NAVAL POSTGRADUATE SCHOOL

NASA Fast Light-weight Altitude-ready Solid-state Circuit Breaker for Hybrid Electric Propulsion

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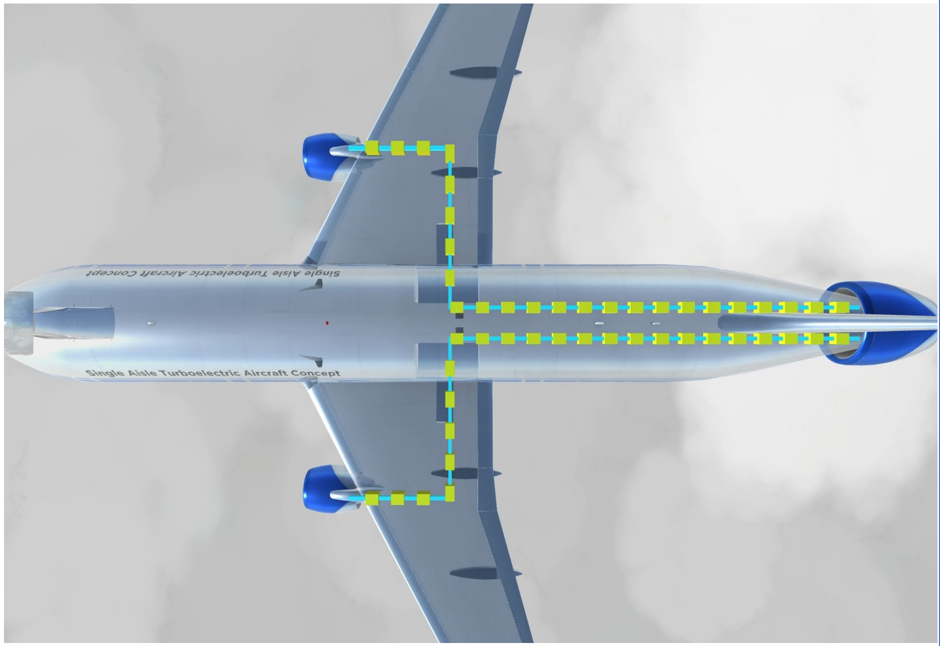
Outline

- Introduction
- Technical Solution
- Prototype Design and Test Results
- Summary

Hybrid Electric Propulsion

NASA STARC-ABL Configuration
(The Single-aisle Turboelectric Aircraft with an Aft Boundary-Layer propulsor)



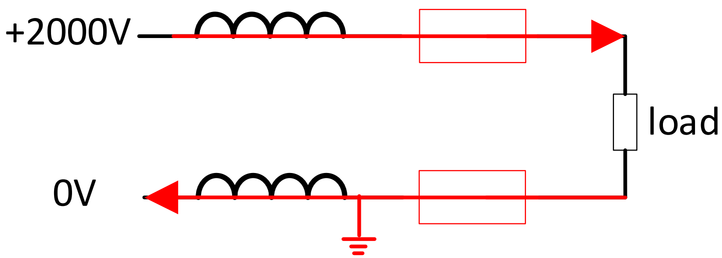
- **Reduce carbon emissions and increase aircraft functionality.**
- **MVDC is necessary to reduce power system weight.**
- **The megawatt medium-voltage light-weight high-efficiency solid state circuit breaker is the key enabler.**

Key Specifications

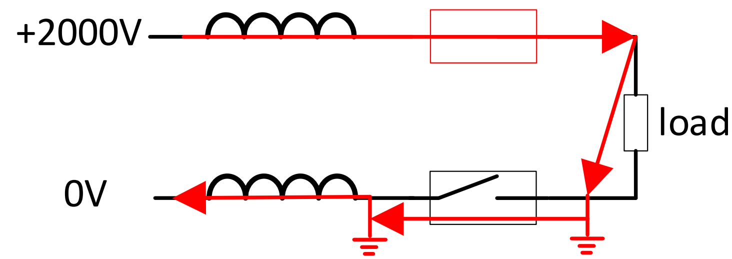
Specifications	**Target**
System inductance	0 to 50µH
Voltage direction	Bipolar
Current direction	Two-way
Galvanic Isolation Requirement	No
PD free (10pC)	**>35kft**
Rated Voltage	**~2000 V**
Rated Current	**1000 to 1200 A**
Efficiency	**~99.5%**
Power Density/Weight	**>100kW/kg or <24kg/53lb**
Protection Speed	10 to 500us
Inlet temperature	40 °C

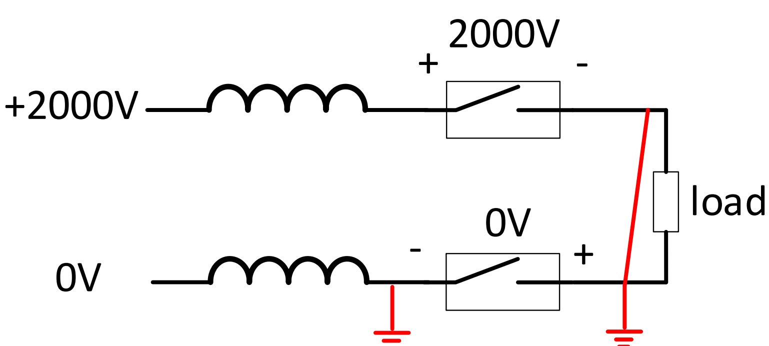
SSCBs Installed in Both DC Buses

The system must continue operating with single point ground fault



A second ground fault can bypass one SSCB





- Each SSCB must be able to clear the fault by itself and block +/-2kV.
- Worst case for design

- The total weight of two SSCBs is <24kg and the total loss is <0.5%.

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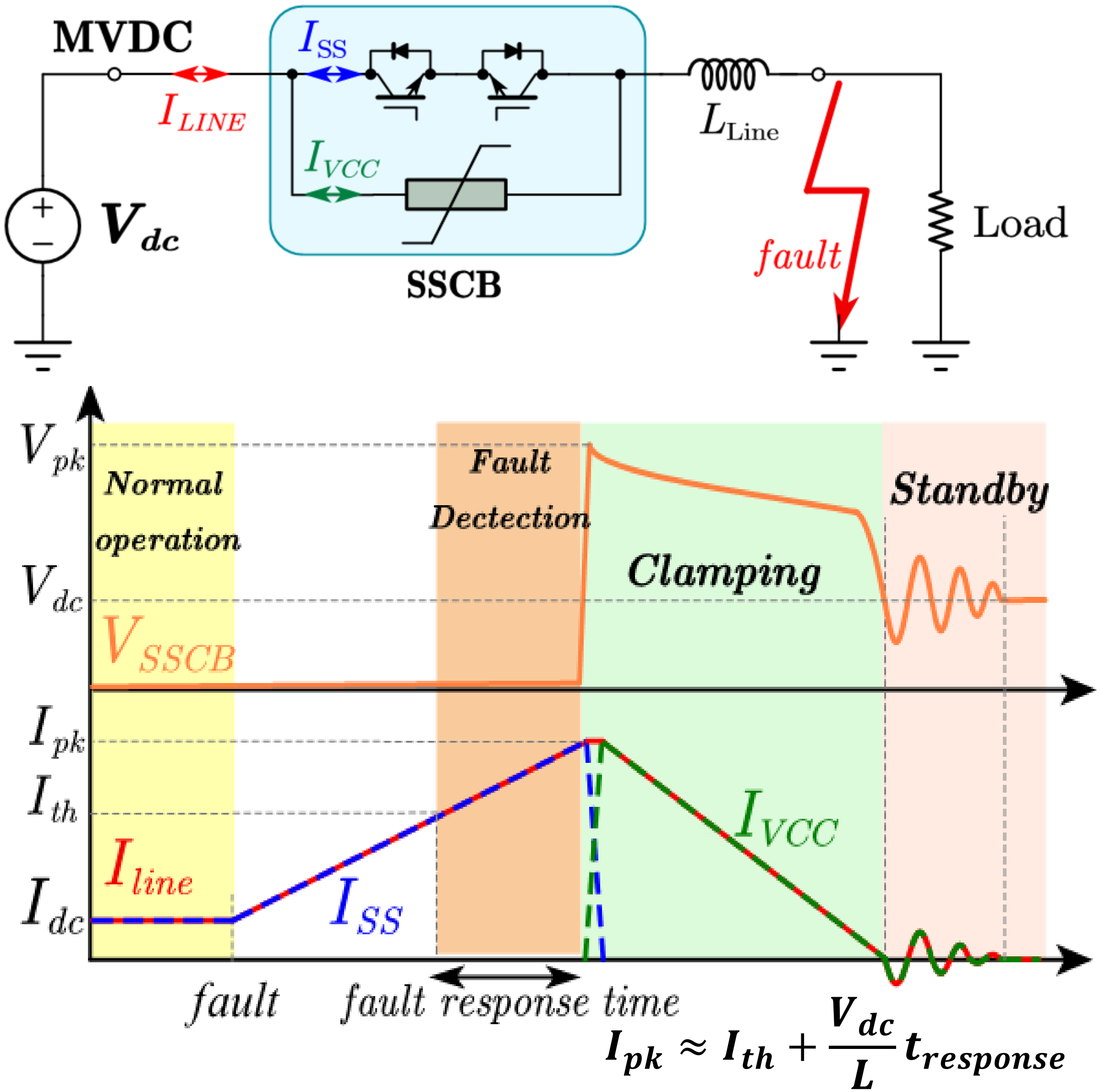
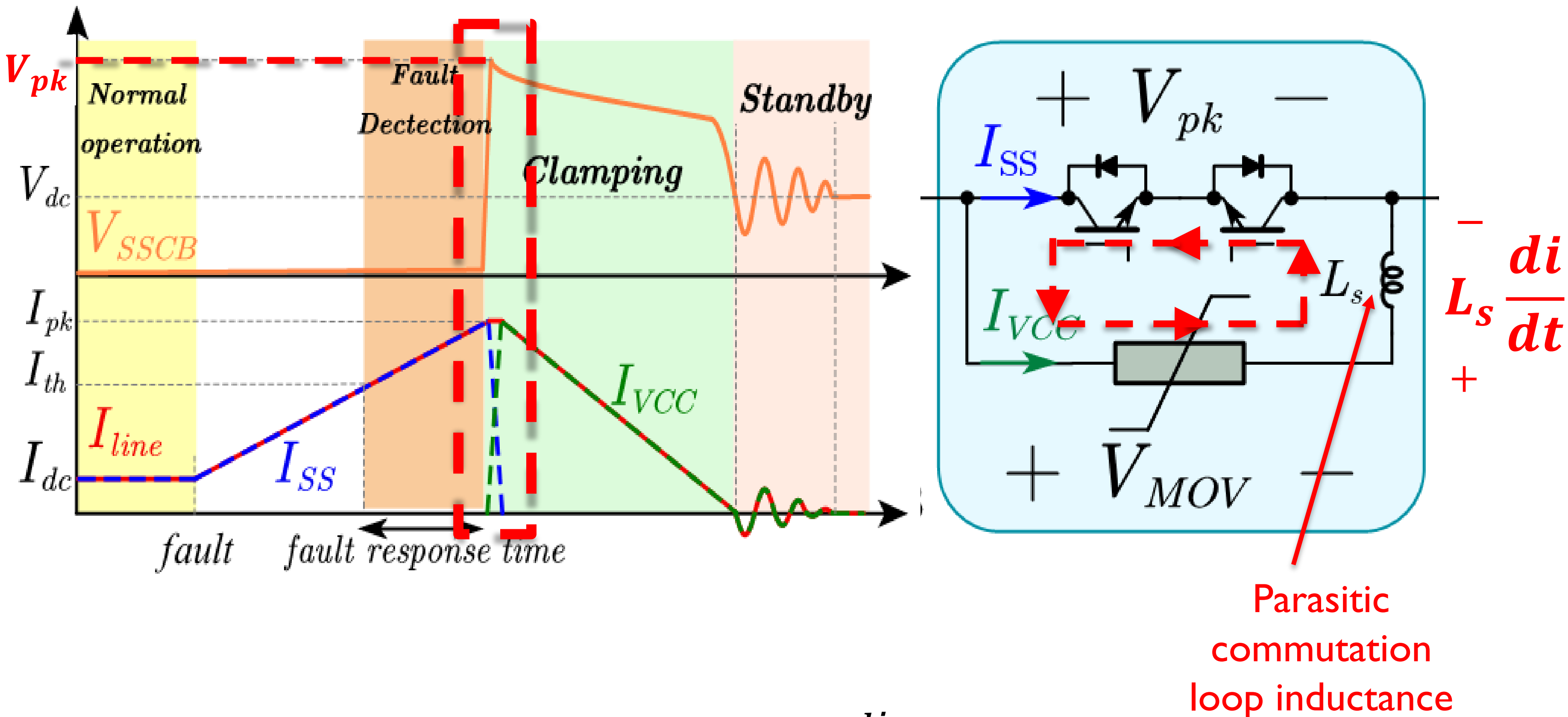
Operation Principle of Classic SSCB



- Semiconductor devices carry load current in normal mode.
- After fault is detected, semiconductor devices are turned off after response time delay, commutating system current to MOV.
- MOV's clamping voltage is higher than dc voltage, reducing the system current to zero.
- MOV can absorb the energy stored in the system line inductance.
- Both MOV and semiconductor devices withstand system dc voltage in off mode.

Key Design Constraint



$$V_{pk} \approx V_{MOV@I_{pk}} + L_s \frac{di}{dt} < V_{CE\_max}$$

SSCB peak voltage must be lower than the semiconductor device voltage rating.

Design Constraint (Cont'd)

MOV Energy Absorption Limit

- MOV has limited capability to absorb energy.

$$E_{MOV} \approx \frac{1}{2} L_{Line} {I_{pk}}^2 \frac{V_{MOV@I_{pk}}}{V_{MOV@I_{pk}} - V_{dc}} < E_{MOV\_max}$$

- For this design, since the system inductance is less than 50μH, if the peak current is limited to ~4kA, the MOV energy is **300J** each for two poles or **1400J** for single pole. This can be met easily with single COTS MOV (**>3kJ**).

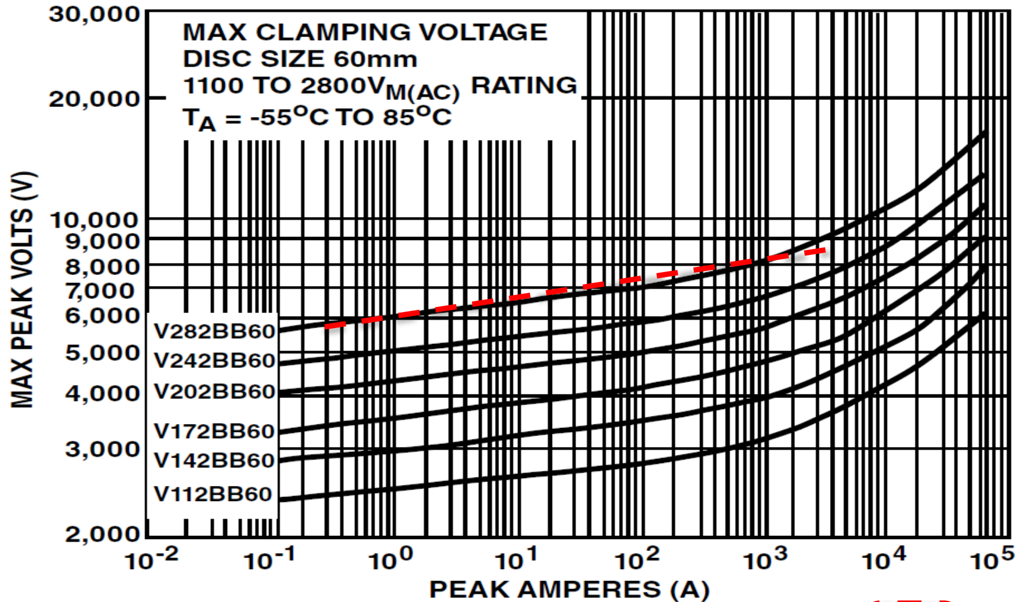
MOV Heat Dissipation Limit

- MOV has very limited heat dissipation capability (e.g.<1W). Thus, at the continuous block voltage, the leakage current is only ~0.1mA.
- In the SSCB, the MOV's continuous block voltage rating must be higher than the system dc link voltage.

$$V_{dc} < V_{MOV\_Continous}$$

MOV Characteristics

V172BB60
500g each



Similar to ohm's law

$$R_\alpha = \frac{log(V_2) - log(V_1)}{log(I_2) - log(I_1)}$$

* Limited by heat dissipation capability.

$$\boldsymbol{log}\left(\boldsymbol{V_{MOV@I_{pk}}}\right) = \boldsymbol{log}(\boldsymbol{V_{dc}}) + R_\alpha\left(\boldsymbol{log}\boxed{\left(\boldsymbol{I_{pk}}\right)} - \boldsymbol{log}\boxed{\left(\boldsymbol{I_{@V_{dc}}}\right)}\right)$$

A few kAs ~0.1mA

For example, V172BB60 can continuously block **2150V** dc, but its peak voltage is **5000V** when carrying 2000A.

The MOV clamping voltage at peak current is much higher than the dc bus voltage.

Motivation to Reduce Peak Voltage

- Lower peak voltage means semiconductor devices' voltage rating can be lower, which can substantially increase the efficiency and power density of the solid-state circuit breaker.

Based on the same IGBT3-E3 technology from Infineon and with the same mechanical dimension (190mmX140mm)

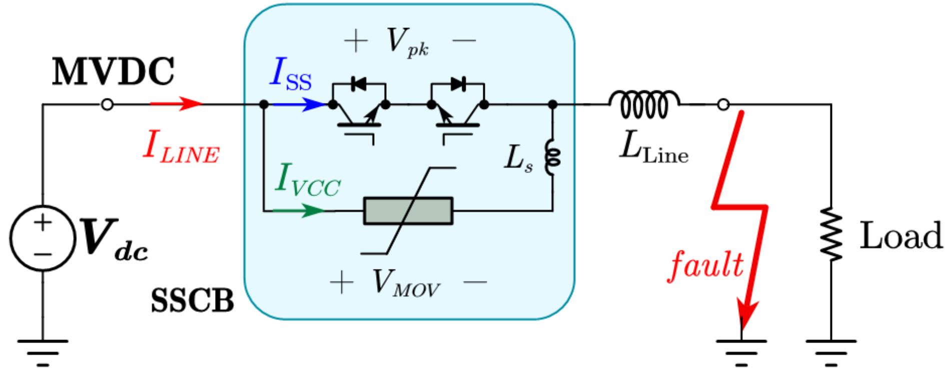
Model Number	Rated Voltage	Rated Current	Loss at 1kA
FZ1500R33HL3	3.3kV	1500A	2.5kW (100%)
FZ1200R45KL3	4.5kV	1200A	2.9kW (116%)
FZ750R65KE3	6.5kV	750A	4.2kW (168%)

- There are more choices from different vendors for lower voltage rating devices.

- Lower peak voltage also means easier insulation design.

Methods to Reduce Peak Voltage (1)

$$V_{pk} \approx V_{MOV@I_{pk}} + \boxed{L_s \frac{di}{dt}}$$



Reduce commutation loop inductance	→ Super compact mechanical layout	→ Insulation design challenges at high altitude Weight Penalty
Reduce device switching speed	→ IGBT with large turn-off resistor is preferred	→ Pay attention to device loss in transient

- Reduce peak current can also help

Methods to Reduce Peak Voltage (2)

$$V_{pk} \approx \boxed{V_{MOV@I_{pk}}} + L_s \frac{di}{dt}$$

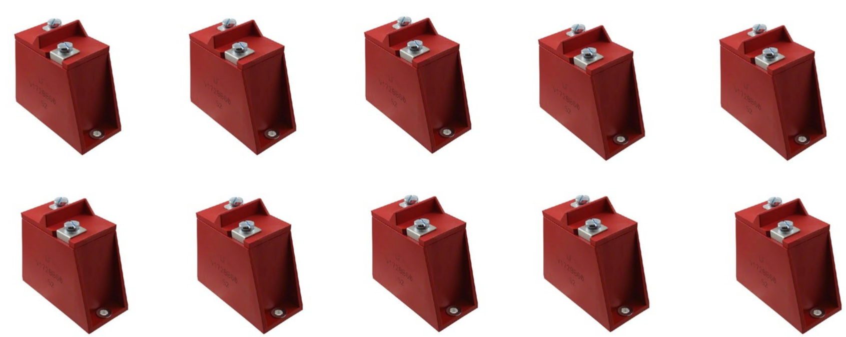
$$\boldsymbol{log}\left(\boldsymbol{V_{MOV@I_{pk}}}\right) = \boldsymbol{log}(\boldsymbol{V_{dc}}) + R_\alpha \left(\boxed{\boldsymbol{log}(\boldsymbol{I_{pk}})} - \boldsymbol{log}(\boldsymbol{I_{@V_{dc}}})\right)$$

Reduce peak current in each MOV → Parallel multiple MOVs → Heavy, bulky, complex

One V172BB60 is 500g

5000V @ 2000A

Ten V172BB60 is 5kg



4300V @ 200A each

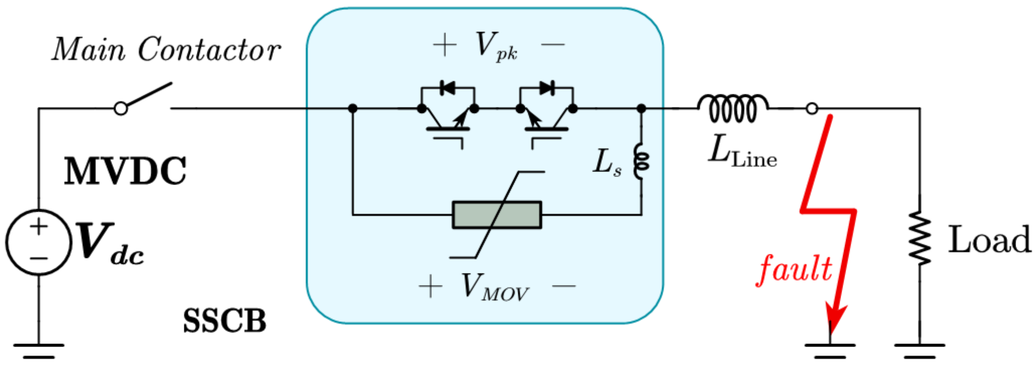
- Reduce peak current can also help

Methods to Reduce Peak Voltage (3)

Additional switch can help to cut MOV leakage current and share MOV voltage in off state.

$$V_{pk} = \boxed{V_{MOV@I_{pk}}} + L_s \frac{di}{dt}$$

$$\boldsymbol{log}\left(\boldsymbol{V_{MOV@I_{pk}}}\right) = \boldsymbol{log}(\boldsymbol{V_{dc}}) + R_\alpha \left(\boldsymbol{log}(\boldsymbol{I_{pk}}) - \boxed{\boldsymbol{log}(\boldsymbol{I_{@V_{dc}}})}\right)$$



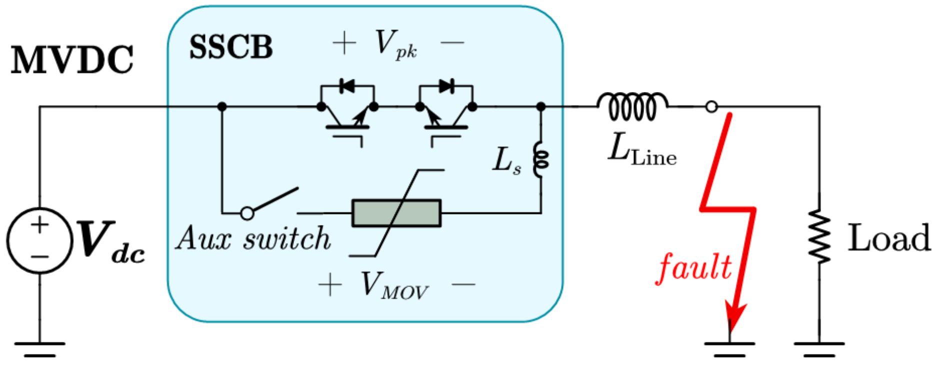
The main contactor can provide galvanic isolation but needs to carry full load current continuously. Too heavy, lossy and not commercially available. Additionally, it requires active control to coordinate with SSCB turn-off action.

Methods to Reduce Peak Voltage (4)

Additional switch can help to cut MOV leakage current and share MOV voltage in off state.

$$V_{pk} = \boxed{V_{MOV@I_{pk}}} + L_s \frac{di}{dt}$$

$$\boldsymbol{log}\left(\boldsymbol{V_{MOV@I_{pk}}}\right) = \boldsymbol{log}(\boldsymbol{V_{dc}}) + R_\alpha \left(\boldsymbol{log}(\boldsymbol{I_{pk}}) - \boxed{\boldsymbol{log}(\boldsymbol{I_{@V_{dc}}})}\right)$$



The auxiliary switch only needs

- to carry MOV surge current with no cooling requirement.
- to clear MOV leakage current at Vdc (<1A).
- to turn on and off based on the SSCB switching actions.

Methods to Limit Fault Current

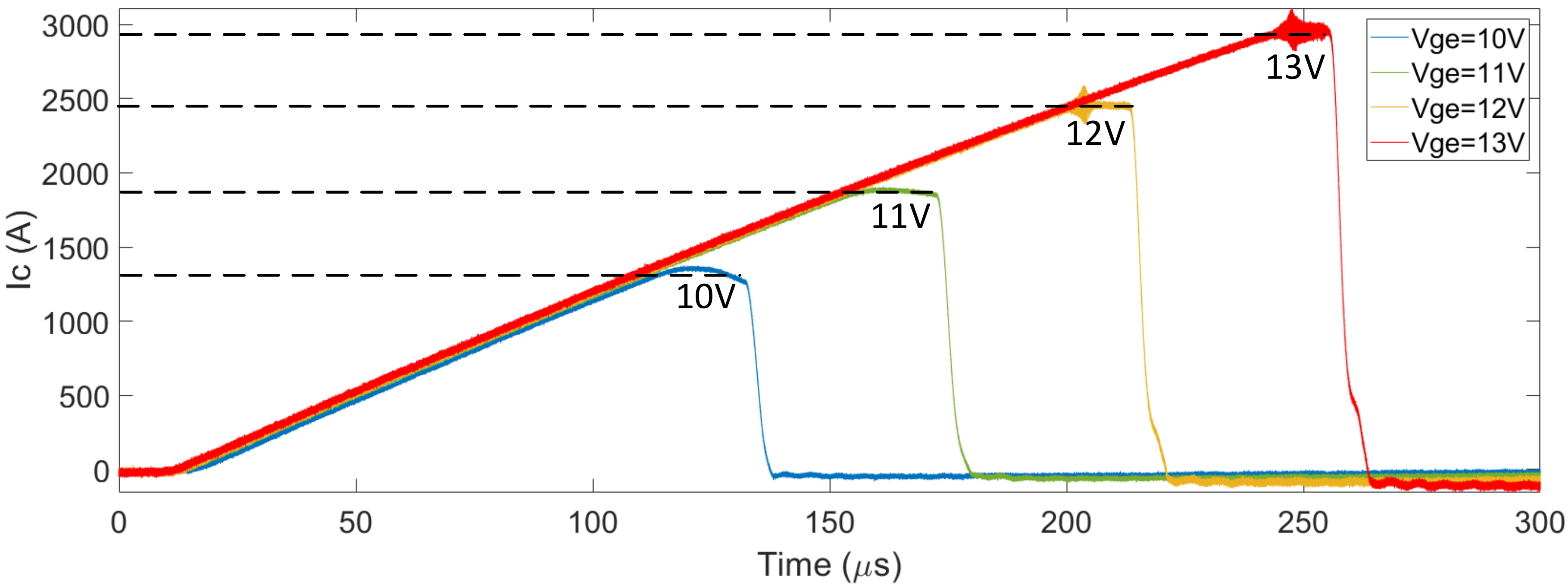
$$I_{pk} \approx I_{th} + \frac{V_{dc}}{L} t_{response}$$

Approach	Method	Drawback
Reduce threshold current (I_{th}) and/or response time ($t_{response}$)	Modify gate drive	Sensitive to system transient and noise.
Increase system inductance	Locate the breaker away from source	Additional safety risk for the power system
	Add additional current limiting inductor	Too heavy and lossy
Leverage IGBT saturation mode	Reduce IGBT gate voltage with gate drive	Very limited efficiency penalty.

IGBT gate voltage is reduced from 15V (typical) to ~12V to limit the peak fault current.

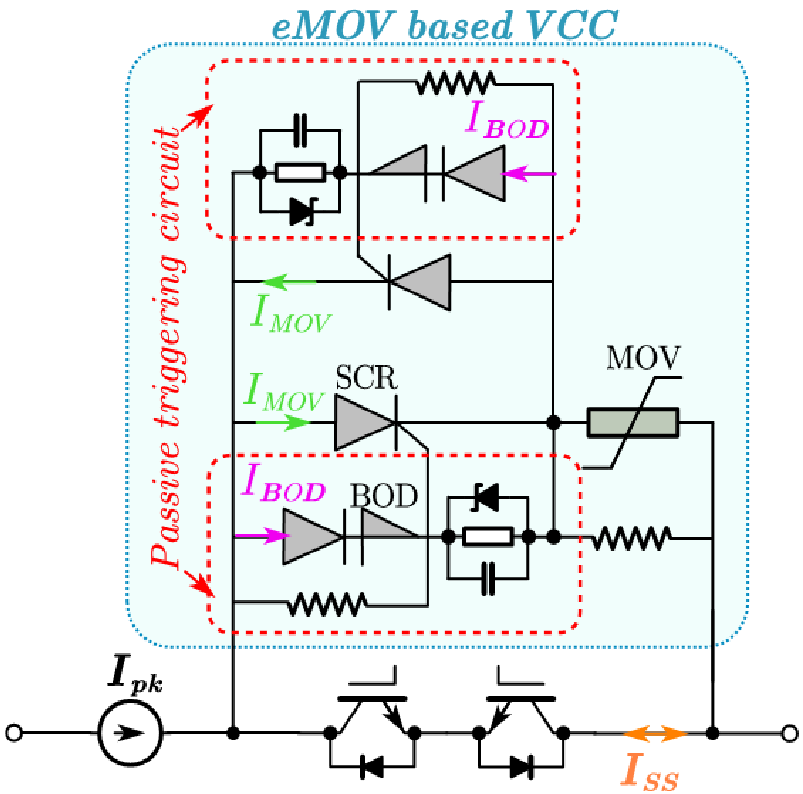
Impact of Gate Voltage on Peak Current

Test results of 3.3kV 1000A IGBT module



Peak current can be limited/controlled with IGBT gate voltage.

Proposed SSCB Topology

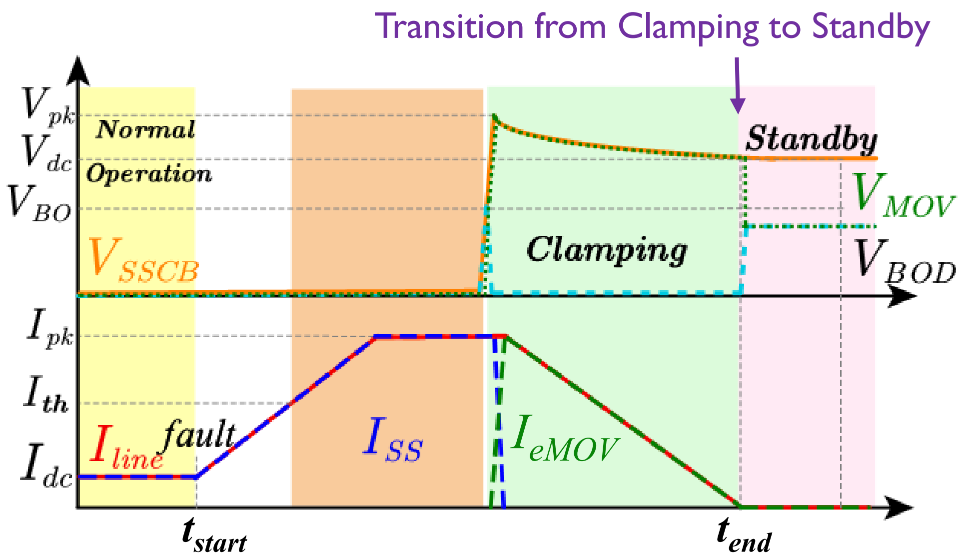


- Aux switch comprised of reliable & mature thyristor based devices without cooling requirement.
- Silicon Controlled Rectifier (SCR)
  - Conducts current (ON state) only when a control current is injected into the "Gate".
  - Can be turned OFF only when the forward current drops below the holding current ($I_{H,SCR}$) rating.
- Breakover diode (BOD)
  - High impedance up to breakover voltage (V_{BO})
  - Breaks over to low impedance state as applied voltage exceeds V_{BO}.
  - Asymmetric device - requires series p-n diode for reverse blocking capability.

- Thyristor with passive triggering circuit can cut MOV leakage current at Vdc and share MOV blocking voltage.
- IGBT can limit peak fault current with reduce gate voltage.

Operation Principle

eMOV Fault Interruption Waveforms



Key Regions

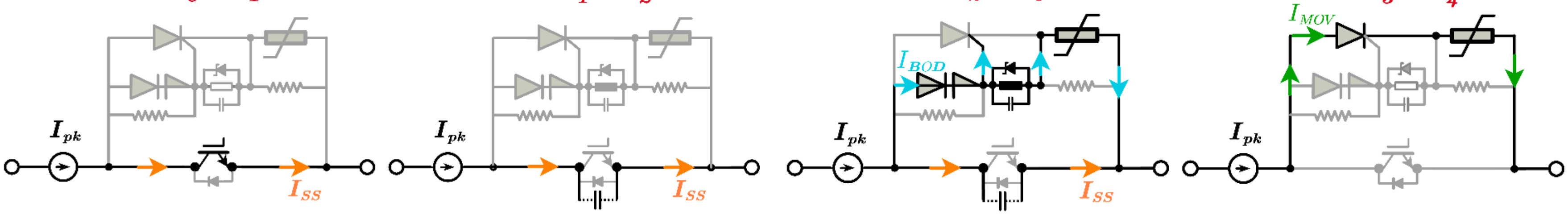
Clamping
↓
Transition
↓
Standby

Three main operating regions:

- Clamping: quickly trigger ON the SCR at the fault interruption (turn-off) transient
  - SCR remains ON until fault current is extinguished and $V_{MOV} = V_{dc}$
- Transition: SCR naturally turns OFF
  - eMOV leakage current at V_{dc} is must be lower than $I_{H,SCR}$
- Standby: system dc voltage is shared by MOV and SCR-BOD pair
  - Allows selection of $V_{MOV,Continuous}$ lower than V_{dc}

Principle of Operation – Clamping

Current Commutation During Fault Transient



0 – t_1: IGBT is ON

$t_1 - t_2$: IGBT in OFF state

- SSCB voltage increases due to the series line inductance
- BOD reaches its breakover voltage V_{BO} at t_2

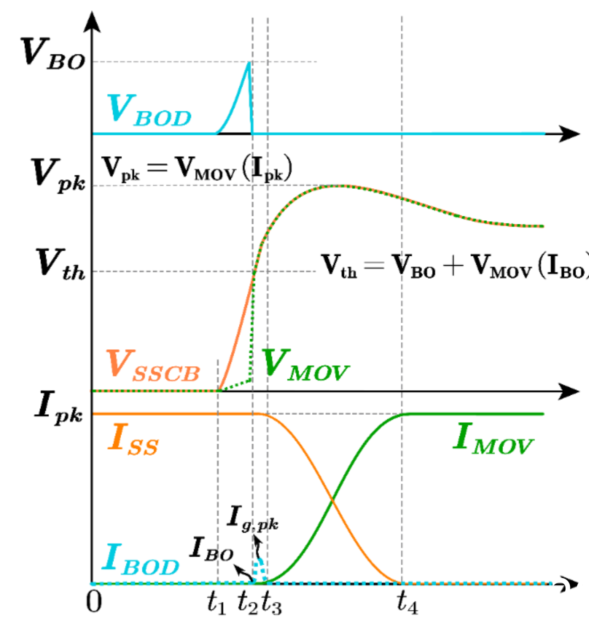
$t_2 - t_3$: The BOD starts to conduct immediately

- BOD provides a peak gate current of $I_{g,pk}$ for SCR turn-on

$t_3 - t_4$: The SCR is in the ON state

- SCR shunts the fault current through the MOV
- The SSCB voltage V_{SSCB} is clamped by the MOV
- $t_4 - t_{end}$: Fault current reduces to zero @ $(V_{MOV}\text{-}V_{dc})/L_{line}$

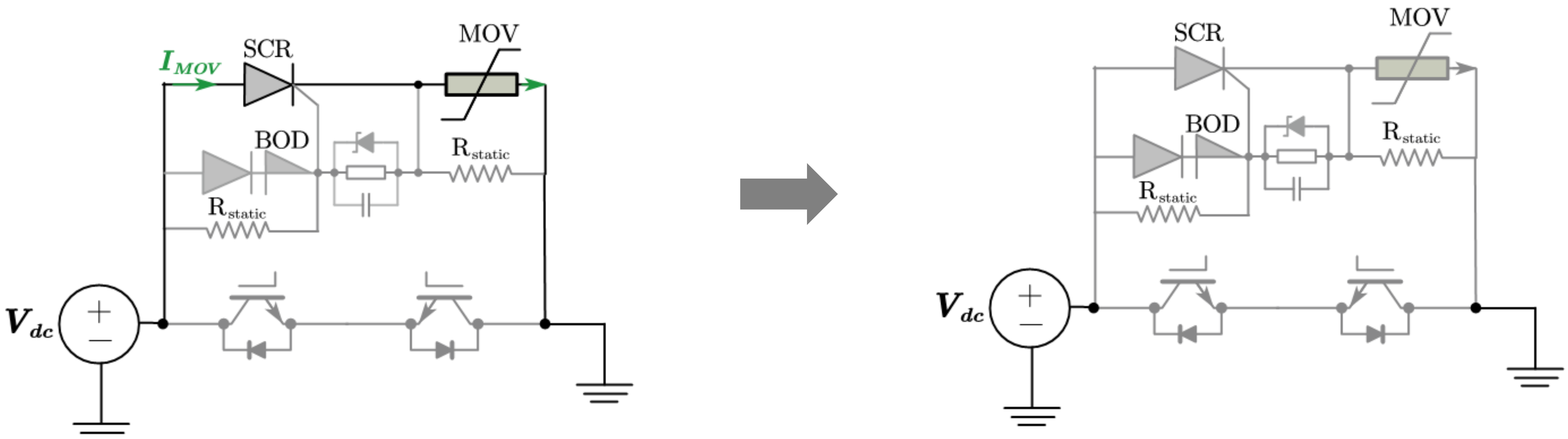
Waveforms



BOD provides a passive triggering mechanism for the SCR turn ON!

Principle of Operation – Transition

eMOV in Transition State (End of Clamping Period)



$I_{MOV} > I_{MOV,lk@V_{dc}}$: **SCR is conducting**

$I_{MOV} = I_{MOV,lk@V_{dc}}$: **SCR turns OFF**

Transition (SCR goes from ON state to OFF state):

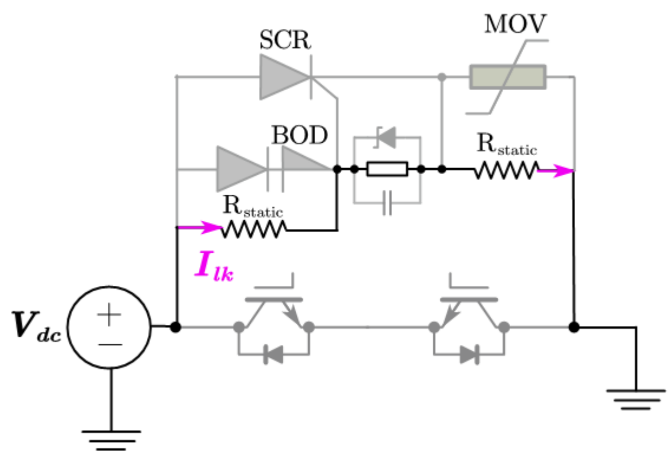
- When fault current approaches zero, the voltage across the SSCB is equal to V_{dc}
- For SCR self turn-off, the MOV selection must ensure that MOV leakage current at V_{dc} ($I_{MOV,lk@V_{dc}}$) is below SCR holding current ($I_{H,SCR}$)

$$I_{MOV,lk@V_{dc}} < I_{H,SCR}$$

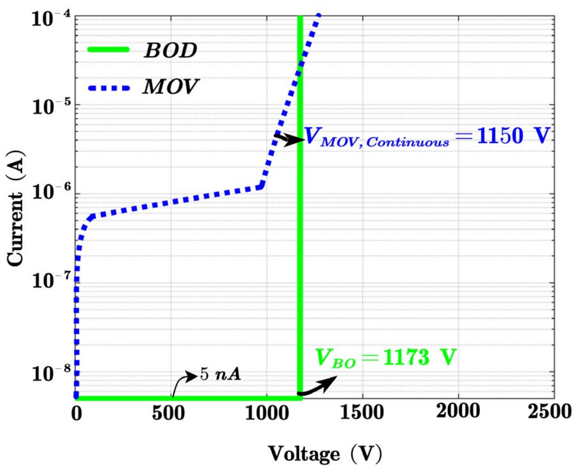
MOV leakage current at V_{dc} must be below SCR holding current for natural turn-off!

Principle of Operation – Standby

eMOV in Standby State



BOD & MOV Static Leakage Currents



Standby operation (SCR in OFF state):

- The BOD & MOV exhibit high disparity in leakage currents (nA *vs.* μA)
- Identical high *M*Ω static balancing resistors (R_{static}) in parallel with MOV and BOD

$$V_{MOV} = V_{BOD} = V_{dc}/2$$

Maximum voltage across MOV in steady state is $V_{dc}/2$

Static balancing resistors => equal voltage sharing in standby state!

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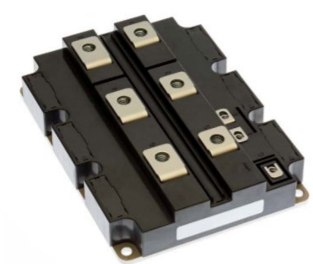
Module Selection

Standard 190mmX140mm single device module

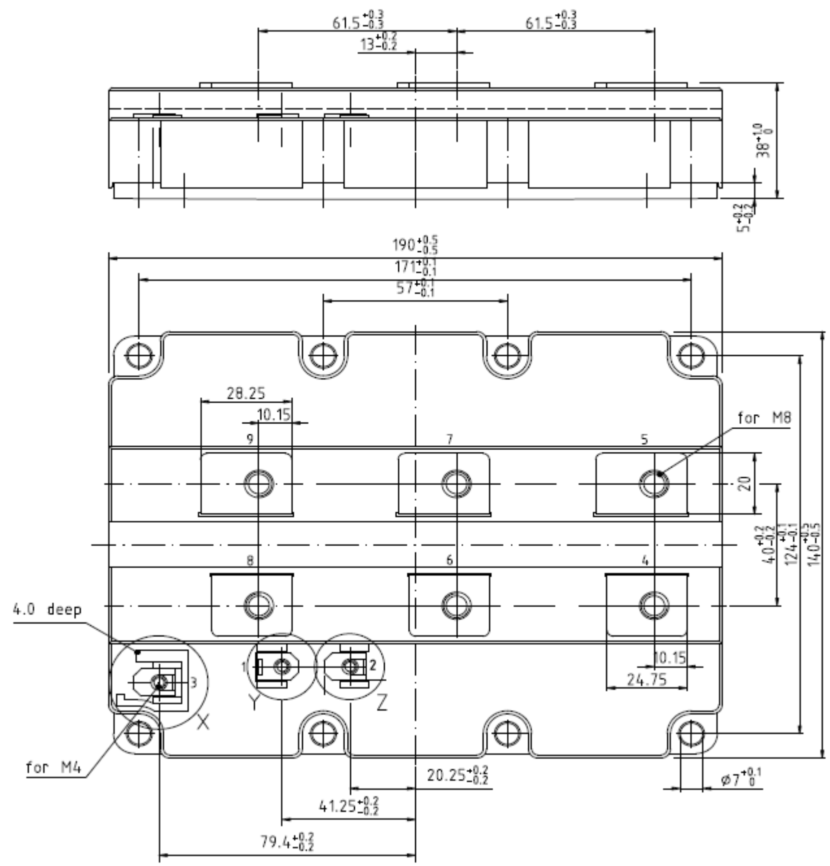
FZ2000R33HE4

FZ1500R33HL3

CM1800HC-66X

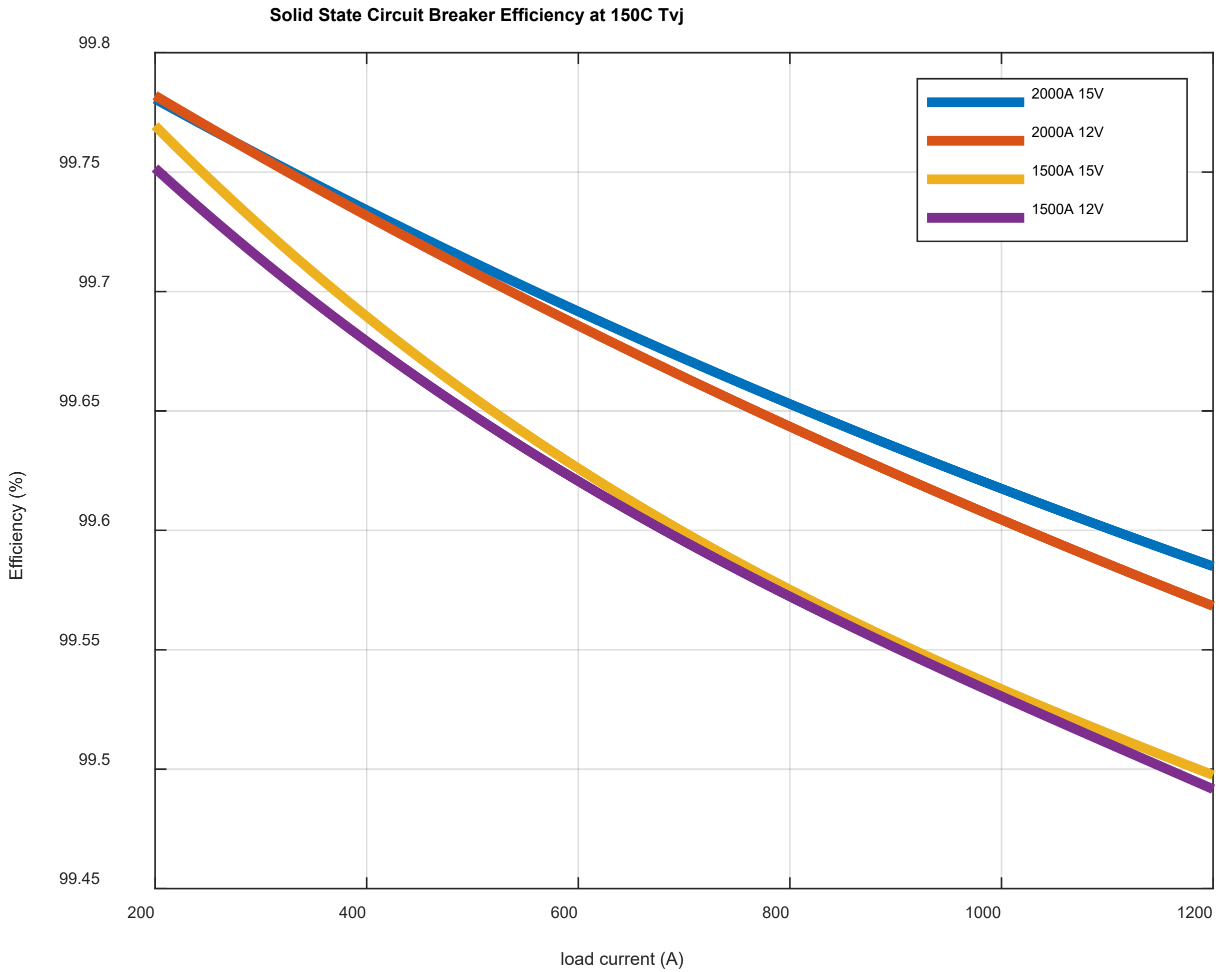


1MBI1500UE



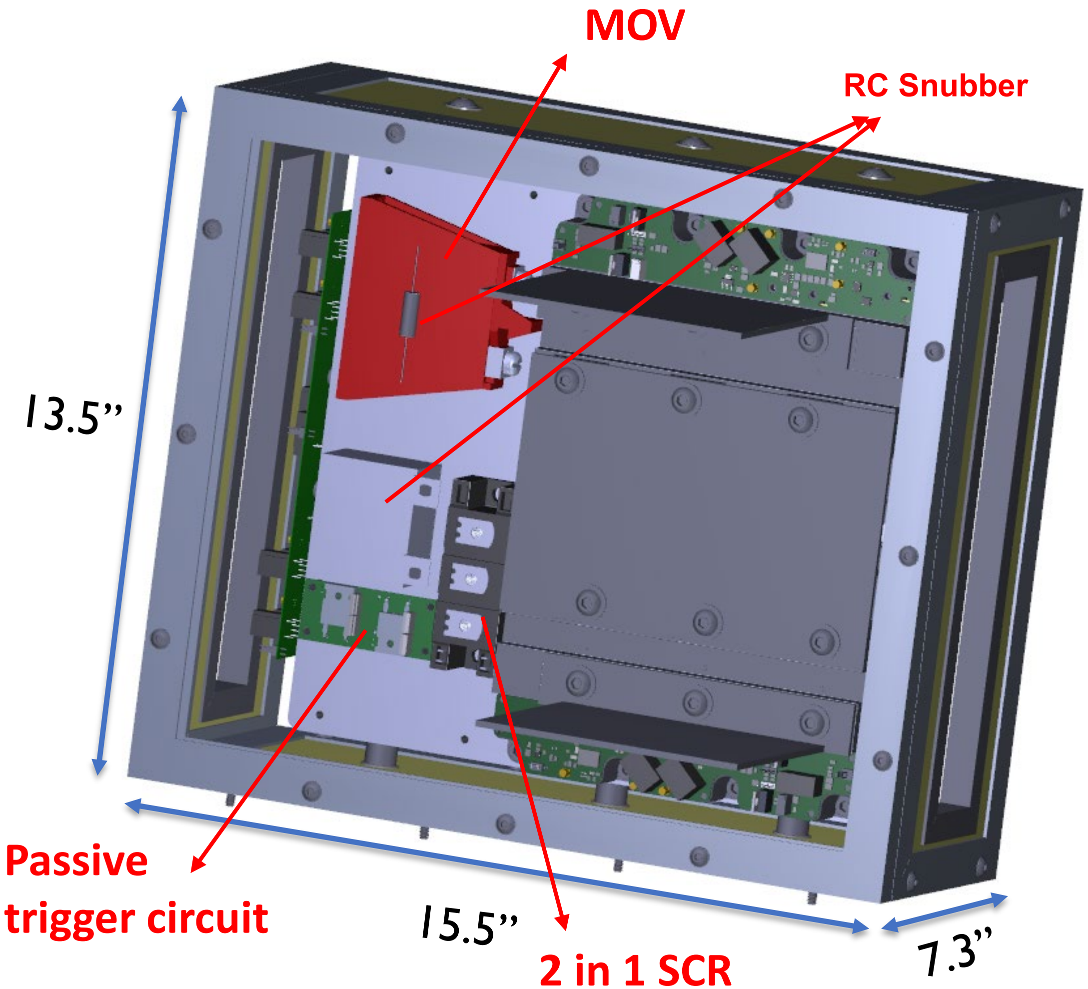
- Commercially available
- No single source
- Interchangeable

Estimated SSCB Efficiency (Two Poles)



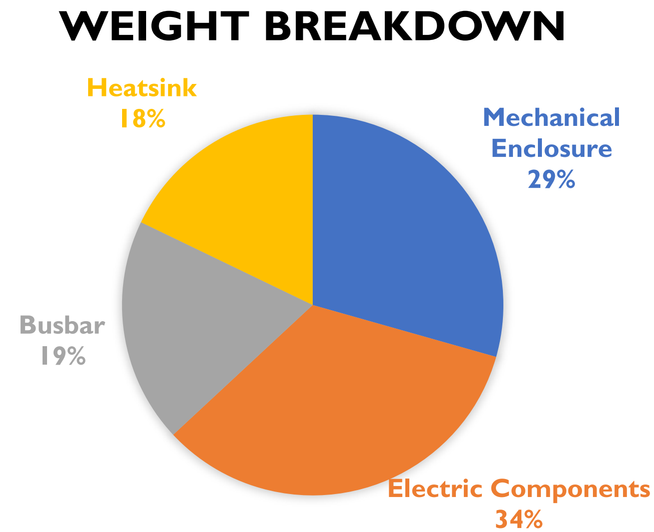
- Reduced gate voltage has marginally impact on efficiency.
- 99.5% efficiency can be achieved.

Mechanical Layout



Total Volume: 0.88 ft^3 or 0.025m^3

- Space taken by the extruded busbar not included.

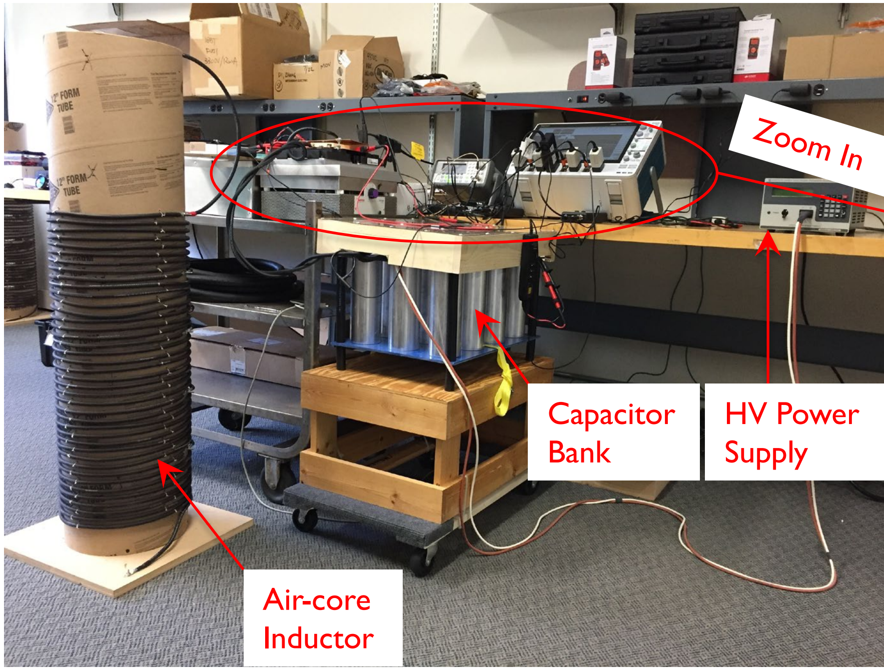


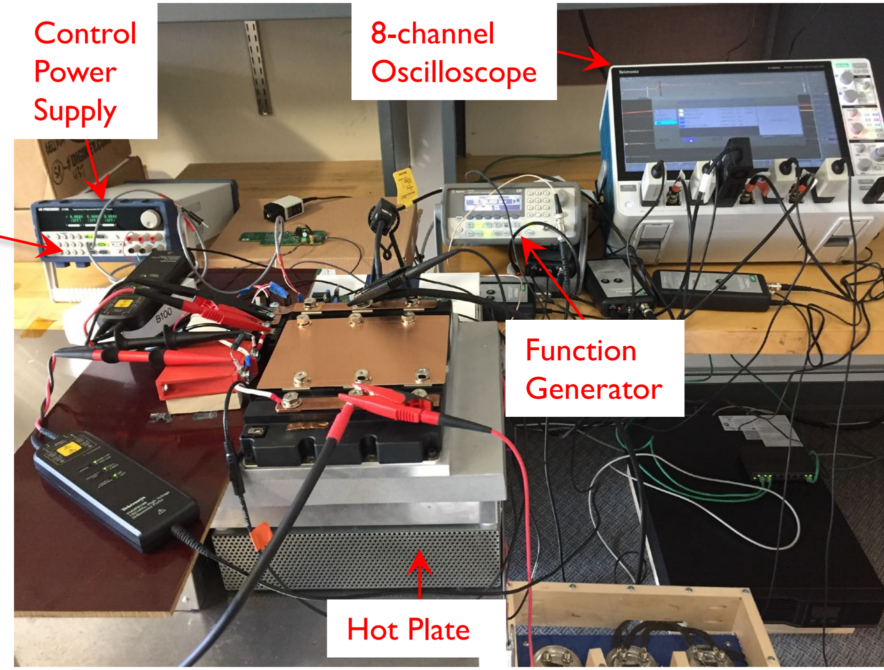
Total Weight: 39.8lb

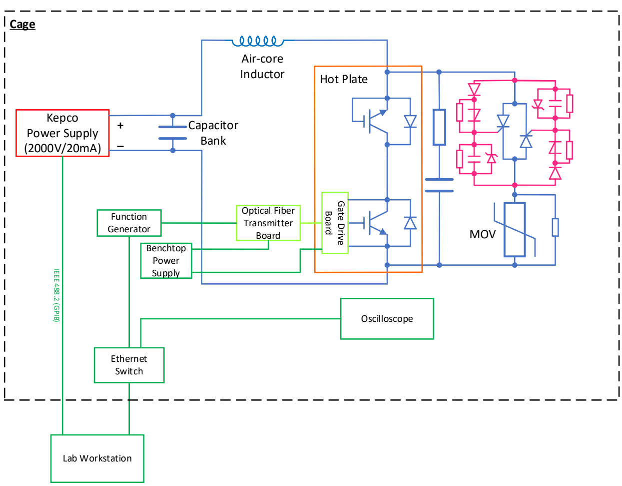
- Additional insulation materials not included.
- Additional mechanical support for the busbars and cable connector not included.

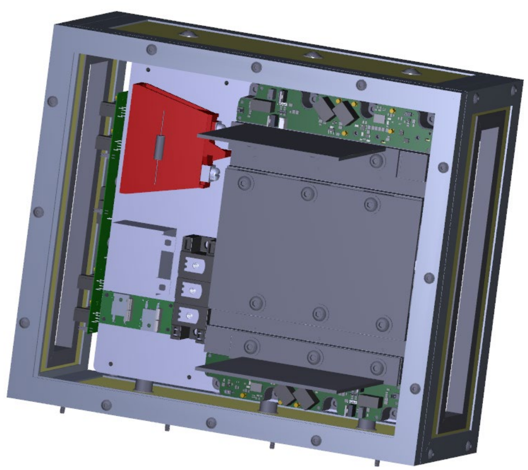
- 96MW/m^3
- 133kW/kg

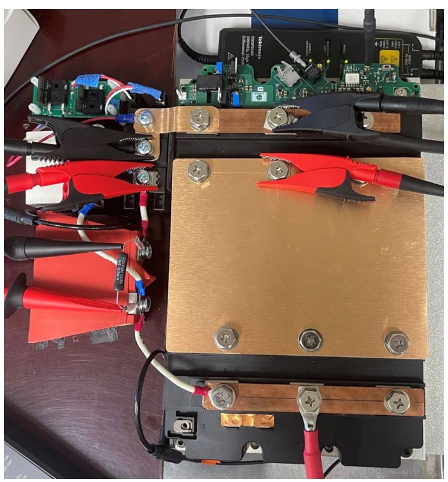
Photo of Switching Test Setup



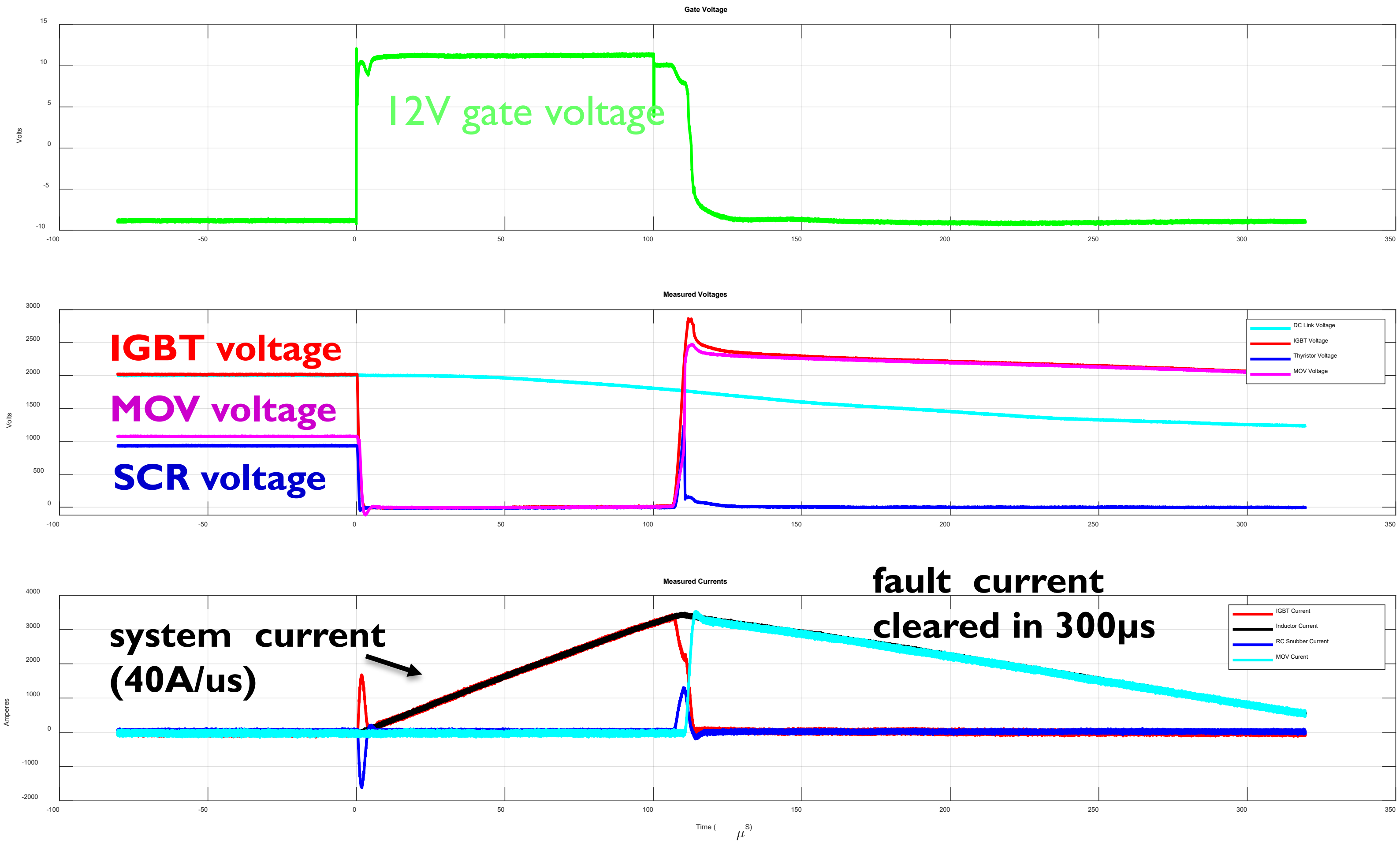






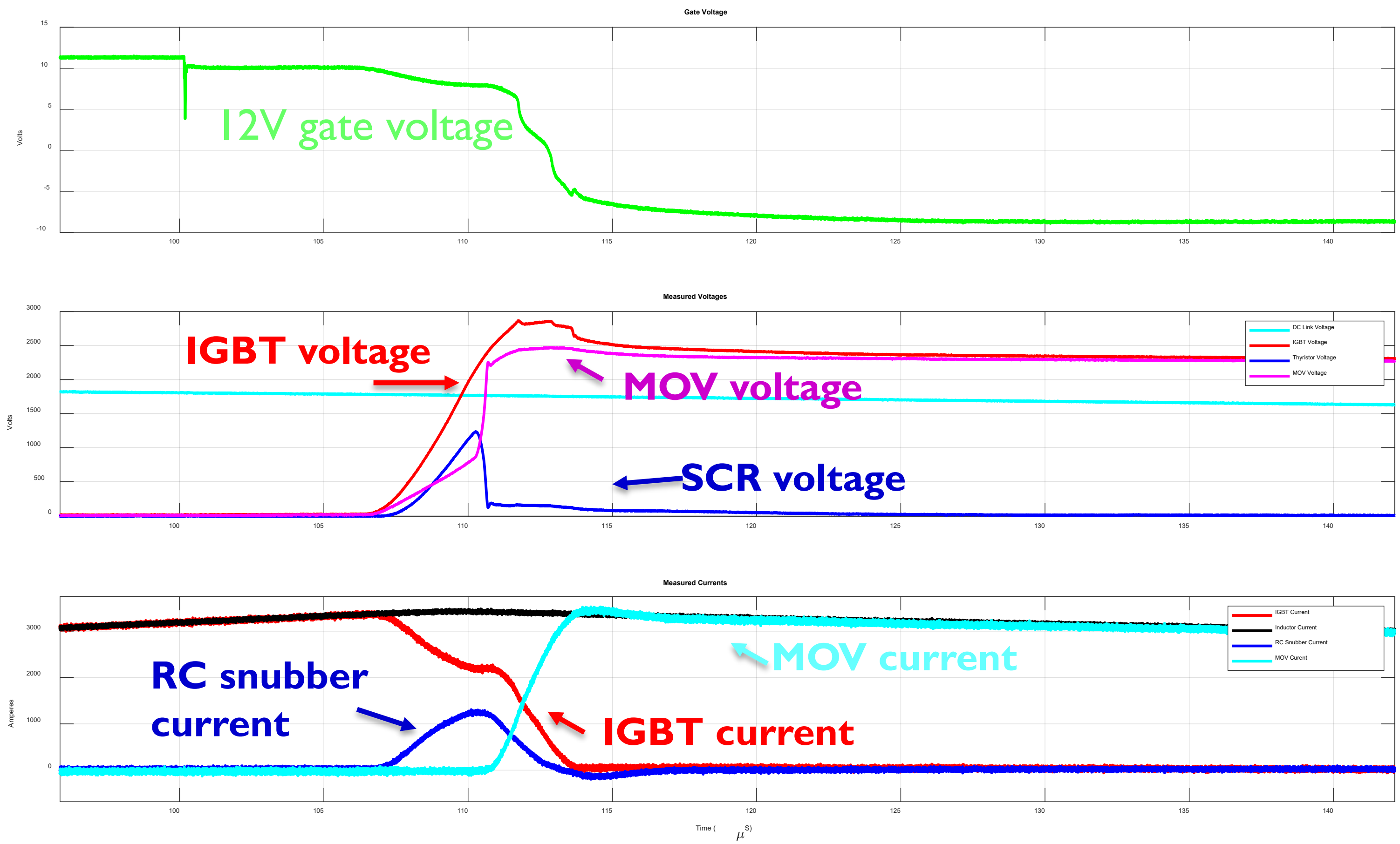


3300V/1500A Module, 2000Vdc, V_{GE_On}=12V, $L_{External}$=50μH



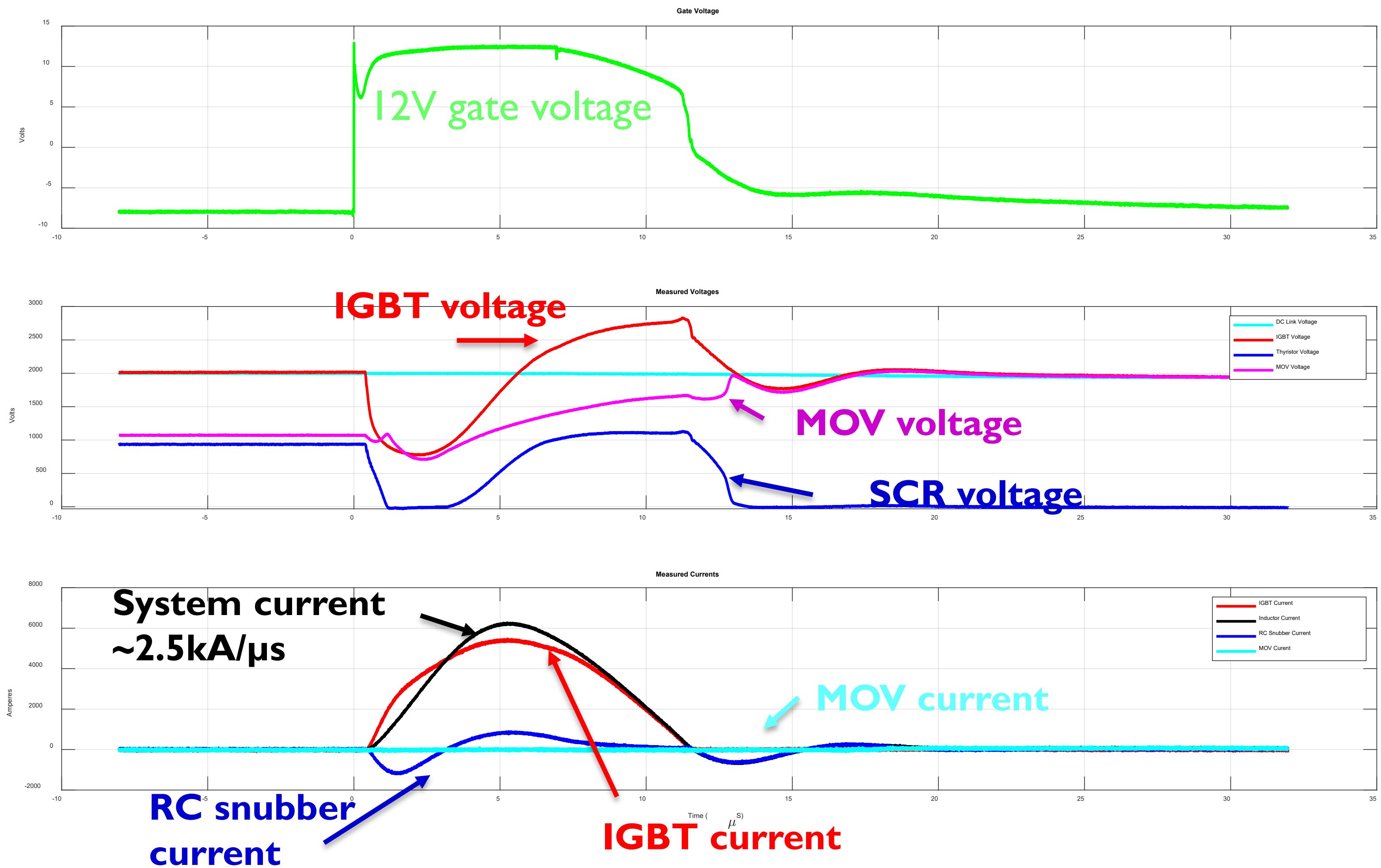
- IGBT is turned off due to DESAT protection. IGBT peak current is 4064A, system peak current is 4141A. IGBT peak voltage is 2766V.
- Measured energy absorbed by MOV is 1032J.

3300V/1500A Module, 2000Vdc, V_{GE_On}=12V, $L_{External}$=50μH



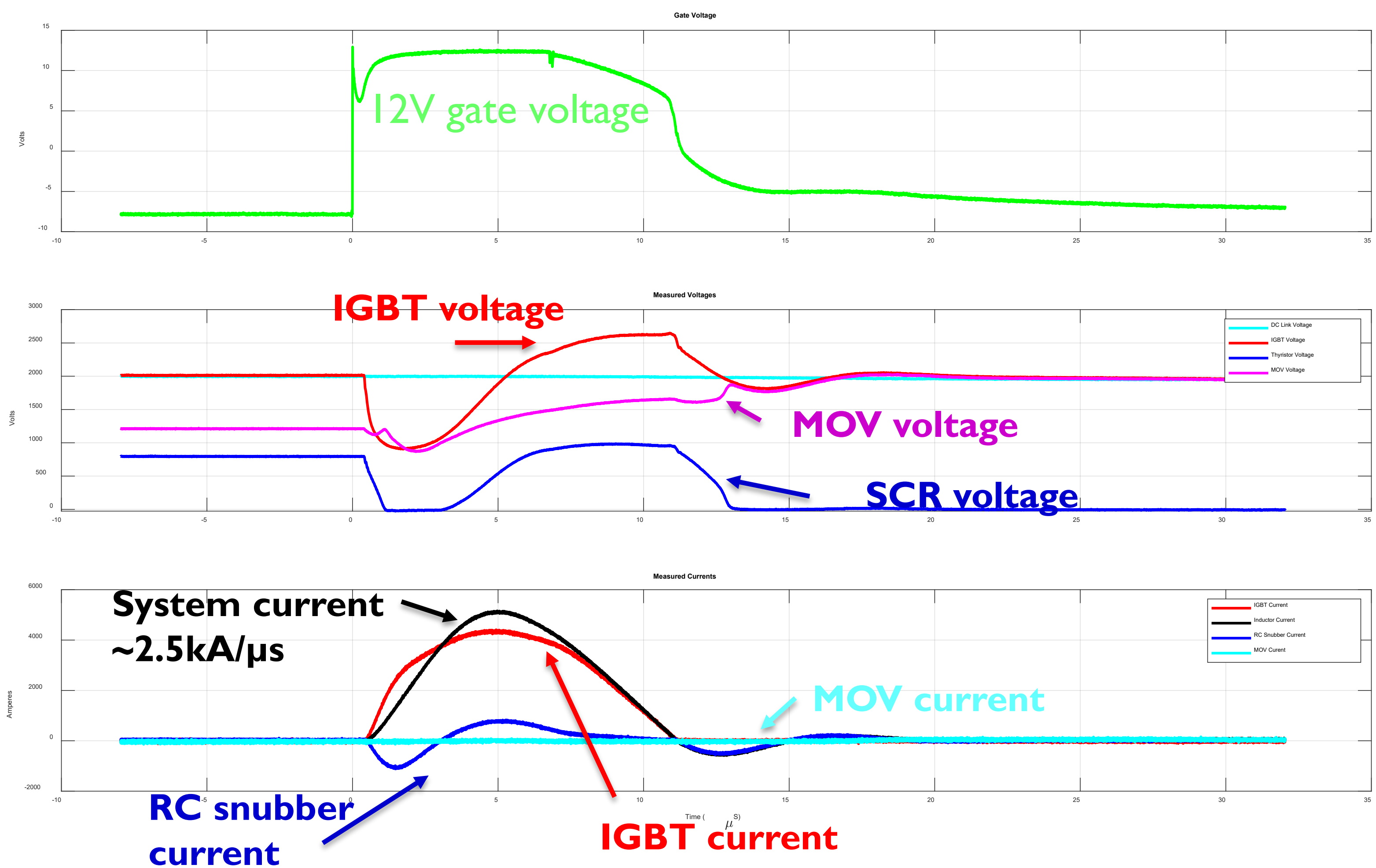
- eMOV is activated when the voltage across SCR is 1211V.

3300V/1500A Module, 2000Vdc, $V_{GE\_On}=12V$, $L_{External}=0.3\mu H$



- IGBT is turned off due to DESAT protection. Current Saturation is apparent.
- IGBT peak current is 5473A, system peak current is 6269A. IGBT peak voltage is 2830V.
- eMOV is activated when the voltage across SCR is 1151V.
- Measured energy absorbed by MOV is 70 J.

3300V/1500A Module, 2000Vdc, V_{GE_On}=12V, $L_{External}$=0.3μH, T_J=100°C



- IGBT saturation current is reduced at higher temperature.
- IGBT peak current is reduced to 4410A (5473A at room temperature).
- IGBT peak voltage is 2649V (2830V at room temperature).

Summary

- A 2kV 1.2kA solid state circuit breaker is designed.
- With eMOV and reduced gate voltage, the proposed solution can meet power rating, power density and efficiency targets.
- Experimental results verified the design.
- The fully assembled solid state circuit breaker will be tested with the whole power train in emulated high-altitude environment in 2023.

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