PoyntEnergy GridLAB

Advanced Conductors

Reliability and Stability Study of the BPA System

October 2025

Executive Summary

The U.S. power grid needs to expand its transmission capacity to meet the projected rise in demand and to provide access to cheap, clean electricity. Among the available options for this expansion, deploying advanced conductors[1] offers an effective solution to reduce project time and cost while nearly doubling the circuits' current carrying capacity. Reconductoring existing transmission lines could present immediate advantages over building entirely new lines, as it may utilize existing transmission towers, environmental permits, rights-of-way, and land, with only minimal modifications needed for the upgraded lines.

This report outlines a planning methodology for identifying regional transmission system upgrades and formulating strategies for the use of advanced conductors in enhancing transfer capacity[2]. Figure A illustrates the workflow and sequence of steps involved in implementing this process. While the primary focus of this study was on reconductoring existing transmission lines across all voltage ratings, the modeling framework developed for advanced conductors is also applicable to new line construction and selection of the right advanced conductor. This framework makes use of commercially available simulation tools and is designed to be power system simulation vendor-agnostic. As such, it is compatible with any industry-grade modeling platform capable of performing dynamic simulations, including GE Power Flow (formerly PSLF), Siemens PSS®E, and PowerWorld, among others. For post-processing and system performance analysis, the framework employs data analytics and statistical methods that can be implemented in a variety of analytical environments such as Python, MATLAB, Julia, and Microsoft Excel.

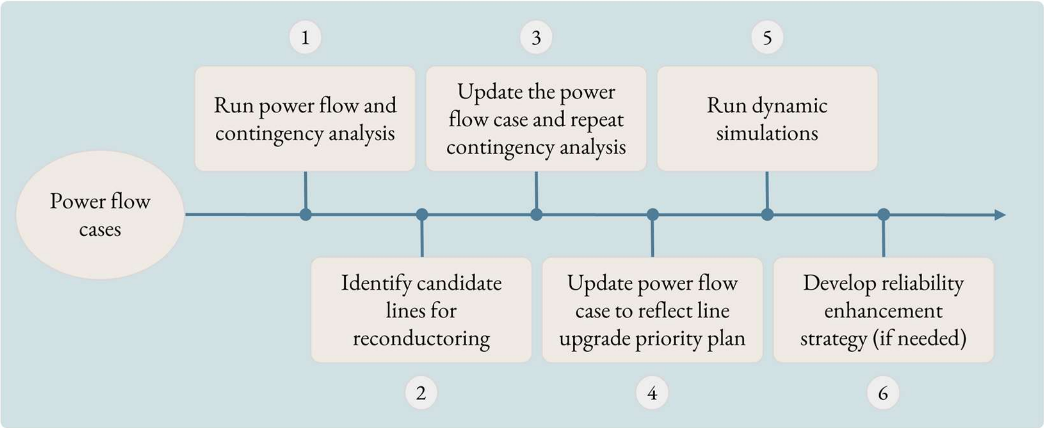


Figure A. The workflow for the reconductoring framework presented in this report.

This study addressed system-level modeling of advanced conductors and evaluated their impact on steady state reliability and transient stability of transmission network. All transmission lines analyzed were alternating current; direct current lines were not included. No assumptions or considerations related to

[1] Throughout this report, the term "advanced conductors" is used to describe both composite core conductors and "enhanced steel core conductors" including enhanced ACSS designs. When applicable, the specific OEM product name or technology name is used.
[2] FERC Order 1920 requires the development of a methodology to "right-size" transmission through the use of Advanced Transmission Technologies including advanced conductors. While BPA is not under FERC jurisdiction, it is common practice for BPA to consider and cooperate with practices being adopted in the broader energy market.

market operations or processes were incorporated. It used operating cases from the Western Electricity Coordinating Council (WECC) and focused on a reconductoring scenario in the Pacific Northwest, within the Bonneville Power Administration (BPA) transmission service area as a case study.

Line Selection Criteria and Prioritization for Reconductoring

This study established four criteria for identifying transmission lines where reconductoring would most effectively enhance system reliability. These criteria are summarized in Figure B.

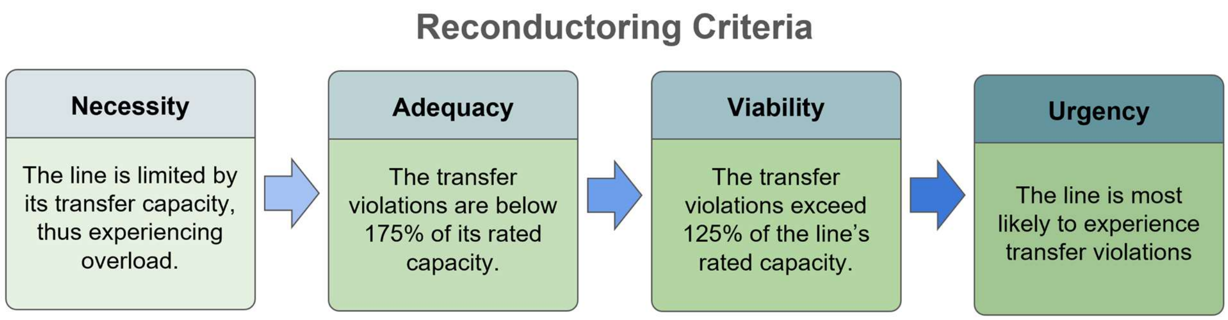


Figure B. The criteria for selection of lines for reconductoring.

Based on the criteria outlined above, the following reconductoring priorities are recommended for the effective and timely deployment of advanced conductors:

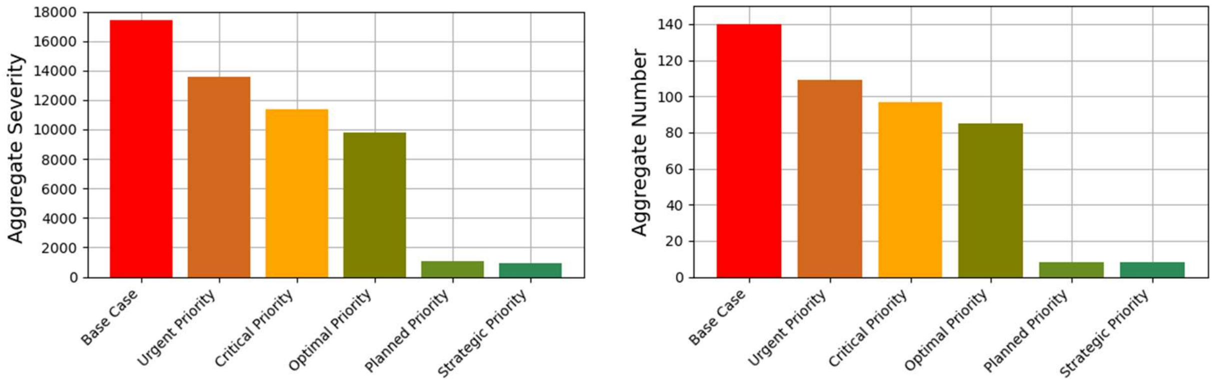
a) **Urgent priority**: A number lines that satisfy all four criteria and are identified through impact analysis as providing the highest positive effect on system reliability if reconductored.
b) **Critical priority:** All lines that satisfy all four criteria.
c) **Optimal priority:** All lines that satisfy the first three criteria.
d) **Planned priority:** All lines that satisfy the first two criteria.
e) **Strategic priority:** All lines that satisfy only the first criterion.

Each successive priority level includes a broader set of lines, meaning more lines are considered for reconductoring as you move down the list. It is recommended that the transmission planners set reconductoring priorities by balancing their system's reliability needs, resources, and regional goals, considering both short- and long-term factors.

Key Findings from the BPA Transmission System

- The steady state analysis found that adding more advanced conductors to the BPA transmission system resulted in consistent system-wide performance improvement. Figure C illustrates the key metrics for reconductoring this system under different priority scenarios. It shows both the severity and number of line transfer limit violations continued to drop as more advanced conductors were deployed in successive priorities.

- It was determined that a full-scale deployment of advanced conductors in the BPA transmission system would involve approximately 400 miles of reconductoring across 56 transmission lines, and would have the potential to reduce the frequency and severity of line transfer limit violations by more than 94%, evidenced in Table A. Even limited upgrades could deliver substantial benefits: upgrading just four branches, a total of 36 miles of reconductoring, could decrease the severity of line transfer limit violations and their frequency by 22%. More upgrades spanning about 100 miles of reconductoring across 17 lines, based on optimal prioritization, could reduce the severity of line transfer limit violations by nearly 44% and the number of violations by approximately 40%.



(a) Aggregate severity of violation

(b) Aggregate number of violations

Figure C. Summary of line transfer limit violations in the BPA transmission system for reconductoring under different priorities - lower values of these metrics indicate better system reliability.

Table A. Improvements in the BPA transmission system for reconductoring under different priorities

Priority Order	Total Number of Lines Reconductored	Total Mileage* of Reconductored Lines	Improvement in Severity of Violations**	Improvement in Number of Violations**
Urgent priority	**4**	**36.36**	**21.82%**	**22.14%**
Critical priority	**10**	**85.33**	**34.65%**	**30.71%**
Optimal priority	**17**	**100.71**	**43.75%**	**39.28%**
Planned priority	**55**	**393.75**	**93.98%**	**94.28%**
Strategic priority	**56**	**398.63**	**94.58%**	**94.28%**

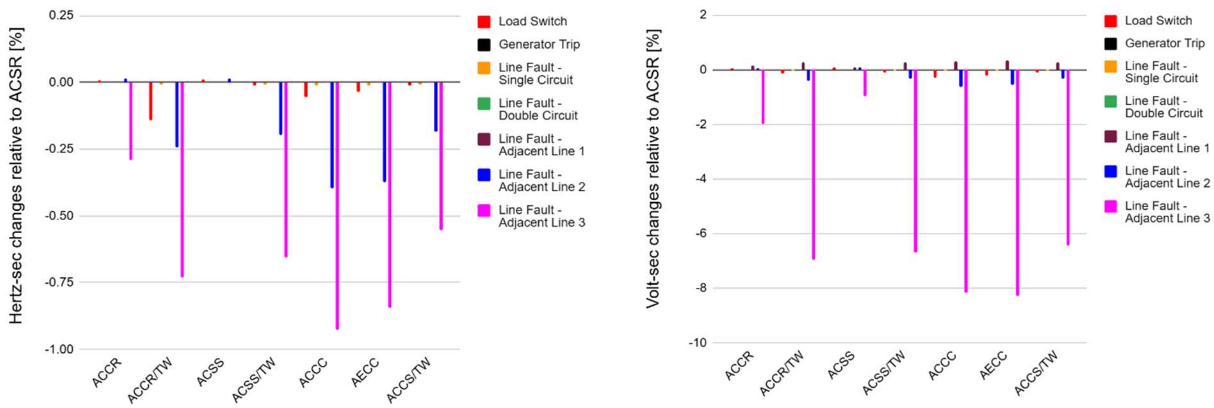
*The mileage is estimated based on the lines' characteristics as provided in WECC base cases.
**These metrics are calculated relative to Base Case and represent system-wide performance

- The dynamic simulations indicated that reconductoring transmission lines with advanced conductors did not present an adverse impact on the dynamics and stability of the BPA system. Most oscillation indices showed improvement by falling below their Base Case values with ACSR conductors, as shown in Figure D, demonstrating a positive overall impact on system-wide dynamic performance resulting from the deployment of advanced conductors. The largest increases in oscillation indices were 0.01% and 0.35% for frequency and voltage, respectively, which are safely negligible.

- This study analyzed a new category of contingencies for transient stability analysis, focusing on faults in components electrically adjacent to reconductored lines where the advanced conductor is an electric path. These contingencies showed the most significant changes in system transients, suggesting that advanced conductors primarily affect local, rather than system-wide, dynamics.

Although not required by NERC TPL guidelines for standard planning studies, this class of contingencies is recommended for inclusion in reconductoring studies.

- Since the dynamic stability issues were identified to remain local, this newly introduced class of contingency analysis might not be required for a high-level assessment to identify priority reconductoring opportunities but should instead be performed at the project level once specific lines are selected for upgrade.



(a) Hertz-sec oscillation index (b) Volt-sec oscillation index

Figure D. Changes in oscillation indices of the BPA system for a set of contingency events after reconductoring lines with urgent priority using different advanced conductor types - negative values correspond to improvements in system's dynamic performance

- The impact of advanced conductors on the system frequency response was found to be safely negligible, with extremely minimal changes in frequency response characteristics observed across all cases with advanced conductors and for all contingencies analyzed.
- This study did not find any voltage stability issues present related to the deployment of advanced conductors. However, it acknowledged that such challenges could arise in regions with existing voltage problems and constraints in reactive power support. Additionally, widespread adoption of advanced conductors in the future should be planned with voltage stability considerations in mind.
- This study did not identify any phase angle stability issues resulting from line reconductoring with advanced conductors. However, such concerns could arise if advanced conductors are used for long transmission lines with voltage ratings of 230 kV and above, especially in systems with pre-existing phase angle stability problems, under heavy loading conditions, or during contingencies.
- The stability analysis found that the most notable changes in system's dynamic performance coincided with the deployment of advanced conductors with significantly lower electrical resistance compared to ACSR conductors. However, this study did not explore the underlying causes of these performance variations or establish a formal correlation between electrical resistance and systems dynamics.

Recommendations

This study offers valuable insights into reliability and stability implications of reconductoring transmission lines with advanced conductors. However, a number of areas of improvement have been identified, which can help advance the state of planning and execution of reconductoring projects. They are set forth as follows.

- Reconductoring a line with advanced conductors could have an impact on relay settings and protection equipment due to changes in the line's characteristics. It may alter the waveform and propagation constant of traveling waves on the line, potentially affecting the accuracy of fault detection and location. This is a critical area that warrants further study to ensure protection systems remain effective and safely adaptive to the deployment of advanced conductors.

- Market tariffs and cost allocation play a critical role in the planning and operation of transmission lines. It would be valuable to study the financial aspects of deploying advanced conductors, considering the potential savings enabled by their reduced electrical losses, as well as the additional revenue generated by their higher ampacity. In addition, further studies are needed to fully understand the diverse value propositions associated with their deployment, particularly in the broader context of social benefits such as job creation, economic growth, and regional development, as well as in advancing key policy goals such as enhanced grid resilience and increased access to clean energy.

- As the benefits of using advanced conductors in transmission lines become increasingly recognized, there remains a need to update the planning standards to take into account their unique characteristics. It is recommended that regulatory entities with oversight of system planning, such as NERC, WECC, and other reliability organizations, review the existing planning standards and make the necessary adjustments for a seamless deployment of advanced conductors through reconductoring or new construction projects. Such reform would entail reassessment of planning criteria and metrics used for evaluating reliability, economic analysis, and risk assessment. It could help streamline projects, facilitate regulatory approvals, and maximize the benefits that these grid-enhancing technologies can provide.

Acknowledgement

This report was prepared for GridLab Inc, under contract by Poynt Energy. The following individuals were actively involved in this study:

Poynt Energy
Amir Sajadi (Lead Author)

GridLab Inc.
Casey Baker

The authors thank Joe Hack for his support and engagement in this study. Special thanks to Dr. Rick Wallace Kenyon of encoord Inc. and Dr. Scott Greene for their insightful discussions and constructive criticism that contributed to the foundation of this work. A sincere appreciation is extended to Dr. Adria Brooks and Zachary Zimmerman of Grid Strategies and Daniel Berkowitz of Bekaert for the time devoted to reviewing this report, as well as for the valuable comments and suggestions.

Disclaimer
This report was revised in October 2025, following its original publication in July 2025, to incorporate the most current information on commercially available advanced conductors and identify the commercial designations of those evaluated. The subsequent review and analysis confirmed that these updates had no material impact on the overall results or conclusions of the report.

Suggested Citation
Sajadi, Amir, Casey Baker, *Advanced Conductors: Reliability and Stability Study of the BPA System*, Technical Report, Poynt Energy and GridLab, October 2025

Table of Contents

1. Introduction …… 10
 1.1. Background …… 10
 1.2. Advanced Conductors …… 10
 1.3. About This Report …… 11
 1.4. Reconductoring Study Framework …… 12
 1.5. Case Study: BPA Transmission System …… 12
2. Advanced Conductors: A Brief Background and Characteristics …… 14
 2.1. What are ACs? …… 14
 2.2. Practical Considerations for Reconductoring using ACs …… 14
 2.3. Electrical Characteristics of ACs vs. ACSR Conductors …… 14
  2.3.1. Electrical Resistance …… 15
  2.3.2. Electrical Reactance …… 16
  2.3.3. Current Carrying Capacity …… 17
3. Criteria for Reconductoring and Guidelines for System Studies …… 18
 3.1. Assessment of Transmission System Adequacy with ACs …… 18
 3.2. Selection Criteria for Lines Reconductoring …… 18
 3.3. Reconductoring Priorities …… 19
 3.4. System Impact Studies …… 20
  3.4.1. Steady State Analysis …… 20
  3.4.2. Dynamic Stability Analysis …… 21
 3.5. Modeling ACs for Power System Impact Studies …… 21
4. Line Selection for Reconductoring in the BPA Transmission System …… 23
 4.1. Philosophy Behind This Process …… 23
 4.2. System Simulations …… 23
 4.3. Simulations Specifics …… 23
  4.3.1. BPA Assets Database Creation …… 23
  4.3.2 Power Flow and Contingency Analysis …… 23

4.3.3. Selection of Candidate Lines for Reconductoring 24
4.4. System Impact Screening Study 26
4.4.1. System Performance Metrics 27
4.4.2. Results of Reconductoring Individual Lines 27
4.5. Annual System Performance Assessment 28
4.6. Results of Different Reconductoring Priorities 28
5. Stability Studies for Impact Assessment of Reconductoring in the BPA System 31
5.1. Philosophy Behind This Process 31
5.2. System Simulations 31
5.3. Selection of Contingencies 31
5.4. Implementation of Contingencies 32
5.5. Preliminary Assessment of Loading Conditions 32
5.6. Impact Assessment of Reconductoring with ACs on System Dynamics 35
6. Conclusion and Recommendations 38
6.1. Conclusion 38
6.2. Recommendations 39
Appendix I. Review Literature on Application of ACs in Power Systems 40
Appendix II. Modeling Transmission Lines for Power System Studies 41
Appendix III. Electrical Parameters of ACSR Conductors vs. ACs 43
Appendix IV. Generic Model of AC for Steady State Impact Assessment 44
Appendix V. Impact Assessment of ACs in the BPA Under Different Reconductoring Priorities 46
Appendix VI. Dynamics Simulations of the BPA System for Reconductoring Lines with Different ACs 52
References 63

1. Introduction

1.1. Background

The U.S. Department of Energy's *2023 Study of National Transmission System Needs* [1] found that the nation's transmission infrastructure must be modernized and significantly expanded by 2035 to meet the evolving needs of the power sector. Aging infrastructure contributes to a higher frequency of interruptions in power delivery, primarily due to reduced reliability and availability. It also leads to increased transmission and distribution costs, largely driven by the rising expenses associated with operation and maintenance. According to the American Society of Civil Engineers [2], 70% of existing transmission lines in the U.S. are 25 years old or older, and a recent report [3] estimated that approximately 200,000 miles of transmission lines across the U.S. and Canada will require modernization over the next decade due to aging. The need for expanded transmission capacity is further driven by rising electricity demand, especially from building and transportation electrification and the rapid growth of data centers, and the resulting requirement to integrate significant new generation capacity. The latest analysis by Lawrence Berkeley National Laboratory [4] highlights strong developer interest in renewable energy, with 95% of active queue capacity requesting interconnection composed of photovoltaic solar and wind resources, representing more than 1.36 terawatts of proposed capacity. These generation facilities are frequently located in remote areas where meteorological conditions ensure reliable output, but which are far from load centers or retiring power plants [5]. In contrast to conventional generation facilities, which were typically sited near demand centers, these remote plants require robust transmission infrastructure to operate efficiently. Ensuring adequate transmission capacity is essential to minimize curtailments, reduce congestion-related costs, and extend a hedge against investment risks in new generation development [6].

The most straightforward approach to addressing the need for increased transmission capacity is to build new transmission lines; however, this is often the most cost-prohibitive and time-consuming option. The design, permitting, and construction of high-voltage transmission lines typically take 10 years or more and require substantial capital investment. For example, the Cardinal-Hickory Creek project, a 102-mile, 345 kV transmission line developed by American Transmission Company, connecting Dubuque County, Iowa, to Dane County, Wisconsin, took a decade to complete and costed over $655 million [7],[8]. Such extended timelines elevate investment risk, potentially deterring investors. As an alternative, grid-enhancing technologies provide a more flexible, lower-risk pathway to expanding transmission capacity while avoiding many of the delays and costs associated with new line construction.

1.2. Advanced Conductors

The use of advanced conductors (ACs) is among the grid-enhancing transmission solutions for increasing transfer capacity and can effectively reduce or delay the need for new line construction. These relatively new technologies have been identified as a promising means of rapidly expanding the transfer capacity of existing power infrastructure through the reconductoring process. However, the application of advanced transmission technologies is not limited to reconductoring; they can also be used in new transmission line construction.

The reconductoring process could offer immediate advantages over building entirely new transmission lines, as it utilizes existing transmission towers, construction and environmental permits, rights-of-way, and land, requiring minimal modifications for the upgraded lines. In other words, it has the potential to eliminate the need to install new towers or obtain additional permits, rights-of-way, or land. As a result, reconductoring a line with ACs may be a more cost-effective option, consistent with the findings of a recent study by the University of California, Berkeley, and GridLab [9].

Idaho National Laboratory recently published a list of projects in the United States that utilize ACs [10] and identified 44 transmission utilities across the country that are using ACs. However, despite these projects, the widespread adoption of ACs to increase the capacity of the existing transmission system remains limited. A recent study [11] finds that, although reconductoring or rebuilding existing transmission lines progresses at only 1 percent annually in the United States, the adoption of ACs remains scarce even within that small fraction, an observation corroborated by the Idaho National Laboratory report [10]. It is important to note that even though 44 utilities have begun deploying ACs, the extent of their use for reconductoring within their service territories remains minimal, typically covering only a few miles.

A review of the existing literature, provided in Appendix I, reveals that the applications of ACs in power systems primarily have studied with a focus on cost analysis and individual conductor performance, and the system-level studies have addressed legacy ACs. This highlights a timely opportunity to introduce a framework for formalizing system-level studies related to deployment of more modern ACs and to enhance understanding of the reliability implications associated with the widespread adoption of these technologies.

1.3. About This Report

This report develops a methodology to identify regional transmission system upgrades and determine strategies for the effective use of ACs to increase transfer capacity. Although the focus of this report is on reconductoring existing lines, the modeling approach for ACs is also applicable to new line construction. The scope of this study was limited to system-level modeling of ACs and the assessment of their impact on steady state reliability and transient stability. All lines considered were alternating current; no direct current were included and no assumptions or considerations regarding market operations and processes were made.

This study investigated the following classes of ACs, which are commercially available and used for reconductoring projects:

- **ACCR**: Aluminum Conductor Composite Reinforced
- **ACCR/TW**: Aluminum Conductor Composite Reinforced/Trapezoidal Wire
- **ACSS**: Aluminum Conductor Steel Supported
- **ACSS/TW**: Aluminum Conductor Steel Supported/Trapezoidal Wire
- **ACCC**: Aluminum Conductor Composite Core
- **AECC**: Aluminum Encapsulated Carbon Core
- **ACCS/TW**: Aluminum Conductor Composite Single/Trapezoidal Wire

Throughout this report, the term ‘AC’ broadly refers to these advanced conductors as a catch-all term, regardless of their particular material or mechanical design, unless a particular advanced conductor is explicitly identified. This study focused on upgrading 795 kcmil Drake aluminum conductor steel-reinforced (ACSR) wires. All recommendations and conclusions were made accordingly.

This study used operating cases from the Western Electricity Coordinating Council (WECC) for simulation models and focused on the reconductoring scenario in the Pacific Northwest within the Bonneville Power Administration (BPA) service territory as a case study. Power flow and transient stability analyses were performed using the PowerWorld simulation platform, and all post-processing computations were conducted using Python.

The objective of this report is to help identify the reliability risks and benefits of using ACs in transmission lines and inform electric utilities and system operators about deployment of this class of conductors to increase transfer capacity in both the near and long term. Additionally, this report may advance the state of practice toward standardizing processes and studies for AC deployment by offering recommendations for modeling ACs, methods for circuit selection in reconductoring, and system performance analysis.

Not all the inferences made in this study about the BPA system can be directly extended or applied to other projects, as they are findings from a specific analysis on this unique system. The materials presented in this report are intended to serve as a use case scenario that utilities across the nation can follow and, collectively, as a guideline for reconductoring projects. It is advised that system planners carefully study the reliability issues specific to each project, considering the conditions, needs, and constraints of the grid under consideration, and adhere to regional standards and priorities.

1.4. Reconductoring Study Framework

The framework for reconductoring studies that this report presents is applicable to transmission lines across all voltage ratings. It relies on commercially available simulation programs and is designed to be software-agnostic. This makes it suitable for all industry-grade modeling platforms capable of running dynamic simulations, such as GE Power Flow (formerly PSLF), Siemens PSS/E, PowerWorld, and PSS®E, to name a few. For post-processing and analysis of system performance, it leverages statistical analysis, which can be implemented in the analytical environment of choice, such as Python, MATLAB, Julia, and Microsoft Excel. Data exchanges between the power system simulator and the post-processing platform can be automated or performed manually.

The workflow and sequence of actions for executing this framework are conceptualized in Figure 1. Details about each step are provided in the next sections of this report, along with a discussion about their implementation.

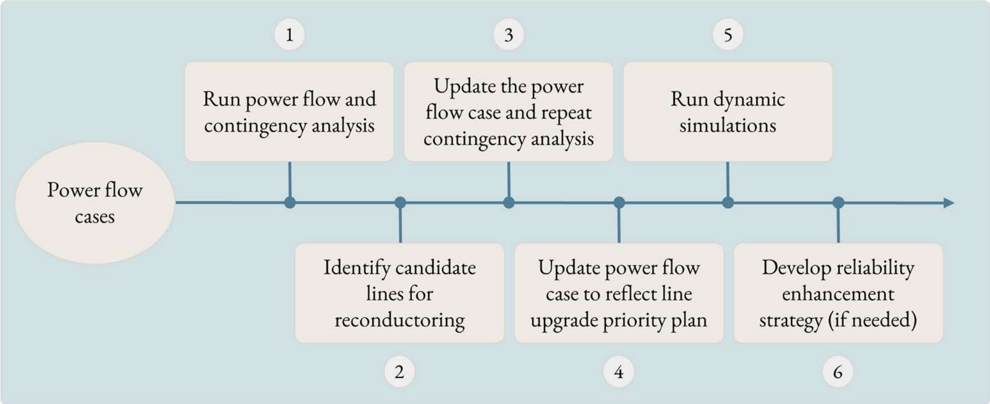


Figure 1. The workflow for the reconductoring framework that this report presents.

1.5. Case Study: BPA Transmission System

The BPA is a transmission system operator in the Pacific Northwest, part of the Western Interconnection that operates under the reliability standards and oversight of WECC. Its service territory, shown in Figure 2, spans from the Canadian border to the California-Oregon border, extending as far east as the western terrains of Wyoming and Montana. Most lines operate at voltage ratings of 115 kV, 230 kV, and 500 kV.

This transmission system is the backbone of power delivery in the Northwest, serving several local utilities and cooperatives. As of January 2024, it served a load that peaks at 11 gigawatts [12].

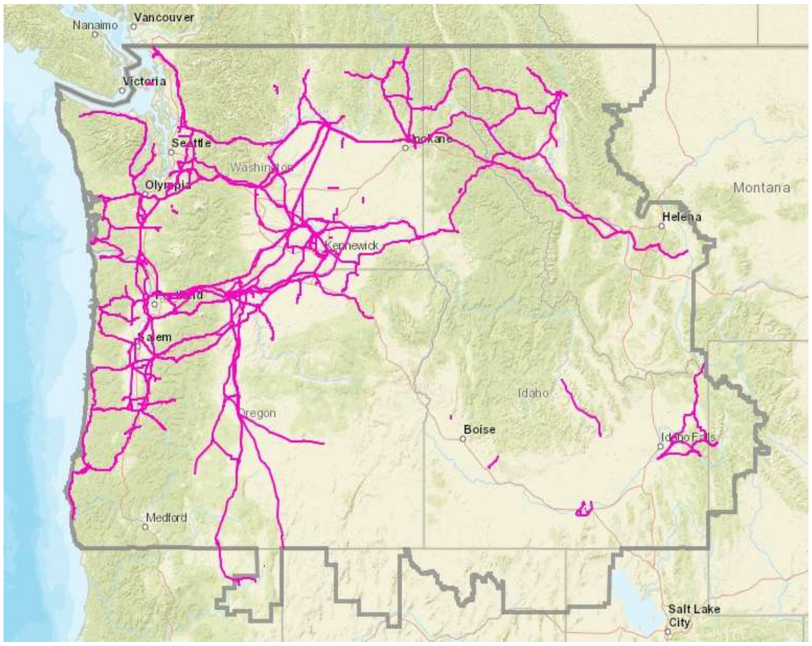


Figure 2. Map of transmission system in the BPA service territory. Source: publicly available transmission map [13]

The BPA transmission system was a timely and relevant choice for this study since the BPA is considering expanding its transmission system to meet the projected load growth in its region [14]. According to [3], pursuing reconductoring to expand transmission system capacity in the BPA region could result in substantial consumer savings, with considerable environmental benefits as well.

2. Advanced Conductors: A Brief Background and Characteristics

2.1. What are ACs?

Legacy ACs use steel core wire with strands of advanced aluminum alloys, as an upgraded version of the conventional ACSR core which remains the industry standard today. They are designed to have higher conductivity than ACSR and operate at high temperature with low deformation, a feature that also earns them the designation "high-temperature, low-sag" (HTLS) conductors. Modern ACs use advanced composite cores and trapezoidal stranding, which allow more conductive aluminum to fit within the conductor's cross-sectional area. This configuration reduces conductor ohmic losses while simultaneously increasing current carrying capacity (also known as ampacity) [11]. Similar to legacy ACs, the design of modern ACs and their core material properties reduce deformation at high temperatures and offer better structural stability [9]. As a result, both legacy and modern ACs are specialized for continuous operating temperatures above 212°F (100°C) and can reliably withstand emergency operating temperatures above 392°F (200°C) [15]. These features are key to enhancing the thermal stability of lines [5] and increasing resilience to prevent wildfires caused by power lines [11].

2.2. Practical Considerations for Reconductoring using ACs

Reconductoring transmission lines using ACs presents both advantages and disadvantages. The advantages are both near-term and long-term. As a short-term benefit, a promising aspect of reconductoring with ACs is the relatively short project duration required to expand transfer capability. A study by the University of California, Berkeley and GridLab [16] finds that reconductoring using ACs can be deployed within 18 to 36 months at a much lower cost compared to constructing new lines, collectively presenting a more feasible investment option for expanding transfer capability with lower risk. The long-term benefits of nationwide deployment of ACs in the U.S. include the potential of generating over $2.2 billion in annual consumer savings simply from reduced energy losses, according to a recent study by Grid Strategies [3]. At the state level, these savings could range from $130,000 to $208 million. The benefits that the use of ACs offer are recognized internationally. For instance, TenneT TSO, which serves the Netherlands and parts of Germany, reconductored the transmission line between Zwolle and Groningen in the Netherlands. This reconductoring project is estimated to generate annual savings of about $750,000 (678,000 Euros) due to a 19% reduction in energy losses [17].

The main drawback of using ACs is the requirement for considerable investment, as they are more expensive than regular ACSR conductors, and such projects often require substation upgrades and tower modifications. In fact, the cost of ACs can be a significant deterrent, reaching more than six times that of conventional ACSR conductors, according to [18], [19].

2.3. Electrical Characteristics of ACs vs. ACSR Conductors

In power system studies, the electrical characteristics of a transmission line are represented by the parameters of its equivalent circuit model, as detailed in Appendix II. As an illustrative introduction and to highlight the key features of ACs, the parameters' values of 795 kcmil Drake ACSR conductors were compared with those of their AC counterparts, consistent with the recommendations in [20]. This analysis found that the most notable difference between ACs and ACSR conductors was their ampacity, which is quintessential to their application. A secondary notable difference was the electrical resistance; ACs have lower resistance than ACSR conductors. The remainder of this section presents additional information on this analysis, which is further detailed in Appendix III, Table III.1.

2.3.1. Electrical Resistance

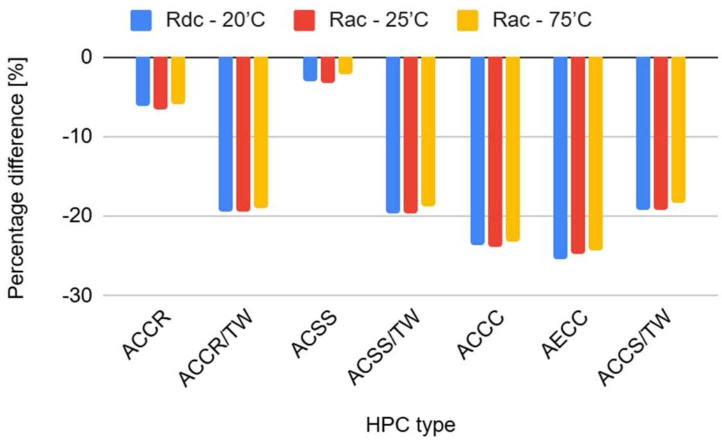


Figure 3. Percentage difference in electrical resistance of different ACs relative to ACSR

The data shown in Figure 3 indicate that at operating temperatures up to 75°C, all ACs have lower electrical resistance than the ACSR conductors. Most notably, AECC, ACCC, ACSS/TW, ACCR/TW, and ACCS/TW conductors exhibit electrical resistance values that are up to 24.66%, 23.91%, 19.72%, 19.52%, and 19.12%, respectively, lower compared to ACSR conductors (at 25'C). Therefore, the deployment of ACs is expected to reduce the electrical losses in the system, assuming the same current flow.

At emergency ratings, ACs are capable of operating at high temperatures for sustained periods of time - exceeding 200°C (392°F) - while conventional ACSR conductors can only operate at temperatures above 100°C (212°F) for short durations. Nonetheless, operating ACs at high temperatures leads to a steep increase in their electrical resistance. Table 1 compares the electrical resistance of ACs at 25°C with that at 200°C (as an approximate temperature for emergency operation for ACs). For ACSR conductors, operation at 200°C (392°F) is not practical, as they begin softening or melting before reaching this temperature. However, a resistance value for ACSR at this temperature was estimated using linear extrapolation and is also included in the table solely for comparison purposes.

Table 1. Ratio of electrical resistance for high temperature to low temperature conditions

	ACSR*	**ACCR**	**ACCR/TW**	**ACSS**	**ACSS/TW**	**ACCC**	**AECC**	**ACCS/TW**
$\frac{R_{AC}\ @\ 200'C}{R_{AC}\ @\ 25'C}$	1.64	1.72	1.71	1.69	1.69	1.69	1.66	1.69

Table 1 indicates that, at 200°C, the electrical resistance of ACs increases by an average of 69% compared to their resistance values at 25°C. In contrast, for ACSR conductors, the resistance increases by about 64% over the same temperature range. This suggests that although the ACs are capable of maintaining their mechanical strength and operating at high temperatures for extended periods of time, the combination of higher resistance and higher current (which could be much higher than the case of ACSR) results in greater electrical losses, impacting the system operation efficiency.

2.3.2. Electrical Reactance

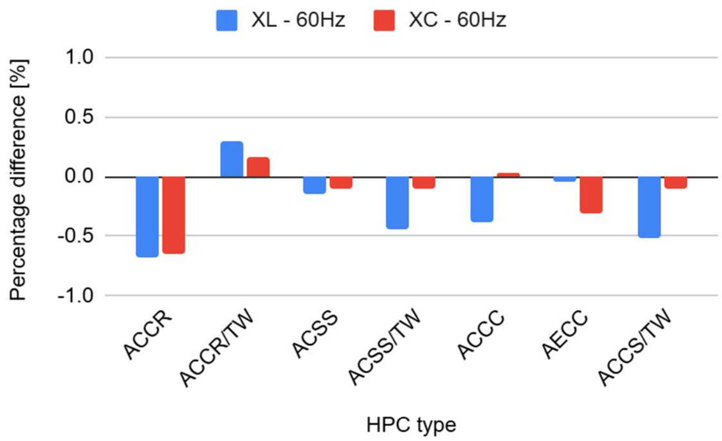


Figure 4. Percentage difference in inductive and capacitive reactance values of different ACs relative to ACSR conductors

The data shown in Figure 4 suggest that the majority of ACs under consideration exhibit inductive reactance (X_L) and capacitive reactance (X_C) values quite similar to those of ACSR conductors for a comparable spacing, with most differences remaining below 0.5%. The exception is ACCR conductor, whose inductive and capacitive reactance values differ from those of ACSR conductors by up to 0.67% and 0.64%, respectively. The inductive reactance of ACCS/TW, ACSS/TW, and ACCC conductors differ from that of ACSR conductor by 0.51%, 0.44%, and 0.39%, while their capacitive reactance differences remain below 0.1% which are negligible. Similarly, the capacitive reactance of AECC conductor differs from that of ACSR conductor by 0.31% whereas its inductive reactance differs by 0.04% - also a negligible difference.

An important point to note is that the changes in reactance values alter the line surge impedance (see Appendix II for details). Variations in line's surge impedance affect its surge impedance load and, consequently, have implications for its power transfer capability, as well as for the reactive power required for adequate voltage regulation. According to St. Clair curves [21], [22], for a given voltage level, an increase in a line's surge impedance may restrict its power transfer capability unless appropriate measures are taken to provide reactive power support and to account for voltage drop, especially when operating at high current levels near the upper limits of AC ampacity. Based on the data shown in Figure 4, the largest change in a line's surge impedance due to reconductoring can occur with the use of ACCR conductors, resulting in 0.65% change. This small variation is unlikely to cause a significant, immediate problem.

2.3.3. Current Carrying Capacity

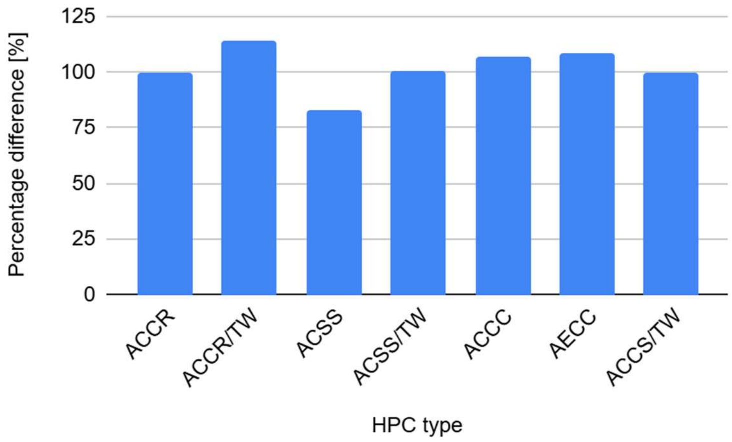


Figure 5. Percentage difference in maximum current carrying capacity of different ACs relative to ACSR conductors

Lastly, the data shown in Figure 5 indicate that reconductoring a line with any of the ACs considered - except ACSS - can double its maximum current carrying capacity. ACSS increases it by approximately 83%. It should be noted that a line's effective current carry capacity is subject to its ambient conditions and varies in real-time.

3. Criteria for Reconductoring and Guidelines for System Studies

3.1. Assessment of Transmission System Adequacy with ACs

The main purpose of deploying ACs is to increase the transfer capacity of transmission lines. Accordingly, the starting point for reconductoring studies should be the assessment of the adequacy of the existing transmission system. This can be achieved by power flow analysis under both intact and contingency operating conditions in order to identify lines that are limited by their transfer capacity. For this purpose, it is advised to use system models that represent all current and future operating assumptions and loading conditions (heavy, light, and shoulder), including load growth, retirements, new generation, planned outages, and extreme weather conditions.

3.2. Selection Criteria for Lines Reconductoring

It is reasonable to assume that a utility may not be able to reconductor all lines experiencing limitations in power transfer in the near term, mainly due to the costs associated with deployment of ACs. Under this assumption, this study introduced four criteria that can be applied to develop reconductoring priority strategies based on the following merits: (1) technical necessity, (2) technical adequacy, (3) financial viability, and (4) reliability urgency. These criteria are summarized in Figure 6 and described as follows.

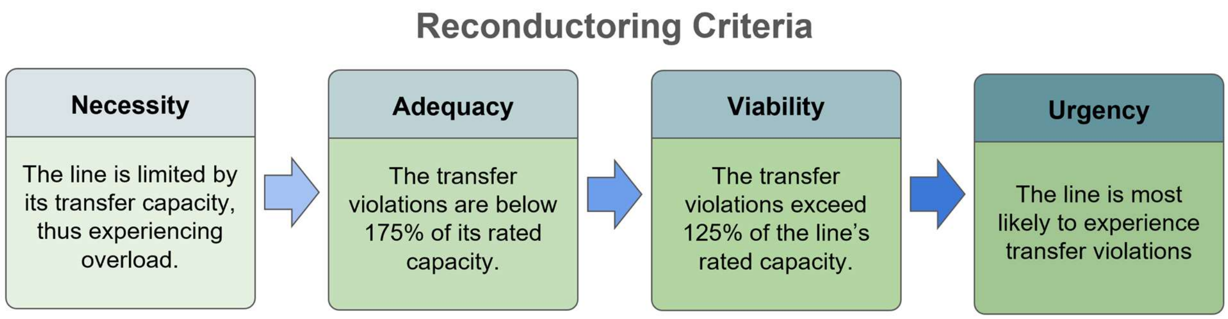


Figure 6. The criteria for selection of lines for reconductoring

Criterion 1: For a transmission line to be considered a candidate for reconductoring, it should be limited by its transfer capacity. Such a constraint takes the form of line transfer limit violations during normal, N-1, or N-k contingency operating conditions. This can be determined based on the analysis of historical performance data from operations, computer simulations using future planning cases (which incorporate future load growth, network topology changes, unit retirements, or new planned generation), or a combination of both. Note that there may be scenarios where a line operates under high loading conditions without violations such that the financial losses from electrical losses could justify its reconductoring. However, this study focused on reliability aspects, not financial considerations, and therefore it did not consider those special circumstances.

Criterion 2: Reconductoring a line using ACs increases its current carrying capacity by at least 75%, as shown in Figure 5. Based on this, a line should be considered for reconductoring only if its transfer limit violations do not exceed 175% of its rated current carrying capacity. This is a conservative recommendation for the cut-off threshold and generic for all ACs evaluated to ensure that reconductoring will effectively address the existing reliability issues for that line. Therefore, this threshold should be adjusted if a specific AC type identified for reconductoring demonstrates an increase in current carrying capacity greater than 75%.

Criterion 3: The next step in the line selection process for reconductoring focuses on determining whether a viable business case exists to justify the required capital investment. It is generally assumed that conventional ACSR conductors can safely tolerate up to 25% overload during emergency operations for a limited period of time, depending on ambient conditions. Therefore, to justify the additional investments for reconductoring on the grounds of reliability needs, the severity of a line's transfer limit violations should exceed 125% of its rated current carrying capacity. Exceeding this threshold indicates that the transfer violation severity, and thus the associated system reliability risk, is substantial, and that the extant ACSR conductors are insufficient of safely to mitigate it. This recommended threshold should be adjusted according to specific system conditions, operational requirements, and the criticality of the load served by the line.

Criterion 4: In cases of limited available resources, where not all lines meeting the first three criteria can be reconductored immediately, priority should be given to those with a more dire need for upgrade. To this end, the number of violations for each line (which indicates violation frequency) serves as an effective metric to determine the reconductoring priority. This criterion ensures that lines with more frequent violations are given higher priority, as they are more likely to operate above their nominal ratings and, thus, present a higher probability of posing a reliability risk. The cut-on threshold for the violation frequency could be established using historical data that accurately reflects transmission system performance, complemented by probabilistic analyses across various load and future planning scenarios, in alignment with regional reliability standards.

3.3. Reconductoring Priorities

Based on the criteria outlined above, the following reconductoring priorities are recommended for the effective deployment of ACs:

a) **Urgent priority**: A number of lines that satisfy all four criteria and are identified through impact analysis as providing the highest positive effect on system reliability if reconductored.
b) **Critical priority:** All lines that satisfy all four criteria.
c) **Optimal priority:** All lines that satisfy the first three criteria.
d) **Planned priority:** All lines that satisfy the first two criteria.
e) **Strategic priority:** All lines that satisfy only the first criterion.

Urgent priority focuses on a number of individual lines identified as being in dire need of upgrade, with the exact number of lines determined based upon the resources available. These lines are identified to bring the most significant improvement in system reliability through impacts study (discussed later in this chapter). Therefore, this priority is intended to allocate investment capital to those with the highest value and return in the form of improving system reliability and operational efficiency. Critical priority consists of a portfolio of lines that require reconductoring without delay, addressing overload issues in near-term. This priority suits projects typically planned for construction within 1 to 5 years. Optimal priority encourages timely reconductoring of critical lines that have the potential to escalate to more severe reliability problems if left unaddressed, and is suitable for medium-term planning, generally within 5 to 10 years. Planned priority involves a structured, orderly deployment of ACs to meet specific overload needs without urgency, preventing major negative consequences. Typically aimed at expansion planning over a 10 to 20-year horizon. Strategic priority allocates resources with a long-term, multifaceted approach to maximize diverse benefits of reconductoring. This non-urgent priority fits into long-range planning, spanning 15 to 30 years to enhance system reliability.

Each successive priority level includes a broader set of lines, meaning more lines are considered for reconductoring as you move down the list. This incremental approach ensures that the most impactful projects are addressed first, while still identifying additional opportunities for long-term system improvement. Transmission system planners should select reconductoring priorities based on their system's specific reliability needs, available resources, and regional priorities, balancing both short- and long-term considerations.

3.4. System Impact Studies

System impact studies encompass two key areas of investigation. The first area is steady state power flow analysis, which examines the existence of operating points (power flow solutions) and ensures sufficient generation and transmission capacity are available to serve the load. The second area is dynamic stability analysis, which evaluates how the system responds to disturbances and transitions between operating points.

The primary objective of steady state analysis within the context of reconductoring projects is to confirm that the deployment of ACs effectively relieves overload violations. However, dynamic stability analysis adopts a "do no harm" approach, aiming to verify that deploying ACs does not introduce any adverse impacts to system stability.

3.4.1. Steady State Analysis

Steady state analysis evaluates the operational feasibility of the power system by considering generator and line constraints. In planning studies, the system is tested for feasible power flow solutions under various loading conditions, including both intact and contingency scenarios. The system constraints include equalities and inequalities: equalities ensure the balance between power supply, demand, and losses, while inequalities enforce limits on generator active and reactive power output and transmission line power current carrying capacity. According to St. Clair curves [5],[22], steady state analysis should focus on three limiting factors: (1) thermal stability, (2) voltage stability, and (3) steady state angle stability.

Thermal stability relates to the conductors' ampacity and the heat generated due to power transfer, a concern that is especially significant in shorter lines. Regarding ACs, their unique physical properties specialize them in sustaining high current carrying capacity and operating at elevated temperatures for extended periods without deformation. Therefore, it is reasonable to assume that the thermal stability concerns can be safely deprioritized for all lines reconductored with ACs [9].

Voltage stability, often characterized by the 5% voltage drop limit, addresses the network constraint in delivering power. It is typically a key concern for long transmission lines where the voltage stability margin is usually much smaller than the thermal stability margin, making it the primary limiting factor. Voltage stability is represented by bifurcation curves, commonly called "nose curves", which depend on system loading and line reactance values. Although ACs have reactance values similar to ACSR conductors, concerns may arise regarding the adequacy of reactive power when ACs transfer significantly higher power flows than ACSR conductors. Consequently, voltage stability has the potential to become a limiting factor in reconductoring projects involving ACs unless there is sufficient reactive power compensation and system reinforcement. To mitigate this risk, it is recommended to perform voltage sensitivity analysis on transmission lines selected for reconductoring with AC, considering both normal operation and contingency scenarios where high-current stress conditions are tested.

Steady state angle stability, also known as power flow security, concerns the phase angle difference between the two ends of a transmission line. The steady state stability margin, often set around 30%, is intended to provide flexibility and security under credible contingency scenarios. Since ACs have inductive reactance values similar to those of ACSR conductors, reconductoring is not expected to pose significant issues in this regard. However, high-current conditions could be challenging since higher power flow is correlated with a higher phase angle, and, therefore, it needs to be carefully studied. Accordingly, it is recommended that power flow and angle stability analyses should be conducted for each reconductoring case, evaluating both normal operation and contingency conditions.

In reconductoring studies, when a transmission line originally using ACSR conductors is upgraded with ACs, the substations at both ends of the line must be evaluated to assess their equipment ratings. This ensures that the increased capacity enabled by the ACs is not constrained by the ratings of terminal equipment such as transformers. If necessary, upgrades to these substation components should be planned to fully utilize the enhanced conductor capacity.

3.4.2. Dynamic Stability Analysis

Dynamic stability analysis addresses the transient behavior of a power system when subjected to disturbances. It evaluates system response to events such as single or multiple component outages and faults, as required by the North American Electric Reliability Corporation (NERC) transmission planning (TPL) standards [23].

Transmission system characteristics are determining factors in power system dynamics. As shown in the previous section, the electrical properties of ACs could differ from those of conventional ACSR conductors, even by a small margin. As a result, the objective of dynamic stability analysis is to verify that deploying ACs does not introduce undesirable oscillations that either degrade the system's dynamic performance or lead to instability. To this end, conducting both small-signal analysis and large-signal stability analysis (commonly referred to as transient stability analysis) is essential, where the behavior of key variables including phase angle, voltage, and frequency, are evaluated at all nodes within the defined impact area.

Another determining factor in power system dynamics is the system's loading condition. Accordingly, stability studies should be conducted under varying loading conditions - namely, heavy, shoulder, and light, to fully assess system behavior throughout the year. In projects where reconductoring is intended to expand transmission capacity for future load growth and new generation interconnections, it is recommended to study the system under both present and projected future loading conditions. This assessment should include a range of loading and dispatch scenarios to capture potential changes in power flow across the network, as well as shifts in regional and inter-regional power transfer patterns.

3.5. Modeling ACs for Power System Impact Studies

As explained in the previous section, ACs can be appropriately represented by their electrical characteristics. Table 2 provides a list of suggested scaling factors to model ACs for system studies in reconductoring projects. These scaling factors were derived for reconductoring 795 kcmil Drake ACSR conductors using commercially available AC counterparts [20]. Therefore, they should be appropriately adjusted when conductors other than those evaluated here are considered or specific seasonal ratings are factored in. To apply them, the parameters of the ACSR line being reconductored should be multiplied by the corresponding scaling factors for the AC of interest. For more details about line parameters, refer to Appendix II.

Table 2. Scaling factors for line parameters to model ACs for replacing 795 kcmil Drake ACSR conductors

AC type	Commercial Designation	R_{ac}	X_L	B	MVA
ACCR	824 T16	0.933	0.993	1.006	2.00
ACCR/TW	958 T16	0.804	1.002	0.998	2.13
ACSS	795 Drake	0.968	0.998	1.000	1.82
ACSS/TW	959 Suwanee	0.802	0.995	1.000	2.00
ACCC	1026 Drake	0.760	0.996	0.999	2.07
AECC	1051 Sun M3	0.753	0.999	1.003	2.08
ACCS/TW	973 Everglades	0.808	0.994	1.000	1.99

4. Line Selection for Reconductoring in the BPA Transmission System

4.1. Philosophy Behind This Process

This step was intended to identify transmission lines in the BPA system that experience power transfer limitations, such that reconductoring them with ACs would not only resolve these violations but also enhance system-wide reliability to the extent possible. Additionally, this step supported the evaluation of large-scale reconductoring scenarios designed to inform long-term system planning.

4.2. System Simulations

Power system simulations were conducted using PowerWorld software (Version 23). Two operating cases were used in this study: (1) the 2025 Heavy Winter (25HW) case and (2) the 2025 Light Summer (25LS) case. Each case represents a 28,000-bus system developed by WECC as part of its annual power flow base case development initiative. Specific details about each case are provided in Table 3.

Table 3. BPA dispatch for the cases studied

Case	25HW	25LS
Generation	26,487 MW	14,687 MW
Net Load	12,012 MW	6,505 MW
Tie-lie exchange	13,583 MW	7,540 MW

4.3. Simulations Specifics

This section outlines the specific considerations and assumptions made in this analysis.

4.3.1. BPA Assets Database Creation

The power flow cases used in this study represented the entire Western Interconnection (i.e., the WECC system). As a result, the outcome of power flow and contingency analysis included violations from across the entire Western Interconnection, not exclusively from the BPA assets. To address this, the first step was to isolate the BPA-specific components by creating a repository of all BPA buses. Then, a second database was created for the BPA transmission lines by selecting all branches with at least one of their two terminal buses found in the first repository. Additionally, all branches representing elements other than lines, such as transformers and compensators, were excluded.

4.3.2 Power Flow and Contingency Analysis

First, power flow analysis was conducted to ensure the models converged and check for any overloaded lines under normal dispatch. Subsequently, contingency analysis was performed to assess system security. The contingencies simulated included single generator outages, line outages, and transformer outages, all confined to the BPA footprint. A total of 2,687 contingency events were evaluated for the 25HW case, and 2,705 for the 25LS case. The difference in the number of contingencies is attributed to variations in asset availability and dispatch depending on the seasonal loading conditions. After performing contingency analysis, the results were post-processed to isolate only those violations associated with BPA assets, using the BPA bus and line databases established earlier. The outcome of contingency analysis is summarized in Tables 4 and 5.

Table 4. Line Transfer Limit Violations in BPA

Case	25HW	25LS
Total transfer limit violations events on BPA lines	140	27
Total number of BPA lines with transfer limit violations	56	15

Table 5. Voltage Violations in BPA

Case	25HW	25LS
Total voltage violations events on BPA assets	108	153
Total number of BPA assets with voltage violations	63	88

The results presented in Tables 4 and 5 indicate that the BPA transmission lines experienced a higher number of transfer limit violations in the 25HW case, whereas BPA assets saw a greater number of voltage violations in the 25LS case. This outcome aligns with the convention of power systems behavior: heavy load conditions challenge the system's loadability, often exposing transfer limitations, while light load conditions can lead to reduced dispatch and a set of generators are likely turned off that would otherwise provide essential reactive power support. This reduction in reactive power regulation capability is reflected in the increased number and frequency of voltage violations observed in the 25LS case.

The main impetus of this study was to evaluate the impact of reconductoring with ACs on resolving line transfer limit violations, which occur when power flow exceeds a line’s nominal rating. Consequently, henceforth, the power flow and contingency analysis concentrated on the 25HW case, due to its greater instances of power transfer constraints, while voltage levels were monitored throughout.

4.3.3. Selection of Candidate Lines for Reconductoring

The four criteria for candidate line selection that were defined in the previous section, were applied to the transmission system in the BPA service territory.

Criterion 1: All 56 lines met this criterion. Figure 7 shows the severity of the overload conditions in the BPA system vs. the rated transfer capacity of each line experiencing violation (MVA transfer limit) and Figure 8 presents a statistical analysis of the system’s contingency performance. Evidenced by the concentration of data points in the bottom left of the plot shown in Figure 7 and the peak of the distribution plot shown in Figure 8(a) being on the lower end of severity spectrum, it was concluded that the severity of most transfer violations remained below 125% of the respective line’s nominal rating, and the vast majority of the violations occurred in lines with a rated transfer capacity below 200 MVA. These lines were predominantly at the lower end of voltage spectrum, typically ranging from 69 to 115 kV. A few lines with rated transfer capacities greater than 400 MVA also experienced transfer limit violations, but the severity remained around 110% of the lines’ nominal ratings. Furthermore, several lines experienced transfer limit violations with severity exceeding 200% of their respective nominal ratings. As shown in the distribution plot in Figure 8(b), the vast majority of lines experienced only one violation, although the number of violations per line reached up to 12.

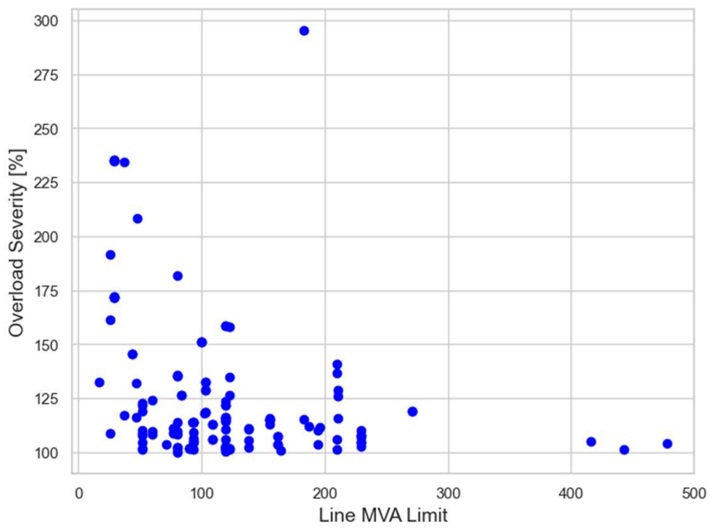
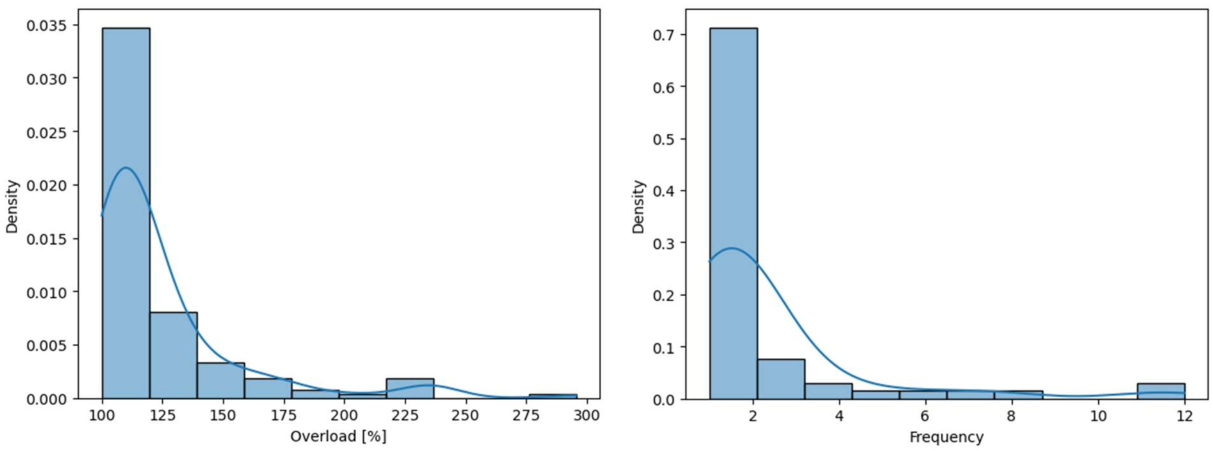


Figure 7. Severity of line transfer limit violations (percentage overload) vs. rated transfer limit of the of violated lines in BPA



(a) Statistical distribution of severity of violations observed

(b) Statistical distribution of frequency of violations per line

Figure 8. Statistical analysis of the contingency performance of the BPA transmission system

Criteria 2 and 3: Eliminating all line violations whose severity was outside the range of 125% to 175% of the MVA limit narrowed down the lines under consideration to 17 lines. The whisker plot for the severity of their violations is shown in Figure 9. Among these lines, 7 lines had one violation, 7 lines had two violations, and 3 lines had three violations.

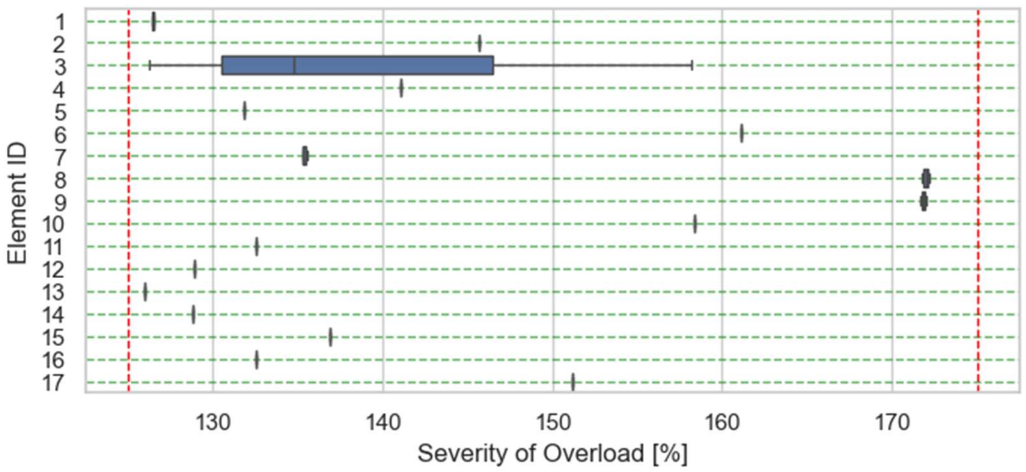


Figure 9. Whisker plot of severity of violations for lines with overload range within 125%-175%

Criterion 4: The threshold for considering a line "high risk" was determined based on a statistical analysis of lines' violation frequencies. Accordingly, a dataset was created listing the number of violations for each of the 17 lines under consideration. The standard deviation of this dataset was then utilized to identify data points that significantly deviated from the mean value of the dataset and, therefore, should be given higher priority in reconductoring due to a higher probability of experiencing transfer limit violations. The dataset had a standard deviation of 0.75 and a mean value of 1.76, respectively. Accordingly, a threshold of 2 violations, rounded down from the mean plus standard deviation value of 2.51, was chosen as the criterion for reconductoring consideration. This threshold is project specific and should be adjusted by planners based on available resources and system reliability requirements. Following this criterion, lines corresponding to element IDs 4, 5, 6, 13, 14, 15, and 16 in Figure 9 were excluded. The whisker plot illustrating the range of violations for the final candidate lines is presented in Figure 10.

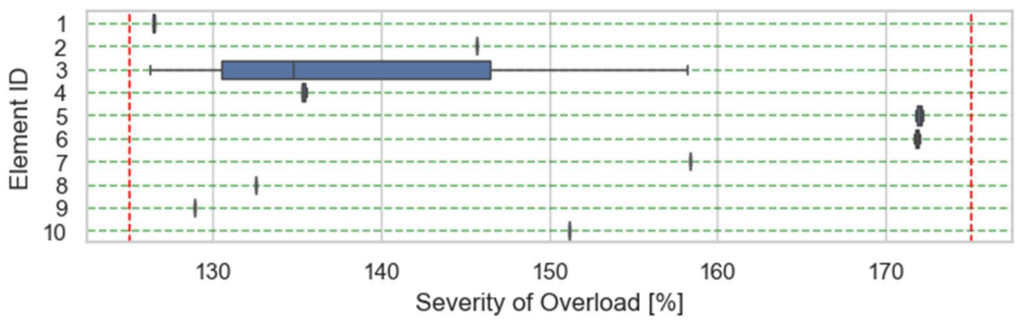


Figure 10. Whisker plot of severity of violations for final candidate lines for reconductoring in BPA

4.4. System Impact Screening Study

It was assumed that not all ten lines can be reconductored in the short term. To identify the most effective lines and prioritize their reconductoring, ten line-specific cases were developed by modifying the original 25HW case with each case representing only one of the ten lines individually reconductored. Then contingency analysis was performed for each of the ten cases using the same contingencies as the original 25HW case.

In these ten line-specific cases, a generic model of ACs was used for impact screening and to broadly address the reliability aspects of reconductoring, without focusing on a specific AC type. This generic model assumes that the MVA rating of each line is doubled and the ohmic losses are reduced by 24%. This assumption is based on the analysis provided in Appendix IV, where the key electrical characteristics of ACs, relative to ACSR conductors, were evaluated in the context of power flow. The primary factors influencing power flow were identified as (1) current carrying capacity and (2) ohmic losses. Changes in reactance resulting from reconductoring with ACs were found to have an insignificant impact on power flow.

This approach provides a reasonable representation of the changes in line characteristics that may result from reconductoring with ACs. More detailed models of specific AC types and their precise impacts on system performance were studied later in dynamic stability analysis, which takes precedence over steady state analysis. In reconductoring projects where a specific AC type has been selected, it is recommended to use the models provided by the manufacturer that are tailored to that AC for more customized analysis.

4.4.1. System Performance Metrics

To quantitatively measure the impacts of line reconductoring with ACs, two metrics were introduced. The first metric, the system's aggregate severity of violations, sums up the percentages by which the BPA lines exceeded their nominal ratings. The second metric, the system’s aggregated number of violations, counts the total number of events in the BPA system where a line surpassed its nominal rating. Lower values of these metrics indicate better system performance.

4.4.2. Results of Reconductoring Individual Lines

The results from reconductoring individual transmission lines in the BPA system are shown in Figure 11. In this plot, data points closer to the bottom left indicate better system performance for their respective cases.

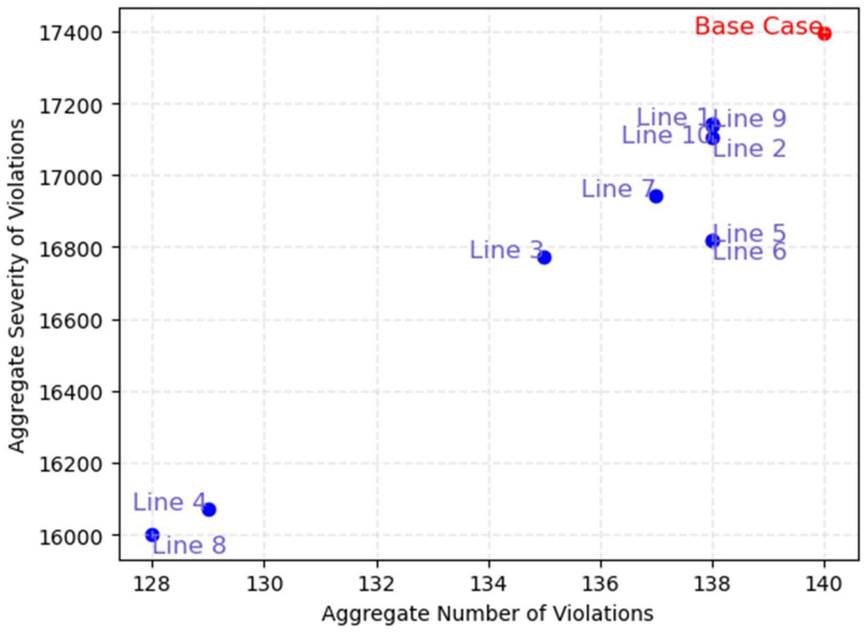
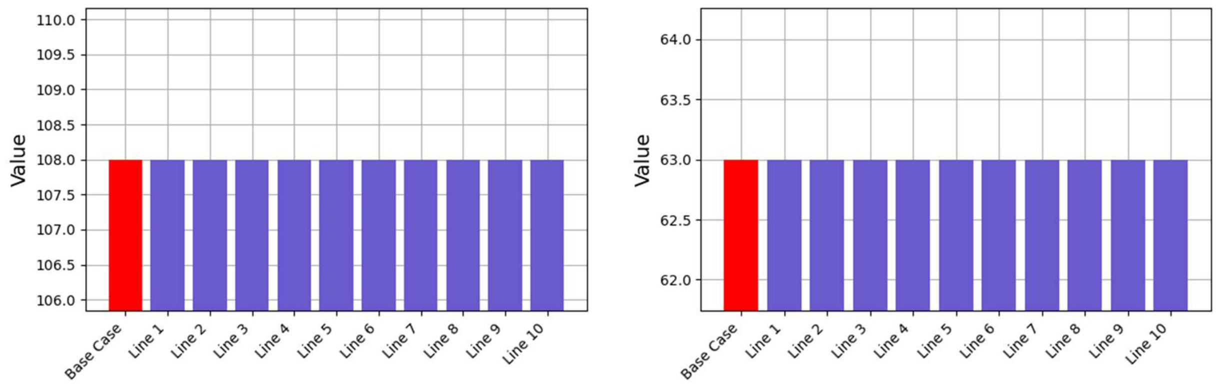


Figure 11. Aggregate severity of violations vs. aggregate number of violations for individual line reconductoring in the BPA transmission system - the closer the data point is to the bottom left, the better the system performance for the respective case

The results reveal that reconductoring Line 4 and Line 8 offered significant potential in reducing both the severity and frequency of overload conditions across the BPA transmission system. While reconductoring Line 5 and Line 6 reduced average violation severity with a smaller improvement in violation frequency, reconductoring Line 3 and Line 7 presented a desirable trade-off between improvements in both severity and frequency. Additionally, the results suggest that reconductoring any of the lines under consideration did not adversely impact voltage regulation in the BPA transmission system, as shown in Figure 12.



(a) Number of voltage violation events

(b) Number of elements with voltage violation

Figure 12. Summary of voltage regulation across the BPA transmission system

According to the results of this analysis, Lines 3, 4, 7, and 8 were identified as the final candidate lines for reconductoring under the 25HW case.

4.5. Annual System Performance Assessment

One may reasonably argue that using the 25HW case alone for reconductoring was insufficient, as it did not capture the operating conditions and subsequent violations presented by light or shoulder loading and their associated dispatch, potentially leading to suboptimal planning. To address this valid concern, it is recommended to repeat the same selection criteria using aggregate statistics from all distinct loading conditions throughout the year to represent annual system performance. Relying on the annual system performance helps identify the lines whose reconductoring brings the most positive impact year-round by reducing the severity and frequency of line transfer limit violations.

This study had access only to heavy and light load cases and therefore relied on both the 25HW and 25LS cases simultaneously to assess the variability of load and dispatch across winter and summer conditions. Accordingly, the same study process was repeated, with the violation datasets from the 25HW and 25LS cases first aggregated before applying any selection criteria. This approach captured the most frequent and severe violations across both cases. Interestingly enough, this more comprehensive approach identified three lines that coincided with a subset of the four lines identified from the 25HW case analysis. It was decided to proceed with all four lines as the basis for the urgent priority, producing a more comprehensive reconductoring scenario.

4.6. Results of Different Reconductoring Priorities

Before proceeding to dynamic analysis for reconductoring the selected lines with urgent priority, the performance of the BPA transmission system was examined under different reconductoring priorities. The results are shown in Figures 13 and 14, and the extent of improvement for each case is quantified and presented in Table 6.

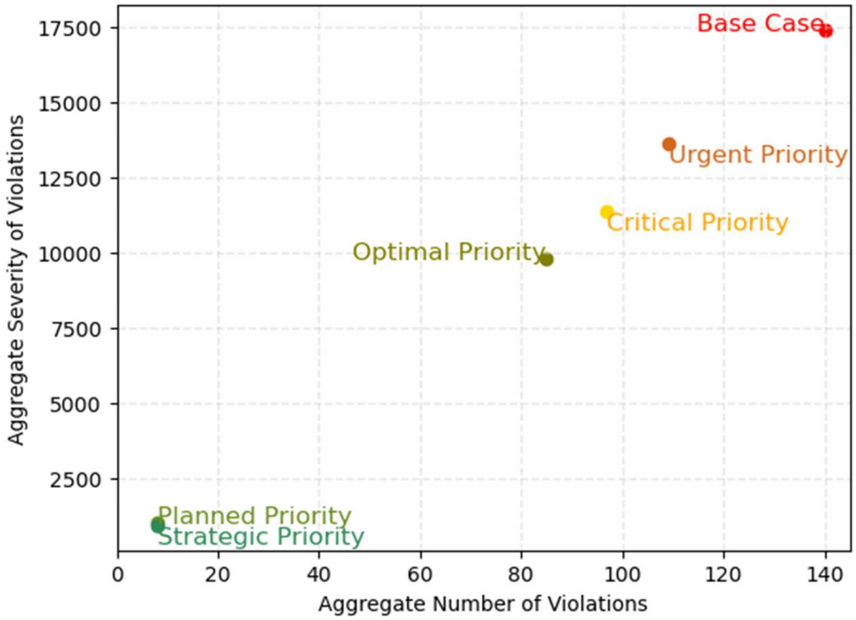
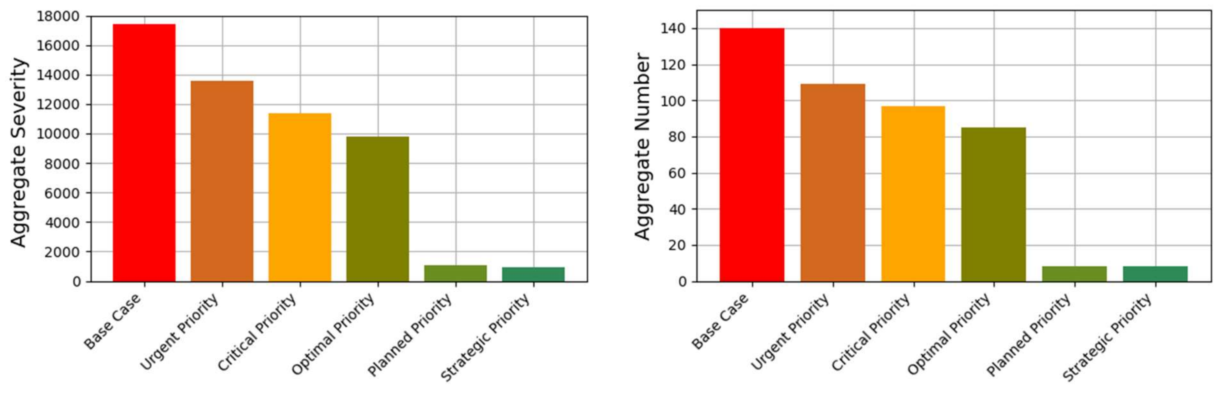


Figure 13. Aggregate severity of violations vs. aggregate number of violations for different reconductoring priorities in the BPA transmission system - the closer the data point is to the bottom left, the better the system performance for the respective case.



(a) Aggregate severity of violation

(b) Aggregate number of violations

Figure 14. Summary of line transfer limit violations in the BPA transmission system for reconductoring under different priorities - lower values of these metrics indicate better system reliability

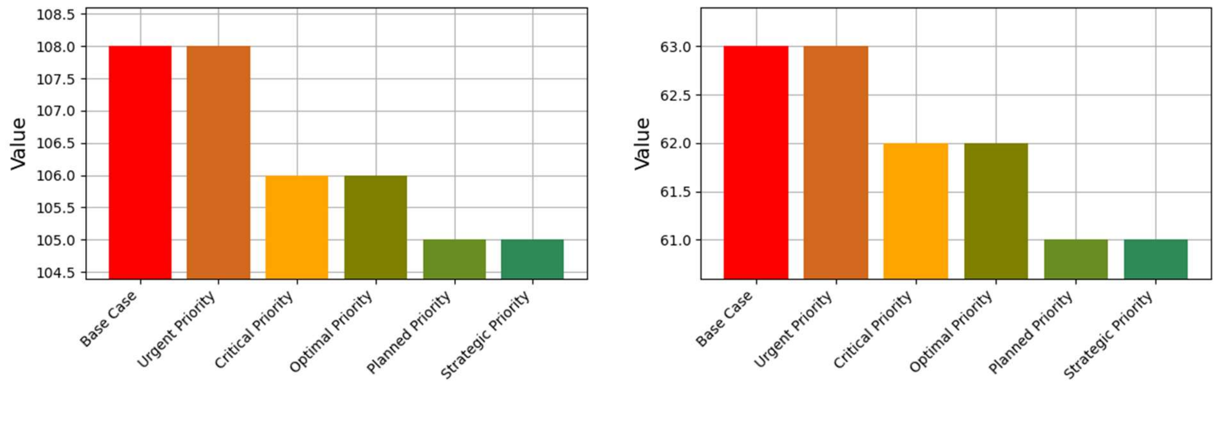
The results clearly demonstrated a monotonic improvement in the performance of the BPA transmission system as the number of ACs deployed increased. Interestingly, reconductoring with urgent priority, modifying only four branches, estimated 36.36 miles in total, reduced the system-wide severity and the number of line transfer limit violations by 22%. For lines with critical priority, with an estimated total of 85.33 miles of reconductoring, it resulted in nearly a 35% reduction in the severity of violations and a 30% reduction in their frequency. Most notably, implementing ACs on lines with optimal priority, requiring modification of 100.71 miles of transmission lines, reduced the severity of transfer violations by almost 44% and the number of events by close to 40% across the BPA system. The last two priorities involved reconductoring a greater number of lines, but the results suggested a practically 94% reduction in violation severity and frequency. Additional results for each reconductoring priority are provided in Appendix V.

Table 6. Improvements in the BPA transmission system for reconductoring under different priorities

Priority Order	Total Number of Lines Reconductored	Total Mileage* of Reconductored Lines	Improvement in Severity of Violations**	Improvement in Number of Violations**
Urgent priority	4	36.36	21.82%	22.14%
Critical priority	10	85.33	34.65%	30.71%
Optimal priority	17	100.71	43.75%	39.28%
Planned priority	55	393.75	93.98%	94.28%
Strategic priority	56	398.63	94.58%	94.28%

*The mileage is estimated based on the lines' characteristics as provided in WECC base cases.
**These metrics are calculated relative to Base Case and represent system-wide performance

The results for voltage regulation across the BPA transmission system under different reconductoring priorities are shown in Figure 15. They indicate that as more lines were reconductored, both the number of elements experiencing voltage violations and the total number of voltage violation events decreased. This suggests that the increased carrying capacity and reduced ohmic losses associated with AC deployment did not adversely affect voltage regulation. However, it was difficult to draw definitive conclusions about voltage regulation from these results, primarily because the generic AC model used in this step omitted minor changes in inductive and capacitive reactance values. The impact of reactance changes - even though small - on voltage regulation was assessed in the next step, dynamic simulations (presented in the following section), where specific lines were selected, and high-fidelity models of each AC technology were developed.



(a) Number of voltage violation events (b) Number of elements with voltage violation

Figure 15. Summary of voltage regulation across the BPA transmission system for reconductoring under different priorities - lower values of these metrics indicate better system reliability

5. Stability Studies for Impact Assessment of Reconductoring in the BPA System

5.1. Philosophy Behind This Assessment

In the previous step, a number of lines in the BPA system were identified whose reconductoring would eliminate their existing transfer limit violations and improve system-wide reliability. Nonetheless, reconductoring a line with AC is considered a modification of existing assets. The purpose of this step was to evaluate whether such a modification would have adverse effects on the dynamic performance and stability of the BPA system.

5.2. System Simulations

System dynamic simulations were conducted using PowerWorld software (Version 23). The stability analysis focused on reconductoring the lines with urgent priority, specifically, lines 3, 4, 7, and 8, as identified in Figure 11. Seven different cases were developed, each representing a specific type of AC. For each case, detailed models of ACs were implemented using the scaling factors introduced in Table 2. The system performance for each case, with its specific type of AC and dynamic response to a set of contingencies, was then compared to that of the Base Case, which assumes the use of ACSR conductors.

All cases were first tested with a 65-second flat run to ensure they initiated correctly and were numerically stable. For event analysis, each case was allowed 5 seconds of initialization, followed by 60 seconds of response after the disturbance, totaling 65 seconds of simulation. During each simulation, all nodal voltage values, frequencies, and phase angles across the BPA system were recorded.

5.3. Selection of Contingencies

The following contingency events were considered for small-signal and transient stability analysis.

- **Small-signal stability analysis**
    - Largest load center
        - Step drop by 10%
- **Transient stability analysis**
    - Single transmission line with the largest MVA flow
        - 3-phase to ground short-circuit fault with clearance after 5 cycles
    - Double circuit transmission line with the largest MVA flow
        - 3-phase to ground short-circuit fault with clearance after 5 cycles
    - Single generator with the largest MW output
        - Loss of generator
    - Transmission lines that share a common bus with the reconstructed lines
        - 3-phase to ground short-circuit fault with clearance after 5 cycles

The transient stability analysis was intended to assess the most extreme system responses. In contrast, small-signal stability analysis was aimed at capturing the generators' responses and their interactions, which could be distorted or hidden during faults or outage events due to topological changes in the network.

The contingency lists were determined specifically for each loading condition to appropriately reflect the respective generators' dispatch and line flows. Therefore, the fault scenarios for the 25HW load cases and those for the 25LS cases differed. No cascading events, stuck breakers, or delayed clearance were modeled (as defined in P3-P6 contingencies in NERC TPL [23]). Other planning studies, such as load factor, power quality, short-circuit, and protection, were beyond the scope of this study. It should be noted that ACs could have an impact on relay settings and protection equipment. The changes in the electrical properties of a line due to reconductoring may modify the waveform and propagation characteristics of traveling waves on that line. Therefore, these effects need to be carefully studied to be better understood, but they fall outside the scope of this work.

The transmission system planners intending to use the methodologies and analyses presented in this report are advised to modify them in adherence to the planning standards published by their respective transmission planning authorities regarding the selection and implementation of dynamic simulations and stability assessments.

5.4. Implementation of Contingencies

Short-circuit faults were modeled by directly applying a symmetrical, three-phase bolted fault on one of the terminating buses of the line, followed by line opening at both ends and fault clearance. This approach represented faults occurring immediately past the breaker on the transmission line, which is the worst-case scenario, as faults along the line itself would be less severe due to the additional impedance of the transmission line. It should be noted that short-circuit faults on transmission lines, such as insulator failures or lightning strikes, can also occur at a certain distance along the line. In such cases, the fault should be applied directly on the line, not on the bus. Additionally, faults may occur on the busbars at either end of a transmission line, representing faults within the substation branch (e.g., faulty components or overload conditions), which would require modeling the substation topology using a node-breaker approach which this study did not have access to.

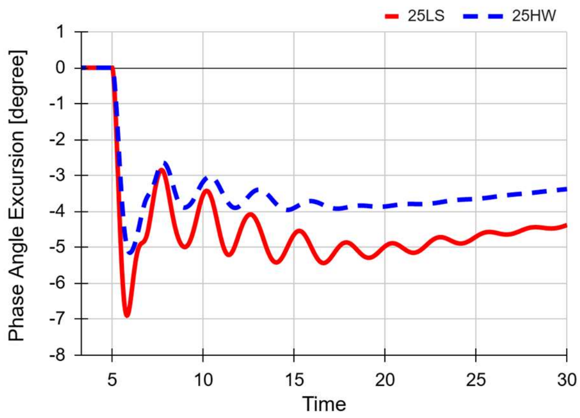
In this study, in addition to testing transient stability for faults on critical transmission lines with the largest MVA flows, which is a common practice in system planning, a new category of faults was introduced. It involves applying faults on transmission lines directly adjacent to reconductored lines to observe the behavior of the reconductored line. For this category of contingencies, the fault was applied at the terminating end shared with the reconductored line.

The generator loss was modeled as an immediate trip of a generating unit, with no faults occurring before or after the event. Similarly, the load step was applied as an instantaneous event, without any preceding or subsequent contingencies.

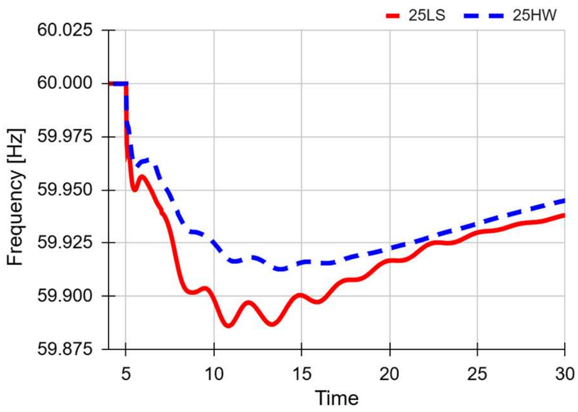
5.5. Preliminary Assessment of Loading Conditions

Transient stability analysis is computationally exhaustive and time-consuming. Therefore, it is common practice to focus this analysis on the worst-case scenario. To this end, before assessing the impact of AC deployment, the two power flow cases, 25HW and 25LS, were evaluated to determine which loading condition represented the worst-case scenario.

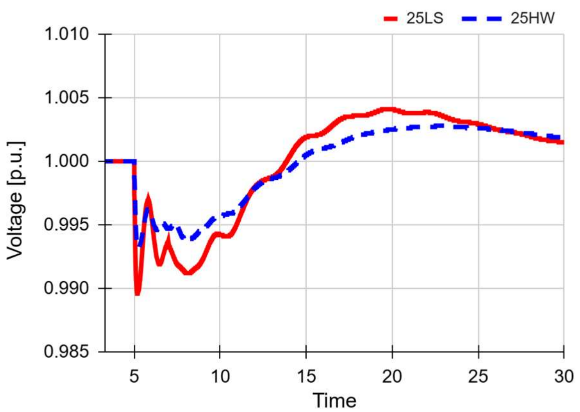
In the contingency selection process for generator outage, the same generation unit was identified in both cases, thereby providing a fair basis for comparison and evaluation of the system’s dynamic response under varying loading conditions. Consequently, both cases were subjected to an exact same generator outage event. The results of this comparison, shown in Figure 16, indicate that oscillations were more pronounced in the 25LS case (plotted in solid red), suggesting they were more challenging to manage.



(a) Phase angle dynamics



(b) Frequency response

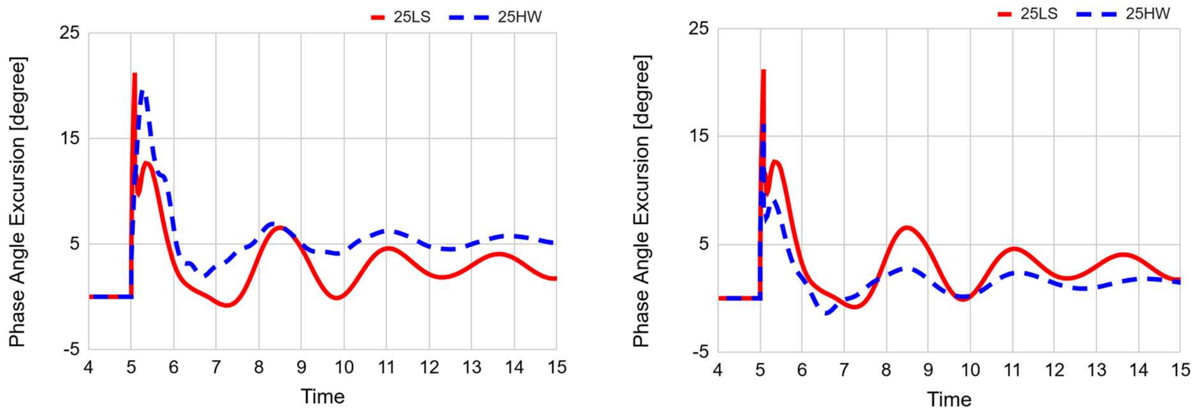


(c) Voltage dynamics

Figure 16. BPA system response following an identical generator outage for 25HW and 25LS cases

Next, system transients were compared for faults on the single transmission line with the largest MVA flow in each power flow case; however, these were two distinct lines identified separately for each case. The results from this analysis, shown in Figures 17(a), 18(a), and 19(a), also revealed that the system response in the 25LS case (depicted in solid red) was more extreme, exhibiting transients with higher amplitude and longer decay times, corroborating the results from the generator outage.

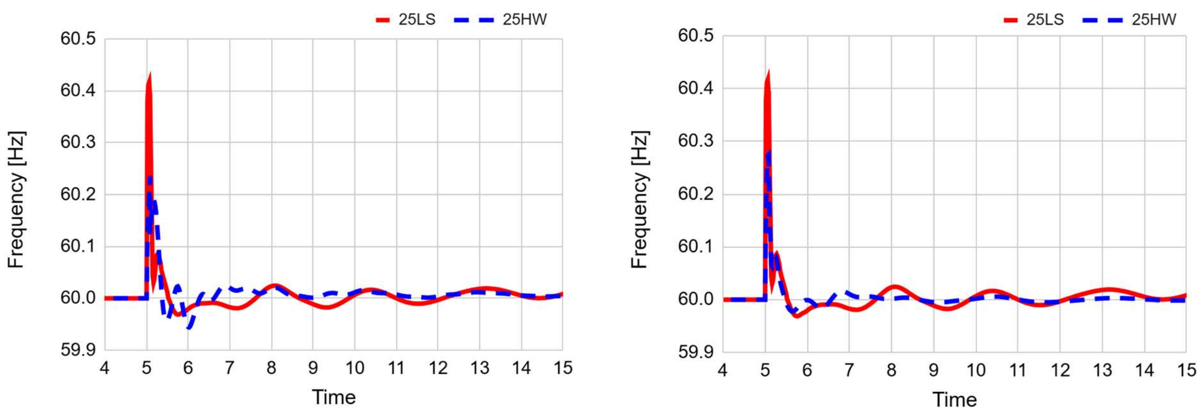
Lastly, both the 25HW and 25LS cases were subjected to an identical line fault, specifically, the single transmission line with the largest MVA flow in the 25LS case. The results from this analysis, presented in Figures 17(b), 18(b), and 19(b), further confirmed that the 25LS case (plotted in solid red) represents the worst-case scenario between the two loading conditions, evidenced by its more severe transients and longer oscillation periods.



(a) Non-identical faults on the line with the largest MVA in each case

(b) Identical fault on the line with the largest MVA in the 25LS case

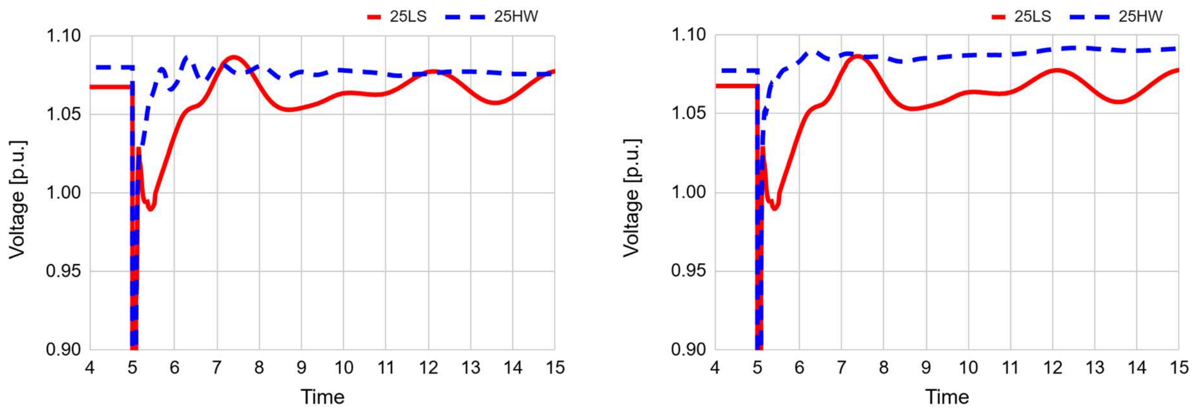
Figure 17. Phase angle dynamics in the BPA system for faults on lines; 25HW and 25LS cases



(a) Non-identical faults on the line with the largest MVA in each case

(b) Identical fault on the line with the largest MVA in the 25LS case

Figure 18. Frequency response in the BPA system for faults on lines; 25HW and 25LS cases



(a) Non-identical faults on the line with the largest MVA in each case

(b) Identical fault on the line with the largest MVA in the 25LS case

Figure 19. Voltage dynamics in the BPA system for faults on lines; 25HW and 25LS cases

Based on the results of this analysis, the 25LS case was identified as the worst-case scenario. Accordingly, the stability analysis henceforth was narrowed down to this particular loading condition.

5.6. Impact Assessment of Reconductoring with ACs on System Dynamics

With the worst-case loading condition determined and the contingency list identified, the next step was to examine the simulation results for each contingency. A visual inspection of the time-domain simulation results, as presented in Appendix VI, revealed that the changes in system dynamics resulting from reconductoring with different ACs were minimal, making it difficult to draw meaningful conclusions. To address this, system-wide oscillation indices were computed using the Hertz-sec and Volt-sec indices for quantitative measurement of the system's dynamic performance. These indices are defined as:

$$Hertz - sec = \sum_{i=1}^{N} \int_{t_0}^{t_s} |f_{0_i} - f_{s_i}|$$

$$Volt - sec = \sum_{i=1}^{N} \int_{t_0}^{t_s} |V_{0_i} - V_{s_i}|$$

where f_{0_i} and V_{0_i}, and δ_{0_i} are the pre-disturbance values of frequency and voltage of ith node in a N-bus system immediately before a contingency takes place at time of $t = t_0$ and f_{s_i} and V_{s_i} are those at the settling time of $t = t_s$. This study assumed $t_0 = 5s$ and $t_s = 65s$. The Hertz-sec index was introduced in [24], and the Volt-sec index was introduced in [25]. These indices represent the cumulative deviation of frequency and voltage over time from their initial values, measured across all buses. They serve as proximity measures to quantify changes in kinetic and potential energy of the system. Thus, smaller values indicate a less oscillatory system and, consequently, better dynamic performance.

For comparative purposes, the scores for each AC case were computed as percentage changes relative to the Base Case (assumed to use ACSR conductors), using per-unit values. A negative score indicates an improvement in system-wide dynamic performance. The results are presented in Figures 20 and 21.

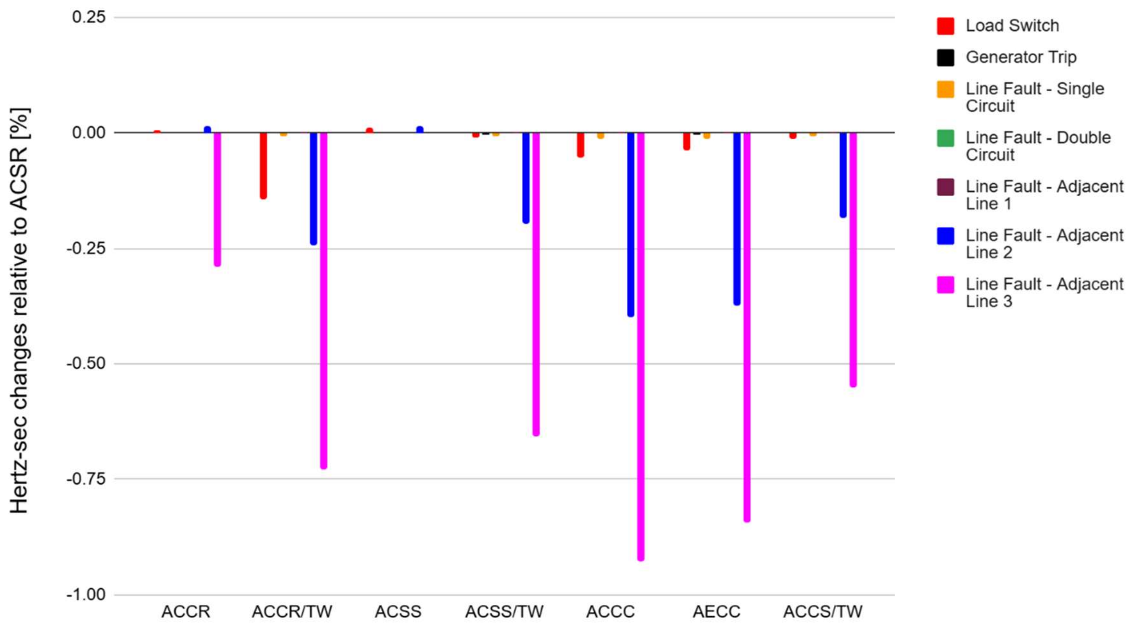


Figure 20. Changes in the Hertz-sec oscillation index of the BPA system for a set of contingency events after reconductoring lines with urgent priority using different AC types - negative values correspond to improvements in system's dynamic performance

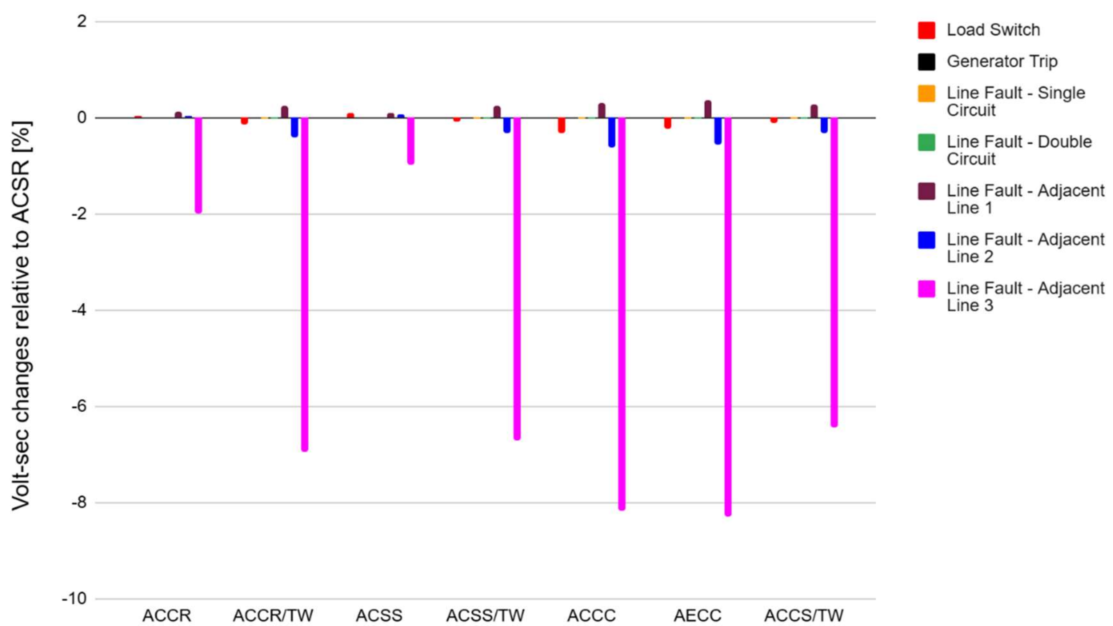


Figure 21. Changes in the Volt-sec oscillation index of the BPA system for a set of contingency events after reconductoring lines with urgent priority using different AC types - negative values correspond to improvements in system's dynamic performance

The results indicate that reconductoring four selected lines with ACs largely had a positive impact on the stability of the BPA system. This is evidenced by the AC cases exhibiting smaller oscillation indices than the Base Case with ACSR for the vast majority of contingency events. The largest reductions in frequency and voltage oscillation indices were 0.92% and 8.28%, respectively. Nevertheless, the largest increase in the frequency oscillation index was only 0.01% following a fault on Adjacent Line 2. Similarly, the largest increase in the voltage oscillation index was just 0.35% following a fault on Adjacent Line 1.

Additionally, the most pronounced improvements were observed for contingencies adjacent to the reconductored lines, which arguably constitute the primary impact zone. This highlights the importance of considering contingencies in close electrical proximity to reconductoring projects during transient stability studies. This category of events, introduced in this study, may not be readily included among the conventional contingencies as defined by TPL [23]. However, the results here underscore their significance and therefore recommend that they be considered essential contingencies. These findings also suggest that the impact of ACs on system dynamics is likely more localized rather than system-wide.

Throughout the analysis, the effect of line reconductoring on frequency response was found to be negligible, as the observed changes in frequency dynamics were extremely small across all AC cases and contingencies studied. Similarly, phase angle and voltage dynamics remained nearly unchanged in most contingencies after reconductoring, except in those close to the reconductored lines. Only very small differences were observed between steady state phase angles and voltage values in the reconductored cases compared to those with ACSR conductors (detailed in Appendix VI). For most phase angles, the differences were only a fraction of a degree, while differences in voltage values were on the order of hundredths of per unit. These differences appeared during the initialization stage of the dynamic simulation - which is essentially a steady state power flow solution. Notably, these differences, despite being a steady state problem, did not appear during the line selection stage because a generic model was used for all ACs for initial screening. The use of high-fidelity model for each specific AC type was therefore deferred to this stage. Importantly, the observed changes in steady state values were very small and, therefore, did not pose any threat to the BPA system.

Based on these observations, it is recommended that system reconductoring planners remain cautious of the potential issues with voltage and phase angle stability. Voltage stability may become problematic when ACs are deployed in areas with existing voltage challenges and limited reactive power availability. Similarly, phase angle stability could become an issue when ACs are deployed for long transmission lines with voltage ratings of 230 kV and above, especially in areas with pre-existing phase angle stability problems or during heavy loading conditions and contingencies. It is advised that the widespread future adoption of ACs should be planned with careful considerations about voltage and phase angle stability.

Finally, the most notable changes in system's dynamic performance were observed in cases with ACCR/TW, ACSS/TW, ACCC, AECC, and ACCS/TW conductors. Interestingly, these classes of AC exhibit the largest difference in electrical resistance with respect to ACSR conductors, approximately 20-24% lower. This reduction alters line impedance and, consequently, affects voltage drop. Despite this observation, this study neither determined the underlying cause nor formally claimed the existence of a correlation.

6. Conclusion and Recommendations

6.1. Conclusion

This report presented a framework for reconductoring transmission lines using ACs, investigating seven commercially available types. The BPA system was used as a case study to demonstrate the framework's implementation and execution, including relevant assumptions and considerations. The results from this case study showcased the utility and practicality of the methods introduced. This methodology is power system simulation vendor-agnostic and applicable to lines across all voltage ratings. Therefore, it is well-suited for implementation using the most commercially available power flow and transient stability simulation packages. The focus of this report was restricted to the reliability matters, and other aspects such as economic considerations of system planning or market operations and policies were not taken into account.

The materials included in this report are intended as a general reference for reconductoring projects. While the conclusions drawn in this study may not be directly transferable to other projects, the methodologies and analytical techniques are. System planners are encouraged to thoroughly assess the reliability aspects unique to each project, considering the specific conditions, requirements, and constraints of the grid under study, and in adherence to regional standards and priorities.

The following summarizes the study's key findings:

- The steady state analysis results indicated a consistent improvement in the performance of the BPA system as the number of ACs deployed increased. The study showed that large-scale deployment of ACs in the BPA system would require close to 400 miles of reconductoring across 56 transmission lines and could ultimately reduce both the severity and frequency of line transfer limit violations by more than 94%. Notably, reconductoring with urgent priority, upgrading only four branches totaling approximately 36 miles, reduced the number of system-wide overload violations and their severity by 22%. Furthermore, implementing ACs on lines with optimal priority, involving about 100 miles of transmission lines, reduced the severity of line overload violations by almost 44% and the number of events by nearly 40% across the BPA transmission system.

- The results from the dynamic simulations indicated that reconductoring lines with ACs did not present an adverse impact on the dynamic stability of the BPA system. Conversely, the majority of oscillation indices were reduced compared to the Base Case with ACSR conductors, reflecting an overall improvement in system-wide dynamic performance following AC deployment.

- This report introduced a new category of contingencies for transient stability analysis, faults occurring on components electrically adjacent to the reconductored lines. The results showed that the most significant changes in system transients occurred under these contingencies, suggesting that the impact of ACs on system dynamics is likely more localized than system-wide. While these contingencies may not typically be included in conventional planning studies, as defined by TPL [23], it is recommended to incorporate this class of events in reconductoring assessments.

- The impact of line reconductoring with ACs on frequency response was found to be negligible, with observed changes in frequency dynamics being extremely small across all AC cases and contingencies studied.

- Although no voltage stability challenges were identified in this study, it was acknowledged that voltage stability has the potential to become a concern when ACs are deployed in regions with existing voltage issues and limited reactive power availability.
- Despite no phase angle stability issues identified in this study, such concerns could arise when ACs are used for long transmission lines with voltage ratings of 230 kV and above, especially in systems with pre-existing phase angle stability problems, under heavy loading conditions, or during contingencies.
- The stability analysis revealed that the most notable changes in system's dynamic performance were associated with the deployment of ACs that had significantly lower electrical resistance than ACSR. However, this study did not investigate the underlying causes of these performance variations, nor did it formally establish a correlation.

6.2. Recommendations

This study provides important insights into the reliability and stability impacts of reconductoring transmission lines with ACs. However, a number of areas for improvement have been identified, which can help advance the state of planning and execution of reconductoring projects. The recommended enhancements are outlined as follows:

- Reconductoring lines with ACs can affect relay settings and protection equipment because changes in line characteristics may alter traveling waveforms and propagation constants. This could impact the accuracy of fault detection and location, making it a critical area for further study to ensure protection systems remain effective and adaptable to AC deployment.
- Market tariffs and energy regulations are crucial factors in transmission planning and operation. Further research is needed to capture the full value of AC deployment, not just financial savings and market revenue, but also broader social benefits such as job creation, economic growth, and regional development. Additionally, ACs can support policy goals like enhancing grid resilience and expanding clean energy access. Such holistic understanding is vital for guiding decision-makers and regulators, especially considering the likely higher upfront costs of AC projects and complexity of cost allocation mechanisms.
- As the benefits of AC deployment continue to be recognized, there is a growing need to update the planning standards, considering the unique characteristics of ACs. It is recommended that regulatory bodies such as NERC, WECC, and other reliability entities, review the existing planning standards and make adjustments needed for seamless deployment of ACs through reconductoring and new construction projects. Such reform would require revisiting planning criteria and metrics for reliability, economic analysis, and risk assessments. It will help ease regulatory approvals and support better integration of ACs into the grid.

Appendix I. Review Literature on Application of ACs in Power Systems

The application of ACs in power systems has been a subject of study in academic literature for more than two decades, which started with the application of more legacy HTLS. In 1999, Southwire [26] showed the properties and performance improvement of ACSS/TW, followed by a more comprehensive analysis in 2001 [27]. The authors of [28] showed the use of ACs could increase the ampacity of transmission lines by 70%, presenting the results from a 132 kV overhead project in Spain (Alcira-Gandía line). In [29], the benefits of ACs' limited deformation were shown using a thermal model, and the clamp needed for them was analyzed. In 2007, CIGRE published a report [30] on the practical aspects of using ACs, focusing on materials, mechanical fitting, and insulators. In 2011, reconductoring a 220-kV transmission line in Romania (București Sud-Fundeni line) using ACs was studied in [31], where the cost of ACs was found to be a determining factor. The authors of [32] showed that reconductoring using ACs could improve the transfer rating of a line and enhance the security limit. They also introduced a method for estimation of positive and negative sequence reactance after reconductoring using ACs. Results from reconductoring of a 220-kV line in Germany [33] showed good performance of ACs in carrying high currents and operating at high temperatures. In [34], the Italian transmission system operator reported on the use of ACs to increase its transfer capacity. The authors of [35] assessed the capital cost for transmission line reconductoring using ACs and evaluated the value of the potential reduced operating cost for a power system, considering load growth and projected growth in renewables. They found that ACs are particularly suited for upgrading existing transmission lines through reconductoring. As part of the same project, the authors of [36] developed a methodology for identifying the lines for upgrading to ACs with the objective of reducing system operational expenses. It was found that reconductoring lines with ACs can be a reasonable option where the thermal rating of the extant transmission system is a limiting factor. It was also found that the use of ACs can reduce the cost of system operation, while the upgrade cost of the existing transmission lines by reconductoring using ACs can be lower than the construction of some new transmission lines, consistent with the findings of [16] and [9]. A transmission expansion planning model for ACs was proposed in [37], showing the increased transfer capacity in a transmission network for a given right-of-way. In [38] and [39], the use of ACs in Sicily and scenarios to export power generation from renewable energy into mainland Italy were studied. A parametric analysis for reconductoring of transmission lines using ACs was presented in [40], where material parameters such as surface temperature, thermal time constant, and emissivity are studied. In [41], a cost analysis of upgrading an existing 230-kV transmission line using ACs was studied, followed by a performance analysis of ACSR conductors vs. ACs in [42], which found the steady state stability limit to be a potential concern. The authors of [43] provided a techno-economic analysis for the use of ACs for Sri Lanka's transmission system, finding the new conductor technology to be the cost-effective solution in terms of loss reduction when constructing new transmission. The aging behavior of ACs under several mechanical tests was studied in [44]. A comprehensive review of the challenges and opportunities pertaining to reconductoring with ACs was provided in [45], covering conductor properties, aging, cost analysis, and environmental aspects. In [46], life expectancy analysis for conductors was discussed, showing up to five times longer life expectancy for ACs than an equivalent ACSR conductor due to reduced bending stress. The authors of [47] provided a high-level review on the technical characteristics of ACs and the aspects related to power systems, e.g., electrical properties, corona effects, etc., but without any data or simulations. The enhancement of transmission capacity in Slovakia was studied in [48], and the authors found the use of ACs to be a promising solution to meet unplanned changes in transfer patterns due to renewable energy. Most recently, the authors of [9] suggested that transmission system reconductoring with ACs can save up to $180 billion in system cost by 2050.

Appendix II. Modeling Transmission Lines for Power System Studies

Transmission lines in a power system are the media around which a network of electromagnetic fields is formed to transfer the electric power produced by generators to load centers in the form of electromagnetic waves. The circuit model of a high-voltage transmission line, with V_i and I_i, $i \in \{1,2\}$, representing the voltages and currents at the terminating ends, respectively, consists of a cascade of partitioned circuits that are interconnected in series to represent the condition of each segment of the line over its entire length, as conceptually depicted in Figure II.1.

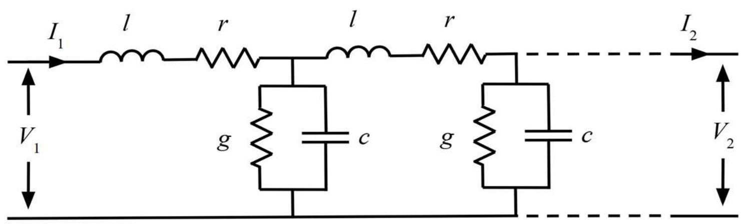


Figure II.1. Distributed circuit model of a transmission line

The physical parameters of the distributed model, shown in Figure II.1, are [49], [50]:

- r: the series resistance that represents the ohmic losses,
- l: the series inductance that represents the inductive storage and flux linkage as a result of the flow of current through conductors
- g: the shunt conductance that represents segmental losses across the line such as corona losses due to air humidity or leakage currents due to dirt on its surface
- c: the shunt capacitance that represents capacitive storage as a result of the voltage difference between energized conductors and the ground

In the transmission line model, g and c are in parallel because the impacts of conductance and capacitance are independent of the amount of current that flows at any point along the conductor and instead, they are functions of voltage. Conversely, r and l are in series because their influences are both functions of the amount of current that flows through the conductor. In most power system applications, these parameters are assumed to be time-invariant because of the timescale of interest, which is normally sub-seconds to seconds.

The effective resistance of a conductor is sensitive to variation of ambient temperature, governed by the temperature coefficient of resistance for its material. It is also sensitive to the form of electric current that flows in it, alternating current vs. direct current. A conductor exhibits slightly higher resistive behavior when alternating current flows in it, as a function of the frequency of current, due to the Skin Effect. Therefore, in a conductor datasheet, the values of its resistor are provided for a number of ambient temperatures for alternating current as well as a base temperature for direct current. Using this information, the effective resistance of that given conductor could be easily extrapolated.

Shunt conductance (g) is often quite small and, thus, can be neglected and so can r since $r << x$. Under these assumptions, the network can be considered lossless. The inductances may be represented as a lumped series inductance (L), expressed by the series inductive reactance, where $X_L = L.\omega$, with $\omega = 2.\pi.f$ representing the angular frequency in radians per second for a synchronized frequency f; that is, 377 radians/second in a 60 Hz power system. Similarly, shunt capacitances can be modeled as a lumped element, characterized by capacitive reactance, X_C, and the susceptance, B, where $X_C^{-1} = B = C.\omega$. Although the inductive and capacitive reactance values vary with changes in ambient temperature and operational frequency, these variations are typically very small and can be safely neglected for practical purposes.

The surge impedance of the line can be approximated as $Z_C = \sqrt{L/C} = \sqrt{L.\omega/C.\omega}$=$\sqrt{X_L.X_C}$. The value of Z_C can be used to calculate the line *surge impedance load (SIL)* as P_{SIL}=$\frac{V_n^2}{Z_C}$, with V_n being the nominal voltage rating. It represents the amount of active power a line can deliver while maintaining the voltage at both ends at their rated values. In other words, this is the natural loading capacity of a line at which the voltage and current at the two ends of the line are in phase, resulting in no reactive power exchange [49].

Also critical in modeling a transmission line for power system studies is the conductor's ampacity, which quantifies the amount of current it can carry. This information is typically available in the datasheet provided by the manufacturer.

Appendix III. Electrical Parameters of ACSR Conductors vs. ACs

For equitable, consistent comparison, the electrical parameters of 795 kcmil Drake ACSR conductors and their AC counterparts are provided in Table III.1. It is important to note that these values are manufacturer-specific and may vary.

Table III.1. Electrical parameters of ACSR conductor compared to those of various AC counterparts

AC type	R_{dc} [Ohm/kft] 20'C $[\times 10^{-3}]$	R_{ac} [Ohm/kft] 25'C $[\times 10^{-3}]$	R_{ac} [Ohm/kft] 75'C $[\times 10^{-3}]$	R_{ac} [Ohm/kft] 200'C $[\times 10^{-3}]$	X_L [Ohm/kft] 60Hz $[\times 10^{-3}]$	X_C [Mohm-kft] 60Hz $[\times 10^{-2}]$	Maximum Ampacity [amps]	Source
ACSR	21.4	22.2	26.3	36.5*	75.6	48.2	910	[51],[52]
ACCR	20.0	20.7	24.7	35.6	75.0	47.8	1,821	[53]
ACCR/TW	17.2	17.8	21.3	30.6	75.8	48.2	1,946	[53]
ACSS	20.7	21.4	25.7	36.4	75.4	48.1	1,662	[54],[55]
ACSS/TW	17.1	17.8	21.3	30.1	75.2	48.1	1,828	[56]
ACCC	16.3	16.8	20.1	28.3	75.3	48.2	1,884	[57]
AECC	15.9	16.7	19.9	27.8	75.5	48.0	1,901	[58]
ACCS/TW	17.2	17.9	21.5	30.3	75.2	48.1	1,819	[59]

*For ACSR, the R_{ac} at 200'C is approximated using the linear extrapolation of temperature coefficient of 0.082 [Ohm/'C].

Appendix IV. Generic Model of AC for Steady State Impact Assessment

Appendix III reviewed the electrical characteristics of the ACs and compared them with those of the ACSR conductor. While they were found to be relatively similar, the largest differences were as follows:

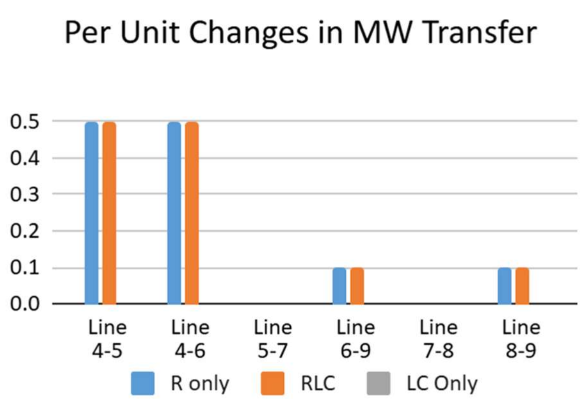
- The largest difference in rated ampacity was a 113% increase for ACCR/TW.
- The largest difference in resistance was practically 24% decrease for AECC and ACCC.
- The largest difference in inductive reactance was 0.67% decrease for ACCR.
- The largest difference in capacitive reactance was 0.64% decrease for ACCR.

An increase in a line's rated ampacity, the first factor, should not necessarily alter the power flow through the line for normal economic dispatch, unless the line is operating precisely at its nominal rating and, therefore, acting as a limiting factor. This is because the line ampacities define a subset of inequality constraints in the mathematical description of the power flow problem, and increasing a line's ampacity expands the feasible region. The increase in a line's ampacity influences the power flow only if the solution lies exactly on the boundary of the feasible region and, thus, it may migrate with the expansion of this region. However, a line's rated ampacity is a critical factor to consider in system analysis because it defines the threshold beyond which transfer limit violations occur.

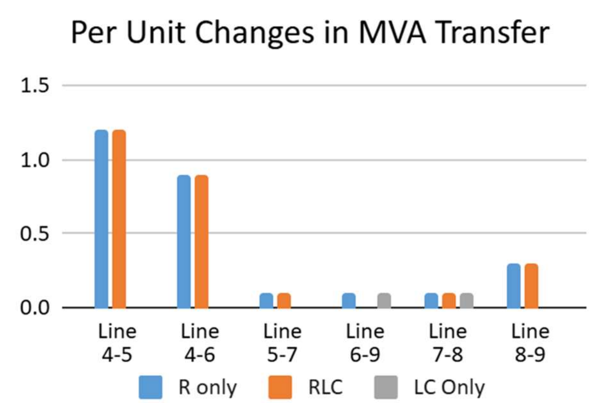
In contrast, changes in the latter three parameters of a line could directly alter the amount of power flowing through the line, as they directly influence the underlying physical phenomena that govern the power flow. To identify the driving factors among the latter three electrical parameters influencing power flow, a sensitivity analysis was conducted using the IEEE 9-bus system [50]. For this purpose, the electrical characteristics of all lines in the system were modified to create the following worst-case scenarios:

1. <u>R Only:</u> reduced R only by 24%,
2. <u>RLC:</u> reduced R by 24% and X_L and X_C by 0.67% and 0.64%, respectively,
3. <u>LC Only:</u> reduced X_L and X_C by 0.67% and 0.64%, respectively.

The results are shown in Figure IV.1. Note that the changes presented here are absolute values for comparative purposes and do not reflect increases or decreases.



(a) Changes to active power transfer



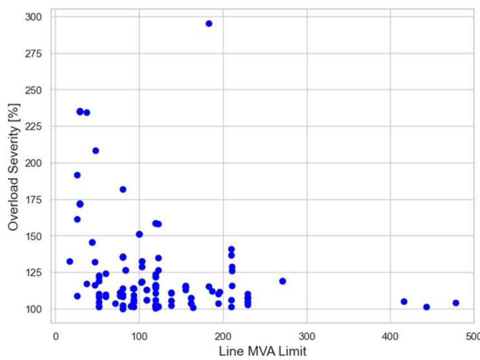
(b) Changes in total power transfer

Figure IV.1. Sensitivity of line flows to changes in electrical parameters of conductors

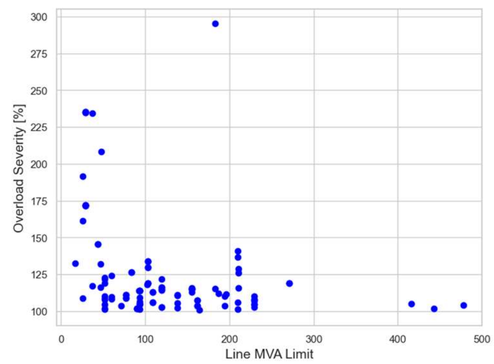
The results indicate that changes in power flow due to modifications in the electrical parameters of lines were primarily driven by variations in ohmic losses, as evidenced by the significant shifts observed in the R-only and RLC cases (shown in blue and orange, respectively). Conversely, the changes in reactance values had a much smaller impact on both active and apparent power transfers, as evidenced by the minimal changes observed in the LC-only case (shown in grey), rendering them less consequential in this context.

The results suggest that a generic model that captures changes in (1) current carrying capacity and (2) ohmic losses, the two primary characteristics of ACs, could be adequate for initial impact screening studies. Such studies aim at identifying potentially problematic lines that could benefit from reconductoring and, therefore, serve as candidate lines for upgrades.

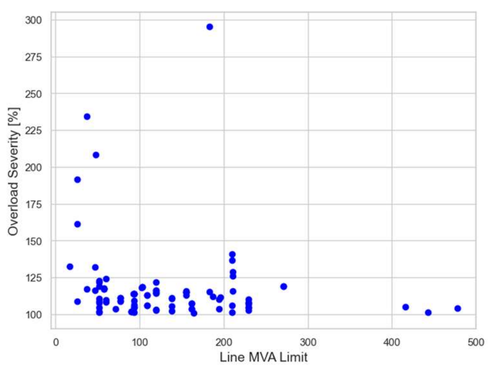
Violation Severity vs. Rated Line MVA Capacity



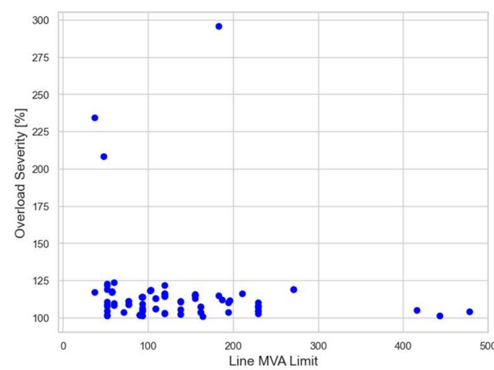
(a) Base Case



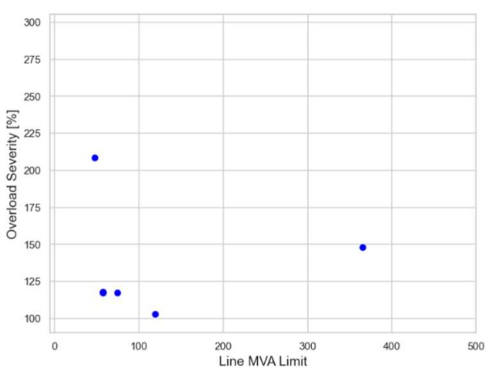
(b) Urgent priority



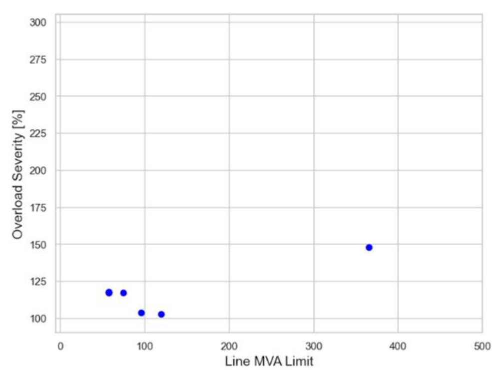
(c) Critical priority



(d) Optimal priority



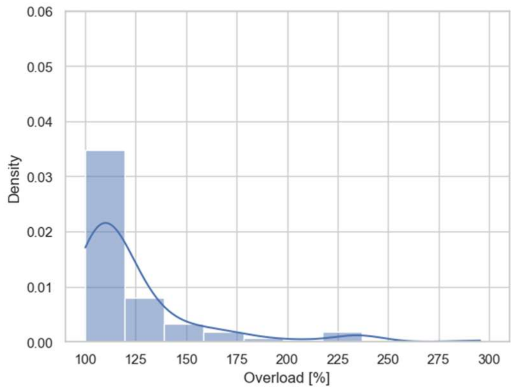
(e) Planned priority



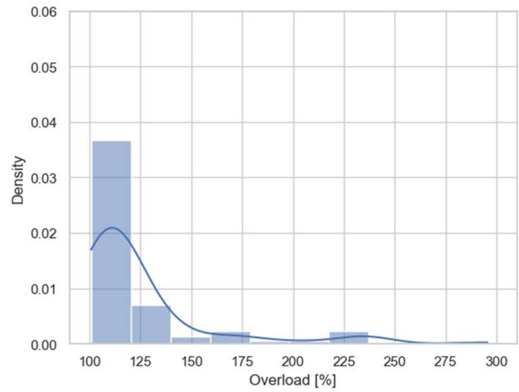
(f) Strategic priority

Figure V.1. Severity of line transfer limit violations vs. rated MVA capacity of the violated lines in the BPA system for different reconductoring priorities

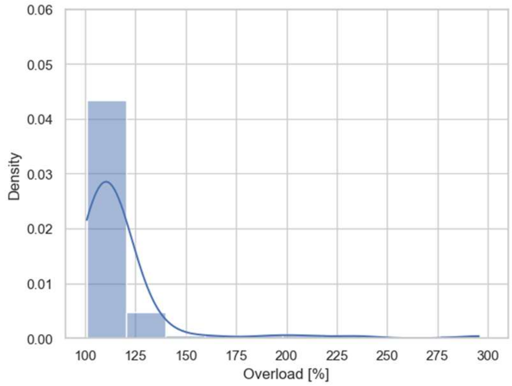
Statistical Distribution of Severity of Violations



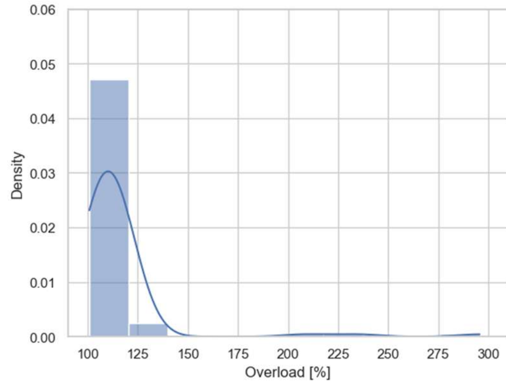
(a) Base Case



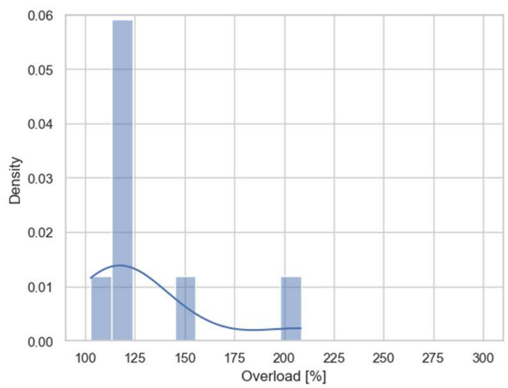
(b) Urgent priority



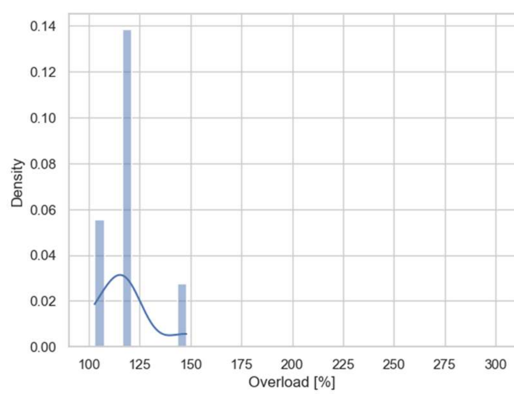
(c) Critical priority



(d) Optimal priority



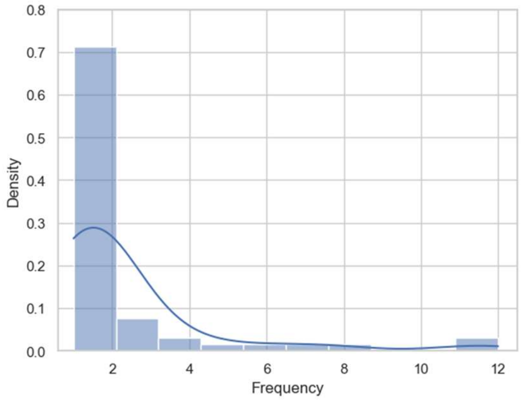
(e) Planned priority



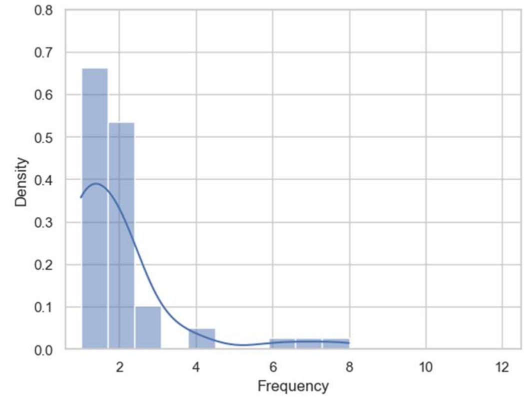
(f) Strategic priority

Figure V.2. Distribution of severity of line transfer limit violations in the BPA transmission system for different reconductoring priorities

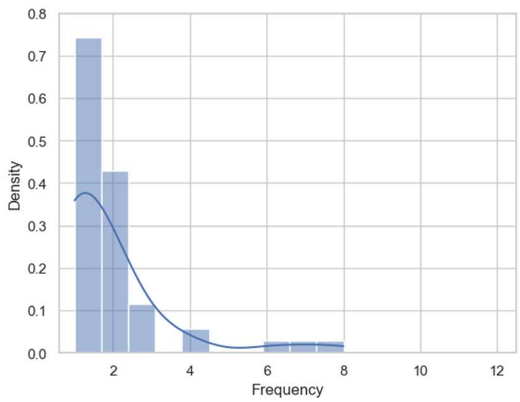
Statistical Distribution of Frequency of Violations for Lines



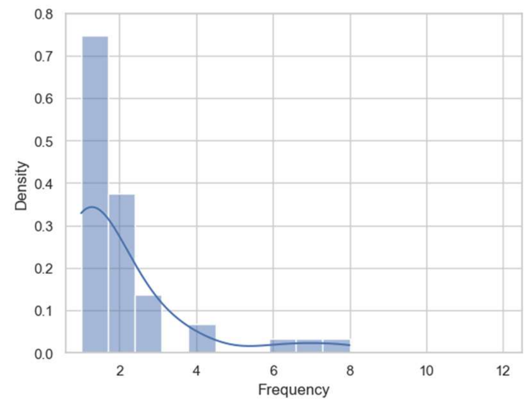
(a) Base Case



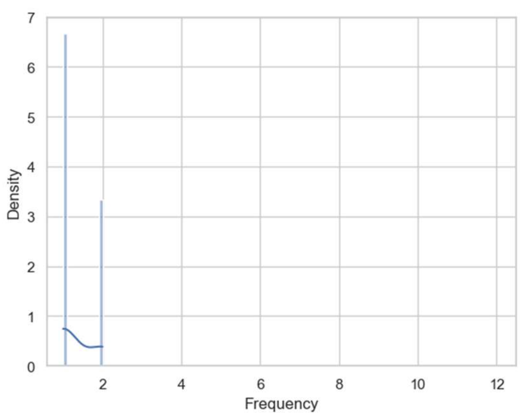
(b) Urgent priority



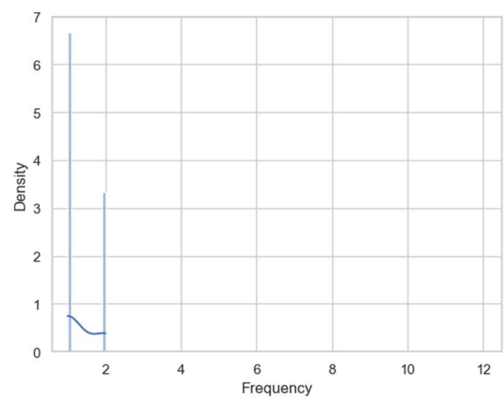
(c) Critical priority



(d) Optimal priority



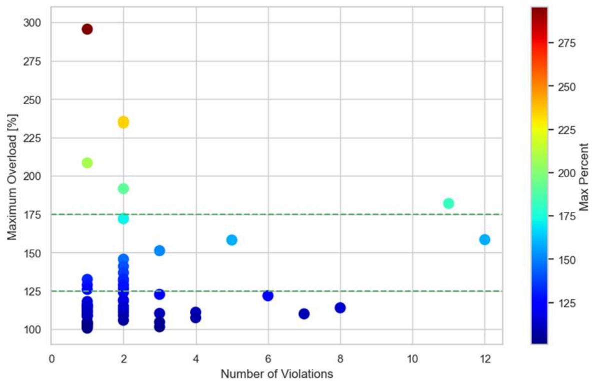
(e) Planned priority



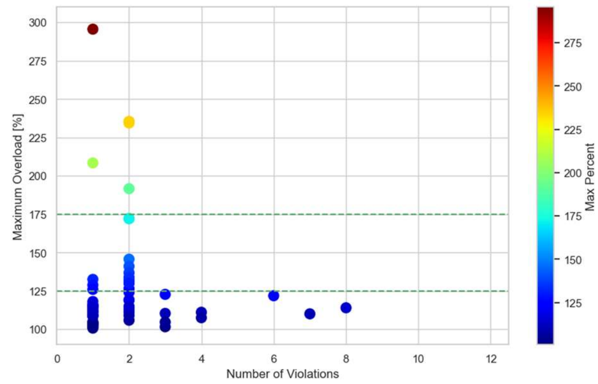
(f) Strategic priority

Figure V.3. Distribution of frequency of line transfer limit violations for the BPA transmission system for different reconductoring priorities

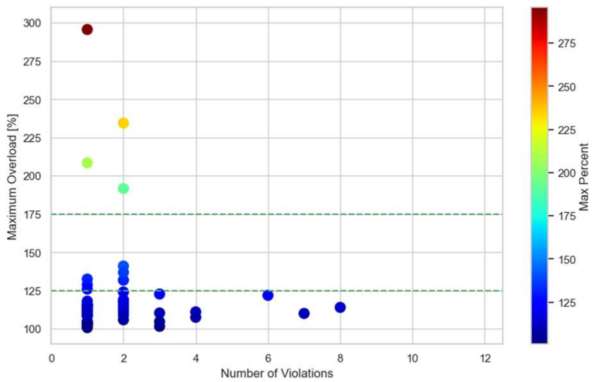
The Worst Line Transfer Limit Violation vs. Frequency of Violations Per Line



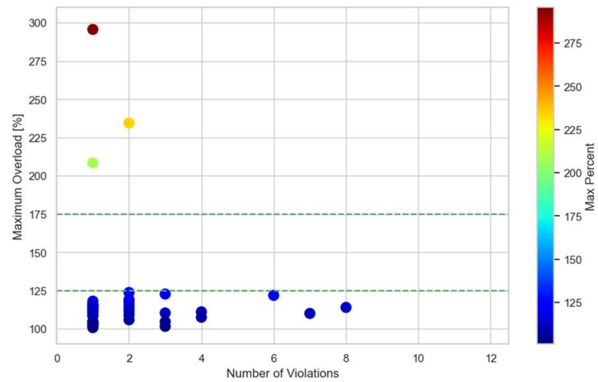
(a) Base Case



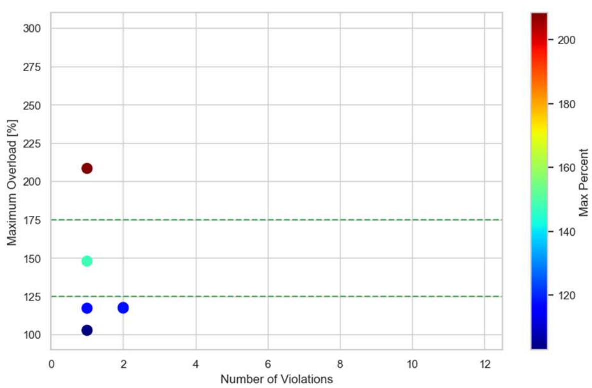
(b) Urgent priority



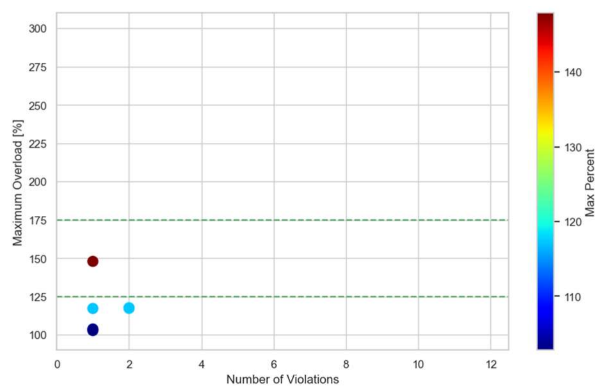
(c) Critical priority



(d) Optimal priority



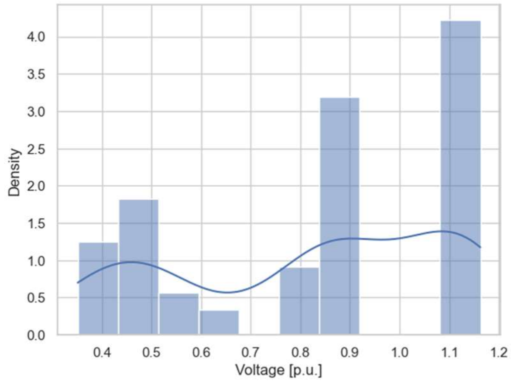
(e) Planned priority



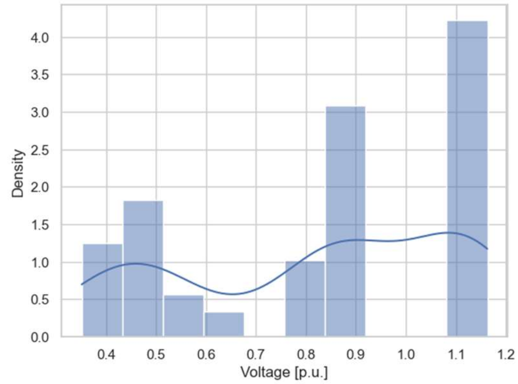
(f) Strategic priority

Figure V.4. The worst transfer limit violation vs. the frequency of transfer limit violations per line in the BPA system for different reconductoring priorities

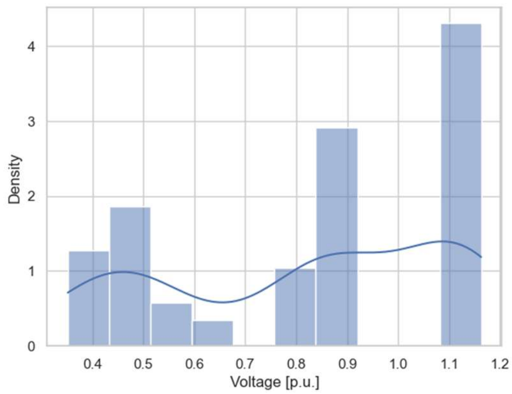
Severity of Voltage Violations



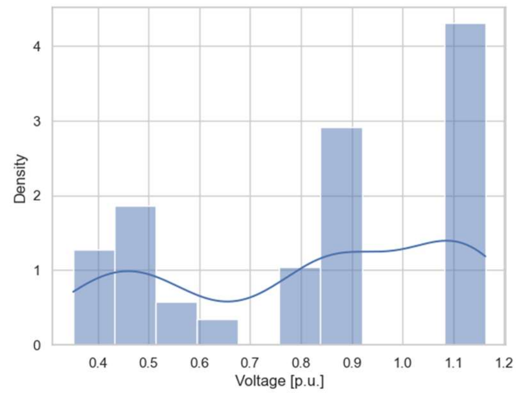
(a) Base Case



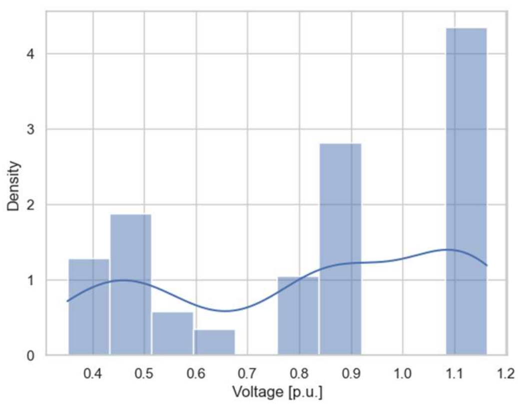
(b) Urgent priority



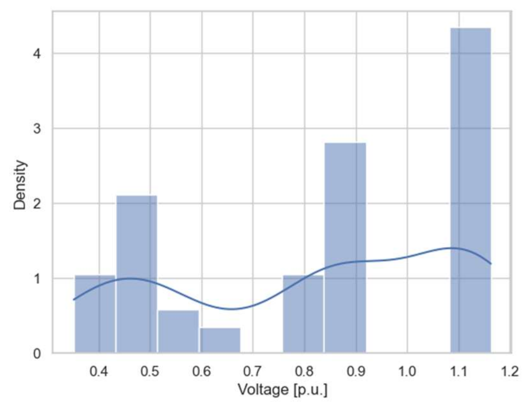
(c) Critical priority



(d) Optimal priority



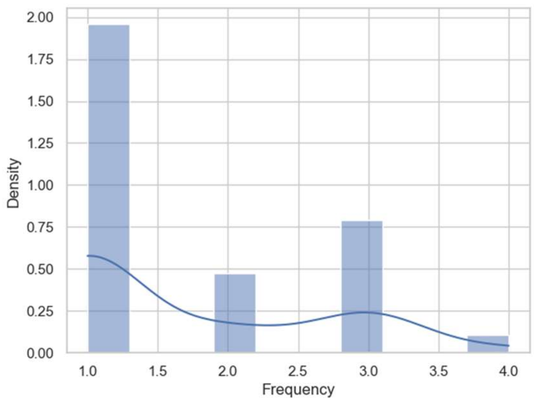
(e) Planned priority



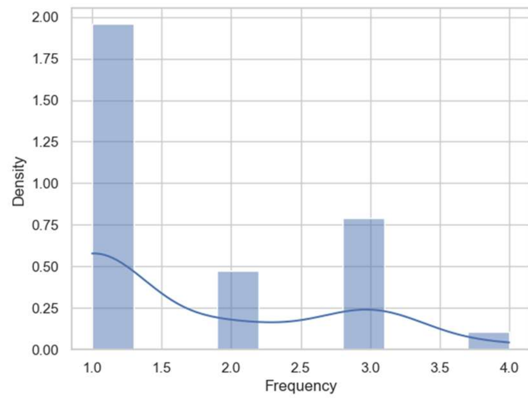
(f) Strategic priority

Figure V.5. Severity of voltage violations on the BPA assets for different reconductoring priorities

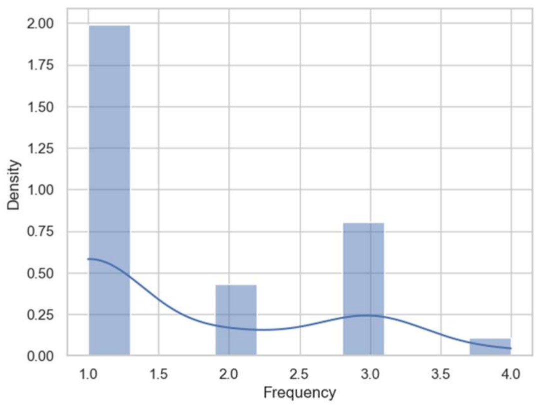
Frequency of Voltage Violations



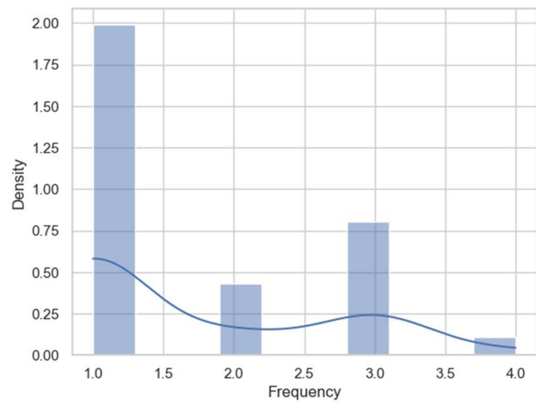
(a) Base Case



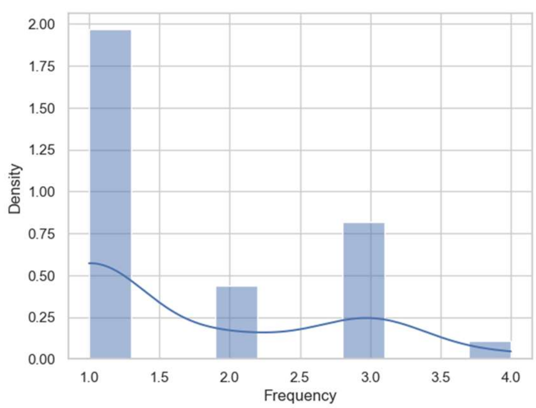
(b) Urgent priority



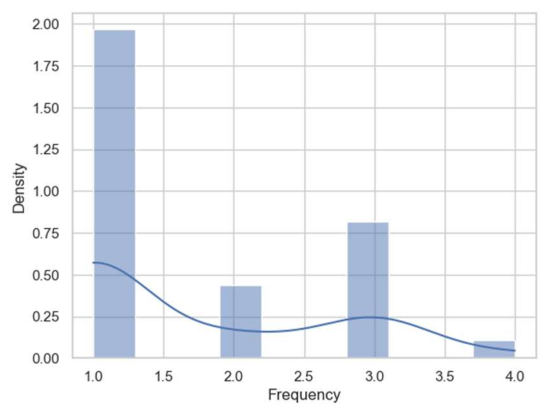
(c) Critical priority



(d) Optimal priority



(e) Planned priority



(f) Strategic priority

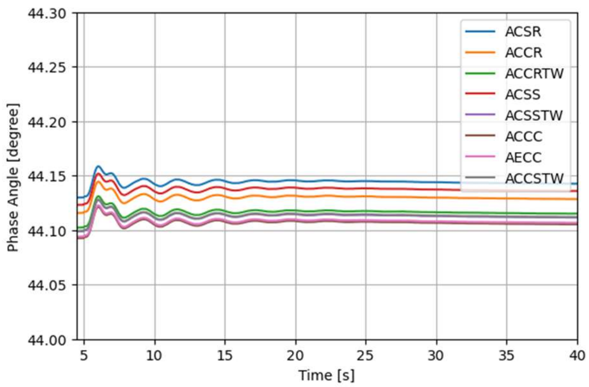
Figure V.6. Frequency of voltage violations per asset in the BPA system for different reconductoring priorities

Appendix VI. Dynamics Simulations of the BPA System for Reconductoring Lines with Different ACs

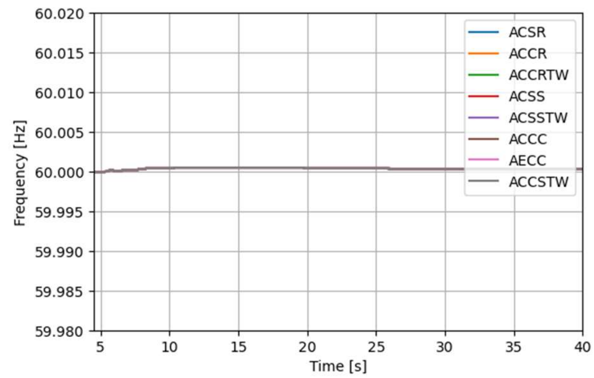
Throughout this section, the time-domain responses of dynamic variables are shown for a substation at a terminating end of one of the reconductored lines for each contingency. The reason for choosing a reconductored line for depicting system dynamics is because the reconductored line is precisely where underlying structural changes could have occurred. Although the response at a single point is presented as an arbitrary choice, the dynamic response of all reconductored lines were quite similar to that of this line across all different ACs, thus others are not shown.

Load Switch

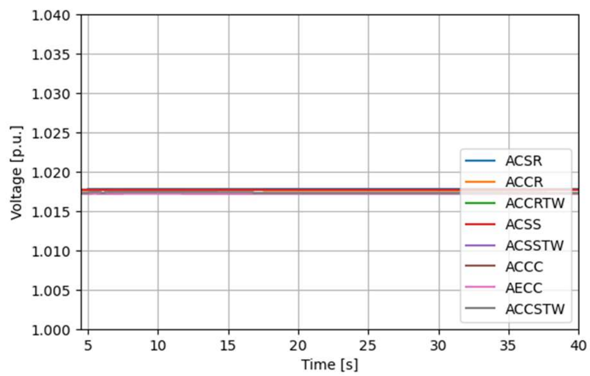
This event represents a 20.2 MW step drop in the load connected to a substation. When such a load switch occurs, it creates a momentary mismatch between generation and load, resulting in a deviation of the network frequency from its nominal value. In effect, the network frequency acts as a signal that alerts nearby generators to adjust their output through governor response, thereby restoring the frequency.



(a) Phase angle dynamics



(b) Frequency response



(c) Voltage dynamics

Figure VI.1. BPA system response following a 20MW load drop

Looking at the results for both the ACSR case and AC cases shown in Figure V.1, a small change in the phase angle steady state values can be observed, along with an extremely small change in the voltage steady state values. However, the pattern of oscillations and the amplitude of transients remain unchanged across all cases. It should be noted that in subfigures (b) and (c), the plots from different cases overlap, so a single trace represents all cases studied. Variations in steady state phase angle and voltage arise from changes in the electrical characteristics of the reconductored lines. Key information about the system performance for this contingency is shown in Table VI.1.

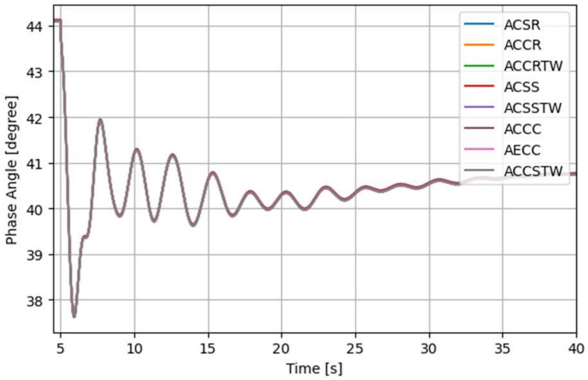
Table VI.1. Key information for the dynamic responses shown in Figure VI.1

	Phase angle				**Frequency**				**Voltage**			
AC	Initial	Settling	Min	Max	Initial	Settling	Min	Max	Initial	Settling	Min	Max
ACSR	44.1303	44.1420	44.1281	44.1587	59.9999	60.0003	59.9999	60.0005	1.0177	1.0178	1.0177	1.0178
ACCR	44.1162	44.1280	44.1140	44.1446	59.9999	60.0003	59.9999	60.0005	1.0176	1.0177	1.0176	1.0177
ACCRTW	44.1028	44.1145	44.1006	44.1311	59.9999	60.0003	59.9999	60.0005	1.0173	1.0173	1.0173	1.0173
ACSS	44.1236	44.1353	44.1214	44.1520	59.9999	60.0003	59.9999	60.0005	1.0177	1.0177	1.0177	1.0177
ACSSTW	44.0992	44.1110	44.0970	44.1276	59.9999	60.0003	59.9999	60.0005	1.0173	1.0173	1.0173	1.0174
ACCC	44.0930	44.1048	44.0908	44.1214	59.9999	60.0003	59.9999	60.0005	1.0172	1.0172	1.0172	1.0173
AECC	44.0944	44.1062	44.0923	44.1228	59.9999	60.0003	59.9999	60.0005	1.0172	1.0172	1.0172	1.0172
ACCSTW	44.0997	44.1115	44.0976	44.1281	59.9999	60.0003	59.9999	60.0005	1.0173	1.0174	1.0173	1.0174

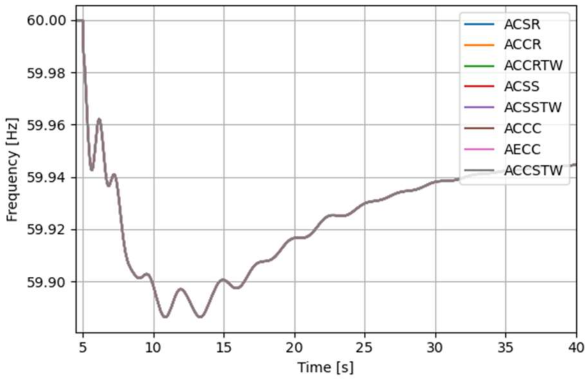
Generator Outage

This contingency represents the loss of a single power plant with a dispatch of 1151.2 MW. Following the loss of the generation unit, an immediate mismatch between generation and load occurs, causing all generators to slow down. As a result, the system frequency begins to decline. The rate of change of frequency depends on the generators' inertia and transmission line characteristics, as these influence the disturbance propagation. This event can also impact voltage due to changes in reactive power.

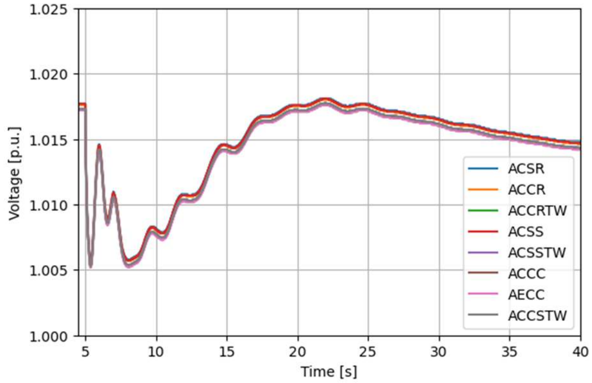
Figure VI.2 presents the results for both the ACSR and AC scenarios. In subfigures (a), (b), and partly (c), the plots for different cases overlap, such that a single trace represents all the cases analyzed. While there is a minor variation in the steady state phase angle and voltage values, the overall oscillation behavior and transient amplitudes remain consistent across all cases. The variations in voltage values can be attributed to changes in certain electrical parameters of the lines introduced by reconductoring. Key information about the system performance for this contingency is shown in Table VI.2.



(a) Phase angle dynamics



(b) Frequency response



(c) Voltage dynamics

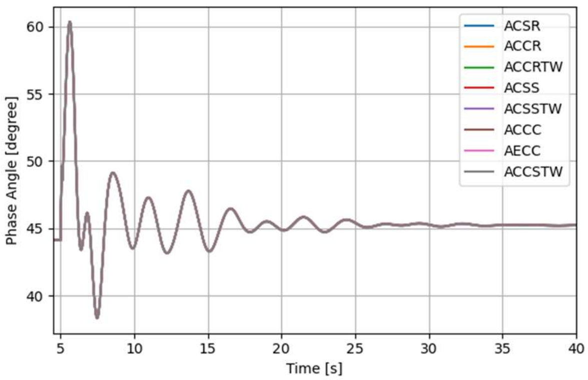
Figure VI.2. BPA system response following outage of a 1150 MW generation unit

Table VI.2. Key information for the dynamic responses shown in Figure VI.2

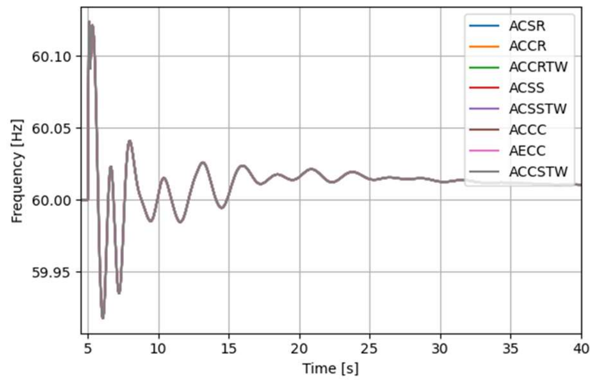
	Phase angle				Frequency				Voltage			
AC	Initial	Settling	Min	Max	Initial	Settling	Min	Max	Initial	Settling	Min	Max
ACSR	44.1303	40.9588	37.6553	44.1327	60.0000	59.9476	59.8863	60.0000	1.0177	1.014	1.0057	1.0181
ACCR	44.1162	40.9446	37.6414	44.1187	60.0000	59.9476	59.8863	60.0000	1.0176	1.0138	1.0056	1.0180
ACCRTW	44.1028	40.9309	37.6279	44.1052	60.0000	59.9476	59.8863	60.0000	1.0173	1.0135	1.0053	1.0177
ACSS	44.1236	40.9521	37.6487	44.1260	60.0000	59.9476	59.8863	60.0000	1.0177	1.0139	1.0057	1.0181
ACSSTW	44.0992	40.9274	37.6244	44.1017	60.0000	59.9476	59.8863	60.0000	1.0173	1.0135	1.0053	1.0177
ACCC	44.0930	40.9211	37.6181	44.0956	60.0000	59.9476	59.8863	60.0000	1.0172	1.0134	1.0052	1.0176
AECC	44.0944	40.9224	37.6196	44.0969	60.0000	59.9476	59.8863	60.0000	1.0172	1.0134	1.0052	1.0176
ACCSTW	44.0997	40.9279	37.6250	44.1022	60.0000	59.9470	59.8863	60.0000	1.0173	1.0135	1.0053	1.0178

Fault on Transmission Line - Single Circuit

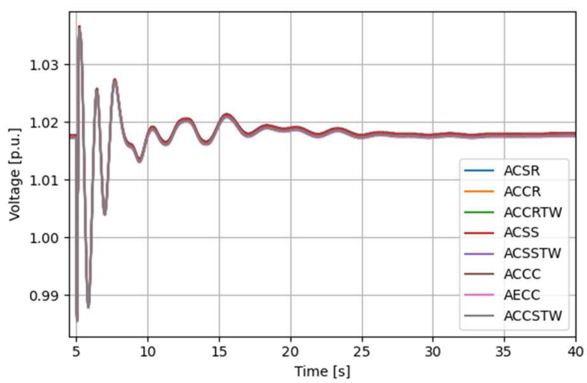
This contingency represents a three-phase, symmetrical, bolted fault on a 500 kV transmission line carrying 1354 MW and 203.9 MVar. When a fault occurs on a line, the electric power transfer drops, but the mechanical power driving the generators continues to be supplied. As a result, the generators speed up due to the excess mechanical power, causing an increase in frequency accompanied by a voltage dip due to changes in impedance. If the fault is cleared within the critical clearing time, the frequency begins to restore, and voltages recover. The system response depends on the fault location and severity, generator inertia and voltage control, and transmission line characteristics.



(a) Phase angle dynamics



(b) Frequency response



(c) Voltage dynamics

Figure VI.3. BPA system response following fault on a transmission line carrying 1354 MW, 203.9 MVar

The results, shown in Figure VI.3, indicate that the system response to this contingency was nearly identical across all AC scenarios examined, closely mirroring the response observed in the Base Case. Consequently, the traces from the different cases overlap completely, forming a single trajectory. The only exceptions were negligible variations in steady state phase angle and voltage values, consistent with previous observations. In all cases, as the fault is initiated, system frequency and phase angle sharply rise while voltage declines. Following successful fault clearance, these variables returned to steady state conditions, exhibiting similar transients and settling times. Key information about system performance for this contingency is provided in Table VI.3.

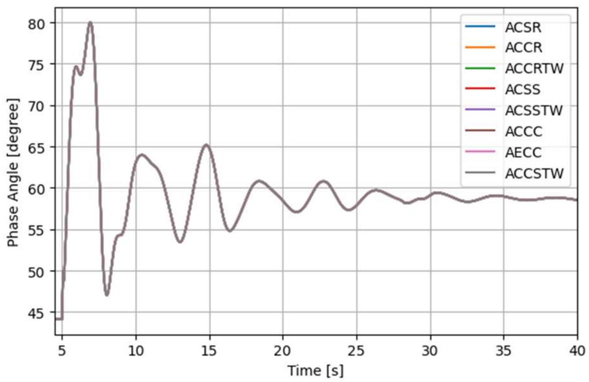
Table VI.3. Key information for the dynamic responses shown in Figure VI.3

	Phase angle				**Frequency**				**Voltage**			
AC	Initial	Settling	Min	Max	Initial	Settling	Min	Max	Initial	Settling	Min	Max
ACSR	44.1303	45.1952	38.3376	60.3770	60.0000	60.0105	59.9175	60.1237	1.0177	1.0185	0.9860	1.0366
ACCR	44.1162	45.1812	38.3244	60.3621	60.0000	60.0105	59.9176	60.1237	1.0176	1.0184	0.9859	1.0365
ACCRTW	44.1028	45.1678	38.3115	60.3488	60.0000	60.0105	59.9176	60.1238	1.0173	1.0181	0.9855	1.0362
ACSS	44.1236	45.1885	38.3313	60.3700	60.0000	60.0105	59.9175	60.1237	1.0177	1.0185	0.9860	1.0366
ACSSTW	44.0992	45.1643	38.3083	60.3449	60.0000	60.0105	59.9176	60.1238	1.0173	1.0181	0.9856	1.0362
ACCC	44.0930	45.1581	38.3026	60.3374	60.0000	60.0105	59.9176	60.1238	1.0172	1.0180	0.9854	1.0361
AECC	44.0944	45.1597	38.3036	60.3402	60.0000	60.0105	59.9176	60.1238	1.0172	1.0179	0.9854	1.0360
ACCSTW	44.0997	45.1648	38.3088	60.3454	60.0000	60.0105	59.9176	60.1238	1.0173	1.0181	0.9856	1.0362

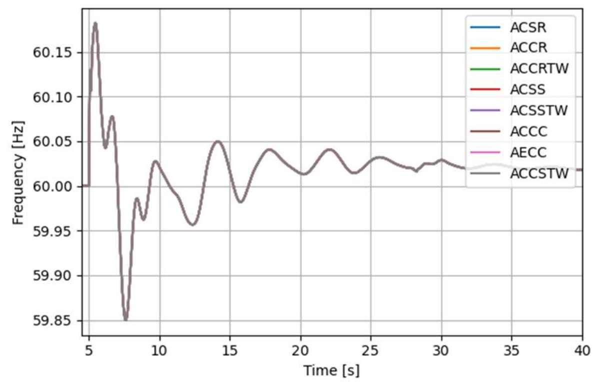
Fault on Transmission Line - Double Circuit

This contingency represents a double-circuit, three-phase, symmetrical, bolted fault on a 500 kV transmission line with the two circuits collectively carrying 2800.5 MW and 403.2 MVar.

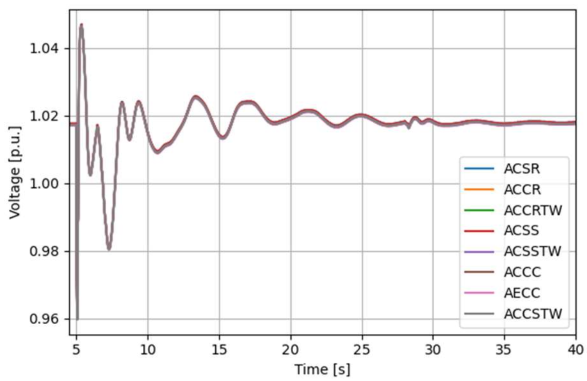
The system responses to this contingency for all AC scenarios closely matched the Base Case response. Consequently, the results from different cases, shown in Figure V.4, overlap and form a single trace. In all cases, as expected, during the fault, the frequency sharply increases, the phase angle rises, and voltages are suppressed. Once the fault is successfully cleared, these variables return to a steady state following the same oscillation pattern and decay rate. Consistent with previous contingencies, only insignificant variations in steady state phase angle and voltage values were observed. Key information about the system performance for this contingency is shown in Table VI.4.



(a) Phase angle dynamics



(b) Frequency response



(c) Voltage dynamics

Figure VI.4. BPA system response following a double-circuit fault on a transmission line carrying 2800.5MW, 403.2 MVar

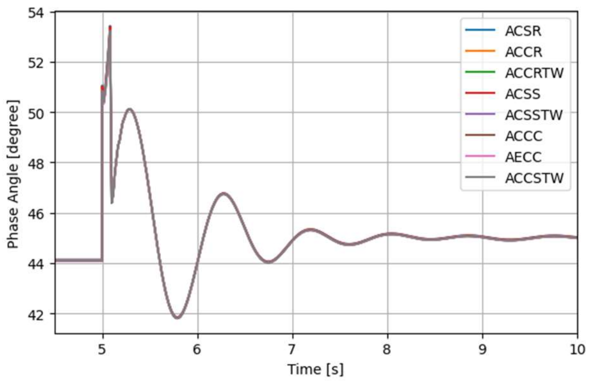
Table VI.4. Key information for the dynamic responses shown in Figure VI.4

	Phase angle				**Frequency**				**Voltage**			
AC	Initial	Settling	Min	Max	Initial	Settling	Min	Max	Initial	Settling	Min	Max
ACSR	44.1303	58.6945	44.1281	80.0385	60.0000	60.0173	59.8496	60.1822	1.0177	1.0186	0.9603	1.0471
ACCR	44.1162	58.6804	44.1140	80.0235	60.0000	60.0173	59.8497	60.1822	1.0176	1.0185	0.9602	1.0469
ACCRTW	44.1028	58.6675	44.1006	80.0106	60.0000	60.0173	59.8497	60.1822	1.0173	1.0181	0.9598	1.0466
ACSS	44.1236	58.6878	44.1214	80.0315	60.0000	60.0173	59.8496	60.1822	1.0177	1.0185	0.9602	1.0470
ACSSTW	44.0992	58.6638	44.0970	80.0065	60.0000	60.0173	59.8497	60.1822	1.0173	1.0181	0.9598	1.0466
ACCC	44.0930	58.6577	44.0908	80.0004	60.0000	60.0173	59.8497	60.1822	1.0172	1.0180	0.9597	1.0465
AECC	44.0944	58.6593	44.0923	80.0019	60.0000	60.0173	59.8497	60.1822	1.0172	1.0180	0.9597	1.0464
ACCSTW	44.0997	58.6643	44.0976	80.0070	60.0000	60.0173	59.8497	60.1822	1.0173	1.0181	0.9598	1.0466

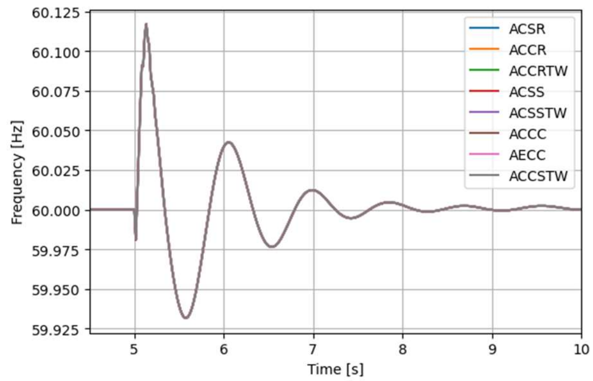
Fault on Transmission Line: Adjacent Line 1

This contingency represents a three-phase, symmetrical, bolted fault on a 115 kV line that carries 12.6 MW and 10.7 MVAr. This line is the first of three examined faults occurring on lines adjacent to reconductored lines and is therefore referred to as Adjacent Line 1 throughout this report.

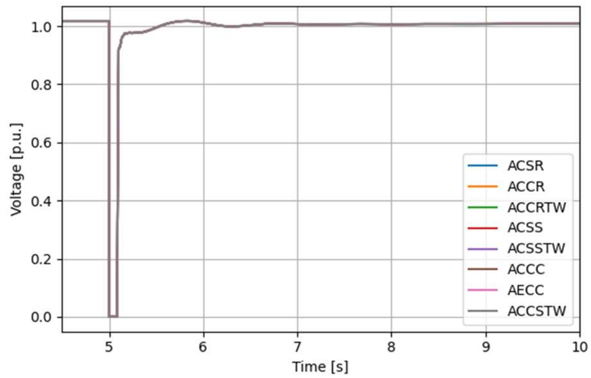
For this contingency, no significant changes in system response were observed, as shown in Figure VI.5. Consequently, the response traces from different cases overlap, forming a single system response. In all cases, the phase angle and frequency settled within 5 seconds of fault clearance, while voltage settled within 2 seconds. Key information about the system performance for this contingency is shown in Table VI.5.



(a) Phase angle dynamics



(b) Frequency response



(c) Voltage dynamics

Figure VI.5. BPA system response following a fault on a transmission line carrying 12.6 MW, 10.7 MVAr

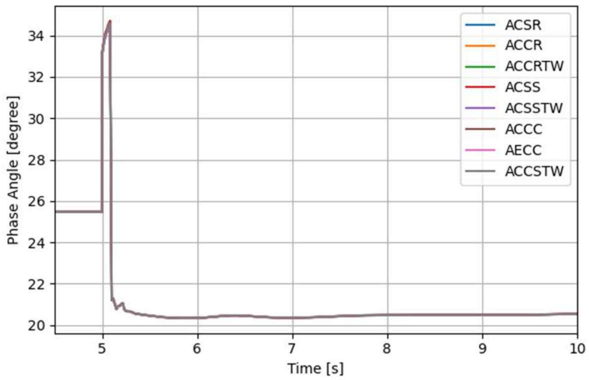
Table VI.5. Key information for the dynamic responses shown in Figure VI.5

	Phase angle				Frequency				Voltage			
AC	Initial	Settling	Min	Max	Initial	Settling	Min	Max	Initial	Settling	Min	Max
ACSR	44.1303	45.1206	41.8496	53.4194	60.0000	60.0007	59.9318	60.1168	1.0177	1.0106	0.0000	1.0180
ACCR	44.1162	45.1058	41.8331	53.3551	60.0000	60.0007	59.9317	60.1168	1.0176	1.0105	0.0000	1.0179
ACCRTW	44.1028	45.0902	41.8142	53.2167	60.0000	60.0007	59.9316	60.1169	1.0173	1.0101	0.0000	1.0176
ACSS	44.1236	45.1138	41.8416	53.3844	60.0000	60.0007	59.9317	60.1168	1.0177	1.0105	0.0000	1.0180
ACSSTW	44.0992	45.0866	41.8110	53.2208	60.0000	60.0007	59.9316	60.1169	1.0173	1.0102	0.0000	1.0176
ACCC	44.0930	45.0805	41.8051	53.1735	60.0000	60.0007	59.9315	60.1170	1.0172	1.0100	0.0000	1.0176
AECC	44.0944	45.0819	41.8062	53.1685	60.0000	60.0007	59.9315	60.1170	1.0172	1.0100	0.0000	1.0175
ACCSTW	44.0997	45.0872	41.8118	53.2273	60.0000	60.0007	59.9316	60.1169	1.0173	1.0102	0.0000	1.0176

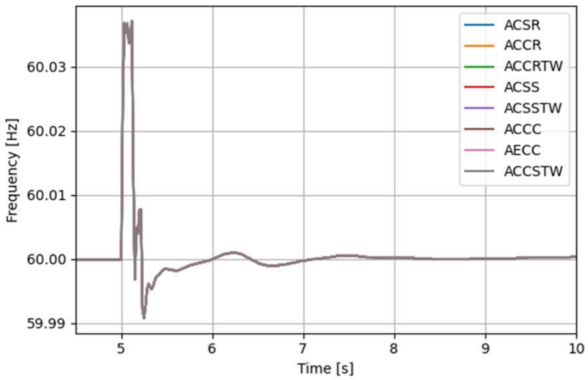
Fault on Transmission Line: Adjacent Line 2

This contingency represents a three-phase, symmetrical, bolted fault on a 115 kV line that carries 58.2 MW and 29.3 MVAr. It is the second of the three lines examined for faults adjacent to reconductored lines and is therefore referred to as Adjacent Line 2 throughout this report.

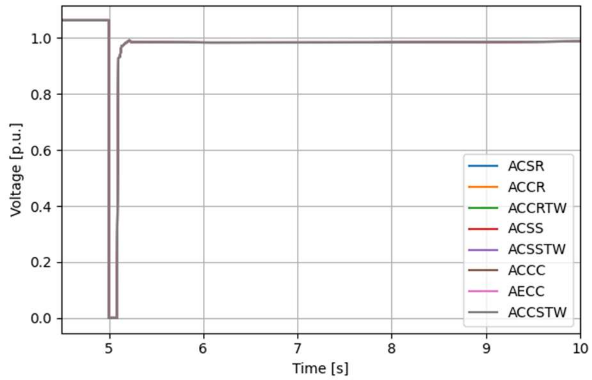
The results from all the cases considered were nearly identical, as shown in Figure VI.6, with the traces overlapping completely. The system response to this contingency was well damped, with no oscillatory behavior observed in voltage measurements. The phase angle settled within 2 seconds of fault clearance, and the frequency stabilized within 3 seconds post-clearance. Key information about the system performance for this contingency is shown in Table VI.6.



(a) Phase angle dynamics



(b) Frequency response



(c) Voltage dynamics

Figure VI.6. BPA system response following a fault on a transmission line carrying 58.2 MW, 29.3 MVar

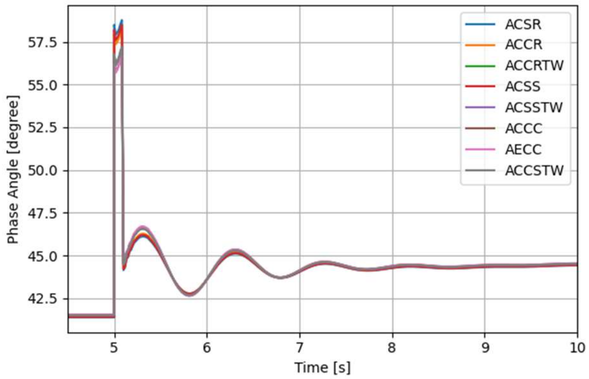
Table VI.6. Key information for the dynamic responses shown in Figure VI.6

	Phase angle				**Frequency**				**Voltage**			
AC	Initial	Settling	Min	Max	Initial	Settling	Min	Max	Initial	Settling	Min	Max
ACSR	25.4624	20.6893	20.3360	34.7136	60.0000	60.0002	59.9908	60.0371	1.0629	0.9944	0.0000	1.0630
ACCR	25.4645	20.6923	20.3388	34.6751	60.0000	60.0002	59.9908	60.0371	1.0628	0.9944	0.0000	1.0629
ACCRTW	25.4775	20.6969	20.3432	34.5816	60.0000	60.0002	59.9908	60.0372	1.0627	0.9945	0.0000	1.0628
ACSS	25.4641	20.6908	20.3376	34.6919	60.0000	60.0002	59.9908	60.0371	1.0629	0.9944	0.0000	1.0629
ACSSTW	25.4750	20.6971	20.3434	34.5870	60.0000	60.0002	59.9908	60.0371	1.0627	0.9945	0.0000	1.0628
ACCC	25.4785	20.6989	20.3451	34.5564	60.0000	60.0002	59.9908	60.0372	1.0627	0.9945	0.0000	1.0627
AECC	25.4799	20.6989	20.3451	34.5516	60.0000	60.0002	59.9908	60.0372	1.0627	0.9945	0.0000	1.0627
ACCSTW	25.4743	20.6969	20.3432	34.5915	60.0000	60.0002	59.9908	60.0371	1.0627	0.9945	0.0000	1.0628

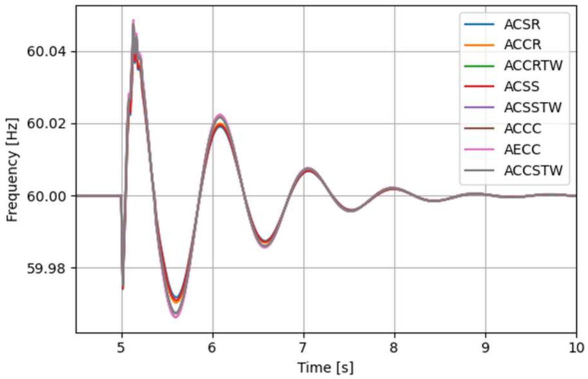
Fault on Transmission Line: Adjacent Line 3

This contingency represents a three-phase, symmetrical, bolted fault on a 115 kV line that carries 24.2 MW and 8.6 MVAr. It is the third and final of the three lines examined for faults on lines adjacent to reconductored lines. For this reason, it is referred to as Adjacent Line 3 throughout this report.

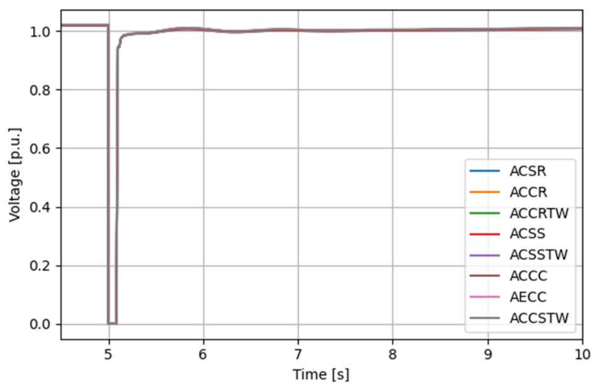
The system response for all cases examined showed a nearly identical oscillatory pattern, with only small differences in the amplitude of oscillations across different ACs. Voltage and phase angle reached a steady state within 2 and 3 seconds after fault clearance, respectively. Frequency oscillations persisted for about 5 seconds before settling at 60 Hz. Key information about system performance for this contingency is shown in Table VI.7.



(a) Phase angle dynamics



(b) Frequency response



(c) Voltage dynamics

Figure VI.7. BPA system response following a fault on a transmission line carrying 24.2 MW, 8.6 MVAr

Table VI.7. Key information for the dynamic responses shown in Figure VI.7

	Phase angle				**Frequency**				**Voltage**			
AC	Initial	Settling	Min	Max	Initial	Settling	Min	Max	Initial	Settling	Min	Max
ACSR	41.3863	44.7270	41.3842	58.7691	60.0000	60.0002	59.9718	60.0435	1.0179	1.0184	0.0000	1.0185
ACCR	41.4360	44.7721	41.4339	58.2597	60.0000	60.0002	59.9703	60.0448	1.0188	1.0192	0.0000	1.0193
ACCRTW	41.5009	44.8369	41.4988	57.1187	60.0000	60.0002	59.9674	60.0474	1.0209	1.0213	0.0000	1.0213
ACSS	41.4112	44.7498	41.4091	58.4903	60.0000	60.0002	59.9710	60.0442	1.0184	1.0189	0.0000	1.0189
ACSSTW	41.5083	44.8424	41.5062	57.1600	60.0000	60.0002	59.9674	60.0474	1.0208	1.0211	0.0000	1.0211
ACCC	41.5343	44.8699	41.5322	56.7673	60.0000	60.0002	59.9663	60.0484	1.0215	1.0218	0.0000	1.0218
AECC	41.5322	44.8687	41.5301	56.7224	60.0000	60.0002	59.9663	60.0485	1.0216	1.0219	0.0000	1.0219
ACCSTW	41.5057	44.8398	41.5036	57.2141	60.0000	60.0002	59.9675	60.0473	1.0207	1.0210	0.0000	1.0211

References

[1] *National Transmission Needs Study*. US-DOE Office of the Secretary of Energy, Washington, DC (United States).

[2] Energy Sector's 2025 Infrastructure Report Card, Available [online]: https://infrastructurereportcard.org/cat-item/energy-infrastructure/

[3] Caspary, J., & Schneider, J. (2022). JS Advanced Conductors On Existing Transmission Corridors To Accelerate Low Cost Decarbonization. *Grid Strategies.*

[4] Rand, J., Manderlink, N., Gorman, W., Wiser, R. H., Seel, J., Kemp, J. M., ... & Kahrl, F. (2024). *Queued Up: 2024 Edition, Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2023*.

[5] Sajadi, A., Loparo, K. A., D'Aquila, R., Clark, K., Waligorski, J. G., & Baker, S. (2016). *Great Lakes Offshore Wind Project: Utility and Regional Integration Study* (No. DOE-CWRU-DE-EE0005367). Case Western Reserve Univ., Cleveland, OH (United States).

[6] Sajadi, A., Ranola, J. P., Kenyon, R. W., Hodge, B. M., & Mather, B. (2022, October). Electric power industry challenges due to increasing shares of inverter-based resources in power systems. *In 2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)* (pp. 1-5). IEEE.

[7] Cardinal-Hickory Creek project, Available [online]: https://www.cardinal-hickorycreek.com/

[8] Power Technology,'*US court lifts block on $655m Cardinal-Hickory Creek transmission line',* Available [online]: https://www.power-technology.com/news/us-court-cardinal-hickory-creek-line/

[9] Chojkiewicz, E., Paliwal, U., Abhyankar, N., Baker, C., O'Connell, R., Callaway, D., & Phadke, A. (2024). Accelerating transmission capacity expansion by using advanced conductors in existing right-of-way. *Proceedings of the National Academy of Sciences*, 121(40), e2411207121.

[10] Rieger C., et al.,"*Advanced Conductor: Use Case Studies*", Idaho National Lab, Tech Report, Report No. INL/RPT-23-75874, December 2023

[11] O'Boyle, M., Baker, C., & Solomon, M. (2024). *Supporting Advanced Conductor Deployment: Barriers and Policy Solutions*. Energy Innovation and GridLab. Available [online]: https://energyinnovation.org/wpcontent/uploads/2024/04/Supporting-Advanced-Conductor-Deployment-Barriers-and-Policy-Solutions.pdf.

[12] American Public Power Association, "*BPA Details How Hydro, Nuclear Generation Maintained Reliability During Cold Snap*", Available [online]: https://www.publicpower.org/periodical/article/bpa-details-how-hydro-nuclear-generation-maintained-reliability-during-cold-snap, Last accessed: 2/2/2025

[13] Bonneville Power Administration ArcGIS Online, Available [online]: https://bpagis.maps.arcgis.com/

[14] Ethan Howland, “BPA plans $3 billion in transmission projects, including 500-kV lines”, *Utility Drive*, Available [online]: https://www.utilitydive.com/news/bpa-bonneville-transmission-projects-oregon-washington-edam/729978/, Last accessed: 2/2/2025

[15] Tokombayev, A., *HTLS upgrades for power transmission expansion planning and operation*, Doctoral dissertation (2014), Iowa State University, Available [online]: https://keep.lib.asu.edu/items/152482

[16] Chojkiewicz, E., Paliwal, U., Abhyankar, N., Baker, C., O’Connell, R., Callaway, D., & Phadke, *The 2035 Report: Reconductoring With Advanced Conductors Can Accelerate The Rapid Transmission Expansion Required For A Clean Grid,* Technical Report, GridLab Inc, 2024

[17] Lamifil, *‘TenneT TSO Netherlands Reduced line losses - AAAC UHC conductor’*, Available [online]: https://lamifil.be/2017/02/tennet-tso-netherlands-reduced-line-losses-aaac-uhc-conductor/

[18] Clairmont, B.. (2008). *High-Temperature Low-Sag Conductors*, Transmission Research Program Colloquium, Sacramento California, 2008

[19] McCalley J., *Energy Transport Technologies*, Lecture notes (2024), Iowa State University, Available [online]: https://home.engineering.iastate.edu/jdm/ee552/Transmission2.pdf

[20] Rieger C., et al.,"Advanced Conductor: Scan Report", Idaho National Lab, Tech Report, Report No. INL/RPT-23-75873, Revision 2 - September 2024

[21] Clair, H. S. (1953). Practical concepts in capability and performance of transmission lines [includes discussion]. *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems*, 72(6), 1152-1157.

[22] Gutman, R., Marchenko, P. P., & Dunlop, R. D. (1979). Analytical development of loadability characteristics for EHV and UHV transmission lines. *IEEE Transactions on Power Apparatus and Systems,* (2), 606-617.

[23] NERC Standard TPL-001-4 - Transmission System Planning Performance Requirements, Available [online]: https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-001-4.pdf

[24] Sajadi, A., Kenyon, R. W., & Hodge, B. M. (2022). Synchronization in electric power networks with inherent heterogeneity up to 100% inverter-based renewable generation. Nature communications, 13(1), 2490.

[25] Kenyon, R. W., and B. Mather. “Quantifying Transmission Fault Voltage Influence and Its Potential Impact on Distributed Energy Resources”. In 2018 IEEE Electronic Power Grid (eGrid), 2018

[26] F.R. Thrash, 1999, “ACSS/TW - An Improved Conductor for Upgrading Existing Lines or New Construction”. IEEE T&D Conf., Vol. 2, pp. 852-857.

[27] Thrash, F. R. (2001, July). ACSS/TW-An improved high temperature conductor for upgrading existing lines or new construction. In 2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No. 01CH37262) (Vol. 1, pp. 182-185), 18-21 June 2001, IEEE

[28] Zamora, I., Mazón, A. J., Criado, R., Alonso, C., Saenz, J. R.,"Uprating using high-temperature electrical conductors [overhead power lines]". In 16th International Conference and Exhibition on Electricity Distribution, 2001. Part 1: Contributions. CIRED. (IEE Conf. Publ No. 482),

[29] Mazón, A. J., Zamora, I., Eguía, P., Torres, E., Miguélez, S., Medina, R., & Saenz, J. R., 'Gap-type conductors: Influence of high temperature in the compression clamp systems". In 2003 IEEE Bologna Power Tech Conference Proceedings, (Vol. 2, pp. 5-pp). IEEE.

[30] Stephen, R., Seppa, T. O., Douglass, D., Pirovano, G., Hill, R., Troppauer, W., ... & Hearnshaw, D. (2007). Considerations relating to the use of high temperature conductors. CIGRE TB, 331.

[31] Mateescu, E., Marginean, D., Florea, G., St IA, G., & Matea, C. (2011, May). Reconductoring Using HTLS Conductors. Case study for a 220 kV double circuit transmission LINE in Romania. In 2011 IEEE PES 12th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance (ESMO) (pp. 1-7). IEEE.

[32] Pierre, B. J., & Heydt, G. T. (2012, September). Increased ratings of overhead transmission circuits using HTLS and compact designs. In 2012 North American Power Symposium (NAPS) (pp. 1-6). IEEE.

[33], Puffer, R., Frehn, T. Fondern, M., Krapp, J., and Riedl, M. "220-kV field study of different high temperature low sag conductors", CIGRE 2014

[34] Filippone, G., Ippolito, M. G., Massaro, F., & Puccio, A. (2014, October). On the roadmap to Supergrid in Sicily: LIDAR technology and HTLS conductors for uprating the 150 kV lines. In IEEE PES Innovative Smart Grid Technologies, Europe (pp. 1-5). IEEE.

[35] Gorur, R., Heydt, G. T., Hedman, K., & Olsen, R. (2014). Making the economic case for innovative HTLS overhead conductors. Power Systems Engineering Research Center (PSERC), Tempe, Arizona, Arizona.

[36] Tokombayev, A. (2014). HTLS upgrades for power transmission expansion planning and operation. Arizona State University.

[37] Kwon, J., & Hedman, K. W. (2015). Transmission expansion planning model considering conductor thermal dynamics and high temperature low sag conductors. IET Generation, Transmission & Distribution, 9(15), 2311-2318.

[38] Favuzza, S., Ippolito, M. G., Massaro, F., Paterno, G., Puccio, A., & Filippone, G. (2015, May). A new approach to increase the integration of RES in a mediterranean island by using HTLS conductors. In 2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG) (pp. 272-277). IEEE.

[39] Ippolito, M. G., Massaro, F., & Cassaro, C. (2018). HTLS conductors: A way to optimize RES generation and to improve the competitiveness of the electrical market - A case study in Sicily. Journal of Electrical and Computer Engineering, 2018(1), 2073187.

[40] Reddy, B. S., & Chatterjee, D. (2016). Analysis of high temperature low sag conductors used for high voltage transmission. Energy procedia, 90, 179-184.

[41] Nuchprayoon, S., & Chaichana, A. (2017, June). Cost evaluation of current uprating of overhead transmission lines using ACSR and HTLS conductors. In 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-5). IEEE.

[42] Nuchprayoon, S., & Chaichana, A. (2018, June). Performance comparison of using ACSR and HTLS conductors for current uprating of 230-kV overhead transmission lines. In 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-5). IEEE.

[43] Yasaranga, H. B. D., Wijayapala, W. D. A. S., & Hemapala, K. T. M. U. (2017). Techno economic analysis of the use of high temperature low sag (HTLS) conductors in the Sri Lanka's transmission system. Engineer: Journal of the Institution of Engineers, Sri Lanka, 50(1).

[44] Kühnel, C., Bardl, R., Stengel, D., Kiewitt, W., & Grossmann, S. (2017). Investigations on the mechanical and electrical behaviour of HTLS conductors by accelerated ageing tests. CIRED-Open Access Proceedings Journal, 2017(1), 273-277.

[45] Riba, J. R., Bogarra, S., Gómez-Pau, Á., & Moreno-Eguilaz, M. (2020). Uprating of transmission lines by means of HTLS conductors for a sustainable growth: Challenges, opportunities, and research needs. Renewable and Sustainable Energy Reviews, 134, 110334.

[46] Liu, H., Kopsidas, K., & Al Aqil, M. (2021, July). Modelling Conductor Life Expectancy for HTLS Conductors. In 2021 IEEE Power & Energy Society General Meeting (PESGM) (pp. 1-5). IEEE.

[47] Jalilian, M., Riba, J. R., & Parvizi, P. (2024). Aluminum Conductor Steel-Supported Conductors for the Sustainable Growth of Power Line Capacity: A Review and Discussion. Materials, 17(18), 4536.

[48] Margita, F., Bena, L., Malska, W., & Pijarski, P., "Possibilities of Increasing the Ampacity of Overhead Lines Using High-Temperature Low-Sag Conductors in the Electric Power System of the Slovak Republic", Appl. Sci. 2024, 14, 7846

[49] Machowski, J., Bialek, J. W., & Bumby, J. R. (2008). *Power System Dynamics: Stability and Control*. John Wiley & Sons.

[50] P. W. Sauer and M. A. Pai, *Power system dynamics and stability,* 2006, Available [online]: https://courses.physics.illinois.edu/ece576/sp2018/Sauer%20and%20Pai%20book%20-%20Jan%202007.pdf

[51] Nexans USA ACSR datasheet, Available [online]: https://www.nexans.us/.rest/eservice/dam/v1/file/224198/ACSR_Electrical_Data.pdf

[52] Southwire ACSR datasheet, Available [online]: https://www.southwire.com/wire-cable/bare-aluminum-overhead-transmission-distribution/acsr/p/ALBARE6

[53] 3M Aluminum Conductor Composite Reinforced datasheet, Available [online]: https://multimedia.3m.com/mws/media/478270O/3m-tm-accr-technical-summary-english-units.pdf

[54] Alcan Cable datasheet, Available [online]: https://www.cablejoints.co.uk/upload/Overhead_Transmission_&_Distribution_Conductors___ACSR,_AAC,_AAAC___Alcan.pdf

[55] Southwire ACSS datasheet, Available [online]: https://www.southwire.com/wire-cable/bare-aluminum-overhead-transmission-distribution/acss/p/ALBARE7

[56] Southwire ACSS/TW, Available [online]: https://www.southwire.com/wire-cable/bare-aluminum-overhead-transmission-distribution/acss-tw/p/ALBARE10

[57] CTC Global ACCC Conductor Data Sheets, Available [online]: https://ctcglobal.com/datasheets/

[58] TS Global TS Rincon datasheet, Available [online]: https://tsconductor.com/technical-resources/

[59] Southwire ACCS/TW, Available [online]: https://www.southwire.com/wire-cable/bare-aluminum-overhead-transmission-distribution/-accs-tw-c7-ts-/p/ALBARE23