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Voltage Flicker Mitigation Using STATCOM: A Review

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***Abstract*: This paper presents a comprehensive literature review on the mitigation of voltage flicker utilizing a Static Synchronous Compensator (STATCOM) to enhance power quality. Voltage flicker, characterized by rapid voltage fluctuations, adversely impacts the reliability and stability of power systems. By employing STATCOM, a flexible AC transmission system device, it is possible to regulate voltage levels dynamically and counteract flicker effects. This review synthesizes various research findings and methodologies developed over the years to address voltage flicker issues. It evaluates the performance, implementation strategies, and technological advancements of STATCOM in real-world scenarios. The objective is to provide a consolidated reference for researchers and practitioners aiming to improve power quality through effective voltage flicker mitigation techniques.**

***Keywords*: STATCOM, FACTS, Voltage flicker, Power quality, transmission.**

1. Introduction

Voltage flicker is a significant power quality issue that can adversely affect the performance of electrical equipment and systems, particularly in multi-machine setups. It is primarily caused by rapid fluctuations in voltage magnitude, often due to fluctuating loads or intermittent generation sources, such as renewable energy. To mitigate these disturbances, various technologies have been explored, among which the GTO-based Static Synchronous Compensator (STATCOM) has been recognized for its effectiveness in enhancing power quality. This literature review synthesizes existing research findings related to voltage flicker mitigation using STATCOM and highlights knowledge gaps while suggesting future research directions.

2. Overview of STATCOM Technology

The STATCOMs are power electronics devices used for reactive power compensation and voltage regulation. They provide fast reactive power support, helping to stabilize voltage levels during transient disturbances. Recent studies have highlighted the effectiveness of STATCOMs in improving the performance of power systems under various operational conditions. For instance, Nguyen et al. (2019) provided an overview of modular multilevel converters in HVDC transmission systems, demonstrating how STATCOM operation during pole-to-pole DC short circuits could enhance system stability and mitigate voltage flicker.

STATCOM (Static Synchronous Compensator) technology is an advanced method used for controlling and regulating the voltage stability in power grids. It is a shunt-connected device, leveraging power electronics to provide fast-acting reactive power compensation and voltage support. STATCOM systems enhance the reliability and efficiency of electricity distribution by dynamically adjusting to fluctuations in load conditions.

One of the critical advantages of STATCOM over traditional synchronous condensers and fixed capacitor banks is its rapid response time. This quick reaction capability is especially beneficial in mitigating voltage sags, flicker control, and stabilizing grid disturbances. Overall, STATCOM technology plays a vital role in the modernization of power systems by ensuring smoother and more efficient power delivery.

3. The Role of STATCOM in Voltage Flicker Mitigation

Recent studies have demonstrated the efficacy of STATCOMs in addressing voltage flicker issues in multi-machine power systems. Miveh et al. (2015) presented a comprehensive review of multifunctional voltage source inverters, which includes the application of STATCOM for flicker mitigation in autonomous microgrids. They emphasized the importance of real-time processing techniques, such as the Recursive Least Square (RLS) algorithm, to track voltage fluctuations effectively.

Mahela et al. (2020) explored the design of a voltage-source-converter (VSC)-based STATCOM specifically for a 100-MVA Electric Arc Furnace (EAF) installation. Their findings indicated that the application of a high-bandwidth control strategy significantly improved the STATCOM's performance in mitigating voltage flicker while maintaining system stability. This approach utilized the DC voltage margin of the VSC to provide active compensating current, thus preventing the need for oversized capacitor banks.

Additionally, Vantuch et al. (2017) investigated the impact of various pulse configurations of STATCOMs on voltage flicker mitigation and total harmonic distortion (THD) reduction. Their comparative analysis between 6-pulse and 12-pulse configurations revealed that a well-designed STATCOM

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could effectively alleviate voltage flicker while minimizing THD, which is crucial for maintaining power quality.

Hemeida et al. (2018) conducted a comparison between STATCOM and Static Var Compensator (SVC)-based fuzzy controllers for stability improvement in wind farm-connected multi-machine systems. Their research highlighted the superior performance of STATCOM in voltage stabilization and flicker mitigation, particularly in systems with high penetration of renewable energy sources.

The integration of STATCOM with renewable energy sources, particularly in distribution systems with high photovoltaic (PV) penetration, has been extensively studied. Chaudhary and Rizwan (2018) reviewed voltage regulation techniques in such systems, emphasizing the essential role of STATCOMs in maintaining voltage stability and reducing flicker caused by the intermittent nature of solar energy generation. Moreover, Ismail et al. (2020) implemented STATCOM technology as a low voltage ride through (LVRT) mechanism for a 9 MW wind farm, showcasing its ability to mitigate voltage fluctuations during grid disturbances.

Recent advancements in control strategies have further enhanced the performance of STATCOMs. Moghbel et al. (2018) explored optimal sizing, siting, and operation of custom power devices, including STATCOMs, for real-time reactive power control. This research highlights the importance of adaptive control mechanisms in effectively managing voltage quality and mitigating flicker. Additionally, Nafeh et al. (2021) developed intelligent fuzzy-based controllers for enhancing voltage stability in AC-DC micro-grids, emphasizing the potential of advanced control algorithms in improving STATCOM functionality.

The integration of STATCOM with other power quality improvement devices has also been a focus of research. Gu et al. (2018) proposed a whale optimization algorithm-based fractional-order proportional-integral controller for unified power quality conditioners and STATCOM tools, indicating that hybrid approaches can significantly enhance power quality and mitigate voltage flicker. These innovations suggest that combining different technologies may yield better results than using STATCOM in isolation.

4. Control Strategies and Algorithms

Number Control strategies play a pivotal role in the effectiveness of STATCOMs in flicker mitigation. Movahedi et al. (2019) proposed a combination of various optimization techniques, including Genetic Algorithm (GA) and Grey Wolf Optimization (GWO), for designing STATCOM controllers. Their findings underscored the importance of advanced control strategies in enhancing transient stability and flicker mitigation in multi-machine power systems.

The RLS algorithm, as discussed by Marei et al. (2012), has been shown to be particularly effective for power quality improvement by providing quick estimation of symmetrical components. This capability is essential for dynamic environments where voltage flicker can occur unpredictably.

Mosaad (2018) introduces a Model Reference Adaptive Control (MRAC) strategy for STATCOMs aimed at enhancing grid integration of wind energy systems. The study demonstrates that MRAC outperforms traditional Proportional-Integral (PI) controllers tuned by Genetic Algorithms (GA) in terms of robustness and efficiency. The adaptive nature of MRAC allows for real-time adjustments based on system dynamics, which is particularly advantageous in fluctuating conditions typical of renewable energy sources. This finding suggests that adaptive control methodologies could significantly improve the response of STATCOMs in varying operational environments.

Cavraro and Carli (2018) propose three strategies for voltage control in power distribution grids, focusing on the reactive power output of microgenerators. Their work emphasizes the importance of local and distributed control strategies, which can enhance voltage stability and reduce flicker. These strategies facilitate a more decentralized approach to voltage regulation, which aligns well with the growing trend towards distributed generation. The integration of these local control methods with STATCOM capabilities presents a promising avenue for mitigating voltage flicker, particularly in grid-connected scenarios.

In the context of smart grids, Elsisi et al. (2021) offer a robust model predictive control paradigm that leverages two particle swarm optimization algorithms for real-time reactive power control. This approach aims to improve voltage quality, addressing uncertainties in the power system. The use of optimization algorithms in conjunction with STATCOMs highlights a trend toward advanced computational techniques that enhance the reliability and performance of voltage control systems.

Tahiri et al. (2021) propose an innovative control technique utilizing an Artificial Neural Network (ANN)-based Distribution Static Compensator (DSTATCOM). This method aims to enhance power quality in Wind Energy Conversion Systems (WECS). The ANN framework allows for the modeling of complex nonlinear relationships inherent in power systems, thus improving the adaptability of STATCOMs to varying operational conditions. The incorporation of ANN indicates a shift towards intelligent systems capable of learning and optimizing control strategies, which could lead to significant advancements in voltage flicker mitigation.

Pal and Gupta (2020) present an improved fault-tolerant control strategy for cascaded H-bridge (CHB) based STATCOMs. Their approach focuses on enhancing output voltage levels and ensuring balance during system faults. Fault tolerance is crucial for maintaining power quality and mitigating flicker during disturbances. By integrating fault-tolerant strategies, STATCOMs can improve reliability and robustness, which are critical for systems increasingly reliant on intermittent renewable sources.

5. Challenges and Limitations

Despite the advancements in STATCOM technology and its applications, several challenges remain. The dynamic performance of STATCOMs can be affected by unbalanced operating conditions, as indicated by Ali et al. (2021), who classified and analyzed inter cluster active power balancing strategies for optimal operation under such scenarios. This highlights a need for further research on the effectiveness of STATCOMs under unbalanced conditions, particularly as the integration of renewable energy sources continues to grow.

Furthermore, Moghassemi and Padmanaban (2020) discussed the enactment of Battery Energy Storage Systems (BESS) in conjunction with STATCOMs, suggesting that while these systems can enhance transient voltage stability, their integration poses additional complexity in control and operational strategies. Therefore, future studies should focus on developing more robust and efficient control systems that can seamlessly integrate STATCOMs with energy storage solutions.

6. Knowledge Gaps and Future Research Directions

The advancements in understanding and mitigating voltage flicker through GTO-based STATCOMs, several knowledge gaps persist. Firstly, while existing research has focused on various control algorithms and system configurations, there is limited exploration of hybrid systems that integrate STATCOM with other power quality improvement devices, such as Dynamic Voltage Restorers (DVR) and Active Power Filters (APF). Future studies could investigate the synergistic effects of such combinations on flicker mitigation.

The majority of research has concentrated on simulation-based analyses. There is a need for more empirical studies that evaluate the performance of STATCOMs in real-world scenarios, particularly in systems with high levels of renewable energy integration, where voltage flicker is most pronounced.

Performance under Diverse Operational Conditions: There is limited research on the performance of STATCOMs in diverse operational conditions, such as variations in load profiles and different types of renewable energy sources. Future studies should explore the adaptability of STATCOM technology in various scenarios.

Long-term Operational Reliability: The long-term reliability and operational effectiveness of STATCOMs, particularly in high-penetration renewable scenarios, require further investigation. Research should focus on the durability of STATCOM components and their performance over extended periods.

Integration with Emerging Technologies: The integration of STATCOMs with emerging technologies, such as microgrids and smart grid infrastructures, presents an opportunity for future research. Understanding how STATCOMs can be optimized within these frameworks will be crucial for enhancing overall power system stability.

Economic Analysis: There is a need for comprehensive economic analyses to assess the cost-effectiveness of implementing STATCOMs in various power systems. Future research should address the financial implications of STATCOM deployment compared to traditional voltage regulation methods.

Lastly, the potential of machine learning and artificial intelligence in optimizing the operation of STATCOMs for flicker mitigation remains largely unexplored. Future research should focus on developing intelligent control systems that can adaptively respond to changing conditions in multi-machine systems to enhance power quality.

7. Conclusion

STATCOMs play a critical role in mitigating voltage flicker and enhancing voltage stability in modern power systems, particularly with the increasing integration of renewable energy sources. The research findings reviewed highlight the effectiveness of STATCOM technology, advanced control strategies, and hybrid approaches in improving power quality. However, significant knowledge gaps remain, particularly regarding performance under diverse conditions and long-term reliability. Addressing these gaps through future research will be essential for optimizing the use of STATCOMs in voltage flicker mitigation and ensuring the resilience of power systems in the face of evolving challenges.

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