A Review on Voltage Stability and LVRT Improvement of Wind Generator Using FACTS Device

Akanksha koshle
Department of Electrical Engineering
Vishwavidyalaya Engineering College,Ambikapur
Surguja,Chhattisgarh, India

Mr. Deman Kosale
(Assistant Professor)
Department of Electrical Engineering
Vishwavidyalaya Engineering College,Ambikapur
Surguja,Chhattisgarh, India

Mr. Mahedhaar Dubey
(Assistant Professor)
Department of Electrical Engineering
Vishwavidyalaya Engineering College,Ambikapur
Surguja,Chhattisgarh, India

***Abstract*— The increasing penetration of wind energy in microgrids presents significant challenges in maintaining voltage stability and ensuring Low Voltage Ride Through (LVRT) compliance during grid disturbances. Voltage sags caused by faults can lead to wind generator disconnection, affecting overall system reliability and power quality. This paper reviews the role of Flexible AC Transmission System (FACTS) devices in enhancing voltage stability and improving LVRT capability in wind-integrated microgrids. Various FACTS-based control strategies, including static compensators and dynamic voltage support mechanisms, are analyzed for their effectiveness in mitigating voltage fluctuations. Simulation studies in MATLAB/Simulink demonstrate how FACTS devices assist in recovering voltage levels and ensuring compliance with LVRT guidelines. The findings highlight the importance of power electronics-based solutions in improving the resilience and stability of renewable energy-integrated microgrids, providing a foundation for future advancements in this field.**

Keywords—Voltage Stability, Low Voltage Ride Through (LVRT), Wind Energy, Microgrid, FACTS Devices, Microgrid Standards, Distributed Energy Resources (DERs).

I. Introduction

The fast integration of renewable energy resources, especially wind power, into contemporary power grids has brought in new challenges of maintaining voltage stability and system reliability. In contrast to traditional synchronous generators, wind turbines are dependent on power electronic converters, and hence they are more prone to voltage fluctuations and grid disturbances. One of the main issues is Low Voltage Ride Through (LVRT), where wind generators need to stay connected with the grid even during voltage sags due to faults or disturbances. Noncompliance with LVRT standards will result in disconnection, diminishing system stability and impacting the performance of the microgrid as a whole.

Some research has investigated ways to improve LVRT capacity in addition to reducing voltage instability in wind-integrated microgrids. For example, [1] presented an optimized STATCOM controller based on the Dandelion Optimizer (DO) for enhancing LVRT performance in wind-integrated grid-connected wind farms, which outperformed conventional optimization techniques like Particle Swarm Optimization (PSO). In the same vein, [2] examined the use of Static Synchronous Compensators (STATCOM) and Static VAR Compensators (SVC) for dynamic voltage stability in microgrids, proving that DSTATCOM performed better than SVC in preventing Fault-Induced Delay Voltage Recovery (FIDVR).

Subsequent research by [3] discussed the contribution of Power System Stabilizers (PSS) to improving LVRT in DFIG-based wind turbines, suggesting coordinated control between PSS and FACTS devices to enhance transient stability. Previous work, for instance [4], proposed a capacitive bridge fault current limiter (CBFCL) to reinforce LVRT ability by reinforcing fault current limitation and reactive power support. Also, [5] put forward an inductance-emulating control scheme for DFIG-based wind generators to eliminate post-fault rotor currents and subsequently limit electromagnetic torque oscillations as well as system instability.

Microgrids, which comprise distributed generation resources, loads, and storage systems, provide an efficient means to bring renewable energy onto the grid. Their voltage stability is considerably affected by grid disturbances and intermittent generation. A high voltage drop during faults is likely at the point of common coupling (PCC), risking wind turbine operation. To overcome such challenges, power electronic-based solutions like Flexible AC Transmission System (FACTS) devices have been extensively researched. FACTS devices like STATCOM and SVC render dynamic voltage support, improving LVRT capability and voltage stability in wind-integrated microgrids.

This review paper concentrates on the use of FACTS devices in enhancing voltage stability and LVRT ability in microgrids based on wind power. Different control strategies using FACTS-based systems are discussed, emphasizing their capability in voltage sag mitigation and improving system robustness. Simulation studies confirm the functionality of FACTS devices in restoring voltage levels and guaranteeing fulfillment of LVRT regulations. Though a lot of improvements have been observed in FACTS-based solutions, there are challenges in configuring and operating them in intricate microgrid environments. The future holds promises for new technologies like intelligent inverters, hybrid smart grid systems, AI-based control systems, and real-time monitoring devices that will play an important part in overcoming these problems and promoting the reliability and sustainability of microgrid operations.

II. Voltage stability and LVRT in microgrid

Voltage stability is crucial in microgrids to ensure that the system operates within acceptable voltage limits under both normal and disturbed conditions. The integration of wind power in microgrids presents a challenge due to its intermittent nature and the limited reactive power support from inverter-based generation. Unlike conventional synchronous generators, wind turbines rely on power electronics, which do not provide inherent voltage and frequency regulation. This increases the risk of voltage instability, especially in weak microgrids with low short-circuit capacity and high impedance. In such systems, voltage drops caused by faults or load variations can destabilize the grid if reactive power imbalances are not addressed effectively. The voltage response of a system to reactive power changes can be expressed as:

$$\Delta V = \frac{\partial V}{\partial Q} \Delta Q \qquad \ldots\ldots\ldots\ldots(1)$$

where $\partial V / \partial Q$ represents the system's sensitivity to reactive power variations

A significant concern in wind-integrated microgrids is Low Voltage Ride Through (LVRT) capability, which ensures that wind turbines remain connected during transient voltage dips rather than disconnecting. This is essential to prevent cascading failures and large-scale system instability. Wind turbines must comply with grid codes that mandate their ability to remain connected and support voltage recovery by injecting reactive power during faults. The required reactive power support during a fault is governed by:

$$Q_{support} = k(V_{PCC} - V_{min}) \qquad \ldots\ldots\ldots\ldots(2)$$

where k is a proportional gain factor, V_{PCC} is the voltage at the Point of Common Coupling, and V_{min} is the minimum allowable voltage. However, due to power electronic limitations, wind turbines alone may not provide sufficient reactive support, necessitating external compensation solutions.

Flexible AC Transmission System (FACTS) devices such as Static Synchronous Compensators (STATCOM) and Static VAR Compensators (SVC) are effective solutions for enhancing voltage stability and improving LVRT performance in microgrids. STATCOMs are particularly beneficial because they provide rapid reactive power support and help maintain voltage levels during faults by adjusting the amount of reactive power injected into the system. Similarly, SVCs operate by regulating the flow of reactive power through controlled inductive or capacitive devices, thereby stabilizing voltage fluctuations. These FACTS devices are crucial for stabilizing microgrids with high penetration of wind energy, ensuring that they remain operational during disturbances.

The integration of FACTS devices into microgrid control systems allows for significant improvements in voltage stability and LVRT compliance. Through advanced control strategies, these devices help maintain the voltage profile and support the system's recovery after disturbances, ensuring reliable operation even in the presence of fluctuating renewable generation.

III. Integration of FACTS Devices for Voltage Stability and LVRT Enhancement

The integration of FACTS (Flexible AC Transmission Systems) devices into microgrids plays a crucial role in mitigating voltage instability and enhancing Low Voltage Ride Through (LVRT) performance, particularly in systems with a high penetration of intermittent renewable energy sources such as wind power. These power electronic devices provide critical support for voltage regulation by controlling reactive power flow and responding dynamically to voltage fluctuations. Since renewable energy sources like wind turbines are prone to causing voltage dips during faults or disturbances, the need for external compensation becomes paramount to maintain system stability. FACTS devices offer the ability to rapidly adjust to these disturbances, thereby ensuring voltage stability and allowing wind turbines to remain connected during transient voltage sags, thereby meeting LVRT compliance standards.

A. STATCOM for Voltage Regulation

The Static Synchronous Compensator (STATCOM) is a voltage-sourced converter (VSC) that provides fast, efficient reactive power compensation to regulate the voltage at the Point of Common Coupling (PCC) in a microgrid. STATCOMs are particularly useful in systems with high renewable energy integration, where reactive power fluctuations from wind turbines can lead to voltage instability. STATCOMs work by adjusting the magnitude of the reactive power they supply or absorb, depending on the real-time voltage conditions in the grid. When a voltage drop occurs during a fault or disturbance, STATCOMs can quickly inject reactive power into the system, which helps to raise the voltage back to normal levels. The reactive power exchange of a STATCOM is given by:

$$Q_{STATCOM} = \frac{V_{PCC} \times (V_{STATCOM} - V_{PCC})}{X} \qquad \ldots\ldots\ldots\ldots\ (3)$$

$Q_{STATCOM}$ is Reactive power injected or absorbed, $V_{STATCOM}$ is STATCOM output voltage, X is Equivalent reactance of STATCOM transformer.

$V_{STATCOM} > V_{PCC}$ injects reactive power (capacitive mode)
$V_{STATCOM} < V_{PCC}$ absorbs reactive power (inductive mode)

This rapid reactive power injection is essential for improving the LVRT capability of wind turbines, as it ensures that the grid voltage remains within permissible limits during short-term disturbances. In the case of a fault, STATCOMs can provide dynamic support by rapidly compensating for the loss of reactive power that typically occurs when a fault is detected. This prevents voltage collapse and stabilizes the grid, allowing wind turbines to stay connected to the grid without tripping, which is crucial for LVRT compliance. The continuous reactive power compensation ensures that the microgrid recovers quickly from voltage sags, maintaining both system voltage stability and the required operational conditions for renewable generation.

B. SVC for Voltage Regulation

The Static VAR Compensator (SVC) is another widely used FACTS device that helps maintain voltage stability and improve LVRT in microgrids. SVCs operate by controlling the amount of reactive power that is absorbed or injected into the system through thyristor-controlled reactors (TCR) and capacitors (TCAP). The thyristor-controlled devices enable fast, continuous adjustment of reactive power in response to voltage fluctuations, providing a stable voltage profile and minimizing voltage deviations that could otherwise lead to instability. The reactive power compensation provided by an SVC is given by:

$$Q_{SVC} = \frac{V^2}{X_{eq}} \quad \text{..........(4)}$$

Q_{SVC} is Reactive power injection or absorption, V is system voltage at PCC and X_{eq} Equivalent reactance of the TCR and TSC combination.

SVCs are particularly effective in steady-state voltage regulation but also contribute to LVRT enhancement by maintaining system voltage during transient faults. During a voltage sag, an SVC will absorb or inject reactive power depending on the grid's voltage condition. This helps maintain the voltage at the PCC, which is essential for preventing wind turbine disconnections during transient disturbances. Unlike STATCOMs, SVCs generally respond more slowly, but their continuous reactive power injection helps ensure that the system does not experience large, sustained voltage drops, reducing the chance of voltage collapse.

For LVRT enhancement, SVCs provide vital support in controlling the grid voltage during faults. When a fault occurs, the SVC reacts by either injecting capacitive reactive power (to boost voltage) or absorbing inductive reactive power (to prevent overvoltage). This reactive power support prevents voltage dips from reaching critical levels and ensures that wind turbines remain connected, thus complying with LVRT standards. While SVCs are slower than STATCOMs in dynamic voltage control, their consistent operation over time allows them to complement STATCOMs, ensuring that both short-term voltage stability and long-term grid regulation are maintained.

C. Comparison and Synergy of STATCOM and SVC for LVRT Compliance

Both STATCOM and SVC provide valuable benefits for improving voltage stability and LVRT performance, but their roles complement each other. STATCOMs excel in providing fast, dynamic reactive power compensation and are particularly useful for maintaining voltage stability during rapid voltage dips caused by faults. This is especially critical in microgrids with renewable generation, where maintaining LVRT compliance is essential to avoid disconnection of wind turbines during transient events. STATCOMs ensure that voltage dips are rapidly corrected, supporting the grid's resilience and improving fault ride-through capability.

In contrast, SVCs offer slower, continuous reactive power compensation that ensures stable voltage regulation over extended periods. Although their response time is slower compared to STATCOM, SVCs are effective in maintaining the voltage level within acceptable limits during minor disturbances and in steady-state operation. The combination of STATCOM and SVC can provide a comprehensive solution for voltage stability in microgrids. STATCOM can address the immediate dynamic voltage fluctuations, while SVC ensures that steady-state voltage conditions are maintained, preventing voltage deviations from destabilizing the system over time.

Table 1 gives detailed technical comparison between SVC (Static VAR Compensator) and STATCOM (Static Synchronous Compensator) based on various parameters relevant to voltage stability and LVRT enhancement in microgrid systems.

TABLE 1 Comparison of SVC and STATCOM

Parameter	SVC	STATCOM
Technology Type	Thyristor-based (TCR & TSC)	Voltage Source Converter (VSC) based
Reactive Power Control	variable reactive power by switching capacitors and inductors	Injects/absorbs reactive power dynamically via VSC
Response Time	Relatively slower due to thyristor switching delays (~10-20 ms)	Faster response due to IGBT-based VSC control (~1-5 ms)
Voltage Support	Effective for steady-state voltage control	Superior dynamic voltage support under transient conditions
Operating Mode	Works in stepwise manner (discrete control)	Provides smooth and continuous reactive power control
LVRT Performance	Moderate LVRT enhancement; limited ability under severe faults	Strong LVRT capability; maintains voltage during deep faults
Voltage Compensation Range	Limited to system voltage range (depends on capacitor/reactor size)	Can generate reactive power even at low voltages
Power Factor Correction	Effective, but stepwise adjustments	Superior, with fast dynamic adjustments

By integrating both STATCOM and SVC devices, microgrids can achieve robust LVRT compliance, ensuring that wind turbines and other distributed energy resources remain connected and continue to supply power during grid faults. The synergy between these devices enables effective voltage control during both transient and steady-state conditions, ensuring that the grid operates efficiently and remains stable even under varying generation conditions.

IV. Control Strategies for FACTS Devices in Microgrids

The control strategies employed for FACTS devices are crucial to ensuring optimal performance in enhancing voltage stability and LVRT capability in microgrids. Effective control of these devices is essential to maintain power quality, prevent voltage instability, and allow seamless integration of renewable energy sources such as wind power. As microgrids operate in a dynamic and often fluctuating environment, robust and adaptive control strategies are needed to handle disturbances and faults. These strategies must ensure that FACTS devices react quickly and efficiently to changes in the grid, maintaining voltage within the specified limits and enabling LVRT compliance.

A. Voltage Control in STATCOMs

For STATCOMs, the primary control objective is to maintain voltage at the PCC during disturbances or faults. STATCOMs achieve this by continuously adjusting the reactive power they supply or absorb, depending on the local voltage conditions. A key control strategy for STATCOMs is the use of a voltage regulation algorithm, which compares the actual PCC voltage with a reference voltage. The control system then adjusts the output of the STATCOM to either absorb or inject reactive power as needed to correct voltage deviations.

PI (Proportional-Integral) controller is employed to regulate the reactive power. The PI controller adjusts the compensating reactive power by processing the error between the desired and actual voltage values. In cases where a voltage dip occurs due to a fault, the STATCOM will rapidly inject reactive power into the system to counteract the voltage drop. This reactive power injection increases the system voltage, allowing wind turbines to remain connected and operate during the fault, thus ensuring LVRT compliance.

In more advanced systems, predictive control strategies can be implemented. These predictive algorithms anticipate voltage fluctuations based on the system's behaviour and can pre-emptively adjust the reactive power output, allowing for even faster responses to voltage dips and reducing recovery time after faults. By combining feedback control (such as PI controllers) with predictive models, STATCOMs can effectively handle both instantaneous and anticipated voltage changes.

B. Reactive Power Regulation in SVCs

The control of Static VAR Compensators (SVCs) focuses on maintaining a balanced reactive power flow within the grid and stabilizing voltage by controlling the charging and discharging of capacitors and inductors. The SVC typically uses a thyristor-controlled reactor (TCR) and a thyristor-switched capacitor (TSC) to regulate the flow of reactive power. The main control objective is to keep the grid voltage within a predefined range by continuously adjusting the reactive power compensation.

SVCs generally operate through a voltage-reactive power feedback loop, where the grid voltage at the PCC is continuously monitored. When the voltage deviates from the desired setpoint, the SVC adjusts the reactive power by switching the capacitors or reactors on or off. In this way, SVCs can either absorb or inject reactive power to counteract the voltage fluctuations.

For enhanced LVRT performance, SVC control strategies are designed to respond to faults by providing dynamic reactive power support. Upon detection of a voltage dip, the SVC will typically absorb reactive power (acting inductively) to mitigate the voltage drop. Conversely, during a voltage rise, it can inject reactive power to prevent overvoltage. By quickly adapting to these changing conditions, SVCs help keep the grid voltage within limits, preventing the disconnection of wind turbines during faults.

C. Coordinated Control of STATCOM and SVC for Enhanced Performance

While both STATCOM and SVC devices can be controlled individually to provide voltage regulation and reactive power compensation, their effectiveness is enhanced when they are coordinated in the microgrid's control strategy. In some cases, a centralized control scheme is employed, where a central controller coordinates the operation of both STATCOM and SVC devices based on real-time grid conditions. The advantage of a centralized approach is that it enables a unified response to voltage fluctuations, ensuring that both devices work together seamlessly to stabilize the grid.

In coordinated control, the primary objective is to determine when and how much reactive power should be injected or absorbed by each device, depending on the voltage condition at various points in the microgrid. For example, if a fault causes a voltage dip, the STATCOM can provide immediate reactive power injection to stabilize the voltage, while the SVC can be used to regulate voltage over a longer period, ensuring steady-state stability once the fault has cleared.

To optimize the control of both devices, hierarchical control strategies are often employed. In this case, the STATCOM's fast response is prioritized during transient disturbances, while the SVC's steady-state voltage regulation comes into play once the system stabilizes. Such coordination improves the LVRT capability of the microgrid and ensures the system remains connected during voltage sags and disturbances.

D. Adaptive Control Strategies for Microgrid Operation

Adaptive control strategies are another important approach for FACTS devices in microgrids. These strategies allow the system to adjust to changing conditions, such as varying load demands or fluctuating renewable generation. In traditional control systems, the parameters of the control algorithms (e.g., PI controller gains) are fixed, which may not be optimal for all operating conditions. In contrast, adaptive control techniques dynamically adjust these parameters based on real-time system conditions.

For instance, the controller in a STATCOM may adaptively adjust the PI controller's gain values depending on the severity of the voltage dip or the amount of renewable generation in the system. This ensures that the reactive power response is optimized for the current system conditions, improving the overall performance of the FACTS device.

In addition, fuzzy logic control can be applied to both STATCOM and SVC devices to handle uncertainties in system behaviour, such as unpredictable changes in renewable generation or load. Fuzzy logic controllers can model complex system dynamics and make control decisions based on linguistic rules that mimic human decision-making. This allows FACTS devices to respond in a more flexible and adaptive manner to changing grid conditions, enhancing the robustness and resilience of the microgrid.

V. Challenges and Future Directions in FACTS Device Integration for LVRT Enhancement

The integration of FACTS devices into microgrids to enhance LVRT capabilities and voltage stability presents several challenges that need to be addressed for effective implementation. As the global energy landscape shifts toward increased reliance on renewable energy sources, particularly wind, the challenges associated with maintaining grid stability during disturbances become more complex. FACTS devices, while highly effective, must evolve to address the dynamic nature of microgrid operation, varying levels of renewable penetration, and the growing complexity of grid infrastructure. Several factors contribute to the challenges in deploying these devices, from control complexities to system coordination issues, and understanding these challenges is essential for optimizing their performance.

A. Dynamic Behavior of Microgrids

One of the primary challenges in integrating FACTS devices in microgrids is the dynamic nature of the system itself. Microgrids are often characterized by high variability due to the integration of renewable generation sources, such as wind and solar power. The output of these generation sources is inherently intermittent, leading to frequent fluctuations in both voltage and power quality. This intermittent nature poses a challenge to voltage stability, as conventional grid control mechanisms are not always effective in handling such fluctuations.

When wind generation is high, voltage can be excessively high during light load conditions, whereas during periods of low generation, voltage may sag, triggering reactive power imbalances. To address these challenges, FACTS devices like STATCOM and SVC need to quickly respond to these fluctuations, but their control systems must be finely tuned to handle the wide range of operational conditions in microgrids.

B. Communication and Coordination of FACTS Devices

Effective communication and coordination between multiple FACTS devices are vital for ensuring optimal performance. In large microgrids or those with several distributed renewable energy sources, the control of individual FACTS devices can become complex. Each device, whether it's a STATCOM or an SVC, operates based on local voltage measurements and reactive power requirements. However, without proper coordination, these devices can end up counteracting each other's efforts, reducing the overall effectiveness of the system.

Centralized control schemes, where a master controller coordinates the actions of all devices based on real-time grid data, can help mitigate this challenge. However, the complexity of implementing a robust communication framework capable of supporting such control schemes in real-time can be a significant hurdle. Delays in communication or inaccurate data can lead to suboptimal performance, particularly in situations requiring rapid voltage recovery, such as during faults or transient events.

C. Integration with Other Grid Technologies

In modern grid infrastructure, FACTS devices do not operate in isolation. They are integrated with other grid technologies, such as energy storage systems (ESS), renewable energy sources, and advanced metering infrastructure (AMI). Coordinating FACTS devices with energy storage can help provide additional reactive power support during voltage dips and improve the overall LVRT performance of the system. However, the integration of such technologies can increase system complexity.

For instance, energy storage systems can be used to inject or absorb active power to support voltage recovery during faults. However, managing the simultaneous operation of FACTS devices, energy storage, and renewable generators requires advanced control algorithms and a robust communication infrastructure. The interaction between these components needs to be carefully managed to ensure that the system operates efficiently and that voltage stability and LVRT compliance are maintained without overloading any part of the system.

Additionally, advanced metering infrastructure provides real-time data on power quality, voltage levels, and grid performance, enabling better control and optimization of FACTS devices. The challenge lies in designing integrated control systems that can process and act on large amounts of real-time data from diverse grid components, particularly in highly dynamic environments with fluctuating renewable generation.

D. Voltage and Frequency Regulation in Islanded Operation

Microgrids often operate in two modes: grid-connected and islanded (or off-grid). When a microgrid operates in islanded mode, it becomes electrically isolated from the main grid. This introduces new challenges in terms of voltage and frequency regulation, as the microgrid must maintain stable operation without the support of the larger grid.

In islanded mode, the power balance between generation and consumption must be maintained more rigorously, and the lack of an external reactive power support source makes voltage regulation more challenging. FACTS devices play an important role in this scenario, especially STATCOMs, which can provide fast reactive power support to counteract voltage fluctuations caused by changes in generation or load. The challenge, however, lies in ensuring that STATCOMs and other reactive power devices can operate effectively in islanded conditions, where their actions are more critical to maintaining voltage stability.

Moreover, when the microgrid transitions between grid-connected and islanded modes, seamless coordination between FACTS devices and other grid technologies (such as inverters in renewable energy systems) is required to ensure stable voltage and frequency. The transition process can cause momentary voltage dips or frequency fluctuations, which can affect the system's ability to maintain LVRT compliance.

VI. Conclusion

The integration of FACTS (Flexible AC Transmission Systems) devices such as STATCOMs (Static Synchronous Compensators) and SVCs (Static VAR Compensators) plays a vital role in enhancing voltage stability and ensuring Low Voltage Ride Through (LVRT) compliance in microgrids, especially those with high renewable energy penetration. STATCOMs are highly effective due to their rapid response times, providing quick mitigation of voltage dips during faults, which is essential for maintaining grid stability and meeting LVRT guidelines. SVCs, although slower in their response, are more cost-effective and provide steady-state voltage regulation during normal operational conditions. Coordinating STATCOMs and SVCs within a microgrid allows STATCOMs to handle dynamic voltage fluctuations, while SVCs regulate stable voltage, ensuring overall system reliability. Adaptive control strategies, such as predictive control and fuzzy logic, have proven beneficial in optimizing the performance of these devices, especially in microgrids with fluctuating renewable energy inputs. However, several challenges persist, including the dynamic behaviour of microgrids driven by the variability of renewable generation and fluctuating loads. The inability of traditional control systems to respond quickly to these changes necessitates the integration of advanced, flexible control mechanisms for FACTS devices.

Despite the significant benefits, challenges such as communication coordination, integration with energy storage systems, and economic feasibility remain obstacles to widespread deployment. Effective communication between FACTS devices is critical to ensure coordinated responses to disturbances, preventing suboptimal performance. Furthermore, integrating energy storage systems with FACTS devices can enhance LVRT performance, but it requires advanced control algorithms to synchronize the operation of both systems. The economic considerations of deploying STATCOMs versus SVCs, especially in smaller microgrids, also require careful evaluation. As microgrids operate in both grid-connected and islanded modes, FACTS devices must adapt to changing conditions while maintaining system stability. Future research should focus on developing advanced control strategies, real-time monitoring systems, and hybrid solutions that combine FACTS devices with energy storage and other grid technologies. Furthermore, economic optimization studies are needed to assess the cost-effectiveness of these systems, ensuring their viability while enhancing microgrid reliability and sustainability.

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