy integration with various commercial software.	Dec. 2024
3002029837	Tech update: Advanced Applications for Transmission Planning	Present case studies with IBR instability and the usage of ARTS tool to identify critical contingencies.	Dec. 2024
3002027108	Tech update: Advanced Applications for Transmission Planning	A summary of the overall process of creating node-breaker, contingency generation, and screening process for planning cases.	Dec. 2023
3002025855	PRE-SW: Advanced Reliability Toolset (ARTS) v2022.2 Beta	This tool includes the legacy Automated Contingency Generation Tool (ACGT) and Contingency Screening and Ranking Tool (CSRT).	Dec. 2022
3002029846	Recommended Planning Criteria and Performance Standards for HVDC	A comprehensive study of HVDC performance standards and requirements for studies of HVDC systems, including a detailed benchmarking analysis of many grid codes worldwide	Dec. 2024
3002029847	System reliability and security impact of increased number of HVDC connections	Analysis of implementation and operation issues of multiple HVDC installations connected in neighboring regions, including control interactions and the need for special protection systems.	Dec. 2024
3002029844	HVDC Planning Guide: 2024 Update	A concise guide for planners to identify studies and other considerations for integrating large HVDC projects. Revised and expanded version	Dec. 2024
3002027098	High Voltage Direct Current (HVDC) Planning Guide - 2023 Update	A concise guide for planners to identify studies and other considerations for integrating large HVDC projects. Revised and expanded version	Dec. 2023
3002027099	Planning Criteria and Performance Standards for HVDC	A comprehensive study of HVDC performance standards and requirements for studies of HVDC systems, including a detailed benchmarking analysis of many grid codes worldwide	Dec. 2023
3002029839	Controlled Transmission Expansion Planning (CPLANET) v3.1	Software tool for optimized transmission solutions that combined advanced transmission technologies, energy storage and conventional projects	Dec. 2024

3002029843	Grid-Enhancing Technologies - Reference Guide	New information and learning on the economic, reliability and environmental benefits of using advanced technologies for transmission grids	Dec. 2024
3002029841	Consideration of Advanced Line Rating in Long-Term Transmission Planning: 2024 Edition	Analyze potential implications of FERC order 881 requirements on long-term planning, and consideration of DLR for designing transmission expansion	Dec. 2024
3002027092	Controlled Transmission Expansion Planning (CPLANET) v3.0	Software tool for optimized transmission solutions that combined advanced transmission technologies, energy storage and conventional projects	Dec. 2023
3002027102	Grid-Enhancing Technologies - Reference Guide	New information and learning on the economic, reliability and environmental benefits of using advanced technologies for transmission grids	Dec. 2023
3002027094	Advanced Line Rating in Transmission Planning	Analyze potential implications of FERC order 881 requirements on long-term planning, and consideration of DLR for designing transmission expansion	Dec. 2023

Related Research

Although no deliverables are shared with other projects or programs, the work across the three research areas is related to other activities as follows:

1. The ARTS research being done is closely coordinated with and designed to complement the research in the Integration of Bulk Renewable Generation (P173) Project Set A.
2. The HVDC work is being coordinated with Transmission and Distribution Infrastructure (TDI) sector.
3. The grid enhancing technologies work is being coordinated with EPRI's GETs Initiative as well as the TDI sector.