NC STATE UNIVERSITY

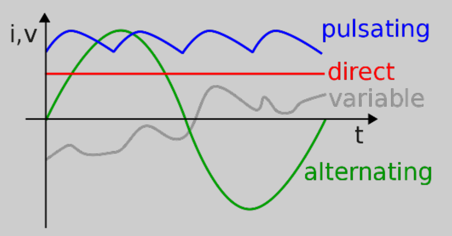
Electrical & Computer Engineering
Landon Mackey, Ph.D. Student
Dr. Iqbal Husain, Committee Chair

FREEDM SYSTEMS CENTER   Coastal Studies Institute, University of North Carolina

Protecting Distributed Renewable Energy Resources with Direct Current Circuit Breakers

Motivation

- The entire world is shifting towards DC from AC. Electric Vehicles, LED lighting, portable electronics, and inverter motor drives are expanding in popularity. while photovoltaic systems, battery storage, and off-shore energy harvesting are growing exponentially.
- Numerous inefficient conversions between AC and DC can be mitigated through DC distribution and protection.
- AC periodically crosses zero, this is not guaranteed for DC, complicating protection schemes.



Introduction and Background

- Repetitive conversion between AC and DC is inefficient and expensive.
- Increasing share of electricity is generated in DC or other variable forms, and nearly all consumer energy is DC.
- Bidirectional medium-voltage distribution systems enable harvesting clean and sustainable energy from wind, sun, and sea while promoting a more robust and adaptive infrastructure to our ever-changing global energy needs.
- The greatest challenge to DC distribution is safely interrupting fault current in the event of a short circuit.

Research Statement

- To develop high-speed, high-efficiency, and scalable protection devices for medium-voltage, bidirectional, DC power flow. These technologies will facilitate the harness and transmission of distributed renewable energy resources and their deliverance to the end customer.

Focus Objectives

Develop bidirectional DC protection devices with:

- Minimal or no on-state energy consumption
- No communication, standalone operability
- Ultra-fast operational time, under 1 millisecond

Critically analyze DC distribution and protection for:

- Barriers to entry outside of protection devices
- Deployment beyond the Microgrid

Selected References

[1] C. Peng, L. Mackey, I. Husain, A. Huang, W. Yu, B. Lequesne, and R. Briggs, "Active Damping of Ultrafast Mechanical Switches for Hybrid AC and DC Circuit Breakers." *IEEE Transactions on Industry Applications, 2018, pp. 5354-5364, Print.*

[2] L. Mackey, C. Peng, and I. Husain, "Progressive Switching of Hybrid DC Circuit Breakers for Faster Fault Isolation" *IEEE Energy Conversion Caucus and Exposition 2018, Portland, Oregon, USA* pp. 1-8, 2018.

[3] Images Collected from Various Sources. All original authors are given credit for their work. Citations available upon request.

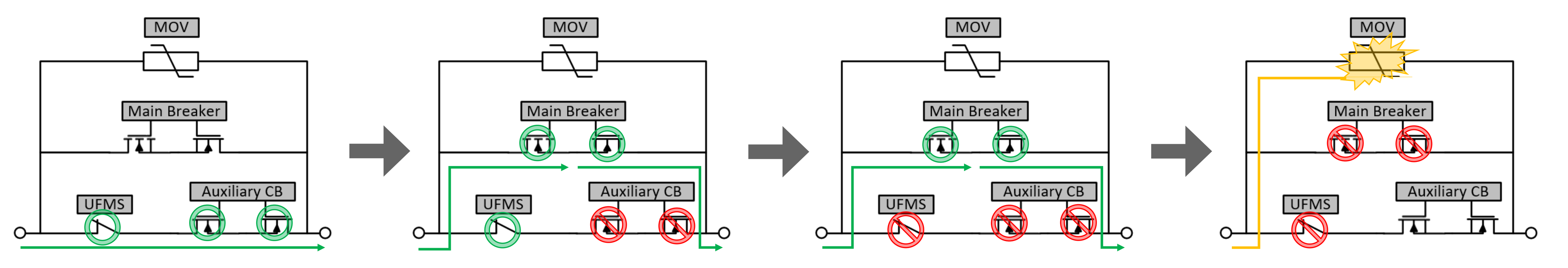
Contact: Landon Mackey, lkmackey@ncsu.edu

FREEDM SYSTEMS CENTER   NSF   Coastal Studies Institute, University of North Carolina

① HYBRID DIRECT CURRENT CIRCUIT BREAKERS (DCCB)

Operating Mechanism of Hybrid DCCBs

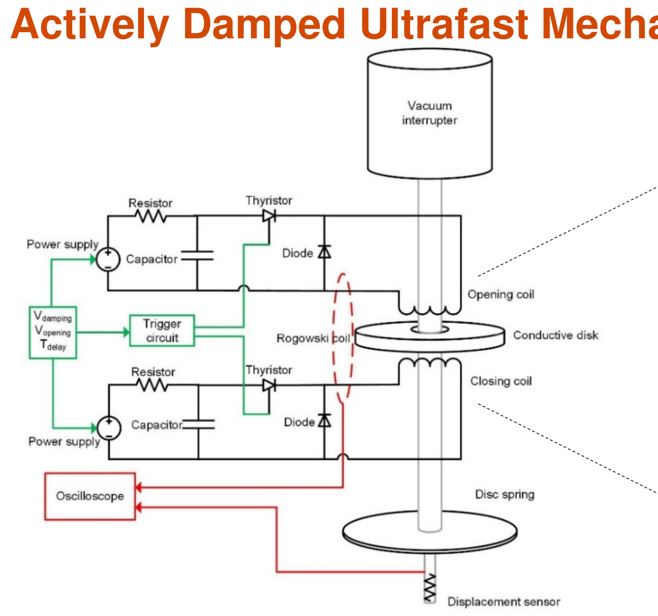
Combine Solid State and Mechanical – **Efficient and Fast**



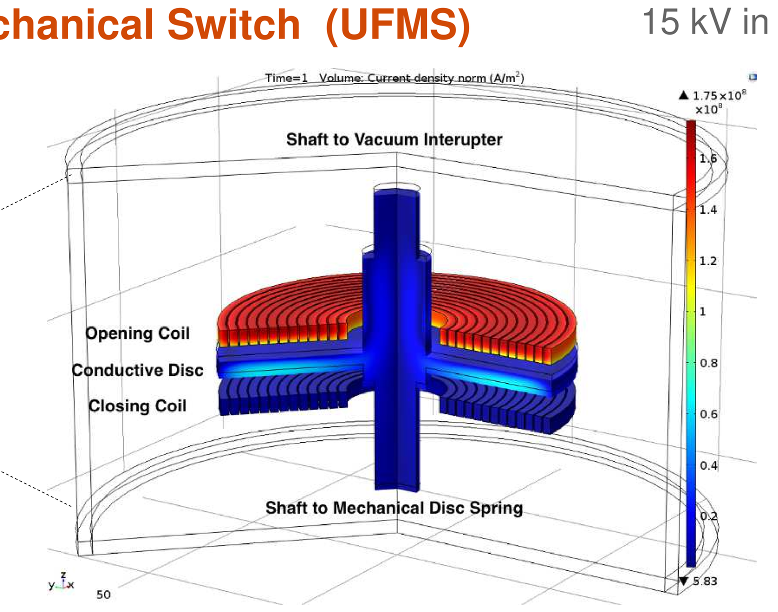
Normal Operation — Current through UFMS and ACB
Fault Detected — Current directed to Main Breaker
UFMS Opening — Operation of mechanical switch
Fault Isolated — Main Breaker open

Actively Damped Ultrafast Mechanical Switch (UFMS)

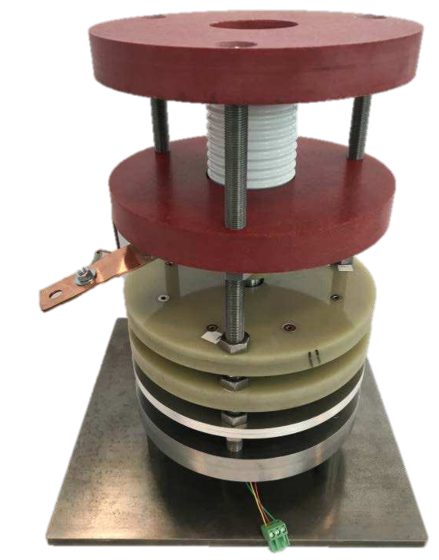
15 kV in 1 ms – **3000% Speed Improvement**



UFMS Functional Block Diagram



Electromagnetic Simulation of Thomson Coil

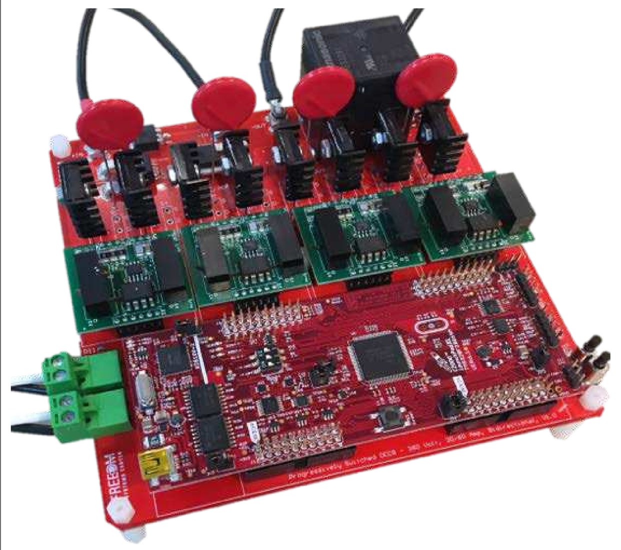


First Generation Prototype UFMS

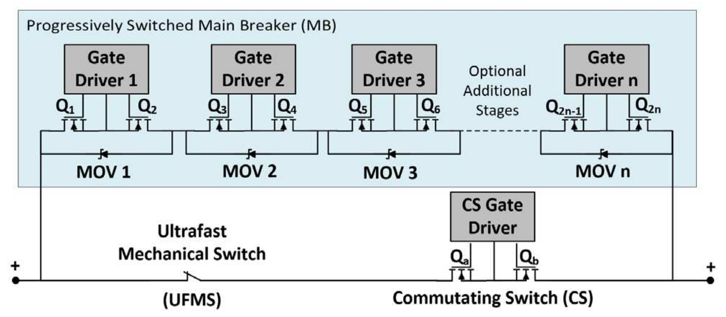
② PROGRESSIVE HYBRID DCCB: A NEW VISION

Progressively Switched Main Breaker (MB) for Faster Fault Isolation

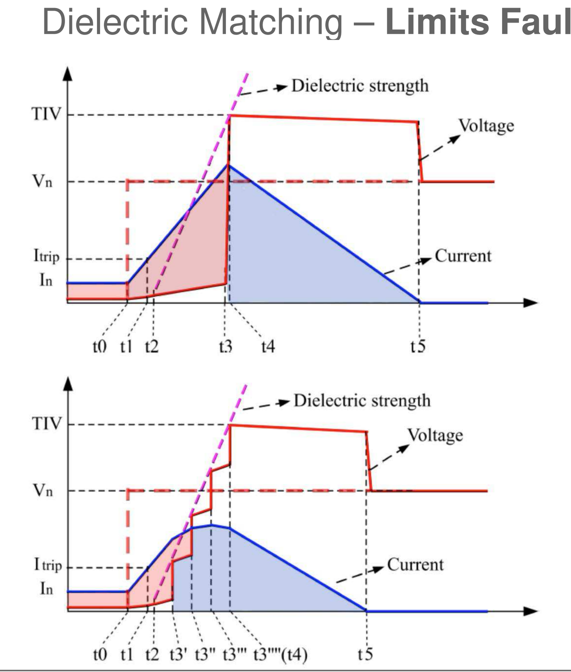
Dielectric Matching – **Limits Fault**



Progressively Switched MB Prototype



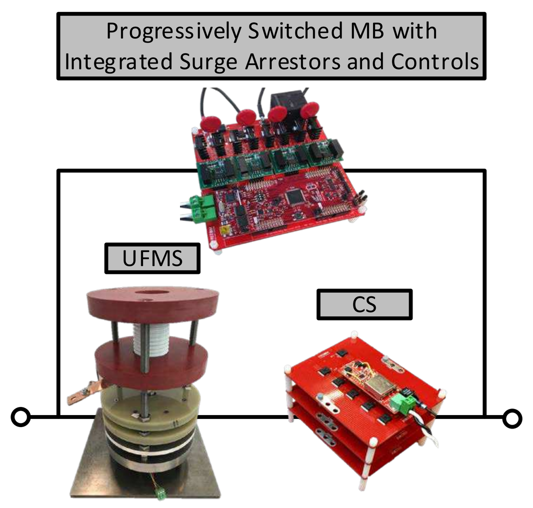
Progressively Switched MB Block Diagram



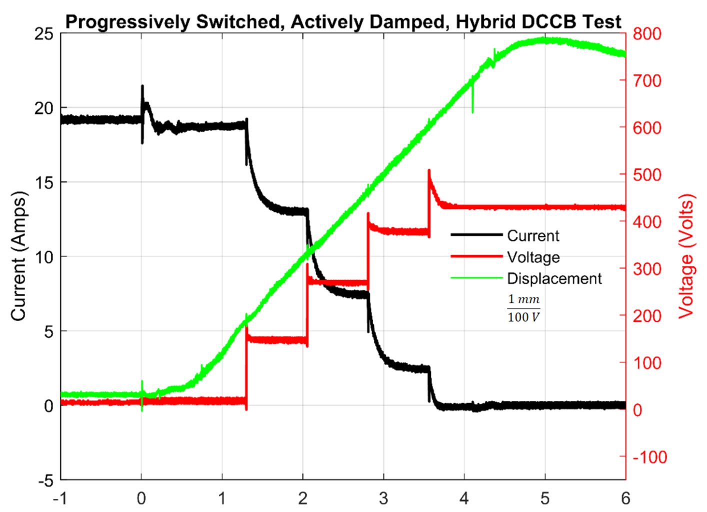
Energy Dissipation of Prior Art DCCB (Top Right) Compared to Progressively Switched Hybrid DCCB (Bottom Right)

Next Generation Switching and Control Schemes

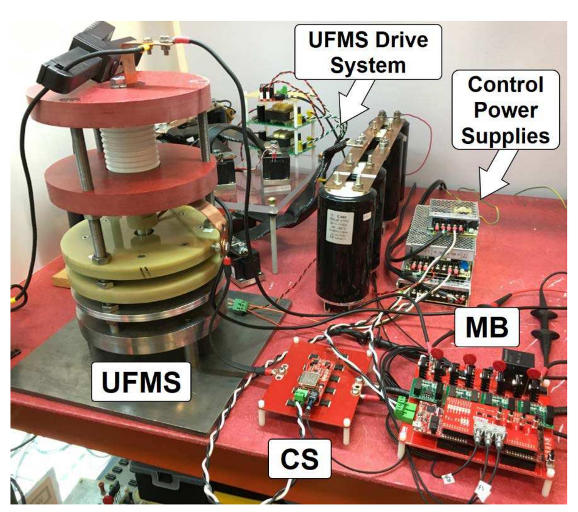
Differential Adaptive Control – **Accelerated Isolation**



Integrated Hybrid DCCB



New Hybrid DCCB Isolation Waveforms



New Hybrid DCCB Test Bench

③ ENABLING THE FUTURE OF ENERGY: DC MICROGRIDS

Performance Metrics of Progressively Switched and Actively Damped Hybrid DCCB

$$i'(t) = \left(-\frac{R_{eq}}{L_{eq}} I_0 + \frac{V_s}{L_{eq}}\right) e^{-\left(\frac{R_{eq}}{L_{eq}}\right)t}$$

Rise Rate of Fault Current

$$i(t) = \left(i(t_n) - \frac{\Delta V_s}{R_n}\right) e^{-\frac{R_n}{L_{eq}}(t-t_n)} + \frac{\Delta V_s}{R_n}$$

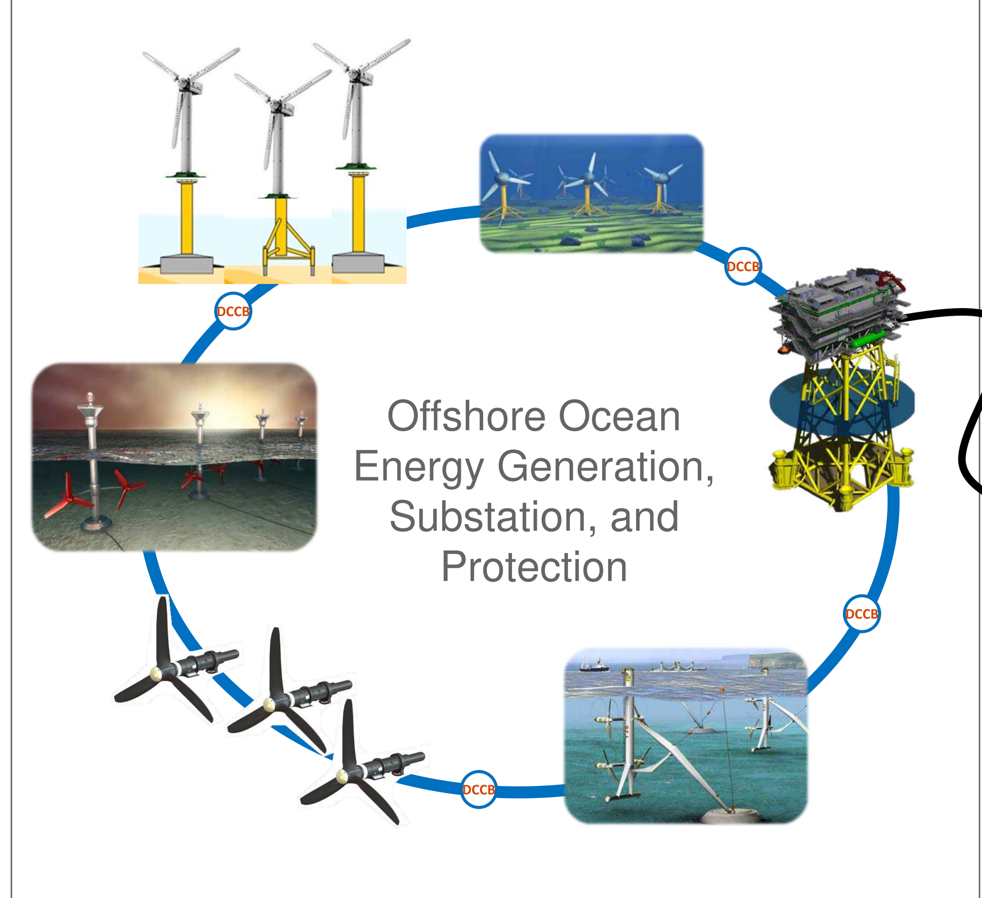
Progressive MB Current over time

$$i^2 t = \left(\frac{1}{3}\right) \left(i_p^2 + i_p\right) \left(i_b + i_b^2\right) t$$

Instantaneous Pulse Energy

Metric	Progressively Switched and Actively Damped	Single-Stage without Active Damping	Units
$t_{isolation}$	3.31	4.23	ms
$E_{absorbed}$	2.52	7.21	J
$2.0mm\,(40kV)$	1.06	1.31	ms
$5.0mm\,(100kV)$	2.01	2.67	ms
$8.0mm\,(160kV)$	3.10	3.98	ms

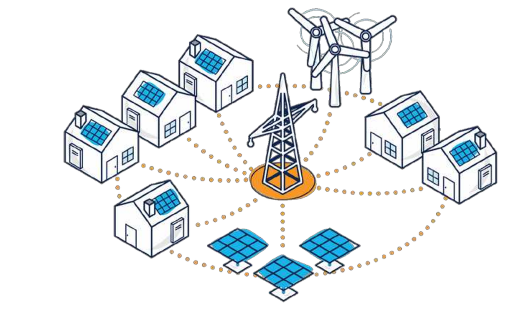
Harnessing the Power of the Sea



Safely Distributing Renewable Energy

Providing Benefits Across the Nation, and the World

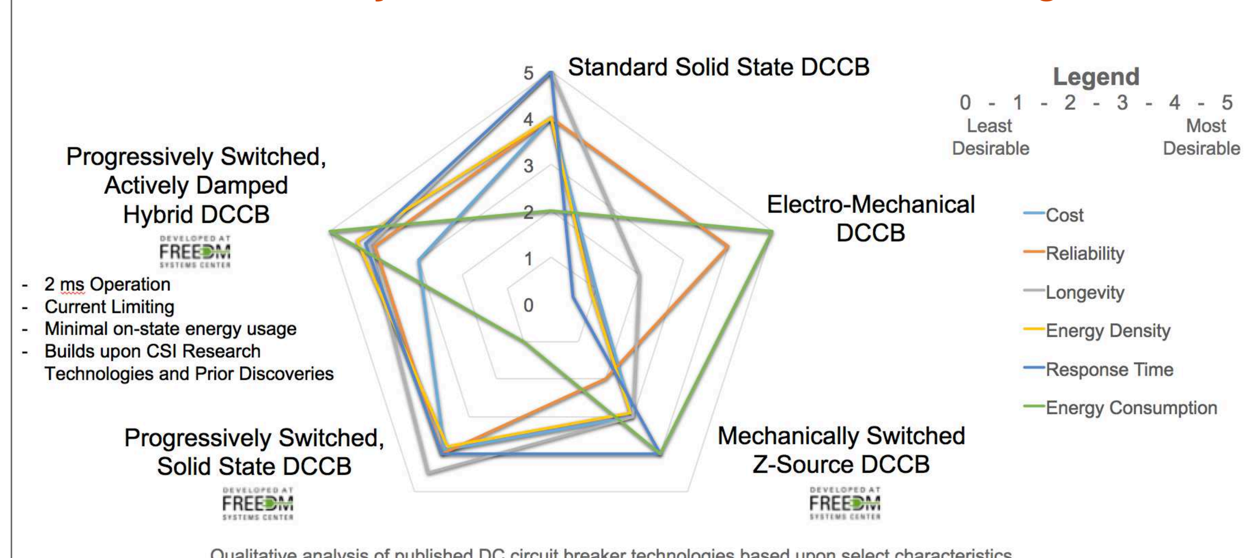
First applications in electric ships such as Military and Leisure craft, More Electrified Aircraft (MEA), All Electric Aircraft (AEA)



Transactive Energy will accelerate growth and stability in the aging national power system.

④ CONCLUSIONS AND FUTURE WORK

Quantitative Analysis of Circuit Breakers Technologies and Next Steps



Qualitative analysis of published DC circuit breaker technologies based upon select characteristics

- Analyze potential of Hybrid DCCBs in non-conventional applications:
  - Industrial facilities
  - Multi-terminal DC distribution
  - Data Centers and Server Farms
- Redirect fault energy to operate gate driver and Thomson Coil Actuator (TCA)
- Implement small scale rural DC Microgrid prototype in Bangladesh
  - Completely renewable DC design
  - Islanded / Grid-tied applications