Design of Active Fault-Tolerant Control System for Multilevel Inverters to Achieve Greater Reliability with Improved Power Quality

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***Abstract:** Modern renewable energy systems often use special converters to improve power quality and synchronize with the power grid. These converters create smooth electrical output similar to a sine wave. However, if any parts of these converters fail, the whole system can fail. This paper suggests a new type of converter called a Fault-Tolerant Cascaded H-Bridge Multilevel Inverter (FT-CHB-MLI) that is more reliable and improves power quality. It also includes a special unit to detect and fix any faulty parts before they cause problems. By using advanced techniques like Phase Disposition Pulse Width Modulation (PD-PWM), this system can quickly detect faults and maintain stability. Simulation tests using MATLAB/Simulink show that this system reduces electrical distortion and increases reliability by 18%. It also outperforms similar systems found in previous studies.*

***Keywords:** inverter fault diagnosis techniques, inverter fault diagnosis techniques, cascaded H-Bridge MLI, Fault-tolerant control.*

I. INTRODUCTION

The paper's objective is to create an active fault-tolerant control system for multilevel inverters in order to increase power quality and dependability. This involves developing a system that can detect and mitigate faults in the multilevel inverter, ensuring that it continues to operate reliably and produce high-quality electrical output even in the presence of faults. The focus is on enhancing the reliability of the multilevel inverter system while also improving the overall power quality of the electrical output.

The main objectives of the thesis concentrate on developing following:

1) A simulation model for DC Source for MLI with FDI.

2) A simulation model for current control strategy.

3) Control systems to improve the power quality of the inverter control system.

4) In the simulation, the configuration for Cascaded structure of the MLI. To implement infrastructure in a micro-grid is shown.

A. MULTILEVEL INVERTERS:

The paper discusses the growing popularity of Multilevel Inverters (MLIs) in Photovoltaic (PV) systems due to their ability to produce high-quality waveforms and handle high nominal power. Originally used in industrial and power train applications, MLIs are now widely employed in utility-scale renewable energy plants. MLIs are categorized into Cascaded H-Bridge (CHB), Continuous Feedback (CFB), and Neutral Point Clamped (NPC), converters, with the CHB converter being commonly used due to its flexibility and scalability. While NPC converters require dual DC-link voltages, H-bridge converters offer advantages such as better power factor, fewer harmonics, and stable voltage MLIs find applications in various fields including magnetic levitation systems, electric traction, industrial processes, and smart houses, contributing to improved power quality and efficiency.

B. STRUCTURE OF A CASCADED H-BRIDGE MLI

The modular structure of Cascaded H-Bridge Multilevel Inverters (CHB MLI) makes them highly versatile and adaptable to different power requirements. By adjusting the configuration of power cells, the power level of these inverters can be easily increased or decreased. CHB MLIs consist of H-Bridge power cells connected in series, allowing for an increase in both power and voltage levels. Each power cell in the MLI employs four switching devices, each with a reverse-connected diode.

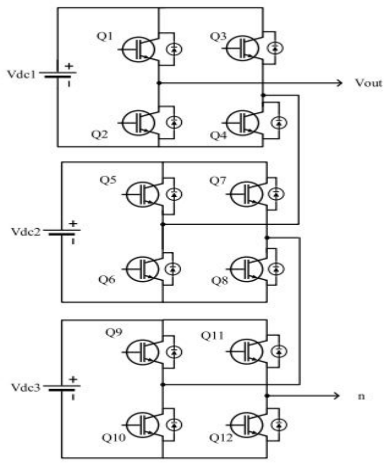


Fig 1. Schematic diagram of 7 levels cascaded H-Bridge multi-level inverter

C. FAULT-TOLERANT CONTROL

Fault-Tolerant Control (FTC) techniques are crucial for enhancing the dependability of machines by preventing failures caused by faults, which are deviations from planned outputs. FTC is especially vital for critical systems like unmanned planes, aerial vehicles, and nuclear power plants, where failure is unacceptable. In solar systems, the inverter's reliability is essential for consistent operation. Although multi-level converters offer advantages such as reduced harmonic content and lower switching losses, they also increase the risk of failures due to the higher number of switching devices. Redundancy is a key strategy in constructing FTC systems, with analytical redundancy being divided into active and passive types. Active redundancy involves fault detection, isolation, and controller reconfiguration, while passive redundancy relies on robust controller designs to handle specific uncertainties and faults. While AFTCS offers comprehensive defect support and online fault detection, it is computationally intensive and slower in operation.

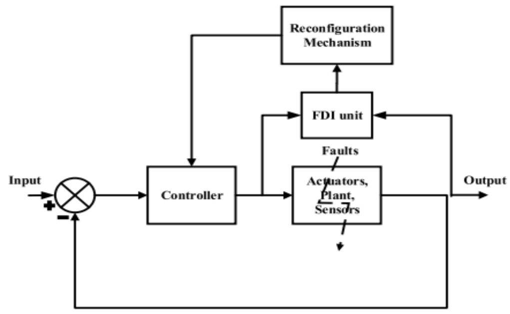


FIGURE 2. AFTCS Architecture [10].

II. LITERATURE SURVEY

This paper shows the continued need for robust and efficient battery inverters in versatile stand-alone photovoltaic (PV) systems. It discusses how multilevel converter topologies can enhance the characteristics of these inverters. A compilation of common multilevel converter topologies is provided, indicating which ones are most suitable for implementing inverters in stand-alone applications ranging from a few kilowatts. [1]

This paper explores a simplified approach to multilevel inverter design using a series connection of low-power modules. Unlike traditional cascade connections, this method reduces complexity and costs by minimizing isolated DC sources and simplifying transformer cabling. A five-level operation is accomplished with only one isolated DC source per phase by using two three-level half-bridge diode clamp converter modules per phase.This series-connected setup distributes the DC-bus voltage evenly across four capacitors, ensuring uniform voltage steps and balanced stress on semiconductor devices. Validation through simulations and a laboratory prototype confirms the feasibility and effectiveness of this approach under various operating conditions. [2]

This paper discusses the analysis and design of a five-level cascaded asymmetric multilevel converter, which offers five voltage levels using fewer components compared to symmetric topologies. This topology provides more voltage levels with fewer switching states and operates with a single DC bus, similar to a hybrid converter but without the typical drawbacks of symmetric topologies. The cascaded asymmetric converter presented is an appealing alternative among five-level converters, offering advantages such as no voltage balancing issues. [3]

This paper addresses a drawback of two-stage switched-capacitor multilevel inverters where switches in the second stage face higher voltage stress. A single-stage switched-capacitor module (S3CM) topology for cascaded multilevel inverters is suggested as a solution to this problem. With this configuration, every switch in the DC source voltage experiences peak inverse voltage. Compared to cascade H-bridge arrangements, it may generate nine voltage levels with just one DC source and two capacitors, greatly decreasing the need for isolated DC sources. It also attains a two-fold voltage boosting increase. A comparative study demonstrates that the suggested S3CM topology results in fewer switches. [4]

In response to the rising demand for renewable energy, grid-connected solar plants have seen a large increase in installed capacity. For utility-scale photovoltaic systems connected to the power grid, this study provides an active neutral point clamped (ANPC) converter with seven stages based on flying capacitors (FC). In order to make effective use of the DC-link voltage, the study also provides a mechanism for controlling the FC voltages and optimising third harmonic injection. The grid-connected converter's performance under steady-state and transient settings is shown by the simulation results, demonstrating its usefulness in real-world applications. [5]

To produce a high-quality output voltage signal with the least amount of Total Harmonic Distortion (THD), Multilevel Inverters (MLI) use Selective Harmonic Elimination (SHE) approaches. SHE can remove (N-1) low-order odd harmonics from the output voltage waveform by calculating N switching angles. In order to achieve low harmonic distortion and produce the correct fundamental component voltage, the selective harmonic elimination technique relies heavily on the modulation index (m) and duty cycle. In order to further minimise Total Harmonic Distortion, this research suggests a unique Optimisation Harmonic Elimination Technique (OHET) based on the SHE scheme. [6]

This study explores fault-tolerant control (FTC) methods to enhance system resilience against component faults and failures. It categorizes FTC techniques into passive and active systems, with active systems responding to fault detection without affecting other parts. The research reviews fault causes, recent advancements in fault detection, and FTC designs, comparing their effectiveness to inspire further development. A new active FTC system is proposed, utilizing online fault detection techniques for improved performance. It employs artificial neural networks and model-based observers to identify faults in sensors and actuators, enhanced by the extended Kalman filter. The system compensates for faults in real-time without needing controller reconfiguration. This approach is applied to design control systems for unmanned aerial vehicles, load frequency control, and fuel cell systems. Numerical simulations demonstrate the superiority of these controllers over traditional methods, showcasing their benefits. [7]

III. PROPOSED METHOD

To demonstrate the enhanced performance of the suggested Fault-Tolerant Cascaded H-Bridge Multilevel Inverter (FT-CHB-MLI), a comparison with current solutions is presented in this section. A fault-tolerant H-bridge system that solely uses the Pulse Width Modulation (PWM) approach is provided in reference [16] for DC motor speed control. Despite its dependability, this method produces an output waveform with a high harmonics content of roughly 48.3%, making the suggested solution impractical in terms of power quality. Similarly, in reference [29], an FT-CHB system is proposed, but it is limited to five levels and exhibits a high Total Harmonic Distortion (THD) of 20.83%, falling short of expectations. In contrast, the proposed FT-CHB-MLI in this work achieves a significant reduction in THD to almost 18%, while simultaneously enhancing reliability through an advanced fault-tolerant architecture incorporating a Fault Detection and Isolation (FDI) unit.

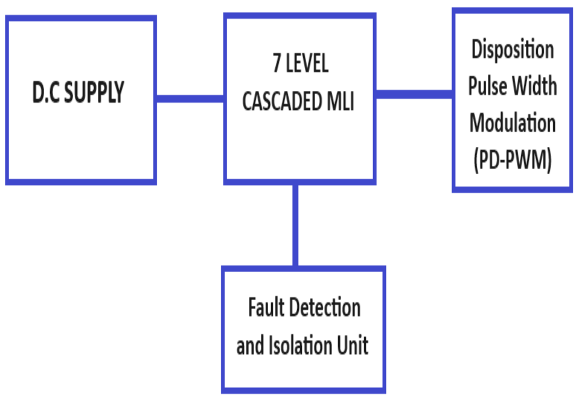
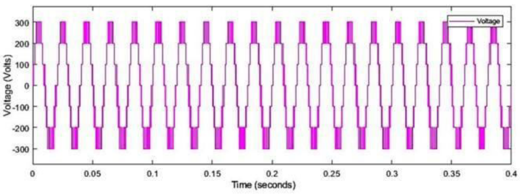


Fig.1 Block diagram for proposed Method

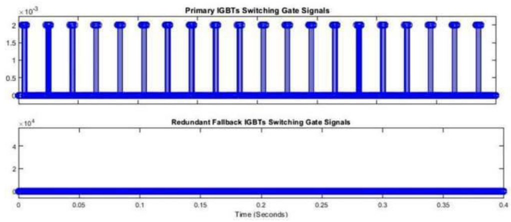
The proposed method aims to design an Active Fault-Tolerant Control System for a 7-level Cascaded Multilevel Inverter (MLI) to enhance reliability and power quality. This system utilizes a DC power supply and Phase Disposition Pulse Width Modulation (PWM) technique. Additionally, it incorporates a Fault Detection and Isolation (FDI) unit to detect and address faults. By combining these elements, the system can achieve greater reliability by effectively managing faults while improving power quality through precise control of the MLI's output voltage.

IV. RESULT

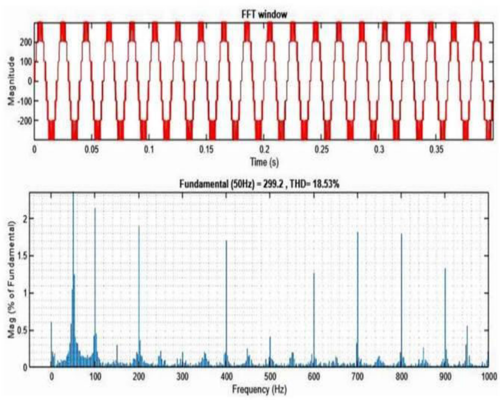
Figure illustrates the output voltages of the proposed 7-level cascaded Multilevel Inverter (MLI), with a magnitude of 300V (peak). Since no faults are applied to any switch in the MLI, the output voltages remain consistent throughout the simulations.



Output waveform without any fault



switching pattern without fault



THD WITHOUT FAULT

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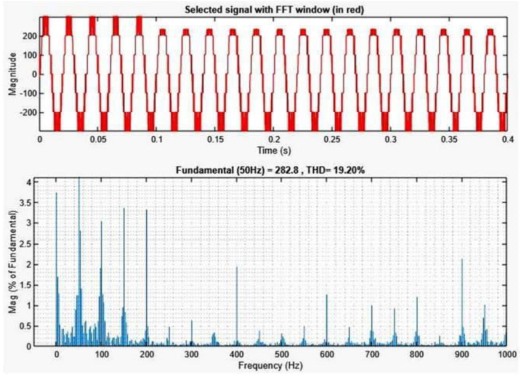
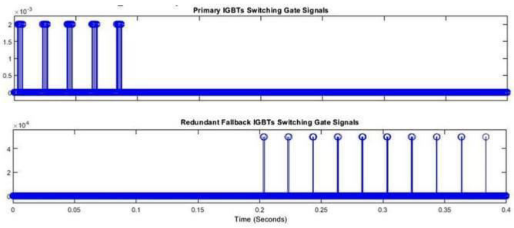
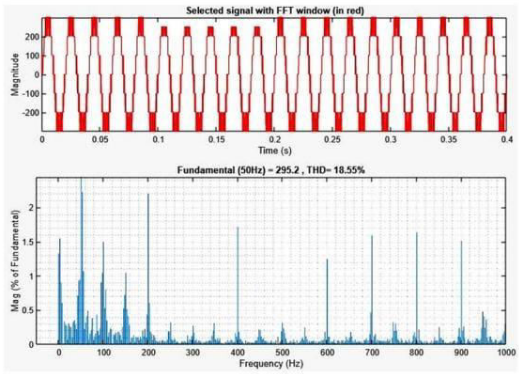


THD WITH FAULT



Switching pattern with FTC



THD with FTC

V. CONCLUSION

This work presents the introduction of a revolutionary 7-level Fault-Tolerant Cascaded H-Bridge Multilevel Inverter (FT-CHB-MLI), which provides better power quality and increased dependability. Total Harmonic Distortion (THD) Mfault diagnostic process of a specialised Fault Detection and Isolation (FDI) machine designed to locate and replace malfunctioning switches. Because of its higher performance, the Phase Disposition Pulse Width Modulation (PD-PWM) technology was used for switching. Experimental testing in MATLAB/Simulink verified the system's effectiveness, reducing THD to nearly 18% and enhancing reliability through advanced fault-tolerant architecture. Reliability analysis using Markov chains confirmed increased reliability. Future research could explore more sophisticated Fault-Tolerant Control (FTC) techniques employing artificial intelligence, along with hardware experimental verification. Additionally, investigating the impact of load variations and modulation index on the proposed AFTCS performance could be a fruitful direction for further study.

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