Z-Source Circuit Breaker Utilizing Ultra-Fast Mechanical Switch for High Efficiency DC Circuit Protection

Landon Mackey, Md Rifat Kaisar Rachi, Chang Peng, Iqbal Husain
College of Electrical and Computer Engineering
FREEDM Systems Center - North Carolina State University
Raleigh, NC 27606
United States
Email: lkmackey@ncsu.edu

***Abstract*—A novel modification to Z-Source DC circuit breakers has been proposed to reduce power consumption from its predecessor significantly. The power thyristor serves as the means of circuit isolation and voltage blocking in the event of a fault in traditional Z-Source DC circuit breakers. However, Z-Source circuit breakers direct full load current through the Thyristor. The resulting voltage difference and current flow yield substantial power consumption, heat generation, and reduced efficiency. Integrating a fast-mechanical switch and associated control, a zero current crossing and circuit isolation is achieved without significant on-state switch losses.**

***Index Terms*—Circuit breaker, z-source, fast mechanical switch, microgrids, power system protection, renewable energy sources, bidirectional power flow, energy efficiency**

I. INTRODUCTION

Inadequate protection options for direct current circuits restricts growth in the DC distribution field. Interruption of current flow in DC circuits is more difficult than in AC circuits due to the absence of a natural current zero crossing. Conventionally, DC circuit protection is implemented by:

1) Single blow fuses which require replacement following each fault
2) Use of over-sized and overrated AC circuit breakers to draw and extinguish an arc on one or both poles of the DC circuit which is often cost prohibitive
3) Solid State circuit breakers which result in substantial on-state power consumption by the semiconductors
4) Hybrid DC circuit breakers that combine a mechanical switch and solid state switches to reduce power consumption, but can be quite complex

The Z-Source circuit breaker is proposed to force a DC current zero crossing with an impedance network to cause current fluctuation and isolation from the voltage source with a power thyristor. However, recent developments in fast mechanical switches facilitate opportunity for replacement of the solid-state switch. Mechanical switches can be robust, do not require cooling, and do not consume significant power in the circuit. Therefore, replacement of the solid state thyristor with a fast-mechanical switch reduces losses within the Z-Source DC circuit breaker. The prototype 400 volt 100 amp device modeled in Fig. 1 reduces power consumption by 131 watts, a savings of 1147 kWh per year per DC circuit breaker which would be paid for by the system operator [1–3].

Rapidly increasing proliferation of DC systems in micro-grids, data-centers, electric vehicles and more requires development of adequate protection for these systems. While the historical DC protections previously mentioned do exist, each faces its own drawbacks. Fuses are single use only and require replacement following each fault, over-rated circuit breakers are often cost prohibitive and solid-state circuit breakers consume significant real power during option. These shortcomings of each technology provide the opportunity to develop a high speed, cost effective and energy efficient alternative for providing DC circuit protection for low voltage systems.

A. Background of Z-Source Circuit Breakers

An impedance network comprised of inductors and capacitors, known as a Z-Source network, was first presented as a power converter input circuit [4]. It facilitates creating a resonant current ripple during fault condition in an otherwise constant DC bias to commutate off the power thyristor isolating the source from the fault. A DC circuit breaker utilizing the dynamic nature of this impedance network was first proposed in 2010 [5].

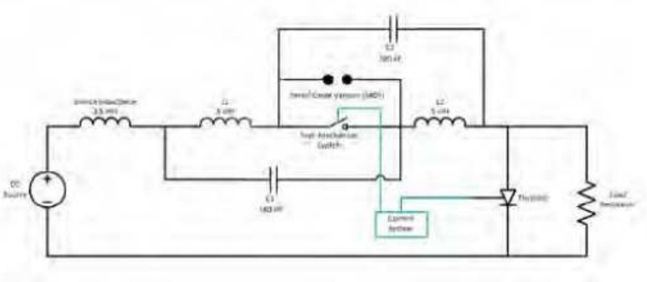

Fig. 1: Z-Source Circuit Breaker Circuit Diagram

Since its first publication in 2010, several new topologies of Z-Source circuit breakers have been researched and published [6–10]. The most commonly accepted of the Z-Source topologies include:

- Crossed Z-Source Breaker
- Parallel-Connected Z-Source Breaker
- Series-Connected Z-Source Breaker

Each topology provides unique characteristics from the use of a common negative return line, to source current limiting through energy storage. This paper will focus on the Parallel-Connected Z-Source Circuit Breaker. However, substitution of the power thyristor with a fast mechanical switch can be implemented in any of the above topologies.

The Parallel-Connected Z-Source circuit breaker, as shown in Fig. 1 forces a zero current crossing through resonance between the impedance network connected in the system. During a fault or forced opening condition, the high $\frac{di}{dt}$ results in energy exchange between the inductors and capacitors and therefore at least one current zero crossing as observed by the switching device.

The current zero crossing provides the timing required to open the fast mechanical switch under a no load condition, therefore preventing an arc from being drawn. Prior art of Z-Source Circuit breakers have used the forced zero crossing to commutate off the Thyristor. Although simple and rugged, this results in multiple challenges:

- Reverse power flow is not achievable for bi-directional systems
- Load transients could cause an inadvertent commutation of the Thyristor, resulting in unintended loss of power to the load
- On state voltage drop of the power Thyristor and load current flowing through it results in continuous energy consumption

Replacing the Thyristor with a fast mechanical switch allows for all of these concerns to be addressed, increasing the efficiency and operational bandwidth of prior art Z-Source Circuit Breakers.

B. Background of Fast Mechanical Switches

Advances in fast mechanical switches make way for the ability to achieve millisecond-switching times while providing negligible on-state resistance, effectively eliminating on-state power consumption. This is an incredible improvement from conventional electromechanical circuit breakers that operate on the order of 40-80 milliseconds to the fast mechanical switch time scale of 1-2 milliseconds.

Growing DC applications include electric vehicles, datacenters, electric warships, DC Microgrids and many more [11–16]. System dynamics of these applications routinely exhibit extremely low inductance, therefore fault currents increase faster in these DC systems than in their equivalent AC systems requiring faster isolation in the event of a fault.

A recent Ultra-Fast Mechanical Switch utilizing Thomson Coil actuation and an active damping control method has achieved 2 millisecond vacuum isolation with up to 60 kV voltage withstand [17]. The device shown in Fig. 2 is instrumental in medium and high voltage fast mechanical switch applications. For low voltage applications such as the Z-Source circuit breaker smaller switches can be readily used to keep cost and complexity to a minimum.

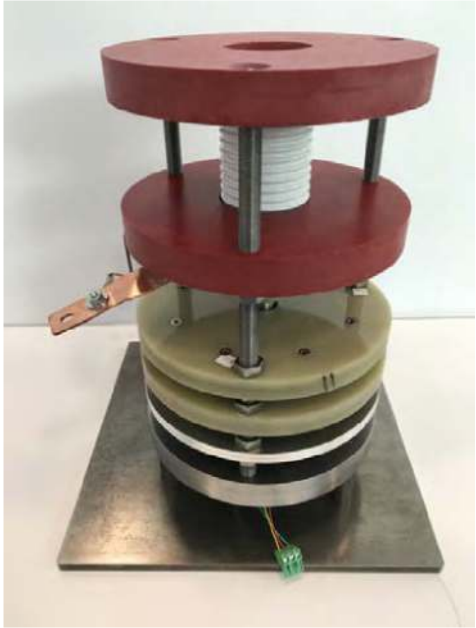

Fig. 2: FREEDM Systems Center Ultra-Fast Mechanical Switch Prototype (IEEE 2016)

The mechanically switched Z-Source circuit breaker utilizes these advances in fast mechanical switches and system dynamics to develop a highly efficient and extremely fast DC circuit breaker.

II. CIRCUIT BREAKER DESIGN

To ensure that resonant Z-Source circuit breakers could be replicated in the mechanically switched world, first a prior art Z-Source circuit breaker was analyzed to replicate circuit dynamics. Following development of the timing sequence and system dynamics, the thyristor in the traditional Z-source breaker was replaced with a fast mechanical switch. Also, an additional source inductor was placed in series to gain necessary time interval between current zero crossing in the event of a fault and to replicate realistic circuit characteristics.

The energy storage components (inductors and capacitors) used in a z-source circuit breaker dictate the system dynamics [18–20]. They lead to the resonant current ripple during fault conditions which provides the zero crossing that is necessary for isolation. The system was implemented in simulation, analytical assessment and finally in test bench prototype testing as described throughout this section.

A. Simulation

Simulation of the system was performed using circuit analysis tools including PSCAD as shown in Fig. 3 and PLECS. Detailed simulation of the system revealed the dynamic interactions between the energy storage devices in the impedance network. Additionally, the current profile of

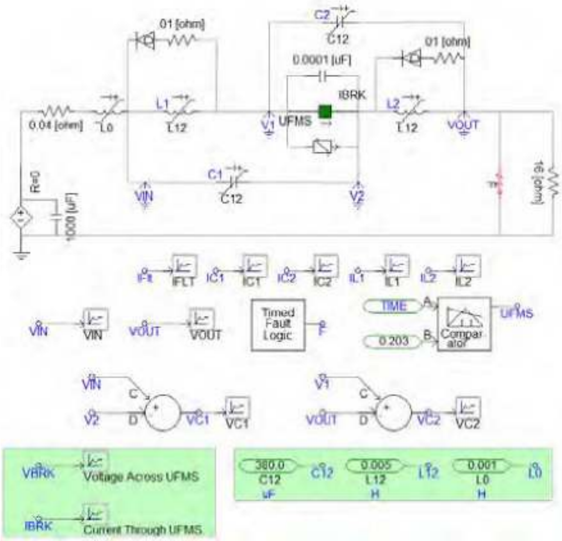

Fig. 3: Simulation setup in PSCAD

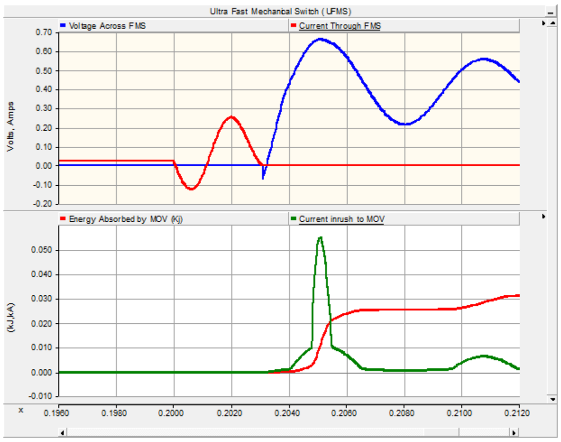

Fig. 4: Voltage and current profile of UFMS (top) and energy absorbed and current inrush to MOV (bottom).

the fast mechanical switch and voltage stress placed on the switch and metal-oxide varistor (MOV) was calculated and observed as shown in Fig. 4. The analysis of these components stresses, values, and interactions proved to be a vital part of the design process to ensure that the calculated interactions would perform as expected prior to physical prototype construction.

The variable time constants and dynamics between the inductors and capacitors results in a resonant energy exchange between these components as the systems attempts to reach equilibrium. This energy exchange is observed in Fig. 5 as the current into and out of each component of the impedance network results in a sinusoidal current profile in an otherwise direct current system.

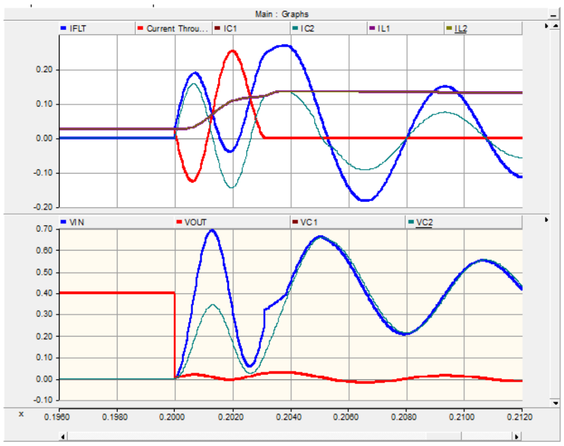

Fig. 5: Current ripple and voltage ripple induced in the fast mechanical switch and impedance network during fault condition.

B. Analytical Assessment

In the proposed design, the source inductor is smaller compared to the impedance network inductors. Therefore, the circuit can be approximated as a series LC circuit (comprised of source inductor and two impedance network capacitor) during fault as the current through the large impedance network inductors cannot change instantly, hence the fault current flows through the series LC path. This simplified circuit schematic shown in Fig. 6 can be used to mathematically represent the first period of transient current during a fault condition.

In Fig. 6, C1 represents series combination of the network capacitors, each with value C. Assuming a zero-pre-fault current, it can be shown in (1) that the source current

$$I_L(t) = \frac{V_S\sqrt{C}}{\sqrt{2L}} * sin\left(\sqrt{\frac{2}{LC}} * t\right) \tag{1}$$

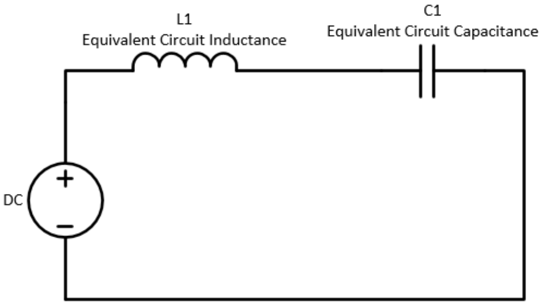

Fig. 6: Z-Source Circuit Breaker Simplified Analytical Schematic

and that the derivative of the source current shown in (2)

$$I'_L(t) = \frac{V_S}{L} * cos\left(\sqrt{\frac{2}{LC}} * t\right) \tag{2}$$

Finally, peak current is shown in (3) where I_0 is the pre-fault load current

$$I_{Peak} = I_0 + \frac{V_S\sqrt{C}}{\sqrt{2L}} \tag{3}$$

This is the current that flows through the mechanical switch inducing zero-crossing. Also, the maximum value of the current derivative at the time of fault is given by $\frac{V_s}{L}$. However, this model is only valid for the time up-to first zero crossing, because after that substantial current flows in the impedance network inductors.

As the current peak, current derivative and frequency have dependency on the passive components, it is possible to optimize the zero crossing time and develop control strategy accordingly.

C. Test Bench Experimentation

A low voltage experimental setup was arranged to verify the analytical assessment and the simulation results. The tests were carried out with zero pre-fault current for 5 different voltage cases (10, 15, 20, 25 and 30 Volts DC) The parameters shown in Table I were used during the test.

TABLE I: Experimental Setup Parameters.

Parameter	Value
• Z-Source Capacitors • Z-Source Inductors • Source Inductor	• 380 µF • 5 mH • 2.5 mH

The prototype shown in Fig. 7 was constructed and testing under normal operating conditions was simulated in the laboratory. Controls were implemented with the use of arbitrary signal generators to allow for timing optimization of the fault isolation sequence.

Fig. 7: Z-Source Circuit Breaker Test Bench Prototype

The following system dynamics measured to observe system response. In Section III several of these measurements are compared to the simulation and analytical results for continuity and validation.

- Source Current
- Switch Current
- Capacitor Voltage
- Switch Voltage

Initial test bench experimentation results indicated in Fig. 8 and in Fig. 9 illustrate the response during testing. It is important to note that fault current, source, voltage, and pre-fault current do not affect the timing sequence of the zero crossing. This is confirmed analytically, in simulation and in experimental testing. The period of the zero crossing is determined by the system dynamics and impedance network.

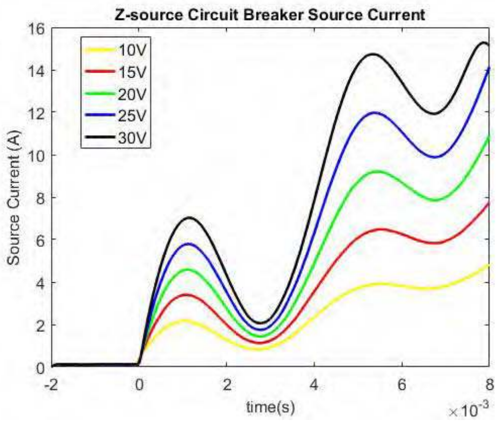

Fig. 8: Z-Source Circuit Breaker Source Current.

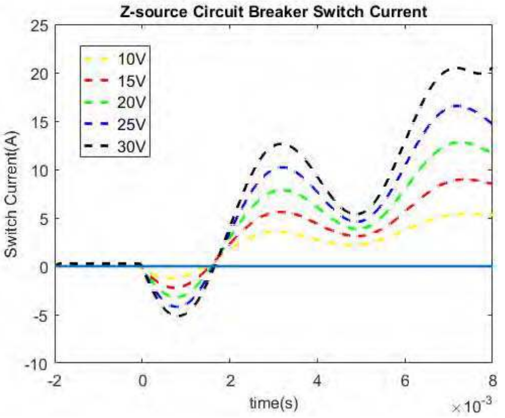

Fig. 9: Z-Source Circuit Breaker Switch Current.

Finally in Fig. 10, it is evident that the source and switch current is approximately opposite of each other initially as shown by the simulation results. Their peaks deviates as the current through the impedance network inductors increase.

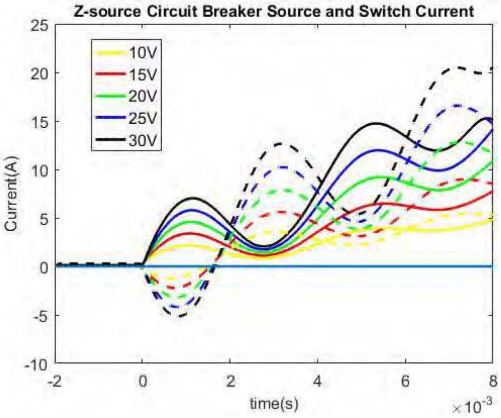

Fig. 10: Experimental Z-Source Circuit Breaker Source (solid lines) and Switch Current (dashed lines).

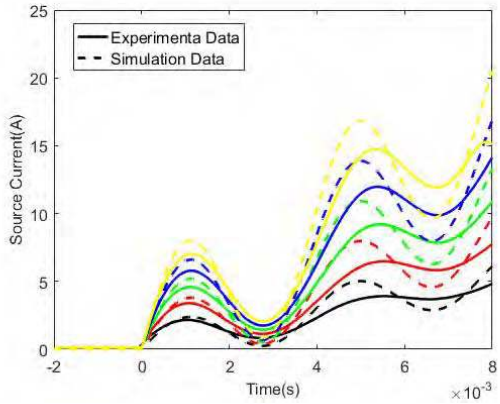

Fig. 11: Experimental and Simulation Source Current.

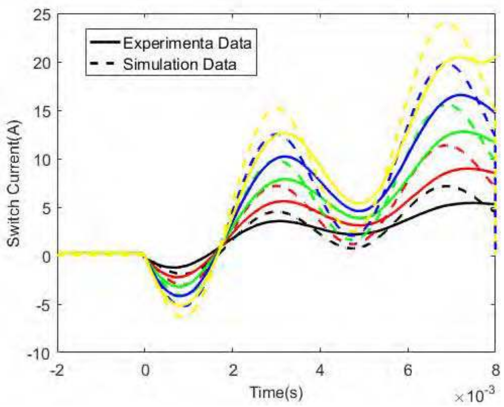

Fig. 12: Experimental and Simulation Switch Current.

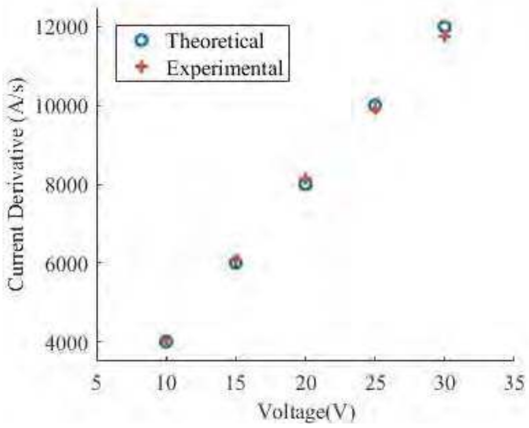

Fig. 13: Comparison of Theoretical and Experimental $\frac{di}{dt}$ to voltage

III. COMPARISON OF SIMULATION, ANALYTICAL AND EXPERIMENTAL PLATFORMS

Upon completion of successful testing of the test bench Mechanically switched Z-Source Circuit Breaker, validation of the simulation and analytical approaches was performed through comparison of results. The Z-Source Circuit breaker circuit dynamics must be appropriately modeled to ensure the systems ability to isolate a fault.

We can see from the following plots in Fig. 11 and Fig. 12 that the simulated source current and switch current is very much like that of the experiment. The simulated current magnitudes are higher because all the elements are assumed to be ideal. In actual test setup, the current magnitude is lowered due to resistance. Also, bot the simulation and experimental result verifies that the zero-crossing time does not change with supply voltage. Because as the analysis showed, it only depends on the passive component values.

The following plot in Fig. 13 shows the comparison between the current derivative as calculated from the analytical model and as derived from the experimental setup. They match very well. The experimental results also verify that the current derivative is proportional to the supply voltage.

IV. RESULT AND ANALYSIS

Coordination of fault initiation and mechanical switch isolation was refined and is shown in Fig. 14. In Fig. 14 the switch current and switch voltage are shown to isolate current flow instantaneously in the circuit. The resonant impedance network and MOV clamp the voltage across the switch and prevent a surge transient recovery voltage, with full blocking voltage achieved in less than two milliseconds. The switch voltage does not exceed the source voltage of 30 volts. Therefore, even under fault condition the switch is protected and therefore components can be sized small.

The Z-Source Circuit breaker has been modeled in both PSCAD and PLECS for transient analysis, analytically assessed and a physical prototype constructed and tested.

The analytical model gives a full understanding of the system dynamics and helps to tune the passive components appropriately. It also leads to design of control system for this DC circuit breaker. The simulations show that the transient

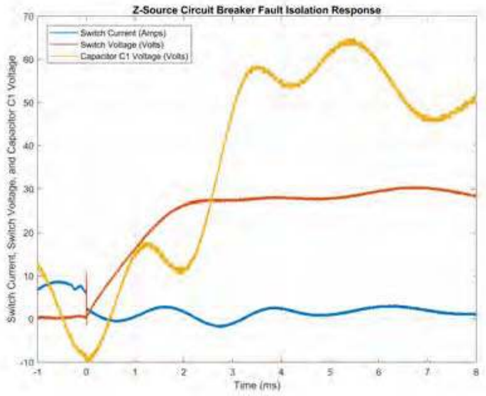

Fig. 14: Prototype Isolation of Mechanically Switch Z-Source Circuit Breaker

surge current is supplied by the resistive, inductive and capacitive (RLC) network and resonance across the mechanical switch is established to allow for a forced zero crossing. Current is pulled through a series of zero crossings by the energy storage in the LC impedance network due to resonance between the inductive and capacitive components. The switch is therefore provided adequate time to draw a significant air or vacuum gap in the mechanical switch. A metal oxide varistor clamps the voltage across the mechanical switch to minimize voltage surge and to ensure restrike or arcing do not occur.

Following analytical assessment and simulation, a low voltage prototype system has been constructed to test actual resonance and zero crossing characteristics. Testing confirms both the natural resonance between energy storage components and adequate timing to open the Fast Mechanical Switch.

V. CONCLUSION

DC circuit protection is a necessary component of future DC systems including electric vehicles, microgrids, building distribution and more. A novel modification to the Z-Source DC Circuit Breaker is proposed, analyzed, simulated, constructed and tested. This modification of removing the power thyristor from the main current path and replacing it with a well coordinated fast mechanical switch improves the energy efficiency of the system by minimizing on state power consumption of the circuit breaker.

Fast mechanical switches are not limited to unidirectional power flow and therefore expand the possibilities for implementation of Z-Source circuit breakers to bidirectional systems such as distributed renewable energy resources.

This paper addressed the critical issue of fast isolation of DC circuits while minimizing the significant power losses associated with load current flowing through solid state switches.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of the University of North Carolina Coastal Studies Institute for carrying out this research.

REFERENCES

[1] K. A. Corzine. A new-coupled-inductor circuit breaker for dc applications. *IEEE Transactions on Power Electronics*, 32(2):1411–1418, Feb 2017.

[2] K. A. Corzine. Circuit breaker for dc micro grids. In *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, pages 221–221c, June 2015.

[3] K. Corzine. Dc micro grid protection with the z-source breaker. In *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, pages 2197–2204, Nov 2013.

[4] Fang Zheng Peng. Z-source inverter. *IEEE Transactions on Industry Applications*, 39(2):504–510, Mar 2003.

[5] K. A. Corzine and R. W. Ashton. A new z-source dc circuit breaker. In *2010 IEEE International Symposium on Industrial Electronics*, pages 585–590, July 2010.

[6] K. A. Corzine and R. W. Ashton. A new z-source dc circuit breaker. *IEEE Transactions on Power Electronics*, 27(6):2796–2804, June 2012.

[7] S. Savaliya, S. Singh, and B. G. Fernandes. Protection of dc system using bi-directional z-source circuit breaker. In *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, pages 4217–4222, Oct 2016.

[8] A. Overstreet, A. Maqsood, and K. Corzine. Modified z-source dc circuit breaker topologies. In *2014 Clemson University Power Systems Conference*, pages 1–6, March 2014.

[9] A. Maqsood, A. Overstreet, and K. A. Corzine. Modified z-source dc circuit breaker topologies. *IEEE Transactions on Power Electronics*, 31(10):7394–7403, Oct 2016.

[10] K. A. Corzine and R. W. Ashton. Structure and analysis of the z-source mvdc breaker. In *2011 IEEE Electric Ship Technologies Symposium*, pages 334–338, April 2011.

[11] P. Prempraneerach, G. E. Karniadakis, and C. Chryssostomidis. Dc fault protection in shipboard power systems using z-source breakers. 2011.

[12] W. Wen, Y. Huang, M. Al-Dweikat, Z. Zhang, T. Cheng, S. Gao, and W. Liu. Research on operating mechanism for ultra-fast 40.5-kv vacuum switches. *IEEE Transactions on Power Delivery*, 30(6):2553–2560, Dec 2015.

[13] P. Prempraneerach, M. G. Angle, J. L. Kirtley, G. E. Karniadakis, and C. Chryssostomidis. Optimization of a z-source dc circuit breaker. In *2013 IEEE Electric Ship Technologies Symposium (ESTS)*, pages 480–486, April 2013.

[14] A. Maqsood and K. A. Corzine. The z-source breaker for ship power system protection. In *2015 IEEE Electric Ship Technologies Symposium (ESTS)*, pages 293–298, June 2015.

[15] A. Maqsood and K. Corzine. Z-source dc circuit breakers with coupled inductors. In *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, pages 1905–1909, Sept 2015.

[16] A. Maqsood and K. Corzine. The z-source breaker for fault protection in ship power systems. In *2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, pages 307–312, June 2014.

[17] C. Peng, L. Mackey, I. Husain, A. Huang, B. Lequesne, and R. Briggs. Active damping of ultra-fast mechanical switches for hybrid ac and dc circuit breakers. In *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, pages 1–8, Sept 2016.

[18] Y. Liu, X. Wei, C. Gao, and J. Cao. Topological analysis of hvdc circuit breaker with coupling transformer. In *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, pages 129–134, June 2015.

[19] A. H. Chang, B. R. Sennett, A. T. Avestruz, S. B. Leeb, and J. L. Kirtley. Analysis and design of dc system protection using z-source circuit breaker. *IEEE Transactions on Power Electronics*, 31(2):1036–1049, Feb 2016.

[20] A. H. Chang, A. T. Avestruz, S. B. Leeb, and J. L. Kirtley. Design of dc system protection. In *2013 IEEE Electric Ship Technologies Symposium (ESTS)*, pages 500–508, April 2013.