Ultra Fast, High Efficiency DC Circuit Protection for Renewable Energy Distribution Systems

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Motivation

Modernization of electric equipment, distributed renewable energy resources (DRER) and the computer revolution have resulted in DC system proliferation as shown in Fig. 1.

- DC circuit protection is a key system need

Figure 1 – The Proliferation of DC Systems is Growing Every Day in Modern Life

Background

- Natural AC zero-crossings quench arc during current interruption as shown in Fig. 2.

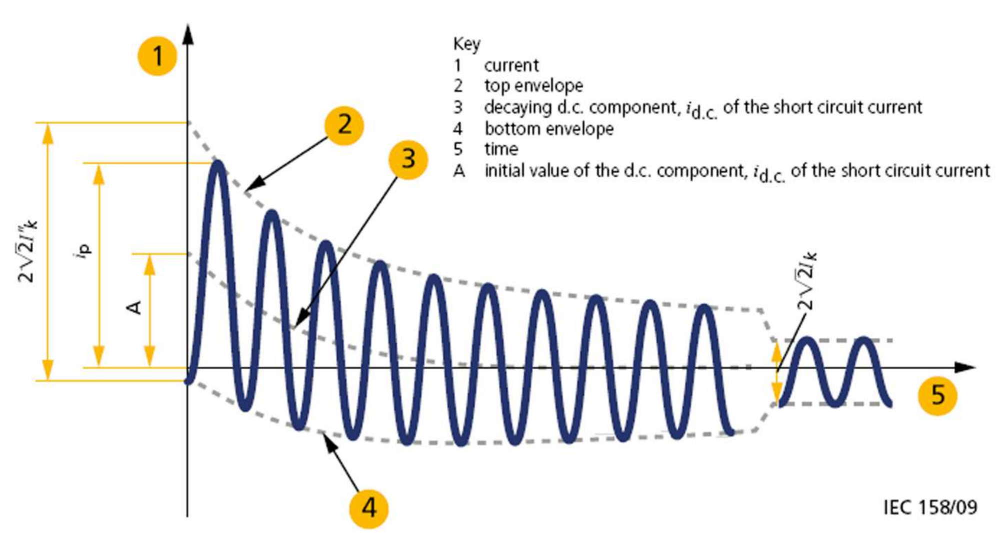

Figure 2 – AC System Fault with Natural Zero Crossing – Does not Occur in DC Systems

- DC constant bias requires forced current zero
- DC faults are often more severe than AC due to low impedance of DC networks and DRERs requiring ultra-fast isolation
- Solid state switches provide fast isolation but consume real power.
- Hybrid or resonant DC protection systems with minimal on-state power consumption are researched and developed by FREEDM Systems Center.

Active Damping of UFMS

- DC circuit protection is predicated on isolation time of the switching devices.

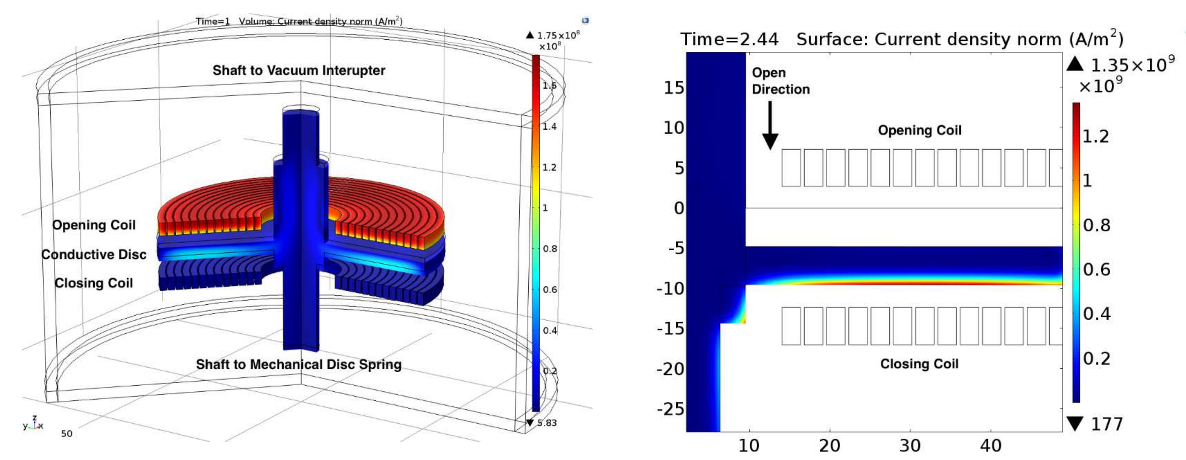

Figure 3 – FEA Model of Thomson Coil Actuator (Left) and Damping Magnetic Flux (Right)

- Thomson Coil Actuation (TCA) is used to developed a medium voltage fast mechanical switch as exhibited in Fig 3.
- Active damping of switch is implemented to improve performance and isolation time.

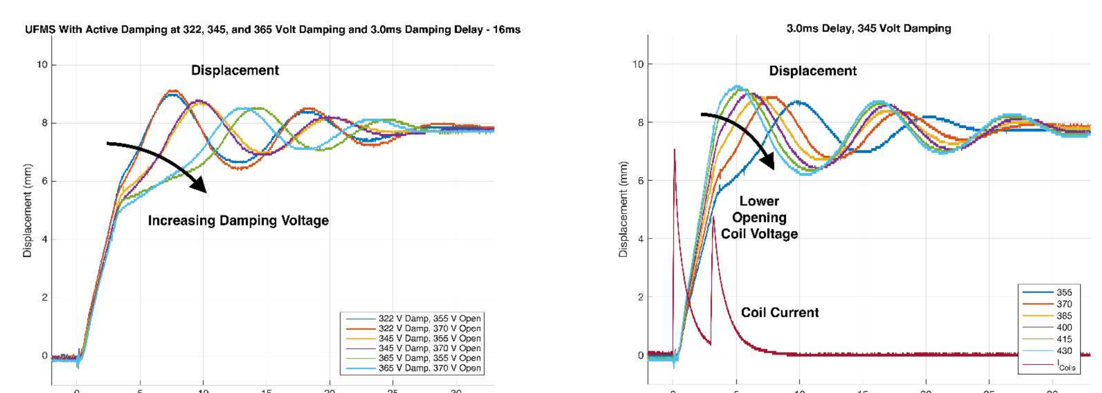

Figure 4 – Effect of increasing Damping Voltage (Left) and lowering Opening Voltage (Right)

- Ultra-fast mechanical switch (UFMS) with active damping achieved:
  - 4.5mm vacuum gap within 2ms
  - Equivalent 60kV voltage withstand in a 15kV switch without rebound, 400% V_{Rated}.
- Dynamic testing shown in Fig. 4.
- Prototype UFMS and hybrid DCCB in Fig. 5.

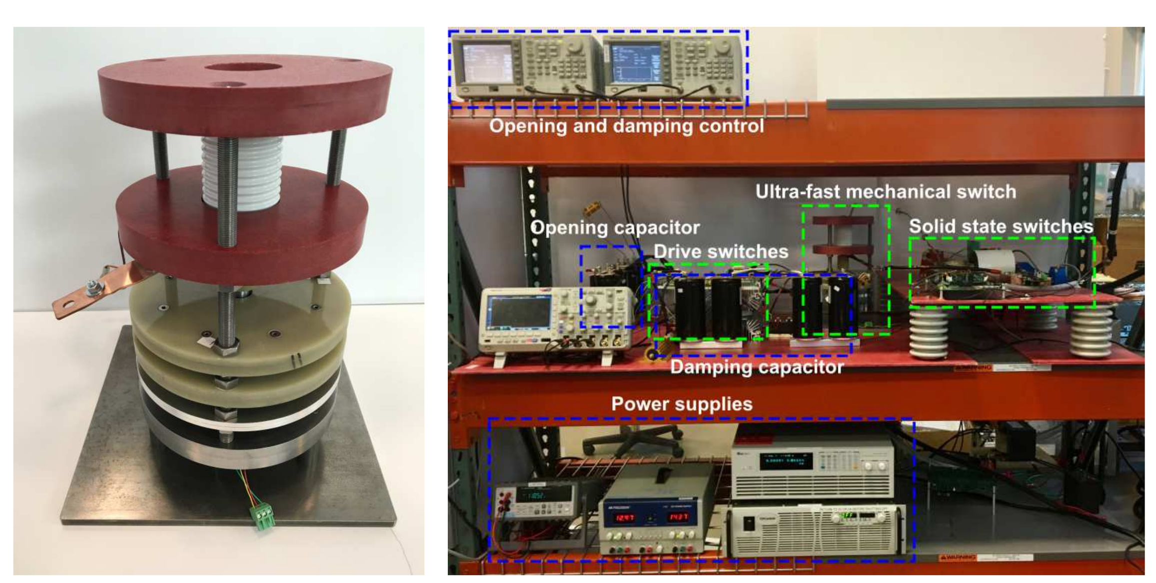

Figure 5 – Ultra-Fast Mechanical Switch (Left), Hybrid DC Circuit Breaker Test Bench (Right)

Z-Source Circuit Breaker

- Prior art Z-source DCCBs use thyristors for isolation with large annual kWh losses.
- Proposed design of Fig. 6 replace the thyristor with an UFMS, minimizing loss.
- Proposed for low voltage DC application.
- Forced zero crossing and metal-oxide varistor utilized ensure switch safety.

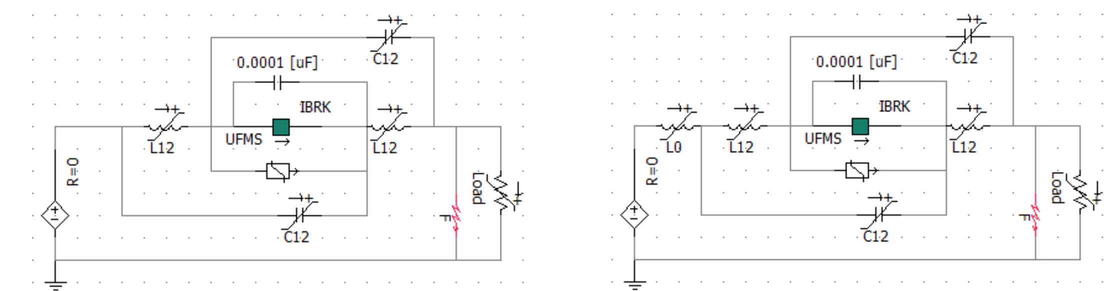

Figure 6 – Z-source breaker without source inductor (left) and with source inductor (right)

- Supplemental source inductance provides the necessary time window for fault detection and isolation in Fig. 7.

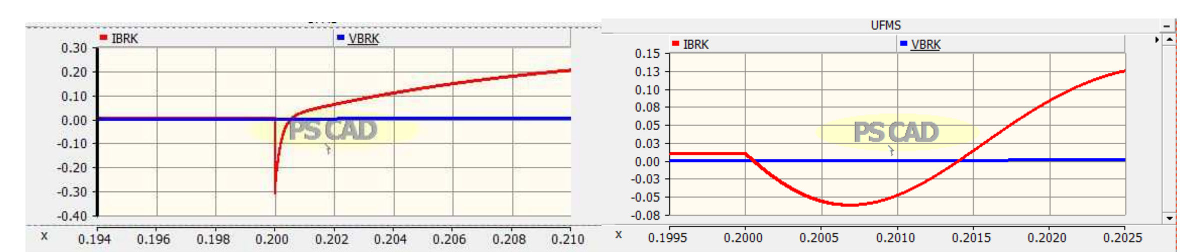

Figure 7 – Mechanical Switch Current without (left) and with (right) Source Inductance Added

Analytical model: Source Current: $I_L(t) = \frac{V_S\sqrt{C}}{\sqrt{2\cdot L}}\cdot \sin\left(\sqrt{\frac{2}{L\cdot C}}\cdot t\right)$

Peak Current: $I_{Peak} = I_0 + \frac{V_S\sqrt{C}}{\sqrt{2\cdot L}}$

Current Derivative: $I_L'(t) = \frac{V_S}{L}\cdot \cos\left(\sqrt{\frac{2}{LC}}\cdot t\right)$

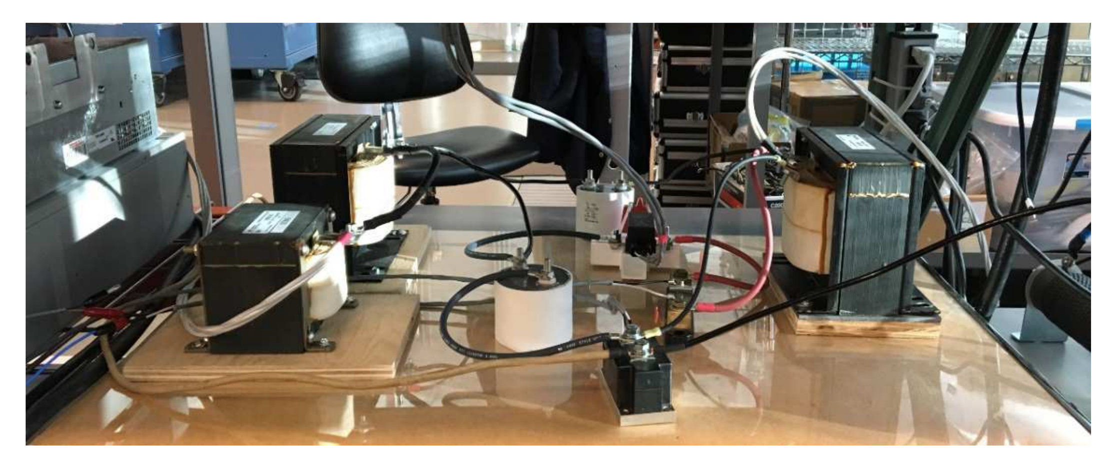

Figure 8 – Z-Source Breaker Test bench (Sensors and Safety Shields removed for Clarity)

- Mechanical switch interrupting 8A in 0.5 milliseconds and forced zero crossing of Z-Source Network at Fault shown in Fig. 9.

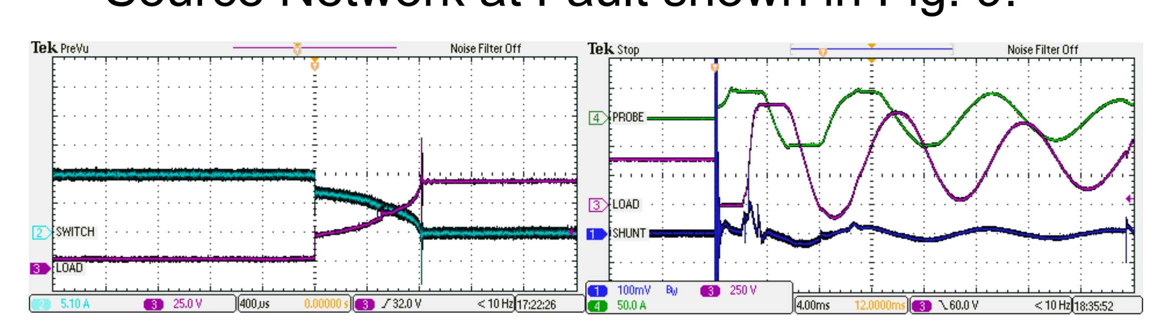

Figure 9 – Mechanical Switch Current interruption (left) and forced zero crossings during fault (right)

Potential Impacts

- DC Systems can be protected in 1-2 milliseconds both at medium and low voltage, this technology can be extended to other types of mechanical switches.
- Minimized on-state power consumption.
- Reduction of voltage stress on protection device by fast fault clearing.
- Eliminate oversize component requirement.
- Open doorways to future advanced DC distribution in Ships, Cities, data centers, etc.

Conclusions and Next Steps

- Active Damping of UFMS significantly improves operation time and performance
  - Electrical team will research development of Generation 2 UFMS with Active Damping optimized mechanical design
- UFMSs are viable improvements to a variety of DCCBs including Z-Source and Hybrid designs to minimize on state power loss
  - Develop current sensing and timing controls for Z-Source DCCB which can be extended to other UFMS based DCCBs
- Advanced control can be integrated into distributed grid intelligence and coordination
  - Next steps include analysis of protection coordination both upstream and downstream of Z-Source Circuit Breaker
- In coming months, the OCAES Electrical team will compare potential solid state switch and driver technologies to implement 100 kV voltage withstand capability within MVDC Circuit Breaker Applications.

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