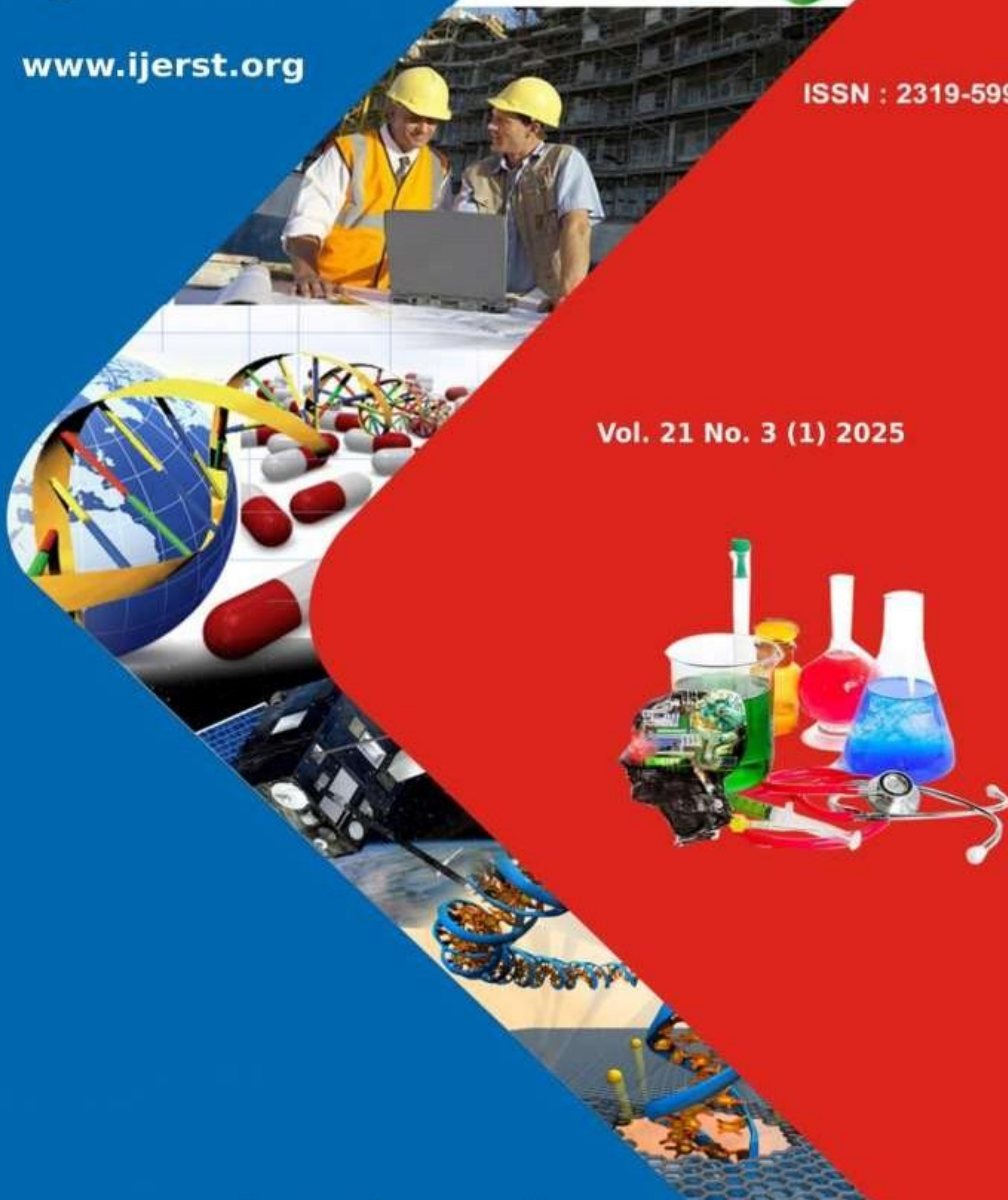
IJERST

International Journal of Engineering Research and Science & Technology

www.ijerst.org

ISSN : 2319-5991



Vol. 21 No. 3 (1) 2025

ijerst.editor@gmail.com
editor@ijerst.com

International Journal of Engineering Research and Science & Technology

*ISSN2319-5991*www.ijerst.com
Vol.21,No.3(1),2025

Research Paper

FAULT-TOLERANTCONTROLSYSTEMFORMULTILEVEL INVERTERS TO ACHIEVE GREATER RELIABILITY WITH IMPROVED POWER QUALITY

ThumulaTharuna[1],P.PurnachanderRao[2]

[1]M.Tech Student, Department of Electrical and Electronics Engineering, Vaagdevi College of Engineering, Khammam - Warangal Hwy, Road, Bollikunta, Telangana 506005

[2]Associate Professor, Department of Electrical and Electronics Engineering, Vaagdevi College of Engineering, Khammam - Warangal Hwy, Road, Bollikunta, Telangana 506005

Abstract *Modern renewable energy systems mostly utilize multilevel converter applications for improved power quality and grid synchronization purposes. A multilevel converter is an electrical device that may offer several amounts of voltage levels at the output in order to make the output more comparable to a pure sine wave. The integrity of the multilevel converter depends on the reliability of individual switches such that the converter will collapse in case of faults in these switches. In this paper, a novel 7-levelFault-Tolerant Cascaded H-Bridge Multilevel Inverter (FT-CHB-MLI) has been proposed that offers high reliability with improved power quality. A dedicated Fault Detection and Isolation (FDI) unit has been built to diagnose the faulty switch and replace it with a standby redundant switch. Total Harmonic Distortion (THD)and the determination of a normalized output voltage factor are employed for fault diagnosis. The Phase Disposition Pulse Width Modulation (PD-PWM) technique has been utilized for switching due to its superior performance as compared to other conventional techniques. This early fault detection method not only idented the issues but also performed preventative actions to keep the system healthy and stable. The proposed system was 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 Signiant 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 was also carried out to demonstrate its superior performance with increased reliability.*

Received: 14-07-2025 Accepted: 28-07-2025 Published: 14-08-2025

1. Introduction

Due to the shortage of fossil fuels and environmental problems caused by conventional power generation, renewable energy, particularly solar energy, has become very popular. Solar-electric-energy demand has grown consistentlyby20%–25% per annum over the past 20 years [1], and the growth is mostly in grid-connected applications. With the extraordinary market growth in grid-connected photovoltaic (PV)systems, there are increasing interests in grid-connected PV configurations. Five inverter families can be defined, which are related to different configurations of the PV system: central inverters; string inverters; multi string inverters; ac module inverters and cascaded inverters.

There are two types of cascaded inverters. Cascaded dc/dc converter connection of PV modules. Each PV module has its own dc/dc converter, and the modules with their associated converters are still connected in series to create a high dc voltage, which is provided to a simplified dc/ac inverter. This approach combines aspects of string inverters and ac-module inverters and offers the advantages of individual module maximum power point (MPP) tracking (MPPT), but it is less costly and more efficient than ac-module inverters. However, there are two power conversion stages in this configuration. Another cascaded inverter is shown in Fig. 1(f), where each PV panel is connected to its own dc/ac inverter, and those inverters are then placed in series to reach a high voltage level. This cascaded inverter would maintain the benefit so for one converter per panel .such as better utilization per PV module, capability of mixing different sources, and redundancy of the system. In addition, this dc/ac cascaded inverter removes the need for the per-string dc bus and the central dc/ac inverter, which further improves the overall efficiency. The modular cascaded H-bridge multilevel inverter, which requires an isolated dc source for each H-bridge, is one dc/ac cascaded inverter topology.

The separate dc links in the multilevel inverter make independent voltage control possible. As a result, individual MPPT control in each PV module can be achieved, and the energy harvested from PV panels can be maximized. Mean while ,the modularity and low cost of multilevel converters would position them as a prime candidate for the next generation of efficient, robust, and reliable grid connected solar power electronics.

A modular cascaded H-bridge multilevel inverter topology for single- or three-phase grid-connected PV systems is presented in this paper. The panel mismatch issues are addressed to show the necessity of individual MPPT control, and a control scheme with distributed MPPT control is then proposed. The distributed MPPT control scheme can be applied to both single and three-phase systems.

In addition, for the presented three-phase grid-connected PV system, if each PV module is operated at its own MPP, PV mismatches may introduce unbalanced power supplied to the three-phase multilevel inverter, leading to unbalanced injected grid current. To balance the three-phase grid current, modulation compensation is also added to the control system. A three-phase modular cascaded multilevel inverter prototype has been built. Each H-bridge is connected to a 185-Wsolar panel. The modular design will increase the flexibility of the system and reduce the cost as well. Simulation and experimental results are provided to demonstrate the developed control scheme.

2. Multilevel Inverter

Due to their appealing features, such as high-quality wave form and high nominal power, Multilevel Inverters (MLIs) have gained popularity among PV systems. As a result, several converters have been developed, including cascade H-bridge converters, neutral point clamped converters, and hybrid multilevel converters. These converters can be used in applications requiring medium and high power. Multilevel converters were originally used in the power train and high-voltage industrial applications. These converters were employed in utility-scale facilities for the first time in the renewable energy area, and the yare still used on a wide scale in utility-scale plants today.

If we split single-phase multilevel converters into three categories, we get Neutral Point Clamped (NPC), Continuous Feedback (CFB), and Cascaded H-Bridge (CHB) converters. When employed in a three-level converter, the diode-clamped converter is also known as the NPC since the mid-voltage level is specified as the neutral point level [4]. The fundamental short coming of NPC converters in terms of the complete bridge is the requirement for dual dc- link voltage[5]. An H-bridge is a pair of capacitors and switches that produces a different input DC voltage. MLIs are used for multiple purposes in voltage going from high level to medium level. Examples include their usage of magnetic levitation systems, electric traction, industrial applications, conveyors, vacuum cleaners, multiple gear systems, cooling systems, power plants, and smart houses. In multi-level inverters, stable voltage, fewer harmonics, noise, and better power factor having an improved power quality can be obtained by a small voltage step.

Structure of a cascaded h-bridge MLI

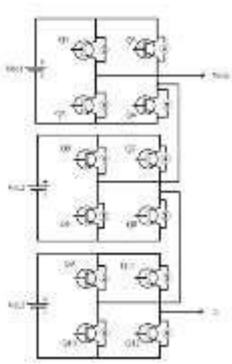
CHBMLI has a modular structure, which is one of the reasons why so many devices have this CHB MLI. By tinkering with the power cells, we may simply increase or reduce the power level of these inverters. The H-Bridge power cells are connected in series with one another, resulting in an increase in the inverter's power and voltage level. The structure of an MLI uses four devices for switching, each of which has a diode linked in reverse to it. ADC input voltage source is linked to each power cell. A Pulse Width Modulation (PWM)output waveform will be generated by these power cells. The wave form will be in the shape of stairs. The Cascaded H-bride inverter is divided into 2 types [7]. They are:

1) A symmetrical Cascaded H-Bridge MLI

2) Symmetrical Cascaded H-Bridge MLI

The input DC source is the basis for this division. An inverter is called a Symmetrical CHB inverter if it has equal valued DC voltage sources. In asymmetrical CHBMLI, unequal DC voltage sources are used. Table 1 examines a variety of devices and their reliability, as well as MLI mechanisms a tall seven levels.

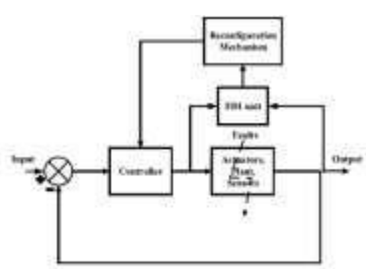
A total of (n - 1) _ 2 power devices used for switching and(n - 1)/2 multiple DC sources are needed for an n-level cascaded H-Bridge Multi-Level Inverter.



Schematicdiagramof7levelscascadedH- Bridge multi-level inverter.

Fault-tolerant control

Fault-Tolerant Control (FTC) techniques are used to increase machine dependability by avoiding occurrences that cause failure due to faults. A fault is defined as a variation in a system's output from its planned output, whereas a failure is defined as a full shutdown of a system. An FTC's primary function is to avoid malfunctions in important systems that might lead to their failure. Systems utilized for essential tasks



AFTCS Architecture

Such as un manned aerial vehicles, planes, and nuclear power plants, can not tolerate failure; hence, FTC is employed to increase the safety and dependability of such systems. [8] One of the most significant components of the solar system's consistent functioning is the inverter's dependability. The advantages of a multi-level converter include reduced harmonic content in the output voltage, lower switching loss, and lower stress, making it the optimum choice for medium-high voltage and high power applications. However, because of the increased number of power switching devices, the multi-level inverter would raise the risk of a defect, lowering the system's dependability. Once the multi-level inverter fails, it will result in massive economic losses or catastrophic accidents. As a result, increasing the dependability of multilayer inverter systems is critical. One of the strategies used to construct an FTC system is redundancy, which is divided into two categories: analytical redundancy and hardware redundancy. Active and passive analytical redundancy are the two types of redundancy.

The active analytical redundancy comprises fault detection, isolation, and controller reconfiguration, but it is complicated, computationally intensive, and sluggish in performance; yet, it has the bonnet of embracing a wide variety of defects. Because it is based on a strong controller design that can deal with the only considered uncertainties and faults in a system, passive analytical redundancy is a relatively simple and quick technique. However, it cannot handle a wide variety of defects.

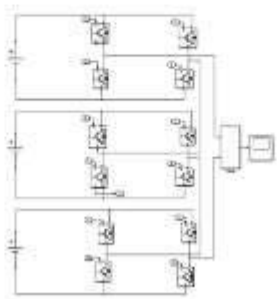
The Fault Detection and Isolation (FDI) unit is the most important part of an Active Fault-Tolerant Control System(AFTCS), and it is responsible for detecting problems in actuators and sensors, as shown in Figure 2. The FDI unit is created by creating an observer model that creates estimated values that are utilized in the event of a component failure. The FDI performs controller reconfiguration after recognizing and isolating a malfunction by employing the estimated parameter values by the observer to adopt new circumstances. AFTCS has the benefit of supporting a wide range of defects and being an online fault detection-based system, but it is also complicated, computationally intensive, and slow to perform

3. Proposed method

A fault detection system and tolerance regulation have been suggested for a single-phase CHB MLI. Since the existing flow direction for open-fault and short-fault is different, the CHBMLI requires safety fuses to distinguish between the two [16]. A control technique for a single-phase cascaded ''off-grid'' solar panel storage system has been presented, as well as a fault-tolerant system in the event of PV failure. When PVs crash, several operating modes, such as normal mode, 50% fault mode, and 100% fault mode, are strongly considered to increase device stability, depending on their states [8]. Hybrid modulation is used to reduce switching errors. The suggested regulation for fault-tolerant systems thus ensures dependable power generation by managing different types of converter cells separately. The semiconductor switches used in H-bridges determine their stability. Faults in these parts can cause the device to stop working completely. In the paper [17], the authors describe a fault-tolerant system with dual redundancy and an FDI device that can locate and replace a defective device with standby in order to prevent the system from shutting down unexpectedly and to maintain operation stability, there by improving reliability. A fault-tolerant H-bridge with dual redundancy and an FDI unit is shown to be a very efficient solution for DC motor speed modulation in this study. The CHB converters maybe connected to the Medium Voltage (MV) grid stations for installation. The point is because transformers have high power and low harmonics, we can accomplish it without them. They're crucial for linking large-scale renewable energy installations to the power grid. In a grid-connected CHB converter, on the other hand, the number of power switching devices can have a substantial influence on its efficiency. The study [18] suggests a methodology based on two zero-sequence voltage injection methods and DC voltage optimization to improve the efficiency of Y-linked CHB converters when one or more module units are bypassed. Using an extension theory-based assessment method, the research proposes a method for diagnosing defects in inverter-driven motor driving systems. A three level NPC inverter is initially created to check and diagnose defects in NPC inverters. The Fast Fourier transformation(FFT) is used to convert the signals of an I (line), i.e. current through the line, from the time domain into a broad range of frequency domain in order to perform a fault analysis with multiple power transistors on the related continuum of characteristics of an inverter. The sorts of faults, links, and coordination in a specific region are then identified as aspects of a thorough review process [19].

The paper [20] describes a defect detection transition control strategy based on a predictive model. An asymmetric zero voltage situation is required for an open-circuit problem diagnosis. The authors suggest a simpler approach that is based on zero-voltage switching and has been tested for both non-linear and linear loads. The authors offer a strategy for identifying short circuit defects based on an output voltage compared to the reference voltage of CHB MLIs with five levels (a neural network for a five-level CHB). A network based technique to defect detection is adopted. The authors in [21] propose the use of MLIs to determine the kind of problem and its location, including five MLIs with several layers. The authors of [22] noted how, while MLIs have enticing properties, their large range of applications is constrained by the standard setup's usage of additional switches. With the fewest amount of unidirectional switches and gate trigger circuits, an elaboration on the contemporary 7-level MLI architecture is achieved, resulting in the lowest switching failures, as well as a smaller size and cheaper installation cost [23].

In this paper, a novel 7-level Fault-Tolerant Cascaded H-Bridge Multilevel Inverter (FT-CHB-MLI) has been proposed that offers high reliability with improved power quality. A dedicated FDI unit has been 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 are employed for fault diagnosis. The Phase Disposition Pulse Width Modulation (PD-PWM) technique has been utilized for switching due to its superior performance as compared to other conventional techniques. This early fault detection method not only identified the issues but also performed preventative actions to keep the system healthy and stable. The proposed system was experimentally tested on the MATLAB / Simulink environment to verify its performance. The simulation results demonstrated that the Total Harmonic Distortion (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.



MATLAB-Simulink model of 7levels cascaded MLI.

The proposed work with literature also depicted its superior performance in achieving its superior power quality and increased reliability.

Further contents of the papers are organized as: section3explainstheresearchmethodology,section 4 explains the reliability analysis, results and discussions are presented in section 5, comparison with existing works is mentioned in section 6, and finally the conclusion is presented in the last section.

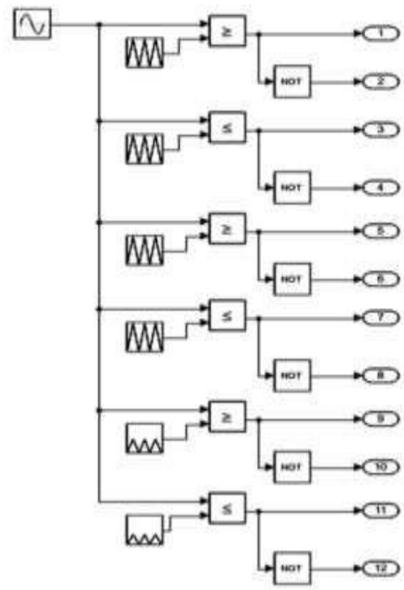
4. Methodology

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.

A. **7LEVELCASCADEDMLI**

The proposed 7-level cascaded MLI is designed using three cascaded H-bridges to achieve the desired seven-level output. Each bridge constitutes four different IGBT/MOSFET switches, and a total of three bridges are used to complete the design model. Overall, twelve IGBT/MOSFETs are used as power electronic switches to shift the converter output into seven levels. Figure 3 depicts the complete circuit of the design model which is implemented in MATLAB-Simulink. Meanwhile, three isolated DC batteries of 100V each are connected with H-bridge to get a peak output level of 300V.

In the simulation circuit, there are 12 IGBT modules with diodes in reverse of each IGBT module. The DC voltage source across each of the IGBT modules with a magnitude of 100 V. whereas, the sinusoidal voltage for the triggering of IGBT modules is 1.5sin 50t. The NOT operators are used for alternative selections of the IGBT modules during output waveform generation. This is a conventional circuit in which there is no fault and without any fault-tolerant circuit.

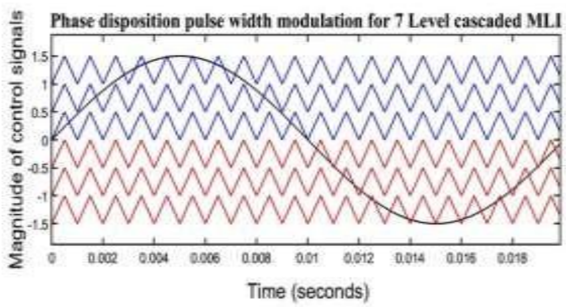


MATLAB-Simulink model of Phase disposition pulse sinusoidal width modulation

B. **PHASEDISPOSITIONSINUSOIDALPULSE** WIDTH MODULATION In paper [24], a Phase Disposition Pulse Width Modulation (PD-PWM) technique for a three-phase five-level NPC-MLI is proposed, which employs a mathematically formulated harmonic mitigation algorithm to reduce the high-frequency Weighted Total Harmonic Distortion (WTHD) content of the inverter output voltage. The practical findings of a three-phase NPC-MLI prototype are quite similar to the suggested control scheme's theoretical calculation and simulated outcomes. Furthermore, a quantitative comparison analysis confirms that the suggested PD-PWM approach has the lowest WTHD content of all the previously presented PWM schemes under consideration, confirming the proposed work's superiority. In [25], a modified rotative PD-PWM (MPD-PWM) technique was suggested to overcome the problem of uneven power distribution. The switching losses were overcome by injecting a common-mode voltage in to the PWM modulator. The phase dispositions in usoidal pulse width modulation

(PDSPWM) comprises a reference sinusoidal signal of 50HZ and 1.5 magnitudes, and six rectangular carrier waves each width a magnitude of 0.5 and 1000Hz carrier frequency are in the same phase, while three carrier waves are above and three are below the zero reference line as shown in Figure 4. All the carriers are in the same phase in this method of PWM. The input sinusoidal signals and carrier wavesareshowninFigure5.C.FAULTANALYSIS OF AN OPEN CIRCUIT SWITCH FOR CASCADEDH-BRIDGE7-LEVELINVERTER

Numerous plausible reasons are possible for the occurrence of faults in power devices used for switching.



Input signals of the phase disposition pulse sinusoidal width modulation.

Their main reason is due to switches. The main causes of switch failure are a huge and sudden drop of load or DC voltage source will be suddenly increased or decreased, due to load. On the load side, there is a possibility of a short circuit or an open circuit of a phase i.e. two phases or a phase to earth and a phase to phase fault.

The causes for these failures are:

1. Semiconductor material quality issues result in the breakdown of the device.

2. The fault of a gate driving source either pulsating transformer or any other source

3. Wrong triggering of gate results in undesired results.

4. Break down due to heat (thermal break down).

The above reasons will, at last, take us to below 2 types of faults:

1. Open Circuit Fault of Switch

2. Short Circuit Fault of Switch.

Short Circuit faults are not much considered, so discussion and analysis of the open circuit faults are done only. Regarding the open circuit faults in a 7-level cascaded MLI, it is clear that there are12 switches for each phase. From this one can infer that the total no. of switches for a 3-φ 7-level Cascaded MLI will be 36 which is quite a tedious task to determine the faulty switch location for which an algorithm was developed to find out if the faulty switch has an open circuit fault. The algorithm is shown in Figure 6. It describes that in case of fault occurrence, the procedure of its identification is divided into two sections:

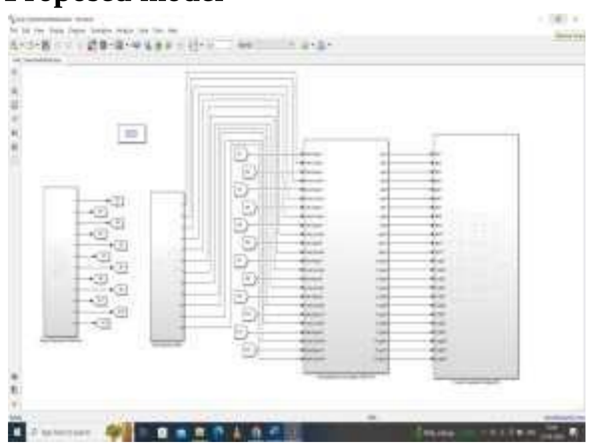
1) Total Harmonics Distortion Measurement

2) Normalized voltage Factor[27]

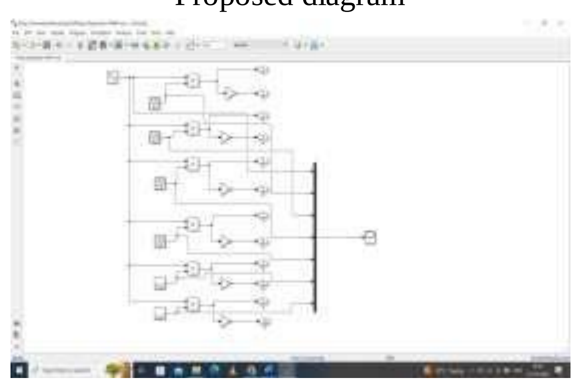
The THD measurement will identify the phase which is faulty. In this way, our inspection is reduced to 12 switches from 36. The phase in which the switch is faulty will have a higher THD with respect to the other phases. After that, we cater to the 12 switches by the normalized voltage factor technique. In this technique, a comparison between the threshold value and the normalized factor one is done. So the faulty switch location will be found.

5. Simulation Results

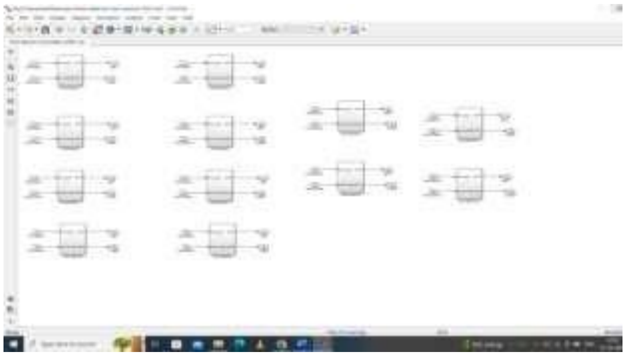
Proposed model



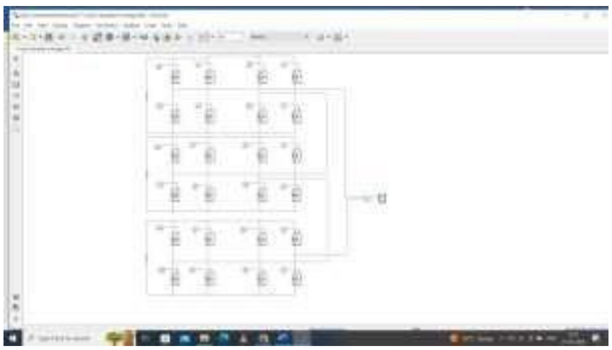
Proposed diagram



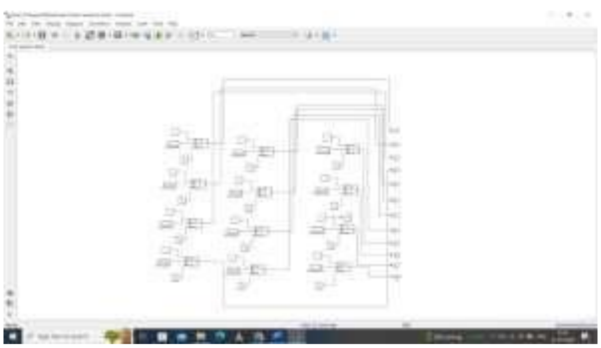
Phase deposition PWM unit



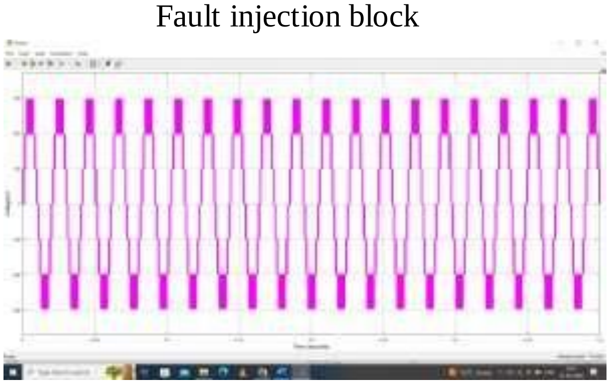
Fault detection an isolation



7level casecaded H bridge multilevel inverter

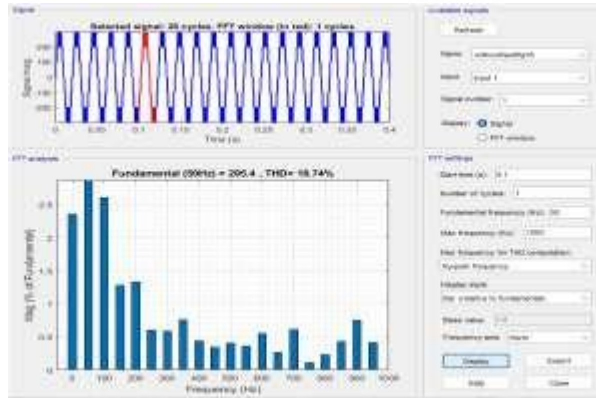


Fault injection block



Seven level output

The output voltages of the proposed 7-level cascaded MLI are shown in Figure 7.6. These output voltages have a magnitude of 300V (peak). As in this situation, there is no fault applied at any switch of the MLI, there for output voltages are equal throughout the simulations.



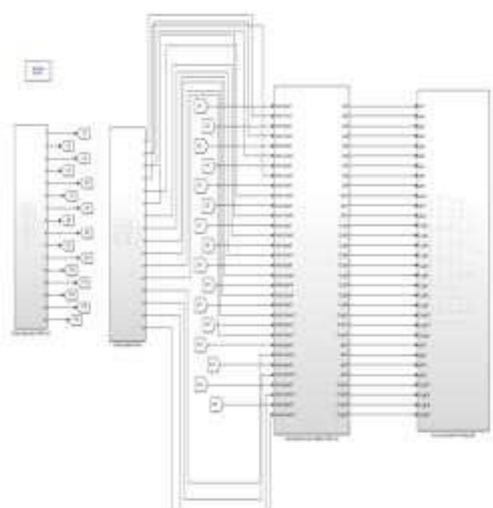
THD value with PI controller

The THD has been measured using the FFT tool of Simulink. A total THD of 18.53% for the normal operation of this CHD MLI. Now the fault is injected by the FIU at 0.1 seconds and the resulting output waveform. The positive peak voltage has reduced to around 200 V and total THD has also increased to 19.2%.

Now the system has been simulated with FTC CHB MLI configuration and the resulting waveform. The results show that the output is affected at 0.1 seconds at the time of fault injection but returns to its normal operation due to the switch over of the faulty switch to the healthy standby IGBT switch.

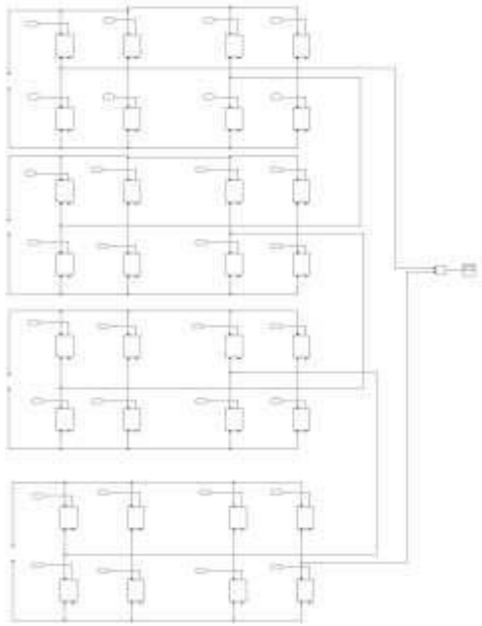
The switching states of both primary and standby IGBTs after the occurrence of fault, which shows the operation of the redundant switch due to the failure of the primary switch. The THD of the output waveform of FT CHB MLI which shows the improvement from 19.2% to 18.55% by the proposed control system. Hence, the objective of reliability enhancement with improved power quality has been successfully achieved.

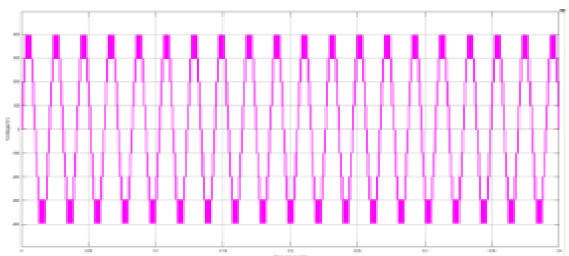
Extendedsimulationmodelwith9level



Casecaded9level

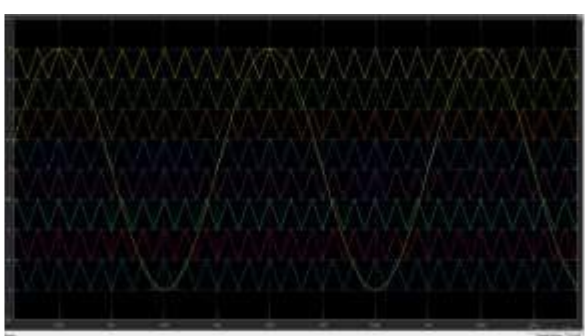
IJERST International Journal of Engineering Research and Science & Technology





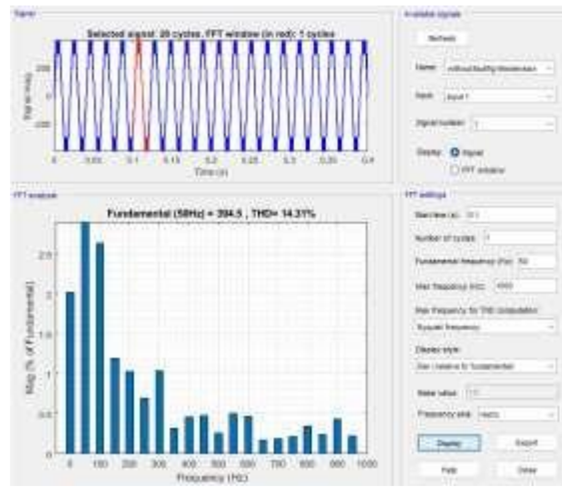
Nine level out put

Figure 7.10 displays the voltages produced by the proposed 9-level cascaded MLI. The highest magnitude of these output voltages is 400V. Since no MLI switch is faulty in this case, the simulation results show consistent output voltages.



Input signals of the phase disposition pulse sinusoidal width modulation

In Figure 7.11, we can see the switching signals that go to the main IGBTs when the 9-level is operating normally. There is no switching signal, thus the backup redundant IGBTs are still in the off state.



THD without fault with PID

Using Simulink's FFT tool, we were able to measure the THD. Under typical conditions, this CHD MLI achieves a total THD of 18.53%. At this point, the FIU injects the fault at 0.1 seconds, and the output waveform is the outcome. Both the positive peak voltage and total THD have dropped to roughly 200 V and 19.2%, respectively.

Here is the resultant waveform after simulating the system with an FTC CHB MLI setup. According to the findings, the output is interrupted for 0.1 seconds during fault injection, but it quickly resumes normal operation after the defective switch is replaced with the healthy standby IGBT switch.

Following the fault's occurrence, the switching states of the main and backup IGBTs reveal how the redundant switch operates in the event that the primary switch fails. The total harmonic distortion (THD) of the FT CHB MLI output waveform shows a reduction of 19.2% to 18.55% as a result of the suggested control method. So, we were able to accomplish our goal of improving power quality while simultaneously increasing dependability.

Conclusion

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.

Thesimulation results demonstrated that the THD has been

References

[1] S. Daher, J. Schmid, and F. L. M. Antunes, ''Multilevel inverter topologies for stand-alone PV systems,''IEEETrans.Ind.Electron.,vol.55,no.7, pp. 2703–2712, Jul. 2008, doi: 10.1109/TIE.2008.922601.

[2] A. Dekka, O. Beik, and M. Narimani, ''Modulation and voltage balancing of a five-level series-connected multilevel inverter with reduced isolated direct current sources,'' IEEE Trans. Ind. Electron., vol. 67, no. 10, pp. 8219–8230, Oct. 2020, doi: 10.1109/TIE.2019.2949537.

[3] S. A. González, M. I. Valla, and C. F. Christiansen, ''Five-level cascade asymmetric multilevel converter,'' IET Power Electron., vol. 3, no. 1, p. 120, 2010, doi: 10.1049/iet-pel.2008.0318.

[4] S. S. Lee, ''Single-stage switched-capacitor module (S3CM) topology for cascaded multilevel inverter,'' IEEE Trans. Power Electron., vol. 33, no. 10,pp.8204–8207,Oct.2018,doi: 10.1109/TPEL.2018.2805685.

[5] G.Konstantinou,S.R.Pulikanti,M.Ciobotaru, V. G. Agelidis, and K. Muttaqi, ''The seven-level flying capacitor based ANPC converter for grid intergrationofutility-scalePVsystems,''inProc.3rd IEEE Int. Symp. Power Electron. Distrib. Gener.Syst. (PEDG), Jun. 2012, pp. 592–597.

[6] P. N. V. S. Ayyappa, C. Srinivas, and T. R. S. Singh, ''A novel way to deal with harmonic eliminationinmultilevelCHBinverterusingwithout filtering technique,'' in Proc. Int. Conf. Electron., Commun. Aerosp. Technol. (ICECA), Apr. 2017, pp. 62–67.

[7] A. R. Abbaspour, ''Active fault-tolerant control design for nonlinear systems,'' M.S. thesis, FIU Electron., 2018, vol. 3917. [Online]. Available: https://digitalcommons.fiu.edu/etd/3917

[8] Z. Ji, J. Zhao, Y. Sun, X. Yao, and Z. Zhu, ''Fault-tolerant control of cascaded H-bridge converters using double zero-sequence voltage injection and DC voltage optimization,'' J. Power Electron., vol. 14, no. 5, pp. 946–956, Sep. 2014.

[9] A.A. AminandK.M.Hasan, ''Areviewoffault tolerant control systems: Advancements and applications,'' Meas., J. Int. Meas. Confederation, vol.143,pp.58–68,Sep.2019,doi: 10.1016/j.measurement.2019. 04.083. [10] R. F. Stengel,''Intelligentfailure-tolerantcontrol,''IEEEControl Syst. Mag., vol. 11, no. 4, pp. 14–23, Jun. 1991.

[11] A. A. Amin and K. Mahmood-Ul-Hasan, ''Advanced fault tolerant air-fuel ratio control of internal combustion gas engine for sensor and actuator faults,'' IEEE Access, vol. 7, pp. 17634–17643, 2019.

[12] M. Sandhu and T. Thakur, ''Modified cascaded H-bridge multilevel inverter for hybrid renewable energy applications,'' IETE J. Res., vol. 1, pp. 1–13, Jul. 2020.

[13] J.-H. Lee and K.-B. Lee, ''A fault detection method and a tolerance control in a single-phase cascaded H-bridge multilevel inverter,'' IFACPapersOnLine,vol.50,no.1,pp.7819–7823, Jul.2017.

[14] Z. Liu, Y. Lu, J. Kong, J. Gong, and S. Wang, ''Multimodal fault-tolerant control for single-phase cascaded off-grid PV-storage system with PV failure using hybrid modulation,'' Microelectron. Rel., vol. 114, Nov. 2020, Art. no. 113772.

[15] S. Khomfoi and L. M. Tolbert, ''Fault detection and reconfiguration technique for cascaded H-bridge 11-level inverter drives operating under faulty condition,'' in Proc. 7th Int. Conf. Power Electron. Drive Syst., Nov. 2007, pp. 1035–1042.

[16] S. Ahmed, A. A. Amin, Z. Wajid, and F. Ahmad, ''Reliable speed control of a permanent magnet DC motor using fault-tolerant H-bridge,'' Adv. Mech. Eng., vol. 12, no. 10, 2020, Art. no. 1687814020970311.