Solid-state Circuit Breakers For Medium Voltage DC Power

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Diversified Technologies, Inc.

About DTI

- Manufacturer & marketer of very high voltage solid-state pulse modulators, power supplies, & power converters
- Core technology allows high frequency switching at high power
- PowerMod™ technology comprised of an extensive patent portfolio developed over more than 20 years
- Company serves international commercial & defense markets in radar, power conversion, high energy physics, and compact high power switching
- ~$14M revenue, ~75 employees, 10 PhDs

Two-Time R&D 100 Award Winner

Overview

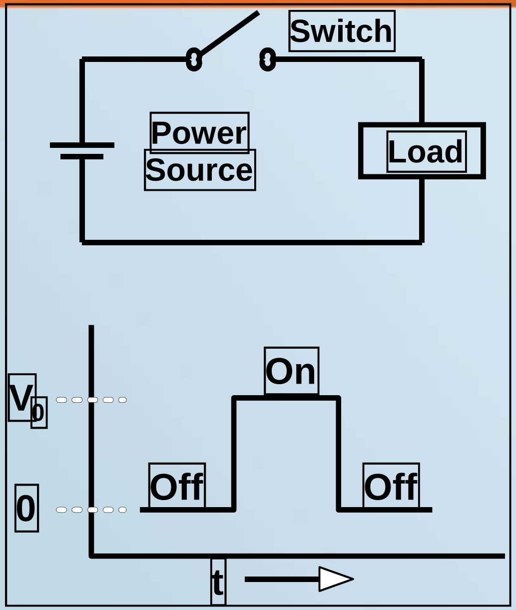
- Circuit Breakers are Required to Disconnect a Power Source from the Load in the Event of a Fault
  - Prevent Damage to the Load
  - Minimize Impact on Overall Power System
  - Limit Interruptions to Other Users / Loads
- Existing HV Breakers are Primarily Mechanical
  - Require Zero-Crossing on Each AC Phase
  - Slow to React
  - Complex Re-Powering Schemes
- DC Systems Pose Novel Challenges
  - No Zero-Crossing
  - Currents Rise Linearly with Time

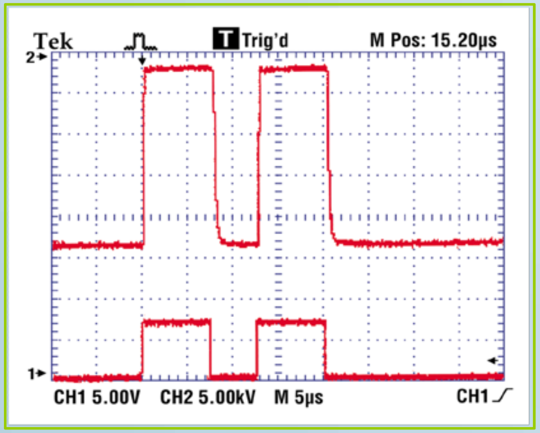
Motivation

- Strong Desire to Move to DC Power Systems
  - Renewable / Distributed Energy
  - Long Distance Transmission
  - Server Farms / Computing Infrastructure
  - Navy All-Electric Ship
- Reliable Breakers Needed to Enable These Applications
- Existing AC Breakers Can't Transition to DC
  - Speed
  - Recovery
  - Isolation

Solid State Switching

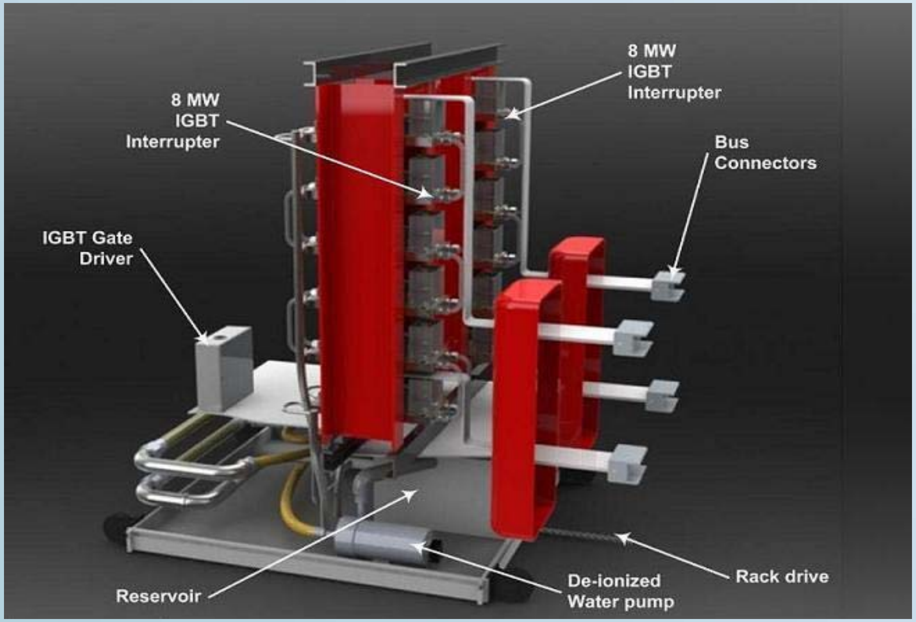
- Series String of Transistors
  - All Operate Synchronously
  - DTI Patented Design
- Very High Voltage and Current Demonstrated
  - Up to 200 kV (200,000 Volts)
  - Up to 5 kA (5000 Amperes)
- Extremely Uniform & Reliable Pulses
  - Sub-Microsecond Switching
  - Arbitrary Pulsewidth & Frequency
  - 50 nS – CW; > 100 kHZ Continuous





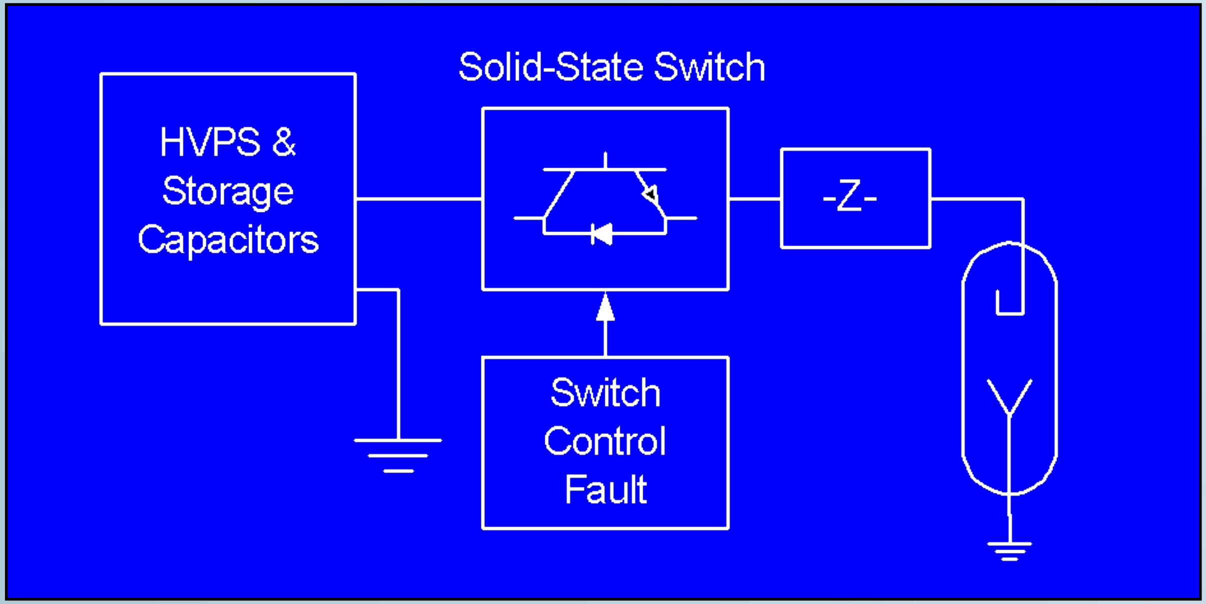
Solution - Series IGBT/IGCT Switch

- Directly Switch High Voltage / High Power
  - Open and Close
  - Fast (µs's)
  - Controllable
- AC Breakers Provide System Level Model
  - Timing and Coordination
  - Mechanical Design



15 kV, 500 A Solid State DC Breaker

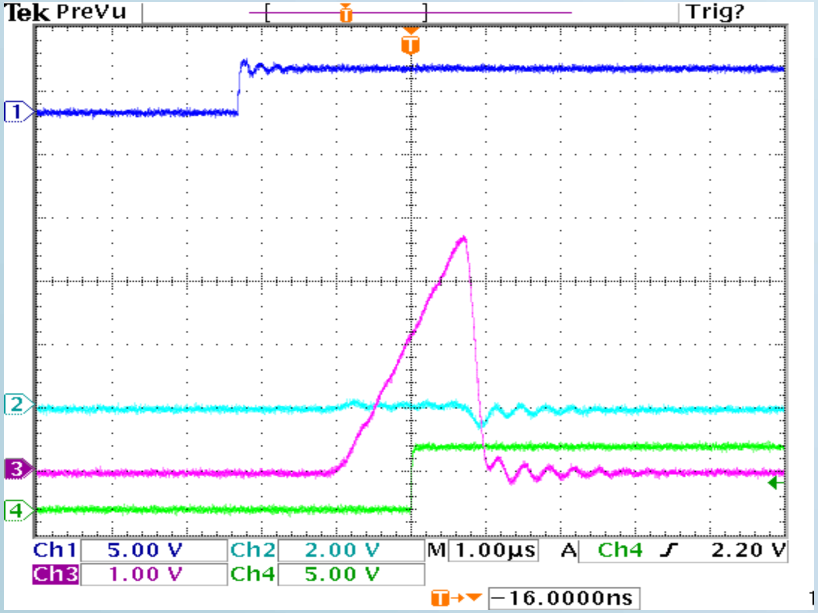
VED Cathode Protection



- Series Switch Provides Arc Protection
  - Large Storage Capacitors OK
  - Pulse Energy Storage
  - Caps Not Discharged During Arc
  - Power Supplies Remain in Regulation
  - Immediate Return to Transmit After Arc
- Same Switch Can Operate as Cathode Modulator

Speed Is Key

- IGBTs / IGCTs Are Proven in HV Applications
- Crowbar Replacements are DC Breaker Prototypes
  - Fast Opening
  - Minimal Impact on Upstream Electronics
  - Controllable Re-Closing after Fault Clears
- Fast Opening Limits Fault Currents (dI/dt = V/L)



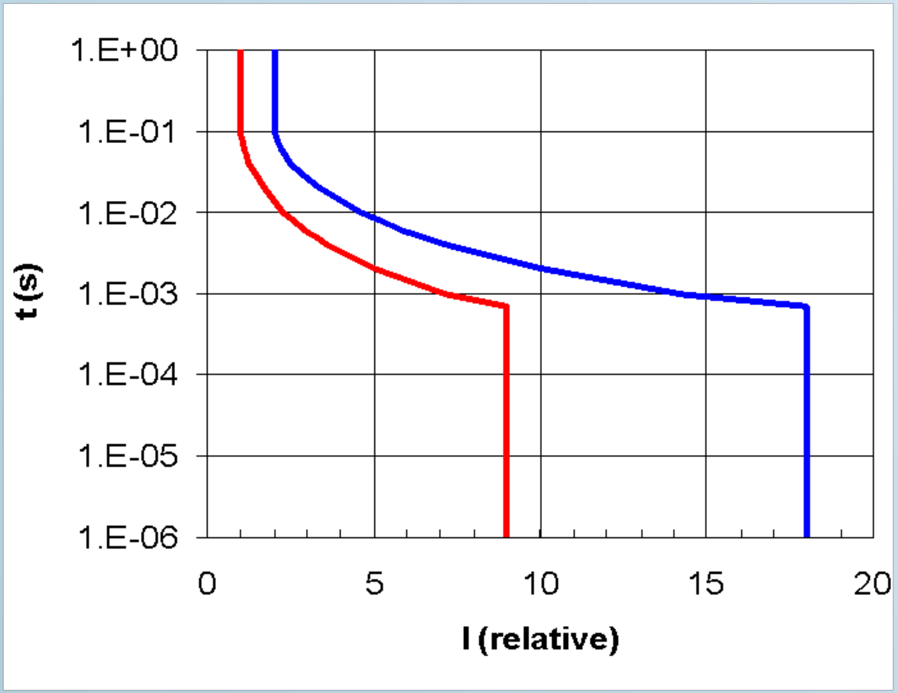
Series Cathode Switch Operation in a Radar System

Efficiency Considerations

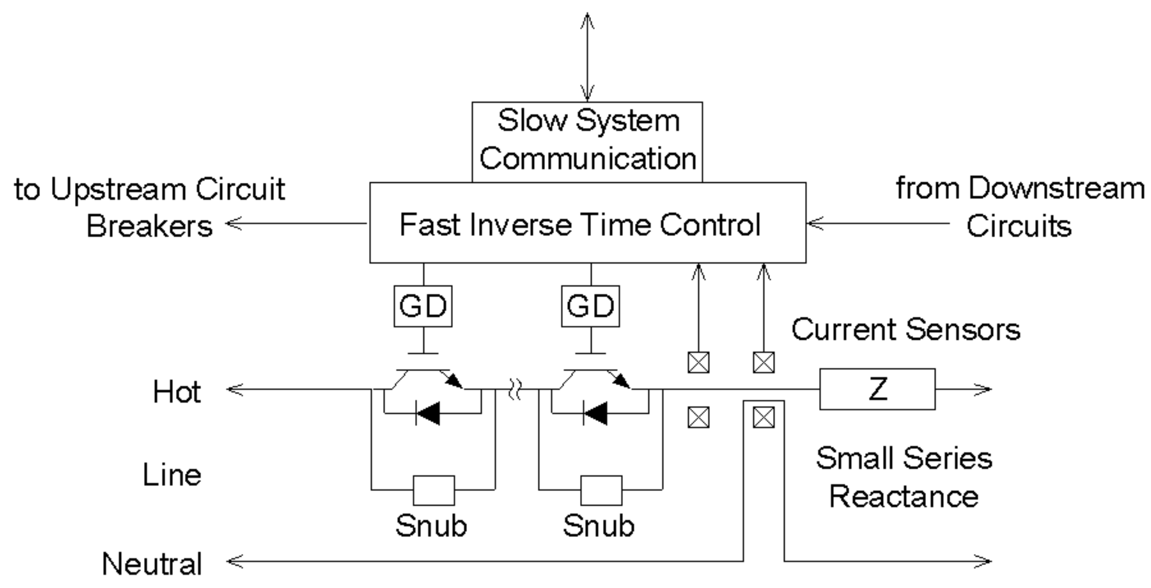
- Semiconductors Have Voltage Drops
  - IGBTs - ~ 2 V / kV Switched (0.2%)
  - 16 kW at 8 MW
- IGCTs Have Lower Losses, But Slower
- Hybrid Approach Is Best Compromise
  - IGBTs Downstream for Speed / Lower Power Requirements
  - IGCTs Upstream at Higher Current
  - Breaker Coordination Simplified
- SiC Would Be Ideal When Available

Breaker Coordination

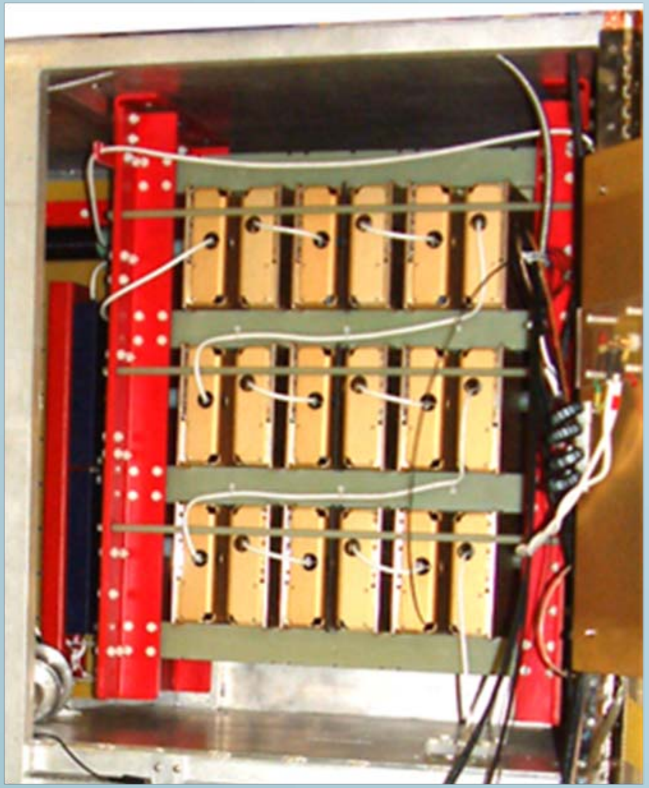
- Coordination Well Understood for AC Power
  - Downstream (Near Load) Breakers Open Fastest, at Lowest Current
  - Upstream Breaker Operation Delayed in Time and Current
- Same Rules Apply to DC Breakers
- No Zero-crossing



DC Breaker Control



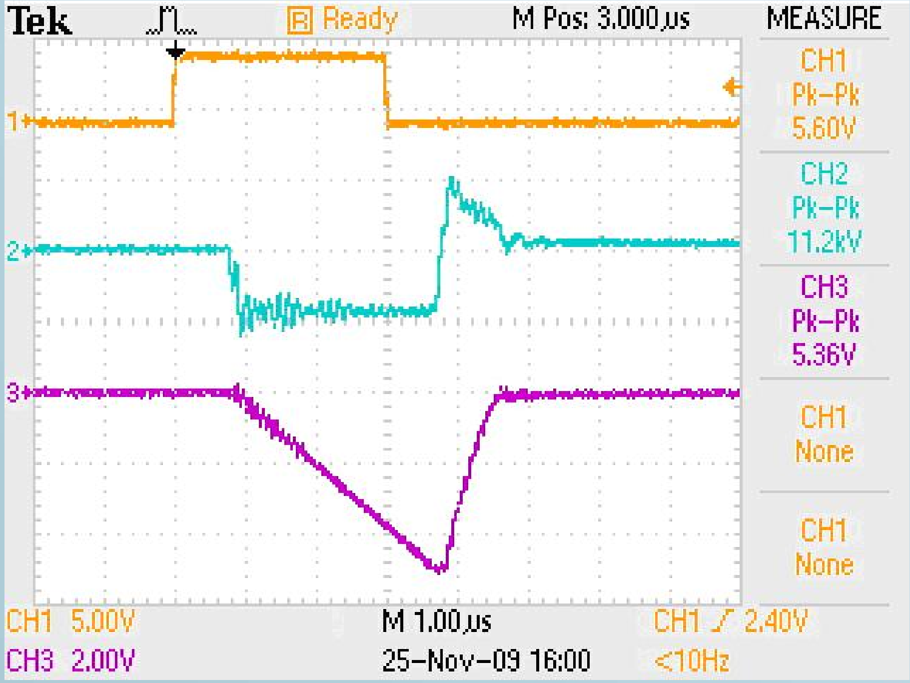
Switch Design



Radar Cathode Opening Switch
50 kV, 20 A (1 MW Average)
Air Cooled

Breaker Switch
16 kV, 500 A (8 MW Average)
Water Cooled

Demonstration (x 1000 Reps)



10 kV Into Near Short (23 nH)
CH1 – Control
CH2 – Load Voltage (10 kV)
CH3 – Load Current (1 kA Peak)

Other Considerations

- Re-Closing After Fault
  - High Speed of IGBTs Allows Flexibility
  - Short Pulse – Verify Fault Has Cleared
  - PWM – Ramp Voltage to Avoid Surge Currents
- Mechanical Design
  - Self-Contained
  - Integrated Controls, Power, Cooling
  - Safety Mechanical Disconnect (at Zero Current)
- Breakers From 1 – 500+ kVDC Possible With Current Switch Technology
- Future Semiconductors Will Eliminate Need For Water Cooling

Conclusion

- DC Power Systems Will Require DC Breakers
- Mechanical Systems Are Not Feasible
- Semiconductor Breakers Are Possible and Desirable
  - Speed
  - Flexibility
- All Major Functions now Demonstrated
- Efficiency / Cooling Remains a Challenge
- Wide Bandgap Devices (SiC) Approaching Availability

Thank You

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