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A Hybrid Reliable Five-Level Fault-Tolerant Inverter for Renewable Energy Sources

R. Dharmaprakash[1], Kota Sarada[2], Parvathi[3], Busireddy Hemanth Kumar[4], E. Parimalasundar[5], and R. Priyanka[6]

[1]*Panimalar Engineering College, Chennai, Tamilnadu, India; Email: rdharmaprakash@yahoo.co.in*
[2]*Koneru Lakshmaiah Education Foundation, Vaddeswaram, A.P, India; Email: sarada@kluniversity.in*
[3]*Ballari Institute of technology and management, Ballari, Karnataka, India; Email: parvathiy@gmail.com*
[4,5]*Mohan Babu University (Erstwhile Sree Vidyanikethan Engineering College), Tirupati, A.P, India; [4]hemub09@gmail.com, [5]parimalpsg@gmail.com*
[6]*S.A Engineering College, Veeraragavapuram, Chennai, India; priyankar@saec.ac.in*

***Correspondence:** *hemub09@gmail.com*;

ABSTRACT- High-gain fault-tolerant multilevel inverters represent a cutting-edge solution for optimizing renewable energy sources, where efficient and reliable power conversion is critical. Multilevel inverters enhance performance by generating a high-quality, nearly sinusoidal output, thus minimizing harmonic distortion and enhancing efficiency. This work explores the hybrid reliable 5-Level fault-tolerant inverter (R5LFTI) for renewable energy sources. The R5LFTI should ensure operational reliability despite component failures. Fault-tolerant features are incorporated to ensure uninterrupted operation, essential for applications with stringent reliability requirements. The proposed R5LFTI inverter system is expected to achieve notable advancements in reliability and output quality, positioning fault-tolerant multilevel inverters as a pivotal technology for improving the performance and feasibility of PV systems in renewable energy and critical backup power applications. Control signals are generated using level-shift PWM to assess the performance of R5LFTI. The analysis for the proposed R5LFTI has been presented in the work under single and multiple switch open circuit faults (OCF). MATLAB/Simulink simulation results have been presented to analyze the topology, demonstrating fault resilience and seamless transitions during fault conditions. Hardware results are also presented to validate the practicality of the proposed R5LFTI under OCF conditions.

Keywords: fault tolerant, reliability, open circuit, multilevel inverter.

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1. INTRODUCTION

In recent decades, global energy consumption has grown exponentially, driven by rapid industrialization, urbanization, and population expansion. As conventional fossil fuel-based energy sources continue to face depletion concerns and pose serious threats to environmental sustainability through greenhouse gas emissions and pollution, the importance of transitioning towards renewable energy has never been greater [1]. Consequently, research and development efforts worldwide have intensified, aiming to harness clean and sustainable energy alternatives such as photovoltaic (PV) systems, wind energy, hydroelectricity, and fuel cells. Among these, solar photovoltaic technology has gained substantial prominence due to its abundance, sustainability, scalability, and declining costs [2].

Solar photovoltaic systems convert sunlight directly into electricity through semiconductor-based solar cells. These cells generate direct current (DC), which, although useful in some isolated applications, is incompatible with most residential, commercial, and industrial applications that predominantly require alternating current (AC) [3]. Therefore, efficient power electronics interfaces—specifically DC-AC inverters—are essential components of PV systems, facilitating the integration of renewable energy into existing power grids and enabling practical utilization by end-users [4]. Initially, conventional two-level inverters dominated the market due to their simplicity and reliability [5]. However, these traditional inverter topologies exhibit notable limitations, particularly in medium-to high-voltage applications, such as elevated harmonic distortion, increased voltage stress across individual switches, higher electromagnetic interference (EMI), elevated switching losses, and limited scalability [6].

To overcome these limitations, multilevel inverters (MLIs) have emerged as a transformative and highly attractive technology in power electronics, particularly suited for integration with renewable energy sources [7]. Multilevel inverter architectures significantly improve power conversion

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efficiency and power quality by synthesizing the AC output waveform in discrete voltage steps, closely approximating a clean sinusoidal waveform [8]. This approach substantially reduces total harmonic distortion (THD), lowers electromagnetic interference, decreases voltage stress across semiconductor switches, and enhances overall system reliability [9]. As a result, MLIs have rapidly gained traction, finding widespread applications in renewable energy grid integration, industrial motor drives, electric vehicles, reactive power compensation, and high-voltage direct current (HVDC) transmission systems [10].

Despite these clear advantages, multilevel inverters inherently involve increased complexity, as they typically incorporate a higher number of semiconductor switches, capacitors, diodes, and other passive or active components [11]. Each added component poses additional points of potential failure, increasing susceptibility to faults and operational disruption. Unexpected inverter failures in such scenarios can lead to prolonged downtimes, significant maintenance costs, reduced energy generation, and ultimately undermine the economic viability and sustainability of solar energy installations [12].
In response to these critical reliability challenges, researchers have focused considerable attention on developing fault-tolerant multilevel inverters (FTMLI) topologies capable of maintaining stable and reliable operation even in the presence of component failures [13]. Fault tolerance fundamentally refers to the system's ability to detect, isolate, and compensate for faults without interrupting normal operation or significantly compromising performance. Incorporating fault tolerance features into MLIs allows the inverter to continue functioning effectively after certain switch, diode, capacitor, or other component failures occur [14]. This capability is especially crucial for critical industrial processes, remote renewable energy installations, autonomous microgrids, and safety-sensitive applications where uninterrupted power delivery is mandatory.

Numerous approaches have been proposed in the literature to introduce fault tolerance in multilevel inverter structures. Early fault-tolerant MLIs typically employed redundant components or modules, enabling the inverter to bypass faulty modules and maintain continuous operation. For instance, modular multilevel converters (MMCs) gained attention due to their inherent modularity and redundancy, allowing faulty cells to be isolated without compromising overall inverter performance [15]. However, this modular redundancy inevitably increased the total component count, complexity, and cost, diminishing the attractiveness of MMC-based solutions for cost-sensitive applications.

Many researchers have explored reconfigurable inverter topologies, utilizing bidirectional switches, advanced relays, or additional control mechanisms to achieve fault-tolerance capabilities. However, these reconfigurable schemes commonly involve increased computational complexity, control difficulty, and additional hardware costs [16].

Despite considerable advancements, existing fault-tolerant MLI topologies still exhibit several limitations. Many FT-MLI designs depend heavily on bidirectional switches, which can be challenging to implement practically due to cost and complexity. Additionally, some topologies fail to sustain rated output power levels after certain faults, leading to noticeable performance degradation under fault conditions. Capacitor voltage imbalance problems frequently arise in several proposed topologies, requiring additional complicated balancing circuits or control strategies [17]. Furthermore, existing solutions often involve the use of multiple isolated DC sources, tap-changing transformers, or excessive redundant components, adding substantial system size, weight, and cost, thus limiting their practicality for large-scale PV applications [18].

Given these unresolved challenges, developing an optimized fault-tolerant multilevel inverter topology that effectively balances component count reduction, improved fault-handling capability, simplified control implementation, and reliable performance under various fault conditions remains a critical and timely research priority. [19]. Addressing these requirements will significantly enhance system reliability, reduce maintenance overheads, improve economic viability, and accelerate widespread integration of photovoltaic systems in global energy networks [20]. This work proposes a hybrid reliable 5-Level fault-tolerant inverter (R5LFTI) specifically tailored for photovoltaic applications. The proposed R5LFTI design strategically reduces the total number of active components—including semiconductor switches and capacitors—while simultaneously enhancing fault tolerance capabilities and reliability. Also, the R5LFTI achieves robust fault tolerance without relying on complex bidirectional switches, additional DC sources, or tap-changing transformers. Furthermore, this topology inherently ensures stable output voltage waveforms, minimal harmonic distortion, and sustained rated power output during component failures, addressing key limitations identified in existing literature.

2. HYBRID RELIABLE 5-LEVEL FAULT-TOLERANT INVERTER (R5LFTI)

The proposed R5LFTI topology, consisting of 10 power switches (S1–S10), a single DC source (VS), a single capacitor (C) for voltage balancing, and a load connected to the output, is shown in *figure 1*. The topology resembles a Hybrid or Cascaded H-bridge multilevel Inverter, which is commonly used in high-power applications. The inverter works by converting DC voltage into a stepped AC voltage waveform through controlled switching operations. The capacitor helps in voltage balancing and energy storage, ensuring smooth operation. The R5LFTI generates multiple voltage levels, such as +VS, +0.5VS, 0, -0.5VS, and -VS by selecting appropriate switching combinations. By carefully controlling these switching states, the inverter synthesizes a multilevel stepped waveform, significantly improving the output voltage quality. This topology offers several advantages, including lower THD, reduced voltage stress on individual switches, and scalability for high-power applications. By precisely managing the switching sequence based on redundancy switching states, the R5LFTI achieves a high-quality AC voltage output with

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reduced harmonics, improved efficiency, and provides reliable output in the event of single and multiple switch faults. The conduction paths of each voltage level of R5LFTI are shown in *figure 2*. The switching strategy of the proposed R5LFTI, including all the redundancy switching states, is shown in *table 1*. The switching state redundancies, which enhance the R5LFTI's ability to remain functional in the event of a fault in any switch. Under standard operating conditions, the proposed R5LFTI is capable of delivering a 5-level output voltage. If a fault occurs, whether in a single switch or multiple switches, the R5LFTI topology almost seamlessly provides a five-level output only by utilising the redundancy switching states effectively. *Table 2* shows the R5LFTI output voltage levels for various single-switch and multiple-switch OCFs.

Table 1. Possible Switching States of Proposed R5LFTI

ON State Switches	Output Voltage level
$S_1S_2S_6/S_6S_8/S_1S_2S_9/S_8S_9$	$+V_S$
$S_2S_5S_6/S_1S_4S_6/S_2S_5S_9/S_1S_4S_9$	$+0.5V_S$
$S_1S_2S_3/S_4S_5S_6/S_3S_8/S_6S_{10}/S_1S_2S_7/S_4S_5S_9/S_7S_8/S_9S_{10}$	0
$S_1S_3S_4/S_2S_3S_5/S_1S_4S_7/S_2S_5S_7$	$-0.5V_S$
$S_3S_4S_5/S_3S_{10}/S_4S_5S_7/S_7S_{10}$	$-V_S$

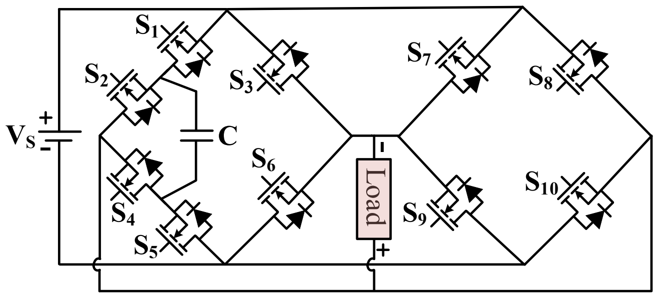
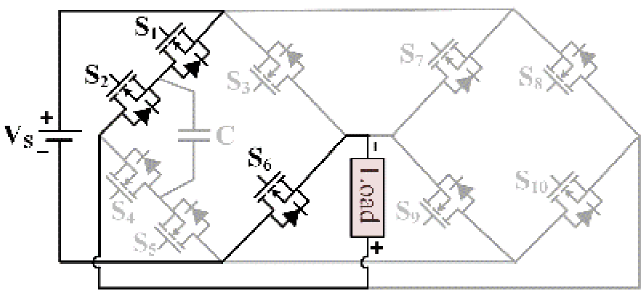
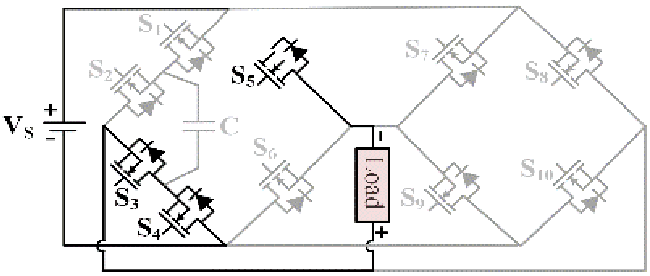


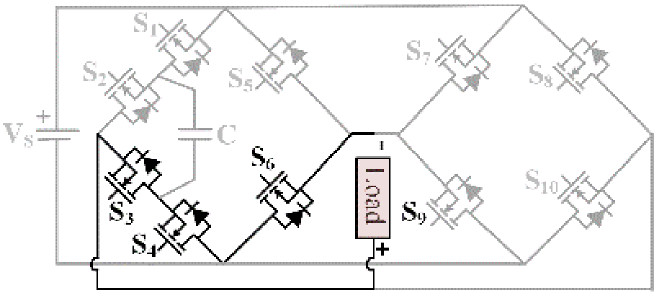
Figure 1. Proposed Hybrid Reliable 5-Level Fault-Tolerant Inverter



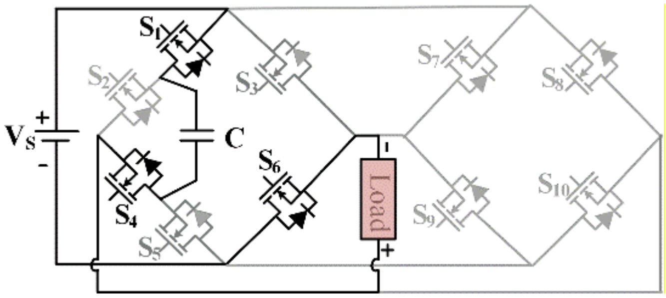
(a) $+V_S$



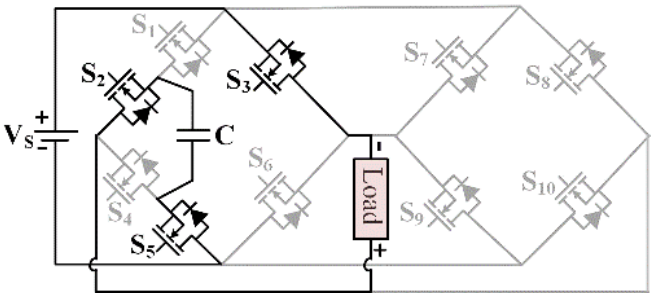
(b) $-V_S$



(c) $0V_S$



(d). $+0.5V_S$



(e) $-0.5V_S$

Figure 2. Conduction paths of R5LFTI for different output voltage levels

Table 2. R5LFTI output voltage levels for various switch(es) OCFs

Faulty Switch(es)	Output Voltage levels	Faulty Switch(es)	Output Voltage levels
S_1	5	S_3 & S_5	5
S_2	5	S_3 & S_6	5
S_3	5	S_4 & S_6	5
S_4	5	S_1 & S_4	5
S_5	5	S_3 & S_4	5
S_6	5	S_1 & S_2	5
S_1 & S_3	5	S_1 & S_5	5
S_1 & S_6	5	S_2 & S_4	3
S_2 & S_5	5	S_4 & S_5	3
S_2 & S_6	5		

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3. RESULTS & DISCUSSIONS

The proposed R5LFTI has been analyzed in a MATLAB Simulink platform. A 100V DC input is used as a voltage source (VS). The R-load of 100Ω is considered. No filter has been used at the load side to filter out the harmonics. To generate gate pulses, a 50 Hz fundamental reference signal and a 2 kHz carrier frequency are considered in PWM control for analyzing the operation of R5LFTI. In carrier-based PWM, the reference sinusoidal wave, whose frequency (FR) is required load frequency, is compared with the high-frequency (FC) carrier to generate gating signals. The flow chart of generating the gate pulses for different fault scenarios is shown in *figure 3*. The OCF in a switch is realized simply by removing the gate pulse to the particular switch. The output voltage varies between +100V and -100V, with each step in switching action showing a 5-level variation in the output voltage at unity modulation index (M) during normal operation. The THD of 5-level phase output voltage is obtained as 22.56%. The results have been obtained by considering two cycles each for prefault, during fault, and post-fault conditions for assessing the performance of R5LFTI. Initially, for two cycles, the R5LFTI operates normally, producing a stable five-level waveform. During a switch fault for two cycles, distortions occur, reducing the voltage levels due to switch failures. Thereby, utilizing the redundancy switching states during the post-fault case, the stable waveform has been obtained, which is shown for two cycles. *Figure 4(a)* shows the output voltages of R5LFTI during normal operation. It is seen that the output voltage has five levels. *Figure 4(b), 4(b),* and *4(c)* represent output voltages of R5LFTI during single switch OCF in Switches S_1, S_3, and S_5, respectively. It is seen that during the fault, the wave waveform is not stable and also has high harmonic content. By using the switching redundancies of R5LFTI, the control scheme is modified such that a balanced output waveform is achieved as similar to the prefault case, which improves the reliability of R5LFTI.

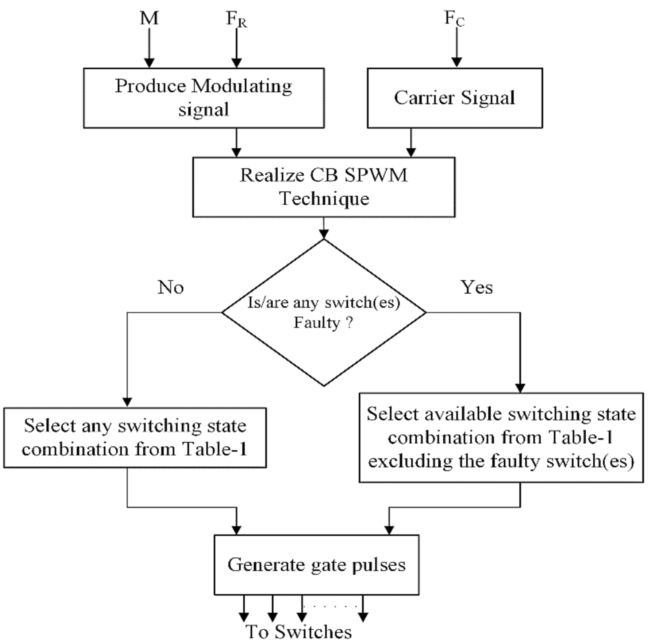
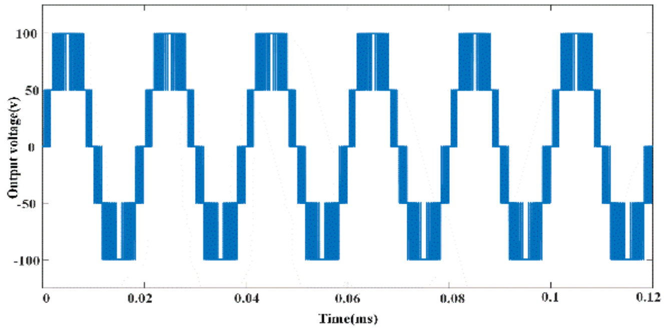
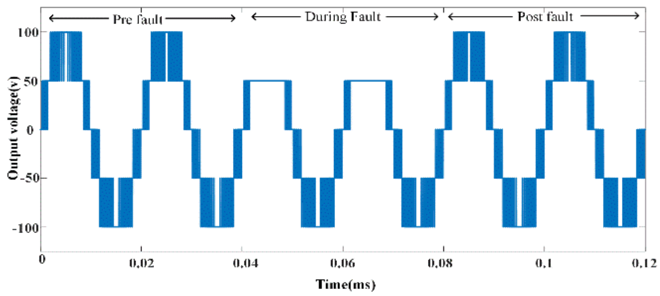


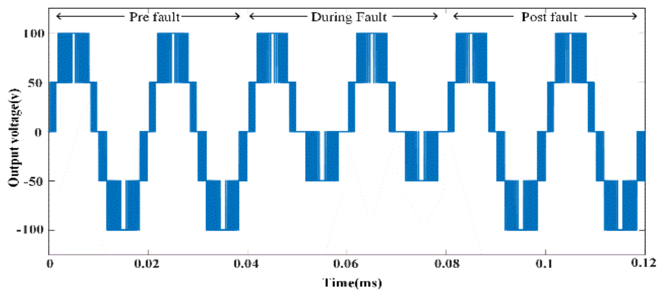
Figure 1. Relay test equipment overall view



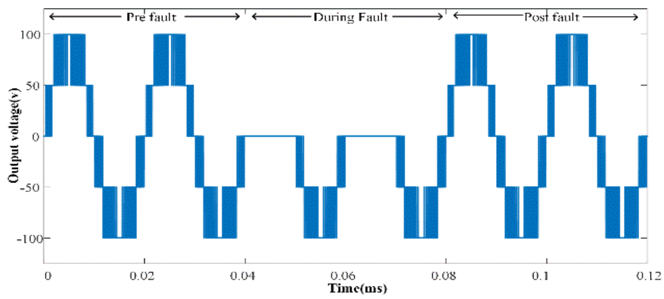
(a) No fault



(b) OCF in switch S_1



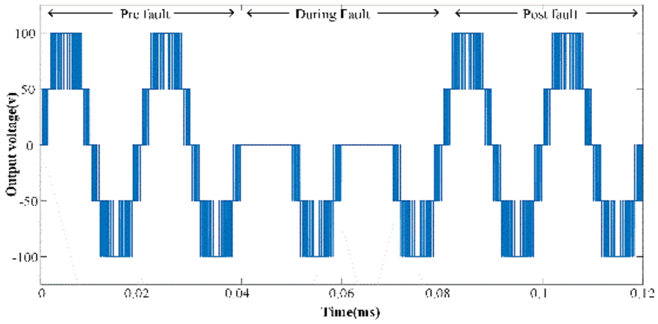
(c) OCF in switch S_3



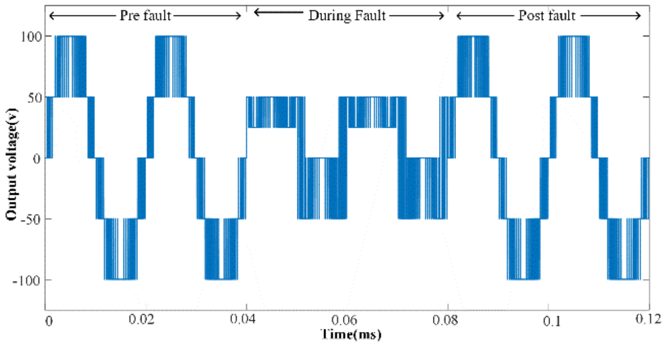
(d) OCF in switch S_5

Figure 4. Simulation output voltage of R5LFTI for various operating conditions

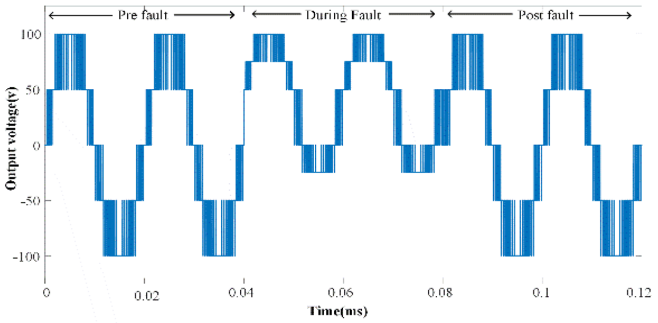
Figure 5(a), 5(b), 5(c) and *5(c)* represents the output voltages of R5LFTI during multiple switch OCFs in S_1 & S_2, S_1 & S_5, S_1 & S_6 and S_2 & S_5 respectively. It is seen that during the multiple switch faults, the R5LFTI output voltage waveform is not the proper shape and also has high harmonic content. By using the switching redundancies of R5LFTI, the control scheme is modified as per *figure 3*, such that a balanced output waveform is achieved as similar to the prefault case, *i.e.*, 5 levels are obtained.



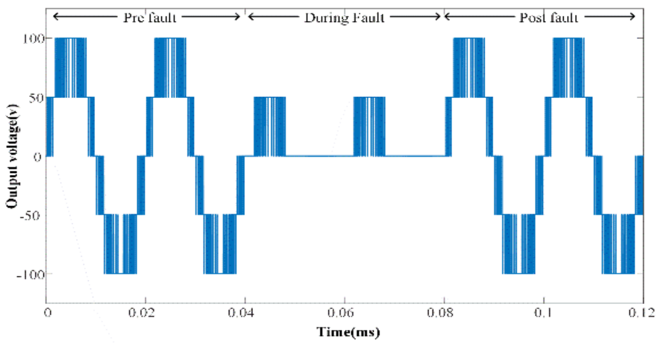
(a) OCF in switches S_1 & S_2



(b) OCF in switches S_1 & S_5



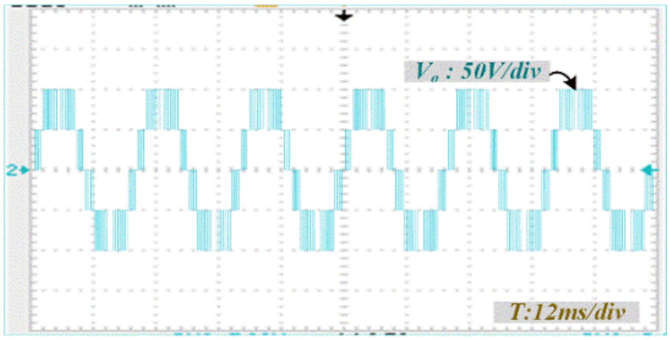
(c) OCF in switches S_1 & S_6



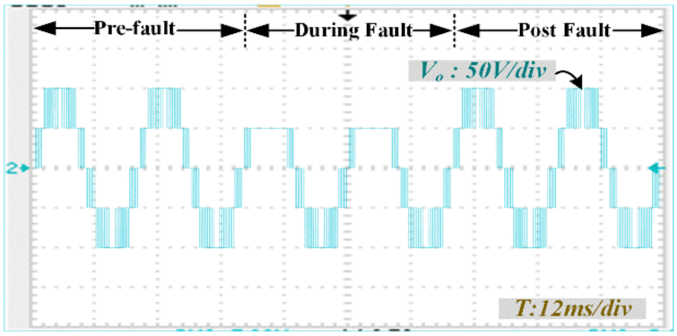
(d) OCF in switches S_2 & S_5

Figure 5. Simulation output voltage of R5LFTI for multiple switch faults

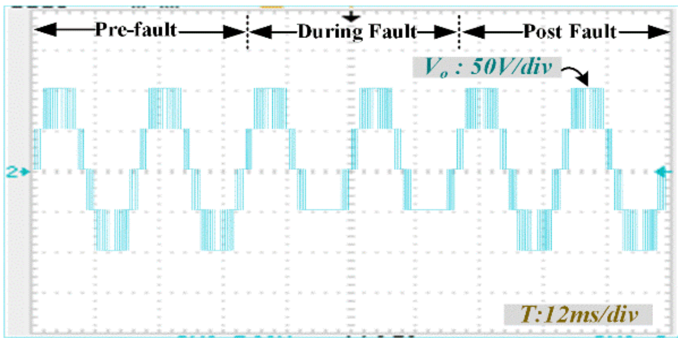
To validate the practicality of the proposed R5LFTI, the hardware results have been presented for the single switch and multiple switch faults, which are shown in the *figure 6*. Post fault scenario, the switching strategy has been modified accordingly from the availability switching state redundancy by ensuring that a stable output voltage waveform with lower harmonic distortion has been obtained. The load current waveform purely depends on the nature of the load and load voltage. So, only the load voltage waveform is presented for different switch fault cases to analyse and validate the performance of the proposed R5LFTI.



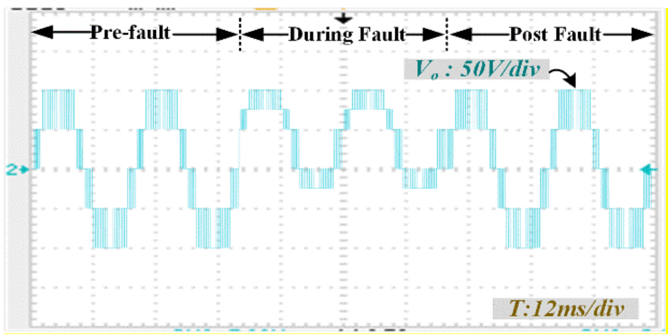
(a) No fault



(b) OCF in S_1



(c) OCF in S_4



(d) OCF in S_1 & S_6

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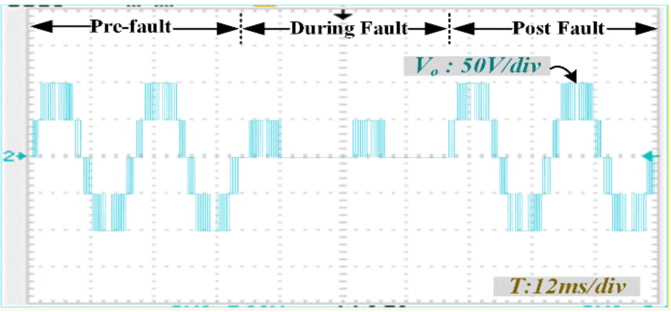
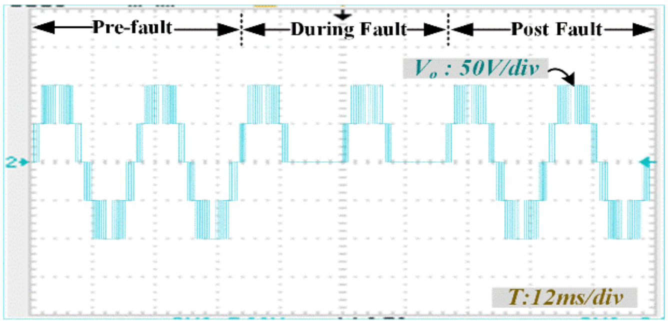


(e) OCF in S_2 & S_5



(f) OCF in S_3 & S_4

Figure 6. Experimental waveforms of R5LFTI output voltage for multiple switch faults

4. CONCLUSION

This work presents a hybrid reliable 5-Level fault-tolerant inverter (R5LFTI) for renewable energy sources. The proposed R5LFTI topology enhances reliability while utilizing fewer components, making it more efficient and cost-effective. The R5LFTI integrates a fault-tolerant mechanism to sustain stable operation even during OCF, ensuring uninterrupted power supply. In the presence of OCFs, whether in single or multiple switches, the proposed R5LFTI maintains functionality by producing a stable five-level output voltage. Compared to traditional designs, the R5LFTI configuration delivers superior performance with a reduced component count, making it a practical solution for power conversion applications like solar PV applications. Simulation results for all the single-switch and multiple-switch fault cases have been presented. Hardware results are also presented to validate the practicality of the R5LFTI, which makes the topology suitable for providing a continued power supply in vital applications for the use of renewable energy sources.

Author Contributions: Conceptualization, BHK and RD; methodology, BHK; validation, BHK, KS, and RP; formal analysis, BHK and RD; investigation, RD, BHK, and EP; resources, BHK and P; data curation, RD and EP; writing—original draft preparation, RD and BHK; writing—review and editing, BHK, KS, and RP; visualization, BHK and P; supervision, BHK. All authors have read and agreed to the published version of the manuscript.

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