QUANTA TECHNOLOGY

ADVANCED TRANSMISSION TECHNOLOGIES PLANNING GUIDE

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Table of Contents

List of Figures

List of Tables

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Terms and Definitions

The abbreviations, acronyms, terms, and their respective definitions used in this report are listed below.

Term	Definition
AAR	Ambient-adjusted ratings
ACCC	Aluminum conductor composite core
ACCR	Aluminum conductor composite-reinforced
ACSR	Aluminum conductor steel-reinforced
ACSS	Aluminum conductor steel-supported
AECC	Aluminum-encapsulated carbon core
APFC	Advanced power flow control
ATT	Advanced transmission technology
BCA	Benefit-cost analysis
COMED	Commonwealth Edison
DLR	Dynamic line rating
EMS	Energy management system
ERIS	Energy resource interconnection service
FACTS	Flexible alternating current transmission systems
FERC	Federal Energy Regulatory Commission
GET	Grid-enhancing technology
GIA	Generator interconnection agreement
HTLS	High-temperature low sag
IROL	Interconnection reliability operating limits
IRP	Integrated resource planning
ISO	Independent system operator
MDU	Montana–Dakota Utilities
MISO	Midcontinent Independent System Operator
M-SSSC	Modular static synchronous series compensator
NERC	North American Electric Reliability Corporation

Term	Definition
NRIS	Network resource interconnection service
PFC	Power Flow Control
PPL	PPL Electric Utilities
PST	Phase-shifting transformer
RAS	Remedial action scheme
REFA	Reconductoring Economic and Financial Analysis
RMI	Rocky Mountain Institute
ROW	Right-of-way
RTO	Regional transmission organization
SCADA	Supervisory control and data acquisition
SOL	System operating limit
SPS	Special protection scheme
SRP	Salt River Project
SSSC	Static synchronous series compensator
TCSC	Thyristor-controlled series capacitor
TO	Topology optimization
VAR	Volt-ampere reactive
VELCO	Vermont Electric Power Company

Table 1. Terms and Definitions

1 Executive Summary

As the U.S. electric grid faces mounting pressure from growing demand and the slow interconnection of new generation resources, a balanced approach that combines traditional transmission development with innovative solutions is increasingly essential. Advanced Transmission Technologies (ATTs), include grid-enhancing technologies (GETs) such as Dynamic Line Ratings (DLR), Advanced Power Flow Control (APFC), and Topology Optimization (TO), along with Advanced Conductors. GETs present cost-effective, modular, and quickly deployable tools to increase transmission capacity, improve system flexibility, and support efficient grid operations. Advanced conductors provide a complementary, longer-term infrastructure solution.

This guide, prepared by Quanta Technology and Rocky Mountain Institute (RMI), provides structured methodologies for integrating ATTs into three core planning domains:

- Transmission planning in RTO/ISO regions
- Interconnection studies for new generation
- Integrated Resource Planning (IRP) and procurement in regulated utilities

Recent policy developments, most notably FERC Orders 2023 and 1920, require utilities and grid operators to consider these technologies during transmission planning and interconnection assessments. This guide presents actionable best practices, modeling techniques, and use cases that reflect how ATTs can meet regulatory requirements while addressing technical, economic, and operational challenges.

Each ATT is examined in depth, including:

- DLR, which dynamically adjusts line ratings in response to real-time environmental conditions and can reduce congestion, supports reliability when integrated into probabilistic planning models.
- APFC, which provides real-time control over power flows, enabling rapid congestion relief and improving the efficiency of existing infrastructure.

- TO, which reconfigures grid topology using existing assets to reduce congestion and losses without new construction.
- Advanced Conductors, which significantly increase line capacity and efficiency, often avoiding the need for new towers or right-of-way.
- Operational considerations, deployment challenges, and performance metrics are discussed alongside case studies from utilities such as PPL Electric, Salt River Project, MDU, and others.

The guide emphasizes that integrating ATTs into planning processes requires institutional coordination, improved modeling practices (especially probabilistic and scenario-based approaches), and stakeholder engagement. Though not a replacement for all conventional infrastructure, ATTs can serve as transitional or permanent solutions that unlock existing grid potential, support rapid interconnection of clean energy, and ultimately reduce system costs for customers.

Key takeaways include:

- ATT deployment must be aligned with system-specific constraints and asset health.
- Effective use requires coordination between planning and operations teams.
- Probabilistic modeling is essential to account for ATT variability.
- Benefits are highest when ATTs are co-optimized with generation and transmission planning.
- While near-term in impact, GETs can complement long-term upgrades; advanced conductors serve durable upgrade needs.

By embedding ATTs into traditional transmission planning frameworks, utilities and regulators can create a more adaptive, resilient, and cost-efficient power system.

2 Introduction

Advanced Transmission Technologies (ATTs), such as grid-enhancing technologies (GETs) and advanced conductors, are emerging as practical solutions to increase grid capacity, reduce congestion, and potentially help expedite interconnections in the near term. These technologies, where applicable, provide utilities and grid operators with quicker deployment pathways and a flexible, cost-effective complement to existing transmission upgrade and expansion options. The most common GET technologies under discussion include dynamic line ratings (DLR), advanced power flow control (APFC), and topology optimization (TO).

While GETs fall into this category of transmission tools, they are more narrowly defined by their objectives of achieving higher efficiency, modularity, and capacity use of the existing grid. Since GETs enhance existing facilities, they provide a practical and relatively quick implementation pathway that is well-matched with maintaining reliability and affordability amidst an era of large-scale grid expansion. Relatedly, advanced or high-performance conductors expand transmission capacity by replacing traditional wires with efficient, higher-carrying capacity lines while minimizing infrastructure build-out and expansion rights-of-way (ROW). In recent years, the competencies and capabilities of these tools have become more widely understood, and their deployment, related policies, and regulations requiring studies have spread.

Although ATTs have demonstrated strong technical performance and have been successfully implemented in international systems, their adoption in the United States has been relatively slow. This report does not address the regulatory and policy solutions available to overcome these barriers. However, the best practices outlined, such as robust benefit-cost analyses (BCA) and clear and factual planning guidelines, can help inform evaluation of these tools.

To unlock the full potential of ATTs, it is essential to establish a consistent methodology for integrating them into grid planning and evaluation. The optimal deployment of ATTs ensures that the existing transmission grid and new investments are reliably and fully used. While primarily an operational tool, DLR could be integrated into transmission planning processes. It increases opportunities for planners to consider their potential in addressing future system needs. Coordination between planning and operations teams within relevant electricity sector organizations, such as regional transmission organizations (RTO) and regulated utilities conducting integrated resource planning (IRP), is increasingly important and will require effort.

This guide focuses on defining and cataloging best practices for integrating GETs and advanced conductors into planning processes to provide decision-makers with the means to select the right solutions that meet both current grid concerns and future needs. In each technology-specific section, we will describe the benefits of ATTs and provide guidance on how to reliably incorporate them into RTO transmission, interconnection planning, and regulated utility IRP paradigms.

It is important to note that GETs and advanced conductors are different technologies providing different benefits. They need to be considered separately in planning and operating the grid.

2.1 Transmission Planning in Regional Transmission Organization and Independent System Operator Regions

In RTO and independent system operator (ISO) regions, grid operators conduct short- to medium-term planning and long-term transmission planning, which is now required under FERC Order 1920[1] [1] [2] [3]. Shorter-term planning processes (a less than 20-year planning horizon) are driven by load growth, reliability, economic, and/or public policy criteria. Long-term transmission planning typically consists of capacity expansion modeling coupled with both reliability and economic analyses:

- **Generation planners use capacity expansion models to identify optimal new generation investments in future years that meet projected demand at a predetermined level of resource adequacy.** This includes consideration for exogenous factors like state policies, renewable portfolio standards, and decarbonization targets.
- **Transmission planners perform reliability and load analyses, consisting of generation and load deliverability analyses under various snapshots of grid conditions such as summer peak**

1 Including rehearing orders 1920-A [3] and 1920-B [4].

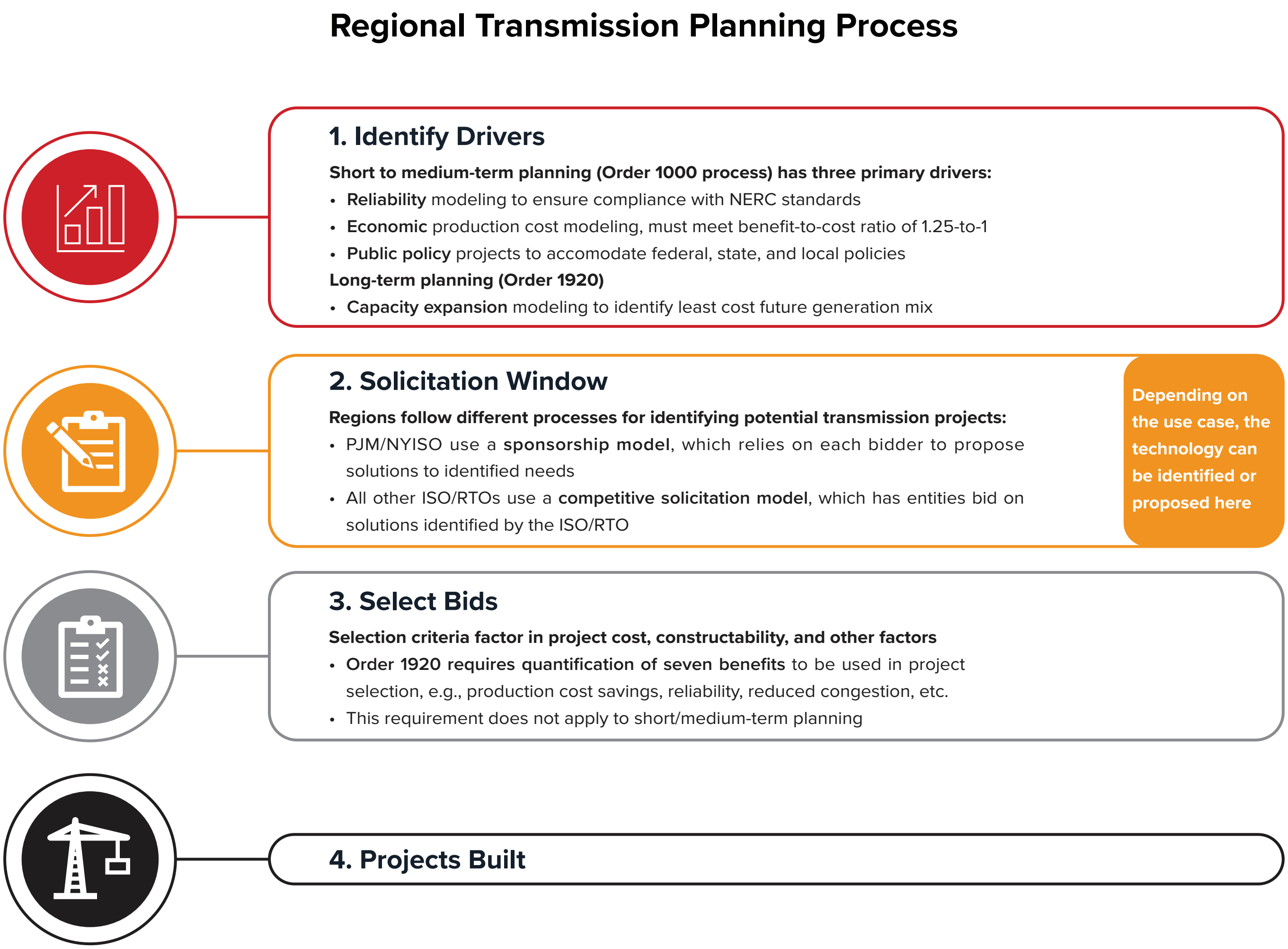

Figure 1. Diagram of Transmission Planning Process in RTOs

load, winter peak, and light-load conditions. In transmission planning processes, reliability analyses typically consist of thermal and voltage violation assessments under North American Electric Reliability Corporation (NERC) transmission planning Reliability Standard cases and the transmission owner's own required NERC-compliant planning criteria.

- **Economic dispatch modeling, or production cost modeling, is typically conducted hourly over a year (8,760-hour basis). These models dispatch the network like it were sent in re-al-world operations, monitoring particular flowgates of interest.** The economic insights over each hour are used for evaluating market congestion, policy impacts [4], and portfolio performance [5].

During the transmission planning processes, solutions to meet system needs can either be proposed by transmission-owning utilities and merchant developers or identified by the RTO and put out to bid, depending on the regional process. Subsequently, in the bid selection process, those solutions are evaluated, and winning bids are selected based on defined criteria. "Figure 1. Diagram of Transmission Planning Process in RTOs" on page 5 provides a visual overview of the transmission planning process in RTO/ISO regions. Per FERC Order 1920-A [2], ATTs must now be considered in all transmission planning processes, and their benefits can be accounted for across all seven benefits [6].

2.2 Interconnection Planning in Regional Transmission Organization and Independent System Operator Regions

The interconnection study process in RTO/ISO regions follows FERC guidelines, most recently updated in FERC Order 2023-A [6]. The process typically consists of interconnection application windows, cluster study assessment, facilities study assessment, and the negotiation and tendering of a generator interconnection agreement (GIA) for a specified level of interconnection service. "Figure 2. Diagram of Interconnection Planning Process in RTOs" on page 7 provides a visual overview of the interconnection study process in RTO/ISO regions. These studies are conducted to ensure the interconnecting generation will not adversely impact grid reliability or will fund the necessary network upgrades to mitigate reliability impacts. In the application window, prospective interconnection customers can typically seek either an energy resource interconnection service (ERIS) or a network resource interconnection service (NRIS). This is especially relevant when considering whether certain ATTs might be applicable as network upgrades for a particular project. FERC Order 2023-A [7] requires the consideration of some ATTs in interconnection studies.

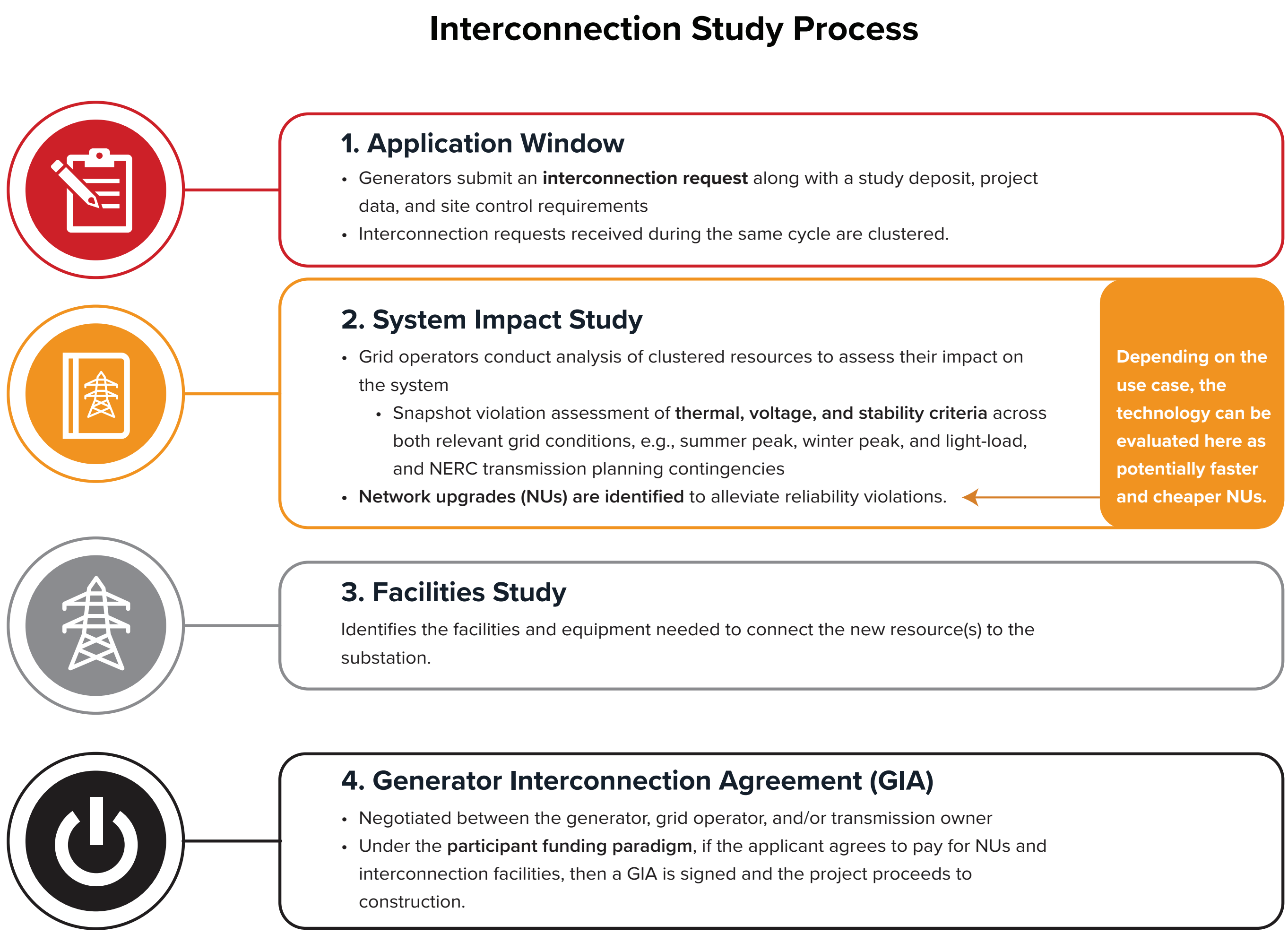

Figure 2. Diagram of Interconnection Planning Process in RTOs

2.3 Integrated Resource Planning and Procurement in Regulated Utilities

In most utility territories, long-term planning involves multiple components: transmission planning (local and regional), IRP[2], generator interconnection, and resource procurement. Due to computational and institutional challenges, each planning component is typically conducted independently rather than through co-optimization. However, the components inform each other—often through an iterative process [8]. For example, future generation resource portfolio outputs from IRPs may

2 Where "integrated" refers to generation, demand-side, and energy storage resources.

be used as input in transmission planning. Planned transmission may also be used as an input into IRPs. Sometimes, moderate levels of co-optimization are introduced, such as allowing the IRP model to select specific types of transmission expansion as an alternative to new generation. Many insights related to considering ATTs in transmission and interconnection planning are transferable between RTO and regulated utility contexts; therefore, this section focuses on opportunities to incorporate ATTs in IRP and resource procurement.

"Figure 3. Diagram of IRP Processes in Regulated Utility Regions" on page 9 provides a visual overview of the typical IRP process conducted by the jurisdictional utility and reviewed or approved by the state regulator. The IRP process involves developing a model and set of assumptions for the future system, identifying possible resource portfolios to meet future needs, and evaluating those portfolios to find the least-cost, lowest-risk portfolio consistent with reliability standards. This is typically done through the evaluation of 2 types of models: capacity expansion and production cost. Capacity expansion models optimize for the least-cost resource portfolio development over long periods (e.g., 20 years). To remain computationally tractable, capacity expansion models make various assumptions. (For example, they represent only a sample of representative days per year or ignoring transmission constraints.) The resource portfolio outputs from capacity expansion are then used as inputs into the production cost model. Holding the resource mix static, the production cost model solves for economically optimal operations. The production cost model runs at a much higher resolution (typically every hour of the year) and allows planners to better understand various portfolios' economic and reliability implications.

ATTs can be incorporated at every stage of the IRP and procurement process. Increasingly, policymakers recognize the potential benefits of doing so and require regulated utilities to consider ATTs in these planning processes. For example, in its 2024 Session, the Virginia House Committee on Labor and Commerce proposed an amendment to the Code of Virginia that was approved into law, requiring electric utilities to consider ATTs in IRP [9]. In the stipulation to Georgia Power's 2023 IRP update, regulators required Georgia Power to consider grid-enhancing technologies in future planning exercises [10]. This is a burgeoning field for utility planners, and consistent methodologies for evaluating ATTs in IRP do not yet exist.

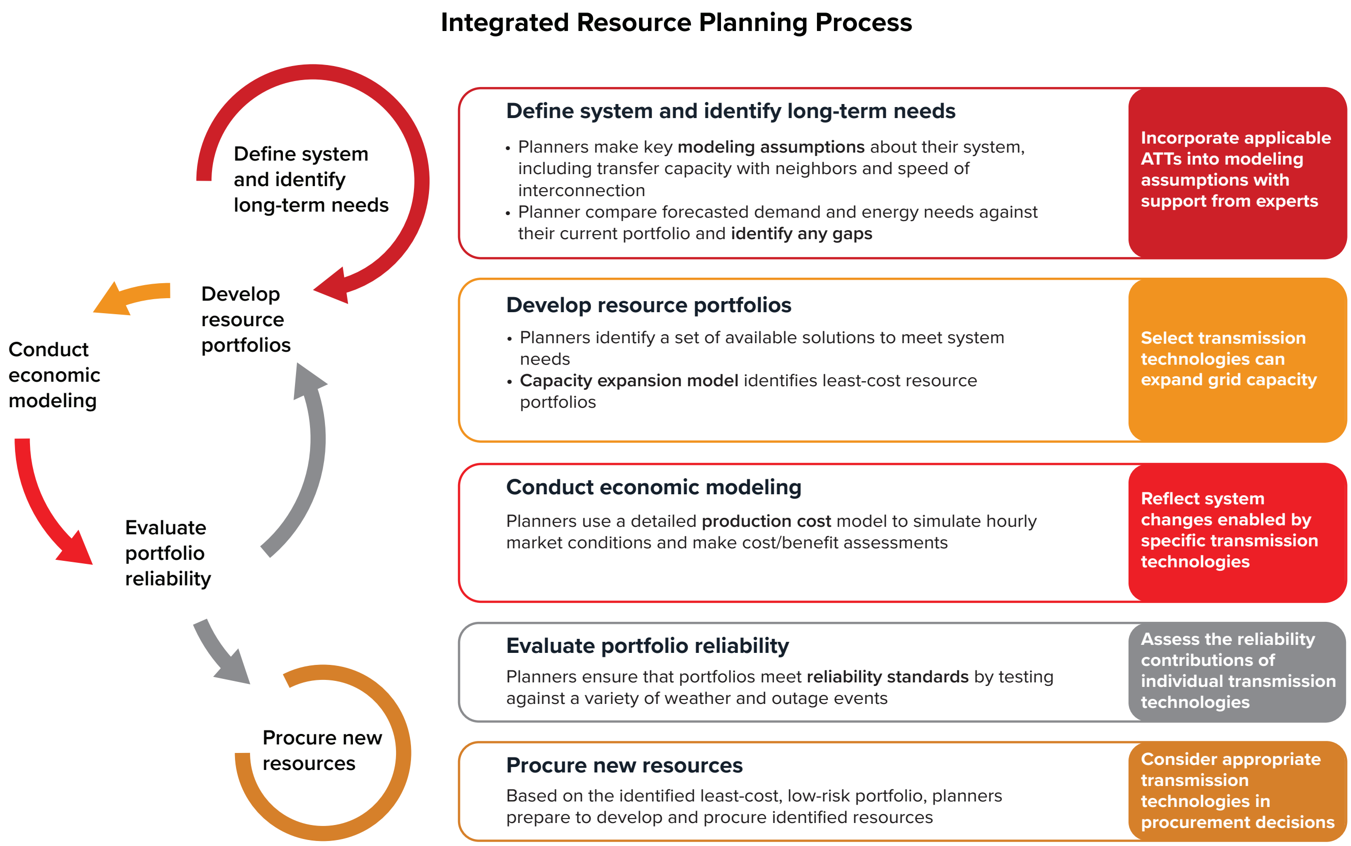

Figure 3. Diagram of IRP Processes in Regulated Utility Regions

While the specific methods to incorporate ATTs will vary by technology type and across each utility's specific planning process, the following high-level options are available to integrate ATTs at each stage of the process, as illustrated in "Figure 3. Diagram of IRP Processes in Regulated Utility Regions" on page 9.

2.3.1 Define System and Identify Long-term Needs

To make calculations more manageable, IRP models tend to represent transmission in highly simplified ways. A typical approach is to use a "pipe and bubble" model, where load and generation are grouped into a few zones (bubbles), and transmission between zones is aggregated and represented as a simple MW transfer limit (pipes). In this case, ATTs can be represented to the extent that they can change the aggregate transfer limits between zones.

2.3.2 Develop Resource Portfolios

Capacity expansion models optimize resource development to meet system needs at the lowest cost, subject to constraints [11]. Transmission (represented as transfer capacity between zones) is sometimes included as a selectable resource in capacity expansion alongside generation. In these cases, ATTs may be modeled directly as capacity expansion candidates. In most cases, transmission expansion is modeled indirectly: either as a cost adder to generation (reflecting interconnection and potentially local transmission expansion costs), as a constraint on the quantity of generation that may be built in a particular transmission-constrained area, or as a constraint on the speed at which new generation can be added to the system. Transmission constraints may also influence other capacity expansion model parameters, including generator capacity credit, system-wide planning reserve margin, or system-wide operational reserve requirements. ATTs could be incorporated into the capacity expansion model as reductions to these costs or alleviations of these constraints. However, for an ATT to be considered in a capacity expansion model, particularly in an IRP context, the incremental benefit of the technology must be reasonably well understood and quantifiable. This includes assessing whether the ATT can realistically be deployed on a given line or path based on asset age, constructability, compatibility with existing infrastructure, and how consistently the ATT delivers performance benefits under relevant system conditions. For example, DLRs are typically applicable to overhead lines but are not appropriate for underground cables, where ambient conditions have little effect on thermal limits.

Incorporating ATTs in the resource portfolio selection stage could demonstrate considerable benefits if alleviating transmission constraints allows the model to select a lower-cost generation portfolio.

2.3.3 Evaluate Portfolio Reliability

As with economic modeling, there may be opportunities to demonstrate the operational benefits of ATTs in utility reliability models. For example, when the effect of ATTs on grid topology is reflected in standard power flow models, this could alleviate reliability violations identified to occur in the absence of the ATT or other network upgrades.

2.3.4 Procure New Resources

Finally, there may be opportunities to include ATTs in resource procurement. Data gathered during procurement—including the ability of ATTs to reduce congestion, hasten generation deployment, unlock higher quantities of new generation, or reduce interconnection costs—can also feed back into future capacity expansion and production cost models.

2.4 Advanced Transmission Technology Integration Context

While ATTs offer compelling benefits for improving grid visibility, operational flexibility, and increased transfer capability, their deployment must be thoughtfully aligned with the utility's system characteristics, infrastructure condition, and long-term investment plans. Fully realizing the value of ATTs often requires enabling investments such as substation expansions, protection scheme updates, and interface modifications. Integrating these technologies into long-term planning and asset management frameworks—rather than treating them as standalone fixes—can help maximize their benefits without introducing operational or coordination challenges. When evaluated within the broader transmission strategy, ATTs can become an effective part of a utility's toolkit, especially in supporting resilience, flexibility, and policy-driven goals.

In many cases, GETs serve best as complementary tools—delivering targeted enhancements to address localized congestion, improve situational awareness, or optimize existing infrastructure—rather than as primary alternatives to large-scale capital projects.

For utilities managing significant capital programs for transmission, substation, or generation build-outs, the incremental capacity gains provided by GETs may not offset the need for substantial infrastructure investments, particularly in systems with aging assets or where large-scale upgrades are already underway. However, once those foundational projects are complete, these technologies may play a more prominent role in supporting asset optimization, deferring future upgrades, or responding to emerging needs cost-effectively and modularly.

3 Dynamic Line Ratings

DLR technology enables utilities to assess the thermal carrying capacity of transmission lines based on forecasts and real-time environmental conditions, such as wind speed, wind direction, solar irradiance, and ambient temperature. Unlike traditional static ratings, which rely on conservative assumptions or ambient-adjusted ratings (AAR), which do not capture real-time variability, hardware-based DLR measures actual ambient conditions to inform line ratings, offering a more accurate and responsive approach. There are many versions of DLR technology, some of which can employ non-contact sensors and advanced analytics to monitor high-voltage transmission lines, providing utilities with valuable insights into line capacity and environmental factors that may affect line performance. This real-time data helps utilities manage transmission bottlenecks, support new energy resource integration, and ensure safe operation during peak demand. While implementing DLR requires upfront time, cost, and training to ensure integration with existing utility or grid operator energy management systems, its cost-effectiveness and speed of deployment make the payback period for this initial investment relatively swift, and technology continues to improve. Hardware-based DLR technology, for example, has made significant improvements in recent years and now requires little to no line outages during installation. Furthermore, numerous technology-focused startups have begun to deploy accurate software-only estimations of DLR, which has the potential to reduce costs further while increasing system coverage.

3.1 Benefits of Dynamic Line Rating Technology

DLR technology benefits include the following:

- **Conditional, yet predictable, enhanced capacity:** DLR offers advantages for day-to-day grid operations and planning by dynamically calculating and adjusting line ratings in response to real-world conditions. This can increase line capacity compared to static ratings or uncover limitations that reduce line ratings, improving energy flow and reducing congestion, especially during cool, windy periods or in areas with high energy generation. While primarily an operational tool, DLR also supports long-term planning by maximizing utilization of existing assets. It can serve as a strategic stopgap solution during long lead times for new infrastructure, helping to manage congestion and maintain reliability. This enhanced situational flexibility allows system planners to establish an interim operational posture while awaiting permanent reinforcements.

- **Operational flexibility:** DLR allows operators to adjust power flows in real-time, easing the strain on overburdened lines and better balancing loads. For example, this can be done by incorporating DLR in interconnection reliability operating limits (IROL) and system operating limits (SOL) management.

- **Utilization of Existing Infrastructure:** DLR maximizes the use of existing infrastructure enabling new generator or load interconnection. DLR is particularly adept at managing thermal overloads—situations where line capacity is exceeded, and overheating is a risk. DLR provides a dynamic solution by adjusting line capacity if and when favorable environmental conditions exist, like wind cooling the conductors.

- **Improved monitoring and risk mitigation:** DLR sensors can monitor real-time environmental impacts on line capacity, allowing operators to shift power flows dynamically and reduce overload risks. In the long-term, DLR data helps utilities make strategic decisions by identifying areas where DLR can meet demand effectively or where infrastructure upgrades may be necessary. By continuously monitoring line conditions, DLR reduces risks such as line sagging into vegetation. An example of DLR benefits is a pilot conducted by AES in which they learned through DLR installation on one of their lines that there was a constrained half-mile line segment limiting the carrying capacity of the line; a combination of reconductoring the constrained segment plus DLR offered an estimated savings of $1.24 million and could be completed with just one year of installation time [12].

3.2 Integrating Dynamic Line Ratings into Planning

Currently, constructing modeling scenarios in planning is based on a fixed set of inputs about the existing system, such as transmission topology and capacity. Integrating DLR into traditional planning frameworks presents challenges due to DLR's inherently variable ratings, which adapt to real-time conditions such as wind and temperature. While DLR's flexibility can enhance capacity during favorable conditions, its variable nature presents challenges for integration into static "snapshot" planning models (such as power flow reliability evaluations) which, even when using ambient-adjusted ratings (AAR), still rely on consistent and conservative assumptions to ensure system reliability under stressed conditions.

Given this risk profile, DLR is generally more suited for addressing market efficiency needs, such as reducing congestion or enabling more economic dispatch, rather than reliability-driven upgrades, which demand predictable and deterministic performance under stressed system conditions. For reliability applications, planners must be confident that the line rating used in the model will be available under all studied contingencies. As probabilistic planning frameworks continue to evolve, they will be critical to enabling planners to assign full confidence to DLR's variable ratings under various system conditions. Once mature and more widely adopted, these methodologies will allow the full value of DLR to be realized, enhancing market efficiency and supporting reliability-driven transmission planning.

3.2.1 Incorporating Dynamic Line Ratings into Transmission Planning Models in Regional Transmission Organization and Independent System Operator Regions

A probabilistic approach is necessary to incorporate DLR effectively into planning studies. This involves detailed probability analyses to estimate the likelihood of DLR providing additional capacity during all relevant planning scenarios, such as peak demand periods. By modeling the frequency at which favorable conditions (e.g., high wind speeds for conductor cooling) occur at a particular location or local region, planners can derive an "effective rating" for DLR-enabled lines as an approximation. The following sequential process can be used to achieve this. Note that while the transmission-owning utility can accomplish Steps 1–3 with their transmission planning staff, third-party DLR vendors offer data and expertise that can be called upon to augment such efforts, particularly for pilot projects:

1. **Baseline assessment:** Given the relevant capacity and capabilities needed for future transmission lines in a particular location, develop a baseline static rating for comparison with dynamic ratings.

2. **Historical environmental data analysis:** Evaluate past weather patterns on an 8,760-hour basis at or near the location(s) of interest to understand the frequency and duration of conditions that cause ratings to be higher or lower than static ratings during planning periods (peak, off-peak, or shoulder demand). The primary variables that significantly impact DLRs are, in order of importance, wind direction (perpendicular to the transmission line length is most effective), wind speed, ambient temperature, and irradiance.

3. **Performance assessment with uncertainty quantification:** Use relevant environmental conditions and calculated static ratings as inputs to simulate dynamic rating uprates or downrates. The 8,760-hour historical environmental data analyses can inform a range of probable future conditions, establishing a range of confidence intervals for snapshot periods of the year. This enables the identification of uprates or downrates during relevant periods of interest with quantifiable levels of risk and certainty. This approach can extend the seasonal ratings to scenario-based ratings that align with planning models.

   In addition to performance modeling, life cycle costs should be considered, including sensor maintenance, calibration intervals, data telemetry infrastructure, and integration with energy management systems (EMS). While modest compared to traditional reconductoring or line build-outs, these operational and maintenance costs may affect the total cost-effectiveness of DLR solutions over time. They should be included in any comparative analysis.

4. **Integration into reliability models:** Set a threshold level that aligns with reliability needs and reflects the minimum probability that DLR-enhanced capacity will be available to meet demand

and contingency requirements. Only using the dynamic rating when there is a sufficient likelihood for that condition to occur ensures the utility of the dynamic rating while accounting for environmental variability. For example, an effective threshold might require that DLR capacity be available with at least 90% confidence during critical system conditions such as summer peak, winter peak, or light-load periods. However, DLR should be incorporated with caution due to its dependence on ambient conditions. Planners must account for the residual risk that enhanced capacity may not materialize in real-time by applying conservative assumptions, maintaining fallback operating margins, or identifying alternative contingencies to ensure system reliability within the remaining uncertainty band. This will produce an "effective rating" during each condition that can be used in the relevant power flow analysis, ensuring RTOs can use DLR to satisfy planning and operational needs. In some cases, that may imply considering operational mitigation measures to deal with situations where the expected rating under the defined confidence level does not materialize; the extra cost of those measures should be considered.

5. **Integration into capacity expansion models:** The information and settings input into the reliability modeling can be reflected in the original capacity expansion modeling conducted before DLR integration. The new capacity expansion models can then take advantage of changed facility ratings to expand or constrain investment build-out appropriately. Furthermore, if the results of capacity expansion modeling indicate the need for additional generation or transmission, Steps 1–5 can be repeated to assess further opportunities to build DLR. To fully value DLR's contributions, these models should co-optimize transmission (at the nodal level) and generation expansion. Parameters within these models that can be affected by the inclusion of DLR include:

   - Reduced time duration until the new generation becomes available.
   - Reduced interconnection costs for new generation.
   - Increased resource candidates for transmission expansion.
   - Increased transfer limits across interfaces.

6. **Integration into economic models:** The dynamic rating calculated in Step 3 can be input into the relevant production cost modeling software for the lines in question. This approach is the most robust way to evaluate the economic impact of dynamic ratings that can be reasonably expected in a future year. Alternatively, a more conservative approach would only reflect the dynamic rating during the most limiting grid and environmental condition pairing that arose in reliability modeling. While this approach is less accurate and will likely underestimate the benefits, it can be a faster way to integrate the analysis into economic modeling.

Together, these steps create a planning process that leverages DLR's dynamic capabilities within a structured framework, enhancing grid flexibility and resilience while meeting reliability standards. This fosters a more adaptable, resilient transmission network, positioning DLR as a valuable addition to traditional planning frameworks, either as a standalone solution or as a cost-effective, complementary solution that is part of a broader transmission portfolio. The overall process could be repeated periodically to reflect the impact of changes to asset health conditions and environmental factors.

3.2.2 Incorporating Dynamic Line Ratings into Interconnection Study Models in Regional Transmission Organization and Independent System Operator Regions

Integrating DLR into interconnection studies could provide a cost-effective and flexible approach to address grid capacity and congestion. In the case of DLR for interconnection, it is crucial to ensure that the integration of DLR is aligned with the reliability standards and operational models of RTOs.

A probabilistic planning paradigm—rather than one reliant solely on deterministic worst-case scenarios—enables a more nuanced and data-informed approach to evaluate DLR's contribution to system reliability and capacity expansion. By capturing the statistical distribution of line ratings under varying weather conditions, planners can better understand the likelihood and duration of capacity gains rather than relying on fixed values that may underrepresent real-world performance.

Using methodologies that probabilistically achieve acceptable levels of grid capacity uprates, planners can be assured that DLR is efficient and reliable in the service of new generation interconnections.

Steps 1–4 in the transmission planning considerations above align with the reliability analyses used for interconnection cluster studies and can be applied to that process with minor adjustments as follows:

1. **Baseline thermal constraint assessment:** Identify a static thermal rating for the relevant transmission line(s) based on either conventional static analysis or information provided by the transmission owner.

2. **Historical environmental data analysis:** No change.

3. **Performance assessment with uncertainty quantification:** Whether the affected interconnecting resource is seeking ERIS or NRIS is an essential additional consideration when assessing DLR as a network upgrade. Since resources seeking NRIS designation must always be deliverable regardless of weather conditions, there must be high confidence in the consistent occurrence of conditions allowing DLR uprates to mitigate thermal overloads, or DLR must be paired with another upgrade to ensure deliverability. A lower threshold level for DLR uprates may be permissible for an ERIS resource, as those only request "as-available" access to the transmission system.

4. **Integration into reliability models:** If the interconnecting resource seeks ERIS, the "effective rating" related to the grid scenario being modeled can be used. If the interconnecting resource seeks NRIS, evaluate whether DLR can be firmed with another upgrade or GET to ensure deliverability. One additional nuance that must be considered when adjusting line ratings is also to check other electrically-close facilities' ratings to ensure that other equipment is not further limiting safe power flow. For example, if a transmission line using DLR can, at times, achieve a higher capacity rating, legacy terminal equipment may need to be up-rated as well.

3.2.3 Incorporating Dynamic Line Ratings into Integrated Resource Planning and Procurement for Regulated Utilities

DLR can assist utilities in managing their grid assets, avoiding unnecessary investments, and enhancing grid performance through the dynamic management of line capacity depending on the current environmental conditions. Such use of DLR can result in meaningful cost savings for customers, a crucial consideration in IRP processes.

One way to approximate the impacts of DLR in IRP studies is to apply DLR data to adjust line ratings based on seasonal weather fluctuations. For instance, higher ratings can be modeled during windy and/or cold months. If IRP capacity expansion and production cost models include transmission constraints, seasonal line ratings can be input directly into the models. Seasonal line ratings can also be incorporated indirectly by influencing other model inputs, including increased availability of new generation, reduced interconnection cost, increased interconnection speed, increased resource capacity accreditation, reduced planning reserve margin requirements, and reduced operating reserve requirements. Estimating the impact of DLR on these model inputs would require additional outside-of-IRP modeling, as described in transmission planning Steps 1–3.

The cost-effectiveness of DLR can be assessed by comparing the costs of implementing DLR (along with associated balance-of-system costs) to the costs of conventional upgrades that would otherwise be needed. To capture the full benefits, utilities must model the potential of DLR to influence generation and conventional transmission investment (through capacity expansion) and reduce operational costs, such as congestion (through production cost modeling). Comparative cost analysis could be performed by inputting DLR as a selectable resource in capacity expansion or by constructing scenarios with and without DLR and comparing the results of the capacity expansion and production cost model.

3.3 Dynamic Line Rating Example Use Case

PPL Electric Utilities (PPL) proposed DLR into the PJM Regional Transmission Expansion Plan market efficiency window as a solution to address transmission congestion costs totaling over $23 million per year. PJM approved their application, and once DLR was incorporated into PPL's system, it significantly outperformed modeling simulations and has successfully saved customers millions of dollars [13]. Over time, DLR data can guide the utility in understanding line capacity patterns, informing future planning and infrastructure investments, and avoiding unnecessary generation curtailment. This scenario has been actualized in multiple DLR deployments in wind-rich Midwestern states, which have shown a more than 40% increase in winter capacity due to line rating adjustments, allowing additional low-cost electricity to flow to customers. For example, Great River Energy's DLR pilot in west central Minnesota showed an increase of at least 25% in line capacity roughly 70% of the time and an average increase of 43% over the static rating, enabling more low-cost wind power production to flow to customers [14].

3.4 Dynamic Line Rating Operational Considerations and Management

DLR hardware and/or software are tools grid operators can leverage to manage grid reliability. DLR hardware is modular and can easily be added to or removed from transmission lines. Over time, DLR must be maintained and recalibrated to ensure accuracy. DLR software can be insightful both independently and for analysis compared to deployed DLR hardware-based sensors. Both of these tools increase the information available to grid operators about the grid system and the ambient conditions it is experiencing. This information can then inform how grid operators can best dispatch and use the available resources.

PPL, the first utility to integrate DLR into its real-time and market operations (in collaboration with PJM), offers an instructive model for both the practical implementation process and the array of use cases that DLR can provide [15]. For instance, PPL uses DLR data to forecast energy requirements, make better-informed decisions about the need for line upgrades, and compare real-time ratings from the sensors against a static ambient-adjusted ratings table, giving operators a backup source of information in case any issues arise. They have also seen significant congestion cost savings on the lines where the DLR was installed. PJM also noted the reliability value provided by the DLR deployment in comments to FERC, explaining that the higher line ratings reported during Winter Storm Elliot allowed PJM to avoid re-dispatching the system, which would have been very challenging under the critical operating conditions experienced during that event [16].

Taking the initial steps to realize the potential and value of DLR entails upfront costs, employee training, and systems integration, as well as potential coordination with the grid operator to ensure the dynamic line ratings are reflected in their operations and dispatch. However, these costs can be quickly surpassed by the savings (e.g., reduced congestion costs and avoided infrastructure investments) realized through the technology's deployment in applicable locations.

3.5 Conclusion

DLR has the potential to enhance grid resilience, serving both immediate operational needs and long-term strategic goals. It allows utilities to use assets more efficiently, respond flexibly to changing demands and environmental conditions, and support proactive maintenance. A probabilistic approach would enable DLR to integrate into traditional planning models, establishing it as a reliable tool for managing thermal constraints, extending asset life, and building a resilient, least-cost transmission network. Adoption has been cautious among many utilities due to practical challenges, such as the need for robust sensing infrastructure, integration with EMS platforms, protection system coordination, and operator training. Real-world examples, such as the PPL deployment, demonstrate that with rising demand and new generation integration, DLR could play a significant role in creating a modernized, sustainable power system.

4 Advanced Power Flow Control

APFC technologies enable dynamic energy flow management across transmission lines by adjusting transmission line impedance to reroute power effectively. These technologies can be broadly categorized into two groups: existing power flow control devices and next-generation advanced power flow controllers.

Several technologies have been used for many years to control power flows and enhance the grid's stability. Examples include thyristor-controlled series capacitors (TCSC) and phase-shifting transformers (PST). Although these technologies are reliable and have a long-established track record, they are not as flexible, modular, or responsive in real-time as newer models to handle the increasingly dynamic state of the grid.

Next-generation advanced power flow controllers are modular and power-electronics-based. In contrast to flexible alternating current transmission systems (FACTS), these advanced controllers offer a greater range of use cases, can be integrated into existing infrastructure, and can be added incrementally as the grid evolves. Their enhanced monitoring and control capabilities provide grid operators with valuable real-time information to improve grid efficiency, manage congestion, and increase system reliability. The latest iteration of APFC technology is a modular

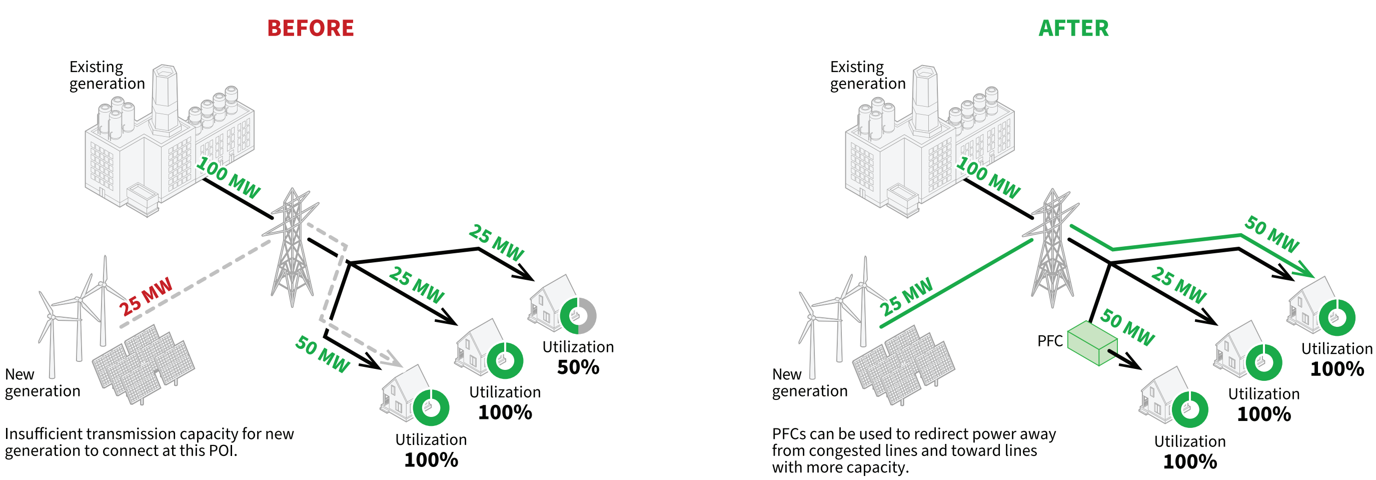

Figure 4. Example of how PFC technology can be applied to enable new generator interconnection (RMI)

static synchronous series compensator (M-SSSC) [17] that can be installed at transmission substations. M-SSSC uses dynamic control to enhance the flexibility and performance of power systems, redistribute power to alleviate congestion on heavily loaded lines, and improve overall system reliability. Their modular design supports diverse grid configurations and can be scaled to meet changing system needs. Additionally, they can provide valuable data that enables grid operators to make more informed decisions for grid management and maintenance.

Using conventional and innovative power flow control (PFC) technologies, utilities can meet short-term grid operational requirements while addressing long-term infrastructure upgrade requirements. An example of using PFC technology to enable new generation interconnection is shown in ”Figure 4. Example of how PFC technology can be applied to enable new generator interconnection (RMI)” on page 22.

4.1 Benefits of Advanced Power Flow Control

APFC benefits include the following:

- **Enhanced capacity on a fast timeline:** APFC technology can enhance grid capacity if the grid topology has parallel underutilized lines. By redirecting power flows, APFC reduces overloads on frequently used lines while maximizing the use of underutilized channels. This redistribution is especially advantageous in regions with high energy flows, where APFC facilitates efficient power routing to better meet demand. APFCs can typically be installed in 12–18 months, compared to the multi-year timelines of most transmission projects.

- **New generation integration:** As a cheaper and faster-to-deploy network upgrade option for interconnecting resources, APFCs can support expedited new entry onto the grid—a particularly valuable benefit in today’s era of grid constraints and rapidly rising electricity demand. Once deployed, these technologies can efficiently route power generation to reduce curtailments, maximize resource use, and accelerate the transition to a lower-cost energy mix.

- **New infrastructure deferral:** By deferring or delaying the need for traditional transmission infrastructure upgrades, APFC can yield significant cost savings for both utilities and ratepayers [18]. For instance, the Vermont Electric Power Company (VELCO) plans to use APFC to extend the life of a PST that connects the states of Vermont and New York, saving customers money by deferring replacement. The PST in question had failed in the past and been repaired, but risks to its performance remained. The APFC installation is expected to mitigate the risk of a future failure by reducing tap changes on the PST while providing redundancy so the line can remain in service in the event of a failure. The APFC solution saved an estimated 16% compared to the series PST alternative and was deployed in half the time [19].

- **Modular:** APFC devices are highly flexible, such that deployments can be designed to be quickly scaled up or down and can be adjusted in real time, which makes it easier to fine-tune the flow of power.

- **Multiple use cases:** APFCs can address thermal and stability issues that may trigger grid reliability violations, offering a cost-effective mitigation option and improving system reliability. The APFC solutions can address voltage concerns, but must be carefully designed to avoid voltage control challenges.

Figure 5. APFC device installed by ISA TRANSELCA, Colombia (Smartwires)

4.2 Integrating Advanced Power Flow Control into Planning

Modeling APFCs in grid studies requires capturing their real-time adjustment capabilities and assessing how the grid responds to changing conditions. Planning models must simulate APFC behavior across various scenarios, including its ability to redistribute power in response to grid conditions and demand fluctuations. They must also account for the full range of use cases that APFCs offer, as noted above.

Managing thermal overload is a critical aspect of planning, especially as networks face rising demand and the need to integrate new generation. APFC devices dynamically regulate power flows across transmission lines, offering a flexible, cost-effective approach to thermal overloads, which occur when current flow exceeds a line's thermal limit and risks overheating. When addressing thermal overloads with APFC in transmission planning, planners must identify overloaded lines, determine optimal deployment locations, and understand APFC interactions with other grid components. APFCs can be installed directly on the overloaded line or on parallel, underutilized lines to alleviate the strain:

- **On the overloaded line:** Installing an APFC on or near the line to reduce power flow and bring the line within its operating limits.

- **On parallel lines:** Alternatively, an APFC on/near parallel lines can draw power away from the overloaded line and distribute power more evenly across the network.

The real-time control capabilities of APFCs are crucial in dynamic conditions, such as demand fluctuations or new generator output variability. For instance, during periods of high wind generation, power flows on some lines may surge, risking thermal overload. APFCs can prevent such lines from exceeding thermal limits by adjusting voltage and reactance in real-time.

In addition to being used for thermal violation purposes, APFC devices can also be used for voltage and stability violations, such as in volt-ampere reactive (VAR) control. Through control of instantaneous reactive power, APFC ensures optimum voltage regulation and fortification of the power system during load or power variations. Also, it minimizes current loading on the grid while simultaneously minimizing resistive losses and overall system inefficiencies. These capabilities serve numerous operational advantages by reducing energy losses and improving system dependability.

4.2.1 Incorporating APFCs into Transmission Planning Models in Regional Transmission Organization and Independent System Operator Regions

As with DLR, APFCs can be incorporated into reliability, capacity expansion, and production cost models. The following steps can be used to build consideration of APFCs into transmission planning:

1. **Baseline assessment:** To assess the potential use cases for APFC, transmission planners must first understand the capacity and capability needs in a particular location; for example, in an area with load growth and already-congested transmission capacity, initial reliability models may reveal thermal violations when additional load or generation is added to the existing system. The magnitude and frequency of these violations are useful in determining whether ATTs can be complementary or substitutable solutions for traditional grid expansion. In this evaluation, planners should account for existing and planned updates to the system, such as reconductoring or a shift from static to dynamic line ratings. Another important location-specific consideration is that, for the thermal benefits of APFCs to be applicable, the local grid topology must be "meshed" (however, APFCs could still be used to address voltage or stability issues on radial lines).

Figure 6. APFC device at Central Hudson,USA (Smartwires)

2. **Performance assessment of APFC and integration into reliability models:** When assessing the performance of M-SSSCs and integrating their consideration into reliability analysis soft-

ware such as PSS/E, three main approaches could be used, depending on the type of violation assessment and complexity required:

a. **Modeling the device as a series reactor/capacitor:** The most straightforward way to model a static synchronous series compensator (SSSC) device is as a series-connected component that modifies the transmission line's effective reactance, similar to a reactor or capacitor. This method is ideal for steady-state analyses where dynamic control is not needed. By injecting a series voltage in quadrature with the line current, the SSSC effectively adjusts power flow and alleviates congestion on overloaded circuits, creating either a capacitive or inductive reactance . This dynamic adjustment changes how power flows through the network, like introducing a variable reactance. The relationship between the injected voltage and the resulting impact on line current defines the device's "effective reactance." By altering this parameter in real time, SSSC can precisely influence power flows, enabling congestion relief, improved use of existing assets, and greater operational flexibility—especially important as the grid becomes more variable and decentralized. This approach works well for straightforward studies, such as the static assessment of thermal and voltage violations. It is crucial to ensure that operational constraints, such as maximum voltage injection and current limits, are accurately represented in the model.

b. **Python-based tools for enhanced M-SSSC integration:** Leveraging Python-based tools offers a more advanced approach. These tools streamline handling complex systems and large datasets by automating the input of parameters, control modes, and deployment scenarios. The tools can adjust injection levels, define the SSSC's operating modes (e.g., voltage, reactance, or current management), and provide detailed performance insights [20]. This approach is particularly effective for conducting sensitivity analyses and identifying optimal SSSC placements across the grid. By evaluating how line currents respond to voltage injections at different nodes, planners can quantify the influence of each SSSC on system flows. The resulting sensitivity metrics help prioritize locations where a voltage injection will yield the most significant impact—such as relieving congestion, balancing loading across parallel paths, or improving transfer capability. This methodology enables a data-driven framework for targeting deployments where SSSC devices can deliver the greatest operational and economic benefit. This method is ideal for more complex studies, such as the approach taken to model APFCs as interconnection network upgrades, as it enables consistent and repeatable simulations across various scenarios and automates the placement of the devices. This method cannot be applied to transient stability assessments.

c. **Using PSS/E's built-in models for M-SSSCs:** The most sophisticated approach for representing SSSCs involves using either PSS/E's FACTS concept or the forthcoming integrated SSSC model. The FACTs method replicates how the M-SSSCs inject voltage into the line and dynamically modify reactance in response to changing grid conditions, enabling comprehensive dynamic modeling of the device's behavior. It is particularly effective for dynamic research where real-time device control is critical, such as transient stability and fault scenarios. In future PSS/E versions, Siemens PTI will release an integrated SSSC model, which will provide the full functionality of the Python script in a simple interface similar to the FACTS module; in the future, this is likely to be the best approach for planners to model and evaluate these technologies. These modules facilitate the analysis of the device's interactions with other grid components during disturbances, providing both steady-state load flow computations and time-domain simulations. This approach offers the most detailed understanding of M-SSSCs' performance in dynamic scenarios, such as grid disturbances, and is essential for assessing their role in enhancing grid stability [20].

Once the requisite performance assessment is conducted, the modeler will re-input the APFC implementations into PSS/E to confirm their efficacy.

3. **Integration into capacity expansion models:** The outputs from the reliability analysis can feed back into the capacity expansion model by updating assumptions about transfer capabilities between zones or across flowgates. Instead of treating APFCs as static upgrades that increase the rating of a specific line, they can be modeled as tools that help shift power flows away from constrained paths or flowgates under certain conditions. Modelers can adjust transfer limits or flow distribution across interfaces where APFCs are expected to relieve congestion to simulate this. This works best when the model includes some level of transmission detail,

like regional flow constraints or simplified flowgate representations, rather than assuming an entirely unconstrained grid. System screening tools (like the method described in Step 2b) can help identify the best locations to simulate APFCs. Once identified, modelers can adjust flowgate limits or congestion costs in both the capacity expansion and production cost models. This allows the models to reflect the potential system benefits of APFCs when making investment decisions across transmission and generation portfolios.

4. **Integration into economic models:** Any changes to the transmission system identified in prior steps can then be reflected back into 8,760-hour production cost models (such as the integration of additional generation without triggering reliability violations, the uprates of certain facilities). These models can show the resulting production cost savings and economic impacts.

4.2.2 Incorporating Advanced Power Flow Controllers into Interconnection Study Models in Regional Transmission Organization and Independent System Operator Regions

The same approach used above for performance assessment and reliability modeling in transmission planning can be used to incorporate APFCs into interconnection studies. Again, the choice of modeling approach depends on the type of grid violation under assessment. All three methods of evaluation apply to interconnection planning. PJM and Commonwealth Edison (ComEd) have studied and approved using APFCs as network upgrades for an interconnecting customer, as detailed in a case study in [18].

4.2.3 Incorporating Advanced Power Flow Controllers into Integrated Resource Planning Models and Procurement for Regulated Utilities

APFC technologies provide utilities with a flexible and cost-effective means to increase grid capacity and reliability. APFC technologies also offer the potential to alleviate congestion on overloaded lines, optimize the use of underutilized infrastructure, and reduce overall operational costs. The modular devices are much less expensive than traditional transmission upgrades and can be deployed incrementally, making them a prudent choice for managing localized constraints over a more extended period.

While APFC technologies can certainly provide utilities with substantial benefits, they may be difficult to demonstrate due to the limitations of the capacity expansion and production cost models typically employed in IRP. IRP models typically include limited or no representation of power flows, which makes it challenging to incorporate APFC technologies directly into the models. However, APFC benefits could be modeled indirectly, similarly to DLRs. This could be done by using external models to estimate the abilities of APFCs to increase transfer capacity between zones, reduce the timelines and costs of interconnecting new generation, unlock new generation capacity for development, and potentially increase system reliability—which can be reflected in IRP models by raising the capacity accreditation of individual generators, reducing the system planning reserve margin, or reducing operational reserve requirements.

4.3 Advanced Power Flow Controllers Example Use Case

Consider a scenario where a local wind farm generates surplus energy, pushing a 230 kV transmission line to its thermal limit. Previously, a costly infrastructure upgrade would have been needed to accommodate this load. However, by deploying an SSSC device on both the overloaded 230 kV line and a parallel 345 kV line, the utility can manage power flow dynamically:

- **On the 230 kV Line:** The SSSC injects inductive reactance, increasing the impedance to lower power flow and preventing thermal overload.

- **On the 345 kV Line:** The SSSC injects capacitive reactance, reducing the impedance to increase power flow onto this underutilized line.

This strategy optimizes the 345 kV line's capacity while preventing overloads on the 230 kV line, achieving grid balance without immediate infrastructure expansion.

An example of power flow optimization using this approach is National Grid's deployment of SSSC technology at 3 existing substations serving a 275 kV and 400 kV line, allowing the utility to manage power flows and minimize congestion dynamically. The use of APFC unlocked 2 GW of capacity while delivering an estimated $400 million in savings to United Kingdom customers [21].

Figure 7. SSSC at National Grid,UK (Smartwires)

4.4 Advanced Power Flow Controller Operational Considerations and Management

APFC devices are compatible with other grid control systems like supervisory control and data acquisition (SCADA) and EMS to enable real-time power and device status monitoring. This compatibility also guarantees that utilities can easily oversee and control the APFC operations within their existing framework. APFC systems are intended to operate in a closed-loop manner to counteract changes in the grid by injecting capacitive or inductive reactance to control the power flow. This capability is advantageous during high demand or periods when energy supply fluctuates, as it minimizes the need for human intervention. However, there are significant tradeoffs to consider when incorporating APFC benefits into planning studies. Planning assumptions typically rely on modeled scenarios, which may not fully reflect real-time operational conditions—such as unforeseen outages, unexpected load behavior, or more volatile generation patterns.

While APFC devices can be operated in an automated, self-controlled manner, they also have interfaces that allow operators to observe the device's performance, change settings if required, and make manual adjustments that they determine will help maintain the stability and effectiveness of the grid. If actual conditions diverge significantly from those assumed in planning, APFC-based benefits should be paired with operational flexibility, fallback options, and ongoing monitoring to ensure performance aligns with reliability and system objectives.

4.5 Conclusion

The success of APFC devices depends on the proper placement of these devices, their connection to real-time grid systems, and adequate maintenance. These technologies solve thermal, voltage, and stability issues and improve system efficiency and reliability.

Deployment feasibility must consider physical space constraints in substations, thermal derating during high ambient temperatures, and integration requirements for protection and control schemes. When managed and coordinated with utility requirements, APFCs can enhance the grid and accelerate the energy transition without the need for significant new infrastructure.

5 Topology Optimization

TO improves transmission grid performance by proactively altering grid topology to better control power flows. Unlike traditional physical expansions or new construction, TO uses advanced software and optimization algorithms to assess prospective reconfigurations and find network states that decrease congestion, minimize losses, and enhance power flow efficiency across the network, especially with variable demand and energy generation. To achieve these enhancements, the software proactively pre-identifies changes to certain system elements, such as opening and closing breakers at substations. TO is a conceptual expansion of transmission switching (the temporary change of the grid topology), but it focuses on planned and optimized changes for better grid performance. TO is distinct from remedial action schemes (RAS) and special protection schemes (SPS), which rely on post-contingency actions imposed automatically via telecontrol. In contrast, TO depends upon the network configuration to naturally determine both pre- and post-contingency flows based on Kirchhoff's laws, without any automatic actions imposed by telecontrol. This results in increased transparency and simplicity for TO and transmission switching compared to RAS and SPS.

However, the ability to open or close breakers to achieve these configurations must be balanced with operational risk considerations. Not all topology changes are risk-free—misoperations or insufficient situational awareness can lead to unintended consequences such as degraded reliability, protection miscoordination, or operator uncertainty during contingencies. As such, TO is most effective when used selectively, supported by robust system modeling, operator training, and safeguards to ensure that the benefits of reconfiguration outweigh the associated risks under current grid conditions.

5.1 Benefits of Topology Optimization

TO benefits include the following:

- **Reduced congestion and/or losses:** TO optimizes power flow distribution over different lines, alleviating congestion on limiting lines while using latent capacity on underutilized lines.

Depending on the objective of the optimization, resistive losses that occur due to congestion can be minimized by redistributing flows through underutilized lines. These adaptations allow grid operators to efficiently handle demand and energy production changes without costly infrastructure investments. Even temporary TO reconfigurations can help plan and manage outages by improving scheduling and coordination, and enabling more requested outages that would otherwise cause reliability violations due to increased congestion [22].

- **Cost savings and fast deployment:** TO utilizes existing circuit breakers and SCADA systems, so it requires no or very little new hardware to be deployed. Once deployed, TO can optimize the entire footprint of the RTO/ISO region and respond to events or congestion patterns not previously seen. TO provides an economical, quick-to-implement alternative to new construction by reconfiguring power flows. It acts as a flexible solution for immediate congestion relief and as a bridge until larger infrastructure upgrades are completed. TO has shown significant cost savings in practice. For instance, the Midcontinent Independent System Operator (MISO) demonstrated $3.5 million in reduced congestion costs and an 86% reduction in wind curtailment during a three-week outage, improving both operational efficiency and cost-effectiveness [23].

- **Improved reliability and resilience:** TO improves reliability by managing overload risks and reducing emergency outage probability. Pilot studies conducted in collaboration with utilities indicate that TO can lower reliability risks in specific scenarios, reinforcing grid performance during high-stress events [23] [24]. In emergencies, TO reroutes power flows around impacted areas, aiding in rapid recovery and avoiding cascade failures. For instance, during Winter Storm Elliott, SPP administered two transmission reconfigurations, bypassing transmission constraints to access an additional 845 MW of generation [25]. TO also strengthens contingency planning by creating alternate power paths, enhancing grid resilience against line failures and severe weather.

5.2 Integrating Topology Optimization into Planning

Due to the intrinsic complexity of transmission networks, every TO reconfiguration impacts system stability, flows, and voltages throughout the grid and can result in advantages and disadvantages. Advanced algorithms that can analyze a wide range of factors and scenarios are needed to optimize these settings, which could make deployment and integration with current grid management systems more difficult. These algorithms output possible system reconfigurations, which need to be closely evaluated to ensure that the ultimate reconfiguration solution identified is well-informed.

The latest exemplification of TO software is NewGrid's Router tool, which can analyze grid details at the node-breaker level to provide configuration options that increase capacity while adhering to reliability standards and integrating into existing EMS.

5.2.1 Incorporating Topology Optimization into Transmission Planning Models in Regional Transmission Organization and Independent System Operator Regions

In practice, TO is integrated into both the planning and operational stages of transmission management. During the planning phase, TO identifies alternative grid configurations that maximize existing infrastructure usage, which can delay or avoid the need for new line construction or could suggest the convenience of different expansion projects, such as alternative substation arrangements.

1. **Baseline assessment:** Similar to APFCs, the evaluation of TO must build from an accurate representation of the existing and planned transmission grid in a particular location, and an expectation of which system reliability violations (thermal, voltage, stability) must be addressed. For TO, the local grid topology must also be "meshed," at least to some extent, to enable alternate reconfigurations.

2. **Performance assessment:** TO algorithms assess various scenarios and system contingencies to ensure that proposed configurations are reliable and meet operational requirements. For example, in cases of thermal overload on high-demand transmission lines, TO helps operators find reconfigurations that redistribute load across parallel corridors with available capacity. In general, experts trained in using and interpreting results from TO algorithms should be relied upon for the most robust assessment possible. The results of TO algorithms can also be used as informational guides to broaden understanding of the underlying connectivity of the grid topology and identify the reconfiguration(s) that produce the most significant benefits for the overall system. The reconfigurations should be evaluated to confirm that no other reliability risks exist to system performance.

3. **Integration into reliability models:** Once suitable reconfigurations are identified, the modified transmission topology can be reflected back into traditional power-flow software, and the models can be re-run with this new information to verify that TO addresses the reliability issues it has been identified to solve.

4. **Integration into capacity expansion models:** Finally, the information and settings input into reliability and economic modeling can be reflected back into the original capacity expansion modeling conducted. The capacity expansion model can then take advantage of changed facility ratings to appropriately expand or constrain investment build-out.

5. **Integration into economic models:** Any changes to the transmission system identified in prior steps can then be reflected back into 8,760-hour production cost models (for example, redistributed power flows, the integration of additional generation without triggering reliability violations, etc.). These models can show the resulting production cost savings and economic impacts.

The incorporation of TO in interconnection studies has the potential to allow RTOs to relieve congestion, lower the likelihood of curtailments, and facilitate the timely interconnection of new generation.

5.2.2 Incorporating Topology Optimization into Interconnection Study Models in Regional Transmission Organization and Independent System Operator Regions

TO can be useful in interconnection studies by providing higher flexibility and efficiency to the grid that could facilitate the integration of a new generator. When identifying the need for network upgrades in response to reliability violations triggered by interconnecting resources, RTOs can use TO to assess possible grid reconfigurations that relieve constraints and enhance system reliability.

Steps 1–3 in transmission planning considerations align with the reliability-focused methods for interconnection cluster studies. These can be applied with minor adjustments as follows:

1. **Baseline assessment:** Identify whether the local grid topology is meshed and, thus, if a reconfiguration may be possible.

2. **Performance assessment:** In evaluating TO as a network upgrade option, some factors that should be considered include how TO can adjust power flows to avoid thermal or voltage violations caused by a new interconnecting resource. TO can be used to mimic breaker operations and determine the best system conditions that minimize the effects of added generation on loaded lines. This is especially useful for integrating variable energy systems, where fluctuations in the output can lead to localized congestion. Additionally, the type of reconfiguration identified must align with whether the affected interconnecting resource is seeking ERIS or NRIS. In the case that a newly interconnecting generation must momentarily or temporarily trip to accommodate the reconfiguration, these are best suited for ERIS connections. Furthermore, TO scenarios must be assessed under different system conditions to ensure that reconfigurations are reliable and conform to the relevant interconnection standards.

3. **Integration into reliability models:** If the interconnecting resource is seeking a level of interconnection service that can be maintained with the application of the identified reconfiguration, the new topology configuration can be reflected in the power flow model and re-evaluated to assess the mitigation of the identified reliability violation.

The incorporation of TO in interconnection studies has the potential to allow RTOs to reduce the costs of network upgrades, lower the likelihood of curtailments, and facilitate the timely interconnection of new generation.

5.2.3 Incorporating Topology Optimization into Integrated Resource Planning Models and Procurement for Regulated Utilities

Similar to APFCs, the benefits of TO manifest through better management of power flows. Because IRP capacity expansion and production cost models tend to have limited representation of power flows, it may be difficult for regulated utilities to represent TO directly in IRP models. But there are still opportunities for utilities to represent benefits indirectly by assessing the impact of TO on capacity expansion and production cost model inputs such as transfer capacity between zones, timelines and costs of interconnecting new generation, availability of new generation capacity, capacity accreditation of individual generators, system planning reserve margin and operational reserve requirements. Another key benefit of TO could be reduced aggregate losses across the system. Since TO is a software-only solution, the costs to analyze and implement reconfiguration solutions are generally much lower than the savings or grid benefits that result, leading to likely favorable BCA outcomes.

5.3 Topology Optimization Example Use Case

Consider a region with a high level of new generation integration where a critical 230 kV transmission line is often congested during peak wind resource availability. TO algorithms could find a recon- figuration that opens a normally closed breaker, thus rerouting power to a lightly loaded 138 kV parallel line. This adjustment reduces the pressure on the 230 kV line, better utilizing existing infrastructure, while maintaining system reliability. The solution also decreases congestion costs, prevents energy curtailment, and optimizes the grid while preserving system reliability.

This approach was effectively applied in MISO in the Rising–Bondville area, where TO reconfigurations saved $57.1 million in congestion costs, prevented 54 hours of overloads, and demonstrated TO's efficacy in relieving grid stress without costly infrastructure expansions during major outages in the area that took place over the course of weeks [24] [26].

5.4 Topology Optimization Operational Considerations and Management

TO's flexible, software-based approach aligns well with grid modernization initiatives by enhancing agility, supporting generator interconnection, and maximizing current infrastructure use while keeping costs low due to the lack of hardware components. One crucial factor to consider when weighing TO applicability in operations or planning paradigms is its ability to facilitate grid maintenance and upgrades by reducing outages or disturbances. TO can effectively balance the load during planned maintenance by rerouting power to avoid congestion on alternative lines, reducing backup line strain, and maintaining grid stability. System planners can also design new transmission and substation configurations to be more flexible and meshed by including the ability to leverage TO reconfigurations later in that asset's life.

System operators and TO technology vendors must work closely together to guarantee that TO software interacts seamlessly with current EMS and other grid management technologies for TO deployment to be effective. This could incur some upfront costs to integrate the new technology, potentially offset by system savings enabled by TO.

5.5 Conclusion

TO offers considerable benefits for grid efficiency, reliability, and affordability. By reducing congestion and maximizing the use of grid infrastructure, TO can support a more reliable and affordable power system. Its further development goes hand in hand with the increasingly digitally-enabled grid of the 21st century.

6 Advanced Conductors

Advanced conductors are enhanced variants of transmission line materials developed to counter the drawbacks of legacy or conventional conductors and address emergent power delivery needs. Conventional, steel-core conductors, such as aluminum conductor steel-reinforced (ACSR) or aluminum conductor steel-supported (ACSS) designs remain the norm today due to their ease of installation and familiarity among transmission-owning utilities. Incremental benefits can be gained over legacy ACSR technology by using enhanced versions of ACSS designs with special mischmetal coatings or trapezoidal configurations; regardless, the thermal expansion behavior of steel remains limiting [27].

Transformative performance increases can be gained by using advanced high-temperature low-sag (HTLS) conductors such as C7 conductors, aluminum conductor composite-reinforced (ACCR), aluminum conductor composite core (ACCC), and aluminum-encapsulated carbon core (AECC) conductors. These composite conductors offer significantly lower line losses, lower lifetime maintenance, lower sag, and increased safe capacity-carrying capabilities while reducing the need for structure upgrades.

Figure 8. ACCC Conductor (CTC Global)

Some of the first generations of C7, ACCR, and ACCC required different installation procedures compared to conventional conductors or used less durable materials, and those challenges limited their uptake. The latest variations of these conductors are built with both high-performance materials and attachment capabilities that enhance overall line capacity and efficiency while also upholding standardized installation methods.

For example, innovations such as assembly design [28] and optical fiber integration [29] are helping to streamline installation procedures and assess core integrity before and after energization.

Extensive, independent tests [30] coupled with a growing number of successful deployments in countries including Belgium [31], Indonesia [32], and China [33] are beginning to validate the performance of these conductors and build industry confidence in them. EPRI has been conducting independent testing of various advanced conductors over the last decade, validating their reliability and suitability for long-term, high-demand applications. Some advanced conductors are fully compatible with standard installation practices, enabling utilities to leverage existing infrastructure without modifications or specialized training.

Figure 9. AECC Conductor (TS Conductor)

Due to innovations in both the materials used and the manufacturing methods, initial asset costs of advanced conductors are typically higher than those of conventional conductors, without consideration for the additional capacity they may bring. In addition, the balance of project costs may also change when compared to conventional conductors due to reduced needs for structure upgrades and/or the increased capacity that needs to be supported by the entire system. For example, if a transmission line is reconductored with advanced conductors to achieve a higher capacity rating, terminal equipment at the substation (e.g., transformers) may also need to be upgraded along with the conductor. Conversely, conductor properties that allow for longer spans or lower sag may enable taller towers to be avoided or fewer structures to be used, though this could require additional engineering and structural analysis to confirm feasibility.

Comparing different types of advanced conductors to identify the ideal product for a particular application is also a complex endeavor. Conductor performance is difficult to directly compare across technologies because variations in material compositions contribute differently to specific performance characteristics. Conductor efficiency depends on the quantity and quality of aluminum in the conductor and can also vary across operating temperatures. For example, below 200 °C, minor improvements in a conductor's ampacity are driven mainly by higher quality aluminum. This, as well as the ability to operate above 90 °C, contributes to some versions of ACSS having improved performance over ACSR. Advanced HTLS conductors enable equivalent high-ampacity operation at much lower operating temperatures (reducing sag and wildfire risks) and even greater ampacity while safely operable at ambient temperatures much higher than 200 °C (improving emergency power flows). They do this by incorporating larger quantities of aluminum within the conductor, as in AECC and ACCC designs. For these reasons, no standalone characteristic is sufficient to build a complete picture of a single conductor's performance. Instead, planners should carefully assess the future needs of their system and evaluate different conductors' performance holistically.

6.1 Benefits of Advanced Conductors

Advanced conductors can address today's mounting problems associated with constrained power transmission and distribution, growing energy demand, and integration of new generation. Benefits include the following:

- **Increased carrying capacity:** The latest advanced conductor technologies offer several advantages, beginning with increased carrying capacity. Their innovative designs use mid to high-strength, lightweight cores and some other superior materials; these enable higher current-carrying capabilities to meet increased power demand with minimal disruption to the grid. Thus, advanced conductors can be an attractive solution for boosting grid capacity within the existing grid footprint, particularly in areas where new infrastructure development might be constrained due to geographic factors or siting and permitting challenges.

- **Improved grid efficiency:** Advanced conductors enhance the efficiency of the grid by diminishing line losses due to the use of less resistive materials and enhanced thermal properties, enabling them to function at higher temperatures without incurring excessive sagging. Their thermal durability makes them well-suited for areas of high demand or difficult operating conditions, such as low clearances. Their efficiency advantages are most realized when they are used to increase capacity during contingency events or short-term peaks rather than sustained high-temperature operation.

- **Longevity and resilience:** Advanced conductors can withstand exposure to high temperatures, ice, wind, and ultraviolet radiation, all of which degrade traditional conductors over time. They can maintain robust performance under harsh environmental conditions and extreme weather, which can translate to reduced operations, maintenance needs, and costs. In addition, the reduced sag and resilience to high temperatures help mitigate wildfire risk [34].

6.2 Integrating Advanced Conductors into Planning

Advanced conductors can offer many advantages when fully integrated into planning processes. Despite their higher upfront price than conventional conductors, reconductoring with advanced conductors could be the most cost-effective solution to medium- to long-term transmission planning needs when evaluated against other proposals that may involve new greenfield transmission development. In recognition of the potential for rapid capacity expansion, federal and state regulatory bodies are increasingly moving to im- plement consideration of advanced conductors in grid planning. The Berkeley Laboratory Grid Integration Group has designed an online tool to help with this evaluation: the Reconductoring Economic and Financial Analysis (REFA) Tool. This resource enables grid planners to conduct techno-economic analysis to compare different conductor and tower options when seeking transmission capacity upgrades [35].

6.2.1 Incorporating Advanced Conductors into Transmission Planning Models in Regional Transmission Organization and Independent System Operator Regions

To incorporate advanced conductors into transmission planning models in RTO and ISO regions, adhere to the following:

1. **Baseline assessment:** Assess the current transmission system's carrying capability, longevity, and needs, and compare it to future needs.

2. **Performance assessment:** Assess applicable advanced conductor technologies for their ability to deliver the necessary increases in capacity while meeting other relevant needs, such

as ease of installation, timeframe of required capacity increase, geographic constraints, etc. Of those technologies that would be suitable for selection, calculate the associated conductor and project costs based on information provided by vendors and/or tools like Berkeley Laboratory's REFA. Over the asset's lifetime, determine if the improvements to capacity and reliability characteristics justify the costs.

3. **Integration into reliability models:** Once a particular technology is chosen, integrate the advanced conductor solution into the relevant power flow model by increasing the carrying capacity according to the capabilities of the selected conductor technology. The modeler can then re-run the power flow model to ensure the new rating solves identified grid violations.

4. **Integration into capacity expansion models:** The advanced conductor solution can then be reflected back into the capacity expansion model by increasing the rating of the relevant transmission facilities. The capacity expansion model can use the increased line capacity to expand or constrain investment build-out appropriately.

5. **Integration into economic models:** Any changes to the transmission system identified in prior steps can then be reflected back into 8,760-hour production cost models (for example, increased carrying capacity, the integration of additional generation without triggering reliability violations, etc.). These models can show the resulting production cost savings and economic impacts, which help inform project selection.

6.2.2 Incorporating Advanced Conductors into Interconnection Study Models for Regional Transmission Organization and Independent System Operator Regions

The same approach used above for reliability modeling can be used to incorporate advanced conductors into interconnection studies.

6.2.3 Incorporating Advanced Conductors into Integrated Resource Planning Models and Procurement for Regulated Utilities

In IRPs, advanced conductors can be a key enabler of increasing grid capability and reliability while avoiding the need for new, greenfield infrastructure. For regulated utilities, the consideration of advanced conductors in IRPs entails evaluating the long-term value of these conductors for their potential to help address demand growth, new energy resource integration, and system reliability.

The major potential benefits of advanced conductors are consistent with those from other ATT technologies: increased transfer capacity between zones, reduced timelines and costs of interconnecting new generation, increased availability of new generation capacity, increased capacity accreditation of individual generators, reduced system planning reserve margin, reduced operational reserve requirements, and reduced aggregate system losses. Because of the relatively high upfront costs and long lifetime of advanced conductors, utilities must analyze the long-term benefits of these technologies, including how their deployment may influence long-term generation capacity expansion and annual production costs far into the future.

6.3 Advanced Conductors Example Use Cases

Advanced conductors have seen a growing number of deployments in the United States and internationally in recent years. In recent projects, Montana–Dakota Utilities (MDU) and Salt River Project (SRP) used AECC conductors to upgrade transmission lines, showcasing AECC's ability to deliver substantial performance improvements without requiring new supporting transmission infrastructure. Additionally, recent ACCC deployments in Colombia and Paraguay reveal the potential for doubling transmission capacity and navigating complex geographic features like river crossings.

6.3.1 Montana–Dakota Utilities Case Study

In 2021, MDU sought to enhance the capacity of an 11-mile stretch of a 230 kV transmission line originally built in 1966 to accommodate new wind farm interconnections. By using AECC conductors, MDU achieved a 78% increase in line ampacity without modifying the existing towers or corridors. This success was made possible by AECC's low-sag characteristics, which enable higher current flows without the risk of excessive sag that could compromise line clearance. The project demonstrated AECC's capacity to handle higher loads efficiently. It provided MDU with a solution to interconnect the new generation without the need for new towers or specialized training, or tools, thus significantly reducing capital expenditure and project timelines [36].

6.3.2 Salt River Project Case Study

Arizona-based utility SRP faced capacity constraints on a key transmission line that serves high-demand urban areas. Rather than constructing new lines or expanding corridors, SRP opted to reconductor the line with AECC conductors in the spring of 2024. The installation team noted that AECC's compatibility with existing infrastructure allowed the project to proceed without specialized fittings or reengineering of tower structures. Since no modifications to the existing system were necessary, this reconductoring effort was completed ahead of schedule and under budget while improving line ampacity by 143% and upgrading carrying capabilities without disrupting the utility's ability to serve the load [37].

6.3.3 San Lorenzo Case Study

In San Lorenzo, Paraguay, the utility ANDE faced challenges around increased energy demand and geographic constraints. They elected to install a new line with an ACCC conductor to double transmission capacity, reduce losses, and enhance overall system stability. Because of the reduced sag of the ACCC conductor, the project spanned 700 meters of the Paraguay River, connecting substations that would have otherwise been difficult to connect. In total, the new 220 kV line spans more than 55 miles [38].

6.4 Advanced Conductor Operational Considerations and Management

As noted, some advanced conductors may be able to serve as a “drop-in” replacement for older conductors, while others may not, depending on their design and material properties. Where compatibility is an issue, further changes to towers, fittings, or connectors may be necessary. Ahead of an advanced conductor deployment, utilities need to evaluate all supporting structures, such as the strength of the towers, the condition of the hardware, and the clearance needed to make the necessary changes for the new conductors. Advanced conductors may be more sensitive to handling and installation because of their material characteristics. Some designs are compatible with traditional installation procedures, while others may require extra training for installation teams. Tensioning, splicing, and securing these advanced conductors require proper procedures to avoid damaging them and enhance their structural stability during deployment. Utilities should engage advanced conductor vendors for specific guidance in the installation of their particular technology.

Advanced conductors tend to require less maintenance than traditional conductors. It is sometimes recommended that monitoring systems be installed to monitor the conductor’s temperature, sags, and tension. These insights enable utilities to detect problems before they occur, manage assets effectively, and guarantee that the conductors perform as expected under varying grid conditions.

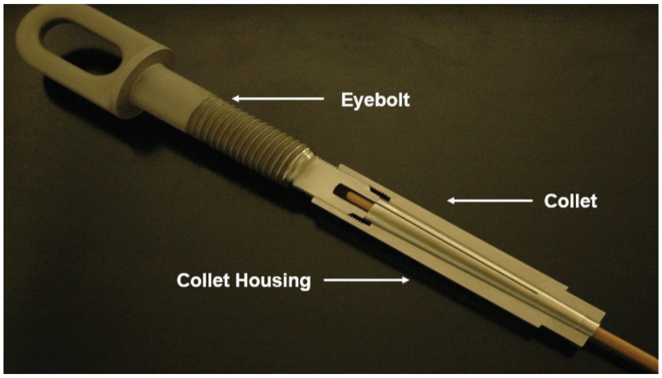

Figure 10. ACCC Collet System (CTC Global)

6.5 Conclusion

Advanced conductors are a promising development for upgrading transmission systems to meet the increasing power demand, support new resource integration, and quickly overcome the capacity constraints of our existing infrastructure. These conductors leverage new materials and superior designs to increase the transmission capability, efficiency, and productivity of the grid while at the same time increasing its reliability. Due to their capacity to work at higher temperatures with low sag, they are ideal for high usage and restricted spaces.

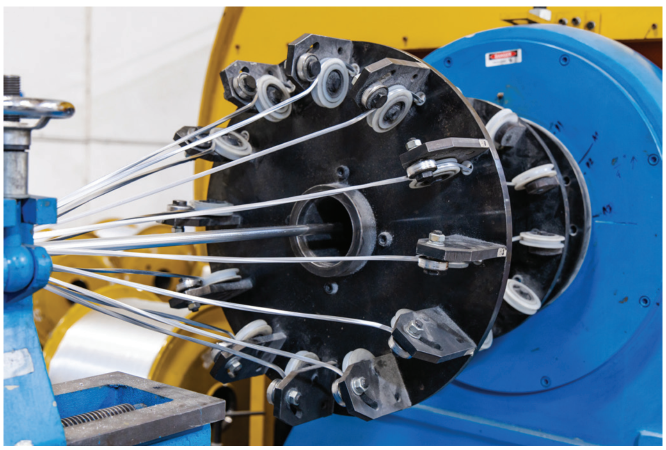

Figure 11. Manufacture of Advanced Conductor (TS Conductor)

However, identifying the best use cases and implementing these conductors can be a complex process that requires advanced planning and tried-and-true procedures. Utilities need to assess the current conditions of the existing structures, select the proper installation methods, and incorporate monitoring systems to guarantee the structures' performance and durability. As utilities continue to build expertise through verification, calibration, and implementation, advanced conductors could soon become a routine solution to upgrades, allowing utilities to meet future load requirements effectively, dependably, and cost-effectively.

7 Conclusions

ATTs can help bridge the gap between planning and operations for a flexible, efficient, and cost-effective grid. To fully leverage the benefits of the technologies, planners need to update their traditional grid planning methodologies and devote resources to ATT assessment and incorporation [39]. The best way to manage today's rapidly expanding and increasingly dynamic electricity system is to establish a flexible, expanded grid capable of adapting and responding to real-time operating needs with the support of modern technology. This forward-looking strategy strongly emphasizes creating a grid that can accommodate long-term capacity expansion while still adjusting to changing operational circumstances and near-term needs. GETs can serve as a modular bridge solution until more extensive enhancements become necessary or feasible, and as a long-term solution in areas where further transmission build-out would be unnecessary or result in overbuild. Advanced conductor technologies ensure that only the highest efficiency transmission investments are made when additional grid build-out is deemed necessary. Together, these ATTs can ensure that grid planners fully use the existing transmission grid reliably, significantly reducing costs to consumers while enabling economic growth. GETs provide these benefits in the near term, while advanced conductors provide longer term solutions.

Some key recommendations for both RTOs and regulated utilities to bridge the gap between transmission planning and operations and achieve a more flexible grid with ATTs are listed below:

- **Integrate transmission and generation planning:** Modelers should seek opportunities to better integrate transmission and generation planning where possible. ATTs offer potential system savings through maximizing the utilization of existing assets, unlocking lower-cost generation investment portfolios, and reducing the cost of system operations. Better integrating transmission and generation planning through co-optimizing transmission and generation expansion models or better reflecting various transmission scenarios in generation capacity expansion will highlight the full range of ATT benefits for both RTOs and regulated utilities.

- **Incorporate flexible grid designs in planning stages:** Flexibility in grid design should be prioritized by transmission planners, who should encourage substation and network configurations that facilitate adaptive technologies. This entails constructing substations with switchable components, redundant pathways, and adaptable bus configurations, enabling future operators to quickly adjust power flows in response to current grid conditions.

- **Adopt probabilistic and scenario-based modeling approaches:** Go beyond conventional static modeling techniques and use scenario-based and probabilistic methods to consider environmental factors, demand trends, and generation variability. For example, planners should model wind speed variations, temperature shifts, and demand spikes to find out how ATTs like DLR and APFC can improve grid efficiency and resilience in conditions that are becoming more dynamic.

- **Collaborate closely across teams:** Communication and collaboration between the planning and operations teams should be improved to ensure that ATTs are seamlessly integrated into both planning and everyday grid management practices. Sharing data, real-time insights, and operational needs can assist planners in developing solutions that are both technically feasible and operationally practical. Such solutions empower operators to fully leverage ATTs' capabilities to manage congestion, thermal constraints, and other grid challenges.

- **Leverage advanced software tools:** Take advantage of advanced software solutions that simulate real-time grid behavior and evaluate various scenarios. Planners should use advanced tools offered by ATT vendors to simulate the technology's potential given certain grid conditions and anticipate potential operational challenges. Integrating these advanced software tools into current grid monitoring and management tools (e.g., SCADA/EMS) is essential for adoption and buy-in.

- **Develop comprehensive standards and guidelines for ATT integration:** Establish best practices and industry standards for integrating ATTs into transmission operations and planning. To guarantee that ATTs are implemented consistently and dependably, this should include modeling, data collecting, and performance assessment instructions. Better acceptance and improved operational alignment will result from developing standards for integrating DLR, APFC, TO, and advanced conductors with conventional grid planning.

- **Design for real-time adaptability and operational flexibility:** Ensure transmission plans adapt to changing operational conditions by considering real-time capabilities during the planning phase. For example, designing APFC devices with modular capabilities or incorporating DLR systems that dynamically adjust ratings based on environmental conditions can help enhance grid responsiveness. This proactive approach minimizes operational bottlenecks once these technologies are deployed and ensures a resilient grid.

- **Monitor and evaluate ATTs performance continuously:** Implement systems for continuous monitoring and evaluation of ATTs in real-world applications. Collecting and analyzing data on ATT performance—such as how APFC devices relieve congestion or how DLR responds to temperature and wind changes—can provide valuable insights to further optimize planning models and operational practices.

- **Engage with stakeholders to foster buy-in and alignment:** Collaborate with regulatory bodies, utility partners, technology providers, and other stakeholders to foster alignment on ATT integration strategies. The growing number of regulatory proceedings and policies regarding ATTs, such as FERC Orders requiring their consideration in planning, underscores the importance of engaging with external stakeholders to ensure a cohesive approach to grid modernization.

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