

Detailed Analysis of Classic Z-source Topology for Protection in DC Power Systems

Análisis detallado de la topología clásica Z-source para la protección de sistemas de alimentación de CC

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Abstract

This paper presents an in-depth analysis of the classic Z-source topology for DC power system protection, an area previously unexplored in such detail. Using OpenModelica simulations, the study offers valuable insights into the Z-source topology's behavior, protection mechanisms, and energy dissipation processes. It includes detailed diagrams, switching states, and explanations of operating principles, supported by waveforms illustrating energy flow through the Z-source components. The findings demonstrate that the Z-source breaker effectively handles fault conditions by disconnecting the source from the load almost instantaneously, within tens of microseconds. The simulations confirm the theoretical models, showing that the Z-source topology efficiently dissipates fault energy through inductors, capacitors, and resistors, thereby protecting sensitive equipment. This thorough analysis enhances understanding of the Z-source topology in DC power systems and establishes a solid foundation for future research and practical applications.

Keywords: DC power systems; power electronics (PE) devices; Z-source breakers; OpenModelica; DC power systems; DC protection; power switch; energy.

Resumen

Este documento presenta un análisis profundo de la topología Z-source clásica para la protección de sistemas de energía DC, un área previamente no explorada con tal detalle. Utilizando simulaciones en OpenModelica, el estudio ofrece valiosos conocimientos sobre el comportamiento de la topología Z-source, los mecanismos de protección y los procesos de disipación de energía. Incluye diagramas detallados, estados de conmutación y explicaciones de los principios operativos, apoyados por formas de onda que ilustran el flujo de energía a través de los componentes Z-source. Los hallazgos demuestran que el interruptor Z-source maneja eficazmente las condiciones de fallo al desconectar la fuente de la carga casi instantáneamente, en decenas de microsegundos. Las simulaciones confirman los modelos teóricos, mostrando que la topología Z-source disipa eficientemente la energía de fallo a través de inductores, capacitores y resistencias, protegiendo así el equipo sensible. Este análisis exhaustivo mejora la

comprensión de la topología Z-source en sistemas de energía DC y establece una base sólida para futuras investigaciones y aplicaciones prácticas.

Palabras clave: sistemas de potencia de CC; dispositivos de electrónica de potencia (PE); disyuntores de fuente Z; OpenModelica; sistemas de potencia de CC; protección de CC; interruptor de potencia; energía.

1. Introduction

1.1. Background

Microgrids allow for the coordination of distributed energy resources (DERs) and are essential in the energy transition. These small-scale power networks can operate independently or in conjunction with the main grid, providing resilience, reliability, and flexibility [1]. By integrating renewable energy sources like solar and wind, microgrids help reduce carbon emissions and support sustainability efforts. They are particularly valuable in remote areas, where access to the central grid may be limited, and in urban environments, where they enhance energy security and efficiency. As the world moves towards a cleaner energy future, microgrids play a critical role in decentralizing power generation and empowering local communities [2], [3].

Microgrids can operate using either AC (Alternating Current) or DC (Direct Current), each with distinct characteristics and applications. AC microgrids are more common and are typically used in scenarios where the microgrid needs to integrate with the existing main grid, as most conventional electrical infrastructure operates on AC [4]. They are well-suited for residential, commercial, and industrial applications where compatibility with the broader grid is essential. On the other hand, DC microgrids are often used in specific applications like data centers, electric vehicle charging stations, or in renewable energy systems where DC sources, such as solar panels or batteries, are predominant. DC microgrids offer higher efficiency for these applications by eliminating the need for multiple conversions between AC and DC, but they are less compatible with traditional grid infrastructure. The choice between AC and DC microgrids depends on the specific energy needs and the types of loads being served.

1.2. Motivation

The increasing prevalence of DC microgrids and the integration of renewable energy resources have heightened the need for effective protection mechanisms within DC power systems. Traditional circuit breakers face challenges in DC environments due to the lack of naturally occurring current zero crossings, which are essential for interrupting fault currents. Consequently, there is a necessity for advanced protection solutions that

can address these challenges and enhance the reliability and safety of DC power systems.

Z-source circuit breakers are primarily used in DC protection systems because they can provide fast and reliable interruption of fault currents. This is critical in DC systems where fault currents can rise rapidly and do not naturally pass through zero as in AC systems. Apart from Z-source circuit breakers, several other protection methods are available for DC systems, including DC fuses, solid-state circuit breakers, current limiting reactors, and fault-tolerant converter designs [5].

While Z-source circuit breakers are frequently mentioned in technical literature, existing works often focus on their applications, benefits, or high-level design without delving deeply into the underlying principles that govern their operation. A detailed understanding of these principles is crucial for engineers and researchers to optimize their use, improve safety, and innovate in the design of DC protection systems. This article seeks to fill this gap by providing an in-depth exploration of the core principles, circuit topologies, and practical considerations that define the functionality and effectiveness of Z-source circuit breakers [6].

1.3. Literature review

Several studies have explored different aspects of DC microgrid protection. A comprehensive review by [7] identifies the types of faults, challenges in protection, and various fault detection schemes in DC microgrids. The study highlights the absence of guidelines and standards, as well as the influence of resistive line impedance on fault clearing times and system stability. Another work by [8] discusses the development of a high-voltage DC circuit breaker utilizing a passive commutation circuit, emphasizing the need for robust and reliable fault interruption methods in high-power applications. Additionally, [9] introduces a figure of merit for power semiconductor devices, indicating that materials with higher mobility and critical electric field for breakdown can significantly reduce power losses in high-frequency circuits. In [10], the authors propose a methodology for coordination of Z-source Circuit Breakers and fuses for Short-circuit protection in DC power networks. In [11], Z-source solid state circuit breakers are reviewed as promising candidates for protecting low and medium-voltage distribution networks.

Further research has focused on the coordination and optimization of protection devices in DC microgrids. [12] proposes a fuse-saving scheme for DC microgrids with high penetration of renewable energy resources, addressing the issues of bidirectional fault currents and miscoordination between protection devices. [13] evaluates the challenges and recent advancements in DC microgrid protection, emphasizing the need for suitable protection schemes and standards. The challenges of DC fault current characteristics, fault detection methods, and protective devices are extensively reviewed by [14], who also explores future trends in DC microgrid protection.

Additionally, [15] discusses the protection considerations in power converter-fed DC systems, highlighting the potential for equipment damage due to capacitive discharge and double ground faults.

The use of Z-source technology for medium voltage networks on ships is proposed in [16]. Through simulations, Z-source performance has been validated for medium voltage at 6.000 V DC, demonstrating instantaneous commutation and fault clearance in tens of microseconds. Furthermore, the paper presents methods for sizing Z-source elements. In [17], a laboratory prototype for low voltage at 400V DC was proposed, yielding positive results. The paper also suggests employing Z-source technology for the protection of power converters supplying motors. In [18], tests were conducted with a low voltage prototype at 280-440V DC and a communication architecture was proposed for DC microgrid implementation. In [19] it is proposed to add resistors to the capacitors to mitigate capacitor inrush currents. Simulations are carried out for medium voltage networks at 6.000V DC, obtaining a reduction of the inrush currents with additional resistors. The concept of the Z-source breaker has emerged as a promising solution for DC protection. The Z-source breaker, as indicated by [20], utilizes a Z-source network comprising inductors and capacitors to enhance protection capabilities. This breaker offers bidirectional blocking, voltage boost capability, enhanced fault tolerance, improved reliability, and efficient energy dissipation during fault conditions.

[16] presents a detailed analysis of the Z-source breaker for medium-voltage DC systems, demonstrating its ability to automatically respond to faults without the need for fault detection and isolate the generation source from fault currents

1.4. Contributions and scope

This paper makes a significant contribution by providing a comprehensive analysis of the classic Z-source topology for DC power system protection. Unlike previous studies, this work delves into unprecedented

detail, offering detailed diagrams, switching states, and thorough explanations of the operating principles with illustrative waveforms. The energy dissipation and flow mechanisms are explained and verified through simulations conducted in OpenModelica. This deep analysis not only enhances the understanding of the Z-source topology's protection mechanisms but also provides a solid foundation for future research and practical applications in DC power systems.

1.5. Document organization

This paper is organized as follows: Section 2 describes the proposed methodology. Section 3 presents the explanation of the principle of operation. Section 4 corresponds to the results that include a deep analysis of the principle operation through simulation. Finally, Section 5 concludes and highlights the most relevant aspects of this paper.

2. Methodology

This paper presents a detailed analysis of the classic Z-source topology for DC power system protection, to accomplish this goal a methodology of five steps was developed which is detail bellow.

- **Introduction to Z-Source Topology Analysis:** This part of the research begins with a detailed analysis of the principle of operation. The four operating states of the classic Z-source breaker are meticulously described and illustrated.
- **Simulation Using OpenModelica:** This phase of the study involves utilizing OpenModelica software to conduct simulations of the Z-source topology. It includes modeling the behavior of Z-source components under different conditions to understand their protection mechanisms and energy dissipation processes.
- **Detailed Diagrams and Explanations:** Throughout the document, detailed diagrams are provided to illustrate both the switching states and operating principles of the Z-source topology. Explanations are supported by waveforms that depict energy flow through Z-source components such as inductors, capacitors, and resistors.
- **Fault Handling Evaluation:** the research evaluates the Z-source breaker's effectiveness in handling fault conditions, focusing on how it disconnects the source from the load almost instantaneously, within tens of microseconds, during fault occurrences.
- **Validation Through Simulations:** This part of the analysis compares the simulation results with theoretical models to validate the findings,

demonstrating that the Z-source topology effectively dissipates fault energy through its components, thereby protecting sensitive equipment from damage.

3. Z-source breaker: detailed explanation of principle of operation

The classical Z-source topology offers an interesting research direction for overcurrent fault protection in DC microgrids [21]. It is also referred to as the Cross Z-source topology. Classic Z-source breakers are known for their natural switching process, quick response, simple control system, ability to isolate fault sources, automatic disconnection of faulty loads, and built-in coordination features [22], [23].

Classic Z-source topology is depicted in Figure 1. It is composed of one SCR, two capacitors (C_1), (C_2) two inductors (L_1), (L_2) in parallel with diodes (D_1), (D_2) and resistors (R_1), (R_2) series array. Assuming that inductors (L_1) and (L_2), capacitors (C_1) and (C_2), diodes (D_1) and (D_2) and resistors (R_1) and (R_2) have the same values (L), (C), (D) and (R) respectively. Z-source is between the voltage source (v_s) and load composed of a capacitor (C_L) and a resistor (R_L). G_f is the conductance used to simulate the fault conductance in the load. The aim of the Z-source breaker is safely disconnect the source when a short circuit occurs. Classic Z-source breaker has four operating states that are described as follows: 1) The first state corresponds to steady-state operation, the source v_s delivers energy to the load R_L . The currents of the source, SCR, inductors and load are equal in steady state to i_L . The current passes through the lowfrequency circuit composed of 0, 1, 2, 3, and 4 which consists of the source, the SCR, inductor L_1 , load R_L and inductor L_2 ; in this state, capacitors C are also charged with the source voltage and they behave as an open circuit (see state 1 Figure 2). 2) Second state is the transient state or fault occurrence state. When a fault occurs in 6, the fault current is supplied by the capacitors C_1 and C_2 in series and C_L . The series capacitors C and C_L form a capacitive voltage divider. Current i_c passes through the high-frequency circuit, formed by the capacitors C_1 and C_2 and SCR following the red line through 7, 6, 9 and 1 in the direction of the source; please see Figure 1. High frequency current of the capacitors increases until is equal to the low frequency current through the inductors i_L , then the SCR is reverse biased and commutates off (source is disconnected); please see i_{SCR} in state 2 of Figure 2. 3) Third state, after SCR is turned off, two series LC circuits are connected to the fault and load through 9, 2 and 7, 4; initiating an LC resonance series. Series resonance can be observed when the voltage across the inductor L_1 matches the voltage across the capacitor C_1 or the voltage across the inductor L_2 matches

the voltage across the capacitor C_2 . When the capacitor voltage is reached by the inductor voltage; the voltage at the output becomes zero due to the disconnection of the source. When the resonant voltage of the inductor and capacitor reach half the source voltage, the voltage across the SCR becomes negative. Then the SCR is forward biased. For this reason, one of the functions of the control is to deactivate the gate before the inductor and capacitor voltages at resonance reach half the source voltage or activate the SCR with a single pulse. The resonance ends when voltages in the inductor tend to become negative, please see state 3 of Figure 2. 4) Fourth state begins when the voltage on the capacitor decays to zero after the resonance has ended. Current from the inductors L_1 and L_2 continues to flow through the diodes and resistors until the current decays to zero, 2, 12, 13 and 4, 10, 11 respectively. The diodes do not allow the inductor current to recharge the capacitor.

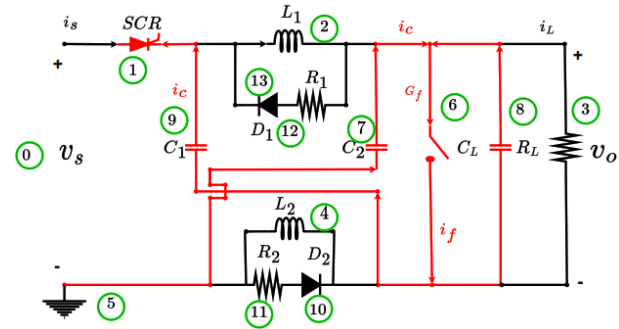


Figure 1. Classic Z-source circuit breaker [16].

4. Results

Figure 3 shows the implementation of the Classic Zsource topology in OpenModelica.

Fault current (i_f), SCR current (i_{SCR}), SCR voltage (v_{SCR}) and load voltage (v_L) of classic Z-source topology, are depicted in Figure 4. Figure 4 A) corresponds to the fault current i_f . Fault occurs in 0.2 s. Please note that i_f rises to a maximum value and then decreases. When the fault current is increasing, fault clearing events occur in the circuit. When the fault current is decreasing, resonance events occur followed by energy dissipation events in the circuit. Figure 4 B) corresponds to the SCR current i_{SCR} . Before fault occurrence, i_{SCR} has a value of 1.000 A which corresponds to the normal operation of the circuit. After fault occurrence i_{SCR} rapidly decreases to zero for clearing the fault. The commutation process is almost instantaneous and occurs when the fault current increases. Voltage in SCR v_{SCR} and load voltage (v_o) are depicted in Figure 4 C. A zero crossing of v_{SCR} is observed which is very important for SCR protection. When v_{SCR} crosses zero, the arc generated during

switching is mitigated, similar to what happens in AC circuits (please see brown line).

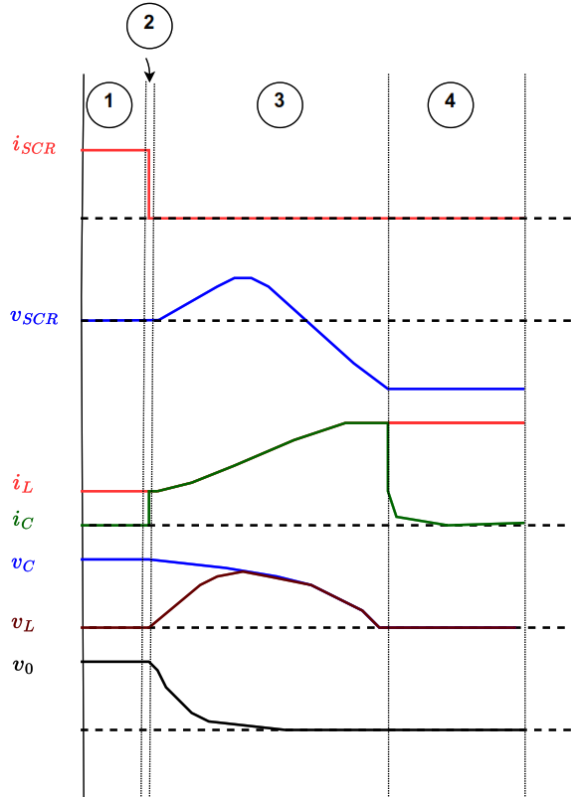


Figure 2. Classic Z-source commutation states, adapted from [16].

In addition, the load voltage v_0 behavior is observed. Once the fault is cleared, the load voltage decays to zero, (please see blue line).

Capacitors current (i_c), inductors current (i_L), capacitors voltages (v_C), inductors voltage (v_L), load current (i_{RL}) and source current (i_s) of classic Z-source topology are depicted in Figure 5. Figure 5 A) corresponds to the moment when the transient current of the capacitor (red line) reaches the steady state, current of the inductor (green line) is observed. In this instant time, the commutation occurs. After disconnection, capacitor current and inductor current are equal because they are connected in series. In Figure 5 B), the series resonance lapse is observed. When the inductor voltage (blue line) is equal to the capacitor voltage (brown line), it corresponds to the series resonance time. Once the resonance is finished, the voltage across the capacitor decays to zero, inductor voltage decays to zero and intend to become negative. Once the resonance is finished, the current across the capacitor decays to zero and the current in the inductor continues to circulate in the circuit snubber. In Figure 5 C), the behavior of the current in the source and the current in the load are depicted. Once fault clearance has occurred, the current in the source (violet line) immediately decays to zero and the current in the load (black line) that also decays to zero. In effect, classic Z-source topology simultaneously protects the source and the load.

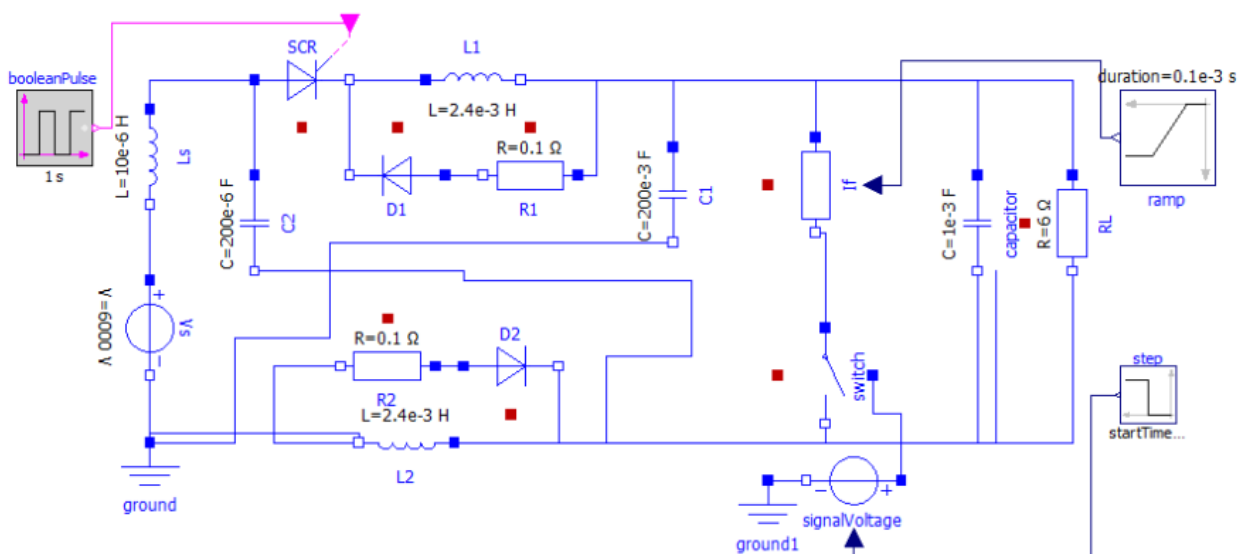
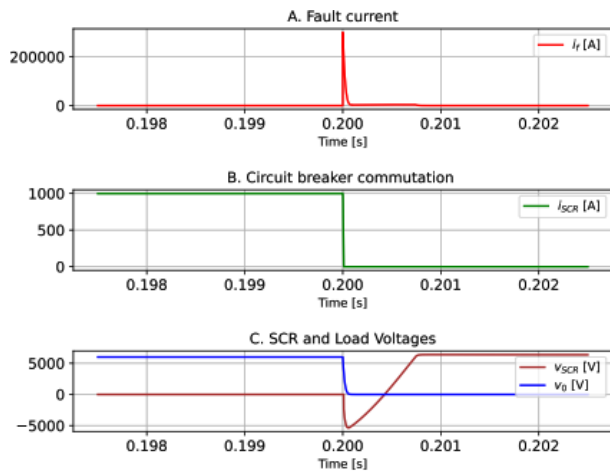
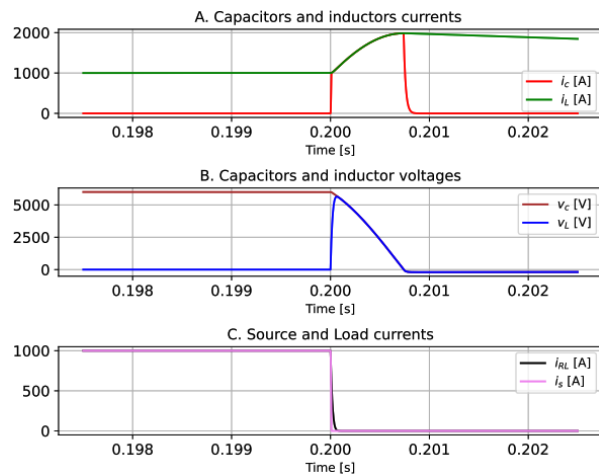


Figure 3. OpenModelica simulation of classic Z-source topology.

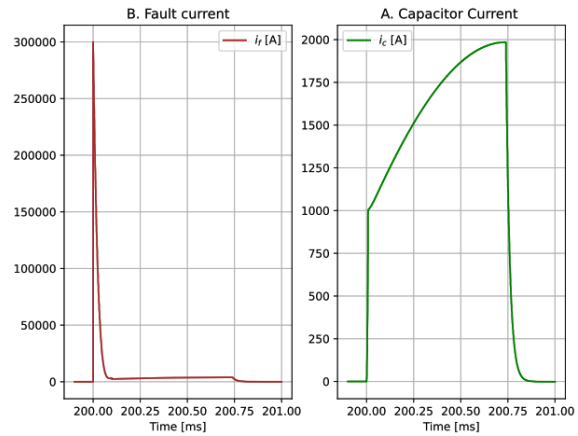
Figure 4. Classic Z-source behavior i_f , i_{SCR} , v_{scr} , v_0 Figure 5. Classic Z-source behavior i_c , i_L , v_c , v_L , i_{RL} , i_s

Fault (i_f) and capacitors (i_c) currents of classic Zsource topology are depicted in Figure 6. It is observed that the current through the capacitor is only 6% of the fault current. This occurs because the capacitor current does not depend directly on the fault current, but rather on the variation of the voltage in the inductor (please see Figure 6).

5. Conclusions

This research paper provided a comprehensive and detailed analysis of the classic Z-source topology for protection in DC power systems, significantly advancing the understanding of this technology. The simulations conducted in OpenModelica offer unprecedented insights into the behavior and protection mechanisms of the Z-source topology, demonstrating its efficacy and reliability. The paper presents an in-depth explanation of the operating principles of the Z-source breaker,

including the different states of operation and the associated waveforms. This detailed analysis helps in understanding how energy dissipation and flow occur through the Z-source components during fault conditions. The insights gained from this analysis provide a solid foundation for future research and practical applications. The detailed diagrams, switching states, and waveforms presented in this paper can serve as valuable references for engineers and researchers working on DC power system protection.

Figure 6. Classic Z-source behavior i_f , i_c

The use of OpenModelica for simulating the Z-source topology has validated the theoretical explanations provided. The results confirm that the Z-source breaker operates as expected, with the SCR current, fault current, and load voltage behaving in accordance with the theoretical predictions. The study highlights the energy dissipation mechanisms within the Z-source topology. The resonance between inductors and capacitors, followed by the energy dissipation through resistors, ensures that the fault energy is safely managed, preventing damage to the system components. The classic Z-source topology effectively disconnects the source from the load during fault conditions. The simulations show that the Z-source breaker can clear faults almost instantaneously, in tens of microseconds, which is crucial for protecting sensitive equipment in DC power systems.

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Autor Contributions

Bayron Perea-Mena: Conceptualization, Data Curation, and writing—original draft, Formal Analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, and Visualization, Writing—Review and Editing. Nicolás Muñoz-Galeano: Conceptualization, Data curation, and writing—original draft, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, and Visualization, Funding Acquisition and Project Administration, Writing—Review and Editing. Jesús María López-Lezama: Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, and Visualization, unding Acquisition and Project Administration, Writing—Review and Editing.

All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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