



Advanced Transmission Technologies Procedure

**Decision Making,
Voltage Violations**

Presented To:

Indiana Utility
Regulatory
Commission



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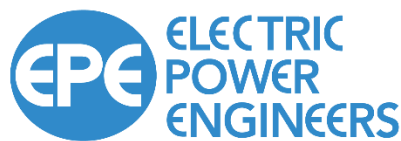
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1. Introduction

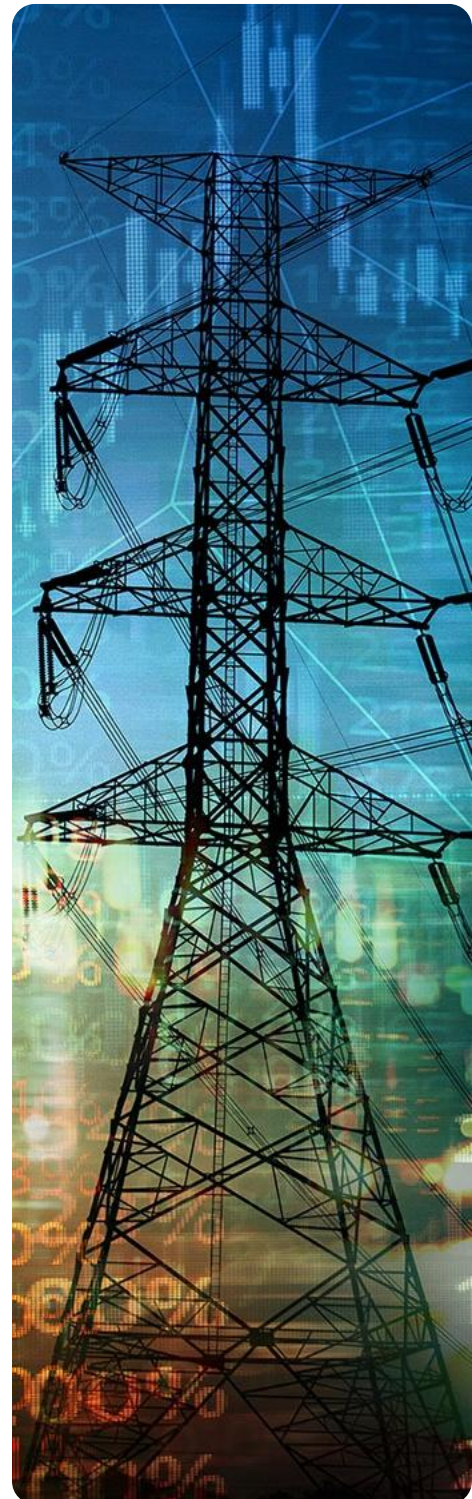
Advanced Transmission Technologies (ATTs) offer planning engineers a suite of non-conventional solutions that can often be deployed more rapidly, cost-effectively, and with minimal disruption to the existing grid compared to traditional transmission infrastructure upgrades.

This document provides a systematic procedure for screening the feasibility of these technologies in addressing voltage violations identified through steady state and stability planning studies.

The methodology presented in this document is built around a structured decision-making framework that begins with a clear understanding of the root-cause of each voltage violation. As outlined in **Section 2**, voltage violations are first classified based on the type of study in which they are identified, either steady state or stability studies. This classification informs the selection and prioritization of appropriate technologies and mitigation strategies.

Section 3 of this document provides detailed guidance on the application of individual technologies, including Synchronous Condensers (SynCons), Static Synchronous Compensators (STATCOMs), and Static VAR Compensators (SVCs). These technologies represent the core set of ATTs evaluated in this document. Although Voltage Source Converters (VSCs) represent an underlying component of STATCOMs, VSC is not treated as a standalone technology in this document. Instead, its capabilities are inherently reflected in the performance characteristics and modular design advantages of STATCOM solutions, which are already considered as a distinct ATT category.

Error! Reference source not found. presents a high-level overview of the ATT feasibility evaluation process, which is detailed throughout this document. The process begins with the identification and verification of voltage violations. This



step constitutes a generic study procedure that is already well-established within current transmission planning and generation interconnection workflows.

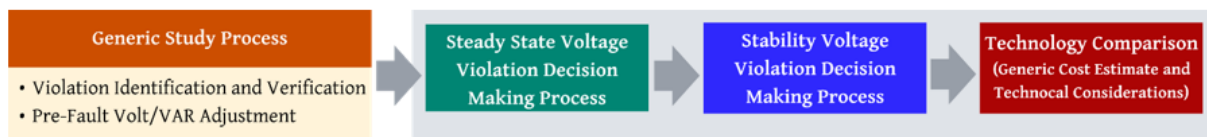


Figure 1. Overview of the ATT Feasibility Evaluation Process for Voltage Violations

Following this initial verification step, the methodology branches into decision-making paths, first the steady state voltage violation process, and then the stability voltage violation process. In practice, these two processes are closely interconnected. A mitigation strategy identified as feasible for a steady state voltage violation must also be evaluated through stability analysis to confirm that it does not introduce adverse dynamic impacts. Similarly, mitigation planning for stability violations often begins by considering steady state adjustments, since operational changes may resolve the stability issue without requiring additional measures.

Finally, **Section 5** presents a comparative evaluation of the key technologies discussed, including their response time, cost, technical attributes, and appropriate voltage levels. This comparison supports engineers in prioritizing technologies for feasibility studies and in documenting rationale for technology selection or exclusion in planning reports.

2. Root-Cause of Voltage Stability Issue

To develop a robust decision-making process for deploying ATTs in response to voltage violations, it is essential to first understand the underlying nature of the problem. Voltage violations are typically categorized based on the type of planning or operational study in which they are identified, either steady state studies or stability studies. Each study type highlights different aspects of system behavior and therefore informs a different set of feasible mitigation strategies.

This classification enables a more targeted evaluation of ATTs by aligning the technical capabilities of each technology with the root cause of the voltage issue. This ensures that the selection of mitigation options remains both technically appropriate and operationally effective.

2.1. Steady State Voltage Violations

Steady state voltage violations refer to conditions in which voltage magnitudes fall outside established acceptable operating ranges or exhibit excessive deviations from pre-contingency values. These violations are typically identified through power flow simulations under normal or contingency conditions. Steady state issues generally manifest as either voltage magnitude violations or voltage deviation violations. A voltage magnitude violation occurs when the voltage at a bus is too low or too high relative to planning limits. A voltage deviation violation occurs when the post-contingency voltage changes too significantly from the pre-contingency value, even if the final voltage remains within the acceptable range.

The acceptable limits for both voltage magnitude and deviation are guided by regulatory and planning standards. These standards provides detailed thresholds in compliance with **NERC TPL-001-5.1** standards. These include:

- **Voltage Ranges:** Expressed as a percentage of nominal voltage for different contingency categories (P0–P7) across both High Voltage (HV) and Extra High Voltage (EHV) levels.
- **Voltage Deviation Limits:** Also given in percent deviation from base voltage, indicating the maximum allowable change following a contingency, for different contingency categories (P0–P7) across both HV and EHV levels

When steady state violations are detected, the first course of action typically involves **Volt/VAR adjustments** within permissible operating limits. If these adjustments are insufficient, reactive power support might need to be included through technologies such as Switched Shunts (capacitor banks or reactors), SVCs, STATCOMs, SynCons, etc. The selection of these technologies will be further discussed in Sections 3 and 4 of this document.

2.2. Stability Voltage Violations

Stability-related voltage violations are identified through dynamic simulations that assess system performance during and after disturbances. These violations reflect the system's ability to maintain acceptable voltage levels in response to events. Unlike steady state issues, these violations are time-dependent and often reflect the dynamic interplay between system inertia, reactive power support, and control system response. Stability violations generally fall into three categories: transient voltage dip, delayed voltage recovery, and voltage oscillation damping.

Transient voltage dip violations occur when system voltages drop significantly during a disturbance and do not recover within an acceptable time frame. These dips can result in widespread tripping of sensitive loads or generation resources, potentially leading to cascading outages. For example, industry practices often reference thresholds such as voltages not dropping below 0.7 per unit for more than 30 cycles, or below 0.8 per unit for more than 2 seconds. Exceeding these limits can trigger protection systems or destabilize converter-based resources.

Delayed voltage recovery refers to conditions where system voltages remain suppressed for an extended period after fault clearance. This may indicate insufficient dynamic reactive support or weak system strength. A commonly referenced threshold is voltage remaining below 0.8 per unit for more than 20 seconds following a disturbance. Such prolonged low-voltage conditions can disrupt service, affect motor loads, and lead to thermal damage in equipment.

Voltage oscillation damping violations occur when post-disturbance voltage profiles exhibit sustained or poorly damped oscillations. These oscillations may reflect unstable control dynamics, inadequate damping from generation or compensation devices, or low short-circuit strength. Two important indicators are the peak-to-peak voltage ratio and overshoot magnitude. For instance, voltage should not exceed 1.25 per unit during post-fault rebound, and the oscillation amplitude (i.e., the difference between peak and valley) should remain within 10 percent of nominal voltage. Larger deviations signal poor damping or instability.

Stability-related voltage violations may, in some cases, be resolved through **pre-fault Volt/VAR adjustments** or by **tuning the dynamic models and control parameters** of nearby facilities, such as generators or existing reactive devices. These adjustments can improve the local voltage response and enhance damping behavior. However, if such measures are not effective in restoring acceptable performance, then the deployment of fast-response technologies may be necessary. Suitable technologies include STATCOMs, SVCs, and SynCons. In systems characterized by low Short Circuit Ratio (SCR), SynCons are often the preferred option due to their ability to provide both dynamic voltage support and rotational inertia. The selection of these technologies will be further discussed in Sections 3 and 4 of this document.

3. Alternative Technologies for Voltage Violations

This section outlines the alternative technologies available for mitigating voltage violations, with a focus on implementation scenarios based on technical capability and industry best practices. The objective is to provide actionable guidance for each technology, considering both steady state and stability-related voltage issues. These implementation guidelines serve not only as a reference for evaluating deployment practicality, but also as a structured basis for documenting infeasibility justifications and preliminary feasibility rationales in planning reports. Each subsection provides focused insights into when and how each technology may be effectively applied, helping planners align mitigation strategies with system needs and operational constraints.

3.1. Static Synchronous Compensators (STATCOMs)

STATCOM is a flexible AC transmission system (FACTS) device used to regulate voltage by providing dynamic reactive power support. This section presents typical planning scenarios where STATCOM implementation may be considered a feasible alternative for mitigating voltage violations. For further background on STATCOM operating principles and industry best practices, refer to the **“Advanced Transmission Technologies Framework”** document prepared by EPE.

- STATCOMs are particularly effective in addressing stability-related voltage violations where fast-response and real-time reactive power injection or absorption is critical. Their ability to respond within a few cycles allows them to support voltage recovery following disturbances, reduce transient dips, and help maintain system voltage within acceptable limits.
- Compared to SVCs, STATCOMs offer superior performance under low-voltage conditions due to their ability to maintain full capacitive compensation even as system voltage drops. This makes them more effective in supporting transient stability in stressed or weak areas of the grid.
- In steady state conditions, when a large amount of reactive power is required, typically above 150 MVAR, a STATCOM can be considered a viable solution. In such cases, it can address steady state violations while also contributing to dynamic stability.
- STATCOMs are also well-suited for applications that require modularity or scalability. Their flexible design allows for staged deployment and fine-tuned control across a wide operating range, providing both inductive and capacitive reactive power support as system conditions evolve.

It is important to note that while STATCOMs offer advanced performance benefits, they are typically associated with higher capital costs compared to conventional solutions.

3.2. Static VAR Compensators (SVCs)

SVC is a FACTS device that delivers fast-acting reactive power support for voltage regulation. Unlike mechanically switched capacitors or reactors, an SVC responds within cycles to voltage deviations, making it highly effective in maintaining system stability. This section presents typical planning scenarios where SVC implementation may be considered a feasible alternative for mitigating voltage violations. For further background on SVC operating principles and industry best practices, refer to the **“Advanced Transmission Technologies Framework”** document prepared by EPE.

- In cases of stability-related voltage violations, SVCs support transient recovery by injecting or absorbing reactive power in real time following contingencies. While SVCs are not as fast or effective under low undervoltage conditions as STATCOMs, SVCs can still contribute to damping oscillations and limiting voltage excursions within seconds following a disturbance.
- SVCs are generally cost-effective and reliable, requiring minimal maintenance due to the lack of rotating parts. They serve well in moderately weak systems but may be less effective in severely low SCR scenarios, where STATCOMs or SynCons are preferred.
- In applications where modularity and scalability are important, SVCs can be configured in expandable blocks. Configurations using modular thyristor-switched capacitor/reactor banks allow capacity adjustments in increments, facilitating staged deployment or future expansions.

It is important to note that while SVCs offer advanced performance benefits, they are typically associated with higher capital costs compared to conventional solutions. On the other hand, SVCs typically have lower capital costs than STATCOMs, they may underperform in scenarios characterized by low SCR or low undervoltage.

3.3. Synchronous Condensers (SynCons)

SynCon is a rotating machine that operates without a prime mover and whose sole purpose is to provide dynamic reactive power support, short-circuit current, and rotational inertia. This section presents typical planning scenarios where SynCon implementation may be considered a feasible alternative for mitigating voltage violations. For further background on SynCon characteristics and planning considerations, refer to the **“Advanced Transmission Technologies Framework”** document prepared by EPE.

- SynCons may serve as an effective solution for addressing stability-related voltage violations, particularly in weak-grid areas or in systems with low SCR. Unlike STATCOMs or SVCs, SynCons inherently provide rotational inertia, which contributes to frequency stabilization and improved voltage stiffness during and after disturbances. In addition, their sub-transient reactance enables them to deliver significant fault current, often five to seven times their rated capacity, thereby strengthening the local short-circuit level and enhancing the performance of protection systems.
- SynCons might be an effective technology for areas with high penetration of inverter-based resources (IBRs), where conventional synchronous machines have been displaced, leading to

reduced system inertia and weakened grid strength. In such environments, SynCons can restore essential system attributes such as rotational inertia, short-circuit current, and voltage support.

- With the continued retirement of conventional synchronous generators, SynCons become practical and cost-effective alternatives, especially through the retrofit of decommissioned generating units. Retrofitting enables planners to repurpose existing infrastructure, significantly reducing capital expenditures and environmental impacts. It also allows for faster deployment and simpler permitting processes compared to new installations.
- SynCons are also suitable for applications where modularity and scalability are critical. They can be deployed as individual machines or in coordinated multi-unit configurations and may be coupled with flywheels to further enhance stored kinetic energy. This flexibility allows utilities to tailor the level of inertia and reactive power support based on evolving system needs, providing redundancy and adaptability over time.

It is important to note that while SynCons offer multiple stability and reliability benefits, they are associated with higher operational and maintenance requirements compared to FACTS devices.

3.4. Transmission Switching

Transmission switching is an operational technique that involves opening or closing selected transmission lines or network elements to modify system topology. It can be a cost-effective alternative for mitigating certain types of voltage violations without requiring new equipment installations. This section presents typical planning scenarios where transmission switching may be considered a feasible alternative. For further background on transmission switching principles and industry applications, refer to the **“Advanced Transmission Technologies Framework”** document prepared by EPE.

- Transmission switching can help address high-voltage violations in transmission systems, particularly when transmission lines are lightly loaded. Under light-load conditions, especially during off-peak periods in winter or spring, the capacitive charging of long transmission lines becomes more significant relative to load demand. This can result in higher receiving-end voltages or notable deviations between pre-contingency and post-contingency voltage levels. By opening a lightly loaded line, the capacitive effect is reduced, which helps bring voltages back within acceptable limits and stabilize the system profile. This approach has been successfully applied in various regional transmission organizations, such as PJM, to control voltage during low-demand conditions.

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- Transmission switching can also help resolve low-voltage issues in certain post-contingency conditions during peak demand periods. In some cases, closing a previously out-of-service line can redirect power flows and improve voltage support in the affected area. While similar switching actions at lower voltage levels, such as 69 kV circuits or transformers, may also be used for localized post-contingency voltage support, these actions are generally considered outside the scope of Advanced Transmission Technologies as they resemble load management rather than network-wide voltage mitigation.

When appropriately applied, transmission switching can improve voltage profiles, enhance system flexibility, and reduce the need for additional reactive power compensation. However, the effectiveness of this approach depends on system topology, real-time operating constraints, and contingency-specific impacts. Careful study and simulation are essential to ensure that switching actions consistently yield positive voltage performance without introducing unintended reliability concerns.

4. ATTs Decision-Making Process for Voltage Violations

As discussed in Section 2, voltage violations are categorized based on the type of planning or operational study in which they are identified, either steady state studies or stability studies. Each study type highlights different aspects of system behavior and therefore informs a different set of feasible mitigation strategies. Accordingly, tailored decision-making procedures are established for each category. While these procedures are presented separately for steady state and stability voltage violations, they are not applied in isolation and must be cross-referenced to ensure comprehensive evaluation.

In practice, a mitigation strategy identified as feasible for a steady state voltage violation should also be evaluated in stability study to confirm that it does not introduce adverse stability impacts. Similarly, the development of mitigation plans for stability-related voltage violations often begins by considering steady state solutions, since adjustments in steady state operating conditions may resolve the stability concern without requiring additional measures.

In certain scenarios, voltage violations may appear in both steady state and stability studies. In such cases, steady state mitigation plans are examined first to determine whether they can address both violations. If these measures are ineffective, stability-specific alternatives are evaluated to ensure that the final solution provides a robust and coordinated resolution to all observed issues.

4.1. Steady State Voltage Violations Decision-Making Process

In response to a voltage violation identified in a steady state study, this section presents a step-by-step procedure for evaluating ATTs and other potential solutions.

illustrates the decision-making flowchart for steady state voltage violations. The process begins once a violation has been detected and proceeds through the following steps:

- **Violation Verification:** The first step is to confirm the validity of the violation before pursuing mitigation measures. This quality check includes verifying the definition and modeling of contingencies, validating study assumptions, and confirming that applicable voltage criteria are correctly applied. If the study case does not include planned transmission upgrades associated with thermal violations, the voltage violations should be reviewed in conjunction with thermal violations, since proposed mitigation plans for thermal overloads may also resolve voltage concerns. This verification step is a standard practice in all transmission upgrade evaluations and, while essential, is considered outside the scope of the ATTs decision-making process.

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- **Pre-Fault Adjustment:** If the violation is verified, the next step is to consider non-infrastructure measures such as pre-fault Volt/VAR adjustments. These adjustments may involve changes to nearby reactive power support devices, generator voltage schedules, and transformer tap settings. If such adjustments resolve the steady state voltage violation, the revised operating point should then be evaluated in a stability study to ensure that the solution does not introduce adverse dynamic impacts.
 - **Calculate MVAR Support:** If pre-fault adjustments are not sufficient, additional reactive power support will be required. The size and location of the required MVAR support should be identified, typically by inserting a generic reactive device, such as a fixed shunt, into the post-contingency case and adjusting it until voltage criteria are met. This provides an initial estimate of the necessary reactive support.
 - **MVAR Support Technology:** Once the required reactive power has been determined, potential technologies can be evaluated. Industry experience indicates that when the required support exceeds approximately 150 MVAR, conventional switched shunt devices may become less practical, and FACTS devices such as SVCs or voltage source converter (VSC) devices such as STATCOMs might be more effective alternatives. Note that reinforcing system voltage with addition of a transmission line might be a feasible alternative which might be a cost-effective alternative depending on transmission line length. The selection of technology for steady state voltage mitigation is based on a combination of subject matter expertise, system needs, and cost-effectiveness, as further described in Section 5 of this document.
 - **Steady State and Stability Feasibility Studies:** Once a mitigation strategy is selected, a comprehensive steady state assessment of the proposed solution should be performed under both pre-fault and post-fault conditions. Following the steady state analysis, a stability assessment must be conducted to confirm that the selected solution does not introduce adverse dynamic or transient performance issues.

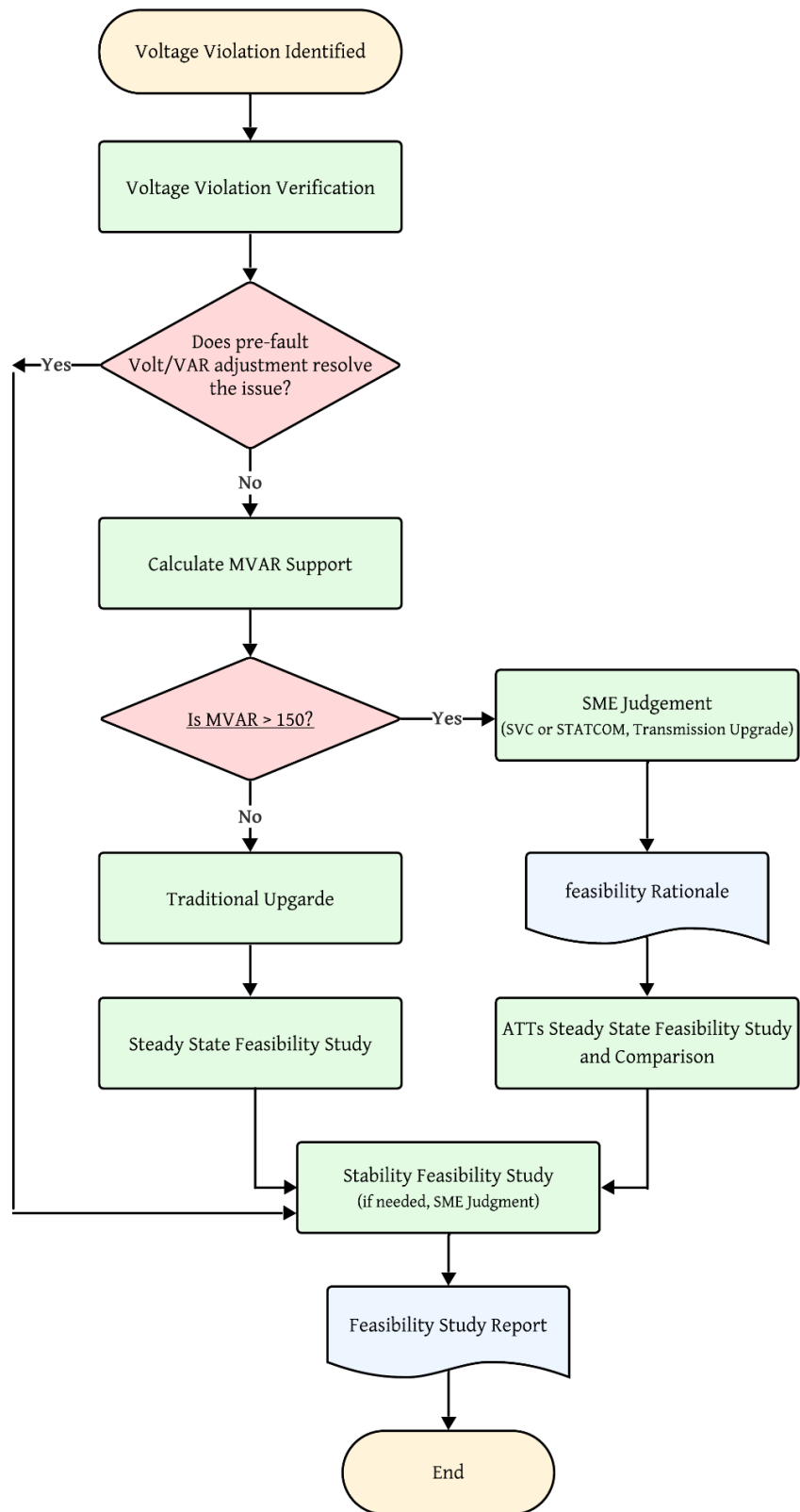


Figure 2. Steady State Voltage Violation Decision Making Flowchart

4.2. Stability Voltage Violations Decision-Making Process

In response to a voltage violation identified in a stability study, this section presents a step-by-step procedure for evaluating ATTs and other potential solutions. Figure 3 illustrates the decision-making flowchart for stability voltage violations. The process begins once a violation has been detected and proceeds through the following steps:

- **Violation Verification:** The first step is to confirm the validity of the violation before pursuing mitigation measures. This quality check includes verifying the definition and modeling of contingencies, validating study assumptions, and confirming that applicable voltage criteria are correctly applied. If the study case does not include planned transmission upgrades associated with thermal violations, the voltage violations should be reviewed in conjunction with thermal violations, since proposed mitigation plans for thermal overloads may also resolve voltage concerns. This verification step is a standard practice in all transmission upgrade evaluations and, while essential, is considered outside the scope of the ATTs decision-making process.
- **Pre-Fault Adjustment:** If the violation is verified, the next step is to consider non-infrastructure measures such as pre-fault Volt/VAR adjustments. These adjustments may include changes to nearby reactive power support devices, generator voltage schedules, or transformer tap settings. Modifying steady state voltage conditions can improve dynamic performance by enhancing pre-fault voltage profiles or reserving reactive power margin in generators for post-contingency voltage support. If these adjustments resolve the violation, the solution should be confirmed in stability simulations to ensure no adverse impacts.
- **Traditional Steady-State MVAR Support:** If pre-fault adjustments are not sufficient, the mitigation process should next examine steady state solutions. Adding reactive power support in steady state, such as fixed or switched shunts, can improve pre-fault voltage levels and reserve generator dynamic reactive capability for use during disturbances. If this approach mitigates the stability voltage violation, a follow-up stability analysis is required to confirm the solution's effectiveness.
- **Dynamic Model Adjustment of Nearby Facilities:** If steady state MVAR support is not effective, adjustments to the dynamic models of nearby facilities should be considered. Modifying control settings, excitation systems, or protection parameters for generators, MVAR support equipment can improve post-disturbance voltage recovery without adding new infrastructure.

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- **MVAR Support Technology:** If dynamic model adjustments are not effective, the feasibility of deploying STATCOMs, SVCs, or SynCons should be evaluated based on the nature of the violation. Section 3 of this document provides detailed guidelines for technology selection. In general:
 - STATCOMs are effective for stability-related voltage violations requiring fast-response, real-time reactive power injection or absorption. They perform well under low-voltage conditions and are suitable where modularity or scalability is needed but may not be practical in low SCR environments.
 - SVCs can provide effective support for damping oscillations and limiting voltage excursions, though their performance under deep undervoltage is less robust than STATCOMs.
 - SynCons are well-suited for weak-grid or low SCR systems, and for areas with low system inertia.
 - **Feasibility Rationale and Technology Comparison:** If one or more alternative technologies appear feasible, a preliminary “Feasibility Rationale” should be documented. This rationale addresses the question: *Why might the technology be feasible for the identified violation?* The intent is not to conduct a full feasibility study but to record the technical basis for proceeding to more detailed evaluation. Section 3 provides technical considerations that can guide the rationale. Where multiple technologies are identified, a technology comparison may be conducted using generic cost estimates, MVAR support ranges, and technical performance criteria to help prioritize options. Section 5 of this document provides a comparative analysis to support this evaluation.
 - **If no Alternative Technologies are Feasible:** If no ATT is deemed feasible for the stability issue, traditional transmission upgrade options should be considered. These may include reinforcement of system voltage by adding new transmission lines.
 - **Feasibility Study:** When one or more alternative technologies are identified as potentially feasible, a detailed feasibility study must be conducted to evaluate technical effectiveness and system impacts. This study should address two key questions: (1) *Can the selected technology successfully mitigate the identified violation?* and (2) *Does the selected technology introduce any new violations or adverse impacts to the system?* The modeling methodology outlined in the “**Advanced Transmission Technologies Framework**” prepared by EPE can be applied to simulate technologies performance.

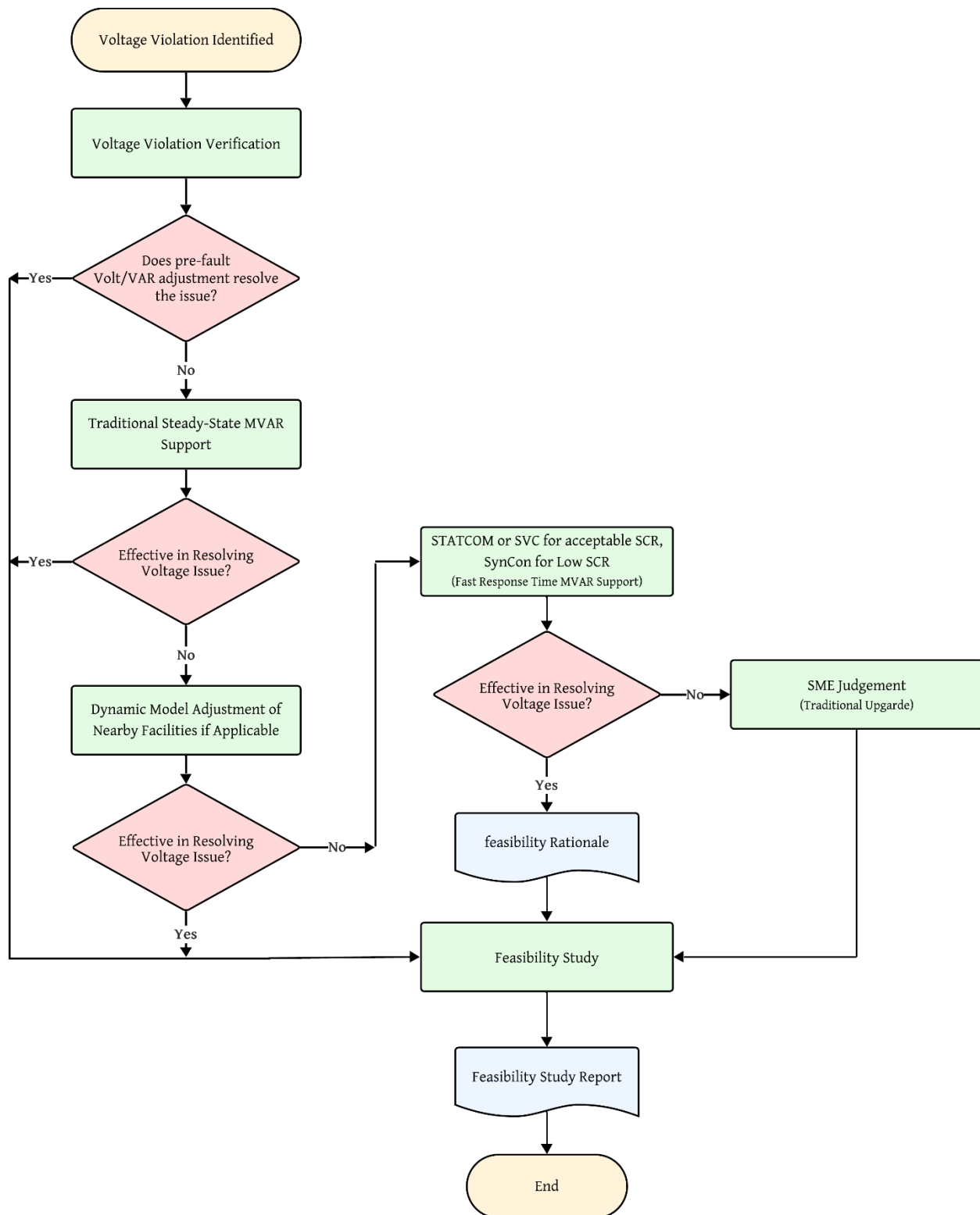


Figure 3. Stability Voltage Violation Decision Making Flowchart

5. Technology Comparison

This section provides a comparative overview of alternative technologies commonly considered for voltage violation mitigation. Table 1 summarizes the key attributes of each technology across several dimensions, including reactive power capability, response time, cost, typical voltage application range, and key technical considerations. The goal of this comparison is to aid planners and engineers in identifying suitable technology options based on system needs, operating conditions, and project constraints. While the focus of this document is on ATTs, switched shunt devices are included in the table as a conventional solution for voltage control to provide a baseline for cost, performance, and applicability comparison. This comparison supports the identification of technically and economically viable solutions, as well as the documentation of preliminary feasibility rationales for planning studies.

Switched shunt devices, such as capacitor banks and reactors, represent the most economical form of reactive power support and are widely deployed in transmission networks as a traditional voltage control measure. Their low cost and modularity make them well-suited for steady state voltage violations, particularly in systems where dynamic performance is not critical. However, due to their relatively slow response and reduced effectiveness under low voltage or dynamic conditions, switched shunts are generally not sufficient for stability-related issues. They are included here to serve as a benchmark for cost and response characteristics against advanced technologies.

SynCons provide both dynamic reactive power and rotational inertia, making them uniquely valuable in weak-grid conditions or areas with high IBR penetration. They improve voltage stiffness and short-circuit strength while supporting protection coordination. Although they require higher capital investment and maintenance compared to static devices, SynCons can be especially effective in low SCR systems or locations requiring both inertia and voltage stability.



STATCOMs offer the fastest dynamic response of all technologies considered, delivering full reactive power support within milliseconds and maintaining capability under deep undervoltage conditions. Their modular multilevel converter design allows for scalable deployment and precise control. While their capital cost is high, STATCOMs are often justified in critical areas with significant dynamic voltage sensitivity. They are most effective in systems with adequate SCR, as they do not inherently increase short-circuit strength.

SVCs provide a cost-effective balance between switched shunts and STATCOMs, offering fast reactive power adjustment and continuous voltage regulation through thyristor-controlled components. They are particularly effective in higher voltage systems with moderate stability challenges. While less modular and less effective under deep undervoltage than STATCOMs, SVCs remain a proven technology in systems with sufficient strength and moderate dynamic needs.

In combination, these technologies form a complete range of tools for mitigating voltage violations. Selection should be based on system characteristics, the nature of the violation, and cost-effectiveness, using switched shunts as a reference point and the advanced technologies as targeted solutions for more complex conditions.

Table 1. Alternative Technologies Comparison

Technology	Reactive Power Source	Range (Approx.)	Response Time	Cost Estimate	Typical Voltage Level	Technical Considerations
Switched Shunt	Static	~1-150 MVAR	~0.3-3 Seconds	Low (20-30 k\$/MVAR)	69 kV-765 kV	Pros: Excellent modularity Cons: Limited response speed Ineffective under low-voltage or dynamic conditions
SynCon	Dynamic	~20-250 MVAR	~0.2-2 seconds	Medium – High (50-80 k\$/MVAR)	69 kV-345 kV	Pros: Provides inertia High fault current capability Voltage stiffness in low-SCR or high-IBR areas Cons: Higher maintenance losses Larger footprint Limited modularity
STATCOM	Static (VSC-based)	~10-400 MVAR	<10ms	High (80-150 k\$/MVAR)	69 kV-500 kV	Pros: Extremely fast dynamic response Full capacitive support under deep undervoltage Highly modular Cons: High capital cost and complexity Not suitable for low SCR areas
SVC	Static (Thyristor-based)	~50-500 MVAR	10-100ms	Medium (50-80 k\$/MVAR)	115 kV-765kV	Pros: Fast dynamic response Cons: Performance drops under deep undervoltage Less modular than STATCOM

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