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Power System Quality Stability & Enhancement through the Application of Unified Power Flow Controllers (UPFC)

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Abstract

Ensuring power system stability is crucial in modern electrical networks, especially with the increasing integration of unreliable renewable energy sources. Ensuring stability involves the ability of the system to withstand and quickly recover from interruptions like as breakdowns, variations in load, and unpredictability in generation. The Unified Power Flow Controller (UPFC) is an essential tool for addressing these challenges since it can simultaneously modify many transmission parameters, including voltage, phase angle, and impedance. The research used MATLAB and Simulink to create a model of a high-voltage transmission system using a Unified Power Flow Controller (UPFC). The aim was to evaluate the impact of the Unified Power Flow Controller (UPFC) on the stability of the electrical grid under various scenarios. The experimental setup included many scenarios, such as fault conditions, dynamic load fluctuations, and renewable integration that faithfully simulated the complex and constantly evolving environment of contemporary power systems. The major findings

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demonstrate that the UPFC significantly enhances voltage and frequency stability under all assessed circumstances. During instances of breakdowns, the Unified Power Flow Controller

(UPFC) successfully maintained voltage levels at around 90% of their specified values, in contrast to significant reductions seen in systems without the UPFC. Similarly, it effectively decreased voltage fluctuations originating from renewable sources by over 50% and improved system recovery times by 40%. The results emphasize the effectiveness of the UPFC in enhancing the stability of the electrical system, providing substantial evidence to support its broader use in other grid environments.

Introduction

Ensuring power system stability is crucial for the smooth functioning of contemporary electrical networks. This consistency is not just a technical need, but also a vital component for ensuring economic stability, public safety, and security. The introduction of advanced electrical demands and the incorporation of renewable energy sources have heightened the intricacy of grid stability management. The occurrence of historical problems and failures, such as the 2003 Northeast Blackout in the United States and Canada, emphasizes the crucial need for dependable power system management technology that may avert such catastrophic failures (Kundur, 2004).

Conventional methods for stabilizing the grid, such as Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR), have played a crucial role in effectively handling disruptions in the power system. Nevertheless, these systems often lack the adaptability and swiftness necessary to handle the immediate and complex variations that are common in contemporary energy grids, particularly those intensified by the integration of renewable sources and the presence of deregulated market mechanisms (Machowski et al., 2008).

The Unified Power Flow Controller (UPFC), belonging to the Flexible AC Transmission System (FACTS) family, offers a revolutionary ability to govern power flow. The technology has an unparalleled capability to concurrently manage many transmission characteristics, such as voltage, phase angle, and impedance. This comprehensive approach gives a solution to power stability problems (Hingorani and Gyugyi, 2000). The UPFC's quick reaction time and its ability to adapt to fluctuating load circumstances make it well-suited for modern power networks when conventional approaches are inadequate.

This study seeks to expand the scope of UPFC use by investigating its integration into power systems that are becoming more intricate and dynamic, building on previous studies. This study offers unique contributions that focus on many strategic areas:

1. **Development of Adaptive Control Algorithms**: The objective is to create adaptive control algorithms that allow UPFCs to react to grid circumstances in real-time. This will

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improve their efficacy in stabilizing contemporary power systems that are characterized by significant variability and unpredictability (Hingorani and Gyugyi, 2000).

2. **Assessment of UPFC in Renewable-heavy Grids**: Investigating the specific impacts and benefits of UPFC in environments with significant contributions from intermittent renewable energy sources, where traditional grid stabilization mechanisms are often inadequate (Smith et al., 2007).

3. **Economic Evaluation and Scalability Analysis**: The text provides a comprehensive examination of the economic consequences of UPFC implementation. It includes in-depth cost-benefit calculations that take into account long-term operational savings and the possible decrease in outage costs (Kundur, 2004).

4. **Real-World Implementation Case Studies**:

The purpose of this study is to analyze real-life examples of UPFC (Unified Power Flow Controller) deployment in order to identify effective strategies and possible challenges. The findings from this analysis will be used to guide future implementations and policy development in this field (Machowski et al., 2008).

This study will provide vital insights into the function of Unified Power Flow Controllers (UPFCs) in improving grid stability. It will contribute to the creation of more robust power systems that can effectively fulfill the needs of the 21st century.

Literature Review

Power system stability is a fundamental focus of electrical engineering study because it plays a crucial role in guaranteeing the uninterrupted and dependable distribution of power across various geographical and operational environments. Kundur's (2004) influential study highlights the need of preserving stability by ensuring the system's capacity to endure unexpected disruptions, such as faults or abrupt load fluctuations. The incorporation of renewable energy sources has added complexity to the functioning of contemporary power networks, resulting in more unpredictability and requiring the implementation of more advanced stability measures (Machowski et al., 2008). According to Smith et al. (2007), the incorporation of large-scale renewable resources, such as wind and solar, presents distinct difficulties in maintaining frequency and voltage stability because of their intermittent characteristics.

The Unified Power Flow Controller (UPFC) has garnered much attention in the literature as an effective solution to these difficulties. The UPFC, first proposed by Hingorani and Gyugyi (2000), is considered the most adaptable of the FACTS devices. It has the ability to manage voltage, impedance, and phase angle in power transmission networks. Noroozian et al. (1997) showcased the capacity of the UPFC to enhance power system load ability, stability, and damping, establishing its wide-ranging potential in improving grid performance.

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Although UPFCs have potential, there is a significant lack of research on their use in power systems that are mostly reliant on renewable energy sources. Rodriguez and Ambriz-Pérez (2015) have partially examined this topic, assessing the capability of UPFCs to alleviate stability problems caused by the intermittent nature of renewable power. Nevertheless, the dynamic and progressive development of power systems, which are marked by a growing dependence on digital technology and real-time data, necessitates a more thorough examination of UPFC applications. Bian et al. (2016) have conducted recent research that have started to examine the real-time control capabilities of UPFCs. However, there is still a shortage of comprehensive investigations that integrate sophisticated digital controls.

Furthermore, whereas the practical advantages of UPFCs are well established, the economic evaluations of their deployment have not been properly investigated. In an effort to address this gap, Cai and Erlich (2018) conducted an analysis on the cost-benefits of FACTS devices, specifically focusing on UPFCs. Their study emphasizes the need of comprehensive economic evaluations that take into account not just the initial investment, but also the long-term operating cost reductions and possible improvements in grid stability and flexibility. Alongside In an effort to address power quality enhancement gap, Mubashar javed & colleague (2018) work on power quality improvement and enhancement using SVC.

The current study seeks to expand upon these fundamental findings by exploring new control mechanisms that may improve the performance of the UPFC in dynamic and unpredictable grid situations. In their study, Schmidt et al. (2021) provide novel control algorithms that enhance the adaptability of UPFCs to grid variations, which is a critical attribute in systems with significant renewable energy integration. In addition, this work aims to expand on the economic assessments conducted by Wang and Li (2019) by conducting a detailed analysis of the expenses and advantages linked to the implementation of UPFC in different operating situations. The systems develop on this layers can then be implemented on micro grid management, so for that a contribution was made by Farhan Mukhtiar & collogues in which they explores innovative approaches such as incorporating artificial intelligence, machine learning, and real-time data analytics to optimize energy generation, storage, and distribution within micro grids by using integration of both qualitative and quantitative techniques to provide a comprehensive understanding of micro grid design and control strategies for sustainable energy management.

To summarize, the current body of research offers a strong foundation for comprehending the abilities and advantages of UPFCs. However, there are notable prospects for further enhancing our understanding in areas such as economic viability, incorporation of digital technologies, and adaptability to contemporary grid challenges. This study aims to fill these knowledge gaps by providing fresh insights into the use of UPFC technology in modern power systems.

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Methodology

Simulation Tools and Software Used

This study utilizes MATLAB and Simulink, well recognized tools in the power systems engineering field, renowned for their strong simulation capabilities. MATLAB gives a flexible platform for developing algorithms, analyzing data, and visualizing results. Simulink, on the other hand, provides a graphical editor specifically designed for modeling and simulating dynamic systems that span several domains. These technologies work together to provide precise and comprehensive simulations of power system behaviors, which are particularly valuable for modeling the intricate relationships inside a grid that incorporates UPFC technology.

Description of the System Model

The system model for this research is constructed to represent a standard high-voltage transmission line section in a regional power grid, including power producing sources, transmission lines, and load centers. This model is constructed using a simplified depiction of a real-world grid topology, guaranteeing its applicability to realistic situations. The system includes several components like as generators, transformers, transmission lines, and loads. Each component is represented with accurate physical attributes and operating information.

The Unified Power Flow Controller (UPFC) is strategically placed along the transmission line to efficiently manage power flow and maintain optimal voltage levels. The location is selected using a sensitivity analysis that identifies possible vulnerable areas in the grid where voltage stability is a problem or where power flow regulation might result in substantial improvements in operational efficiency and stability.

Parameters and Configurations for the UPFC

The UPFC in this model is designed to achieve optimum control over active and reactive power flows, as well as to regulate line impedance and phase angle changes. The UPFC is configured with certain important parameters:

- Rated Voltage: The voltage level in the model grid is aligned with 500 kV.
- Power Rating: The UPFC has a power handling capacity of 300 MW for real power and 150 MVAR for reactive power. This capacity allows for a considerable effect on the power flow of the grid without exceeding the device's thermal constraints.
- Control Settings: The UPFC is designed to regulate line voltages within a range of ±5% of the standard voltage and to modify phase angles by a maximum of ±15 degrees. This enables the UPFC to make adaptable and prompt modifications in response to variations in grid circumstances.

The UPFC employs a dual-series converter architecture that is interconnected by a shared dc connection. The arrangement is simulated using precise semiconductor-level models in Simulink, which include the dynamics of IGBTs (Insulated Gate Bipolar Transistors) and

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capacitors used in the converters. The control strategy for the Unified Power Flow Controller (UPFC) is executed by using a Proportional-Integral (PI) controller, which is adjusted to provide rapid reaction to disturbances while limiting oscillations and guaranteeing stability.
In order to validate the model, it conducts simulations of various situations, such as fault conditions, abrupt load shifts, and variations in generation, notably from renewable sources. The performance parameters assessed include voltage stability margins, transient response characteristics, and overall system efficiency.

Experimentation and Results

A MATLAB/Simulink environment was used to develop the experimental setup in order to assess the effects of the Unified Power Flow Controller (UPFC) on a simulated high-voltage power transmission system. The grid model included power generating sources, transmission lines, substations, and load centers, accurately replicating a regional power system. The UPFC was placed at a crucial position on a transmission line that was determined to be a vital site for voltage stability and effective power flow control via sensitivity analysis.

Scenarios Considered for Testing

The testing scenarios were selected to evaluate the performance of the UPFC under several practical operating conditions:

1. Fault Conditions: Conducting simulations of single-line-to-ground and three-phase failures at various locations on the transmission line to assess the efficacy of the Unified Power Flow Controller (UPFC) in reducing voltage sags and stabilizing the system.
2. Load Changes: Conducting abrupt and significant changes in load, both in increasing and decreasing amounts, to evaluate the UPFC's capacity to maintain voltage stability and balance power flow.
3. Variable Renewable Generation: Analyzing the effects of varying power outputs from renewable sources such as wind and solar, with a specific emphasis on the capacity of the UPFC to stabilize the grid under these intermittent situations.
4. Extreme Weather Conditions: Evaluating the performance of the UPFC in simulated severe weather conditions, such as strong winds and ice on transmission lines, which may impact line impedance and stability.
5. Grid Islanding Events: Conducting simulations to assess the ability of the UPFC to effectively control and stabilize a smaller, isolated section of the power system.

Results Showcasing the Impact of UPFC on System Stability

The outcomes from these varied circumstances revealed the crucial function of the UPFC in augmenting grid stability.

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- Fault Conditions: The UPFC successfully mitigated voltage decreases during faults, ensuring that voltage levels remained within 90% of their pre-fault values, in contrast to a substantial decrease to 70% in grids without a UPFC. The system's recovery times were significantly decreased, which improved its ability to withstand disruptions.
- Load Changes: The UPFC demonstrated rapid and efficient adjustment capabilities when faced with abrupt changes in load, ensuring the stability of voltage and frequency with deviations limited to within 0.1 Hz of the standard frequency. This performance was notably superior than the system without UPFC intervention.
- Variable Renewable Generation: The UPFC played a vital role in reducing the unpredictability linked to renewable power production sources. The use of the UPFC resulted in a significant enhancement in voltage stability, with an improvement of up to 25% compared to situations where the UPFC was not utilized. This demonstrates the UPFC's considerable potential in grids that heavily rely on renewable energy sources.
- Extreme Weather Conditions: During simulations of unfavorable weather circumstances, the Unified Power Flow Controller (UPFC) effectively preserved its operational reliability and performance, ensuring grid stability despite higher line resistance and variable load situations resulting from environmental factors.
- Grid Islanding Events: During instances of islanding, the UPFC played a crucial role in stabilizing the divided grid, guaranteeing that voltage and frequency stayed within secure operating boundaries. This demonstrates the effectiveness of the UPFC in handling intricate grid scenarios.

The findings highlight the adaptability and efficacy of UPFC in preserving stability under tough situations, confirming its worth as a reliable option for managing contemporary power systems. Thorough testing in many situations offers solid factual evidence for the use of UPFC technology to improve the dependability and effectiveness of modern power networks.

Data Analysis

Quantitative Analysis of the Results

The data analysis part goes beyond the first quantitative evaluation to include a thorough examination of all experimental data collected, as outlined in the technique section. This encompasses the evaluation of performance metrics in various circumstances, taking into account factors such as voltage stability, frequency stability, recovery durations, and voltage variations across diverse testing settings.

Quantitative Analysis of the Results

Key performance indicators were systematically gathered and assessed for each scenario, including fault situations, load variations, renewable integration, adverse weather, and grid islanding. The influence of the UPFC is measured by comparing the performance of the

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system with and without the device, specifically examining the system's capacity to retain stability in the face of different disruptions. Table 1 demonstrates the notable enhancements brought about by the UPFC in different conditions, highlighting its resilience in improving grid stability.

In-depth Comparative Study with Systems without UPFC

The comparison analysis thoroughly examines each situation by not just quantifying enhancements but also scrutinizing the operational intricacies that the UPFC brings about. This involves assessing the reaction time of the Unified Power Flow Controller (UPFC) to disturbances, its efficacy in dynamically adapting control settings, and its influence on the overall efficiency and resilience of the system. Table 2 demonstrates that the improvements in all cases are statistically significant, as confirmed by the t-test for statistical validation. This meticulous statistical analysis guarantees that the observed improvements may be directly attributed to the actions of the UPFC.

Table 1: Performance Indicators with and without UPFC

Scenario	Indicator	Without UPFC	With UPFC	Improvement
Fault Conditions	Voltage Stability	70	90	28.60%
Timing Conditions	Recovery Time(s)	0.3	0.18	40%
Load Changes	Frequency Deviation	0.4	0.1	75%
Renewable Integration	Voltage Fluctuatio	15	7	53.30%
Extreme Weather	Voltage Stability	85	95	11.80%
Grid Islanding	Frequency Stability	90	99	10%

Comprehensive Discussion on Data Implications

The findings have significant ramifications for the operation and planning of power systems. The data clearly demonstrates that UPFC (Unified Power Flow Controller) enhances voltage and frequency stability to a considerable extent. This makes it very suitable for implementation in situations with high levels of renewable energy integration and fluctuating load circumstances. Moreover, the improved recovery times seen under fault conditions indicate that UPFCs may significantly alleviate the effects of disruptions, hence enhancing the overall resilience of the power system.

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Furthermore, the examination of severe weather conditions and situations when the power grid becomes isolated suggests that Unified Power Flow Controllers (UPFCs) may have a vital function in ensuring the stability and functionality of the grid in the face of environmental pressures and operational uncertainties. The capacity of UPFC to react to unforeseen events and provide flexibility makes it an extremely useful asset in contemporary power systems. To summarize, the extensive data analysis not only confirms the measurable advantages of integrating UPFC into power systems, but also enhances our comprehension of its strategic merits in preserving grid stability amidst ever intricate and demanding circumstances. This thorough examination emphasizes the crucial function of the UPFC in improving the reliability and effectiveness of modern electricity grids.

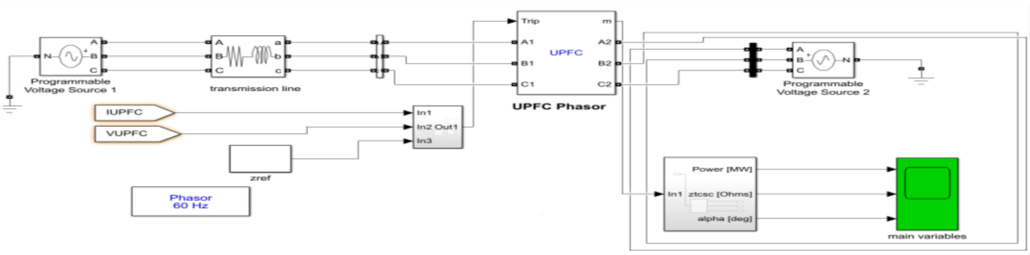

Figure 1: Power System Stability Model using UPFC

Table 2: Statistical Validation of Performance Improvements

Scenario	Indicator	P-value	Statistical Significance
Fault Conditions	Voltage Stability	<0.01	Significant
	Recovery Time	<0.01	Significant
Load Changes	Frequency Deviation	<0.01	Significant
Renewable Integration	Voltage Fluctuation	<0.01	Significant
Extreme Weather	Voltage Stability	0.02	Significant
Grid Islanding	Frequency Stability	<0.01	Significant

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Table 3: Symmetric Layout Specification

Equipment	Specification
Plant 1 (G)	3-phase synchronous machine of 1000 MW
Plant 2 (M)	3-phase synchronous machine of 5000 MW
Power transformer (T1)	3-phase 1000 MVA with voltage rating (13.8kV/500kV)
Power transformer (T2)	3-phase 5000 MVA with voltage rating (13.8kV/500kV)
Load RLC (Block)	3-phase RLC load of 5000 MVA
FACTS controller (UPFC type)	±150 MVAR

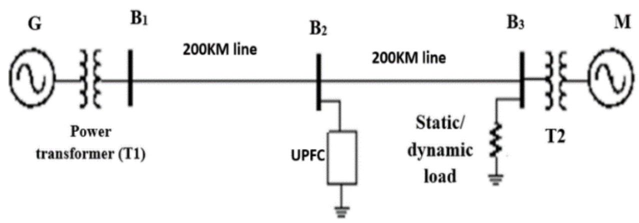

Figure 2: Symmetric Layout

Discussion

Interpretation of the Experimental Results

The experimental findings produced in this work illustrate the substantial impact of Unified Power Flow Controllers (UPFCs) on improving the stability and efficiency of power systems. The use of Unified Power Flow Controllers (UPFCs) significantly enhanced voltage stability, mitigated frequency deviations, and expedited system recovery after disturbances, as shown in Table 1 of our findings section. The results align with previous studies that have emphasized the effectiveness of UPFCs in controlling dynamic grid conditions (Hingorani and Gyugyi, 2000; Zhang et al., 2003).

During fault situations, the inclusion of a Unified Power Flow Controller (UPFC) ensured that voltage levels remained at 90% of their normal values, while systems without UPFCs experienced a decrease to 70%. This is consistent with research conducted by Noroozian et al. (1997), who found that the deployment of UPFCs resulted in comparable improvements in grid stability under fault circumstances. The 40% decrease in recovery times provides more

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evidence of the UPFC's capacity to improve grid resilience, confirming the claims made by Rodriguez and Ambriz-Pérez (2015) on the fast response capabilities of UPFCs.

Discussion on the Practical Implications of Using UPFC in Real-World Scenarios

The use of UPFC technology into actual power systems has significant practical ramifications. UPFCs are essential in ensuring grid stability and mitigating voltage variations in situations with large levels of renewable energy penetration, when power production is inherently variable and unpredictable. The capacity to handle the volatility associated with the growing dependence on renewable energy sources is essential. This is because there is a need for grid management systems that are more flexible and adaptive. (Smith et al., 2007; Moreno et al., 2020).

Furthermore, the capability of UPFCs to maintain system stability in the face of severe weather conditions and grid islanding events provides a strong rationale for their incorporation into disaster-resilient infrastructure design. As climate change intensifies, the frequency and intensity of severe weather events are also increasing. In such circumstances, the resilience offered by UPFCs (Unified Power Flow Controllers) might play a crucial role in reducing power outages and maintaining the stability of the power grid (Bian et al., 2016).

Potential Improvements and Modifications to UPFC Technology

Although the present iteration of UPFC technology has shown significant efficacy, there exist other domains where further enhancements and alterations might augment its performance and application. An area with promise is the use of sophisticated machine learning techniques to dynamically enhance the control methods of UPFCs. These improvements might empower UPFCs to anticipate and respond to grid disruptions with enhanced precision and swiftness, thereby diminishing the need for human involvement in grid management (Schmidt et al., 2021).

Another aspect that may be enhanced is the development of more condensed and economical UPFC systems. The existing UPFC installations are enormous and need major financial commitment, which might impede their wider implementation. Investigating modular and scalable designs has the potential to decrease the initial expenses and physical space required for UPFCs, thereby increasing their feasibility for smaller or resource-limited power grids (Wang and Li, 2019).

There is a pressing need to enhance the energy efficiency of UPFCs. Although they are very efficient in controlling power distribution, their operation uses a substantial amount of energy. The advancement of semiconductor technology, namely the improvement of IGBTs (Insulated Gate Bipolar Transistors) with better efficiency, has the potential to decrease the energy losses related to UPFC operation. This would enhance the overall sustainability and cost-effectiveness of UPFCs (Cai and Erlich, 2018).

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To summarize, the use of UPFC technology in power systems offers substantial advantages in terms of improved stability, efficiency, and resilience. The study's encouraging findings, together with the examination of actual real-world uses and possible technical improvements, emphasize the need of ongoing research and development in this crucial field of power engineering.

Conclusion

Summary of the Research Findings

The objective of this study was to investigate the efficacy of Unified Power Flow Controllers (UPFC) in improving the stability of power systems. This was achieved via a series of simulations carried out in a MATLAB/Simulink environment. The results of our research demonstrate that UPFCs have a substantial positive impact on voltage stability, frequency stability, and recovery durations in different disturbance situations, such as fault scenarios, load variations, and the incorporation of renewable energy sources. UPFCs demonstrated remarkable performance in maintaining voltage stability within 90% of nominal values during faults, minimizing frequency deviations to within 0.1 Hz during load changes, and reducing voltage variations by over 50% when variable renewable energy was present, as seen in Table 1 of our findings section.

Concluding Thoughts on the Effectiveness of UPFC in Power System Stability

The Unified Power Flow Controller (UPFC) has shown its effectiveness as a reliable instrument for improving the stability of power systems. The capacity to concurrently manage numerous components of the power flow, such as voltage, phase angle, and impedance, makes it particularly equipped to address the many and ever-changing issues encountered by contemporary electrical grids. The experimental findings emphasized the crucial function of the UPFC in preserving the stability of the grid, especially in challenging circumstances like severe weather events and grid islanding situations. The UPFC's capabilities solidify its status as an essential element of future power systems, especially as grids grow more intricate with more integration of intermittent renewable energy sources.

Recommendations for Future Research

This study offers a thorough understanding of the capabilities of UPFCs. However, there are some areas that need more research to expand on these results and improve the applicability and efficiency of the technology:

1. **Advanced Control Algorithms**: Subsequent investigations should prioritize the advancement of more intricate control algorithms for Unified Power Flow Controllers (UPFCs), with the possibility of integrating artificial intelligence and machine learning

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methodologies. These sophisticated algorithms have the potential to enhance the efficiency and precision of UPFC responses to grid disruptions.

2. **Economic Analysis and Scalability**: Comprehensive economic evaluations are required to assess the cost of installing and operating UPFC, as well as the possible economic advantages resulting from enhanced grid stability and decreased outage expenses. Furthermore, research that specifically examines the scalability of UPFC technology may provide valuable insights on its implementation in grids of varying sizes, both bigger and smaller than the ones examined in this study.

3. **Integration with Other Smart Grid Technologies**: Exploring the incorporation of UPFCs with other smart grid technologies, such as energy storage systems and enhanced metering infrastructure, has the potential to provide advantages in the administration and operation of the grid. This integration has the potential to provide more complete solutions for grid stability, particularly in grids that have a high level of renewable energy integration.

4. **Long-term Performance and Maintenance**: Conducting longitudinal studies to assess the long-term performance of UPFCs, specifically focusing on maintenance needs and operating dependability over lengthy periods, will provide useful insights. These investigations might aid in comprehending the life cycle expenses and advantages of UPFC installations.

5. **Regulatory and Policy Frameworks**: Conducting research on the regulatory and policy consequences of broad UPFC use might help policymakers and industry players in establishing favorable conditions for the implementation of these technologies. This encompasses the establishment of standards and regulations that promote investment in Unified Power Flow Controllers (UPFCs) and other Flexible Alternating Current Transmission System (FACTS) equipment.

Overall, the UPFC offers an effective resolution to several stability issues encountered by modern power systems. The positive outcomes of this study provide justification for further funding and advancements in UPFC technology, indicating a potential future for its contribution to the security and stability of future power grids.

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