Y9.ET4.2: Fault Isolation Device (FID) Development - Power Electronics

Project Leader: Alex Huang (NCSU)

Students: Xiaoqing Song (NCSU), Richard Woodley (NCSU)

1. Project Goals

Fault Isolation Device (FID) as a fast opening and reclosing device is a critical component in a fault current limited power grid or DC grid. In particular, this project was launched to develop a hybrid FID which utilizes an ultra-fast mechanical bypass switch to further reduce the on-state losses of the FID as well as to maintain a high interruption speed.

2. Role in Support of Strategic Plan

The FID is one of the key enabling technologies of FRREDM. In particular, it enables the ultra-fast protection philosophy pursued by FRREDM in order to maximize system availability by minimizing fault clearing time. FREEDM System is current limiting, hence the grid voltage will decrease quickly in the event of a fault. Ultra-fast fault isolation is therefore absolutely needed. In a DC grid, ultra-fast protection is also needed. Our work therefore will also have significant impact to medium voltage DC grid protection.

3. International Collaboration

No international collaborations are currently taking place in this project.

4. Fundamental Research, Educational, or Technological Advancement Barriers and Methodologies Used to Address Them

This hybrid circuit breaker concept is not new in itself, but our goal of achieving quarter cycle fault clearance time is novel and extremely challenging. Several fundamental challenges exist and therefore require substantial fundamental research to overcome.

1: Fast mechanical switch (FMS): The FMS needs to have a separation speed in the order of 1ms in order to keep the overall interruption time smaller than 2ms. The FMS also needs to have an ultra-low conduction loss. Our FMS concept is based on the patented idea of integrating a piezo-electric actuator and the mechanical contacts with a vacuum switching chamber. This concept has never been applied to high voltage and high current circuit breaker applications therefore it has several fundamental challenges, which will be described in detail in VII_Y9.ET4.1.docx.
2. Main breaker (MB) Turn-off capability and Blocking Capability: The MB needs to be implemented by a high voltage power semiconductor switch that on one hand has a breakdown voltage higher than the transient interruption voltage but also has a large interruption current capability (Safe Operation Area or SOA). Our design approach was to use 15 kV SiC ETO which can meet the voltage requirement without connecting any additional devices in series. However, having the turn-off current to be higher than I_{PEAK} is a significant and fundamental challenge from device point of view. This is also the world's first known fundamental effort in developing and understanding SiC ETO's turn-off capability. The methods used to overcome these challenges are based on modeling and simulation combined with hardware testing. To address the high cost issue of the SiC ETO, the main fundamental approach is to design/verify the SiC ETO can interrupt very high fault current therefore a small chip size SiC ETO can be used. This work is also a fundamental contribution to the PSD subthrust since it addresses a scientific challenge for SiC bipolar power devices.

5. Major Achievements

MB Turn-off Capability Study and Progress:

The MB blocking capability and turn-off capability requirement for the Gen-III FID are derived based on the nominal 7.2kV/1MVA system. Depends on if the system is a current limited system like the FREEDM system or a traditional system, 400A or 1400A current turn-off capability is needed for the MB solid state switch. As mentioned before, this remains a major challenge for any solid state switch to achieve.

As reported in previously years, our approach in the MB implementation is to develop revolutionary >15kV SiC ETO devices. Supported by Cree Inc., our progress in SiC ETO and its application in circuit breaker represents a breakthrough in semiconductor technology.

A fundamental theory has been developed by Dr. Huang which suggests that SiC bipolar devices such as the SiC ETO will have superior turn-off capability when compared with Si power switches, as shown in Fig. 1. Si bipolar power devices typically fails at around 200 kW/cm^2. Our theory suggests that the SiC ETO device could have a SOA as large as 28 MW/cm^2. In other words, the electric current that can be turned off can reach 2800A/cm^2. So far, we have successfully demonstrated a turn-off capability around 400A/cm^2 with a small snubber and 200A/cm^2 without a snubber. No failure has been observed so far. Due to limited devices available for this research, we have not attempted to increase the current further. Future work will attempt to test the device at higher currents to valid the theory.

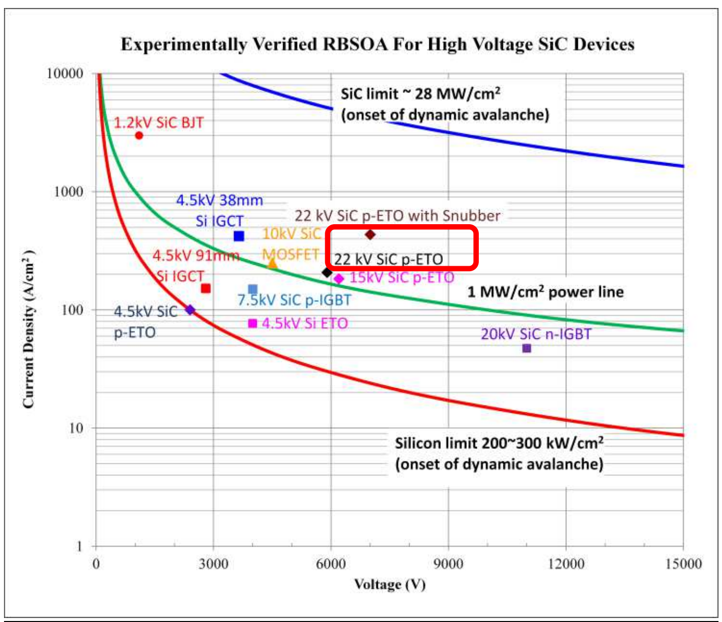

Figure 1: Theoretical and achieved SOA for the ultra-high voltage SiC ETO. Substantial advancement over silicon device has been demonstrated

High Current MB Switch Study:

In additional to increase and explore the turn-off limitation of one single ETO device, device parallel is being considered to increase the ETO turn-off current to >>400A. A preliminary study on device parallel operation is shown in Fig.2, which confirms the uniformity of the GTO devices in terms of current conduction. This feature is favorable to allow a number of ETO devices be paralleled. This work is ongoing and will be reported in the future.

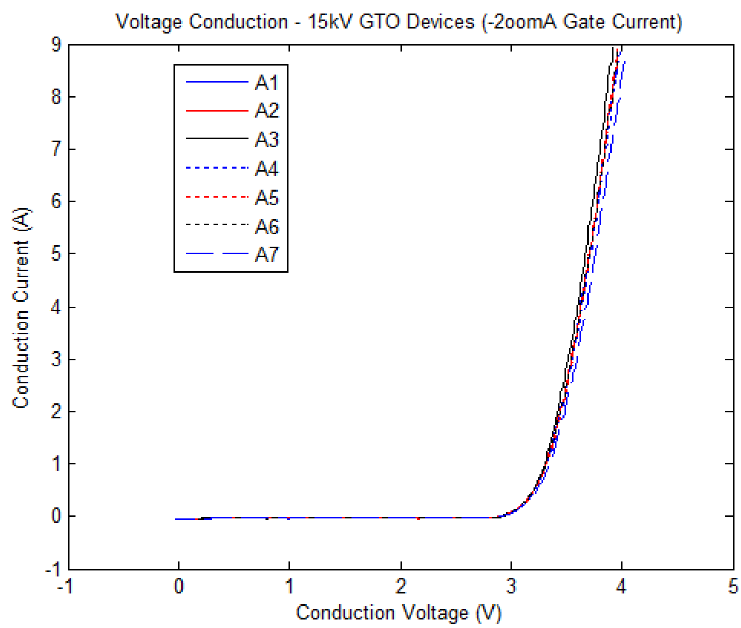

Figure 2: I-V characteristics of several 15 kV GTO devices tested

MB Voltage Capability Study and Progress:
The voltage capability of the MB is again derived based on the 7.2kV/1MVA nominal FREEDM system specification. Based on a conservative 20% over voltage design, the peak voltage of the MB will reach about 12 kV limited by a MOV devices. The 15kV SiC ETO's blocking voltage capability is experimentally verified up to 15kV at different temperatures. Fig. 3 shows the blocking capability of the 15 kV SiC GTO, which determines the 15kV SiC ETO's blocking capability. It demonstrated less than 1uA leakage current at up to 15kV blocking voltage at a wide range of temperatures, which means the 15 kV SiC ETO device is capable of meeting the voltage requirement without connecting any additional devices in series.

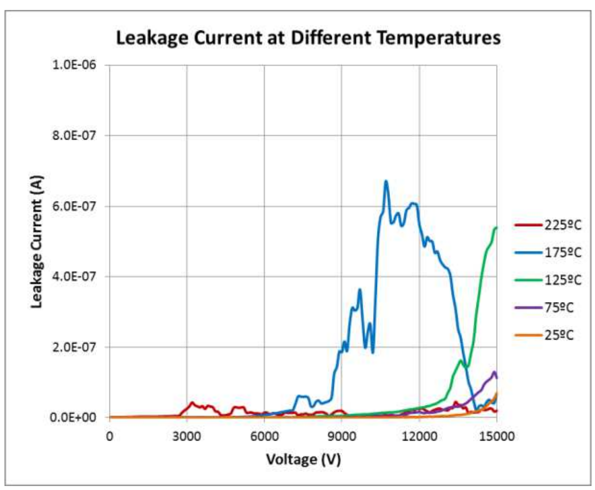

Figure 3: 15 kV SiC GTO blocking capability test up to 15 kV

System Integration and Current Interruption Test:
A comprehensive control/protection system has been developed which controls the MB, AB as well as the FMS. This system has been tested and validated. System, integration has been demonstrated. The FMS used in a FMS developed at NCSU under an associate project funding. In Fig. 4, the FID has been tested

under an inductive circuit at 7kV, 100A, which represents a more realistic circuit interruption scenario. Two MOVs are used to clamp the MB voltage to 7.2kV. Before t1, the hybrid FID is in on state, and the 100 A current conducts through the MS and the CS. The voltage across the hybrid FID is almost zero. At t1, the CS is turned off, and the 100 A current starts to commutate to the MB. After about 100 µs delay when all the current commutated to the MB, the MS is turned off. After another 1.5 ms delay, the MB is turned off at t2. The voltage across the hybrid FID starts to increase linearly with the dv/dt limited by the snubber capacitor (0.5 µF). The voltage rise time takes about 35 µs before it reach the MOVs clamping voltage (7 kV) at t3. Then all the remained energy in the line impedance are absorbed by the MOVs which takes about 105 µs. At t4, the current reaches zero, and due to the SiC PiN diode used in the test setup for protection, there are some reverse recovery current. At t5, the hybrid FID is in off state and the 100A current is interrupted in 1.75 ms, demonstrating the ultra-fast interruption speed of the hybrid FID.

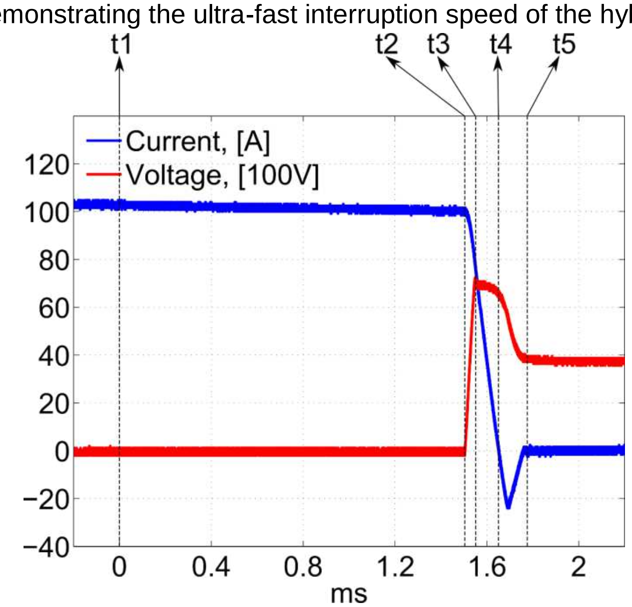

Figure 4: The photograph of the power electronic parts for current interruption.

6. Other Relevant Work Being Conducted Within and Outside of the ERC

Example of another Hybrid Breaker:

ABB HVDC hybrid circuit breaker has a rated voltage of 320 kVDC, a rated DC transmission current of 2 kA DC, and a current breaking capability of 9 kA DC. It is made for HVDC, it uses IGBTs instead of our developed lower loss SiC semiconductors, and has estimated a turnoff time within 2 ms with an upper limit of 5 ms[1].

Examples of other Fast Mechanical Switches:

Currently, fast transfer switches have been developed from Thomson coils, propellant-based systems, or coupled electromechanical and hydraulic systems. In contrast, the novel FMS described above is compact and does not need high current pulses (as in the Thomson coil designs), is clean, compact, and can be automatically reset (as compared to the propellant based systems), and is expected to be simpler and much faster than the coupled electromechanical and hydraulic systems.

Within the center, another FMS was also developed at NCSU under a sponsored project. It uses Thomson coil actuator mechanism and has achieved about 1 ms speed.

---

[1] J. Hafner, B. Jacobson, "Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids", Paris, France, 2011, pp.1-2.

7. Expected Milestones and Deliverables

- Integration of the MB, AB with FSU developed FMS
- Testing of the Gen-III FID to reach rated voltage and current

8. Plans for Next Three Years

In order to be applicable for a full scale system, the Gen-III FID needs to carry substantially more current. Future developments should focus on that aspect. The AB switch is considered low risk and the MB is the higher risk area. Additional work is needed to demonstrate much high current interruption capability so that large operational margin exists for our application.

9. Member Company Benefits

This project has no industrial member participation.

10. Commercialization Impact or Course Implementation Information

N/A

11. Publications

[1] X. SONG; A. Huang; M. C. Lee; C. Peng, "Theoretical and Experimental Study of 22-kV SiC Emitter Turn-off (ETO) Thyristor," in IEEE Transactions on Power Electronics, vol.PP, no.99, pp.1-1, doi: 10.1109/TPEL.2016.2616841
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7589044&isnumber=4359240
[2] X. SONG; C. Peng; A. Huang, "A Medium Voltage Hybrid DC Circuit Breaker—Part I: Solid State Main Breaker Based on 15 kV SiC Emitter Turn-off (ETO) Thyristor," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol.PP, no.99, pp.1-1
[3] C. Peng; X. Song; A. Q. Huang; I. Husain "A Medium Voltage Hybrid DC Circuit Breaker, Part II: Ultra-fast Mechanical Switch" Journal of Emerging and Selected Topics in Power Electronics
[4] C. Peng, I. Husain, A. Q. Huang, B. Lequesne and R. Briggs, "A Fast Mechanical Switch for Medium-Voltage Hybrid DC and AC Circuit Breakers," in IEEE Transactions on Industry Applications, vol. 52, no. 4, pp. 2911-2918, July-Aug. 2016.
[5] C. Peng, A. Huang, I. Husain, B. Lequesne and R. Briggs, "Drive circuits for ultra-fast and reliable actuation of Thomson coil actuators used in hybrid AC and DC circuit breakers," 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, 2016, pp. 2927-2934.