Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 13, No. 2, June 2025, pp. 309~323
ISSN: 2089-3272, DOI: 10.52549/ijeei.v13i2.6288

A New Fault Tolerant Scheme for Switch Failures in LLC Resonant Converter

Xu Lili[1], Muhamad Nabil Hidayat[2], Nik Hakimi Nik Ali[3]
[1,2,3] School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Malaysia
[1,2] Hunan Railway Professional Technology College, China

Article Info

Article history:

Received Jan 7, 2025
Revised Mar 21, 2025
Accepted Apr 10, 2025

Keywords:

LLC resonant converter
Fault tolerance
Topological transformation
Fault monitoring
Fault diagnosis

ABSTRACT

The LLC (Inductance Inductance capacitance) resonant converter offers advantages such as high power density, high efficiency, and compact size, making it widely used in photovoltaic power generation systems. Its operational reliability is crucial for the continuous performance of these systems. However, complex operating conditions and variable climates can adversely affect power equipment. Switch fault diagnosis and remedial measures are essential aspects of designing isolated full-bridge DC-DC converters, significantly enhancing overall system reliability. When a switching component fails, the resonant converter cannot operate near its resonant point, leading to substantial reductions in efficiency and output power. To improve system fault tolerance and reduce maintenance costs, this paper proposes an improved LLC topology and a rapid switch short-circuit fault diagnosis method for phase-shift full-bridge converters. By real-time monitoring of the average voltage of the resonant capacitor, the method quickly identifies switch short-circuit faults within a single switching cycle, enabling topological control of faulty and redundant components. The modified topology ensures stable output voltage and power while allowing the converter to operate near the resonant frequency. The paper discusses the working principle, design considerations, and implementation of this approach. Simulation results verify the effectiveness of the proposed method.

Corresponding Author:

Muhamed Nabil Hidayat
Energy Storage Laboratory (BEST), College of Engineering Universiti Teknologi MARA
Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia
Email: mnabil@uitm.edu.my

1. INTRODUCTION

The LLC resonant converter has gained widespread attention and application in recent years due to its numerous advantages, including a wide input voltage range, high power density, and the capability to achieve soft switching. These attributes make it an ideal candidate for various applications such as renewable energy grid integration, electric vehicles (EVs), rail transportation, and onboard auxiliary power systems [1], [2]. The structural configurations of LLC converters generally include half-bridge, full-bridge, and T-bridge designs. Among these, the full-bridge LLC converter stands out due to its superior voltage blocking capability and higher boost ratio, which allow the use of components with lower voltage ratings, ultimately reducing system cost [3]. However, the increased number of power switching devices in the full-bridge topology introduces significant challenges in ensuring system reliability. Industry surveys reveal that switching devices are among the most failure-prone components in power electronics, with a failure rate reaching approximately 31% [4].

When a fault occurs in the switching devices of an LLC converter, maintaining stable operation becomes increasingly difficult. Faults, particularly open-circuit faults (OCFs), can disrupt the converter's performance, making it challenging to operate near the resonant point and regulate the output voltage effectively [5]. Additionally, the resonant capacitor may experience voltage spikes during a fault, potentially causing further damage to switching devices and leading to system instability [6].

If an Open Circuit Fault (OCF) occurs in the switching tube of a full-bridge LLC converter during operation, the converter will be unable to function properly. This type of fault can arise due to several factors, such as driver malfunctions leading to signal loss or damage to the semiconductor switch [7], [8]. Unlike short-circuit faults, which generate excessive current and trigger the system's protection mechanisms, open-circuit faults are more challenging to detect and mitigate in real time. Consequently, the system may struggle to respond effectively unless the fault is accurately diagnosed and addressed promptly [9]. When an OCF occurs, the system must typically take two critical steps to prevent further damage. First, it must quickly and accurately identify the fault location. Second, it should either isolate the fault or enable continued operation through fault-tolerant measures.

2. RELATED WORKS

A lot of scholars have proposed various approaches to enhance the fault tolerance of converters. Current fault tolerance methods primarily rely on module redundancy to improve converter reliability. This involves isolating any module that experiences an open circuit fault from the circuit and subsequently replacing it with a suitable standby module, thereby maintaining some level of power transmission capability during fault-tolerant operation [10]. For instance, Huang et al. introduces a fault-tolerant method that employs redundant half-bridges in parallel on the primary side. When a failure occurs in the full-bridge converter on the primary side, the system can transition to half-bridge operation and be reconstructed into a full bridge using redundant transformers and half-bridges . However, this topology increases both the size and cost of the converter [11]. Additionally, Bhakar et al. proposes a fault-tolerant operation mode for Dual Active Bridge (DAB) converters . By incorporating resonant capacitance, the faulty half-bridge converter can be transformed into an LLC resonant half-bridge converter, which enhances the voltage post-failure but does not achieve the rated output voltage as in [12]. Another approach presented purposed by Wang et al., introduces a redundant topology with three bridge arms at the front stage. In the event of a failure in any one bridge arm, the redundant arm takes over its function, providing high fault tolerance. However, this topology requires the addition of two additional switching devices, thereby increasing system costs [13]. Furthermore, Zhao et al. proposes a fault-tolerant method involving a closed fault bridge arm to improve the reliability of DAB converters , however, this approach also fails to achieve rated output power in the steady state following a fault. In the realm of modular converters, post-fault operation is predominantly realized by adding redundant modules [14]. For example, Liu et al. discusses the integration of redundant modules to facilitate fault-tolerant operation of a single DAB open circuit within a modular system, enhancing converter reliability in high-voltage direct current (HVDC) transmission applications [15]. Table 1 summarizes the methods, characteristics, and limitations of fault-tolerant techniques for LLC converters with different topologies.

Table 1 Fault tolerant methods proposed in various converters

References	Methods	Applied topology	Characteristics	Limitation
[10]	Add a redundant half bridge	Full bridge LLC converter	Easy and effective but the cost increases significantly.	Adding a transformer increases the volume and the cost increases significantly
[12]	Replace fault primary-arm by using the redundant arm	Full bridge LLC converter	Easy but the cost increases significantly.	Complex control strategy
[13]	Add redundant modules	Modular converter	1)Suitably in cascaded system with redundant modules; 2) Easy but the cost increases significantly.	Cannot be employed in single phase converter
[15]	The resonant capacitor is added to convert DAB into LLC converter	Full bridge DAB converter	Easy and low cost but fault tolerance does not work well.	Postfault power range is limited, especially when the voltage conversion ratio is low.

Conventional fault detection and fault isolation methods exhibit obvious limitations in terms of detectionspeed, number of FD signatures, universality, accuracy, computational burden, and implementation cost due to the added sensors [16]. In the same time, it is evident that previous studies have not addressed fault diagnosis specifically for LLC converters. Consequently, the effectiveness of existing diagnostic methods is significantly diminished when applied to LLC converters, as the diagnostic signals may remain identical across multiple switches in the event of an Open Circuit Fault (OCF) [17].

For effective fault diagnosis and localization, the employed method should be straightforward, rapid, and accurate. The initial step in mitigating the impacts of open circuit faults involves identifying the fault through a systematic diagnosis strategy. Several commonly utilized fault diagnosis methods include :

inductance current of the resonator tank and the voltage at both ends of the transformer, the polarity of the DC component of the inductive current and the mean value of the transformer voltage. For instance, Tang et al. presents a fault detection strategy utilizing a Luenberger state observer along with inductive current and output voltage sensors to identify open circuit faults in the switch tube of boost converters [18]. Gao et al. processing the diode voltage and gate driver signal within the converter to derive logic signals serves as a basis for fault diagnosis [19]. Although this method demonstrates effectiveness, its applicability is somewhat limited. Another approach identifies the fault branch and locates the specific position of the faulty switch by analyzing the input and output voltage signals of the rectifier bridge arm; however, this method requires the addition of five extra switches and is exclusively applicable to three-phase traction converters [20]. Additionally, Shi et al. introduces a fault detection method for Dual Active Bridges (DAB), which employs four supplementary voltage sensors to monitor the midpoint voltage of the bridge arm [21]. The measured data is processed and compared with normal voltage values to diagnose any faulty switches. Wang et al. proposed a precise open-circuit fault diagnosis (OCFD) method for phase-shifted LLC resonant converters using the integral of the bridge arm midpoint voltage,which exclusively depends on the integral value of the voltage at the midpoint of the primary-side switching bridge arm [22]. Li et al. proposed an adaptive fault diagnosis (FD) observer based on the Lyapunov function is given to simultaneously estimate the fault, disturbance, and state with packet losses. Different from the traditional robust fault-tolerant control (FTC), a new active fault-tolerant tracking controller is designed based on the model predictive control framework, which has better adaptive fault-tolerant performance [23]. Table 2 provides a summary of prior fault diagnosis methodologies employed in full-bridge LLC converters, highlighting the diagnostic signals used, their characteristics, and the associated limitations of each approach.

Table 2 Fault diagnosis methods and fault tolerant proposed in various converters

References	Diagnosis signals	Applied topology	Characteristics	Limitation
[19]	The rectifier module of the traction converter inputs and outputs voltage signals	Modular converter	1) No additional sensor required; 2) Easy but the cost increases significantly.	Many accessory components, only suitable for three-phase high-power traction converter
[20]	Inductor current and output voltage	DC-DC Boost converter	State Observer + Detection sensor Suitable for monitoring open circuit faults, gain anomalies	Suitable for BOOST converter only
[21]	Diode voltage and gate driver signal	DC-DC buck converter	Easy and effective but the cost increases significantly.	Adding a transformer increases the volume and the cost increases significantly
[22]	The midpoint voltage of the bridge arm	DAB converter	Easy but the cost increases significantly.	Complex control strategies

Despite these challenges, research focusing on fault diagnosis and fault-tolerant operation of LLC converters remains limited. Most existing studies emphasize short-circuit faults, which trigger system protection mechanisms due to excessive current, while OCFs are comparatively more difficult to detect and mitigate in real time [24]. The lack of effective diagnosis and fault-tolerant strategies for LLC converters under OCF conditions could significantly compromise their performance and reliability [25]. Given these challenges, this paper aims to investigate strategies that enable LLC converters to maintain normal operation under fault conditions. Specifically, this study focuses on diagnosing open-circuit faults in switching devices and implementing fault-tolerant methods to restore the converter's functionality. The ultimate goal is to ensure stable output voltage and reliable operation even when faults occur, thereby enhancing the overall robustness and reliability of the LLC converter in practical applications.

The contribution of this article is as follows.

i) Rapid Fault-Tolerant Scheme for Open-Circuit Faults in High-Frequency LLC Converters. This paper introduces a rapid fault-tolerant scheme for detecting and locating open-circuit faults in power switches of high-frequency LLC converters within a single switching cycle by monitoring the voltage of the resonant capacitor. This method requires only a single voltage sensor and is compatible with various control strategies, thereby minimizing additional hardware costs.

ii) Novel Fault-Tolerant Topology Reconfiguration for LLC Resonant Converters. This paper proposes a novel topology reconfiguration strategy for fault-tolerant LLC resonant converters that ensures continuous operation even after multiple switch failures. Initially configured as a full-bridge LLC converter, when primary-side fault occurs, the primary side is converted to half-bridge operation, while the secondary side is converted to two full-bridge parallel operation upon. This adaptive approach enhances system reliability with minimal additional components and maintains consistent voltage and current stresses across all operating modes, simplifying circuit design and control systems.

iii) Experimental Validation of Effectiveness and Rapid Diagnosis: The effectiveness and rapid diagnostic capability of the proposed method are validated through experimental results, highlighting the potential of LLC converters in enhancing overall system reliability.

The structure of the rest of the article is as follows. Section 2 thoroughly investigates the proposed system, encompassing topology transformation fault diagnosis policy and fault tolerant policy. Section 3 presents an evaluation of the experiment along with the corresponding discoveries and verification of the proposed method. Finally, conclusions are presented in section 4.

3. METHOD

Faults in power converters, such as open-circuit and short-circuit failures, can significantly impact system performance and reliability. Effective fault diagnosis and fault-tolerant strategies are essential to ensure the stable operation of converters under fault conditions. This section explores various methods and techniques for fault diagnosis and tolerance in LLC converters, with a particular focus on addressing open-circuit faults.

3.1 Analysis of open-circuit fault characteristics

Based on the comparative analysis presented, this paper proposes a novel fault-tolerant method for LLC converters addressing open-circuit faults in switching tubes, specifically utilizing the Bypass Arm (BA) control scheme. When a switch on the inverter side fails, the pulse for the bridge arm associated with the faulty transformer IGBT is blocked to restore the converter to a normal operational state. This approach effectively mitigates the effects of the Open Circuit Fault (OCF) by disabling the gate drive signal of the complementary switch, thereby counteracting the fault. The BA based fault tolerant scheme allows the converter to transition into half-bridge operation following a brief fault tolerant process, as illustrated in Figure 1(a). During this fault-tolerant operation, only one set of switches in the inverter bridge remains active, resulting in the input voltage to the resonator comprising either a fully negative or fully positive component. While the voltage and current waveforms maintain symmetry, there is a reduction in gain. For example, as depicted in Figure 1(b), when switch S1 occur an open circuit fault, the drive pulse for S3 is always set to 1, while the bypass arms S2 and S4 working normally.

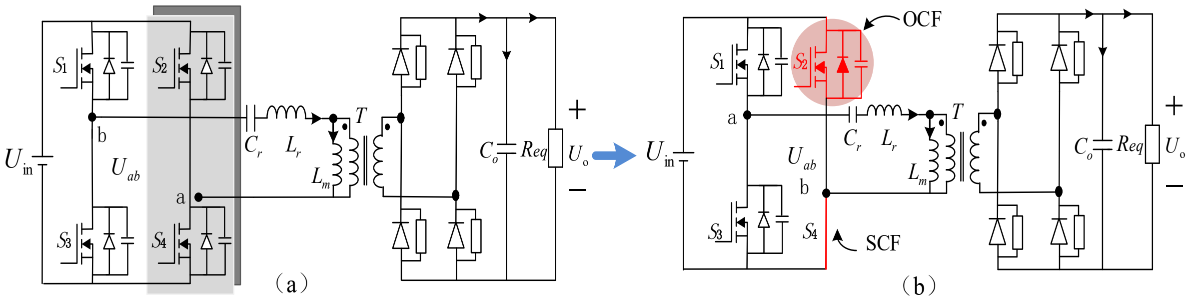

Figure 1. Equivalent circuit using an BA method (a) Topology during normal operation and (b) Topology after S2 open circuit fault

The LLC full-bridge converter primarily consists of an inverter circuit, a resonator, and a rectifier circuit. Under normal operating conditions, the converter functions in full-bridge mode, where the DC input voltage (U_{in}), is transformed into a square wave voltage (U_{ab}) via the inverter circuit. This square wave voltage passes through the resonator and rectifier circuit to produce a DC output voltage U_o.

When switch *S1* in the converter fails, the topology shifts from full-bridge to half-bridge operation. At this point, only one set of switches in the inverter bridge remains operational, resulting in the resonator cavity receiving an input voltage without a negative component. The output voltage is then elevated to the rated value by the series rectifier bridge arm. Figure 1 illustrates the circuit topology transformation that occurs before and after the switch failure in the traditional LLC resonant converter. In this figure, Lr, Cr, Lm, and Reqrepresent the resonant inductance, resonant capacitance, excitation inductance, and equivalent resistance, respectively. Additionally, U_{ab}denotes the equivalent input voltage of the resonator tank, corresponding to the primary voltage of the transformer when U_{in1} is *n=1*, and the secondary voltage of the transformer when $U_{o1}$is *n=1*. This paper employs the fundamental wave analysis method to derive the DC voltage gain before and after the switch fault. The Fourier expansion of the input voltage U_{ab} of the resonator prior to the fault is presented as equation1, ω_s is angular frequency.

$$u_{ab}(t) = \sum_{n=1}^{\infty}[\frac{4NU_o}{\pi} sin(\omega_s t)] \quad (1)$$

The gain expression of the FHA equivalent circuit of the LLC resonant converter is shown as equation 2.

$$H(j\omega) = \frac{U_{p1}(j\omega)}{U_{in1}(j\omega)} = \frac{R_{eq}||j\omega L_m}{j\omega L_r + \frac{1}{j\omega C_r} + R_{eq}||j\omega L_m} \quad (2)$$

R_{eq} is the load equivalent to the original side of the transformer and the equivalent load is obtained: $R_{eq} = \frac{U_{p1}}{I_{p1}} = \frac{8N^2}{\pi^2}$R. Simplifying the above formula, the DC gain of converter before fault can be derived as equation 3.

$$G(F_x, m, Q) = |H(j\omega)| = \frac{(m-1){F_x}^2}{N\sqrt{(m{F_x}^2-1)^2 + Q^2(m-1)^2{F_x}^2({F_x}^2-1)^2}} \quad (3)$$

m is the normalization of excitation inductance and resonant inductance, $m = \frac{L_m+L_r}{L_r}$. F_x is the frequency normalization, $F_x = f_s/f_r$. Q is the quality factors, can be normalized to: $Q = \frac{\sqrt{\frac{L_r}{C_r}}}{R_{eq}}$.

When switch S1 fails, the converter is converted to half-bridge operation, and the Fourier series expansion of Uab is shown in equation 4:

$$u_p(t) = \sum_{n=1}^{\infty}[b_n \, sin(\frac{2\pi nt}{T})] \quad (4)$$

The gain expression of the LLC resonant converter is shown in equation 5:

$$H(j\omega) = \frac{U_{p1}(j\omega)}{U_{in1}(j\omega)} = \frac{R_{eq}||j\omega L_m}{j\omega L_r + \frac{1}{j\omega C_r} + R_{eq}||j\omega L_m} \quad (5)$$

The DC gain expression obtained by simplifying the above formula and normalization is shown in equation 6:

$$M(F_x, m, Q) = |H(j\omega)| = \frac{(m-1){F_x}^2}{2N\sqrt{(m{F_x}^2-1)^2 + Q^2(m-1)^2{F_x}^2({F_x}^2-1)^2}} \quad (6)$$

As in equation (3) and equation (6), it can be obtained that after single-phase full-bridge LLC has a single tube fault, the output DC voltage gain can be halved after BA fault-tolerant operation. Taking $Lr = 5$μH, $Lm = 26$μH, $Cr = 480$μF, n = 2, $R = 60\Omega$ as parameters, m = 4, Q = 0.4, the voltage gain curve is shown in Figure 2. Where, Fx(y) represents the voltage gain curve before the fault, and Fx(z) represents the voltage gain curve after the fault. It can be seen from Figure 2 that the traditional LLC converter controlled only by PFM reduces the voltage gain by half after the switch failure, and cannot run near the resonant point while keeping the output voltage unchanged.

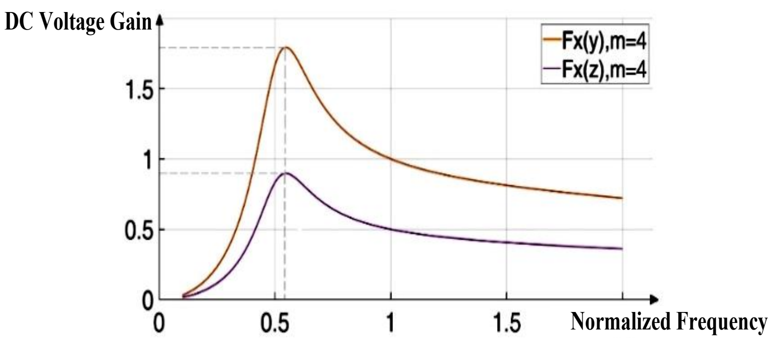

Figure 2. DC voltage gain at the output before and after fault

To address the issue of low output voltage following a fault in the LLC converter, this paper proposes an enhanced rear-stage series topology for the single-phase LLC full-bridge converter that ensures the output voltage reaches its rated value. The primary side features four MOSFETs (S_1 to S_4) that form an active bridge. The resonant circuit includes a resonant inductor (Lr), a resonant capacitor (Cr), a magnetizing inductor (Lm), and a transformer (T). Additionally, a redundant bridge arm and a series-controllable switch are incorporated on the secondary side. By utilizing the controllable switch, the two sets of secondary-side bridge arms can be connected in series, thereby maintaining a constant output voltage and facilitating continuous and stable operation of the system following a switch tube failure. Figure 3 illustrates the circuit configuration before and after the switch failure of the improved LLC resonant converter.

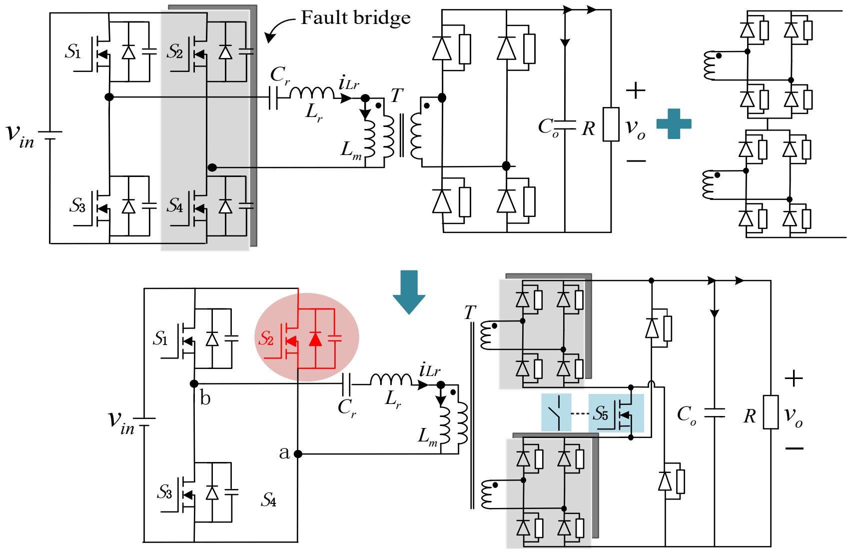

Figure 3. Topology of proposed LLC converter.

3.2 Proposed Fault-Tolerant Policy

Most research articles primarily recommend ceasing the operation of the entire LLC converter or reducing it to low voltage following an open circuit failure. In contrast, this paper explores reliable fault-tolerant methods and the available operating ranges for individual LLC converters. To ensure the safe operation of the LLC converter, the definition of fault tolerance can be summarized as follows:

i) The parameter design of the converter's main components—specifically, the MOSFET, resonant inductor, high-frequency transformer, and output capacitor—should be based on normal operating current. Consequently, it is crucial to prevent overcurrent conditions that could lead to further damage to other components following a failure.

ii) Following a fault, the inductance current of the resonator tank should not be higher than the maximum operating value, better with a preference for achieving zero bias.

iii) After a fault occurs, the converter should strive to convert as much power as possible. In systems designed for high reliability, it is important that a portion of the power remains available even after a failure.

Before developing the fault-tolerant strategy for the converter, two key assumptions were established based on the actual operating conditions: After a fault occurs, the resonant inductor current (i_{Lr}), must not exceed its maximum value under normal operating conditions, and there should be no bias. Typically, components such as MOSFETs, resonant inductors, isolation transformers, and output capacitors are designed to handle normal current levels. Therefore, preventing overcurrent and subsequent damage is critical. Following a fault, the converter should maximize power conversion. In high-reliability systems, it is essential to maintain power supply even after a failure.

3.3 Fault-tolerant topology analysis

Building upon the aforementioned constraints, this paper proposes and conducts an in-depth analysis of a novel fault-tolerant method for LLC converters, termed the Bypass Arm (BA) method. This fault-tolerant strategy is specifically designed to address scenarios where an open-circuit fault occurs in the primary side of a bridge arm or when such a fault affects another bridge arm. The primary objective of this method is to ensure uninterrupted operation while minimizing the impact on the overall system performance.

The proposed fault-tolerant topology is implemented in a post-stage series LLC resonant converter, which functions in four distinct operating modes during fault conditions. These modes are comprehensively illustrated in Figure 4, along with their structural principles and corresponding waveforms. To facilitate a better understanding of the system behavior, the switching devices in the converter are categorized into three states: on, off, and fault. In the associated analytical diagrams, the following conventions are adopted:

i) Black lines indicate open paths where the circuit operates as intended.

ii) Gray lines represent disconnected paths that are inactive during operation.

iii) Red lines highlight paths associated with faults or abnormal conditions.

For consistency, the directions of currents and voltages in the structural diagrams are annotated to reflect their positive orientation, ensuring uniformity throughout the analysis.

When an open-circuit fault occurs in switch S1, the converter undergoes a transient period before stabilizing into steady-state operation. During this steady state, the circuit transitions through four distinct working conditions, as shown in Figure 4. Each of these states is associated with a specific structural configuration and current flow pattern.

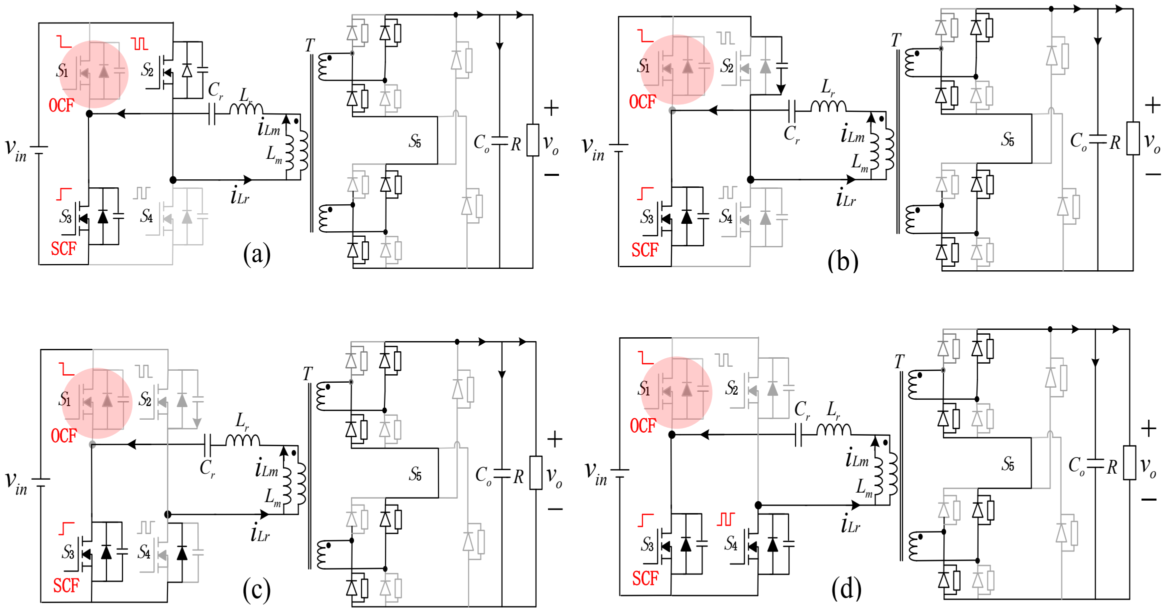

Figure 4. New working states of LLC under S1 open current fault condition (a)-(d)four distinct modes of propose LLC converter

When an open circuit fault occurs in S1 of the front bridge, the converter switches to steady state operation after a period of transient time. The changes of resonant current iLr, excitation current iLm and input voltage of primary side of transformer are shown in Figure 5.

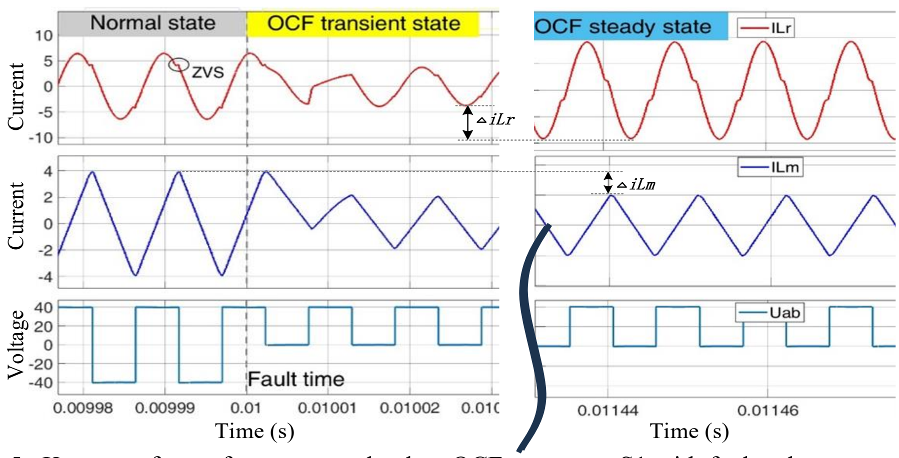

Figure 5. Key waveform of resonant tank when OCF occurs on S1 with fault-tolerant control scheme

When an open circuit fault occurs in switch S2 , the converter can be divided into four working states, as shown in Figure 6.

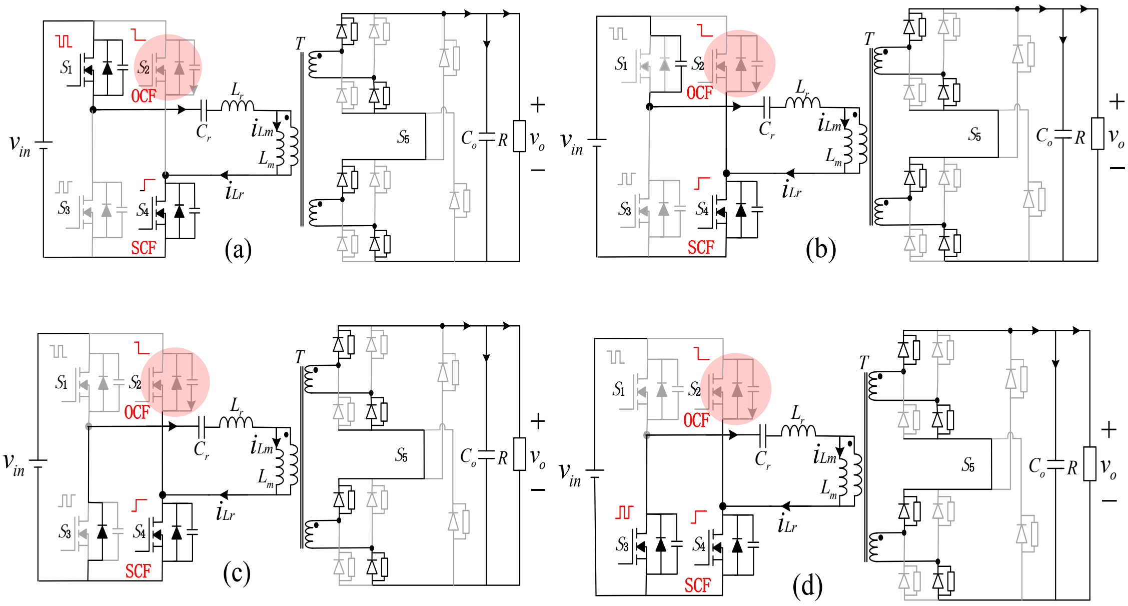

Figure 6. New working states of LLC under S2 open current fault condition (a)-(d)four distinct modes of propose LLC converter

When an open circuit fault occurs in S2 of the front bridge, the changes of resonant current iLr, excitation current iLm and input voltage of primary side of transformer are shown in Figure 7.

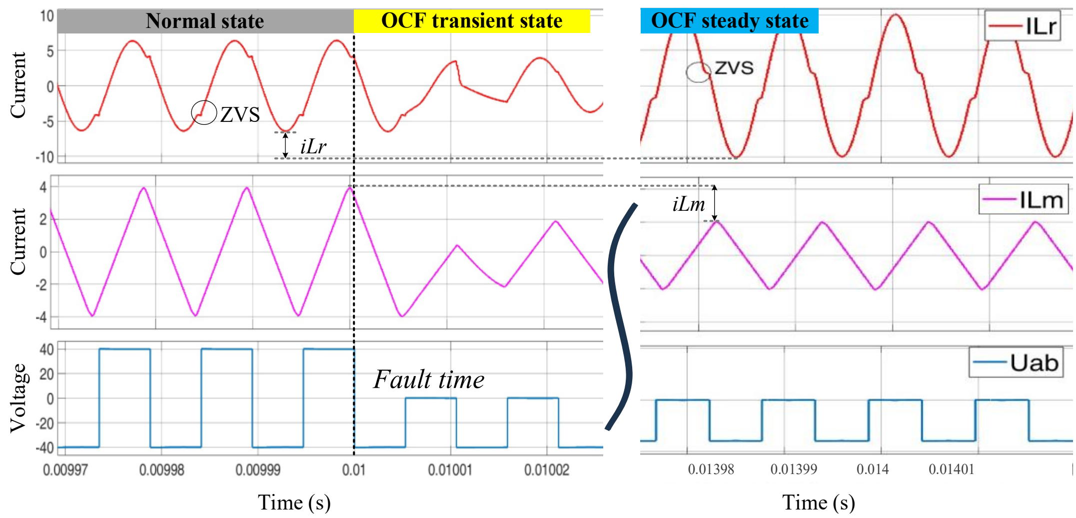

Figure 7. Key waveform of resonant tank when OCF occurs on S2 without fault-tolerant control scheme

3.4 Fault Diagnosis Policy

The converter fault diagnosis strategy proposed in this text is the resonant tank average voltage measurement method, which requires monitoring only three values: the resonant tank voltage ucr, output voltage Uo, and output current Io, as shown in Figure 8. This method does not require additional components, significantly reducing system costs, and can diagnose faulty switches within a single switching cycle.

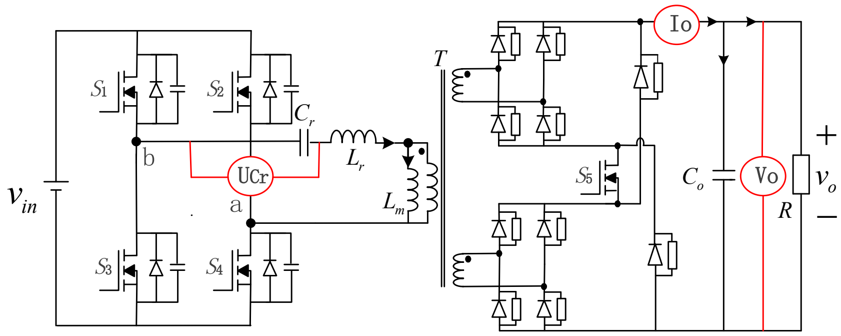

Figure 8. Distribution of reference variables for fault diagnosis of the converter

The converter control block diagram is illustrated in Figure 9, where S denotes the switch driver signal, and Ucrrepresents the average value of the resonant cavity voltage, which serves as the fault detection criterion. When the absolute value of Ucr is less than ε, the converter operates in a normal working state. In this scenario, the driving signal U_{S2}, U_{S3} for switches S2 is high, while the driving signal U_{S1}, U_{S4} for S4 is low, indicating that the converter functions correctly under a full-bridge pulse frequency modulation (PFM) control strategy. When a switch fails, the absolute value of Ucr will exceed ε. At this stage, two types of faults may be identified:

i) If the fault detection circuit indicates that the average value of Ucr over a period is greater than ε, the fault is identified as an open S2. In this case, the converter driver circuit sets the S4 driver signal to 1, and the system transitions to half-bridge pulse frequency modulation (PFM) control.

ii) Conversely, if the fault detection circuit detects that the average value of Ucr is less than −ε, the fault is identified as an open S1. Here, the converter driver circuit sets the S3 driver signal to 1, and the circuit also switches to half-bridge PFM control.

Calculating the average voltage is more straightforward than conducting analyses in the frequency or phase-frequency domains, thereby facilitating real-time monitoring and processing. As depicted in Fig. 9, the implementation involves a data acquisition module that collects real-time voltage signals across the resonant capacitor, followed by their computation and processing. The average voltage over one switching cycle is calculated and compared against a preset range corresponding to normal operating conditions. Detection of any deviation from this range indicates a fault, triggering the topology conversion module. This approach enables effective monitoring of the LLC resonant converter's operational status, ensuring timely fault detection and enhancing system reliability.

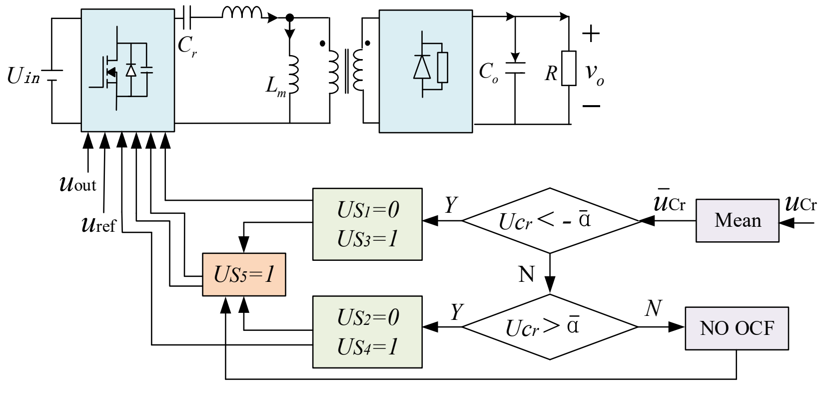

Figure 9. Converter fault diagnosis logic flow chart

The simulation waveforms for two different switch faults are shown in Figure 10 and Figure 11. In Figure 10, when switch S_1 is open, the average value of the resonant tank voltage Ucr exceeds the threshold ε, indicating a fault in switch S2. Consequently, the converter's drive circuit sets the S_3 drive signal to high, transitioning to half-bridge plus boost topology operation. In Figure 11, when switch S_2 is open, the average value of *Ucr* is less than ε, indicating a fault in switch S_2. The converter's drive circuit then sets the S_4 drive signal to high, switching to half-bridge plus boost topology operation.

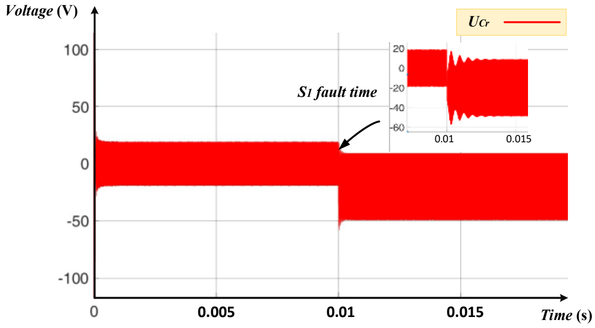

Figure 10. Open circuit fault diagnosis waveform of the S1 open circuit fault

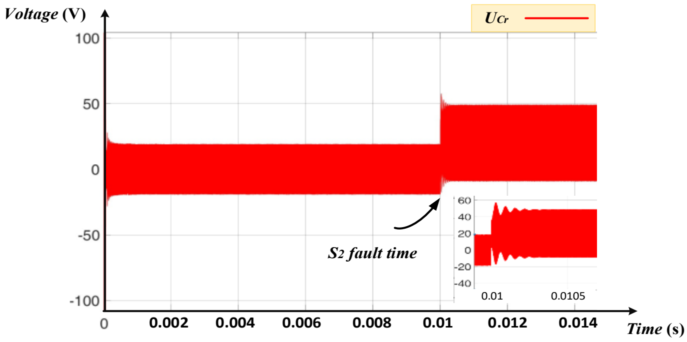

Figure 11. Open circuit fault diagnosis waveform of the S2 open circuit fault

3.5 Transformer Size and Cost Analysis in Converters

In the proposed fault-tolerant LLC resonant converter, the fault-tolerance functionality necessitates adjustments to the transformer's turns ratio, which may impact its size, weight, and cost.

3.5.1 Considerations for Transformer Size and Cost

Implementing an integrated transformer design can help mitigate these issues. In LLC converters, utilizing printed circuit board (PCB) windings for the integrated transformer can reduce AC resistance, decrease volume by approximately 43%, and reduce weight by about 28% [28]. The cost of a transformer is closely related to its design and the materials used. Implementing integrated transformers and matrix designs can lead to cost savings. For instance, the study in [27] employing a matrix transformer can reduce internal copper losses by over 50%.

3.5.2 Design Optimization for Fault-Tolerant Operation

To maintain the efficiency and cost-effectiveness of a fault-tolerant LLC converter, an integrated resonant transformer can be employed. By utilizing the leakage inductance, the need for discrete resonant inductors is eliminated, thereby enhancing efficiency, reducing size, and lowering costs [28]. However, designing such transformers requires addressing issues related to leakage flux caused by air gaps in the magnetic core, which can increase winding losses and temperature rise. Strategies such as incorporating multiple small air gaps in series within the core or optimizing the winding structure can help mitigate these issues. With advancements in power electronics, new magnetic materials and advanced manufacturing processes are expected to further enhance transformer performance, meeting increasingly stringent application requirements [29].

4. RESULTS AND DISCUSSION

To verify the power transmission capability of the converter, experiments were conducted to assess both the fault conditions and the fault-tolerant operating conditions of the LLC converter. It is assumed that an open-circuit fault occurs in switch S_1. A fault-tolerant model was simulated using MATLAB, and the results were compared with those derived from theoretical analysis. The experimental parameters are detailed in Table 4.

Table 4. Parameters of the converter

Name of Parameter	Value
Input voltage (Uin)	40
Output voltage (Uout)	80
Switching frequency(fs)	20KHZ
Tank circuit capacitance (Lr)	5μH
Tank circuit capacitance (Cr)	480pF

4.1 Analysis of experimental results

To validate the effectiveness of the proposed solution, a simulation circuit was constructed using the SIMULINK module in MATLAB, with an input voltage U_{in}=40V and an output voltage Uo=80. At t=0.01s, an open-circuit fault occurs in switch S_1. To ensure the stability of the system under Pulse Frequency Modulation (PFM), the frequency output of the Proportional-Integral (PI) controller is limited. Given that the normal resonant frequency of the dual-element resonant tank is 100 kHz, the upper limit of the PI controller is set to 100 kHz and the lower limit to 80 kHz.

As shown in Figure 12, at the moment of the fault, the resonant current of the improved topology exhibits minimal overcurrent and oscillation, and stabilizes within a very short time.

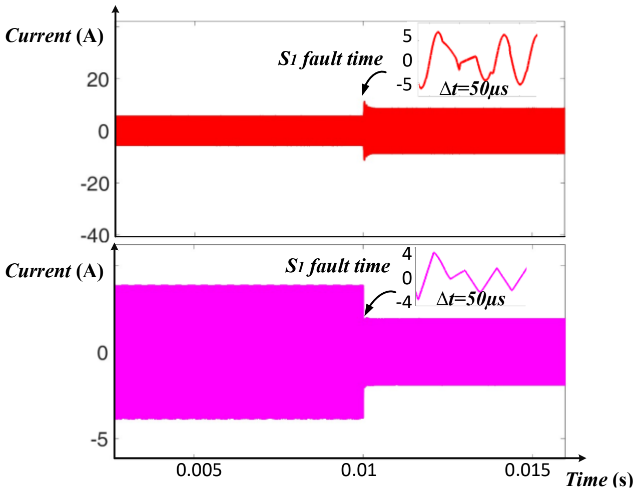

Figure 12. Resonance current waveform diagram

Figure 13 presents the input and output waveforms of the converter without fault-tolerant design, and Figure 14 illustrates the waveforms of the output voltage (U_o) and output current (I_o) of the proposed LLC resonant converter when an open circuit fault occurs in S_1 or a short circuit fault occurs in S_3. The figure demonstrates that, upon the occurrence of a single-switch fault, traditional converters fail to maintain output voltage stability under variable frequency control. In contrast, the improved LLC resonant converter's output voltage remains unaffected and exhibits a smooth waveform, with negligible disturbance at the fault occurrence instant.

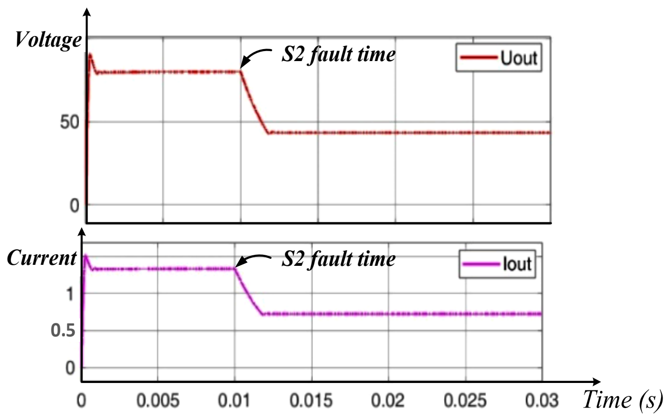

Figure 13. Output voltage and current waveform diagram original topology output

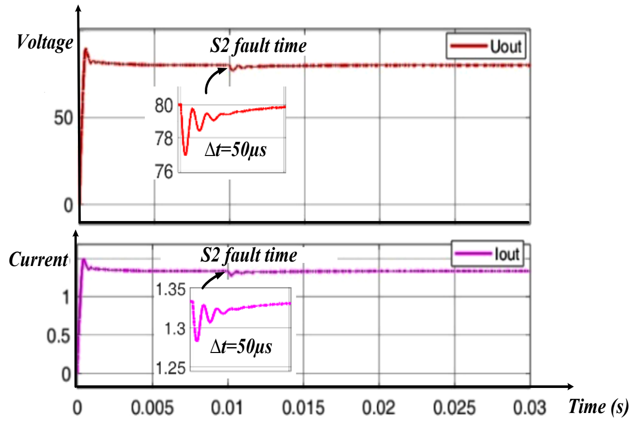

Figure 14. Output voltage and current waveform diagram of proposed converter topology output (S1 have open circuit fault at 0.01s)

Figure 15 illustrates the waveforms of the output voltage (Uo) and output current (Io) of the proposed LLC resonant converter when an open circuit fault occurs in S_2 or a short circuit fault occurs in S_4. It can be seen from the figure that when a single switch fault occurs, the output voltage of the improved LLC resonant converter is not affected, the waveform is very smooth, and the interference at the moment of fault occurrence is negligible. The fault tolerance performance is even better than that of the S1 or S2 fault waveform.

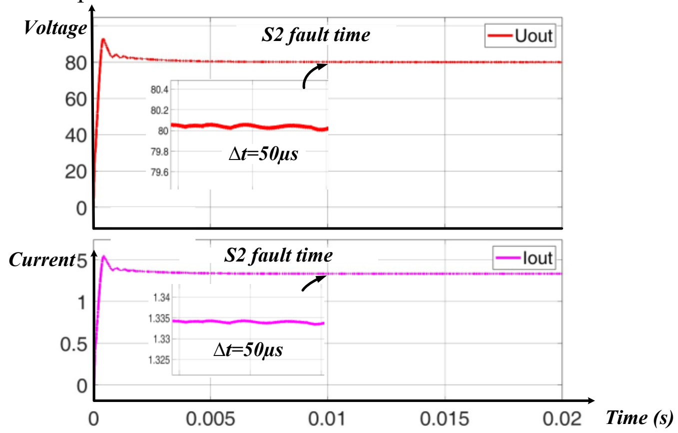

Figure 15. Output voltage and current waveform diagram of proposed converter topology output (S2 have open circuit fault at 0.1s)

4.2 Comparative analysis

Regarding the issue of fault tolerance in resonant converters, scholars have proposed solutions that can be broadly categorized into two types: those that improve resonant components and those that involve cascaded systems. Improved resonant component solutions feature simple drive designs and moderate efficiency. However, due to the fixed values of the added hardware and a narrow adjustable gain range, their fault tolerance is relatively weak, making them less suitable for fault scenarios. Cascaded system solutions can offset the impact of faults by adjusting the gain of the preceding or following stages. However, they involve more complex drive designs, higher costs, and lower overall efficiency due to the two-stage conversion process. This paper focuses on improved component-type converters. To assess the feasibility of the proposed solution, a comparison with similar literature is presented below.

Table 5 shows the comparative analysis of the proposed converter with some existing fault-tolerant converter topologies. The existing topologies in [30], [31], and [32] have been proposed for DC-DC converter. Comparison is done on different parameters like the number of components, fault type, design complexity, fault tolerance capability, size, and remark. The following can be observed from Table 5.

1) Converters presented in [30]–[32] can provide multi-switch fault repair capability at DC-DC converter.

2) Among all, only the proposed converter and [30] can provide full power capability after fault conditions of all switches. However, [31] can maintain most of the power output after failure, so that the system can continue to work. However, [32] can maintain 2/3 of the output power after failure, and the original system works in a low power state..

3) Converters presented in [31] and [32] can be used for a very special construction, which is not always feasible.

4) The fault diagnose capability is superior for the proposed converter alone since it can detect OC/SC faults in all the switches independently.

5) The converter proposed in [31] requires lesser number of component than the proposed converter but it can only be applied to OCF fault and it has poor multi-switch fault repair ability.

Table 5. Comparison of supplementary element, fault type, complexity and size in different topologies

Feature	Proposed Method	[30]	[31]	[32]
Additional component	1 switch	No additional components	4 switch 4 gate drivers 2 DC capacitor	6 capacitors
Primary side fault	Applicable for primary side	Applicable for primary side	Applicable for primary side	Applicable for primary side
Secondary side fault	Not applicable	Applicable for secondary side	Applicable for secondary side	Not applicable
Fault type	OCF and SCF	OCF only	OCF and SCF	OCF only
Control & complexity	Easy implementation	Easy implementation	Large complexity	Medium complexity
Size	Small size	Small size	Large size	Medium size
Output power process after fault	Po	79% Po	Po	2/3 Po
Remarks	Applicable for LLC Constant power after fault	Applicable for a certain load carrying capacity in DAB	Not applicable for DAB. Switch rating is 2 times the pre-fault current	Parallel and stacked MLCCs

The comparison indicates that the proposed solution has a straightforward drive design, higher efficiency, and a topology with strong fault tolerance. In summary, the analysis demonstrates the feasibility of the proposed solution.

5. CONCLUSION

This paper analyzes and discusses the variations in voltage gain and resonant capacitance voltage of the full-bridge LLC resonant converter before and after a switching open-circuit fault (OCF) , specifically examining the variations in voltage gain and resonant capacitance voltage. The study identifies the challenges faced by traditional LLC converters, such as the voltage gain and the inability to maintain stable operation near the resonant point during OCF conditions. To address these limitations, this paper proposes a novel fault-tolerant control strategy and an enhanced LLC converter topology with high fault tolerance.

The proposed approach integrates a bypass arm (BA) fault-tolerant scheme and an improved secondary-side series topology. The BA scheme facilitates rapid fault isolation and topological reconfiguration, allowing the system to transition seamlessly into half-bridge operation. This prevents excessive damage to components and maintains partial functionality. Additionally, the improved series topology on the secondary side employs a redundant bridge arm and a controllable switch, enabling the output voltage to remain at its rated value even after a switch tube failure. The control strategy for fault diagnosis and reconfiguration was rigorously evaluated through simulation, demonstrating its ability to detect faulty components accurately within a single switching cycle. By adjusting the driving signals of the switching devices, the converter topology is reconstructed, restoring rated output voltage and current in minimal time. This rapid recovery significantly reduces the impact of faults on system performance and ensures continued operation without requiring a complete shutdown.

ACKNOWLEDGEMENTS

The authors thank the Funds of Hunan Railway Professional Technology College Project (No. ZXKC-JS20230101).

REFERENCES

[1] Ding W, Yang S, Hu Y, “Performance Improvement for Segmented-Stator Hybrid-Excitation SRM Drives Using an Improved Asymmetric Half-Bridge Converter,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 898-909, 2019, doi: 10.1109/TIE.2018.2833034.

[2] A. R. Ghanbari, A. A. Raie, “Proposing a Multimode Switching Control Method for a Half-Bridge Converter to Improve Its Efficiency Over the Entire Load Variations,” *IEEE Transactions on Industrial Electronics*, vol. 67, no. 3, pp. 1910-1920, 2020, doi: 10.1109/TIE.2019.2903743.

[3] Wang, H., Blaabjerg, F, “Power Electronics Reliability: State of the Art and Outlook,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 6476-6493, 2021, doi:10.1109/jestpe.2020.3037161.

[4] Shi, Y., Feng, L., Li, Q., Kang, J, “High Power ZVZCS Phase Shift Full Bridge DC–DC Converter With High Current Reset Ability and No Extra Electrical Stress,” *IEEE Transactions on Industrial Electronics*, vol. 69, no. 12, pp. 12688-12697, 2022, doi:10.1109/tie.2021.3130346.

[5] C. Song, A. Sangwongwanich, Y. Yang, and F. Blaabjerg, “Open-Circuit Fault Diagnosis and Tolerant Control for 2/3-Level DAB Converters,” *IEEE Transactions on Power Electronics*, vol. 38, no. 4, pp. 5392-5410, 2023.doi:10.1109/tpel.2022.3233313.

[6] Liu, F., Ruan, X., & Jiang, Y, “Resonant Peak Suppression Approaches for Improving the Dynamic Performance of DCX-LLC Resonant Converter Based Two-Stage DC–DC Converter,” *IEEE Transactions on Industrial Electronics*, vol. 70, no. 6, pp. 5685-5695, 2023, doi:10.1109/tie.2022.3192604.

[7] Zhao H, Cheng L, “Open-switch fault-diagnostic method for back-to-back converters of a doubly fed wind power generation system,” IEEE Transactions on Power Electronics, vol. 33, no. 4, pp. 3452-3461, 2018, doi:110.1109/TPEL.2017.2705985.

[8] Chen Mingyun, He Yigang, “Open-circuit fault diagnosis method in NPC rectifiers using fault-assumed strategy,” *IEEE Transactions on Power Electronics*, vol. 37, no. 11, pp. 13668-13683, 2022, doi:10.1109/TPEL.2017.2705985.

[9] C. Fan, K. Xiahou, L. Wang, and Q. H. Wu, “Hybrid Fault Diagnosis of Multiple Open-Circuit Faults for Cascaded H-Bridge Multilevel Converter Based on Perturbation Estimation Convolution Network,” *IEEE Transactions on Instrumentation and Measurement*, vol. 73, pp. 1-12, 2024.doi:10.1109/tim.2024.3351234.

[10] Shu H, Shao Z, Jiang Y, “ A new modular multilevel converter topology with capability of DC faults clearing under blocking and non-blocking mode,” *Transactions of China Electrotechnical Society*, vol. 37, no. 21, pp. 5526-5540, 2022, doi: 10.19595/j.cnki.1000-6753.tces.211154.

[11] Huang J, Chen G, Shi H, “A Cost-Reliability Trade-Off Fault-Tolerant Series-Resonant Converter Combining Redundancy and Reconstruction,” *IEEE Trans Power Electron*, vol. 36, no. 10, pp. 11543-11554, 2021, doi:10.1109/TPEL.2021.3072383.

[12] Bhakar PS, Jayaraman K, “A New Fault-Tolerant Scheme for Switch Failures in Dual Active Bridge DC-DC Converter,” *IEEE J Emerg Sel Top Power Electron*, vol. 10, no. 6, pp. 7627-7637, 2022, doi:10.1109/JESTPE.2022.3177345.

[13] Wang W, Liu Y, Zhang P, Yuan Y, Zhao J, Loh PC, “A Fault-Tolerant LLC Converter With High Reliability and Low Cost for Two-Stage Converters,” *IEEE Trans Power Electron*, vol. 38, no. 8,pp. 9647-9659, 2023, doi:10.1109/TPEL.2023.3281601.

[14] T. Kim, H.-W. Lee, and S. Kwak, “Open-Circuit Switch-Fault Tolerant Control of a Modified Boost DC–DC Converter for Alternative Energy Systems,” *IEEE Access*, vol. 7, pp. 69535-69544, 2019. doi:10.1109/access.2019.2919238.

[15] Liu J, Zhao N, “Improved fault-tolerant method and control strategy based on reverse charging for the power electronic traction transformer,” *IEEE Transactions on Industrial Electronics*, vol. 65, no. 3, pp. 2672-2683, 2018, doi: 10.1109/TIE.2017.2748032.

[16] Khan, S. S., & Wen, H. ,“Universal Sensorless Open-Circuit Fault Detection and Isolation Method of Dual-Active-Bridge Converters With Low-Cost Diagnostic Circuit.” *IEEE Transactions on Power Electronics*, vol. 37, no. 11, 13652-13667, 2022, doi:10.1109/tpel.2022.3182382.

[17] Shi, L., Liu, B., Duan, S., He, J., Cai, T., Sun, J., & Sheng, W. ,“ Voltage Autobalance Characteristic Analysis and Clamp Circuits Design of Hybrid-Clamped Three-Level LLC Converter.” *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 6026-6035. 2019, doi:10.1109/tia.2019.2929023.

[18] Givi H, Farjah E, Ghanbari T, “Switch and diode fault diagnosis in nonisolated DC-DC converters using diode voltage signature,” *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1606-1615, 2018, doi:10.1109/tie.2017.2733486.

[19] Guo Y, Song Z, Xia J, Zhang X, “Fault Diagnosis and Fault-Tolerant Control for the Sensors of DC-DC Boost Converter,” *Chinese Control Conf CCC*, vol. 6, pp. 7594-7599, 2018, doi:10.23919/ChiCC.2018.8483340.

[20] Shu C, Wei L, Rong-Jun D, Te-Fang C, “Fault Diagnosis and Fault-Tolerant Control Scheme for Open-Circuit Faults in Three-Stepped Bridge Converters,” *IEEE Trans Power Electron*, vol. 32, no. 3, pp. 2203-2214, 2017, doi:10.1109/TPEL.2016.2558491.

[21] Shi H, Wen H, Chen G, Bu Q, Chu G and Zhu Y, “Multiple-Fault-Tolerant Dual Active Bridge Converter for DC Distribution System,” *IEEE Transactions on Power Electronics*, vol. 37, no. 2, pp. 1748-1760, 2022, doi: 10.1109/TPEL.2021.3106508.

[22] Wang, W., Li, Y., Wang, Q., Fang, C., Peng, Y., & Shuai, Z. , “Switch Open-Circuit Fault Diagnosis Method Using Bridge Arm Midpoint Voltage Integral for LLC Resonant Converter,” *IEEE Transactions on Power Electronics*, vol. 39, no. 10, 13795-13807, 2024, doi:10.1109/tpel.2024.3427134.

[23] Li, L., Yao, L., & Wang, H. “Model Predictive Fault-Tolerant Tracking Control for PDF Control Systems With Packet Losses,” *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, pp. 1-11, 2021, doi:10.1109/tsmc.2021.3103814.

[24] Z. Geng and M. Han, “Fault Localization Strategy for Modular Multilevel Converters in Rectifier Mode Under Submodule Switch Open-Circuit Failure,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 67, no. 12, pp. 3222-3226, 2020.doi:10.1109/tcsii.2020.2987957.

[25] A. K. Gupta and M. Kumar, “Characterization and Localization of Open Circuit Faults for n-Phase Interleaved Buck Converter,” *IEEE Transactions on Industry Applications*, vol. 60, no. 2, pp. 3273-3283, 2024.doi:10.1109/tia.2023.3332053.

[26] Z. Yan, L. Liu, C. Chen, H. Liu, W. Zhou, and R. Mai, “Optimized Design of Integrated Planar Matrix Transformer for LLC Converter in Consumer Electronics.” *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 10, no. 2, pp. 2254-2264, 2022.doi:10.1109/jestpe.2021.3123299.

[27] M. Qiu *et al.*, “A High Conversion Ratio Matrix Autotransformer Switched-Capacitor Converter for 48 V Datacenter

Application." *IEEE Transactions on Power Electronics,* vol. 40, no. 1, pp. 1359-1375, 2025.doi:10.1109/tpel.2024.3452651.
[28] S. A. Ansari, J. N. Davidson, and M. P. Foster, "Inserted-Shunt Integrated Planar Transformer With Low Secondary Leakage Inductance for LLC Resonant Converters." *IEEE Transactions on Industrial Electronics,* vol. 70, no. 3, pp. 2652-2661, 2023. doi:10.1109/tie.2022.3165259.
[29] K.-W. Kim, M.-Y. Kim, J.-I. Kang, and Y. Jeong, "High-Efficiency Multioutput LLC Resonant Converter With Multiwinding Transformer and Cost-Effective Analog Control Circuit." *IEEE Journal of Emerging and Selected Topics in Industrial Electronics,* vol. 4, no. 4, pp. 1034-1044, 2023.doi:10.1109/jestie.2023.3276344.
[30] Zhao N, Liu J, Shi Y, et al, "Mode analysis and fault-tolerant method of open-circuit fault for a dual active-bridge DC-DC converter," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 8, pp. 6916-6926, 2020, doi:10.1109/TIE.2019.2937066.
[31] T.-T.Le,M.-K.Nguyen,T.-D.Duong,C.Wang,andS.Choi, "Open-circuit fault-tolerant control for a three-phase current-fed dual active bridge DC-DC converter," *IEEE Trans. Ind. Electron.*, vol. 70, no. 2, pp. 1586–1596, 2023. doi: 10.1109/TIE.2022.3156036.
[32] L. F. Costa, G. Buticchi, and M. Liserre, "A family of series-resonant DC–DC converter with fault-tolerance capability," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 335–344, 2018. doi:10.1109/TIA.2017.2757900.

BIOGRAPHY OF AUTHORS

Lili Xu received the B.Eng. degree and master's degree in electric engineering from the Anhui University of Technology. She is currently pursuing the Ph.D. degree with the University Technology MARA, Malaysia. She research interests include switching mode power supplies, DC-DC power converters and renewable energy.She can be contacted at email: 2022635934@uitm.edu.my.

Muhamad Nabil Hidayat is a seasoned expert in energy audit assessment and renewable energy management, well-versed in Japanese work culture. He obtained Ph.D. from Tottori University and currently leads the Battery Energy Storage Technology (BEST) Laboratory at Universiti Teknologi MARA's MNA Facility. With over a decade in the field, he's successfully executed local and international Energy Efficiency Projects, including the Rural Electrification Project in Malaysia, projects with SEDA and GREENTECH under RMK-11, and a Sustainable Renewable Energy Project in Toyama Prefecture, Japan. He can be contacted at email: mnabil@uitm.edu.my.

N. H. NIK ALI received the B.Eng. degree (Hons.) in electrical power engineering from Universiti Tenaga Nasional (UNITEN), Malaysia, in 2013, and the Ph.D. degree in electronics and electrical engineering from the University of Southampton, U.K., in 2017. He has worked as a Research Fellow with the School of Electronics and Computer Science, University of Southampton, from 2018 to 2019. He was a Postdoctoral Researcher with the Institute of Power Engineering (IPE), UNITEN, from 2019 to 2020. Currently, he is a senior lecturer at Universiti Teknologi MARA (UiTM) Shah Alam, Malaysia. He is also a Graduate Member of the Board of Engineers Malaysia (BEM). His research interests include condition monitoring of high-voltage cables and transformers, partial discharge measurement, HV insulation/dielectric materials, transformer rating analysis, lightning analysis, electric vehicle supply equipment (EVSE), and any applications related to applied signal processing.

Muhammad Umair obtained Ph.D. in Electrical Power Engineering from University Putra Malaysia. His research interests lie in high voltage engineering, renewable energy, and exploring alternative energy sources to foster sustainability. He is dedicated to contributing to advancements in energy, focusing on innovative solutions to meet the demands of a sustainable future, and emphasizing the importance of alternative and renewable energy sources.