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Enhancing Multilevel Inverter Performance with an Active Fault-Tolerant Control System for Improved Reliability and Power Quality

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ABSTRACT: This paper proposes a novel 7-level Fault-Tolerant Cascaded H-Bridge Multilevel Inverter (FT-CHB-MLI) designed to enhance reliability and improve power quality in renewable energy systems. The system incorporates a Fault Detection and Isolation (FDI) unit that diagnoses faulty switches and replaces them with redundant standby switches. Fault diagnosis is performed using Total Harmonic Distortion (THD) and a normalized output voltage factor. The Phase Disposition Pulse Width Modulation (PD-PWM) technique is used for switching, offering superior performance compared to conventional methods. This proactive fault detection approach not only identifies faults but also takes corrective actions to maintain system stability. The system was simulated in MATLAB/Simulink, with results showing a significant reduction in THD to about 18% and a noticeable increase in system reliability. Reliability analysis using Markov chains confirmed the system's enhanced dependability. A comparison with existing literature further highlighted the superior performance and increased reliability of the proposed FT-CHB-MLI system.

KEYWORDS: Fault tolerant control, Cascaded H-Bridge MLI, 7-Level Multilevel Inverter, Inverter fault diagnosis Technique.

1. INTRODUCTION

Multilevel Inverters (MLIs) have become increasingly popular in medium- and high-power applications, particularly in renewable energy systems, electric vehicles, and industrial motor drives, due to their ability to produce high-quality waveforms with minimal harmonic distortion. These inverters, including Cascade H-Bridge (CHB) converters, neutral point clamped (NPC) converters, and hybrid types, excel in reducing harmonic distortion, improving power quality, and ensuring efficient high-voltage power handling. MLIs offer key advantages, such as stable voltage, improved power factor, and reduced noise, making them ideal for applications in renewable energy plants, industrial processes, and high-voltage systems. Their modular structure allows for easy scaling, making them adaptable to various voltage and power requirements, which is essential in grid-connected power plants and renewable energy systems like photovoltaic (PV) installations.

The CHB-MLI, a type of modular inverter, uses multiple H-bridge power cells connected in series to create high-voltage outputs. These can be either symmetrical, with equal DC sources, or asymmetrical, with unequal DC sources. The modular design of the CHB-MLI enables easy scalability and flexibility, as adding or removing power cells can adjust the inverter's power and voltage levels. The use of Pulse Width Modulation (PWM) ensures high-quality output voltage waveforms that reduce harmonic distortion.

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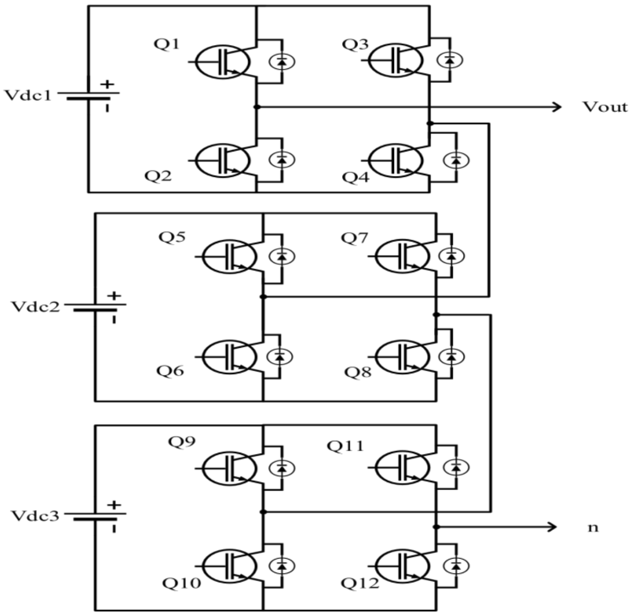

Fig 1:Schematic diagram of 7 levels cascaded H-Bridge multi-level inverter

CHB-MLIs are highly efficient, cost-effective, and easy to maintain, making them suitable for a wide range of applications. Their ability to provide high-quality power while handling large power levels makes them increasingly popular in renewable energy systems, where efficiency and reliability are paramount for energy conversion.

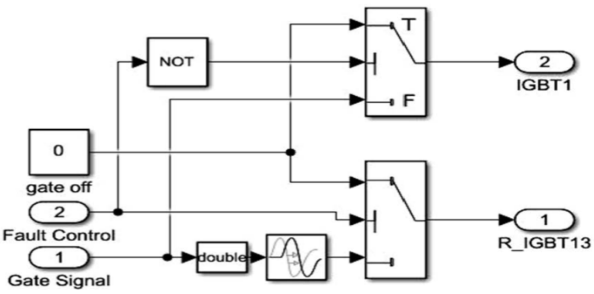

Fig 2: Fault tolerant-control Switching Model

However, one of the significant challenges of MLIs is fault management, as failures in switching devices can lead to system downtimes or degraded performance. To address this, Fault-Tolerant Control (FTC) strategies have been developed. FTC systems are designed to detect and isolate faults early, ensuring continued operation despite faults. Key to FTC systems is the Fault Detection and Isolation (FDI) unit, which monitors and isolates faulty components while reconfiguring the system for continued operation.

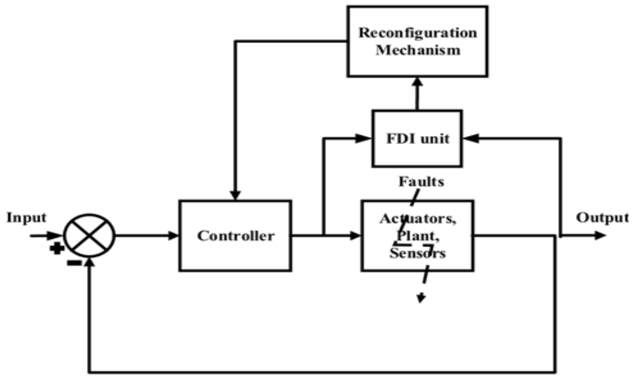

Fig 3: AFTS Architecture

Active Fault-Tolerant Control Systems (AFTCS) go a step further, adjusting the system's behaviour dynamically in response to faults. AFTCS offers the advantage of handling a wider variety of faults but also introduces complexity and slower response times. Nevertheless, AFTCS is highly effective in ensuring the reliable operation of MLIs in critical applications, particularly in renewable energy systems, where uninterrupted power supply is crucial. Through fault detection, isolation, and active system reconfiguration, AFTCS ensures that MLI systems continue to provide high-quality, stable power even in the face of faults.

2. PROBLEM FORMULATION

Multilevel inverters, particularly Cascaded H-Bridge Multilevel Inverters (CHB-MLI), are crucial in modern power conversion systems due to their high efficiency and low harmonic distortion, especially in renewable energy applications. However, their reliability is often compromised by faults in power devices, such as open-circuits, short-circuits, and thermal stress-induced failures. These faults can lead to performance degradation, reduced voltage quality, increased harmonic distortion (THD), and system outages, which are unacceptable in critical applications like renewable energy generation and industrial processes.

Traditional fault-tolerant systems often fail to detect faults in time, leading to performance degradation and unplanned downtime. Additionally, they lack effective fault isolation and recovery mechanisms, making it difficult to maintain system operation in a degraded mode. Furthermore, implementing fault-tolerant systems can increase system cost and complexity, limiting their adoption in resource-constrained environments.

3. METHODOLOGY

In this section, the structure of the FT-CHB-MLI is discussed; then the schematics of the Cascaded 7-level H-bridge inverter are elaborated and after that, the fault analysis of a switch in case of an open circuit is done.

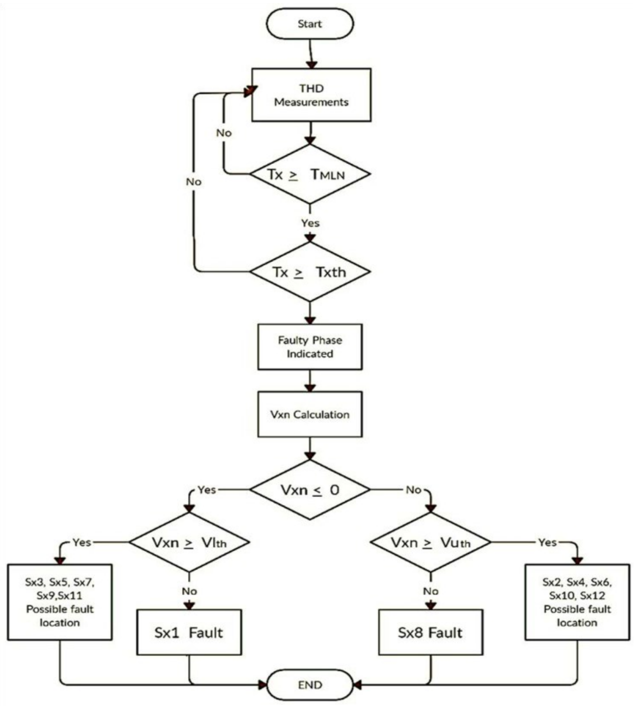

Fig 4: Algorithm for Fault Diagnosis

3.1. 7-Level Cascaded H-Bridge MLI

- The system uses three cascaded H-bridge inverters, each consisting of four IGBT/MOSFET switches, for a total of twelve switches.
- The inverter operates with three isolated 100V DC batteries, delivering a peak output of 300V.
- The output waveform is generated using a sinusoidal voltage with a frequency of 50 Hz and a magnitude of 1.5 sin(50t). The switches alternate using NOT operators, without any fault-tolerant measures in place.

3.2. Phase Disposition Sinusoidal Pulse Width Modulation:

- This modulation technique uses a reference sinusoidal signal (50 Hz, 1.5 magnitude) along with six rectangularcarrier waves (1000 Hz, magnitude 0.5), all in phase.
- The approach aims to reduce Weighted Total Harmonic Distortion(WTHD),offering superior harmonic mitigation compared to other PWM methods.

3.3. Fault Analysis of Open Circuit Switch in Cascaded H-Bridge Inverter:

- Faults in power devices can occur due to factors like semiconductor material failure, gate driver issues, incorrect triggering, or thermal breakdown.
- The focus here is on analysing open circuit faults, which can be identified using a twostep algorithm:
  - Total Harmonics Distortion (THD) Measurement
  - Normalized Voltage Factor

The faulty phase will exhibit significantly higher THD compared to others. After identifying the faulty phase using THD, a comparison of the normalized voltage factor is done to pinpoint the exact faulty switch location.

The proposed FTC system for IGBT-based 7-level cascaded MLI has been implemented in MATLAB and Simulink environment and is shown in Figure 9. To explain this model in a better way, it has been divided into three major parts i.e. PD-PWM FDI system, and power electronics-based model of 7-level cascaded MLI.

The model consists of individual subunits as follows:

1. Fault Injection Unit
2. Phase Disposition Unit
3. Fault Injection Block
4. Fault Detection and Isolation Unit
5. 7-Level CHB MLI

4. SIMULATION CIRCUITS

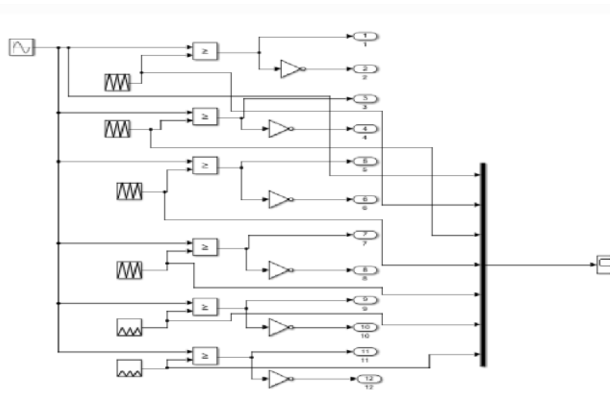

Fig 5: MATLAB Simulink model of PD-PWM

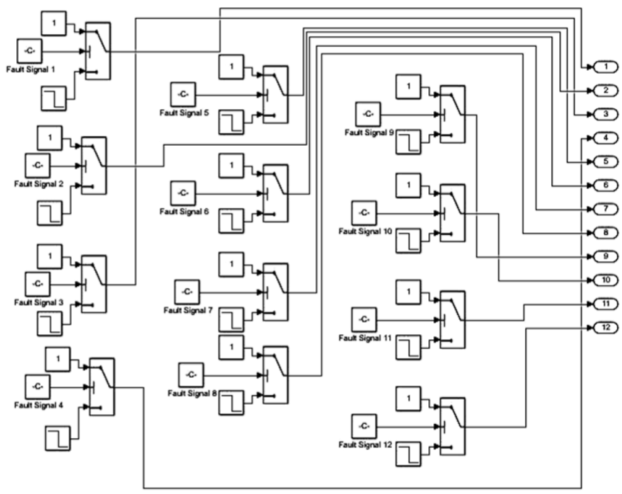

Fig 6: Fault Tolerant-Control Block

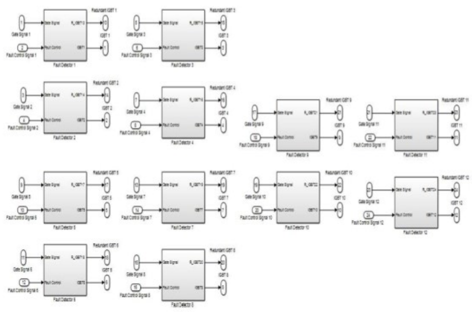

Fig 7: Internal blocks of FDI

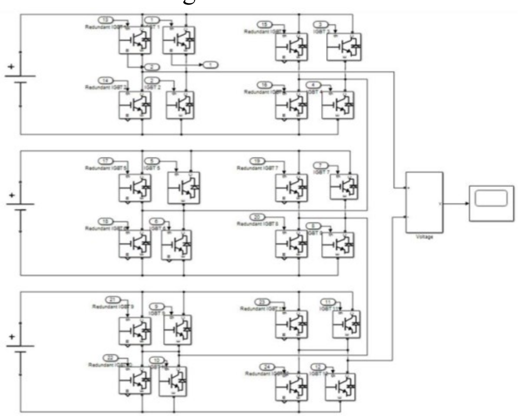

Fig 8: FD-CHB-MLI Simulink Switches model

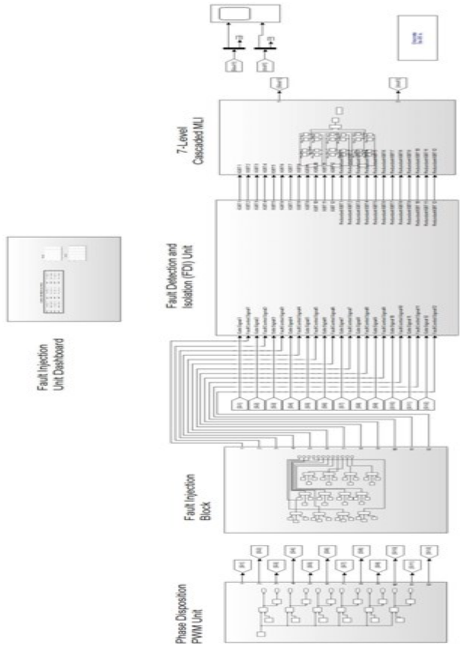

Fig 9: Proposed FD-CHB-MLI model

4. RESULTS AND DISCUSSIONS

5.1. Simulation Results of 7-Level Cascaded MLI Normal Operation

- Output voltages have a magnitude of 300V (peak) with no fault applied
- Switching signals to primary IGBTs are shown, with standby redundant IGBTs remaining off
- Total THD is 18.53%

5.2. Fault Injection

- Fault is injected at 0.1 seconds, resulting in reduced positive peak voltage (200V) and increased THD (19.2%)

5.3. Fault-Tolerant Control (FTC) System

- System is simulated with FTC CHB MLI configuration
- Output waveform returns to normal operation after fault injection due to switch over of faulty switch to healthy standby IGBT switch
- THD is improved from 19.2% to 18.55%

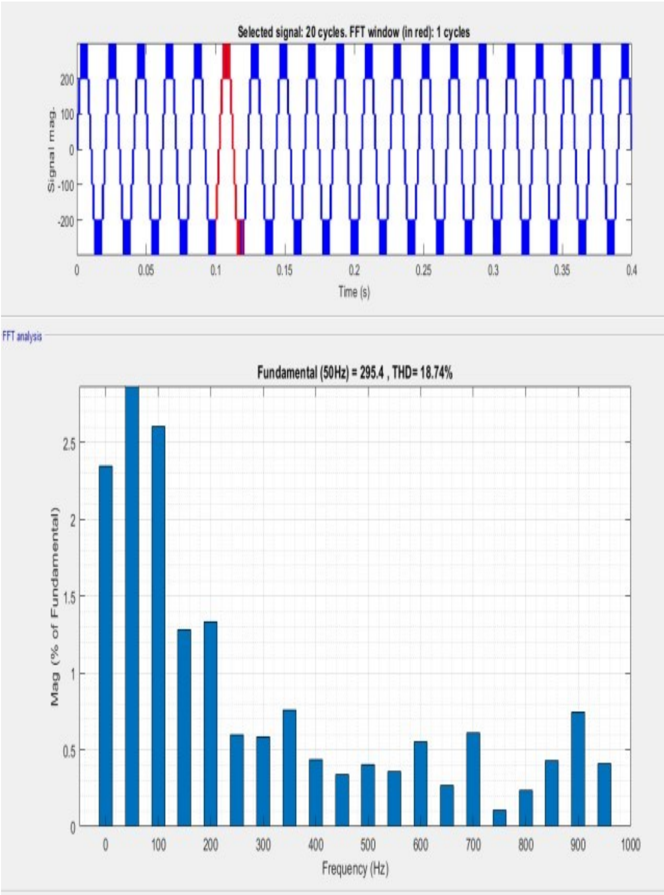

Fig 10: THD with Fault

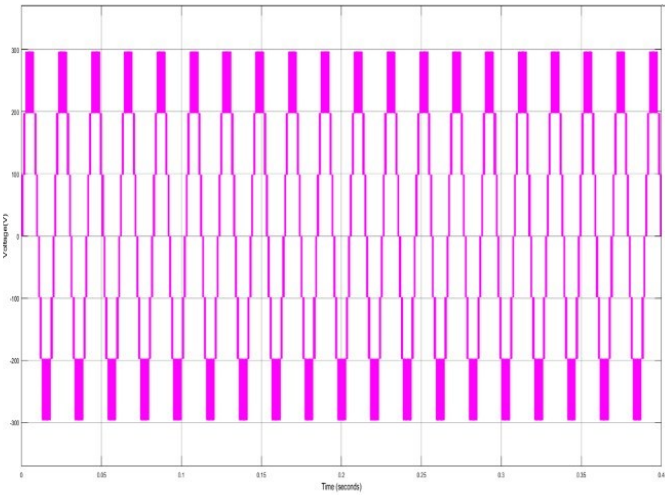

Fig 11: Output Waveforms without Faults

Table 1: Comparison with previous and proposed model

Component	Reference [16]	Reference [29]	Proposed Work
Power Switches	8	8	24
THD	48.3 %	20.83%	18%
Reliability	Moderate	High	High
Complexity	Simple	High	Moderate
Switching Technique	PWM	LSPWM	PD-PWM

19.2% to 18.55% by the proposed control system. Hence, the objective of reliability enhancement with improved power quality has been successfully achieved.

5.4. Comparison With Existing Works

In this section, a comparison of the proposed FT-CHM-MLI has been performed to demonstrate its superior performance.

In [16] A fault-tolerant H-bridge system is proposed for DC motor speed control with the PWM technique only resulting in a very large harmonics content of about 48.3% in the output waveform which makes the proposed solution not feasible from the power quality point of review through its highly reliable. The solution proposed in [29] FT-CHB is proposed but it is only for five levels that also results in a high THD of 20.83% which is not up to the mark. In this proposed work, the THD has been reduced to almost 18% with a significant increase in reliability with advanced fault-tolerant architecture consisting of an FDI unit.

5. CONCLUSIONS

In this paper, a novel 7-level Fault-Tolerant Cascaded H-Bridge Multilevel Inverter (FT-CHB-MLI) was proposed that offers high reliability with improved power quality. A dedicated Fault Detection and isolation (FDI) unit was built to diagnose the faulty switch and replace it with a standby redundant switch. Total harmonic distortion and the determination of a normalized output voltage factor were employed for fault diagnosis. The Phase Disposition Pulse Width Modulation (PD-PWM) technique was utilized for switching due to its superior performance as compared to other conventional techniques. The proposed system was experimentally tested on the MATLAB / Simulink environment to verify its performance. The simulation results demonstrated that the THD has been reduced to almost 18% with a significant increase in reliability with advanced fault-tolerant architecture consisting of FDI units. The reliability analysis was carried out using Markov chains that also showed its increased reliability. A comparison of the proposed work with literature also depicted its superior performance in achieving its superior power quality and increased reliability.

A more sophisticated FTC technique using artificial intelligence in the future could more precisely pinpoint the Fault location with a better understanding with hardware experimental verification. Another direction is to study the effect of load variations and variations in the modulation index on the performance proposed AFTCS.

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