1 Introduction

The transition from AC to DC distribution systems in renewable energy, electric vehicles (EVs), aerospace, and data centers has accelerated the demand for fast, reliable protection devices [1]. Unlike AC systems, where fault currents naturally reach zero each cycle, DC systems lack a current zero crossing, making fault interruption more difficult and requiring faster and more robust solutions [2].

Traditional mechanical DC circuit breakers are limited by their slow response time and arc-based energy dissipation [3]. In contrast, solid-state circuit breakers (SSCBs), based on semiconductor devices such as IGBTs, MOSFETs, and thyristors, offer microsecond-scale interruption, high reliability, and silent operation [12]. However, the fast switching in SSCBs leads to significant voltage overshoots due to system inductance, requiring clamping techniques such as MOVs, snubbers, or active clamps [12].

Recent studies have explored various SSCB topologies, including thyristor-based breakers [4], fault current bypass structures [8], and hybrid designs combining semiconductors with fuses or counter-current injection methods [3]. Voltage clamping remains a crucial challenge, as overvoltages threaten semiconductor reliability. New approaches, such as RC-MOV snubbers [12] and electronic MOVs (eMOVs) [12], have been developed to enhance clamping performance. Additionally, smart fuses tailored for EV applications offer a compact, programmable alternative to conventional protection [11].

Commercial adoption is also increasing: ABB has introduced SSCBs in its ABB SACE S3+ Smart Power line for low-voltage DC microgrids [9], Eaton integrates solid-state protection in aerospace and EV platforms, while Schneider Electric explores DC smart fuses for renewable and battery storage applications. Startups such as Atom Power (USA) have commercialized fully digital SSCBs for residential and industrial use, demonstrating the shift from electromechanical to solid-state protection.

Given these developments, this project focuses on the design and analysis of a 16 A, 350 V DC solid-state breaker (e-fuse) using MATLAB/Simulink, with emphasis on fault current interruption, voltage clamping, and performance validation under low-voltage DC conditions.

2 Literature Review

2.1 Solid-State Breaker Fundamentals

Solid-State Circuit Breakers (SSCBs) are increasingly explored for LVDC grids, PV systems, electric vehicles, and smart distribution. Rodrigues *et al.* [1] highlight their ability to interrupt fault currents within microseconds, making them superior to mechanical circuit breakers. Thyristor-based SSCBs, while offering high current capacity and low on-state voltage due to conductivity modulation, are limited by turn-off constraints and require auxiliary commutation networks [4]. Song *et al.* emphasize that conventional SCRs cannot self-turn-off, motivating solutions such as gate-commutated thyristors (GCTs) and integrated gate-commutated thyristors (IGCTs), which provide bidirectional blocking and enhanced surge handling. State-of-the-art thyristors can achieve ratings up to 12 kV/1.5 kA.

With the emergence of wide-bandgap semiconductors, SiC MOSFETs have enabled compact SSCBs due to their fast switching speeds, low conduction loss, and higher blocking voltage capability [5]. Kheirollahi *et al.* [8] demonstrate that SiC-based SSCBs can achieve sub-microsecond interruption while maintaining efficiency, though conduction voltage drops at medium currents remain a limitation.

2.2 Voltage Clamping and Snubber Techniques

DC fault interruption is inherently challenging due to the absence of current zero-crossings, leading to significant voltage overshoot during turn-off. Traditional mitigation techniques employ MOVs, RC snubbers, and their combinations. RCD snubbers suppress voltage spikes and damp oscillations, with RC–MOV hybrids shown to improve energy dissipation and damping [12]. Gregis *et al.* [2] reviewed recent clamping methods, including the electronic MOV (eMOV), which enhances intervention speed while reducing gate stress. Kheirollahi *et al.* further demonstrate that combining MOVs with RCD networks provides both controlled dv/dt and robust fault energy absorption. Nevertheless, passive snubber capacitors can slow down interruption during low fault currents, posing a trade-off between speed and energy handling.

2.3 Hybrid and Bypass-Based Breakers

Hybrid approaches combine active semiconductors with passive or auxiliary devices to improve interruption speed and reduce losses. Virdag *et al.* [9] simulate counter-current injection hybrids, where an LC network generates an opposing pulse to force a current zero, enabling reliable interruption by thyristors. Fuse-assisted hybrid SSCBs, as proposed by Zen *et al.* [10], integrate a high-speed fuse with semiconductors, achieving compact, arc-less protection for hundreds of volts and kiloampere-level faults. Bypass-based SSCBs [8] employ an auxiliary branch that diverts fault energy, thereby reducing stress on the main switch and improving system robustness.

2.4 Smart Fuses

Recent developments bridge the gap between mechanical fuses and SSCBs. Zen *et al.* [6] and Zhao *et al.* [7] introduce semiconductor-assisted smart fuses designed for EV battery systems. These solutions achieve precise and programmable fault clearing while maintaining compact form factors, providing cost-effective alternatives to full SSCBs in automotive and renewable applications.

2.5 Industrial Adoption

Industry deployment underscores the maturity of SSCB technologies. ABB integrates SSCBs into data center LVDC grids and shipboard networks [9]. Eaton and Schneider focus on EV and renewable platforms, while Atom Power commercializes digital SSCBs for residential and commercial markets. These implementations confirm SSCBs' viability for smart and resilient DC distribution.

3 Research Gap

While many SSCB concepts have been demonstrated at high power, gaps remain for low-voltage, medium-current DC systems (hundreds of volts, tens of amps). Most published designs are either tailored for high current levels (hundreds to thousands of amperes) or higher-voltage MVDC systems. For example, Kheirollahi *et al.* report a 375 V SSCB rated at 170 A, and Zen *et al.* demonstrate a 1 kA SSCB for LV/MVDC applications. In contrast, little attention has been given to compact SSCBs in the range of $\sim$16 A at 350 V, which is highly relevant for residential, commercial, and small-scale renewable DC buses.

At this scale, challenges such as conduction loss become more significant: Song *et al.* emphasize that the semiconductor on-state voltage drop introduces disproportionately higher losses in moderate-current systems compared to mechanical contacts. Additionally, incorporating complex snubber or MOV networks to absorb fault energy adds cost, leakage, and bulk, which is undesirable in low-power equipment. Many reported designs also depend on bulky MOV arrays, heavy fuses, or stacked semiconductor devices to meet voltage ratings—approaches that are unnecessarily complex for a 350 V/16 A bus.

Therefore, there is a clear gap in SSCB research for cost-effective, low-loss, compact breakers optimized for medium-current LVDC applications. Specifically, a topology that can redirect and dissipate fault current through a freewheeling diode offers a simpler and more efficient alternative to bulky snubber networks or fuse-assisted designs. By leveraging the diode's ability to provide a controlled current decay path, such an SSCB can achieve arc-less fault interruption with reduced device stress, minimized losses, and lower system cost—filling the unmet need in this application space.

4 Motivation and Objectives

Traditional fuses and mechanical DC breakers are slow and susceptible to arc formation, making them unsuitable for protecting sensitive LVDC circuits. The proposed project addresses this challenge with a simple and effective solid-state design: a MOSFET in series with the load and an antiparallel diode across the load. During normal operation, the MOSFET supplies power. When a fault occurs, a current-sensing feedback circuit compares the line current with a reference threshold. If the actual current exceeds this reference, the MOSFET is turned off permanently, while the diode provides a freewheeling path to dissipate the stored inductive energy and clear the fault current safely. This approach enables ultrafast interruption, arc-less operation, and reduced component count compared to conventional SSCB topologies that rely on bulky snubbers or MOV networks.

A 16 A, 350 V SSCB is highly relevant for practical applications. EV chargers and battery buses often operate around 300–400 V at 10–20 A, especially in residential charging and light electric vehicles. Likewise, DC microgrids for data centers, telecom, and small renewable systems employ intermediate DC buses (48–400 V), where 16 A corresponds to a few kilowatts. In such systems, slow protection can cause damaging transients and equipment failures, whereas a solid-state approach ensures faster, cleaner fault isolation. Recent work by Nandakumar *et al.* validated a 400 V/14 A SSCB prototype, showing that this design range is both feasible and impactful.

4.1 Objectives

The objectives of this project are as follows:

1. To design and simulate a 350 V, 16 A solid-state DC circuit breaker using MATLAB/Simulink.
2. To implement fault detection through a feedback-controlled current sensing scheme that permanently disables the MOSFET when current exceeds a reference threshold.
3. To employ a freewheeling diode as a low-cost, reliable path to dissipate and clear fault current, avoiding bulky snubbers or MOV networks.
4. To evaluate performance of the proposed SSCB in terms of interruption speed, fault current limiting, and conduction losses.

5 Methodology

The SSCB was modeled and simulated in MATLAB/Simulink. The model topology (Fig. 6) consists of a 350 V DC source in series with a source inductance (to emulate cable/system inductance). The main switching element is a power MOSFET (SiC or IGBT) placed in series. An anti-parallel diode is connected across the load which damps the voltage transient and absorbs inductive energy (as it freewheels fault current through it). This branch temporarily carries the inductive current during turn-off, limiting the stress on the main switch.

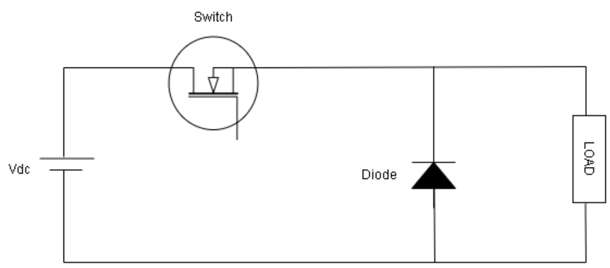

Figure 1: Model topology of the DC Solid-State Breaker

5.1 Fault Conditions

In simulation, a fault is applied by shorting the load (placing a switch in parallel to the load) at a specified time. The source inductance ensures a finite di/dt. The SSCB logic monitors the current: once the current exceeds a threshold (slightly above 16 A), the control triggers. Current is sensed by a current sensor, which rises sharply during a fault (a known detection method). Upon detection, a gate-driver circuit sends a turn-off signal to the MOSFET. The MOSFET opens the main path, commutating current into the diode where it freewheels.

5.2 Protection Logic

The fault detection is implemented via a comparator that measures the MOSFET's drain current. When the current surpasses the preset limit, the MOSFET gate is driven low (turn-off). This aligns with literature emphasis: the detection time is a critical part of total interruption time. In the MATLAB model, we assume instantaneous detection and switching (ideal comparator and driver) to focus on the electrical dynamics.

5.3 Simulation Setup

The model uses Simulink's components for the MOSFET, voltage source, current sensors, voltage sensors, inductance, resistance, and diode. The simulation is run with a time step of ~ 0.1 s to resolve the fast turn-off transients. First, the system reaches steady state. At $t = 0.02$ s (20 ms), a fault is applied. The MOSFET is turned off at a delay after fault detection. The waveforms of current and voltage during turn-off are recorded. This approach follows similar studies (e.g., Virdag *et al.* simulated a thyristor-based DC breaker in Simulink; Kheirollahi *et al.* used LTSpice for their SSCB).

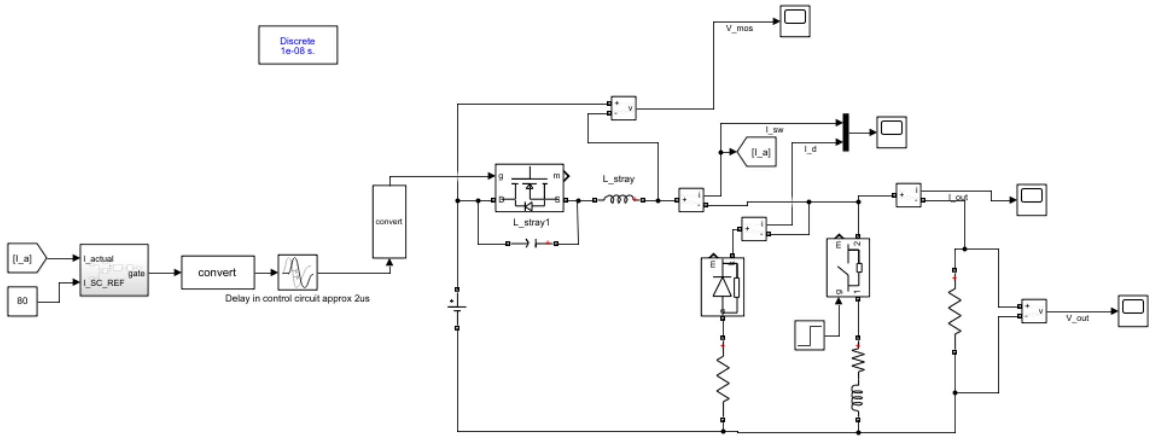

Figure 2: Simulink model of the proposed SSCB

6 Results and Discussions

This section presents the simulation results of the proposed 350 V, 16 A solid-state DC circuit breaker.

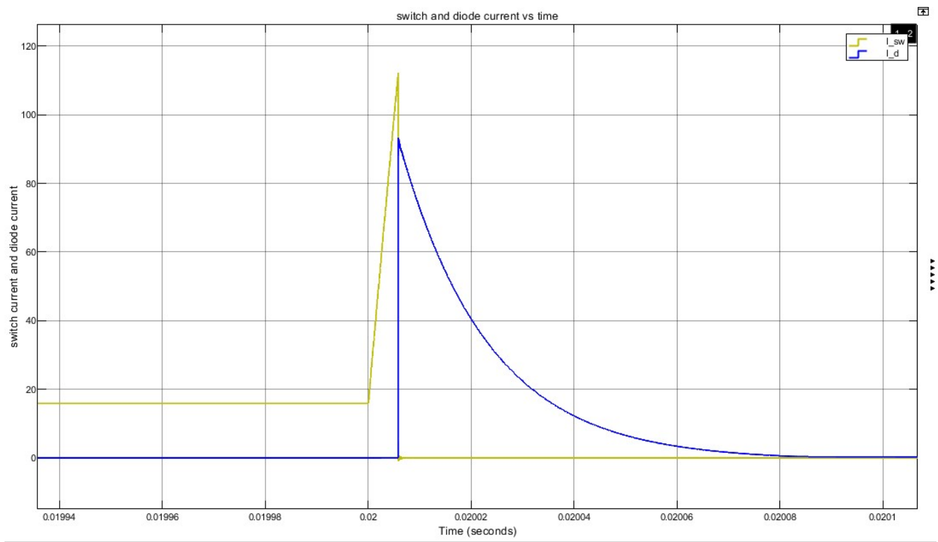

Figure 3: Current through switch and diode

Waveform Interpretation of fig. 3

- **Pre-Fault (0.0192–0.0199 s):** Diode carries nominal load (∼20 A), switch current ≈0 A, aligning with low-loss standby in anti-parallel SiC MOSFET designs for bidirectional DC flow.

- **Fault Spike (∼0.02 s):** Rapid rise indicates short-circuit inception, with currents sharing during initial detection.
- **Decay Phase (0.02–0.021 s):** Exponential tail-off shows commutation to diode for inductive absorption, preventing overshoot; switch current lags slightly, typical of turn-off transients.

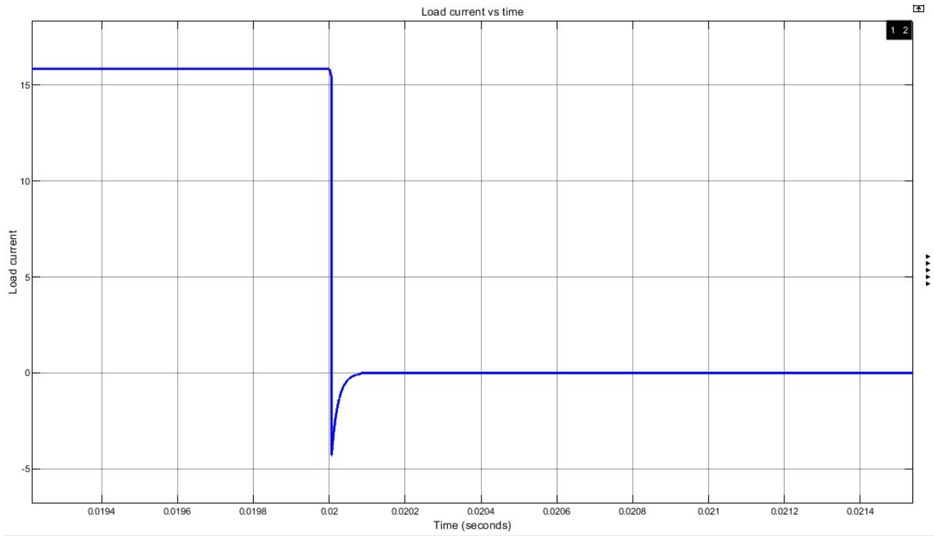

Figure 4: Current through load

Interpretation of fig. 4

The graph shows output current (I_{out}) over ∼0.022 s, starting at a stable 15 A plateau (nominal operation), dropping sharply to zero around 0.02 s upon fault detection, with a minor undershoot. This models a 16 A, 350 V DC e-fuse in steady state before rapid isolation, preventing fault escalation in applications like EV charging or microgrids.

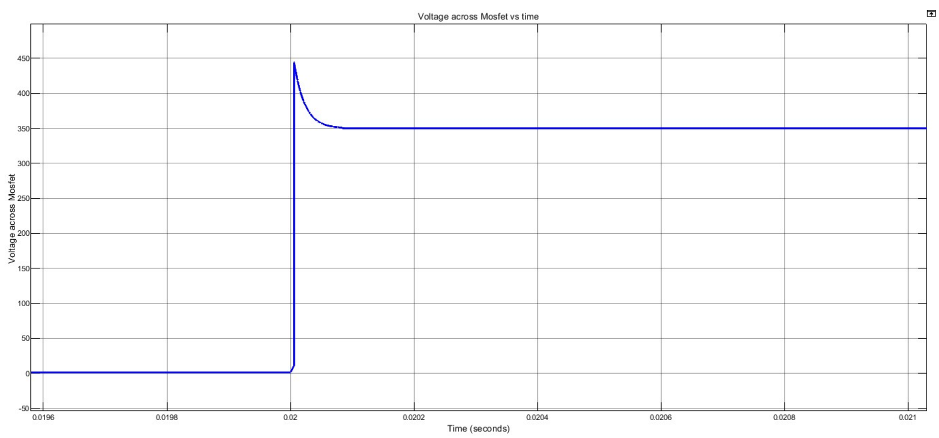

Figure 5: Voltage across MOSFET (switch)

Waveform Interpretation of fig. 5

- **Steady-State (0.0192–0.0199 s):** $V_{\text{mos}} \approx 0$ V, indicating full conduction with minimal voltage drop across the SiC MOSFET.
- **Fault Trigger and Rise (∼0.02 s):** Voltage jumps to 350 V (bus voltage) as the MOSFET turns off.
- **Overshoot and Decay (0.0201–0.021 s):** Steady 350 V hold confirms reliable off-state blocking, with no visible overshoot due to clamping, enabling safe recovery and digital reset.

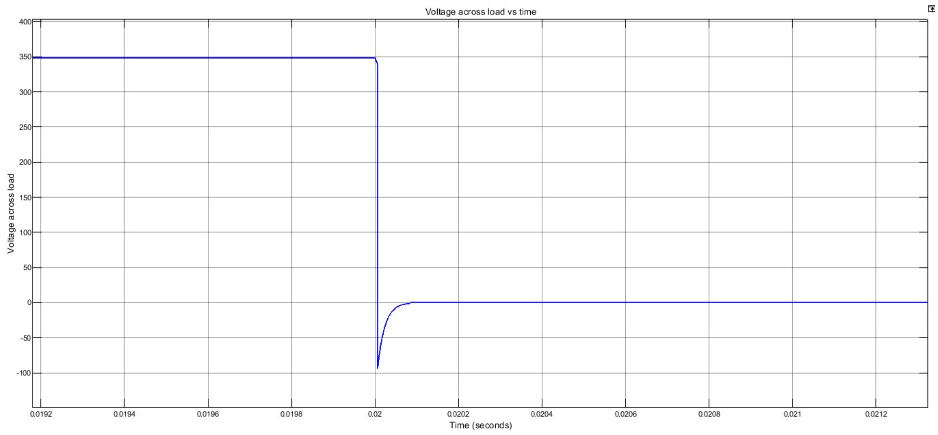

Figure 6: Voltage across load

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Waveform Interpretation of fig. 6

- **Normal Operation Phase (∼0.0194–0.0199 s):** $V_{\text{load}} \approx 350$ V, consistent with steady-state power delivery to a 16 A load, with minimal voltage drop due to low-resistance conduction in the SSCB.
- **Fault Detection and Turn-Off (∼0.02 s):** A rapid drop to ∼0 V occurs as the SSCB interrupts fault current, commutating energy to auxiliary paths (diode), isolating the load from the faulted bus.
- **Post-Interruption (0.0201–0.021 s):** V_{load} remains near 0 V, indicating successful load disconnection, with no significant overshoot due to clamping, ensuring safe operation and digital reset capability.

7 Conclusion

The Simulink analysis confirms the 16 A, 350 V DC e-fuse's capability in delivering ultrafast, arc-less fault protection with $< 10\ \mu$s response times, validated by V_{load} (350 V to 0 V), V_{mos} (0 V to 350 V), and current waveforms ($I_{\text{sw}}/I_{\text{d}}$ peaks and drops to 0 A). The diode-based clamping network effectively suppresses overvoltage and controls dv/dt stress across the switch, thereby enhancing the reliability and safety of the system.

Simulation results confirmed that the proposed e-fuse can isolate short-circuit faults while maintaining acceptable voltage and current stress levels, validating its suitability for low-voltage DC applications such as EV subsystems, renewable energy microgrids, and battery energy storage. Compared with conventional mechanical fuses and breakers, the e-fuse offers faster operation, reusability, and intelligent control capability, aligning with ongoing industrial trends towards smart protection devices.

The findings highlight that medium-current SSCBs remain an active research area, particularly in balancing trade-offs between conduction loss, cost, and clamping performance. Future work may extend this study by implementing hardware prototypes, exploring wide-bandgap semiconductor devices for lower losses, and integrating communication features to realize fully digital, smart DC protection solutions.

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