TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 23, No. 6, December 2025, pp. 1676~1686
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v23i6.26926

A design and reconfigurable phase shift inductor inductor capacitor converter for switch failures

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Article Info

Article history:

Received Jan 21, 2025
Revised Sep 12, 2025
Accepted Oct 19, 2025

Keywords:

Fault diagnosis
Fault monitoring
Fault tolerance
Inductor inductor capacitor resonant converter
Topological transformation

ABSTRACT

The reliability of a converter operation strongly affects overall system performance and is vital for uninterrupted power-electronic operation. Harsh operating conditions and environmental stresses degrade device performance and reduce reliability. In particular, a switching device failure may prevent an inductor inductor capacitor (LLC) resonant converter from operating near its resonant frequency while still maintaining stable output voltage, potentially causing loss of operation as well as significant drops in both efficiency and power delivery. To address this challenge, this paper proposes a fault-tolerant topology and control strategy for the LLC converter under open circuit switch (OCF) faults. The proposed method integrates a bypass arm with a secondary-side series configuration; when a primary-side open-circuit fault occurs, the auxiliary switch is activated to bypass the faulty leg, reconfiguring the secondary side into a voltage doubler rectifier (VDR). This reconfiguration enables continuous operation with an output voltage doubled relative to the normal condition, while minimizing performance degradation. Simulation results confirm that, even under a single-switch OCF, the proposed approach maintains an efficiency of 98% with output voltage fluctuation limited to less than 1%. Compared to conventional methods, the proposed strategy greatly enhances reliability and fault tolerance, making it well-suited for high-efficiency power conversion applications.

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1. INTRODUCTION

The demand for high reliability in power electronic systems has significantly increased with the rapid development of renewable energy and electric vehicle applications [1]. Among various power converter topologies, the inductor inductor capacitor (LLC) resonant converter has gained widespread attention due to its high efficiency, soft-switching capability, and compact design [2]. However, the reliability of such converters is severely challenged by open-circuit faults in power switches, which can lead to system malfunction, output voltage instability, and even complete shutdown.

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. Extensive research efforts have been devoted to improving fault tolerance in resonant converters. Existing methods, such as half-bridge reconfiguration, modular redundancy, and advanced control strategies, have achieved notable results in maintaining system operation under faulty conditions [5]. Nevertheless, these approaches often suffer from drawbacks such as increased circuit complexity, reduced efficiency, and limited adaptability to multiple fault scenarios [6]. In particular, the performance of LLC converters under single-switch open-circuit faults has not been sufficiently addressed in the literature. Despite these challenges, research on fault diagnosis and fault-tolerant operation of LLC converters remains limited. Most existing studies primarily focus on short-circuit faults, which typically trigger protection mechanisms due to excessive current [7]. On the other hand, open circuit switchs are comparatively more difficult to detect and mitigate in real time [8].

Despite recent advances in fault-tolerant techniques for LLC resonant converters, a significant gap remains: open-circuit faults in single power switches have not been adequately addressed under realistic operating conditions, including temperature fluctuations, load variations, and intermittent inputs typical of renewable energy sources. These gaps leave delays in detection, insufficient regulation of output under fault, and inefficient performance under partial failure. This issue has great practical importance for renewable energy systems and electric vehicle powertrains, where converters must reliably maintain efficiency and output stability even under component faults. The proposed topology, which combines a bypass-arm strategy with a secondary-side series configuration, is designed to fill this gap by delivering uninterrupted power, stable output voltage under open-circuit fault conditions, making it well-suited for deployment in high-reliability applications.

The paper is organized as follows: section 2 presents the proposed topology together with the fault-diagnosis and control strategy. Section 3 analyzes the performance through simulation results, and section 4 provides conclusions and outlines potential directions for future work.

2. METHOD

Faults in power converters, including open-circuit and short-circuit failures, can severely degrade system performance and reliability. To ensure stable operation under fault conditions, effective fault diagnosis and fault-tolerant strategies are indispensable. Fault diagnosis involves three essential steps: fault detection, isolation, and identification. This section investigates diagnostic approaches with a specific focus on open-circuit fault (OCF) in LLC resonant converters, which remain relatively underexplored compared with OCF diagnosis.

2.1. Fault diagnosis methods for LLC converters

Open-circuit faults in a full bridge resonant converter can arise from driver malfunctions or semiconductor switch failures, disrupting normal operation [9]. Unlike short-circuit faults, which trigger protection mechanisms due to excessive current, OCFs are more difficult to detect and mitigate in real time [10]. Effective diagnosis requires rapid, accurate identification of the fault location, followed by isolation or fault-tolerant control to maintain operation. Common diagnostic methods involve monitoring resonator tank currents, transformer terminal voltages, the direct current (DC) component polarity of the resonator current, and the average transformer voltage. For example, Tang *et al*. [11], employed a Luenberger observer with inductive current and output voltage sensors for OCF detection in boost converters. Jin *et al*. [12], a simplified and fast technique for detecting and localizing OCFs in modular multilevel converters (MMCs) is presented. Gupta and Kumar [13], propose a method for detecting and localizing both switch and diode faults by exploiting the nonideal characteristics of semiconductor switches. Other methods include additional switches or voltage sensors for dual active bridge (DAB) converters [14]. Wang *et al*. [15], a precise open-circuit fault diagnosis (OCFD) method for LLC resonant converters uses the integral of the bridge-arm midpoint voltage to localize faults and support maintenance. However, these approaches exhibit limitations in universality, cost, and real-time applicability to LLC converters, as multiple switches can produce indistinguishable diagnostic signals during OCF [16].

2.2. Fault-tolerant strategies of LLC converter

Conventional approaches to OCFs typically halt converter operation or reduce voltage, compromising system reliability. To enhance fault tolerance, this study defines the following requirements: i) the main components including metal–oxide–semiconductor field-effect transistors (MOSFETs), resonant inductors, high-frequency transformers, and output capacitors must be designed based on nominal current ratings to avoid secondary overcurrent-induced failures; ii) following a fault, the resonant tank current must not exceed the maximum allowable operating value, with an ideal target of minimizing bias to ensure safe operation; and iii) the post-fault system should retain the ability to transfer as much power as possible, since partial power delivery is critical in high-reliability applications such as renewable energy systems and electric vehicles.

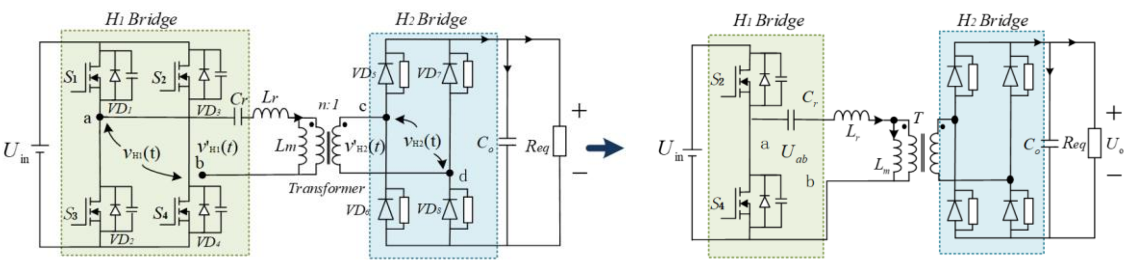
A number of fault-tolerant schemes have been proposed in the literature. Module-redundancy-based approaches dominate the field, wherein faulty modules are bypassed and replaced with redundant ones to sustain limited power transfer [17]. For example, Huang *et al*. [18] introduced a method employing redundant half-bridges in parallel on the primary side, enabling reconstruction into a full-bridge after failure; however, this significantly increases converter size and cost. Bhakar and Jayaraman [19] proposed reconfiguring a faulty DAB into an LLC resonant half-bridge converter by incorporating resonant capacitance, which improves post-fault voltage but fails to achieve rated output. Similarly, Wang *et al.* [20] developed a three-arm redundant topology, where a spare arm compensates for any failed one, thereby enhancing fault tolerance at the expense of additional switches and system cost. Zhao *et al.* [21] presented a closed-fault-bridge strategy to improve reliability in DAB converters, yet it also fails to restore full-rated power. Velmajala and Sandepudi [22] introduces a high step-up interleaved non-isolated DC–DC converter that achieves fault-tolerant operation without redundant switches by incorporating a fuse-MOSFET pair for effective short-circuit protection. In modular systems, redundancy remains the mainstream solution. But Benzine *et al.* [23] presents a DC fault-current calculation method. It divides fault response into stages and incorporates saturation via short-time numerical computation.

Recently, converter-topology and control strategies oriented specifically to the LLC converter fault-tolerant operation have emerged. For instance, Xiong *et al*. [24] propose a fast open-circuit fault diagnosis for LLC converters, which lays a foundation for subsequent fault-tolerant control. Kim *et al*. [25] present a "double fault-tolerant LLC resonant converter" capable of enduring two short-circuit faults via reconfiguration and minimal added redundancy. While effective, these strategies increase system size, complexity, and cost, and may fail to achieve the rated output voltage under OCF conditions. In contrast to methods that often rely on spare modules or half-bridge reconfiguration after a fault, our proposed topology includes (on the inverter side) a full/half-bridge automatic switching strategy and (on the rectifier side) an enhanced rear-stage series topology. The method proposed in this paper offers a cost-effective, compact alternative that ensures continuous operation and voltage stability without extensive hardware redundancy.

2.3. Analysis of open-circuit fault characteristics

The full-bridge LLC converter consists of an inverter, a resonator, and a rectifier. Under normal operation, the DC input voltage U_{in} is converted by the inverter into a square-wave voltage U_{ab}, which passes through the resonator and rectifier to generate the DC output voltage U_o. Figure 1(a) illustrates the circuit topology transformation in a traditional LLC converter. In this Figure 1, Lr, Cr, Lm, and R_{eq} denote the resonant inductance, resonant capacitance, magnetizing inductance, and equivalent resistance, respectively. U_{ab} represents the equivalent resonator input voltage.

To address OCF, a bridge arm (BA)-based topology is proposed for single-phase full-bridge LLC converters. When a primary-side switch fails, the corresponding bridge arm gate drive is blocked, enabling controlled half-bridge operation. This isolates the faulty switch while maintaining continuous power delivery, offering a practical advantage over traditional redundancy-based approaches. During BA fault-tolerant operation, only one inverter switch set remains active, producing a fully positive or negative resonator input voltage. Voltage and current waveforms maintain symmetry, though the output gain slightly decreases. For instance, if S_1 fails, S_3 drive remains high while bypass arms S_2 and S_4 operate normally, as shown in Figure 1(b) .



(a) (b)

Figure 1. Equivalent circuit using an BA method: (a) topology during normal operation and (b) topology after S_2 open circuit fault

Corresponding to the transformer primary voltage when the turns ratio $n = 1$, and the secondary voltage when $n = 1$. The DC voltage gain before and after the fault is derived using fundamental harmonic analysis. The Fourier expansion of the resonator input voltage U_{ab} is expressed in (1), where ω_s denotes the angular frequency.

$$u_{in}(t) = \sum_{n=1}^{\infty}[b_n \sin(\frac{2\pi nt}{T} - \varphi)] \tag{1}$$

The fundamental component can be expressed as (2).

$$b_1 = \frac{2}{T}\int_{t_0}^{t_0+T} f(t)\sin(\frac{2\pi nt}{T})dt\Big|_{t_0=0,n=1} = \frac{4NU_o}{\pi}(\omega t - \varphi) \tag{2}$$

Figure 2 is an fundamental harmonic approximation (FHA) equivalent two-port network of the LLC resonant converter. The voltage gain of the full-bridge LLC resonant converter, as represented by its FHA equivalent circuit, is expressed in (3).

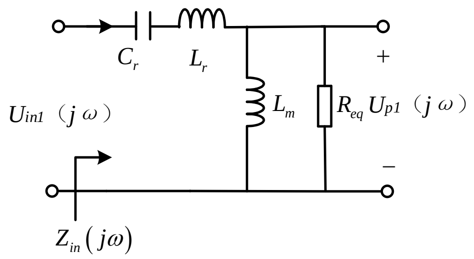


Figure 2. FHA equivalent two-port network of the LLC resonant converter

$$H(j\omega) = \frac{U_{p1}(j\omega)}{U_{in1}(j\omega)} = \frac{R_{eq}||j\omega L_m}{j\omega L_r + \frac{1}{j\omega C_r} + R_{eq}||j\omega L_m} \tag{3}$$

here, R_{eq} denotes the load referred to the primary side of the transformer, given by:

$$R_{eq} = \frac{U_{p1}}{I_{p1}} = \frac{8N^2}{\pi^2}R \tag{4}$$

By simplifying this expression, the DC voltage gain of the converter can be derived in (5).

$$G(F_x, m, Q) = |H(j\omega)| = \frac{(m-1){F_x}^2}{N\sqrt{(m{F_x}^2-1)^2 + Q^2(m-1)^2{F_x}^2({F_x}^2-1)^2}} \tag{5}$$

m is the normalization of magnetizing 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 S_1 experiences an open-circuit fault, the converter transitions to half-bridge operation. The corresponding input voltage can be expressed using its Fourier series expansion, as shown in (6).

$$u_p(t) = \sum_{n=1}^{\infty}[b_n \sin(\frac{2\pi nt}{T})] \tag{6}$$

The gain expression of the LLC resonant converter is shown in (7):

$$H(j\omega) = \frac{U_{p1}(j\omega)}{U_{in1}(j\omega)} = \frac{R_{eq}||j\omega L_m}{j\omega L_r + \frac{1}{j\omega C_r} + R_{eq}||j\omega L_m} \tag{7}$$

By simplifying and normalizing this expression, the DC voltage gain under fault conditions is obtained, as presented in (8):

$$M(F_x, m, Q) = |H(j\omega)| = \frac{(m-1){F_x}^2}{2N\sqrt{(m{F_x}^2-1)^2+Q^2(m-1)^2{F_x}^2({F_x}^2-1)^2}} \quad (8)$$

From (6) and (8), it can be observed that, following a single-switch fault in a single-phase full-bridge LLC converter, the output DC voltage gain is reduced by approximately 50% under conventional BA fault-tolerant operation. Using parameters $Lr = 5\ \mu H$, $Lm = 26\ \mu H$, $Cr = 480\ \mu F$, $n = 2$, $Req = 60\ \Omega$, the corresponding voltage gain curves are depicted in Figure 3, where $Fx(\text{y})$ and $Fx(z)$ represent the pre-fault and post-fault gain, respectively. As illustrated, the traditional LLC converter controlled solely by pulse frequency modulation (PFM) cannot operate near the resonant point while maintaining a stable output voltage after a switch failure.

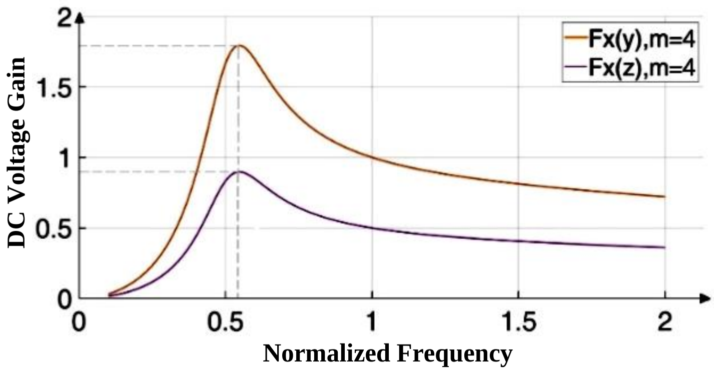


Figure 3. DC voltage gain at the output before and after fault

The primary side comprises four MOSFETs (S_1 to S_4) forming an active bridge, while the resonant circuit consists of a resonant inductor (Lr), a resonant capacitor (Cr), a magnetizing inductor (Lm), and a transformer (T). The converters output voltage after a fault will be half of its previous value, because the HB-RC only produces half of the output voltage of the FB-RC, which is undesirable.

To overcome this limitation, an enhanced rear-stage series topology is proposed for the single-phase full bridge LLC converter, ensuring that the output voltage remains at its rated value post fault. To overcome this issue, a voltage doubler circuit is used with a secondary rectifier. The rectifier has two split capacitors and an additional switch which connects the high-frequency transformer to the middle point of the capacitors, as shown in Figure 4. Moreover, switch S_5 is normally open, and the rectifier functions as a regular full-bridge rectifier. Switch S_5 is turned on in the fault situation, and the leg made up of diodes D2 and D4 is bypassed. The midpoint of capacitors C1 and C2 is connected to the bottom side of the secondary winding.

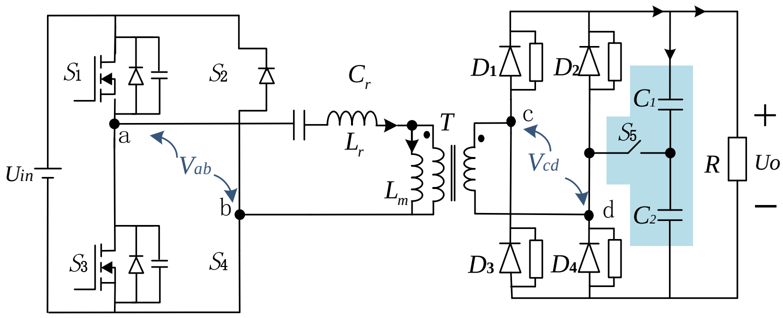


Figure 4. Topology of the proposed LLC converter

Voltage V_{ab} has an average value of zero in normal operation, and the output voltage is given by V_{cd}. After a failure in the switch S_2, the full bridge resonant converter (FB-SRC) is reconfigured as a half bridge resonant converter (HB-SRC), and switch S_5 is turned ON, allowing the output stage to function as a voltage doubler rectifier (VDR). As a result, the output voltage will remain constant, as expected. The effect of the reconfiguration is only seen on the current, which must be twice as large as before, to process the same amount of power. Half-bridge SRC exhibits these characteristics.

2.4. Proposed fault-tolerant converter policy

The development of the fault-tolerant strategy is based on two key operational assumptions: i) following a fault, the resonant inductor current must remain below its maximum rated value without bias; and ii) the converter should continue to convert power efficiently, maintaining partial power delivery in high-reliability applications. Based on these constraints, a novel BA-based fault-tolerant method is proposed for LLC converters. This strategy targets open-circuit power switch (OPS) on the primary-side bridge arms and ensures continuous operation while minimizing performance degradation.

The operation possibilities in Figures 5(a), and the operation in normal and faulty conditions is depicted in Figures 5(b) and (c), respectively. In normal operation, the switch S_5 is open, and the rectifier operates as a standard FB-CR. In a fault case, the switch S_5 is activated, and then the leg composed of the diodes D_2 and D_4 is bypassed. The bottom side of the secondary winding is connected to the middle point of the capacitors C_1 and C_2, becoming a VDR. Therefore, the circuit operates as a VDR, and the output voltage value is twice the output voltage value in normal operation.

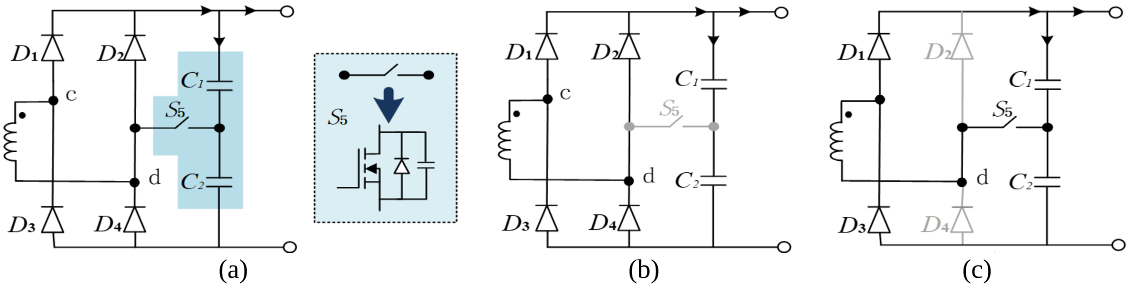


Figure 5. Topology of LLC under S_2 open current fault condition: (a) operation possibilities, (b) operation in normal mode and (c) operation in VDR

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 6. This method does not require additional components, significantly reducing system costs, and can diagnose faulty switches within a single switching cycle.

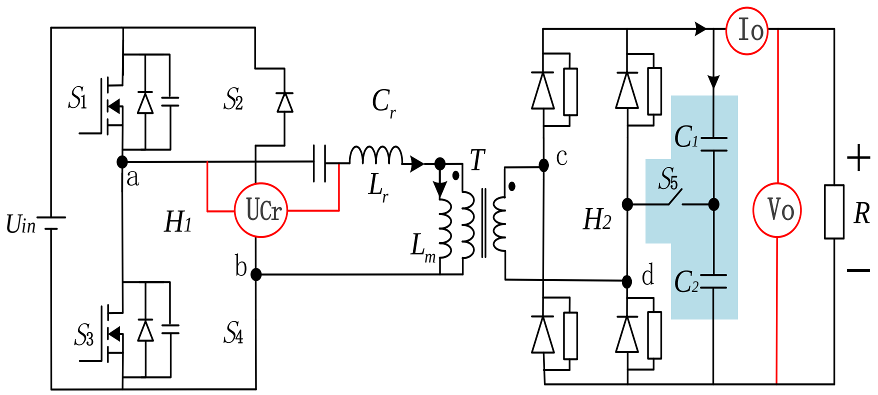


Figure 6. Distribution of reference variables for fault diagnosis of the converter

The control block diagram of the proposed converter is shown in Figure 7. Here, S denotes the switch driver signal, and $\bar{u}_{Cr}$ represents the average resonant capacitor voltage, which is employed as the fault detection criterion. During normal operation, when $|\bar{u}_{Cr}|<\varepsilon$, the converter functions under a full-bridge PFM strategy, where the driver signals S_2, S_3 are high, and S_1 S_4 are low. Once a fault occurs, $|\bar{u}_{Cr}|>\varepsilon$, triggering the fault-tolerant mechanism. Two fault scenarios are distinguished: i) general OCF: if the average $\bar{u}_{Cr}$ over a switching cycle exceeds ε, the fault is classified as S_2 open-circuit fault, the converter driver circuit sets the S_4 and S_5 driver signal to 1, and the converter transitions to half-bridge PFM control; ii) conversely, if the fault detection circuit detects that the average value of $\bar{u}_{Cr}$ is less than $-\varepsilon$, the fault is identified as an open S_1. Here, the converter driver circuit sets the S_3 and S_5 driver signal to 1, and the circuit also switches to half-bridge PFM control.

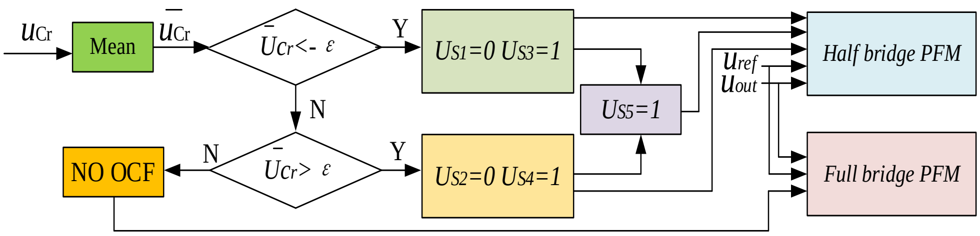


Figure 7. Converter fault diagnosis logic flow chart

3. 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 the switch S_2 at 0.1 seconds. 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 1.

Table 1. Parameters of the converter

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

At $t = 0.1$ s, an OCF occurs in switch S_2. Figure 8(a) shows the case where the resonant capacitor voltage exceeds ε (u_{Cr}>ε); the topology immediately transitions from full-bridge operation to the half-bridge boost configuration, and the system stabilizes within 2.4 ms. In contrast, Figure 8(b) illustrates the scenario where the resonant capacitor voltage drops below $-\varepsilon$ (u_{Cr}<-ε); under this condition, the converter also shifts to the half-bridge boost configuration and reaches steady state within 2 ms (one switching cycle).

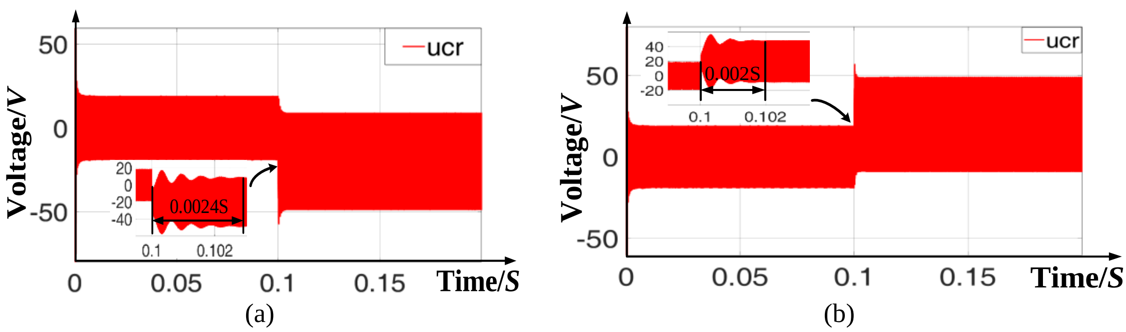


Figure 8. Open circuit fault diagnosis waveform of the primary side of the converter: (a) S1 open circuit fault and (b) S2 open circuit fault

Simulation results under an S_2 open-circuit fault validates the effectiveness of the proposed fault-tolerant strategy. As shown in Figure 9(a), the conventional LLC topology controlled by a proportional–integral (PI) regulator sustains only 48 V output voltage and 0.7 A output current, corresponding to approximately 60% of their rated values. In contrast, the proposed converter, illustrated in Figure 9(b), restores the rated 80 V and 1.33 A within a single switching cycle. Furthermore, the transient response exhibits negligible overshoot, with voltage and current deviations limited to 1.8 V and 0.03 A, respectively less than 3% of the rated values.

In Table 2 summarizes key performance metrics of the traditional converter and proposed converter across different stages to facilitate quantitative comparison. These results demonstrate that the proposed topology significantly enhances both fault recovery speed and steady-state accuracy compared to conventional approaches.

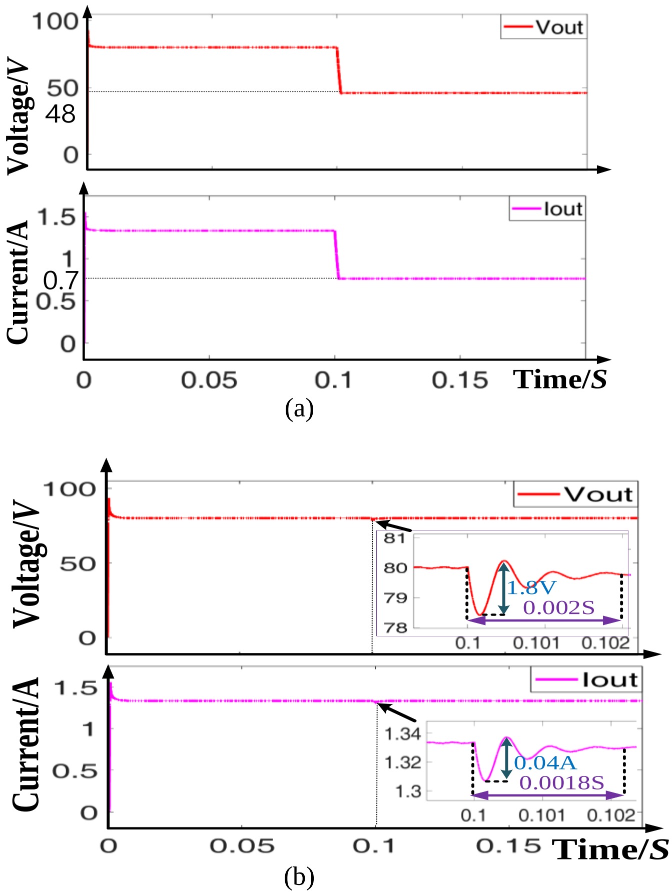


Figure 9. Output voltage and current waveform diagram (S_2 have open circuit fault at 0.1s): (a) original topology output and (b) proposed converter topology output

Table 2. Dynamic performance comparison s_2 open-circuit fault

Fault-tolerant stage	Metric	Traditional converter	Proposed converter
	Offset error (V)	32	1.8
Output voltage	Voltage fluctuation rate (%)	40	2.25
	Recovery time (ms)	Dev.	2
	Offset error (A)	0.8	0.04
Output current	Current fluctuation rate (%)	53.33	3.52
	Recovery time (ms)	Dev.	1.8

4. CONCLUSION

This paper proposes a novel fault-tolerant topology and control strategy for LLC resonant converters aimed at mitigating single-switch open-circuit faults. By combining a bypass-arm strategy with a secondary-side VDR configuration, the converter retains its rated output voltage under fault conditions, while limiting performance degradation. Simulation results show that the proposed method achieves approximately 98%

efficiency, with output voltage fluctuations of less than 1%, demonstrating consistent reliability in the presence of switching faults. Compared with conventional methods, our approach offers improved fault tolerance, high efficiency, and significantly reduced hardware complexity, marking it as a strong candidate for high-reliability power conversion applications.

Nevertheless, this work has limitations: it addresses only single-switch open-circuit faults (specifically S1 or S2 failures), and validation so far is confined to detailed simulations. All waveform plots have been enhanced to include additional annotations such as response time, overshoot, and transient features, to support deeper insight. In future work, experimental validation under dynamic operating conditions and extension to multiple-switch fault scenarios are planned, together with an investigation into detection speed, thermal behavior, control response, and sustained voltage stability, to establish practical applicability further.

FUNDING INFORMATION

The authors thank the Research Project of Hunan Railway Professional Technology College (Project No. KJ202502).

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Nik Hakimi Bin Nik Ali		✓	✓	✓	✓					✓				
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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