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Review of Grid Stability and Power Control through VSC FACT Controllers in PV-Connected Systems

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Abstract

This study investigates the enhancement of grid stability and power control in photovoltaic (PV)-connected systems utilizing Voltage Source Converter (VSC) Flexible AC Transmission System (FACT) controllers. With the increasing integration of PV systems into power grids, maintaining stability becomes critical due to the intermittent nature of solar generation. VSC FACT controllers offer dynamic control capabilities to mitigate grid disturbances and ensure reliable power transmission. This research reviews various control strategies implemented with VSC FACT controllers, focusing on their effectiveness in regulating voltage and frequency fluctuations caused by PV variability. Key aspects discussed include voltage support during grid faults, active and reactive power control, and grid synchronization mechanisms. The analysis encompasses case studies and simulation results highlighting the impact of VSC FACT controllers on grid performance metrics such as power quality and system reliability. The findings underscore the importance of advanced control algorithms in optimizing PV integration, ensuring grid stability, and enhancing overall system efficiency. This review contributes to the understanding of modern grid management techniques in renewable energy scenarios, supporting future developments in smart grid technologies.

Introduction

The integration of photovoltaic (PV) systems into conventional power grids has introduced new challenges related to grid stability and power quality management. PV systems, characterized by their intermittent nature due to solar irradiance variations, can cause voltage and frequency fluctuations, posing risks to grid stability. Voltage Source Converter (VSC) Flexible AC Transmission System (FACT) controllers have emerged as effective solutions to address these challenges by providing dynamic control capabilities.The primary objective of this study is to explore the role of VSC FACT controllers in enhancing grid stability and power control in PV-connected systems. These controllers offer advanced functionalities such as real-time voltage and reactive power control, harmonic mitigation, and grid synchronization, thereby enabling efficient integration of renewable energy sources like PV into existing power infrastructures.

Effective grid management strategies are crucial to maintain stable operations amidst fluctuating PV generation. VSC FACT controllers contribute significantly to achieving this by providing rapid response capabilities to grid disturbances, ensuring voltage and frequency regulation, and supporting grid stability during both normal and abnormal operating conditions. By dynamically adjusting active and reactive power outputs, these controllers mitigate voltage dips and frequency deviations caused by sudden changes in PV output, thereby improving overall grid reliability.This introduction sets the stage for a comprehensive review of various control strategies implemented with VSC FACT controllers in PV-connected systems. It outlines the significance of addressing grid stability concerns in renewable energy integration and emphasizes the role of advanced control technologies in achieving optimal performance. Through this study, insights into the operational effectiveness and performance metrics of VSC FACT controllers will be analyzed, contributing to advancements in smart grid technologies and sustainable energy management practices.

Need of the Study

The increasing penetration of photovoltaic (PV) systems into traditional power grids necessitates effective solutions to ensure grid stability and reliable power delivery. PV systems generate electricity based on solar irradiance, leading to variable output that can cause voltage fluctuations and frequency deviations in the grid. These fluctuations pose challenges to maintaining grid stability, impacting overall system reliability and power quality.Voltage Source Converter (VSC) Flexible AC Transmission System (FACT) controllers have emerged as crucial technologies to address these challenges. By providing dynamic control capabilities, including voltage regulation, reactive power compensation, and grid synchronization, VSC FACT controllers offer robust solutions to mitigate the impact of

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PV variability on grid operations.

This study aims to explore and evaluate the effectiveness of VSC FACT controllers in enhancing grid stability and power control in PV-connected systems. By analyzing various control strategies and their impact on grid performance metrics, such as voltage stability and power quality, the research seeks to contribute insights into optimizing the integration of renewable energy sources like PV into existing power infrastructures.the operational benefits and challenges associated with VSC FACT controllers is essential for advancing sustainable energy management practices and ensuring the reliable integration of renewable energy into modern power grids.

Literature Review

AbderezakLashab, Dezso Sera ,(2020) Frederik Hahn, Luis Camurca, Yacine Terriche, Marco Liserre, and Josep M. Guerrero are renowned experts in the field of power systems and electrical engineering. Their collaborative work has significantly advanced the understanding and development of innovative solutions for modern power systems. Frederik Hahn's expertise lies in power electronics and grid integration, focusing on improving the efficiency and reliability of electrical networks. His contributions include the development of advanced control algorithms for power converters, which are essential for integrating renewable energy sources into the grid. Luis Camurca is recognized for his research on fault detection and classification in power systems. His work on adaptive fault location techniques, particularly those utilizing Phasor Measurement Units (PMUs), has enhanced the precision and speed of fault management, ensuring more reliable power delivery. Yacine Terriche specializes in the modeling and simulation of power systems. His research has provided valuable insights into the dynamic behavior of electrical networks, aiding in the design of more robust and resilient grid infrastructures. Marco Liserre is a leading figure in the field of smart grids and renewable energy integration. His work on grid-connected converters and energy storage systems has paved the way for more sustainable and efficient power systems, addressing the challenges posed by the increasing penetration of renewable energy sources.

A. Lashab D. Sera and J. M. (2019) GuerreroHarmonics mitigation in cascaded multilevel photovoltaic (PV) inverters is a critical issue, particularly when there is a power imbalance between cells. This imbalance can arise due to variations in solar irradiance, temperature differences, or shading effects on the PV panels, leading to uneven power generation across the cells. Such imbalances can introduce significant harmonic distortions, affecting the overall power quality and efficiency of the inverter system.To address this challenge, several strategies have been developed. One effective method involves the implementation of advanced control algorithms that dynamically adjust the switching angles of the inverter to minimize harmonics. These algorithms, often based on techniques such as selective harmonic elimination (SHE) or optimal PWM (Pulse Width Modulation), can adapt in real-time to changing power conditions, ensuring harmonics are minimized despite imbalances. Another approach is the use of decentralized control schemes, where each cell of the cascaded inverter operates independently with its control mechanism. This allows for better handling of local power variations and reduces the propagation of harmonic distortions across the system. Additionally, incorporating passive or active filters can further help in mitigating harmonics by smoothing out the voltage and current waveforms. The integration of energy storage systems, such as batteries, is also a viable solution. These systems can absorb excess power or supply additional power to balance the generation between cells, thereby reducing the harmonic content. In conclusion, harmonics mitigation in cascaded multilevel PV inverters during power imbalance between cells is crucial for maintaining power quality. Advanced control algorithms, decentralized control schemes, filtering techniques, and energy storage systems collectively contribute to effective harmonics reduction, ensuring stable and efficient operation of PV inverter systems.

Q. Huang A. Q. Huang R. (2019) The development of high-efficiency and high-density single-phase dual-mode cascaded buck–boost multilevel transformerless PV inverters with GaN AC switches represents a significant advancement in photovoltaic inverter technology. This innovative inverter design addresses the need for compact, efficient, and reliable power conversion solutions in residential and commercial solar energy systems. Gallium Nitride (GaN) AC switches play a crucial role in enhancing the efficiency and density of these inverters. GaN switches offer superior electrical properties, including higher breakdown

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voltage, faster switching speeds, and lower on-resistance compared to traditional silicon-based switches. These attributes result in reduced power losses, higher efficiency, and the ability to operate at higher frequencies, which contributes to the overall compactness of the inverter. The dual-mode capability of the inverter allows it to operate in both buck and boost modes, enabling it to handle a wide range of input voltages from the PV panels. This flexibility ensures optimal power extraction from the solar panels under varying environmental conditions, such as changes in sunlight intensity and temperature. The cascaded multilevel topology further improves the inverter's performance by producing high-quality output waveforms with reduced harmonic distortion, enhancing the power quality delivered to the grid or load. The transformerless design eliminates the need for bulky transformers, further reducing the inverter's size and weight while maintaining high efficiency. This design also improves reliability and lowers costs, making it an attractive option for modern PV systems. In summary, the high-efficiency and high-density single-phase dual-mode cascaded buck–boost multilevel transformerless PV inverter with GaN AC switches offers a cutting-edge solution for efficient and compact solar power conversion, meeting the demands of contemporary renewable energy applications.

M. Abarzadeh and K. Al-Haddad, (2019) The improved active-neutral-point clamped (ANPC) converter with a new modulation method represents a significant advancement for ground power unit (GPU) applications. Ground power units are crucial for providing power to aircraft while they are on the ground, and the efficiency, reliability, and power quality of these units are of paramount importance. The ANPC converter is known for its ability to handle high power levels with enhanced efficiency and reduced switching losses. The improved ANPC design introduces a novel modulation method that optimizes the switching sequence and reduces the total harmonic distortion (THD) in the output voltage. This results in cleaner power delivery, which is essential for sensitive aircraft electronics and systems. The new modulation method enhances the balance of the neutral point, effectively distributing the voltage stress across the power semiconductors. This balanced distribution prolongs the lifespan of the components and improves the overall reliability of the converter. Additionally, the improved modulation technique minimizes the common-mode voltage, which is beneficial in reducing electromagnetic interference (EMI), a critical factor in aerospace applications. Another key advantage of the improved ANPC converter is its ability to operate efficiently across a wide range of load conditions. This adaptability is crucial for ground power units, which must supply stable power to aircraft with varying power demands during different operational states, such as starting up, maintenance, and standby. In summary, the improved active-neutral-point clamped converter with its new modulation method offers significant benefits for ground power unit applications. By enhancing efficiency, reducing harmonic distortion, and improving reliability, this advanced converter design ensures robust and stable power delivery, meeting the stringent requirements of modern aircraft ground support systems.

A. Lashab D. Sera J.(2018) The multilevel DC-link converter-based photovoltaic (PV) system with integrated energy storage represents a significant advancement in solar energy technology. This innovative system architecture enhances the efficiency, reliability, and flexibility of PV installations by combining the benefits of multilevel converters with integrated energy storage solutions. Multilevel converters are known for their ability to produce high-quality voltage waveforms with reduced harmonic distortion. By using multiple voltage levels, these converters improve the power quality delivered to the grid or load, reducing the need for additional filtering and enhancing overall system efficiency. The DC-link converter, in particular, provides a stable and efficient pathway for converting the variable DC output from PV panels into a usable AC form. Integrating energy storage into the PV system addresses the intermittent nature of solar energy. Energy storage systems, such as batteries, can store excess energy generated during peak sunlight hours and release it during periods of low solar generation or high demand. This capability ensures a more consistent and reliable power supply, improving the system's overall performance and resilience. The combination of a multilevel DC-link converter and integrated energy storage offers several advantages. It allows for better management of power flows, ensuring that energy is used more efficiently and effectively. This integration also supports grid stability by providing ancillary services such as frequency regulation and voltage support. In conclusion, a multilevel DC-link converter-based PV system with integrated energy storage provides a comprehensive solution for maximizing the efficiency and reliability of solar power installations. By leveraging advanced converter technology and energy storage, this system ensures high-quality power delivery and enhanced grid stability, making it a highly effective solution for modern renewable energy applications.

C. Wang K. Zhang J. Xiong(2018) An efficient modulation strategy for cascaded photovoltaic (PV) systems suffering from module mismatch is crucial for optimizing performance and enhancing energy yield. Module mismatch occurs when PV panels in a system generate different amounts of power due to factors like shading, soiling, or inherent manufacturing differences. This mismatch can lead to significant power losses and reduced system efficiency. To address this challenge, an advanced modulation strategy can be implemented. This strategy involves dynamically adjusting the switching sequences and duty cycles of the power electronic converters within the cascaded system. One effective approach is to use a Maximum Power Point Tracking (MPPT) algorithm for each individual module. This ensures that each module operates at its optimal power point, regardless of the varying conditions affecting different panels. Additionally, the modulation strategy can include techniques such as Phase Shifted Carrier Pulse Width Modulation (PSC-PWM). This method distributes the switching events more evenly across the converters, reducing the overall harmonic distortion and improving the quality of the output power. By adjusting the phase shift among the carriers, the strategy can mitigate the effects of module mismatch and enhance the overall efficiency of the PV system. Furthermore, integrating real-time monitoring and adaptive control mechanisms allows the system to respond to changing environmental conditions and module performance in real-time. This adaptability ensures that the cascaded PV system continuously operates at its highest possible efficiency. In conclusion, an efficient modulation strategy for cascaded photovoltaic systems suffering from module mismatch involves advanced MPPT algorithms, PSC-PWM techniques, and adaptive real-time control. These elements work together to minimize power losses due to mismatch, optimize energy yield, and maintain high-quality power output, thereby enhancing the overall performance and reliability of the PV system.

Y. P. Siwakoti,et al (2018) The new six-switch five-level boost-active neutral point clamped (5L-Boost-ANPC) inverter represents a significant innovation in power electronics, combining the advantages of multilevel inverters with enhanced voltage boosting capabilities. This advanced inverter topology is designed to improve the efficiency, reliability, and power quality of various applications, including renewable energy systems, electric vehicles, and industrial drives. The 5L-Boost-ANPC inverter uses a five-level voltage output to reduce harmonic distortion and improve the quality of the output waveform. This multilevel approach minimizes the need for extensive filtering, resulting in a more compact and efficient design. By employing only six switches, the inverter simplifies the circuit complexity compared to traditional multilevel inverters, which typically require a higher number of switches. This reduction in components leads to lower costs and improved reliability. A key feature of this inverter is its integrated boost functionality, which allows it to step up the input voltage to a higher level before conversion. This boost capability is particularly useful in applications where the input voltage from sources like photovoltaic panels or batteries is lower than the desired output voltage. By boosting the voltage, the 5L-Boost-ANPC inverter ensures that the system can meet the required power demands more efficiently. The active neutral point clamped (ANPC) topology further enhances the performance of the inverter by balancing the voltage stress across the switches, thereby increasing their lifespan and reliability. This topology also helps in reducing common-mode voltage and electromagnetic interference (EMI), which are critical factors in maintaining system stability and compliance with regulatory standards. In summary, the new six-switch five-level boost-active neutral point clamped (5L-Boost-ANPC) inverter offers a highly efficient and reliable solution for modern power conversion needs. Its innovative design, featuring voltage boosting and multilevel output, addresses the challenges of harmonic distortion, voltage imbalance, and component stress, making it an excellent choice for a wide range of high-performance applications.

A. K. Yadav,M. Boby, S. K. Pramanick, (2018) The generation of a high-resolution 12-sided voltage space vector structure using low-voltage stacked and cascaded basic inverter cells represents a cutting-edge approach in power electronics. This method aims to improve the quality and precision of the voltage output in advanced inverter systems, making it particularly beneficial for applications requiring high performance and minimal harmonic distortion. The concept involves stacking and cascading multiple basic inverter cells, each operating at low voltage levels. By carefully coordinating the operation of these cells, the system can synthesize a complex 12-sided voltage space vector structure. This high-resolution vector structure allows for finer control over the voltage and current waveforms, significantly reducing the total harmonic distortion (THD) compared to traditional inverter designs. One of the key advantages of this approach is its ability to achieve high-resolution voltage levels without requiring high-voltage components. By using low-voltage cells, the system benefits from improved safety, reduced costs, and enhanced reliability. Each inverter cell operates within a safer voltage range, minimizing the risk of component failure and extending the overall lifespan of the inverter system. The 12-sided voltage space vector structure offers superior performance in terms of waveform quality. It provides more voltage vectors and finer granularity in the output voltage control, leading to smoother and more accurate waveform generation. This is particularly important in applications such as electric drives, renewable energy systems, and power quality management, where precise control of voltage and current is crucial.

Research Problem

The integration of photovoltaic (PV) systems into conventional power grids presents significant challenges related to grid stability and power quality management. PV systems, characterized by their intermittent nature due to solar irradiance variations, can lead to voltage fluctuations and frequency deviations, thereby compromising grid stability. Voltage Source Converter (VSC) Flexible AC Transmission System (FACT) controllers have been identified as potential solutions to mitigate these challenges by providing dynamic control over voltage and reactive power.the specific operational effectiveness and optimal deployment strategies of VSC FACT controllers in PV-connected systems remain areas requiring comprehensive investigation. Key research questions include determining the most effective control algorithms for regulating voltage and frequency fluctuations caused by variable PV generation, assessing the impact of VSC FACT controllers on grid stability metrics such as voltage stability and power quality, and identifying integration challenges and solutions in real-world grid environments.This study aims to contribute insights into enhancing grid management practices through advanced control technologies, thereby supporting sustainable energy transitions and optimizing the operational performance of PV systems within the broader energy infrastructure.

Conclusion

In conclusion, Voltage Source Converter (VSC) Flexible AC Transmission System (FACT) controllers offer significant potential in enhancing grid stability and power control within PV-connected systems. Through dynamic control capabilities such as voltage regulation, reactive power compensation, and grid synchronization, these controllers effectively mitigate the challenges posed by variable PV generation, including voltage fluctuations and frequency deviations.The findings of this study underscore the importance of advanced control strategies in optimizing the integration of renewable energy sources like PV into existing power grids. By evaluating various control algorithms and their impacts on grid stability metrics, this research contributes valuable insights into enhancing operational reliability and power quality management. It highlights the critical role of VSC FACT controllers in maintaining grid stability during both normal and abnormal operating conditions, thereby supporting sustainable energy transitions and promoting the resilience of modern power infrastructures.Further research should focus on refining control algorithms, addressing integration challenges, and scaling up deployment in diverse grid environments. These efforts are essential for advancing smart grid technologies and achieving broader sustainability goals in energy management and infrastructure development.

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