

Article

A Transient-Minimized DC Fault Protection with Z-Source Circuit Breakers in Hybrid Microgrids

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Abstract

With the growth of emerging data centers and electric vehicles, DC power distribution and hybrid microgrids are attracting growing attention. Due to the lack of a natural zero-crossing point in DC current, reliable DC fault protection is critical. This paper introduces a transient-minimized fault protection scheme utilizing Z-source circuit breakers (ZCBs), leveraging their unique features during the activation process. These features are analyzed to provide the theoretical foundation for achieving transient-minimized DC fault protection, which eliminates high spikes in fault current, relieves stress on power devices in the system, and enhances transient stability. The effectiveness of this method is validated through simulation tests of a 100 MVA islanded hybrid microgrid using ZCBs based on experimentally verified models. Test results demonstrate that system oscillation is reduced by 13% in frequency and 74% in voltage, while completely eliminating voltage sags. With the help of ZCBs, the system also recovers more quickly after fault clearance. The results also demonstrate that the proposed method remains effective under various fault and load conditions.

Keywords: DC protection; hybrid microgrid; transient stability; z-source circuit breaker

1. Introduction

This section provides an overview of hybrid microgrid developments, DC fault protection schemes, and the family of Z-source circuit breakers. Building on this background, the novelty and major contributions of this work are highlighted at the end of the section.

1.1. Development of Hybrid Microgrid

During the past two decades, distributed generation (DG), microgrid, and smart grid technologies have developed rapidly. DC sources and loads (such as photovoltaic cells, fuel cells, and energy storage systems (ESSs)) can be directly connected to DC power networks with the advantages of high efficiency and the absence of high-frequency harmonics compared to traditional AC networks. ESSs include large-scale systems ranging from tens of kVA to hundreds of MVA, such as those in data centers and electric vehicles. Therefore, as a cost-effective strategy for integrating local distributed energy resources, microgrids have gained substantial traction for their ability to deliver reliable power to next-generation power networks [1]. By linking AC and DC power networks, hybrid microgrids integrate the strengths of both systems to enhance the efficiency and reliability of modern smart grids.

In recent years, some professionals and researchers around the world have been investigating hybrid microgrids with regard to sizing, power management and control, diagnosis and protection, etc.



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(a) For the sizing of DGs, paper [2] presented the application of the Turbulent Flow Water-Based Optimization (TFWO) algorithm for determining the optimal sizing of isolated hybrid microgrids and compared its effectiveness with the Harris Hawks Optimization (HHO), Whale Optimization Algorithm (WOA), and Jellyfish Search Optimizer (JSO). Two hybrid microgrid configurations, developed using the meteorological data of Zafarana, Egypt, were investigated to minimize the annual system cost and CO₂ emissions while maintaining predefined reliability constraints. The results demonstrate that the TFWO algorithm provides superior optimization performance by achieving lower operating costs, faster convergence, and greater robustness than the other optimization methods.

(b) On the topic of power management and control, in 2021, paper [3] proposed a distributed power management method for hybrid AC/DC microgrids that uses coordination factors to improve power sharing among distributed energy resources and to regulate AC voltage, frequency, and DC bus voltage through coordinated control of the bidirectional interlinking converter (BIC). The proposed method enhances power-sharing accuracy, reduces communication requirements, and is validated through hardware-in-the-loop experiments, showing reliable operation even when communication delays or failures occur. Also, the study of [4] proposed a distributed energy management framework for hybrid AC/DC microgrids based on a combined alternating direction method of multipliers (ADMM) and modified crow search algorithm (MCSA). By allowing neighboring agents to coordinate power dispatch through minimal data sharing, the approach achieves faster convergence, reduces operating costs, and outperforms traditional optimization techniques. In 2022, paper [1] introduced a decentralized, priority-based power control strategy for interlinking converters in hybrid AC/DC microgrid clusters. By relying only on local voltage and frequency measurements, the proposed method enables optimal power sharing without communication networks, enhances power quality and system resilience, and is validated through hardware-in-the-loop experiments under varying load conditions and converter failures. Later, paper [5] presented a distributed normalized power coordination (NPC) method with virtual synchronous generator control for hybrid AC/DC microgrids. The strategy improves global power sharing, provides cross-inertia support, and restores voltage and frequency while minimizing oscillations through optimized inertia allocation.

(c) For diagnosis and protection, in 2023, an artificial neural network (ANN)-based intelligent protection method was developed for islanded hybrid microgrids to detect, classify, and locate faults under varying distributed generation conditions [6]. Later, in 2025, paper [7] surveyed existing protection and fault diagnosis techniques for hybrid AC/DC microgrids and identified the shortcomings of conventional methods. It concluded with AI-driven and adaptive protection strategies that improve fault detection, reliability, and system resilience for future hybrid microgrids.

These studies highlight the importance of advanced technologies for the operation of hybrid microgrids. However, DC fault protection remains a critical challenge for ensuring reliable system operation, as it significantly affects system safety and transient stability during and after fault conditions. Addressing this challenge motivates the research presented in this paper.

1.2. DC Fault Protection and Z-Source Circuit Breaker (ZCB)

DC circuit breakers are essential devices for fault protection in hybrid microgrids. Unlike AC current, DC current has no natural zero-crossing point, making it significantly more difficult to extinguish the arc generated during DC short-circuit faults [8]. The sustained high-energy arc between the contacts of a DC circuit breaker accelerates breaker degradation, increasing both installation and maintenance costs for power systems [9–11]. To address this challenge, extensive research has been conducted on the development

and improvement of DC circuit breakers to support the wider adoption of modern and emerging power system technologies, including DGs and smart grids in hybrid microgrids.

To date, DC circuit breaker technologies can generally be classified into three categories, as shown in Figure 1. As introduced in [12], the use of oversized AC circuit breakers is well-established in terms of manufacturing, application, and maintenance. However, as an “oversized” mechanical circuit breaker, they are relatively expensive and do not fully utilize their current- and power-handling capabilities during normal operation. With the rapid development of power semiconductor technology over the past few decades, solid-state circuit breakers have gained increasing attention because they provide more compact and faster DC fault protection. Unlike conventional AC circuit breakers, however, solid-state circuit breakers limit short-circuit current and interrupt power flow by driving semiconductor devices into a high-resistance state rather than by mechanically opening contacts. Hybrid circuit breakers combine the advantages of both conventional mechanical and solid-state circuit breakers, but they also introduce greater structural complexity.

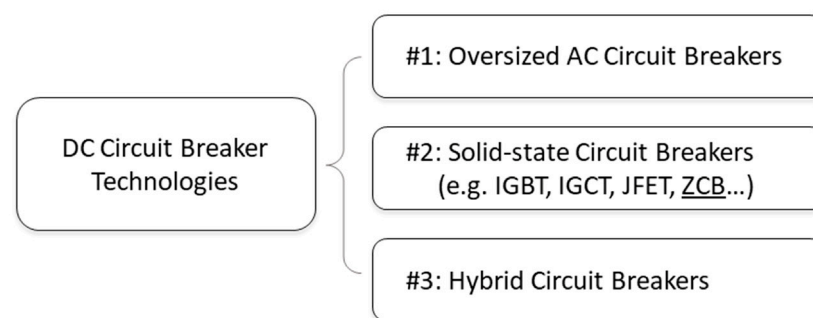


Figure 1. Classification of three solutions for DC circuit breakers.

Z-source circuit breakers (ZCBs) use thyristors (i.e., SCRs) as their primary power-flow handling devices, making them well-suited for high-power DC fault protection in hybrid microgrids. Since the Z-source concept [13] and the Z-source circuit breaker [14] were first introduced in 2002 and 2012, respectively, numerous ZCB topologies and related technologies have been investigated. In [15], C. E. Ugalde-Loo and their co-authors presented a comprehensive review of ZCB topologies developed up to 2022 and analyzed the advantages and disadvantages of different configurations based on existing studies. Figure 2 illustrates the classification of ZCB topologies and configurations.

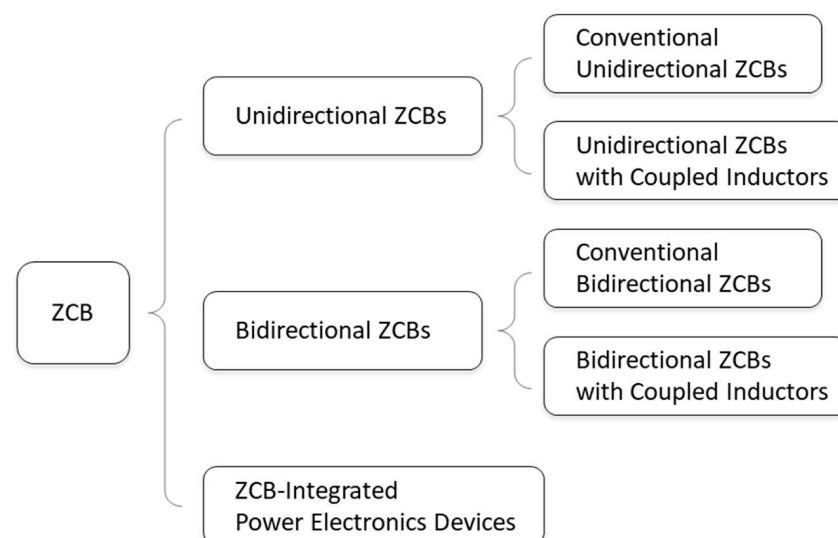


Figure 2. Classification of ZCB topologies and configurations.

In general, unidirectional ZCBs are used to protect downstream passive loads in power networks, whereas bidirectional ZCBs provide two-way current and power flow, enabling protection for active loads such as DGs, EV charging stations, and emerging data centers with large backup ESSs. In addition, coupled inductors have been incorporated into conventional ZCB topologies to address the problem of false triggering caused by load variations while also reducing the size and weight of ZCB devices [15].

Since 2022, research into ZCBs has expanded significantly. For instance, a modified ZCB was proposed to address three critical issues: (1) excessive starting current in the main thyristor, (2) unintended power delivery to the load during ZCB commissioning and reclosing, and (3) reverse current flow through the load during ZCB startup and reclosing [16]. Building on this work, the same authors developed a modified Q-ZCB with reduced weight and volume for next-generation electric aircraft in 2023 [17], subsequently validating its performance experimentally under high-impedance fault conditions in 2024 [18]. Other recent advancements include an intrinsic fault detection method for a load-independent controllable ZCB [19], as well as an accurate method for determining the minimum detectable fault ramp rate in coupled-inductor-based ZCBs [20]. Furthermore, several ZCB-integrated power electronic topologies, as shown in Figure 2, have been introduced, such as an integrated design combining a ZCB with a Ćuk DC-DC converter [21] and a novel circuit integrating cryogenic power electronics with superconducting ZCB technology [22]. Given these rapid technological advancements, studying the operational characteristics of ZCBs and their system-level impacts on power networks has become increasingly important.

Unlike device-level studies, this work investigates the system-level impact of ZCB devices in enhancing the transient stability of an islanded hybrid microgrid during DC fault protection. The main contributions of this paper are as follows:

- Analyzes the features of ZCBs during the activation process in detail, which establishes the theoretical foundation for utilizing ZCBs to achieve transient-minimized DC fault protection;
- Provides a system-level assessment of the effect of ZCBs on the transient stability of a 100 MVA islanded hybrid microgrid testbed, in contrast with most earlier studies, which focus on the topology, the design of components and the bench-scale validation of the breaker itself;
- Analyzes system indicators such as peak current, recovery time, and frequency and voltage oscillations to validate the transient performance improvements, advantages, and limitations of ZCBs in hybrid microgrid protection.

These contributions are essential for relieving stress on power devices and potentially extending their lifespans. Furthermore, they minimize the impact of DC faults on the system by reducing transients and accelerating post-fault system recovery.

The remainder of the paper is organized as follows: Section 2 introduces the topology of a bidirectional ZCB, and discusses its role and key features in DC fault protection; Section 3 presents the modeling of the 100 MVA islanded hybrid microgrid equipped with ZCBs built up in a Matlab (R2025a)/Simulink environment. The studied system primarily consists of two 50 MVA turbine-driven generator sets and a hybrid AC/DC distribution network; Section 4 presents test results under DC fault conditions, evaluating the dynamic response of the power network and verifying the effectiveness of ZCBs in improving the transient stability of the hybrid microgrid as a whole; finally, Section 5 summarizes the main findings and presents the conclusions.

2. Characteristics of ZCBs in DC Fault Protection

This section briefly introduces a bidirectional ZCB circuit topology and its internal current flow paths. Based on these circuit characteristics, two key features of DC fault protection are highlighted, establishing the theoretical foundation for utilizing ZCBs to achieve transient-minimized DC fault protection in this study.

2.1. Topology of Bidirectional ZCB

This paper adopts the topology of the Inter-Cross-Connected Bidirectional Z-source Circuit Breaker (ICC-BZCB), a conventional bidirectional ZCB configuration, as illustrated in Figure 3. Owing to the superior current- and power-handling capabilities of thyristors compared with many other power semiconductor switching devices, the proposed ZCB is well-suited for DC protection in MW-scale and higher-power distribution networks. The topology, power loss, efficiency, and component specifications of the ICC-BZCB have been extensively analyzed and validated through both simulations and experimental studies [23–26]. Furthermore, as shown in Figure 3, the cathodes of the two thyristors (T_1 and T_2) are interconnected, allowing the circuit to employ a single common-cathode thyristor module. This configuration reduces the physical size of the BZCB and facilitates more compact implementation. In this study, the DC load is modeled as a parallel RC circuit comprising the load resistance (R_L) and load capacitance (C_L).

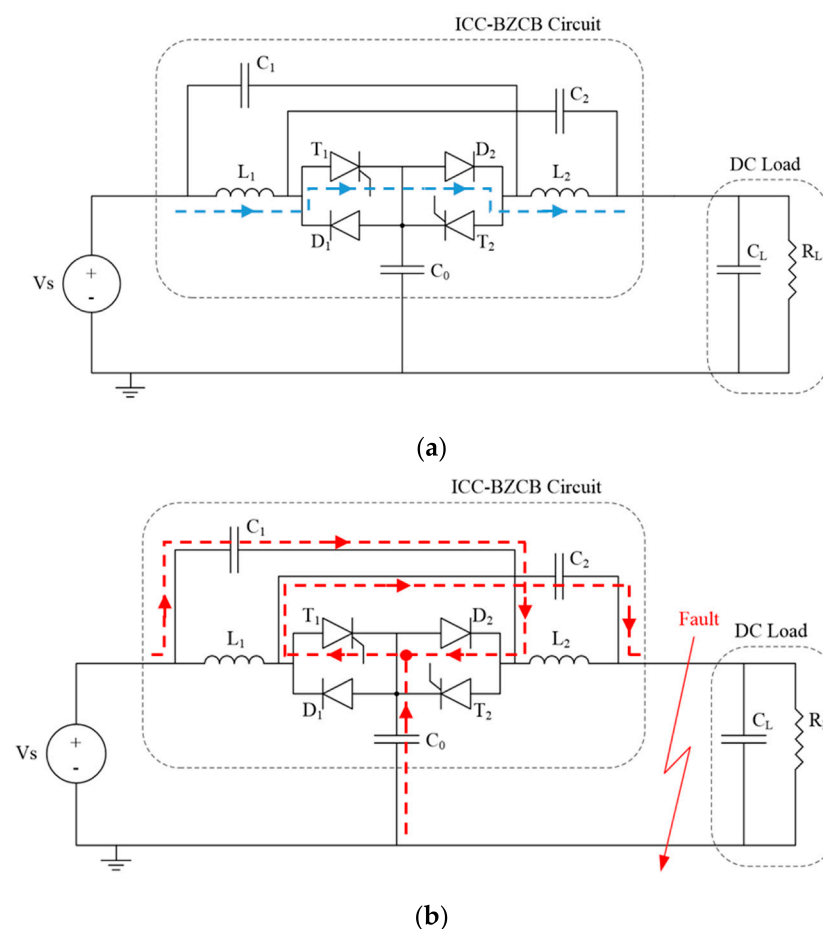


Figure 3. Operating topology and current flow paths of the inter-cross-connected bidirectional ZCB (ICC-BZCB): (a) normal operating condition; (b) thyristor turn-off condition.

During normal operating condition, the main current flows through the thyristor (T_1), diode (D_2), and two inductors (L_1 and L_2) within the ICC-BZCB, as indicated by the blue dashed line in Figure 3a. After a fault occurs, the currents from C_0 and C_1 merge at the

cathode of T_1 , as marked by the red dot in Figure 3b. The combined current then flows in the reverse direction through T_1 , naturally commutating the thyristor, as illustrated by the red dashed line in Figure 3b. Once T_1 is turned off, the ZCB enters a rapidly decaying resonant oscillation mode, dissipating the energy stored in its passive components. A detailed transient analysis of the circuit, along with experimental validation, is presented in [23,26]. Based on this topology, models of the ICC-BZCB and a 100 MVA hybrid microgrid are developed, and their relevant tests are presented in Sections 3 and 4, respectively.

2.2. Features in DC Fault Protection

Z-source circuit breakers, including ICC-BZCB, have some notable features in the DC protection against fault currents, especially in the aspects of the ultra-fast action of fault clearance and the nonexistence of fault current spikes. Compared to other available solutions of DC circuit breakers, ZCBs demonstrate quite different behaviors under fault conditions, which would significantly improve transient stability in power systems:

- “Ultra-fast action of fault clearance at μs level”: the high-frequency oscillation generated by the L-C resonant circuit enables the ZCB to interrupt fault currents within several tens of microseconds. Compared with conventional AC circuit breakers, which typically operate on the millisecond timescale, the ZCB achieves fault current interruption hundreds of times faster.

Figure 4 compares the conceptual fault current waveforms under three scenarios: fault current interruption by ZCBs, interruption by conventional circuit breakers, and an unlimited fault current. After a fault occurs at T_{fault} , the fault current rises rapidly to $I_{\text{peak_default}}$ and remains at this high level in the absence of any fault current limiting or interruption mechanism. With a conventional circuit breaker, the fault is detected after the current reaches $I_{\text{peak_default}}$ value, and the faulty branch is disconnected within several milliseconds. Comparatively, it is noticed that the resonant circuit of the ZCB is triggered within only several microseconds after fault occurrence, producing a damped oscillatory current that rapidly decays to zero. This behavior enables ultra-fast fault current interruption and significantly shortens the fault clearance time in the power circuit.

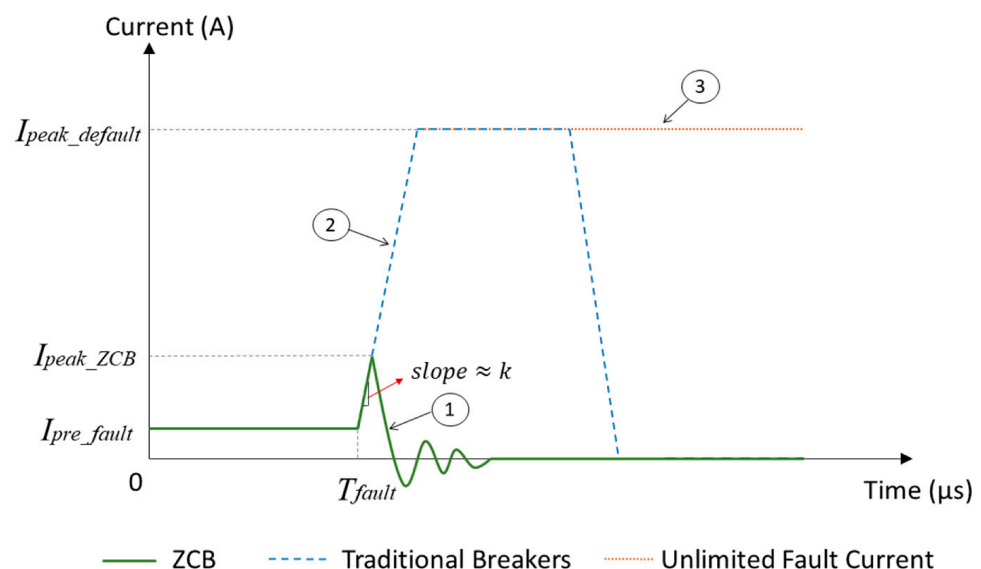


Figure 4. Conceptual comparison of fault currents under three scenarios: (1) limited by ZCBs, (2) limited by conventional circuit breakers, and (3) unlimited without any breakers.

- “Nonexistence of fault current spike”: unlike conventional circuit breakers, which are triggered by the absolute fault current level, the ZCB responds to faults based on the fault conductance ramp, as defined in (1). Based on the circuit analysis presented in [23], the term “ k ” is defined as the threshold of fault conductance ramp for ZCB tripping. If the actual fault conductance changing rate exceeds k when a fault occurs, the ZCB’s resonant circuit is activated, enabling it to clear the fault rapidly. Otherwise, the ZCB is not triggered and remains in its normal conducting state. The threshold k can be adjusted by selecting the ZCB component parameters according to (2).

$$k = 1/(R_f \times T_{\text{changing}}), \quad (1)$$

where k is the fault conductance ramp; R_f is the fault resistance; and T_{changing} is the transition time of the fault resistance from its pre-fault value to its final value.

$$k = [81 \times (2C + 3C_L)]/[32 \times (C^2) \times (R_L^2)], \quad (2)$$

where C is the Z-source capacitance for the case where $C = C_0 = C_1 = C_2$; R_L is the load resistance; and C_L is the load capacitance, as indicated in Figure 3.

As shown in Figure 4, because the ZCB is triggered by the slope of the fault current (which is approximately equal to the fault conductance ramp, “ k ”), the fault current spike can be significantly suppressed or even completely eliminated, resulting in “ $I_{\text{peak_ZCB}} \ll I_{\text{peak_default}}$ ”. These two key features of ZCB in fault protection provide the theoretical foundation for achieving transient-minimized DC fault protection and enhancing the transient stability of power systems.

In addition, the ZCB offers several other notable features, including controllable fault-clearing time, low power loss during normal operation, the ability to handle high-voltage and high-current applications (owing to the characteristics of the thyristor), and low manufacturing and maintenance costs. These advantages make the ZCB a promising DC protection device for practical applications in the power industry.

3. Modeling of a Hybrid Microgrid with ZCBs

This section details the modeling of the 100 MVA islanded hybrid microgrid within the Matlab/Simulink environment. Based on the target DC loads requiring protection, the ZCB model parameters are specified and validated through preliminary component-level testing. These developed models establish a foundation for the system-level studies presented in Section 4.

The methodology of this study is structured as follows: first, the hybrid microgrid model is constructed in Section 3.1; second, the ZCB model undergoes component-level validation in Section 3.2; third, both models are integrated for system-level testing; and finally, fault tests and sensitivity sweeps are conducted and analyzed in Section 4.

3.1. Modeling of a Hybrid Microgrid

A model of a 100 MVA islanded hybrid microgrid was built in the Matlab/Simulink environment. This power scale is representative of realistic distribution-level applications, providing the rationale for the system-level approach adopted in this study. In this hybrid microgrid, two 50 MVA turbo generators are interconnected through a 4.16 kV AC power cable to form a distribution network, which supplies two 25 MW, 0.8 P.F. lagging AC loads and two 15 MW, 5 kV DC loads, as shown in Figure 5. Gas turbines, T1 and T2, drive two synchronous generators, G1 and G2. Two buses, “AC Bus 1” and “AC Bus 2”, supply the AC loads and are interconnected through a tie-line for power sharing and distribution. The “AC-DC” blocks represent three-phase 6-pulse diode AC-to-DC rectifiers, each equipped with a conventional AC circuit breaker labeled as a “CB” block on its AC

side. Two buses, “DC Bus 1” and “DC Bus 2”, supply the DC loads, with each DC bus protected by its respective ZCB. The AC loads represent major traditional loads like AC motors for industrial and residential usage and the DC loads represent modern loads like data centers and EVs.

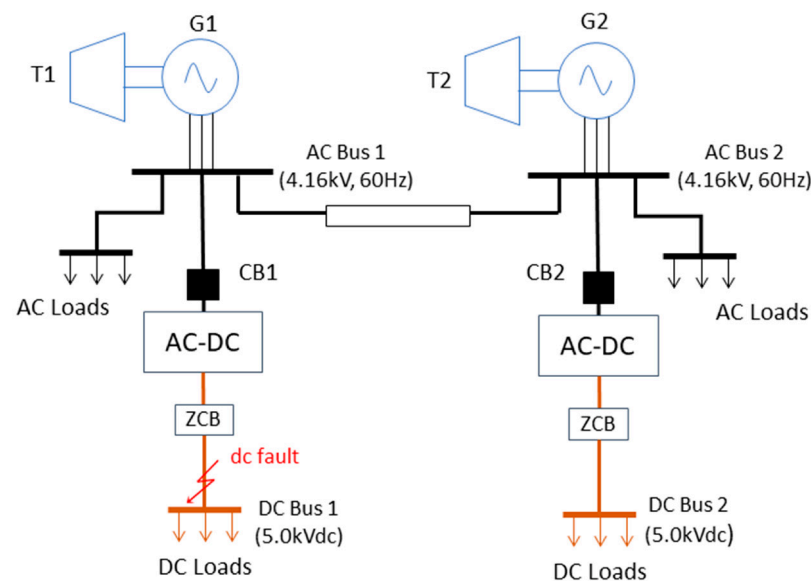


Figure 5. Layout of a 100 MVA islanded hybrid microgrid.

This model of a hybrid microgrid serves as a baseline for testing the transient stability with/without ZCB installation. The model of the turbo generator is based on Rowen’s heavy-duty gas turbine model [27], the full-order synchronous generator model [28], and the IEEE type AC8B excitation system model [29,30]. The control parameters for the automatic voltage regulator (AVR) and the amplifier are tuned within the exciter to ensure voltage stability. The three-phase 6-pulse diode AC-to-DC rectifiers consist of front-end transformers, diode bridges, and output L-C filters. The AC loads are modeled as lumped R-L elements. The DC loads are modeled as lumped R elements powered by AC-DC rectifiers. Table 1 lists the key parameters of the hybrid microgrid model.

Table 1. Parameters of Hybrid Microgrid.

Turbo Generator		
Rated Power	50	MVA
Rated Voltage	4.16	kV
Power Factor	0.95, lagging	-
Rated Frequency	60	Hz
Inertia Constant	4.0	s
Friction Factor	0.04	-
Stator Resistance	0.002	p.u.
Stator Leakage Inductance	0.135	p.u.
d-axis Magnetizing Inductance	1.35	p.u.
q-axis Magnetizing Inductance	1.35	p.u.
d-axis resistance of damper	0.05	p.u.
d-axis leakage inductance of damper	0.02	p.u.
q-axis resistance of damper	0.05	p.u.
q-axis leakage inductance of damper	0.04	p.u.

Table 1. Cont.

Control Settings of Turbo Generator		
Turbine Governor Setting	4% (in droop mode)	p.u.
Proportional Gain of AVR in Exciter	400	-
Integer Gain of AVR in Exciter	0.08	-
Derivative Gain of AVR in Exciter	0.001	-
Differential Time Constant of AVR in Exciter	0.001	s
Maximum Output Limit of AVR in Exciter	10	p.u.
Minimum Output Limit of AVR in Exciter	0	p.u.
Amplifier Proportional Gain in Exciter	1	-
Amplifier Time Constant in Exciter	0.0001	s
Maximum Exciter Limit of Amplifier in Exciter	10	p.u.
Minimum Exciter Limit of Amplifier in Exciter	0	p.u.
4.16 kV, 60 Hz AC Cable		
Cable Resistance	0.16	mΩ
Cable Inductance	0.28	μH
Three-Phase 6-Pulse Diode AC/DC Rectifiers		
Turns Ratio of Power Transformer	1.04:1 (at full DC load) 1.09:1 (at no DC load)	-
Diode Forward Voltage	1.5	V
Inductance of Output L-C Filter	1.0	mH
Capacitance of Output L-C Filter	800	μF
AC Loads		
AC-Load Voltage	4.16	kV
AC-Load Power	25	MW
AC-Load Power Factor	0.8, lagging	-
DC Loads		
DC-Load Voltage	5	kV
DC-Load Power	15	MW

3.2. Modeling of ZCB

A model of ZCBs was built based on the topology of ICC-BZCB and also tested in the Matlab/Simulink environment, as shown in Figure 6. The topology of ICC-BZCB has been experimentally validated in [23,26], making it highly suitable for the system-level study presented in this paper. Table 2 lists the parameters of the ZCB model. The parameters of ZCB model are determined using the specification methods outlined in [23,26], where R_f is set to half of the rated resistance of DC load as 0.83Ω , $T_{changing}$ is set to $15 \mu s$, and R_L is set to the rated resistance of DC load as 1.67Ω . Based on these parameters, the margin of the fault-conductance ramp (k) equals $0.08 \times 10^{(6)} \text{ S/s}$. According to [23,26], the ZCB parameters are designed sequentially. First, the Z-source capacitance is calculated using (1) and (2) based on the target values of R_f and $T_{changing}$. Second, the Z-source inductance is determined to satisfy the boundary condition in (3). Finally, the thyristors and diodes are selected based on their required voltage and current ratings. In this configuration, the ZCB model is automatically triggered by a short-circuit fault when the fault-conductance ramp exceeds the established threshold margin of $0.08 \times 10^{(6)} \text{ S/s}$ in this study. This ZCB tripping rule is generally applicable to fault cases with high-resistance and low-resistance.

$$L \gg [C \times (R_L^2)]/30, \quad (3)$$

where L is the Z-source inductance for the case where $L = L_1 = L_2$;

C is the Z-source capacitance for the case where $C = C_0 = C_1 = C_2$;
 R_L is the fault resistance.

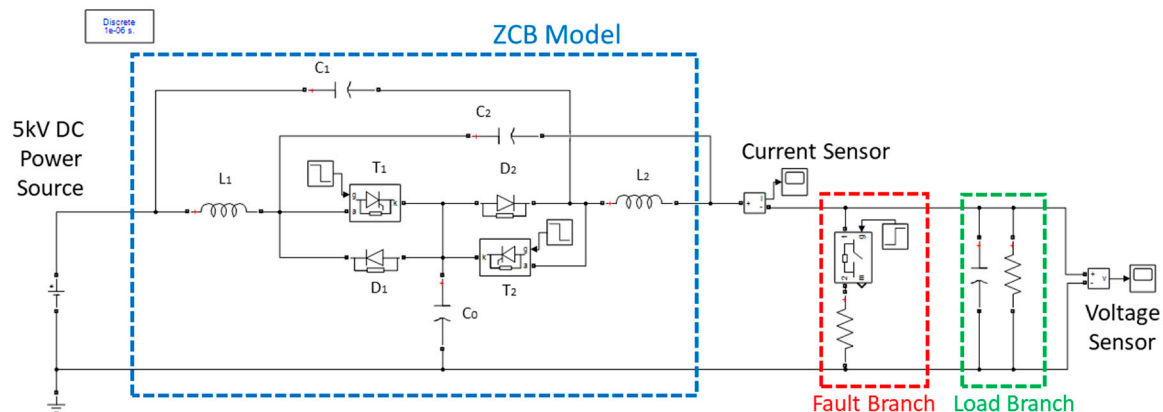


Figure 6. Testbed of the ZCB model.

Table 2. Parameters of ZCB Model Testbed.

ZCB Model		
C_0, C_1, C_2	40	μF
L_1, L_2	80	μH
SCR On-State Resistance	1.0	$\text{m}\Omega$
SCR Forward Voltage	0.8	V
Diode On-State Resistance	1.0	$\text{m}\Omega$
Diode Forward Voltage	0.8	V
Load Branch		
Load Resistance	5.0	Ω
Load Capacitance	20	μF
Fault Branch		
Fault-branch Resistance	1.0	Ω

In preparation for the system-level tests in Section 4, the ZCB model was preliminarily tested at the component level with a 5 kV DC power source to verify its effectiveness under a fault condition. In this preliminary test, the pre-fault DC load is set to 33.3% of the rated capacity, in contrast to the 100% full DC load utilized during the system tests in Sections 4.1 and 4.2. Figure 7 shows the fault current cutoff by the ZCB model measured by a current sensor. At 5.0 s, a short-circuit fault occurred at the load side, caused by adding a fault branch in parallel, which contributes a two times rated current in total. The ZCB model was triggered by the high changing rate of the fault current and cut off the faulty branch within about 300 μs successfully, which makes the ZCB model ready for its integration into the hybrid microgrid model.

The modeling and simulation framework for the hybrid microgrid can evaluate various fault scenarios to validate the performance of ZCBs. To emulate a low-impedance short circuit, a minimal fault resistance is applied. Because the ZCB is tuned to trigger at fault conditions exceeding the established k threshold of $0.08 \times 10^{(6)}$ S/s in this study, the simulation also accounts for short-circuit conditions with high resistance, demonstrating minimized transients and system oscillations. Also, the microgrid topology incorporates lumped loads distributed across two separate buses connected by a tieline, accurately reflecting remote-line and multi-branch scenarios. To evaluate the system under rigorous conditions, the total load is established at 80 MW, representing 80% of the total generation

capacity, including DC loads operating at their full rated current levels. The test results of this paper capture a worst-case scenario, proving that ZCB utilization significantly improves transient stability.

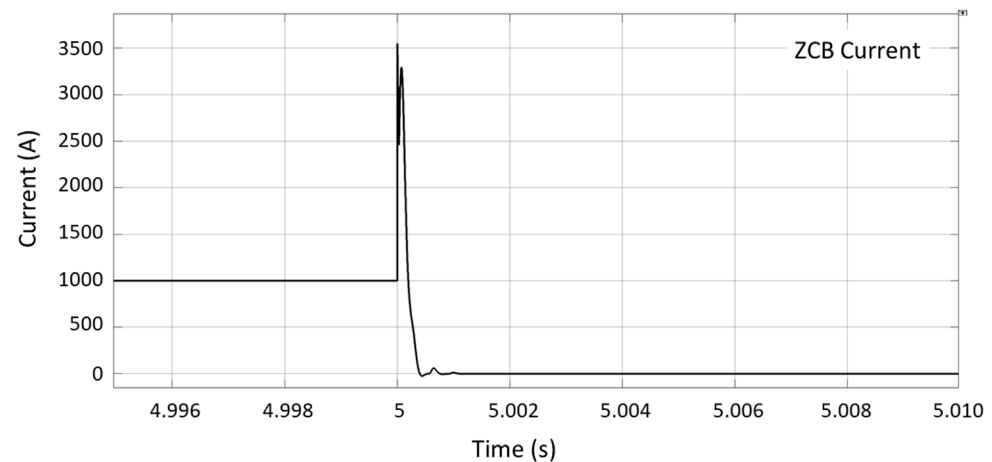


Figure 7. Fault current cutoff by ZCB model.

4. Test Results and Analysis

This section includes the test results and relevant analysis of using ZCBs to improve transient stability in the 100 MVA hybrid microgrid. The Simulink simulation is configured with a discrete, fixed-step solver using a time step of 10 μ s. For benchmarking reference, a 200 s simulation run requires approximately 2.5 h of execution time on a desktop computer equipped with an Intel Core i5-8300H CPU (2.30 GHz), 16.0 GB of RAM, and an NVIDIA GeForce GTX 1050 Ti GPU (4 GB). Given that the transient and dynamic responses of the hybrid microgrid testbed are heavily governed by the turbogenerators, the generator's frequencies and voltages are utilized as key metrics for transient performance in this study. Based on the system layout shown in Figure 5, the system frequency is established under the turbine governors of T1 and T2, and the system voltage is built up via the exciters of G1 and G2. The startup process of turbine-generator sets takes about 110 s, as shown in Figure 8. After the system's starting-up, the AC loads and DC loads are powered at 120 s by closing circuit breakers at the terminals of G1 and G2. The tie-line between the AC_Bus_1 and AC_Bus_2 closes at 150 s to form a 100 MVA hybrid microgrid, and afterward, the whole hybrid system operates in a stable and ready state for fault tests of transient study. No spurious tripping of the ZCB was observed during the system startup phase shown in Figure 8. The same ZCB parameters presented in Table 2 are adopted for the system-level tests conducted in Section 4.

4.1. Fault Test with Conventional CB

In the tests with conventional circuit breakers, a short-circuit fault occurs at 170 s near the "DC Bus 1" in Figure 5 and results in high fault currents in the distribution network. The fault is a pole-to-pole short circuit with a fault branch resistance of 1.0 Ω , located as marked in Figure 5. In the system testbed, this fault branch is emulated using the configuration shown in Figure 6, which consists of a fault-branch resistance and a controlled switch connected in series. At 170 s, the fault branch is introduced into the network by closing the controlled switch within a single time step of 10 μ s. The fault remains active until the protective devices isolate the faulty line. The tests in Sections 4.1 and 4.2 have a full rated DC load of 3.0 kA at pre-fault, with an additional 5.1 kA contributed by the fault branch during the fault.

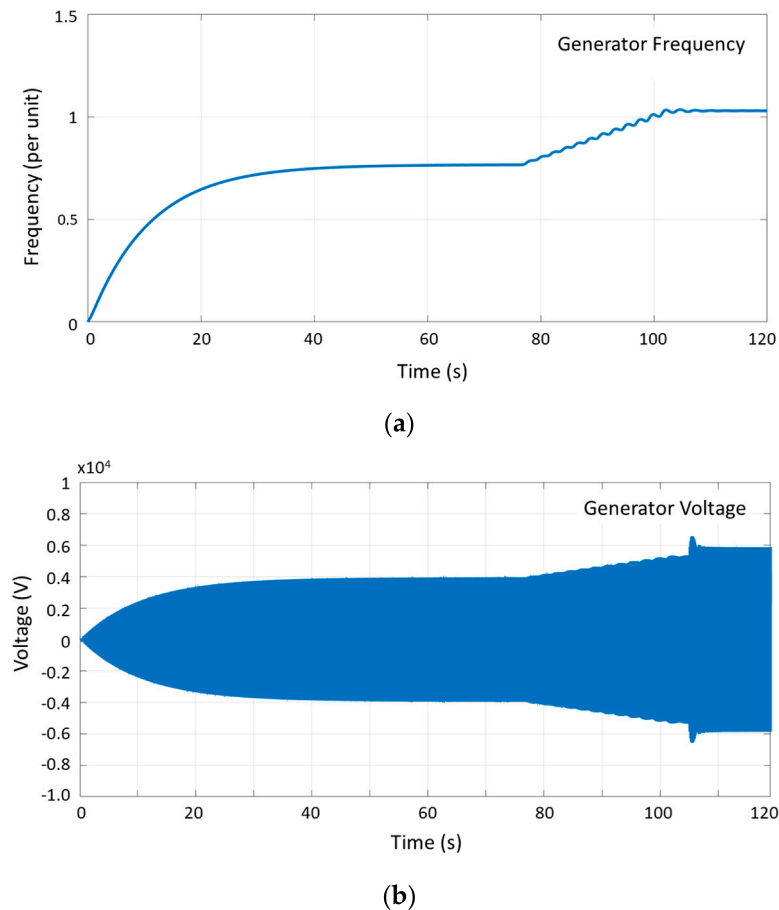


Figure 8. The frequency (a) and instantaneous terminal voltage (b) of turbine generators during the starting-up process.

In this scenario, the fault is cleared by a 2-cycle AC circuit breaker labeled as “CB1” at the input terminal of the “AC-DC” rectifier, shown in Figure 5. Figures 9 and 10 present the DC fault current, generator frequencies, and RMS bus voltages during the fault clearance process using the AC circuit breaker. These figures illustrate the transients and system oscillations within the hybrid microgrid during and after the fault. The key data extracted from these waveforms are summarized in Table 3 and compared against the configuration utilizing ZCBs.

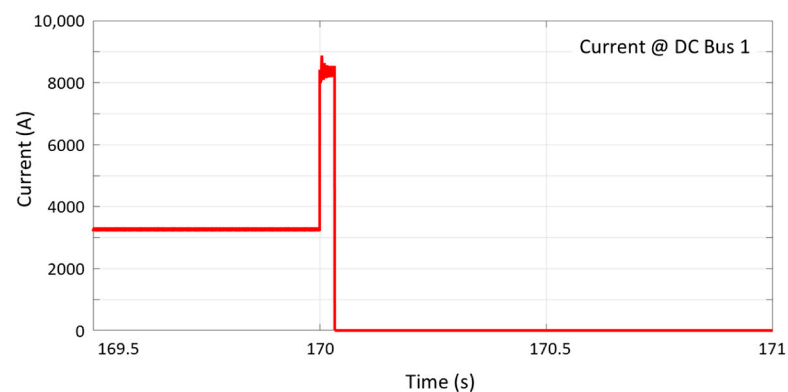
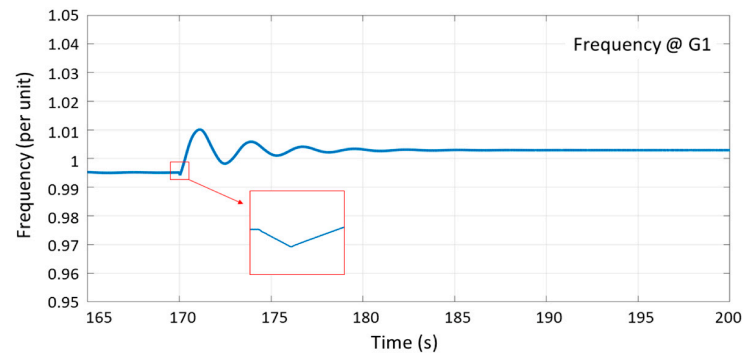
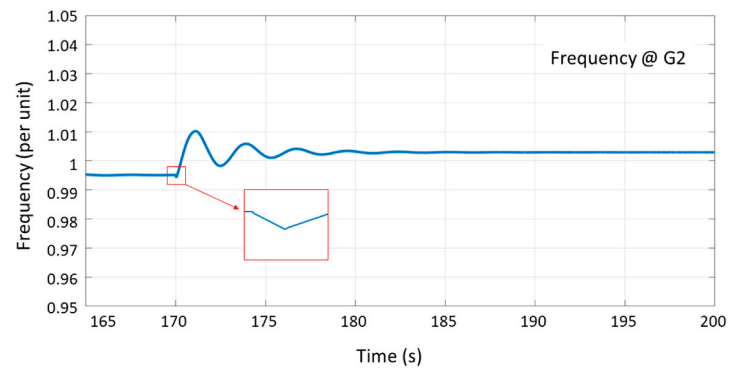


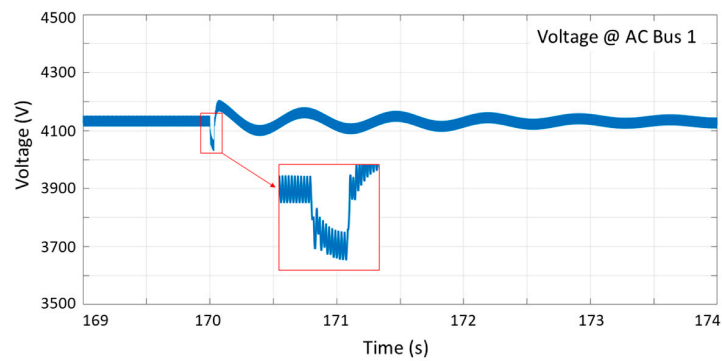
Figure 9. Clearance of DC fault current with a conventional circuit breaker.



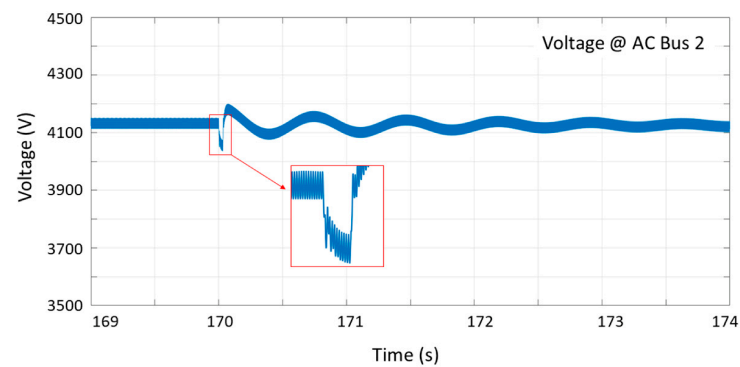
(a)



(b)



(c)



(d)

Figure 10. The generator frequencies (a), frequency of turbogenerator #1; (b) frequency of turbogenerator #2; and bus voltages (c) at “AC Bus 1” and (d) at “AC Bus 2” during fault-related transients, under a conventional circuit breaker.

Table 3. Comparison of Transient Data during Fault (Conventional CB vs. ZCB).

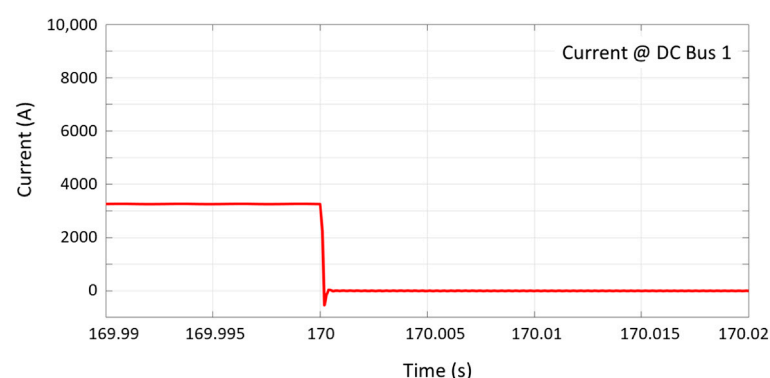
	Conventional CB	ZCB	Improvement (in %)
Peak Fault Current (at DC Bus 1)	8.9 kA	3.2 kA	64.0%
Fault Clearance Time	32 ms	380 μ s	98.8%
Frequency Oscillation (at AC Bus 1)	0.015 p.u.	0.013 p.u.	13.3%
Frequency Oscillation (at AC Bus 2)	0.015 p.u.	0.013 p.u.	13.3%
Frequency Oscillation Time	7.5 s	7.5 s	0%
Voltage Oscillation (at AC Bus 1)	120 V	30.2 V	74.8%
Voltage Oscillation (at AC Bus 2)	100 V	25.5 V	74.5%
Voltage Sag (at AC Bus 1)	80 V	0	100%
Voltage Sag (at AC Bus 2)	77 V	0	100%
Voltage Recovery Time	4.6 s	2.5 s	45.7%

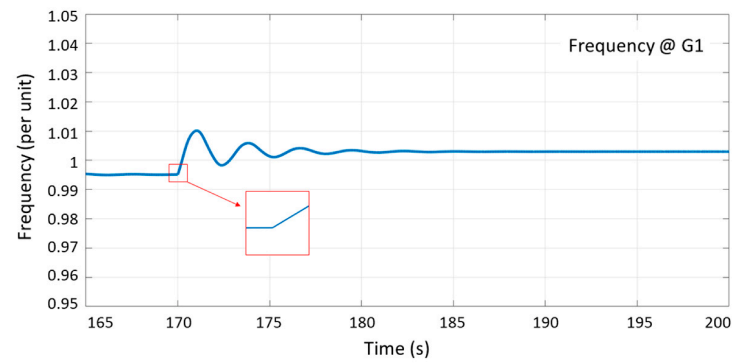
From these figures, we can see that after the fault occurs, the DC current at “DC Bus 1” increases from 3.2 kA to 8.9 kA sharply and then is cleared by the triggering of the conventional circuit breaker within 32 ms, as shown in Figure 9. There are some drops in transient frequency, as highlighted in Figure 10a,b. Also, there are big voltage sags in AC bus voltages, as highlighted in Figure 10c,d. The voltage sag at “AC Bus 2” is slightly smaller than the one at “AC Bus 1” due to its further distance from the fault location.

After the fault clearance, the DC loads at “DC Bus 1” lose power supply, whereas the DC loads at “DC Bus 2” are immediately reenergized right at 32 ms. There is a rebalance process between TG1 and TG2 in the power distribution network, which is demonstrated as a post-fault oscillation in generator frequencies and AC bus voltages, as shown in Figure 10. The oscillation in frequency lasts about 7.5 s, and the oscillation in voltage lasts about 4.6 s. The periods of these oscillations relate to the inertia constant and time constants of turbine generators, and the distribution of load power within the hybrid microgrid.

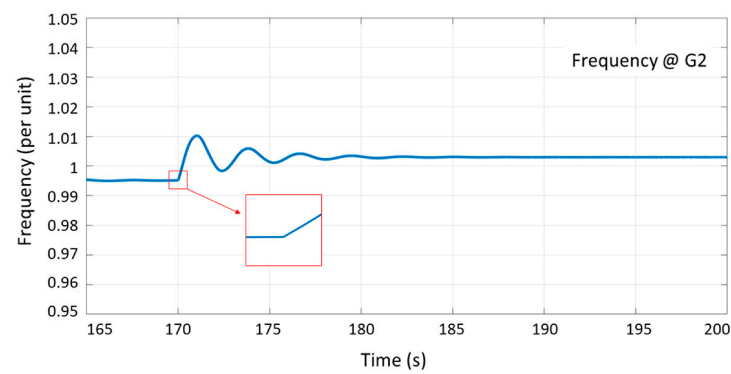
4.2. Fault Test with ZCB

Another fault test is performed with the ZCB installed and activated at the output terminal of the “AC-DC” rectifier shown in Figure 5. Figures 11 and 12 present the DC fault current, generator frequencies, and bus voltages in rms during the fault clearance process with the ZCB, respectively. The related key data are summarized in Table 3.

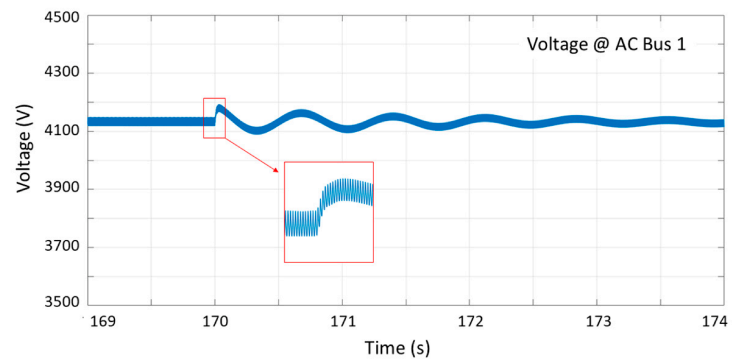
**Figure 11.** Clearance of DC fault current with ZCB.



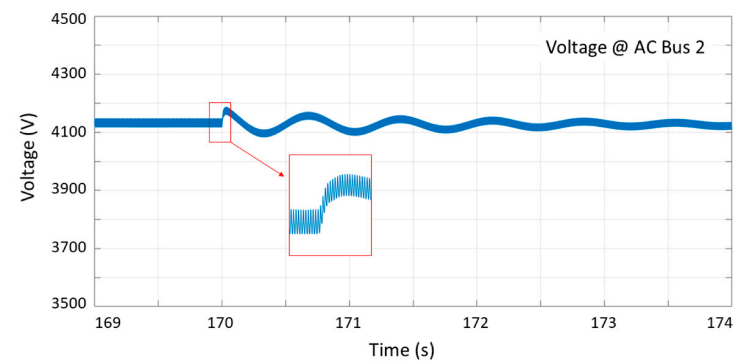
(a)



(b)



(c)



(d)

Figure 12. The generator frequencies (a), frequency of turbogenerator #1; (b) frequency of turbogenerator #2; and bus voltages (c) at “AC Bus 1” and (d) at “AC Bus 2” during fault-related transients, under the ZCB.

In this test, the actual fault-conductance ramp (k) corresponding to the injected $1.0\ \Omega$ fault reaches $0.10 \times 10^{(6)}\ \text{S/s}$, which exceeds the threshold margin of $0.08 \times 10^{(6)}\ \text{S/s}$. Consequently, it is noticed that, by applying the ZCB, the DC fault current can be directly reduced to negative to turn off the thyristor inside the ZCB automatically, which eliminates the fault current spike completely, as shown in Figure 11. It greatly helps to relieve the stress on power devices in the system. Also, the transient drops in frequency disappear, as highlighted in Figure 12a,b. In addition, there is no voltage sag in AC bus voltages, as highlighted in Figure 12c,d.

4.3. Result Analysis

Table 3 clearly demonstrates the improvements in system transient performance achieved by applying ZCBs in DC fault protection, specifically regarding peak current in the DC distribution network and frequency and voltage oscillations in the AC distribution network. The peak fault current at “DC Bus 1” was significantly reduced from 8.9 kA to 3.2 kA. Correspondingly, the energy delivered to the fault reduced from $2.1 \times 10^{(6)}\ \text{J}$ to $3.6 \times 10^{(3)}\ \text{J}$. This improvement is attributed to the two unique features of ZCB fault protection described in Section 2.2: ultra-fast fault clearance at the microsecond level and the absence of a fault current spike. As shown in Figure 13, the peak reverse stress on the SCR is 6.7 kV, which provides a reference for SCR component selection. In this study, the ZCB isolates the faulty line within only 380 μs , compared to 32 ms for a conventional AC circuit breaker. Here, frequency oscillations are measured as the peak-to-valley values during the fault. With the ZCB, the frequency deviations at both “AC Bus 1” and “AC Bus 2” are slightly reduced from 0.015 p.u. to 0.013 p.u. However, the duration of the frequency oscillation remains at approximately 7.5 s. This prolonged oscillation is driven by the large inertia constants of the turbine governor relative to the fault transient. Note that the frequency deviations in the waveforms shown in Figures 10 and 12 differ between the pre-fault and post-fault conditions due to the disconnection of the faulty load branch. For the steady-state operation of the islanded microgrid, frequency deviations are maintained within [59.5 Hz, 60.5 Hz], i.e., [0.992, 1.008] in per unit. These deviations are managed by the droop control of the turbine generators during steady-state operation and are therefore irrelevant to the transient analysis presented in this paper.

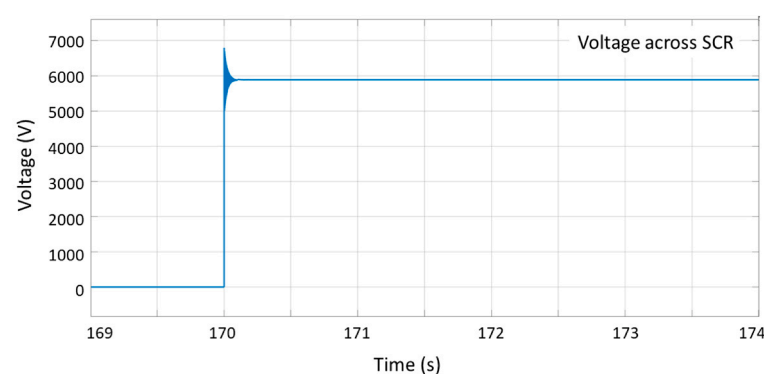


Figure 13. Voltage across the SCR in ZCB.

Regarding system voltage stability, the rapid fault clearance of the ZCB greatly mitigates voltage oscillations at “AC Bus 1” and “AC Bus 2” from 120 V and 100 V (with a conventional circuit breaker) to 30.2 V and 25.5 V, respectively. Here, voltage oscillations are measured as the peak-to-valley values during the fault. In addition, the ZCB completely eliminates AC voltage sags, as highlighted in Figure 12c,d. In contrast, a conventional circuit breaker results in the AC voltage sags that reach 80 V at “AC Bus 1” and 77 V at “AC Bus 2”. Here, voltage sags are defined as the difference between the pre-fault value

and the absolute valley value during the fault. By suppressing these voltage sags, the voltage oscillation duration decreases from 4.6 s to 2.5 s. This improvement stems from the elimination of voltage sags at the AC buses. This elimination accelerates the exciter's response, which is mainly governed by the 1 ms AVR time constant shown in Table 1. Consequently, the system achieves a faster post-fault recovery to a stable state. Due to the AC/DC rectifier coupling, the DC voltage sags reach 433 V at "DC Bus 1" and 413 V at "DC Bus 2" when using a conventional circuit breaker. In contrast, the ZCB completely eliminates these DC voltage sags during the fault. Ultimately, the primary benefits of the ZCB are concentrated on the voltage and current transients, whereas the frequency dynamics remain dominated by the time constants of the turbine governor.

The tests in Sections 4.1 and 4.2 have a full rated DC load of 3.0 kA at pre-fault, with an additional 5.1 kA contributed by the fault branch during fault. Based on the tests above, two series of tests are performed on the ZCB under various fault and load conditions:

- (a) Variable Fault Current Tests: the resistance R_f is adjusted to vary the fault current contribution from the fault branch to 2.4 kA, 5.1 kA, 7.5 kA, and 15.0 kA. These tests have a full rated DC load of 3.0 kA at pre-fault;
- (b) Variable Pre-fault Load Tests: initial DC load conditions of 3.0 kA, 2.0 kA, and 1.0 kA are evaluated. These tests have a fault current of 5.1 kA from the fault branch during fault.

Table 4 summarizes the test results under varying fault current levels. When the fault current is only 2.4 kA, the ZCB fails to interrupt the faulty line. This failure occurs because the associated fault-conductance ramp (k) is only $0.048 \times 10^{(6)}$ S/s, which remains below the established threshold margin of $0.08 \times 10^{(6)}$ S/s defined during the parameter specification process in Section 3.2. This aligns with the design intent to prevent unintended ZCB tripping during load variations and starting transients under normal operation. Conversely, when the fault current is within the range of 5.1 kA to 15.0 kA (specifically tested at 5.1 kA, 7.5 kA, and 15.0 kA), the ZCB successfully isolates the faulty line in all instances. While minor differences are observed in the peak fault current levels and fault clearance times, these are driven by a stronger resonant commutation within the ZCB due to the higher fault current from the DC load side. Ultimately, these minor variations exert no noticeable impact on the transient and dynamic performance of the system's AC frequency and voltage.

Table 4. Comparison of Transient Data under Various Fault Current Levels with ZCB.

Fault Current	2.4 kA	5.1 kA	7.5 kA	15.0 kA
Peak Fault Current (at DC Bus 1)	-	3.2 kA	3.26 kA	3.34 kA
Fault Clearance Time	-	380 μ s	350 μ s	340 μ s
Frequency Oscillation (at AC Bus 1)	-	0.013 p.u.	0.013 p.u.	0.013 p.u.
Frequency Oscillation Time	-	7.5 s	7.5 s	7.5 s
Voltage Oscillation (at AC Bus 1)	-	30.2 V	30.0 V	30.2 V
Voltage Sag (at AC Bus 1)	-	0	0	0
Voltage Recovery Time	-	2.5 s	2.5 s	2.5 s

Table 5 summarizes the test results under varying pre-fault DC load levels. The data indicates that as the initial DC load decreases, the peak fault current exhibits a marginal, corresponding reduction. Concurrently, the fault clearance time decreases because less time is required to drive the lower initial DC load current to zero. Furthermore, because a smaller DC load reduction occurs after the faulty line is isolated, fewer oscillations are induced in the system's AC frequency and voltage. Notably, all cases examined in both Tables 4 and 5 completely eliminate voltage sags to zero.

Table 5. Comparison of Transient Data under Various Pre-fault DC Load Levels with ZCB.

Initial Load Level	3.0 kA (100%)	2.0 kA (67%)	1.0 kA (33%)
Peak Fault Current (at DC Bus 1)	3.2 kA	3.14 kA	3.06 kA
Fault Clearance Time	380 μ s	365 μ s	230 μ s
Frequency Oscillation (at AC Bus 1)	0.013 p.u.	0.0096 p.u.	0.0051 p.u.
Frequency Oscillation Time	7.5 s	4.4 s	2.4 s
Voltage Oscillation (at AC Bus 1)	30.2 V	17.2 V	6.2 V
Voltage Sag (at AC Bus 1)	0	0	0
Voltage Recovery Time	2.5 s	1.7 s	1.0 s

In the hybrid microgrid testbed developed for this study, the ZCB is modeled based on the electrical connections of its internal physical components, including inductors, capacitors, SCRs, and diodes. Synchronous generators are represented by full-order models, while the AC/DC rectifiers utilize detailed switching models. Consequently, the testbed accurately captures real-world transient and dynamic behaviors, as well as the interactions among various electrical devices. The prior literature indicates that the turn-off behavior of a ZCB can be influenced by its interconnected devices, such as the upstream DC-link capacitance and the downstream load capacitance. Specifically, the rectifier's DC-link capacitance affects the voltage retention of the DC output during the resonant commutation for the SCR turnoff inside ZCB. Meanwhile, the load capacitance impacts the minimum detectable fault conductance ramp, as expressed in Equation (2). These external capacitances surrounding the ZCB can interact with its internal L-C resonant circuit, shifting the turn-off threshold and potentially causing a turn-off failure under certain fault current levels. However, owing to the sufficient parameter redundancy specified in Section 3.2, the ZCB's cutoff performance remains resilient against external interference. This ensures the successful observation of the interactions between the ZCB and the turbogenerators, which dominate the transient and dynamic behaviors investigated in this study.

In these tests, the transient performance of conventional AC circuit breakers is compared directly against that of ZCBs. While other solid-state and hybrid DC breakers can also enhance transient stability depending on their fault detection schemes, their effectiveness is limited by their controls. Specifically, if these solid-state and hybrid DC breakers rely on overcurrent relays, severe current spikes remain inevitable. However, owing to the rapid turn-off characteristics inherent to solid-state and hybrid DC topologies, they still outperform traditional AC circuit breakers. Furthermore, ZCBs utilize thyristors, making them highly suited for high-power distribution systems. Consequently, ZCBs offer distinct advantages for achieving transient-minimized operations in high-power applications.

5. Conclusions, Limitations, and Future Directions

From the study in this paper, it is proven that the transient stability can be greatly improved by utilizing ZCBs, which enables a “transient-minimized” operation in DC fault protection in the hybrid microgrid system. The elimination of the high spike in fault current helps to relieve the stress on power devices and potentially extends their lifespans. The oscillations in frequency and voltage are reduced to minimize the impact of DC fault on the system and accelerate system recovery during post fault. Test results demonstrate that system oscillation is reduced by 13% in frequency and 74% in voltage, while completely eliminating voltage sags. The results also demonstrate that the proposed method remains effective across various fault current levels and different pre-fault DC load conditions. This effectiveness includes the consideration of faults with high-resistance and low-resistance at full load within the ZCB parameter specification under study. These findings are especially significant for critical loads, such as data centers handling mission-critical operations and

life-support devices in medical and hospice facilities, which contain expensive electronics and demand minimal operational interruption.

Several limitations of this study present promising avenues for future research. First, as a single-shot protective device, the ZCB requires specific recommissioning procedures, such as inductor/capacitor recharging and thyristor re-firing, which were not investigated in this work. Analyzing these processes would clarify DC-bus load availability differences between ZCBs and conventional circuit breakers during restoration and reclosing. Second, a detailed performance comparison between the ZCB and other solid-state/hybrid breakers remains to be fully explored. Comprehensive simulation studies are needed to address these comparative aspects in future work. While beyond the current scope of this paper, these aspects represent valuable directions for future research.

Beyond this study, the research directions could be expanded for other aspects of ZCB's application in power systems as follows: (a) Although prior literature has examined the impacts of front-end DC-link rectifier capacitance and downstream load capacitance separately, evaluating their integrated effect on the turn-off behavior of a ZCB during a fault remains an open and compelling research topic. This integrated analysis should account for various configurations, including different rectifier types (e.g., 12-pulse/24-pulse phase-shifted rectifiers and pulse-width-modulated active-front-end rectifiers), cable lengths, and diverse loads, such as uninterruptible power supply units in data centers, renewable sources, and grid-forming converters. Ultimately, these upstream and downstream devices introduce distinct coupled elements into the ZCB circuit that warrant detailed investigation. (b) In addition to the pole-to-pole DC faults examined in this study, the performance of the ZCB under pole-to-ground faults can be further investigated. Given the grounding configurations of DC loads (either grounded or ungrounded), future research can comprehensively analyze the associated capacitor discharges and the detectability of pole-to-ground fault conditions. (c) Driven by advancements in modern internet of things (IoT) technologies, future research can expand to investigate ZCB restoration and reclosing strategies. Furthermore, the coordination of multiple ZCBs with other protection devices should be explored within the context of medium-voltage DC power systems [31] and hybrid microgrids.

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