ARC-SAFE: Accelerated Response Semiconducting Contactors and Surge Attenuation for DC Electrical Systems

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Exceptional service in the national interest
Medium Voltage DC systems lack suitable circuit breaker (CB) technologies – limits system performance and adoption

- Solar and Wind power generation growing rapidly
- Electric ship and rail power management, electric vehicles

- Mechanical CBs are large and respond relatively slowly
- Solid State CBs promise faster response times, smaller form factors
- Current DC CB available for low voltage/power or higher voltage/power applications


https://www.navsea.navy.mil/Home/Team-Ships/PEO-Ships/Electric-Ships-Office/

https://afdc.energy.gov/vehicles/electric_basics_ev.html

Wide bandgap semiconductors (SiC, GaN) enable lower conduction losses & higher power density

Targeting 10 kV/100 A CB performance

Uniqueness of Approach

- Normally “On” leg to use mature SiC devices with novel circuit architecture
- Normally “Off” leg to use optically-triggered GaN PCSS (good isolation)
- Power Dissipation leg to investigate metal oxide varistors, other technologies
Proposed Solid State Circuit Breaker (SSCB) Architecture

- **Architecture includes**
  - Cascaded JFET HV switch topology
  - Normally-On JFETs have low on-resistance and low auxiliary drive loss
  - Normally-Off Photoconductive semi-conducting switch (PCSS) triggers immediately after a fault to shunt current
  - Capacitor for absorbing + dissipating energy from flyback current
  - Control circuit powered from high-side voltage tap

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>Blocking Voltage</td>
<td>10 kVDC</td>
</tr>
<tr>
<td>Rated Power</td>
<td>1 MW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>99.97 %</td>
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<tr>
<td>Response Time</td>
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• Forward-leg performance verified in hardware up to 1 kV
• Novel voltage balancing approach works as expected for both transient and steady-state response

Prototype demonstrated good steady state voltage balancing at 1 kV

Forward Leg Prototype Board

Breaker demonstrates ~ 2 µs switching rise time
10kV Forward Leg Simulations (Circuit Level)

- 10kV Forward Leg to include eight Cascaded JFETs and two parallel legs to reduce device overstressing
- Simulations show design are scalable to 10 kV

Simulated 10kV Waveforms
System-Level Simulations for 1.2 kV Breaker

• System-level simulations created to understand circuit breaker design trade-offs. Includes different switching timing schemes, cable length, and fault resistance
• Model includes entire circuit breaker (Normally-on and normally-off leg)
• Individual switch power dissipation and temperature values were computed.
• Additional simulations were done to specify system operation
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• Additional simulations were done to specify system operation
• Cumulate simulations indicate
  • Approx. 1 µF Shunt capacitor desired
  • PCSS delay timing < 2 µsec for Cable length ≤ 1 km
  • PCSS delay timing < 5 nsec for Cable length ≤ 2 km
• These changes will be applied to the 10 kV system in the next iteration
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Cascaded JFET Circuit (normally-on leg)

PCSS (normally-off leg)

Shunt Leg

- Cascaded JFET Circuit (normally-on leg)
- PCSS (normally-off leg)
- Shunt Leg
- Control circuit powered from high-side voltage tap

- Normally-On JFETs have low on-resistance and low auxiliary drive loss
- Normally-Off Photoconductive semi-conducting switch (PCSS) triggers immediately after a fault to shunt current
- Capacitor for absorbing + dissipating energy from flyback current
- Control circuit powered from high-side voltage tap
- Small laser energy (~30µJ, 6ns, gap overfilled) triggers PCSS into “on” state, well below breakdown field
- Highly repeatable on state persists well after laser pulse duration (high gain mechanism)
- Future path for vertical GaN PCSS to increase voltage/current performance
Vertical GaAs PCSS – Paralleled Current Filaments

- Measurement, done with low impedance underdamped circuit
- Underdamped circuit- remaining voltage not a good indicator of lock-on voltage (but must be relatively low)
- Preparing measurement using 1 kΩ load (overdamped) to perform accurate lock-on voltage measurement

GaAs vertical PCSS switching characteristics

2-D array of current-sharing filaments