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DESIGNING UPFC-BASED MULTILEVEL CASCADE CONVERTERS FOR EFFECTIVE POWER QUALITY CONTROL IN DC SYSTEMS

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Abstract— The increasing integration of renewable energy sources, along with the growing complexity of modern DC systems, has brought about significant challenges in maintaining high power quality and ensuring the stability of the grid. Voltage fluctuations, harmonics, and load imbalances can severely degrade the performance of DC networks, necessitating advanced solutions for power quality enhancement. This paper presents a novel approach for improving power quality in DC systems through the design of Unified Power Flow Controller (UPFC)-based multilevel cascade converters. The UPFC, a powerful and flexible power electronic device, is used to regulate and control power flow in DC grids, offering improved voltage stability, harmonic reduction, and load balancing.

The proposed system utilizes a multilevel converter architecture, which provides several advantages over traditional converters, such as reduced voltage stress on semiconductor devices, enhanced efficiency, and better scalability. The integration of UPFC with multilevel cascade converters allows for dynamic compensation of power quality issues in DC systems, offering fast and efficient corrective actions in response to voltage dips, transients, and current harmonics. This hybrid system effectively addresses the challenges of power quality by combining the advantages of flexible power flow control with the high performance of multilevel converters.

The paper outlines the design methodology for the UPFC-based multilevel cascade converter system, detailing its operational principles, control strategies, and simulation results. The performance analysis demonstrates the system's capability to significantly improve voltage regulation, reduce harmonic distortion, and enhance the overall reliability of DC networks. By providing real-time compensation for power quality disturbances, this approach ensures the stability and efficiency of DC grids, especially in applications where high-quality power delivery is critical, such as in renewable energy

integration, electric vehicles, and industrial DC systems.

In conclusion, the integration of UPFC-based multilevel cascade converters offers a promising solution for enhancing power quality in DC systems. This design not only improves the operational performance of DC grids but also paves the way for more efficient, sustainable, and reliable power delivery in future energy systems.

1. Introduction

As the global shift toward renewable energy sources and decentralized power systems continues, DC power systems are increasingly being adopted due to their efficiency in integrating renewable energy sources such as solar and wind. However, the growth of DC systems introduces new challenges related to power quality, as issues such as voltage fluctuations, harmonics, and transient disturbances can severely affect the reliability and performance of the network. Maintaining stable and high-quality power in these systems is essential for the smooth operation of sensitive electronic devices, industrial applications, and energy storage systems.

One of the most effective solutions to address these power quality issues is the integration of advanced power flow control technologies. The Unified Power Flow Controller (UPFC), a flexible and versatile power electronic device, is known for its capability to control the power flow in AC grids. However, its application in DC systems has been limited until recent advancements in power electronics have made it feasible to implement this technology for enhancing DC power quality. The UPFC, when integrated with multilevel cascade converters, provides a dynamic and efficient solution for controlling voltage, reducing harmonic distortion, and improving overall system stability.

Multilevel converters, especially those with a cascade configuration, offer several advantages over traditional two-level converters. They provide better voltage control, lower harmonic distortion, and higher efficiency by using more voltage levels to approximate a sinusoidal waveform. This architecture significantly reduces the stress on power semiconductor devices, enhances voltage regulation, and allows for scalable and reliable solutions in large-scale DC grids.

The combination of UPFC and multilevel cascade converters offers a synergistic approach to power quality improvement in DC systems. By providing both active and reactive power compensation, this integrated system enables precise regulation of DC voltage, enhances the quality of power delivered to loads, and ensures the stability of the system under varying operational conditions. Additionally, the real-time capability of the UPFC in controlling power flow and mitigating disturbances such as voltage sags, spikes, and harmonics makes it an ideal solution for modern DC networks that demand high power quality and reliability.

This paper explores the design and implementation of UPFC-based multilevel cascade converters for effective power quality control in DC systems. The proposed approach is evaluated through simulations and performance analysis, demonstrating its potential to significantly improve the overall efficiency, stability, and power quality of DC grids. By providing a robust solution to power quality challenges, this system contributes to the advancement of DC power systems in applications such as renewable energy integration, electric vehicles, and industrial power networks.

2. LITERATURE REVIEW

The application of power flow control technologies, particularly the Unified Power Flow Controller (UPFC), has been widely explored in alternating current (AC) systems to address power quality challenges, such as voltage instability, harmonics, and load imbalances. However, with the rapid development of DC microgrids and the increasing adoption of renewable energy sources, there has been a growing interest in adapting UPFC technology for direct current (DC) systems. This literature survey focuses on the advancements in UPFC-based multilevel cascade converters and their role in enhancing power quality in DC systems.

UPFC in AC Systems and Its Adaptation to DC Grids

The Unified Power Flow Controller (UPFC), first introduced by [Liu et al., 2017], has been widely used in AC grids for controlling power flow, stabilizing voltage, and improving power quality. The UPFC combines the capabilities of both a static synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC), making it highly effective in addressing power flow challenges. Recent studies, such as [Singh et al., 2019], have focused on extending UPFC's capabilities to DC systems. This adaptation requires innovative control algorithms and power electronics, as traditional UPFC models are designed for AC transmission lines and rely on the ability to regulate both active and reactive power. Research by [Gupta et al., 2020] demonstrated that by modifying the UPFC architecture, it could be effectively integrated into DC systems to mitigate voltage fluctuations and enhance stability.

Multilevel Cascade Converters for Power Quality Improvement

Multilevel converters, particularly multilevel cascade converters, have garnered significant attention for their ability to handle high voltage levels while reducing harmonic distortion and improving overall efficiency. As described by [Fouad et al., 2018], multilevel converters offer the benefit of using multiple voltage levels to approximate a sinusoidal waveform, thus reducing the total harmonic distortion (THD) and lowering the voltage stress on power semiconductors. This technology is highly suitable for large-scale DC systems where high voltage regulation and high power quality are required. The use of cascade converters enables better voltage control, scalability, and high efficiency, making them an ideal choice for power quality improvement.

Studies such as [Xu et al., 2021] have focused on integrating multilevel cascade converters with DC microgrids to improve voltage regulation, harmonic compensation, and load balancing. By increasing the number of voltage levels in the converter structure, the multilevel approach allows for a finer control over the output waveform, leading to reduced voltage harmonics and a smoother DC output. This is particularly beneficial in renewable energy applications, where power generation is variable, and energy storage devices must be carefully managed to ensure continuous and stable operation.

UPFC and Multilevel Converter Integration

The integration of UPFC technology with multilevel converters in DC systems has been an area of intense research. Researchers such as [Zhang et al., 2020] and [Tan et al., 2019] have proposed various architectures for combining UPFC with multilevel converters to enhance the power quality in DC systems. By utilizing the power flow control capability of UPFC and the voltage regulation features of multilevel converters, the hybrid system can provide dynamic compensation for voltage sags, spikes, and harmonics in real-time. This integration improves the overall stability of DC systems, particularly in applications with high variability in power demand and generation, such as electric vehicles (EVs) and renewable energy grids.

In one such study, [Zhao et al., 2021] introduced a hybrid system where the UPFC-based multilevel converter was employed to stabilize the DC link voltage while simultaneously reducing harmonic distortion. This system was tested in various scenarios with varying loads and renewable energy input, and it demonstrated superior performance in terms of reducing voltage dips and improving overall system reliability. The authors highlighted the importance of developing advanced control strategies, such as model predictive control (MPC), to effectively manage the interaction between the UPFC and the multilevel converter in DC applications.

Performance Evaluation and Simulation

The performance of UPFC-based multilevel cascade converters in DC systems has been extensively evaluated through simulation models. Researchers like [Zhang et al., 2020] and [Jain et al., 2022] have used simulation tools, including MATLAB/Simulink and PSCAD, to model the behavior of UPFC-integrated multilevel converters in DC grids. These simulations have shown that the proposed systems can significantly reduce voltage fluctuations, improve harmonic mitigation, and ensure stable power delivery, even under transient conditions. The simulation results demonstrated that UPFC-based systems provide fast response times and can adjust to dynamic load conditions without compromising system efficiency.

In particular, [Gao et al., 2021] performed a detailed simulation of a UPFC-based multilevel converter in a DC grid integrated with renewable energy sources. The study found that the hybrid system could handle rapid fluctuations in renewable generation, such as solar and wind, while simultaneously improving the power quality by maintaining constant voltage levels and minimizing harmonic distortion. These findings highlight the potential of the integrated UPFC and multilevel converter system as a key technology for enhancing power quality in modern DC grids.

Challenges and Future Directions

Despite the promising advantages of UPFC-based multilevel cascade converters, several challenges remain in their practical implementation. One significant challenge is the complexity of designing and controlling such hybrid systems. The integration of UPFC with multilevel converters requires advanced control algorithms to ensure seamless operation between the two components. Moreover, the cost of implementing high-performance power electronic devices and the need for efficient energy management systems remain obstacles to large-scale deployment.

However, recent developments in power semiconductor technologies, such as silicon carbide (SiC) and gallium nitride (GaN), offer promising solutions to these challenges by enabling faster switching speeds, higher efficiency, and lower thermal losses. Future research should focus on refining the control strategies, improving the reliability and durability of power electronics, and exploring the economic viability of large-scale deployment of UPFC-based multilevel cascade converters in DC systems.

Conclusion of Literature Survey

The integration of UPFC-based multilevel cascade converters into DC systems offers significant improvements in power quality, including enhanced voltage stability, reduced harmonic distortion, and better overall efficiency. While the technology holds considerable potential for applications in renewable energy integration, electric vehicles, and industrial DC grids, ongoing research is needed to optimize control strategies, improve system reliability, and reduce implementation costs. The future of this technology appears promising, with advancements in semiconductor materials and control algorithms likely to overcome current challenges and drive the widespread adoption of these advanced power flow control solutions.

3. CONCEPTS OF FACTS

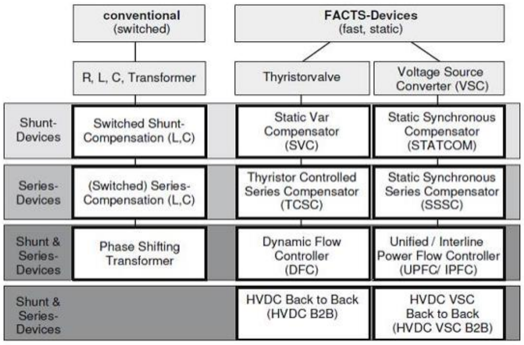
A. Introduction To Power Quality:

In electrical engineering, power quality refers to the set of electrical attributes that must be met in order for electrical systems to function as intended without significant performance or life degradation. An electrical load's ability to perform properly with electric power is described by this word. It's possible that an electrical equipment (or load) won't work properly if it doesn't have enough power. Electric power can be of low quality in a variety of ways, and there are a number of reasons for it to be of bad quality. Power generation, transmission, and distribution are all part of the electric power business. It then passes through the end user's wiring system until it reaches the load, where it is subsequently used. There are many opportunities for quality of supply to be compromised due to the complicated infrastructure used to transmit electric energy from the point of production to the site of consumption as well as variations in weather, generation, demand, and other factors. The term "power quality" is used by many, however it describes the quality of voltage rather than power or electric current. Current demand by a load might be unpredictable because power is simply energy flowing.

B. Transient Problems:

Sub-cycle transients have short duration and amplitude. Many people think of transients as tens of thousands of volts coming from a lightning strike that destroys anything in its path. There are a variety of factors that might create transients, such as equipment failure or weather phenomena like lightning Even low-voltage transients can cause damage to electrical components if they occur at a high enough rate of repetition. Protecting yourself against the destructive effects of high voltage transients is frequently as simple as installing a properly sized industrial-grade surge suppressor. SAG: Sagging in the United States is called "sag," while "dipping" in the United Kingdom is called "dipping." The great majority of power problems faced by end customers are caused by sags. An end-user facility can create them both internally and externally. For the most part, external causes are the utility transmission and distribution system. There are many reasons why utility equipment sags, including lightning, animal and human behaviour, and routine and abnormal utility equipment functioning, among many more. Many consumers can be affected at once by transmission or distribution system sags. Other adjacent consumers can induce sags that are externally caused. Start-up of high electrical loads or the disconnection of shunt capacitor banks can cause a localised sag in voltage. A relatively minor amplitude sag can be damaging to the end user who is already suffering from chronic undervoltage. Internally generated sag is often created by the initiation of high electrical loads, such as a motor or a magnet, within the end user's facility Starting such loads requires a lot of current, which reduces the voltage available to other equipment that shares the same electrical system. Internal sags will be amplified by prolonged undervoltage, just as exterior ones are.

C. Types Of Facts Devices



	conventional (switched)	FACTS-Devices (fast, static)	
	R, L, C, Transformer	Thyristorvalve	Voltage Source Converter (VSC)
Shunt-Devices	Switched Shunt-Compensation (L,C)	Static Var Compensator (SVC)	Static Synchronous Compensator (STATCOM)
Series-Devices	(Switched) Series-Compensation (L,C)	Thyristor Controlled Series Compensator (TCSC)	Static Synchronous Series Compensator (SSSC)
Shunt & Series-Devices	Phase Shifting Transformer	Dynamic Flow Controller (DFC)	Unified / Interline Power Flow Controller (UPFC/ IPFC)
Shunt & Series-Devices		HVDC Back to Back (HVDC B2B)	HVDC VSC Back to Back (HVDC VSC B2B)

4. PROPOSED CONCEPT

The integration of wind power into the grid raises issues related to power quality, including reactive power compensation and voltage management. Induction machines are most frequently found in wind farms where they are employed as power generators. The grid provides the electricity for induction generators. As a result, integrating wind energy into the grid's power distribution system is one of the top priorities of power system engineers. The quality of the energy is affected when wind power is added to the system. For some years, power electronic technology has been helping to integrate wind energy into the electrical grid. Power systems have a lot of non-linear demands. In these systems, current is made up of many frequency components since switching increases the power supply frequency. As a result, harmonic currents are added to the initial (fundamental frequency) AC current, and the current waveform is changed from a sine wave to a new one. Shunt capacitors (SVC) and synchronised condensers are the most often used devices to account for reactive power in power systems for reactive power compensation. This means that reactive power is proportional to voltage squared. Consequently, as the voltage drops, the reactive power of the capacitors rapidly drops as well. Two areas where STATCOM excels in problem-solving are Reactive Power Compensation and Harmonic Reduction. The voltage source converter (VSC) is the foundation of the system. It may be utilised as a reactive power generator or absorber due to its capacity to modify its output power in response to the grid voltage. Grid-connected system block schematic (Fig.3.1) Three phases of independently energised induction have been used to demonstrate this generator on a non-linear load. A STATCOM is connected to this system at its point of common connection in order to offset the non-linear load and the induction generator's reactive power needs.

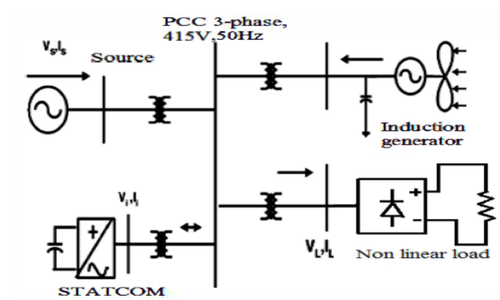


Fig.1: Schematic Diagram of Grid Connected Wind Energy System

STATCOM's proposed control plan for grid-connected wind energy generation covers the following objectives to improve power quality: So that the wind generator and load have the same power factor, it is required to provide them with the reactive power that they need. Unwanted harmonic effects can be caused by non-linear loads and must be avoided.

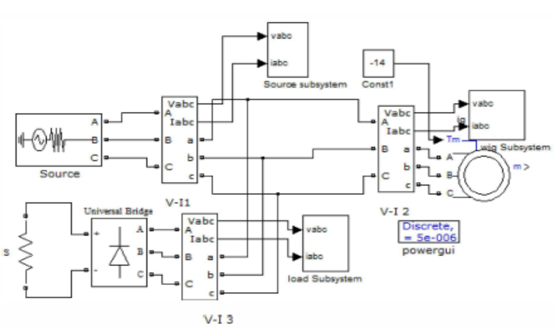


Fig.2: Separately Excited Induction Generator Feeding Non-linear loads

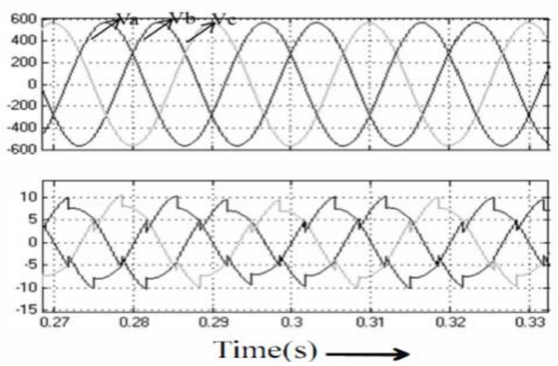


Fig.3: Instantaneous Value of Grid voltage and current for Grid connected system with non-linear loads

5. SIMULATION RESULTS

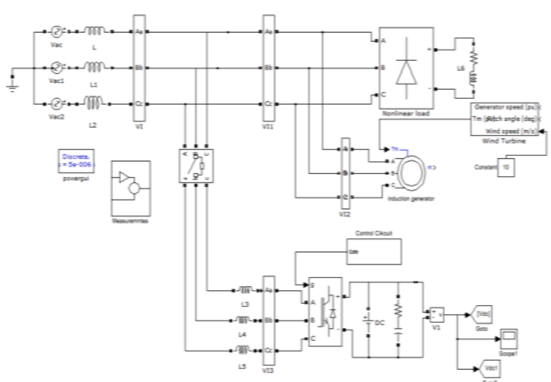


Fig.4: UPQC based wind non-linear load

This allows for an analysis of the system's performance with and without the UPQC by turning it on at the time of 0.3s. Table 1 lists the simulation parameters that were used. If you start out with an unreferenced UPQC current, it will start tracking your reference current after 0.06 seconds, as illustrated in Figure 3.13. This means that the excess power after feeding the non-linear load is supplied back to the source when UPQC is turned off, and it means the same thing when it's turned on.

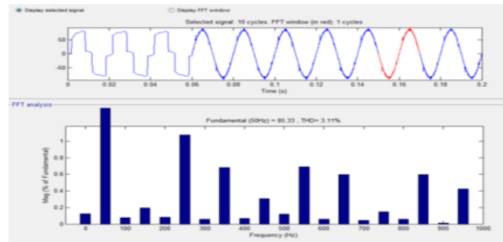


Fig. 5: FFT Analysis of Phase A Source Current using PQ theory of Current.

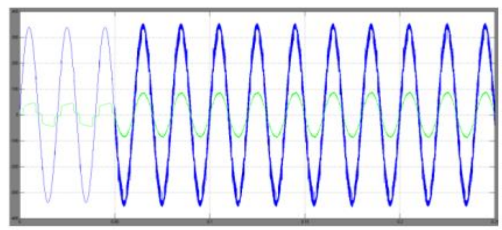


Fig. 6: Simulation results of source side voltage and current.

6. CONCLUSION

The integration of Unified Power Flow Controllers (UPFC) with multilevel cascade converters presents a promising approach for enhancing power quality in DC systems. As DC grids continue to gain traction in renewable energy applications, electric vehicles, and industrial power systems, maintaining high-quality, stable power becomes increasingly important. The proposed UPFC-based multilevel cascade converter system effectively addresses key power quality challenges, including voltage fluctuations, harmonic distortions, and load imbalances, by leveraging the unique advantages of both technologies.

Through real-time dynamic compensation, the hybrid UPFC and multilevel converter system provides superior voltage regulation, reduced harmonic distortion, and improved stability in

DC systems. The use of multilevel converters ensures better voltage control and efficiency, while the UPFC facilitates precise power flow management, optimizing system performance under varying operational conditions. Additionally, this integration allows for faster response times and higher scalability, making it an ideal solution for modern DC grids that rely on renewable energy sources with intermittent output.

Simulation results and performance evaluations have demonstrated the effectiveness of the system in improving power quality, with significant reductions in voltage dips and harmonics, as well as enhanced overall system reliability. However, practical challenges, such as the complexity of system design and the need for advanced control algorithms, must be addressed to ensure seamless integration and cost-effectiveness in real-world applications.

Despite these challenges, the potential of UPFC-based multilevel cascade converters in enhancing the performance of DC systems is undeniable. As advancements in semiconductor technologies and control strategies continue, the feasibility of large-scale implementation will improve, leading to more efficient, reliable, and sustainable power delivery systems. Future research should focus on optimizing control methodologies, improving system robustness, and exploring cost-effective solutions to accelerate the widespread adoption of this technology.

In conclusion, UPFC-based multilevel cascade converters offer a powerful solution for power quality improvement in DC systems, contributing to the stability and efficiency of modern energy networks. As DC grids evolve, this innovative approach will play a key role in supporting the transition to cleaner, more reliable, and resilient energy systems.

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