## 2.4 Fault Isolation Device (FID)

| Year 10 Projects and Participants | | | |
|---|---|---|---|
| Project Number | Project Title | Participants | Institution |
| Y10.HIL.1 | System Demonstration on HILTV at MV level via PHIL | Steurer | FSU |
| Y10.HIL.2 | Volt-VAR Control on FREEDM Systems | Baran | NCSU |
| Y10.HIL.3 | Implementation and test of CoDES on HIL Testbed | Chow | NCSU |
| Y10.HIL.4 | PHIL FREEDM System Demonstration with Gen-III FID and Gen-III SST | Huang | NCSU |

Affiliated with a partner project: "NSF PFI: AIR - TT: Fault-Tolerant Fast Mechanical Disconnect Switch", PI: Luklas Graber, Georgia Tech, Co-PI: Mischa Steurer, FSU. See also:

https://www.nsf.gov/awardsearch/showAward?AWD_ID=1700887

### 2.4.1 Intellectual Merit and Impact

True to the goal of the project, the center has delivered Gen-1 and Gen-2 fault isolation device (FID) with adequate voltage and power ratings that are capable in supporting the FREEDM Systems Center's vision for controlling transients during fault turn-on and turn-off in a medium voltage circuit.

In the course of 10 years of this project, the center has developed, tested and integrated into GEH test bed a Si-IGBT based solid-state only Gen-1 FID designed for 15 kV class voltage and 50 A continuous current and up to 400 A of fault current in Y5 and a 200 A [1], [2], 15 kV piezoelectric actuated-fast mechanical switch (part of hybrid Gen-2 FID) based on the patented idea of integrating a piezo-electric actuator and the mechanical contacts with a vacuum switching chamber was tested and successfully demonstrated in Y9.

In the course of 9 years of development, the project gave the center immense understanding about fault transients and mitigation strategies and fault management in future power systems in conjunction with FREEDM Systems center's vision. Recorded data and conclusions from research have been reported and published regularly motivating researchers and industry to apply the new generation of MV-class fault protection and isolation techniques as a baseline for their research or product development.

The value of a 15-kV fast mechanical switch was investigated with a team at the 2015 NSF I-Corps project [3]. The team consisted of a technical lead (faculty mentor), the entrepreneurial lead (graduate student), and the I-Corps mentor. The project took place in the Chicago area in summer 2015. Nearly one hundred interviews with potential customers, suppliers, competitors, and market experts were conducted over a period of just a few weeks. The information gained from those interviews helped to determine the value proposition of the switch and additional information about how to penetrate the market or with whom to collaborate. Two niche markets were identified that seem promising for finding initial customers. Those niche markets are US utilities in densely populated cities and all-electric Navy ships. For these two markets, the ability to isolate a fault quickly and to limit the fault current are valuable and would justify increased costs of a high-speed switch. However, it also became clear that the ratings of FID Gen-3 are not satisfying the needs of those markets. For utilities, the current level has to be at least 600 A continues and preferably 900 A continuous. The 15-kV rated voltage seem to fit their needs. However, they require to pass 95-kV lightning impulse testing. For electric ships, the switch should be able to isolate DC currents of up to

2,000 A. The voltages are not expected to surpass 10 kV. Both customer segments expect switching times well below 2 ms.

Encouraged by the outcome of the I-Corps project, it was decided to explore higher current ratings to satisfy the requirements by the expected initial customers. A new NSF sponsored project “PFI:AIR - TT: Fault-Tolerant Fast Mechanical Disconnect Switch”, led by Georgia Institute of Techology in collaboration with Florida State University is focusing on designing and building a minimum viable prototype for the initial customer segment [4]. The project also includes further investigation of the value proposition and understanding the customer needs. Furthermore, the project includes research components with respect to high performance electrical contacts and bushings with the capability to conduct thermal loads from the vacuum side to the air side. Additional IP has been generated and an invention disclosure was filed.

### 2.4.2 Technical Approach

The design of piezoelectric based high speed disconnect switch was evaluated and improved in FREEDM Systems Centers development of a 15 kV, 100 A alternating current hybrid breaker based on SiC semiconductors with a 100 A continuous load current capability with over currents of 200 A for a short period of time [3], [4].

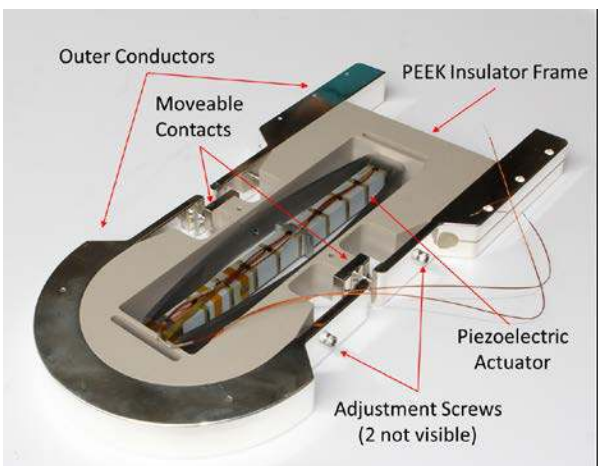


Fig. 1a: Contacts setup with piezoelectric actuator

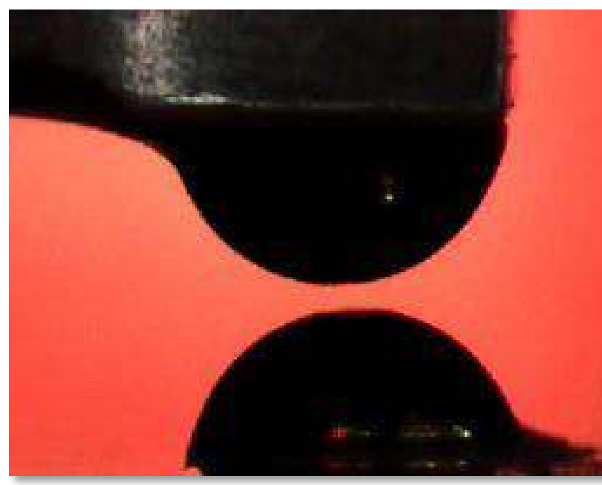

Fig. 1b: Contact separation when open

Fig. 1a shows the construction of the disconnect switch including its piezoelectric actuator but without the vacuum chamber. Prior to affixing the piezoelectric actuator in vacuum, it is necessary to determine contact spacing throughout the current path during dynamic operation. The dynamic operation of the device is driven by a ramp in voltage across the piezoelectric actuator. Contact separation testing shows that 150 V applied to the piezo actuator creates a total contact separation of 4x0.4 mm. Fig. 1b shows one separated contact. A DSP based controller board is utilized to safely actuate the piezoelectric actuator with a ramp speed of 600 µs to prevent mechanical stresses to harm the piezoelectric actuator and to damp the vibrations that can cause the contacts to bounce off each other after opening. The DSP controller board reacts to a logic high signal from the NCSU’s solid state controller and sends a ramp signal to Techron power amplifier to ramp up to 150 V in 600 µs. The communication between two controllers is verified during Y9 SV demonstration [5].

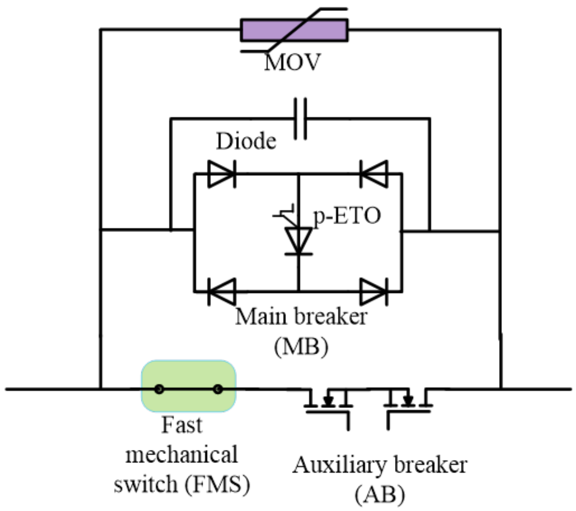


Fig. 2: Circuit diagram for hybrid-FID

After making sure that the PA-FMS can withstand AC and DC voltages seen during the hybrid FID's opening sequence, the team integrated the PA-FMS into the full hybrid fault isolation device. The PA-FMS, an auxiliary breaker (AB) and an Emitter Turn-off Thyristor (ETO) based solid state main breaker (MB) were combined together to form a hybrid-FID circuit as shown in Fig. 2. Actual setup is shown in Fig. 3.

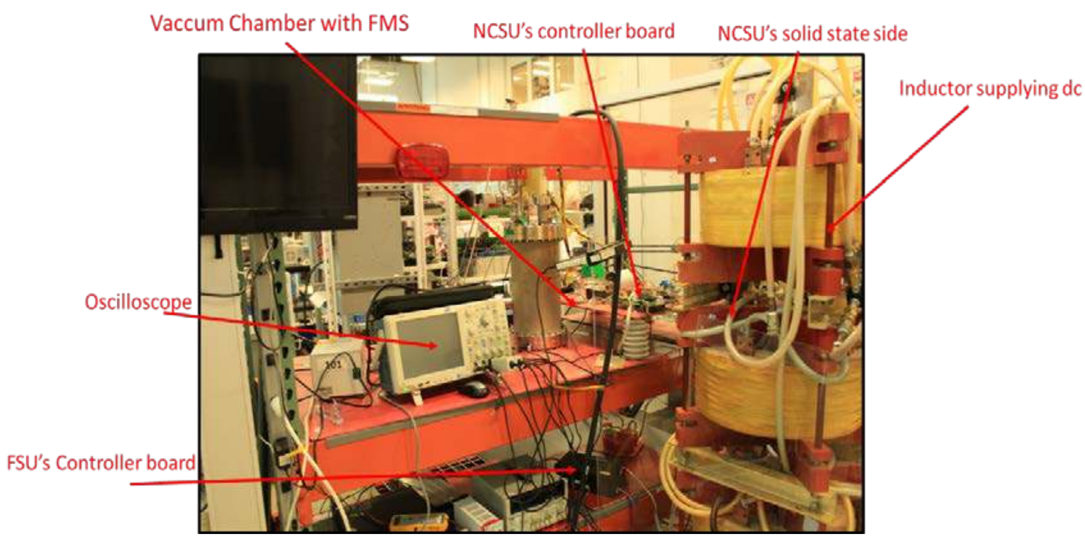


Fig. 3: Hybrid FID setup during Y9 Site Visit Demonstration

Breaker isolation tests up to 800 Vdc and 15 Adc steady state and 1.2 kVdc transient were performed, results shown in Fig. 4.

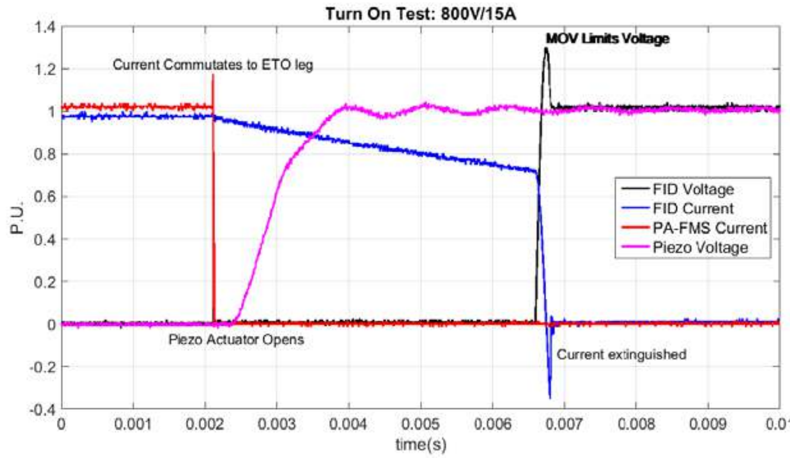


Fig. 4: Hybrid FID opening test at 800 V, 15 A

The AB on the solid state side of the hybrid-FID provides a forced zero current turn-on point to the PA-FMS. It is essential for reliability and safety because there are no natural zero crossings during a fault in dc system. The piezo voltage is ramped right after AB turn-off which separates the PA-FMS contacts, thus isolating the faulted line. The fault energy commutates to the ETO leg which extinguishes the fault current after a 3 ms user defined safety margin to make sure that the PA-FMS contacts ae truly open. A transient recovery voltage is established on all the three parallel branches and the MOV limits the over-voltage. This test was essential in demonstrating the plug-n-play capabilities of the PA-FMS and its ruggedness as it was subjected to harsh vibrations during ground transportation to Raleigh, NC.

### 2.4.3 Unique Approaches:

The innovative approach of this project was to utilize a hybrid arrangement and to develop the ultra-fast piezo actuated disconnect switch.

### 2.4.4 Scientific Breakthroughs:

The FMS was taken to Georgia Tech to further explore its voltage withstand capabilities and it was subjected to two tests:

- Asymmetric DC Voltage Withstand Test
- Symmetric AC Voltage withstand Test

The FMS was subjected to multiple runs of asymmetric DC voltages up to 27 kV with a ramp rate of 16.66 kV/sec and the breakdown voltages as high as 25 kV were recorded.

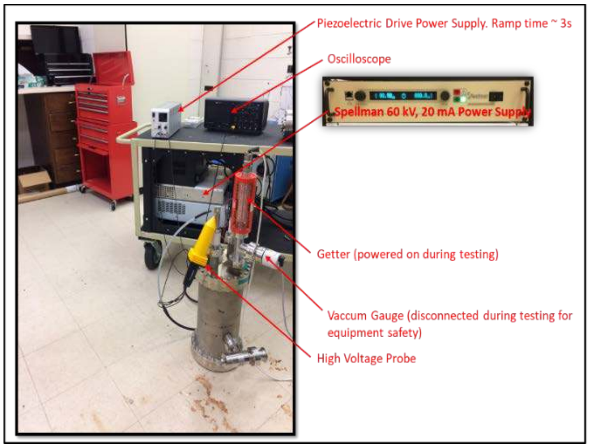


Fig. 5a: Setup for Asymmetrical DC Voltage withstand test.

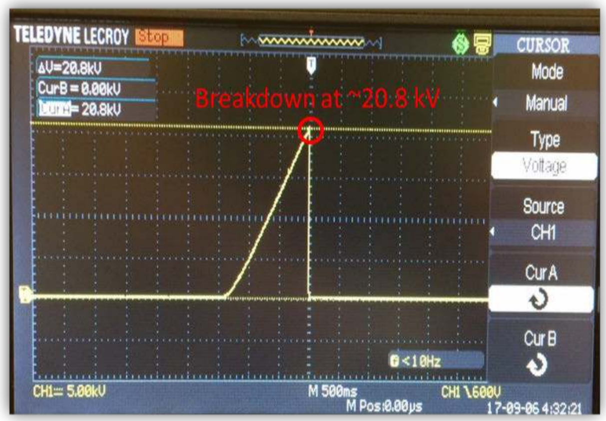


Fig. 5b: Oscilloscope visual of breakdown at 20.8 kV

Fig. 5a shows the test setup for asymmetrical DC voltage test using a Spellman 60 kV, 20 mA power supply as the source. Fig. 5b shows an oscilloscope capture of the breakdown at 20.8 kV.

Similar to asymmetrical dc tests, symmetrical ac tests were performed showcasing breakdown capabilities up to 34.78 kV Vpeak. An ‘Oil Dielectric Test Set DTS 60A’ is used as a Symmetric AC Power Source and the test setup and oscilloscope visual is shown in Fig. 6 and Fig. 7.

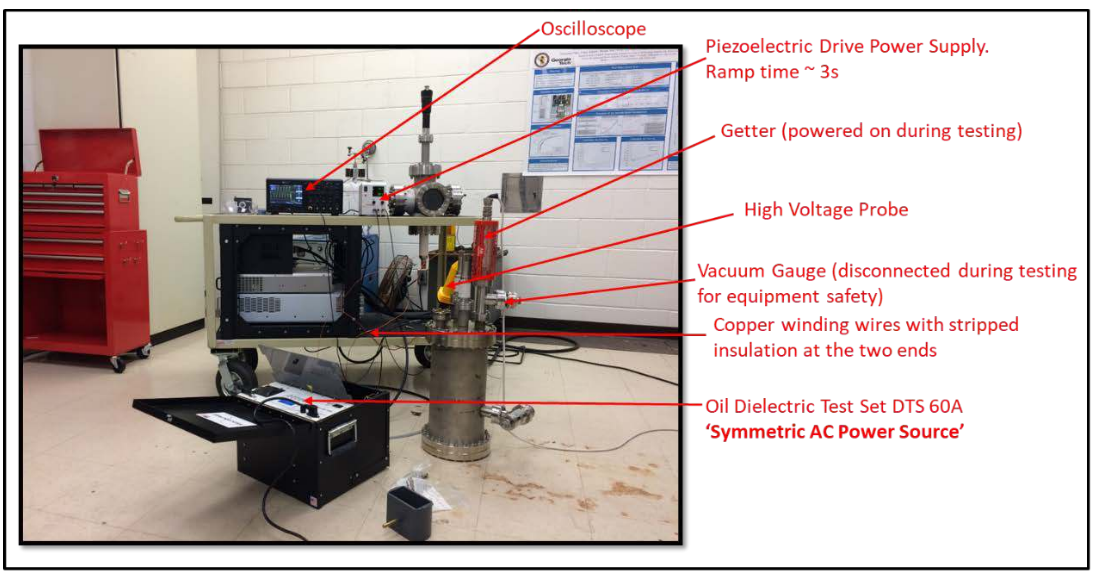


Fig. 6: Test setup for Symmetric AC Voltage Withstand test.


Fig. 7: Oscilloscope visual showing Symmetric AC Breakdown Energy

## 2.4.5 Technology Innovations:

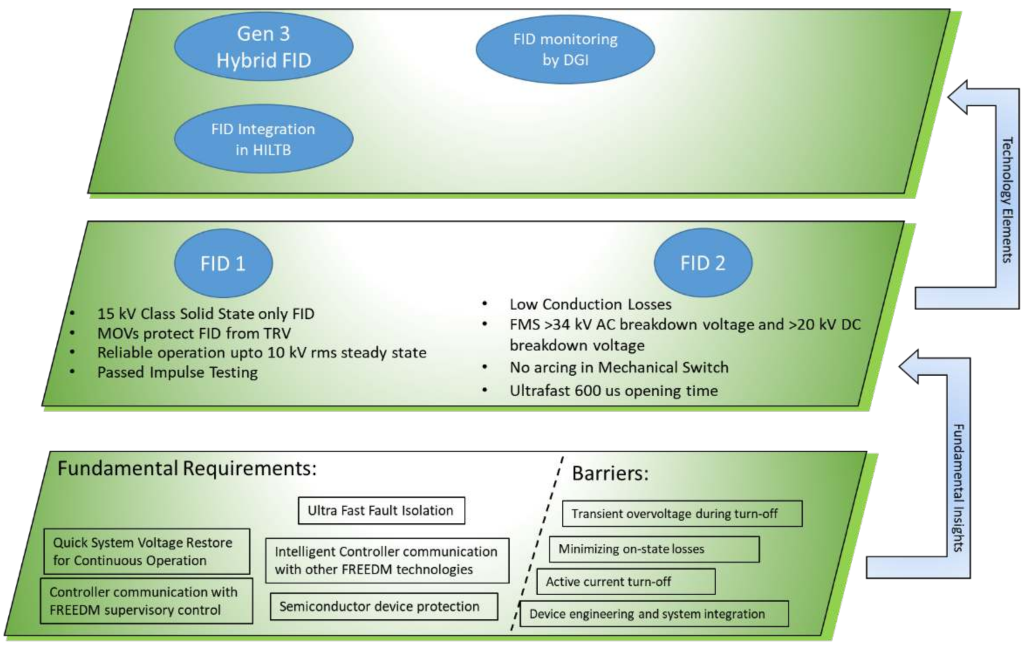


Fig. 8: Three plane diagram showing FID research and developments

Center has been able to address all the barriers in fault protection and mitigation techniques in 9 years of research and delivered working hardware of FID-1, the Fast Mechanical Switch and the Hybrid-FID with FMS during the 9 year course of the project as shown in Fig. 8.

## 2.4.6 Validation of the Research

The developments of the FID thrust have been validated using unit test as described above and in [1] - [7].

### 2.4.7 Intellectual Property (Licensing and Patents)

| IP License Number or Name | IP License Title or Name | IP Category: FP, PP, C, T | Brief Description of Technology | Owner of IP | Year Awarded |
|---|---|---|---|---|---|
| US20160329182A1 (appl. of full patent) and 15/214,015 & 61/930,755 (two provisional patents) | Ultrafast electromechanical disconnect switch | PP | Integration of actuator inside the switching chamber for high-speed applications; piezoelectric actuators, magnetostrictive actuators, and electrodynamic (“Thomson coil”) actuators. | FSU | 2016 |
| 62/574,985 | Electrical Contact Geometry for Switchgear Applications | PP | Uniform field geometries that are suitable for high-speed switchgear with their limited contact separation in open state. | Georgia Institute of Technology | 2017 |

FP= Full Patent; PP = Provisional Patent; C= Copyright; T= Trademark

### 2.4.8 References


1. O. Vodyakho et al., "Development of solid-state fault isolation devices for future power electronics-based distribution systems," 2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), Fort Worth, TX, 2011, pp. 113-118
2. O. Vodyakho, M. Steurer, D. Neumayr, C. S. Edrington, G. Karady and S. Bhattacharya, "Solid-state fault isolation devices: application to future power electronics-based distribution systems," in IET Electric Power Applications, vol. 5, no. 6, pp. 521-528, July 2011.
3. L. Graber, “I-Corps: Market Analysis and Customer Needs Identification for the Commercialization of a High-Speed Disconnect Switch,” NSF Project #1547045, I-Corps. $50,000. https://www.nsf.gov/awardsearch/showAward?AWD_ID=1547045
4. L. Graber, M. Steurer, J. Goldman, “PFI: AIR - TT: Fault-Tolerant Fast Mechanical Disconnect Switch,” NSF Project #1700887, Engineering Research Centers, Accelerating Innovation Rsrch. $200,000. https://www.nsf.gov/awardsearch/showAward?AWD_ID=1700887
5. L Graber, C Widener, S Smith, M Steurer, “Thermal-Electrical Study of an Ultra-fast Disconnect Switch with a Piezoelectric Actuator,” *COMSOL Conference*, Boston, MA, 2014.
6. L Graber, S Smith, D Soto, I Nowak, J Owens, M Steurer, “A new class of high speed disconnect switch based on piezoelectric actuators,” *IEEE Electric Ship Technologies Symposium (ESTS)*, p. 312-317, 2015.
7. M. Bosworth, D. Soto, R. Agarwal, M. Steurer, T. Damle, L. Graber, “High speed disconnect switch with piezoelectric actuator for medium voltage direct current grids,” *IEEE Electric Ship Technologies Symposium (ESTS)*, p. 419-423, 2017.