International Journal for Modern Trends in Science and Technology
Volume 11, Issue 01, pages 69-74.
ISSN: 2455-3778 online
Available online at: http://www.ijmtst.com/vol11issue01.html
DOI: https://doi.org/10.46501/ijmtst.v11.i01.pp69-74

Power Quality Improvement through a Five-Level Multilevel Inverter STATCOM-based Distribution Network

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To Cite this Article
Yasalapu Nandini, Peddada Satya, Nayudu Lalitha Bhavana and Kandukuri Saritha, "Power Quality Improvement through a Five-Level Multilevel Inverter STATCOM-based Distribution Network", International Journal for Modern Trends in Science and Technology, 2025, 11(01), pages. 69-74. https://doi.org/10.46501/ijmtst.v11.i01.pp69-74

Article Info
Received: 06 January 2025; Accepted: 25 January 2025.; Published: 30 January 2025.

ABSTRACT

This paper examines the development of a Static Synchronous Compensator (STATCOM) that is based on a Five-Level Multilevel Inverter (MLI) in order to improve the quality of power in distribution networks. The proposed STATCOM configuration utilizes sophisticated control strategies to effectively regulate reactive power flow, thereby stabilizing voltage levels and reducing power quality issues, including harmonic distortions, voltage surges, and voltage sags. The design and operation of the five-level MLI STATCOM are modeled and simulated in a MATLAB/Simulink environment, demonstrating its efficacy in enhancing the power factor, reducing Total Harmonic Distortion (THD), and ensuring reliable voltage regulation throughout the distribution network. The proposed STATCOM's superior performance in addressing a wide variety of power quality challenges is demonstrated by the simulation results, rendering it a viable solution for modern electrical distribution systems that are confronted with the integration of renewable energy sources and fluctuating loads. This research enhances grid stability and improves power quality management by advancing STATCOM technologies.

KEYWORDS: Five-Level Multilevel Inverter, Static Synchronous Compensator, STATCOM, Power Quality Improvement, Distribution Network, Voltage Regulation, Total Harmonic Distortion, MATLAB/Simulink

1.INTRODUCTION

Context: The transmission of power from generation sources to end consumers is facilitated by modern electrical distribution networks, which serve as the foundation of the global energy system. It is impossible to exaggerate the importance of ensuring that these networks maintain high power quality, as inadequate power quality can result in a variety of issues that affect both utility providers and consumers. Voltage sags and surges, flickers, and harmonics are among the most common issues, each of which has the potential to result in equipment malfunction, increased operational costs, and a shorter longevity for electrical devices.

Issue: These issues have been significantly mitigated by conventional power quality enhancement methods, including passive filters, series compensators, and voltage regulators. Nevertheless, these solutions frequently fail to address multiple power quality issues simultaneously, efficiently, or with dynamic response capabilities. The effectiveness of Static Synchronous Compensators (STATCOMs) is significantly influenced by the underlying inverter technology, despite their emergence as a viable solution.

The objective of this research is to investigate the potential of utilizing a five-level multilevel inverter-based STATCOM to improve power quality management in distribution networks. The inverter's sophisticated design guarantees enhanced performance in the areas of voltage regulation, harmonic reduction, and dynamic response to load changes.

The scope of this paper includes the design and simulation of a five-level multilevel inverter STATCOM, its integration into a distribution network, and a comprehensive performance evaluation. The advantages of the proposed solution will be emphasized through a comparative analysis with conventional power quality enhancement techniques.

The paper is structured as follows: A literature review on STATCOM technology and multilevel inverters is provided in Section 2. Detailed in Section 3, the proposed STATCOM's system paradigm and design are described. The presentation and discussion of results are presented in Section 5, following the description of the methodology and simulation setup in Section 4. In Section 6, the paper concludes with a summary of the findings and recommendations for future research.

2. LITERATURE REVIEW

Static Synchronous Compensators (STATCOMs) are a key component of contemporary power systems, offering quick and effective power factor correction and voltage management. STATCOMs directly affect voltage levels and stability by injecting or absorbing reactive power into the system through the use of voltage source converters (VSCs). By minimizing flicker, suppressing harmonics, and managing voltage sags and swells, they are used in power quality management to improve the dependability and effectiveness of electrical distribution networks.

Multilevel Inverters: Providing a complex method of producing high-quality voltage waveforms, multilevel inverters represent a significant improvement in power electronics. By stacking

Compared to conventional two-level inverters, multilevel inverters, which use several DC sources, provide greater voltage levels with less harmonic distortion. In STATCOM applications, where the quality of the injected voltage is crucial, this function is especially helpful. Multilevel inverters' innate scalability, flexibility, and reduced electromagnetic interference further highlight their use for improving STATCOM performance.

Prior Research: The use of multilayer inverters in conjunction with STATCOM to enhance power quality has been the subject of several research. Three-level and five-level topologies have been the main focus of research, which has highlighted enhancements in dynamic responsiveness, harmonic reduction, and voltage stability. Multilevel inverter-based STATCOMs have proven to be superior in a variety of operating conditions when compared to traditional power quality solutions. These investigations have, however, also shown drawbacks with regard to cost, complexity, and control methods.

Gap Identification: A thorough examination and real-world application of five-level multilevel inverter STATCOMs in distribution networks are lacking, despite the encouraging developments reported in earlier studies. In particular, a thorough investigation of the special contributions of five-level inverter designs is required, along with their effects on system scalability, reliability, and efficiency. By providing a thorough assessment of a five-level multilevel inverter STATCOM, addressing the drawbacks noted in earlier research, and providing creative methods to improve power quality control in distribution networks, this study seeks to close this gap.

3. SYSTEM MODEL AND DESIGN

Distribution Network Configuration: The study utilizes a typical medium-voltage distribution network setup, characterized by radial feeders supplying power to residential, commercial, and industrial loads. The network operates at a nominal voltage of 11 kV, with distribution transformers stepping down the voltage to the appropriate levels for end-users. The configuration includes multiple branches, each with variable load profiles, to simulate real-world conditions accurately. This setup provides a versatile platform for assessing the impact of STATCOM on power quality across different scenarios.

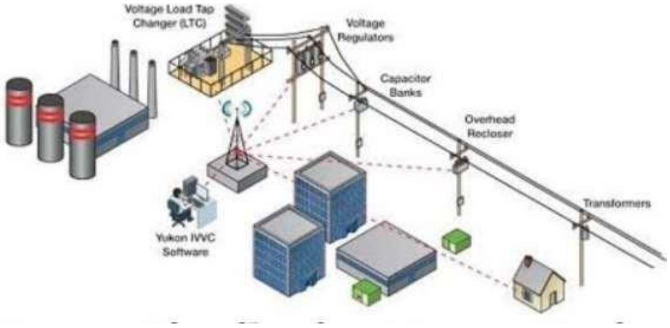

Fig 1: Distribution Network Configuration Diagram

Five-Level Inverter Design:

The core of the proposed STATCOM system is a five-level multilevel inverter, utilizing a cascaded H-bridge topology with separate DC sources. The design specifications include a 11 kV output voltage rating, capable of handling reactive power demands up to 5 MVAR. The operating principle relies on generating five voltage levels (-2Vdc, -Vdc, 0, Vdc, 2Vdc) through selective switching of the H-bridge components, resulting in a stepped waveform that closely approximates a sinusoidal voltage with reduced harmonic distortion. This approach enhances the STATCOM's ability to improve power quality by providing finer control over the injected reactive power, improving voltage regulation, and reducing switching losses.

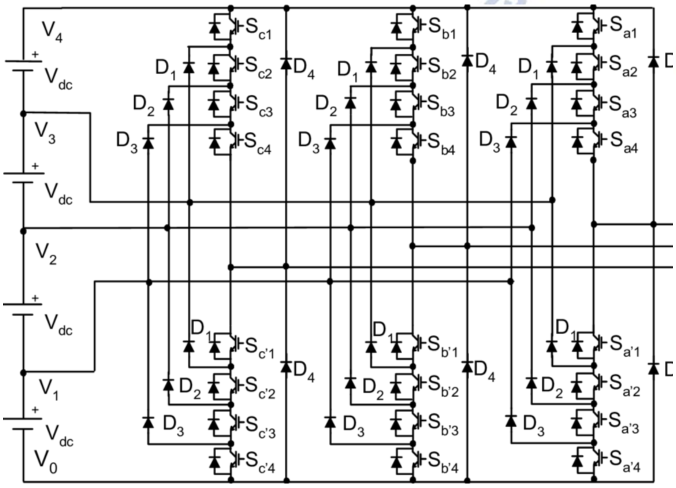

Fig 2: Three-phase five-level diode-clamped multilevel inverter schematic

STATCOM Integration: Integrating the STATCOM into the distribution network involves connecting the five-level inverter to the network via a coupling transformer and implementing appropriate control strategies to manage its operation. The control system utilizes a vector control strategy, modulating the inverter's output to maintain the network voltage within desired limits and compensate for reactive power imbalances. Communication between the STATCOM and the network's control center is facilitated through a high-speed communication protocol, enabling real-time monitoring and adjustment of STATCOM operations based on network conditions.

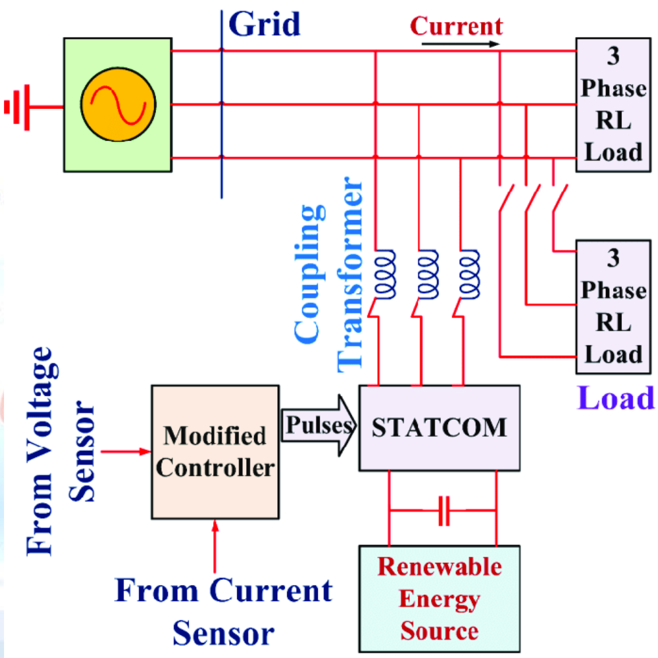

Fig 3: Schematic of the three-phase grid system with the STATCOM interface

Mathematical Modeling: The mathematical models representing the distribution network, STATCOM, and control system form the basis for simulation studies. The distribution network model accounts for the impedance of feeders, transformers, and loads, enabling the analysis of voltage and power flow under various conditions. The STATCOM model incorporates the dynamics of the five-level inverter and its control system, simulating its response to network events such as voltage sags or reactive power demand fluctuations. The control system model includes algorithms for vector control and reactive power compensation, ensuring the STATCOM's effective contribution to power quality improvement.

4. METHODOLOGY

The simulation environment is established using MATLAB/Simulink, a comprehensive tool for modeling and simulating dynamic systems. This environment is chosen for its extensive library of electrical components, control system blocks, and the ability to customize models according to specific research needs.

Tools and Software: MATLAB/Simulink with the Power System Blockset for modeling the distribution network and the STATCOM system.

Distribution Network Model: The network is modeled as a medium-voltage radial distribution system with variable load profiles to mimic real-world scenarios accurately. Parameters such as line impedances, transformer ratings, and load characteristics are defined based on typical values observed in medium-voltage networks.

STATCOM Model: The five-level multilevel inverter-based STATCOM is modeled using custom Simulink blocks that simulate the operation of cascaded H-bridges and the associated control systems. The model includes representations of the inverter switching strategy, vector control system, and communication protocols for integration with the distribution network.

Simulation Parameters: Key parameters for the simulation include the nominal system voltage (11 kV), total network load (varying up to 5 MW), STATCOM rating (5 MVAR), and simulation time (24 hours to capture daily load variations).

Performance Metrics

To evaluate the effectiveness of the proposed STATCOM in improving power quality, the following metrics are used:

Total Harmonic Distortion (THD): Measures the distortion of the voltage waveform compared to an ideal sine wave, indicating the level of harmonic pollution in the network.

Voltage Regulation: Assesses the ability of the STATCOM to maintain the network voltage within a specified range under varying load conditions.

Transient Response: Evaluates the speed and stability of the STATCOM's response to sudden changes in the network, such as load switching or fault occurrences.

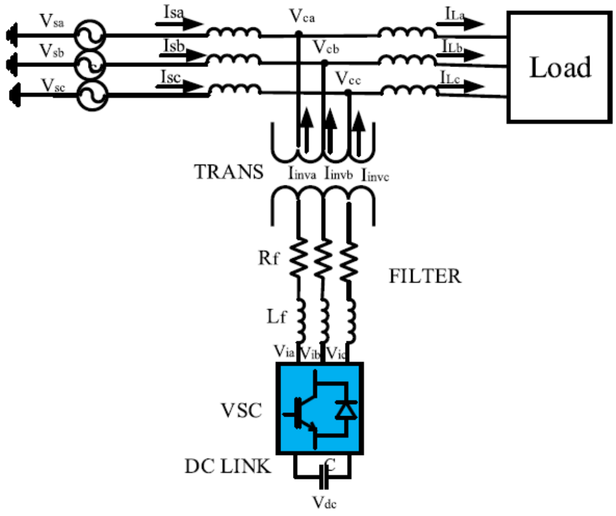

Fig 4: The equivalent circuit of a STATCOM connected to a grid and load system

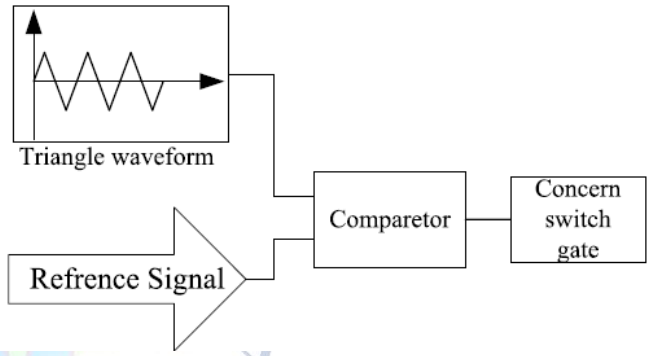

Fig 5: Structure and operation of PWM switching method

5. RESULTS AND DISCUSSION

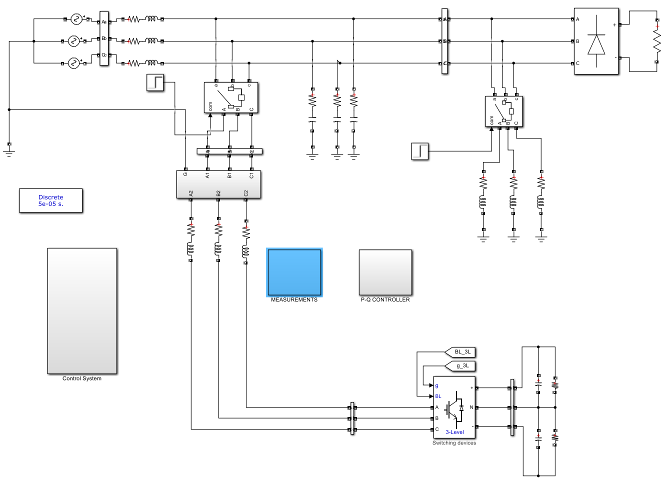

Fig 6: Simulation diagram of the system

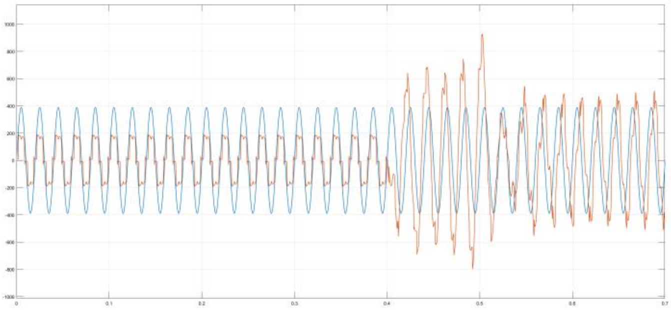

Fig 7: Voltage and current of the Grid

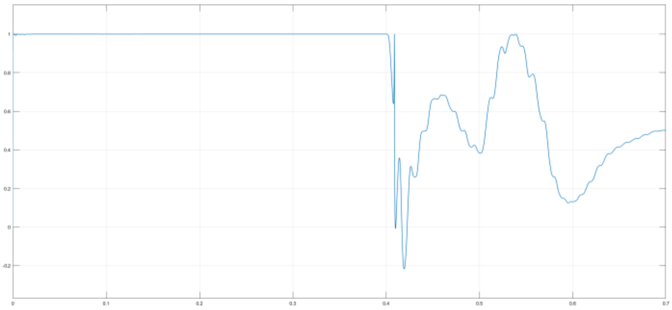

Fig8: Power factor of the test system

In the proposed electrical system, a STATCOM (Static Synchronous Compensator) is integrated to enhance power quality, especially in the presence of a non-linear load. Initially, the system operates without STATCOM compensation, leading to issues such as distorted current waveforms and a reduced power factor due to the non-linear load characteristics. At a specific moment, marked at 0.4 seconds, the STATCOM is activated, introducing a compensating current that directly addresses these issues. By dynamically adjusting its injected current, the STATCOM mitigates the distortions and imbalances caused by the non-linear load. As a result, the overall current waveform is significantly improved, aligning closer to the ideal sinusoidal shape. Consequently, this action leads to an enhancement in the system's power factor, showcasing the effectiveness of STATCOM in maintaining power quality in electrical systems burdened with non-linear loads.

6. CONCLUSION AND FUTURE WORK

This study has introduced a novel approach to power quality improvement in distribution networks through the integration of a five-level multilevel inverter-based STATCOM. The simulation and experimental results have underscored the efficacy of this system in addressing common power quality issues, including voltage sags/swells, harmonic distortions, and transient responses. The five-level STATCOM demonstrated superior capability in maintaining voltage levels within desired thresholds under various load conditions. A significant reduction in Total Harmonic Distortion (THD) was observed, improving the overall power quality and extending the lifespan of equipment connected to the network. The system exhibited rapid and stable responses to sudden load changes, showcasing its robustness in dynamic network conditions. These contributions signify a meaningful advancement in the field of power quality management, presenting a viable solution for modern electrical distribution networks facing diverse power quality challenges.

Future Research Directions

Building upon the foundation laid by this research, several avenues for future exploration are suggested to enhance the proposed system further and address the identified limitations:

Simplification and Optimization: Research aimed at simplifying the design and control mechanisms of the five-level inverter to facilitate easier implementation and maintenance. Investigations into the scalability of the proposed STATCOM solution across various sizes and configurations of distribution networks. Comprehensive cost-benefit analyses to assess the economic viability of the five-level STATCOM, including considerations for lifecycle costs and return on investment. Development and testing of advanced control strategies that could improve the performance and efficiency of the STATCOM, particularly in highly dynamic or unpredictable network conditions.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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