Low-cost Magnetics-less Isolated Bidirectional GaN Power Converters for Grid-Tied Storage

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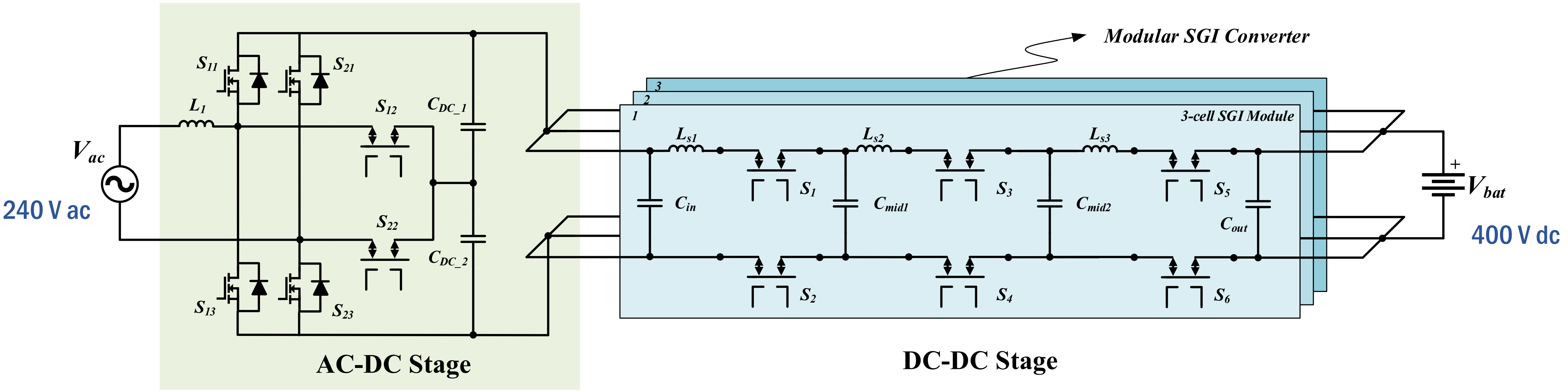
Magnetic-less Galvanically Isolated AC-DC Converter for Energy Storage



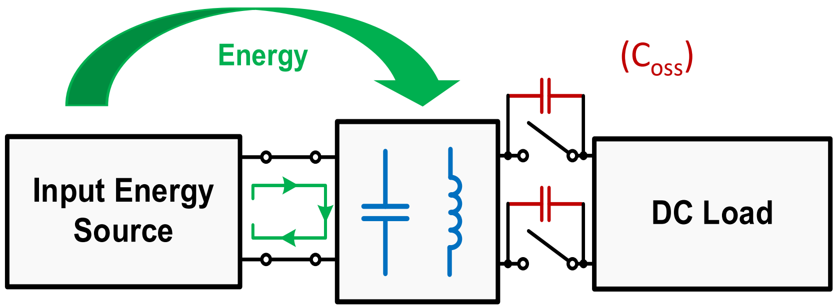
7.5-kW magnetic-less galvanically isolated ac/dc converter for Energy Storage Systems (EES)

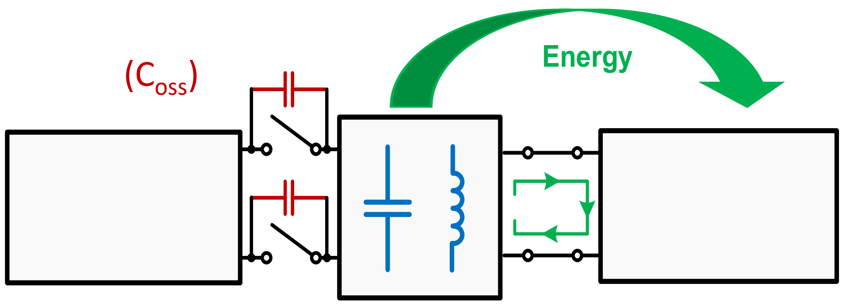
Features:

- Semiconductor based galvanic isolation (SGI)
- Bi-directional Gallium Nitride (GaN) based circuit design
- Low cost

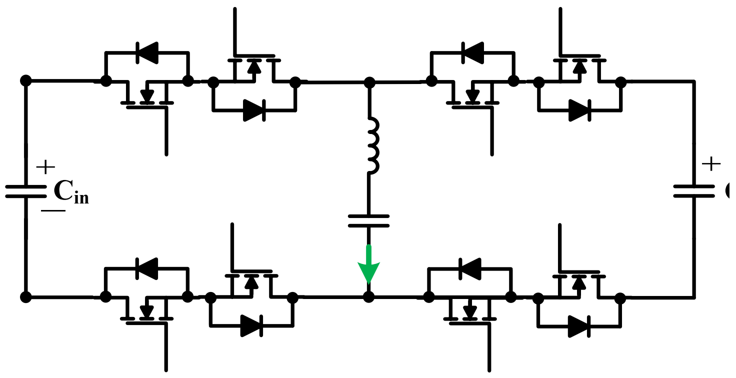
Semiconductor based Galvanic Isolation

Principle of Semiconductor based Galvanic Isolation

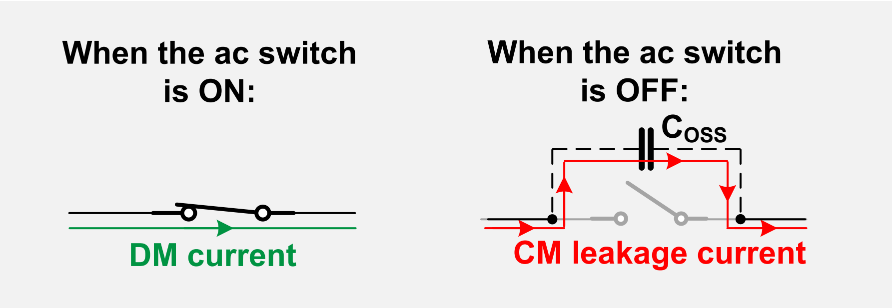




Switched Capacitor Cell based SGI



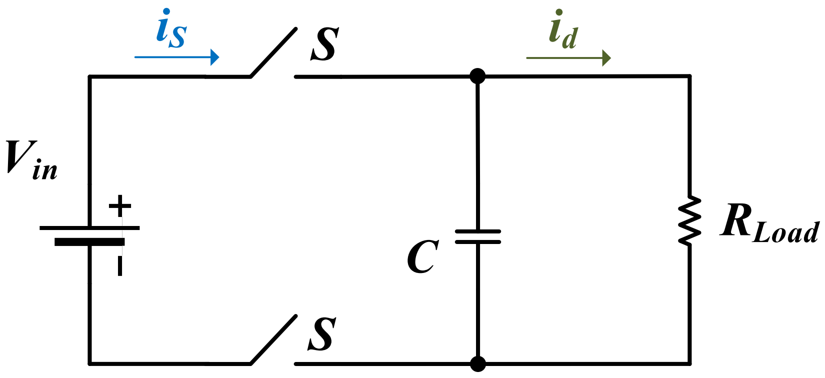
Current through a Switch



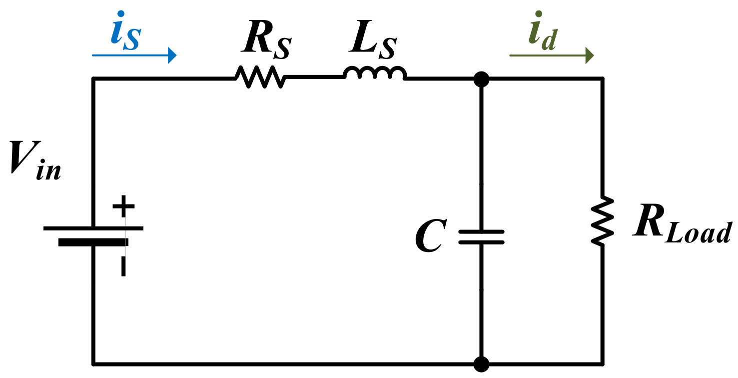
Common mode (CM) leakage current needs to be limited to meet safety standards!

Compared to Si devices, SiC and GaN devices with smaller Coss can result in greatly reduce leakage current.

Zero Current Switching of the Switched Capacitor Cell



A basic switched capacitor cell



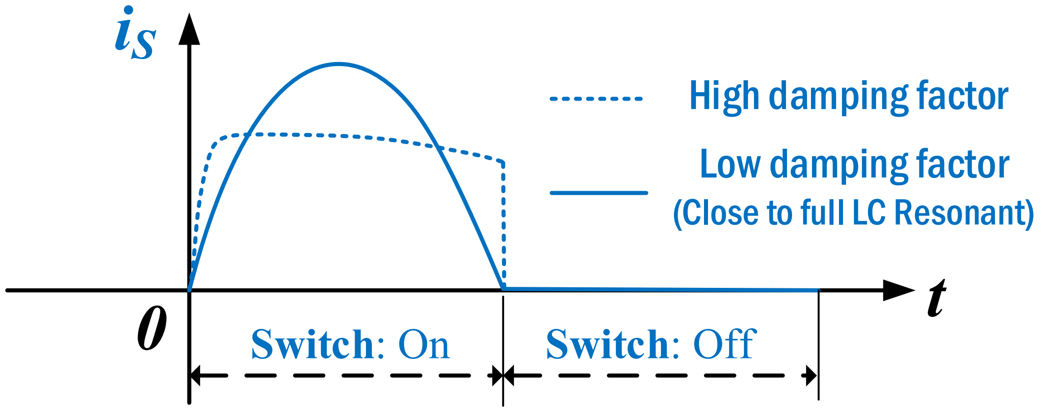
Equivalent circuit when the switches are on

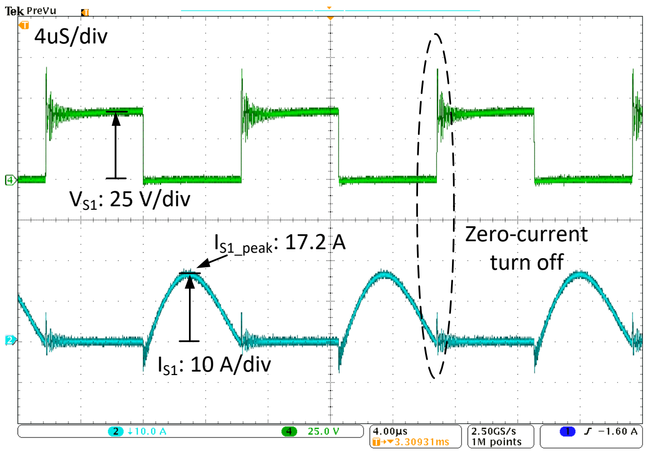
R_S: Stray resistance

L_S: Stray inductance

$R_{Load} >> R_S$

Damping factor: $\zeta = \frac{R_S}{2}\sqrt{\frac{C}{L_S}}$





Typical ZCS waveform of a switched capacitor cell*

When the switched cell is designed with low damping factor, zero current switching can be realized by switching at the LC resonant frequency.

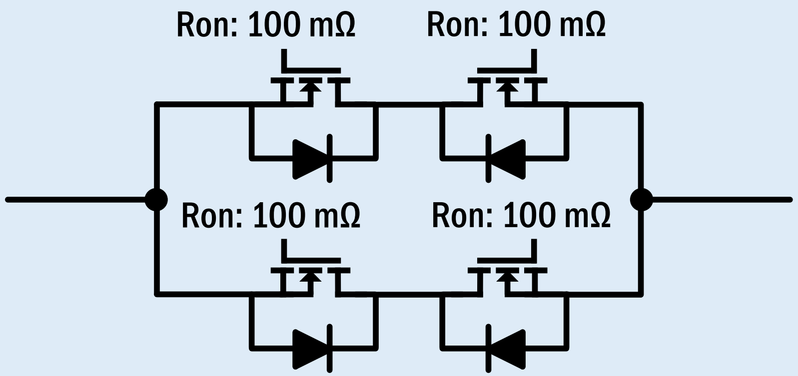
What Makes It a Bi-Directional Switch

Two Features of a Bi-Directional Switch:

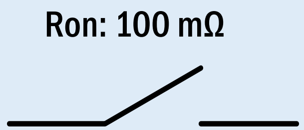
- Conducting current in both directions
- Blocking voltage in both directions

The 4:1 Ratio:

- Four identical uni-directional devices are needed to form one bi-directional switch with the same on resistance



Four 100-mΩ uni-directional MOSFETs



One 100-mΩ bi-directional switch

Problems:

- 4 times semiconductor usage
- Complex gate drive and layout
- Unbalanced transient current sharing

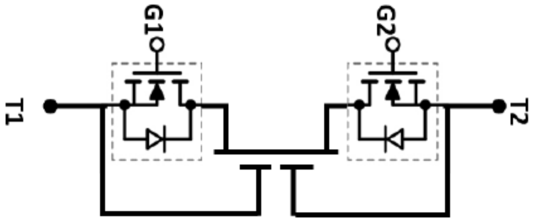
Note: There have been developments of Reverse Blocking Si IGBTs , Reverse Conducting Si IGBTs, and Bi-directional SiC MOSFET. None can significantly reduce the 4:1 ratio.

A Bi-Directional GaN Device

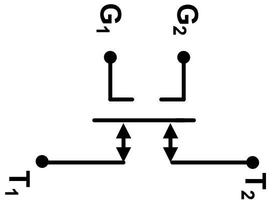
A GaN based bi-directional device:

- One cascode device with two gates
- 60 mΩ at 25 °C

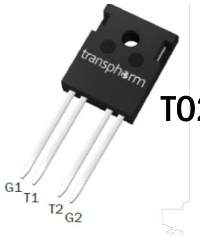
A device that significantly reduces the 4:1 ratio



Device Structure



Device Symbol



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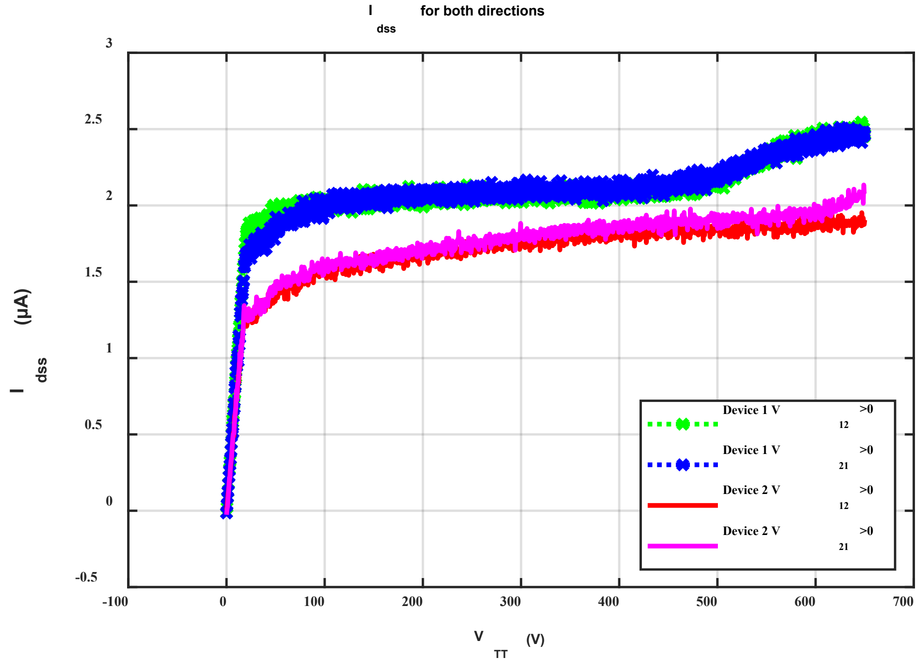
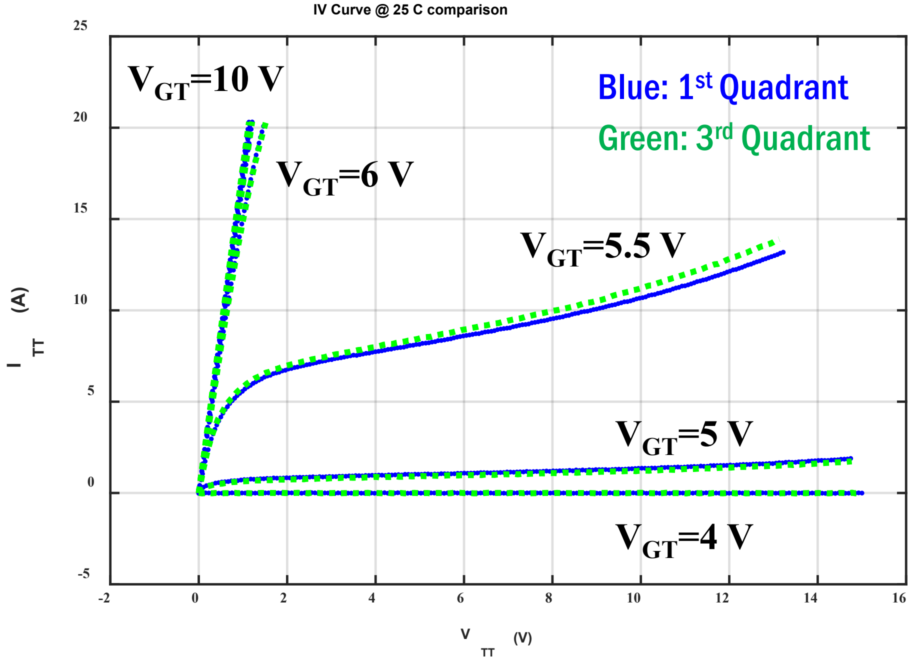
Device Package

Bi-directional Blocking



Bi-directional Conducting



Earlier Achievement: 2.5-kW 1-MHz 3-Cell SGI Prototype

2.5-kW, 400-V, 1-MHz SGI Module

- Modular and magnetic-less circuit topology
- No bulky magnetic components
- Small switched capacitor (1.2 μF) enabled by 1-MHz switching
- High efficiency and power density
- Low cost two-layer PCB
- More manufacturable than transformer based isolated dc-dc converters

Prototype specifications

- Dimensions: 11.4 cm × 6.2 cm × 5.2 cm
- Power density: 6.8 kW/L
- Peak efficiency: 97.6 %

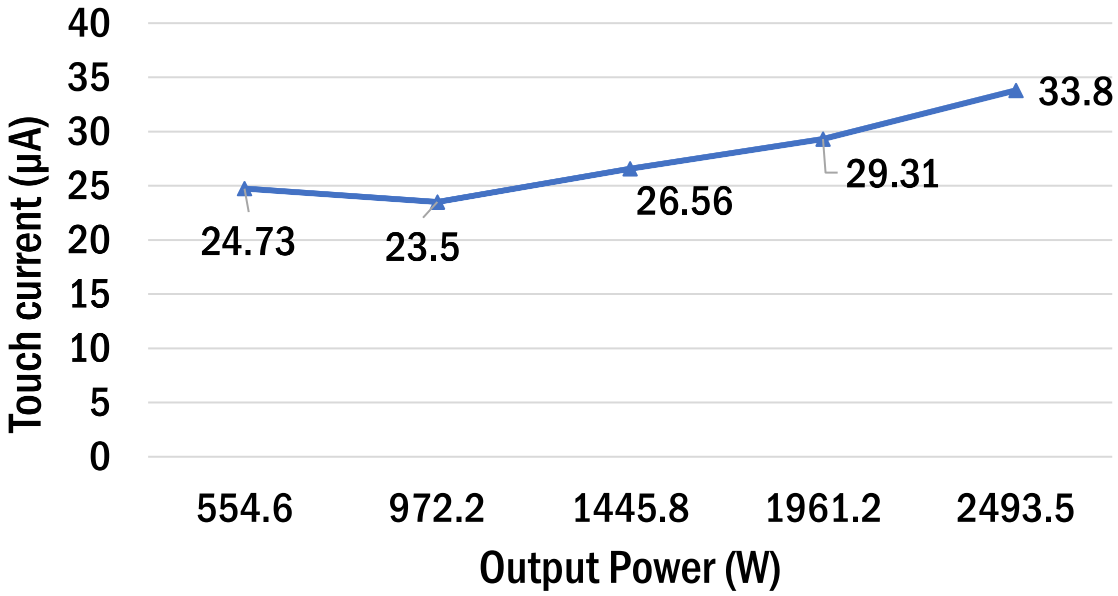
Prototype	PCB Cost (for 1 set)
1-kW high-frequency transformer based Dc-dc[1] (With a 16-layer planar transformer)	$ 504.92
2.5-kW 3-Cell SGI	$ 58.14

(For same lead-time and quantity)

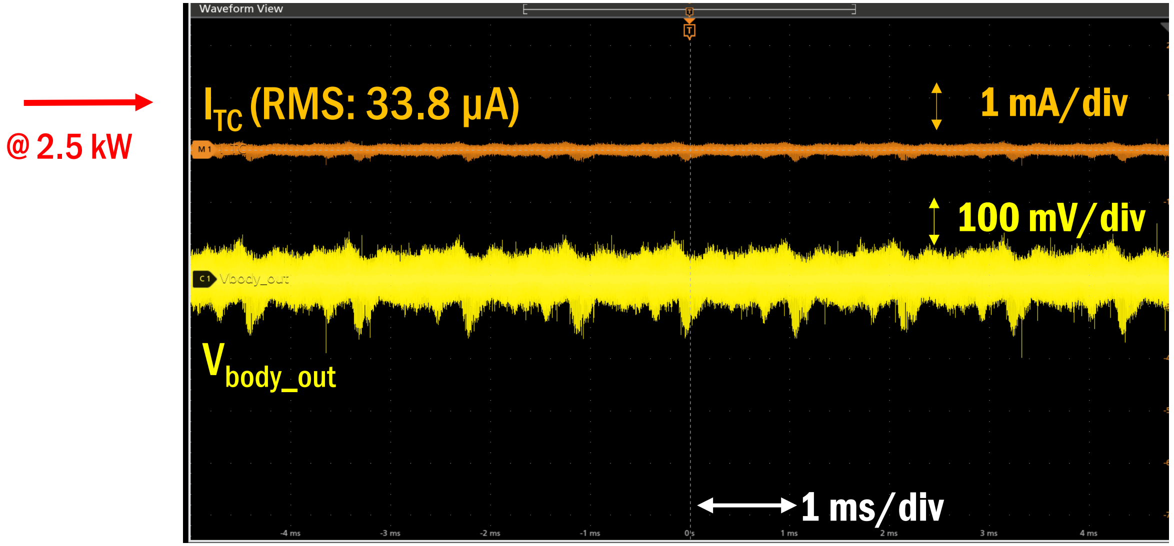
Z. Zhang, et al., , "A Quasi-Switched-Capacitor-Based Bidirectional Isolated DC–DC Converter With High Voltage Conversion Ratio and Reduced Current Ripple," in *IEEE Trans. on Power Electronics*, vol. 39, no. 4, pp. 4426-4437, April 2024

2.5-kW 3-Cell SGI Touch Current Evaluation

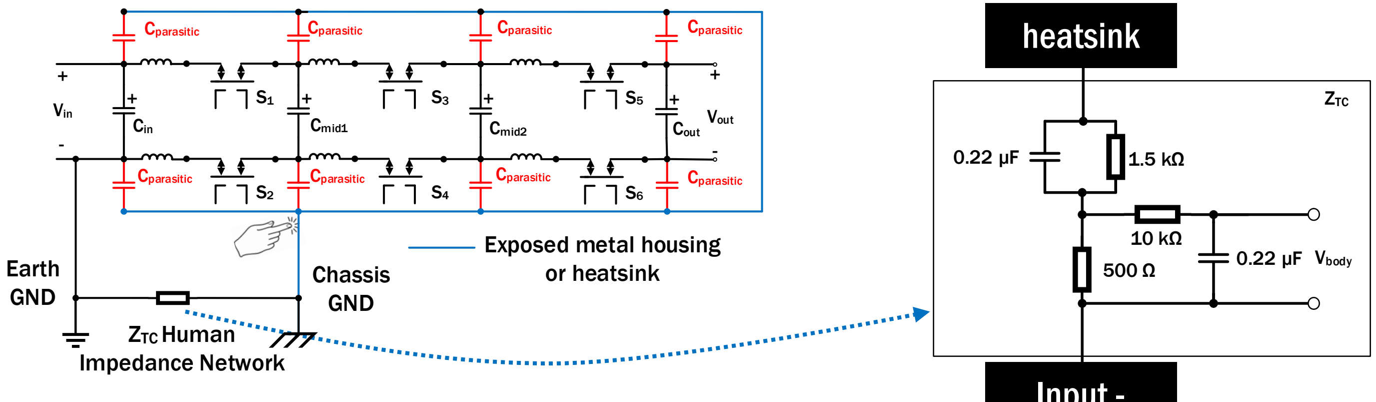
Converter Touch Current @ Different Load Conditions



Touch current measurement at 2.5 kW



- Touch current measured based on IEC 60990



Measured TC stays well below IEC standards (< 0.5 mA).

Progress from July 2025 to May 2026

- Studies of Navitas GaN MBDS
  - Static and dynamic characteristics
  - Short circuit capability
  - Series operation for 800 V applications
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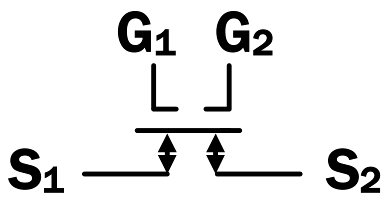
- Paralleled operation of SGI modules

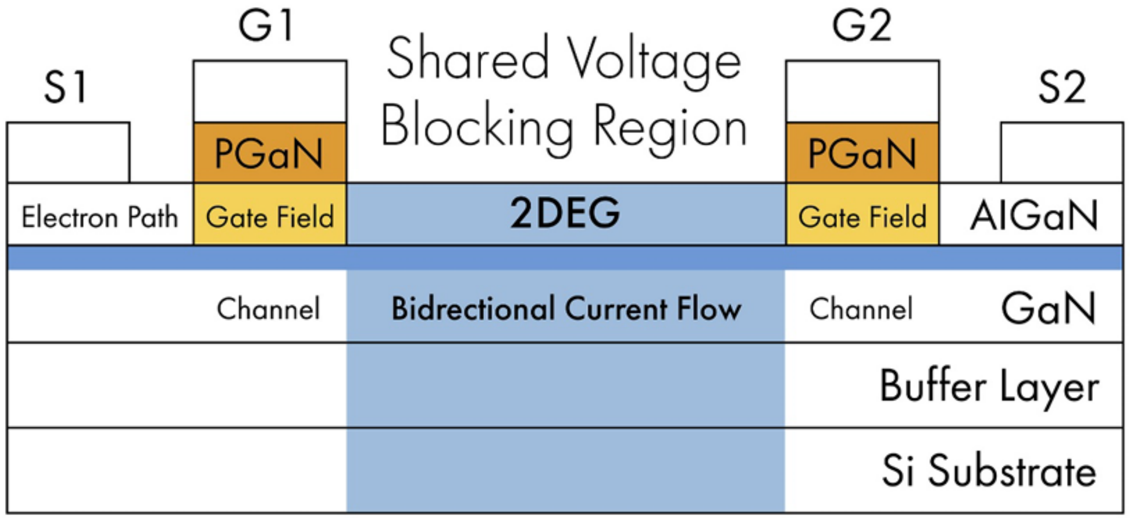
650-V GaN MBDS from Navitas

The 650-V 52mΩ GaN monolithic bidirectional switch (MBDS) from Navitas:

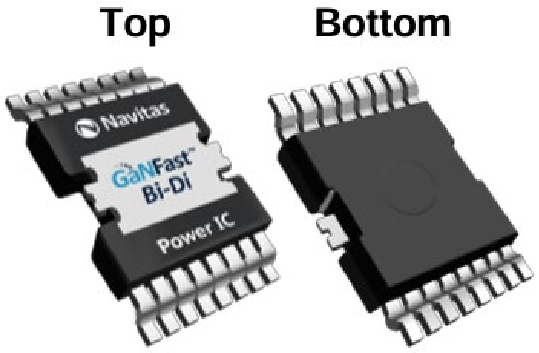
- Monolithic integration
- Common-drain structure



Device symbol

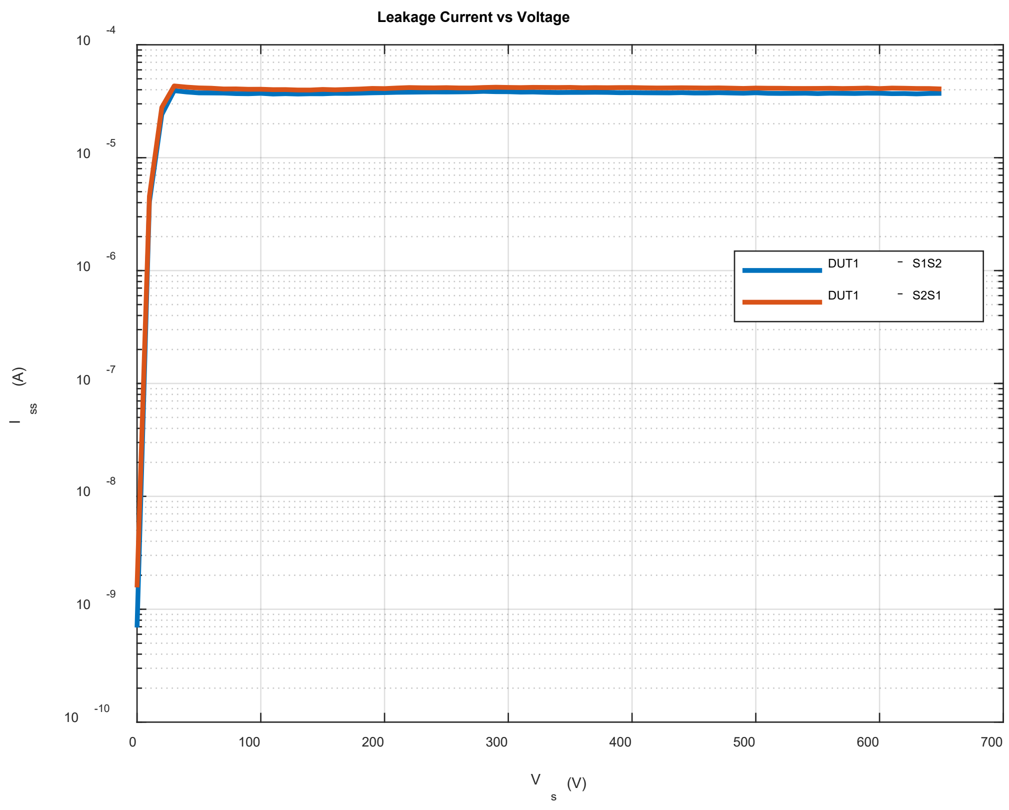


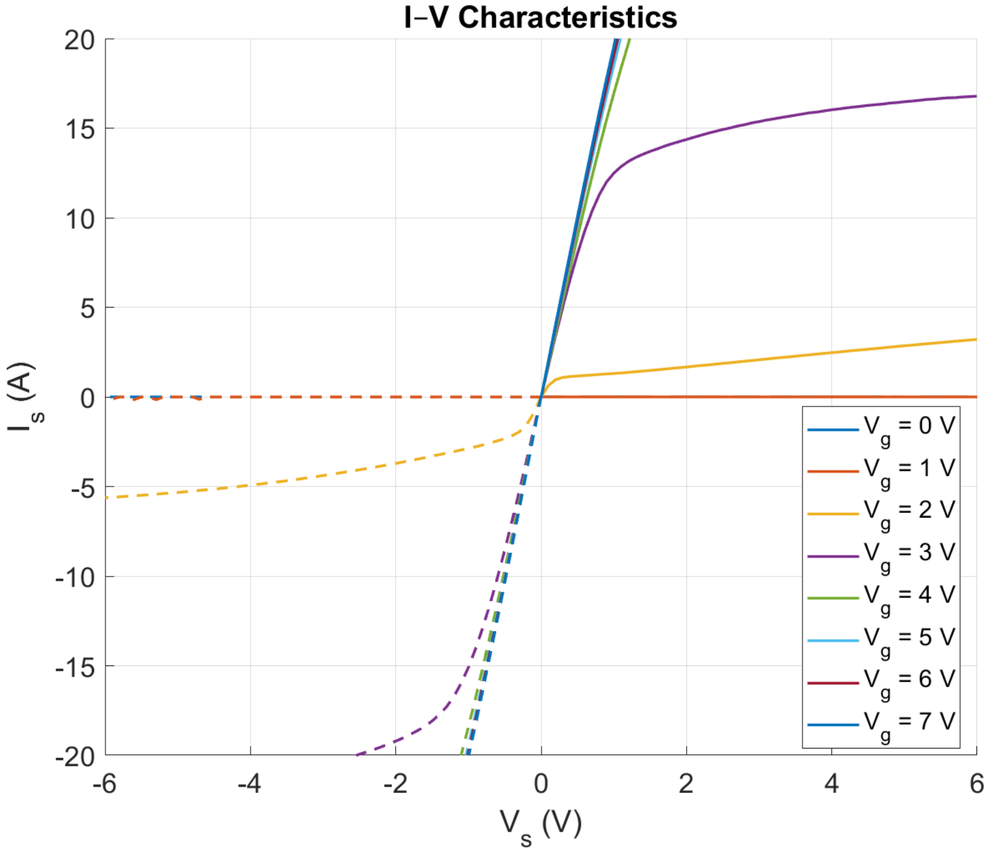
Device structure



Top-cooled device package

Symmetrical Bi-directional Blocking and Conducting

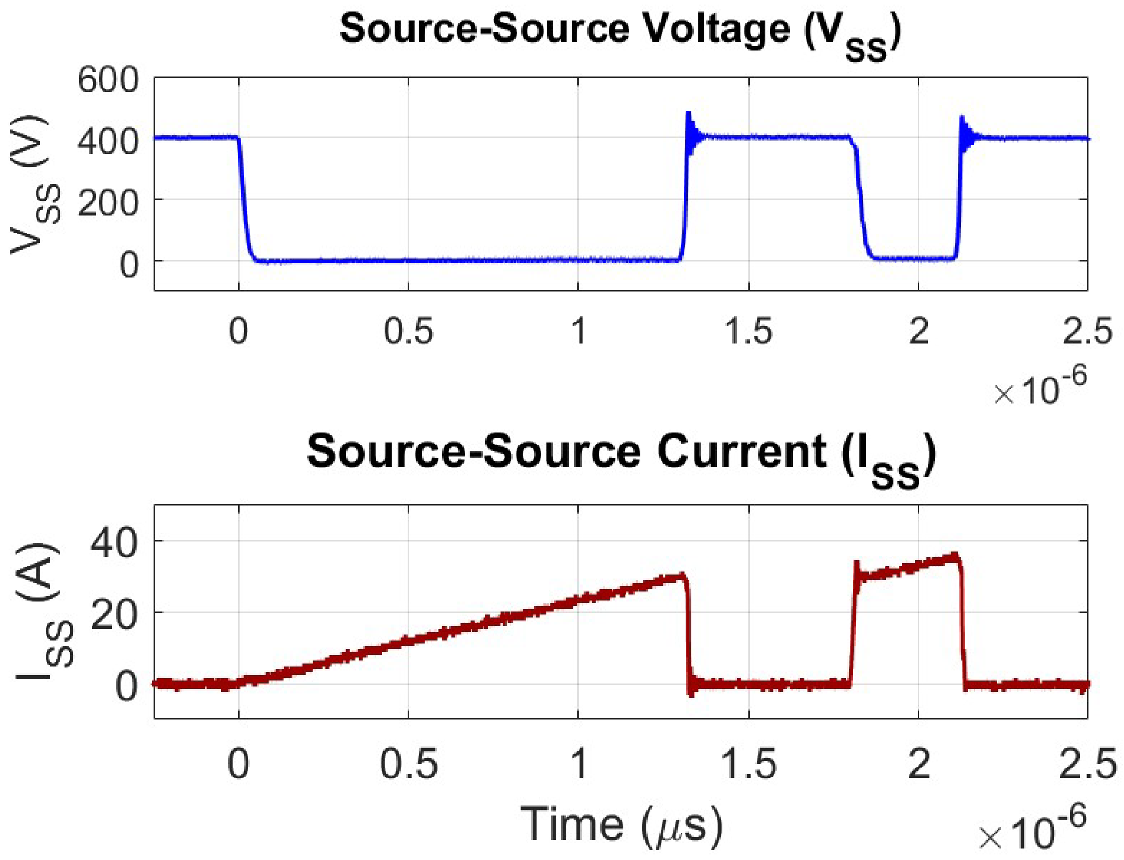


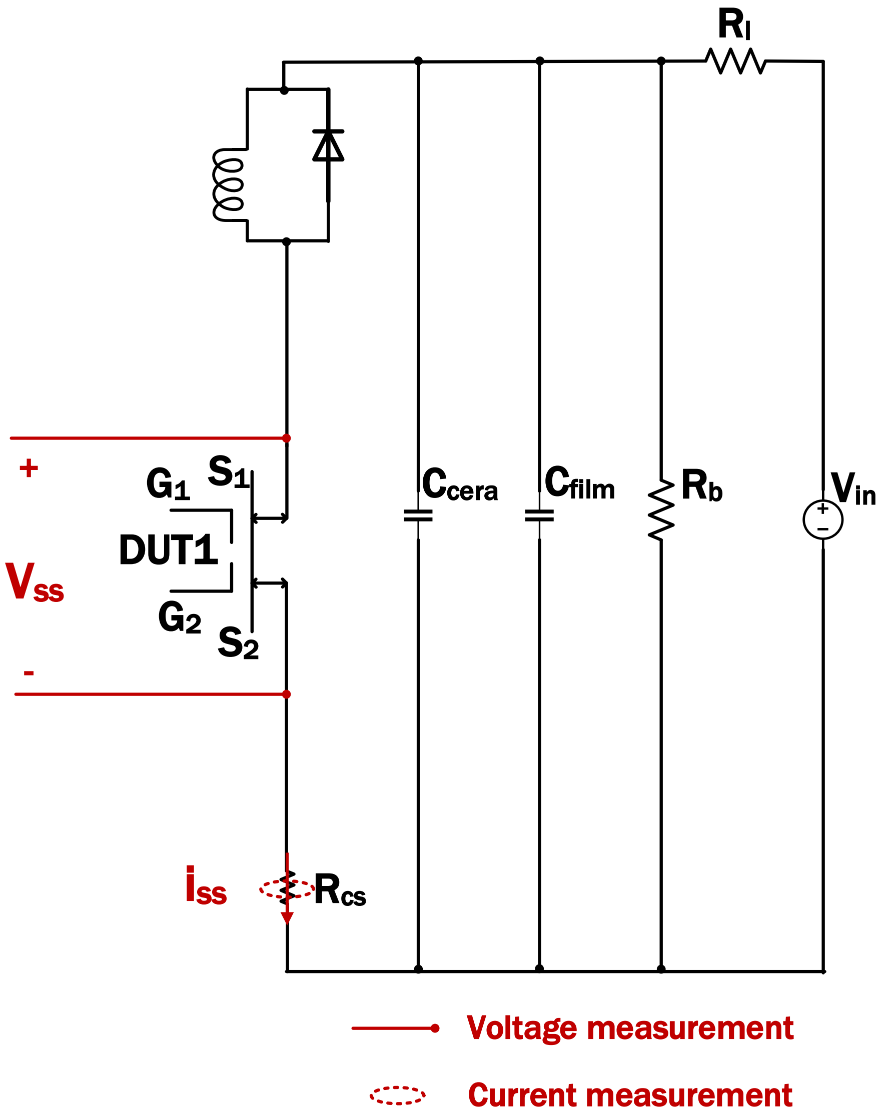


Bidirectional blocking with a leakage current of 40 μA at 650 V

Bidirectional conducting with an on resistance of 48 mΩ when gate voltage is higher than 4 V

Double Pulse Test of GaN MBDS at 400 V/30 A





Turn-on dv/dt: 15.7 V/ns **Turn-on di/dt: 2.0 A/ns**

Turn-off dv/dt: 30.0 V/ns **Turn-off di/dt: 9.1 A/ns**

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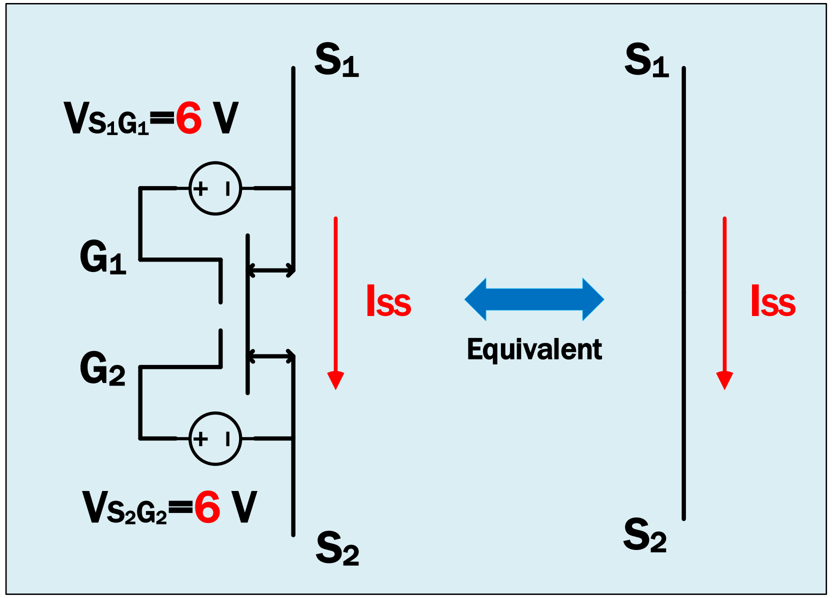
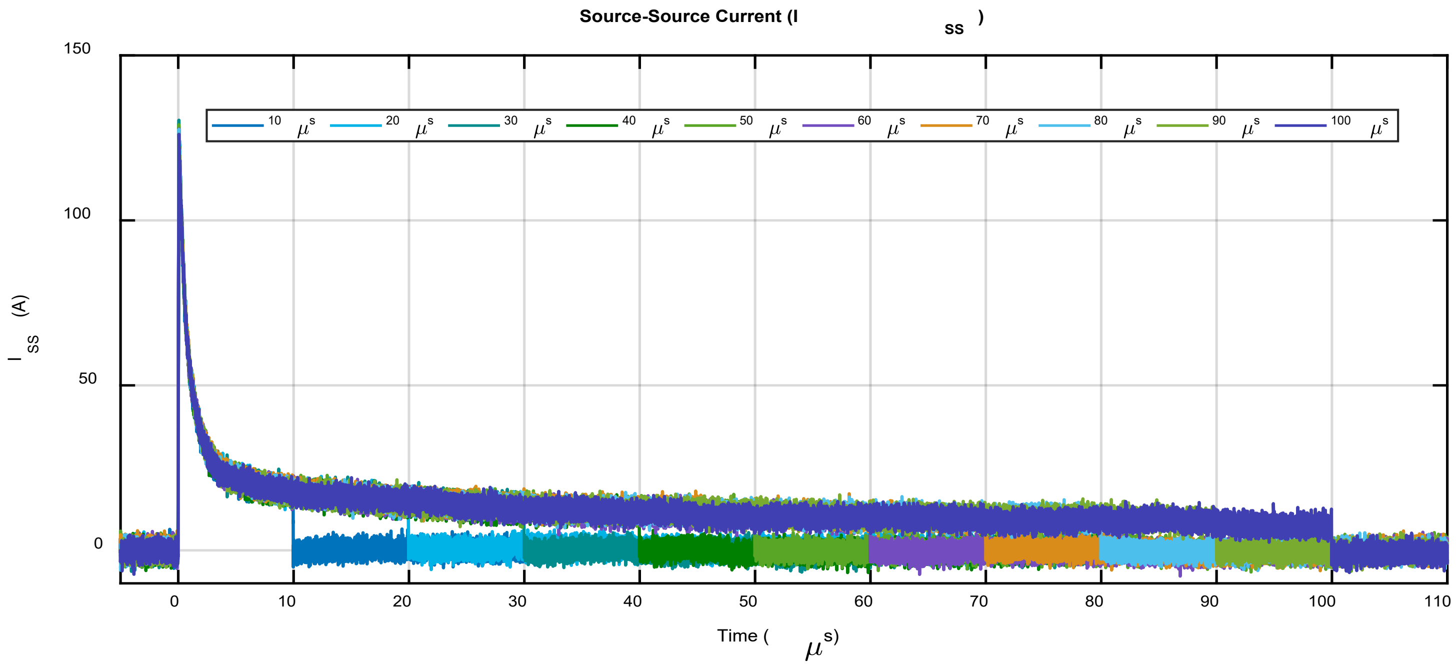
- Paralleled operation of SGI modules

Short Circuit Withstand Time with Both Gates On





Device	DC Bus	I_{pk}	SC Energy @ 100us	SCWT
Navitas GaN MBDS	400 V	130 A	502.5 mJ	> 100 μs

The MBDS has excellent intrinsic short circuit current capability!

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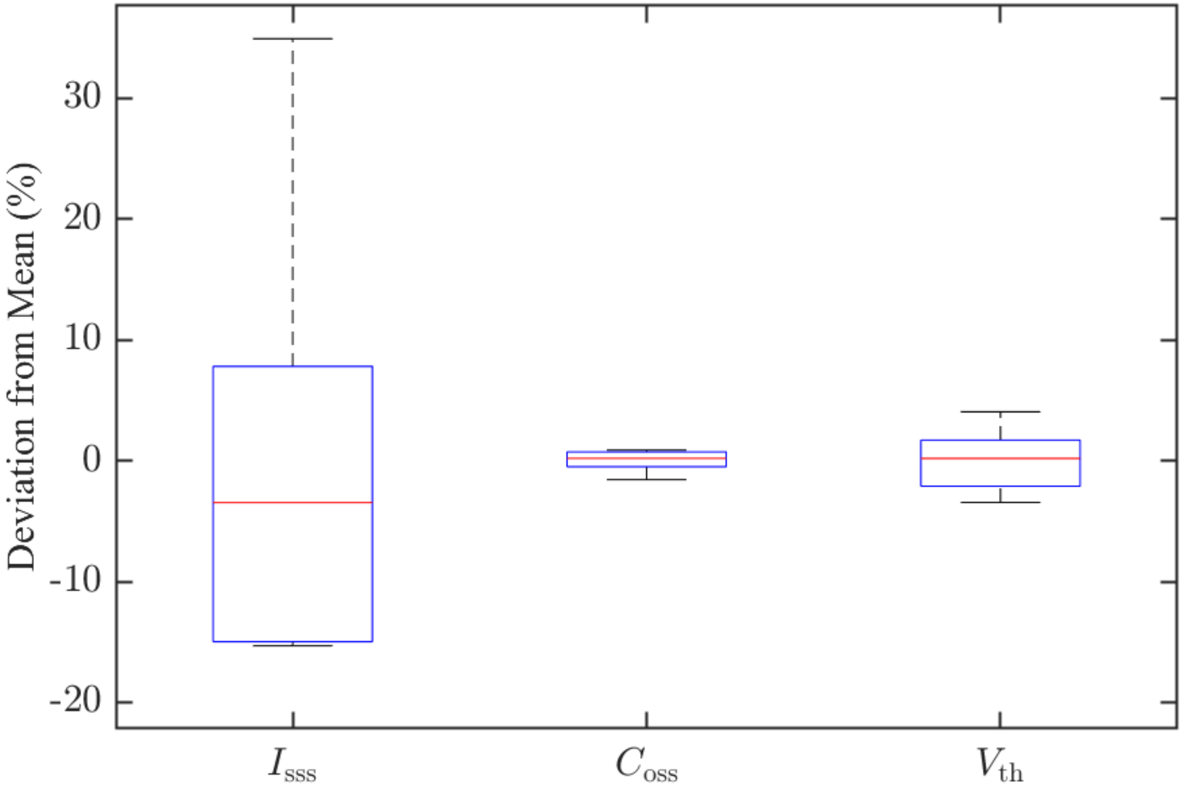
Challenges for Series Operation of GaN MBDS: Device Parameter Mismatch

Ten devices from the same production batch are characterized.



Device-to-device parameter variation

- **Leakage current, I_{SSS}:**

  Determines static voltage balancing

- **Output capacitance, C_{oss}:**

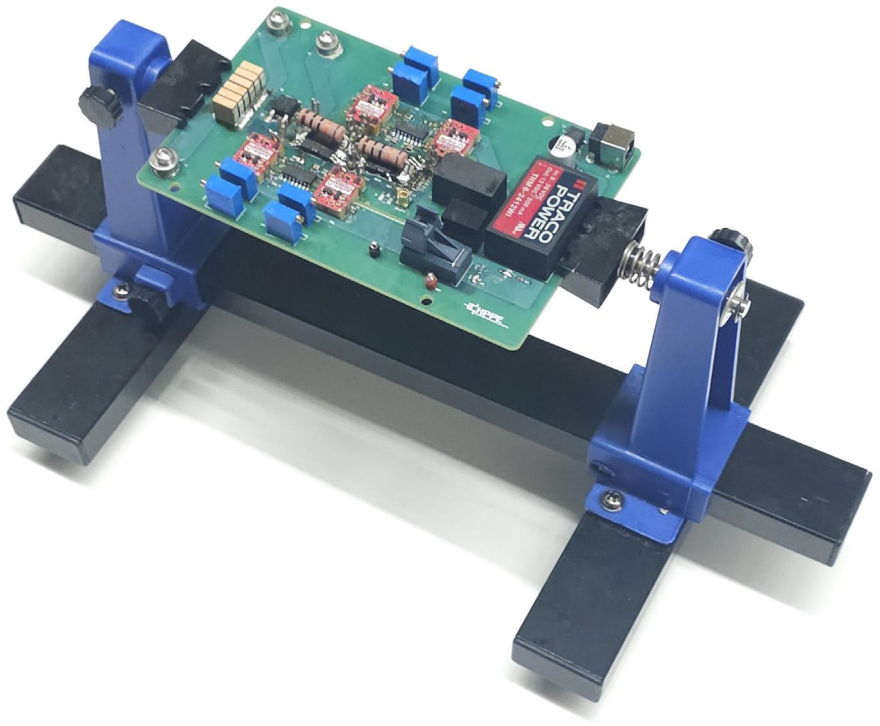
  Determines switching speed during switching transients

- **Threshold voltage, V_{th}:**

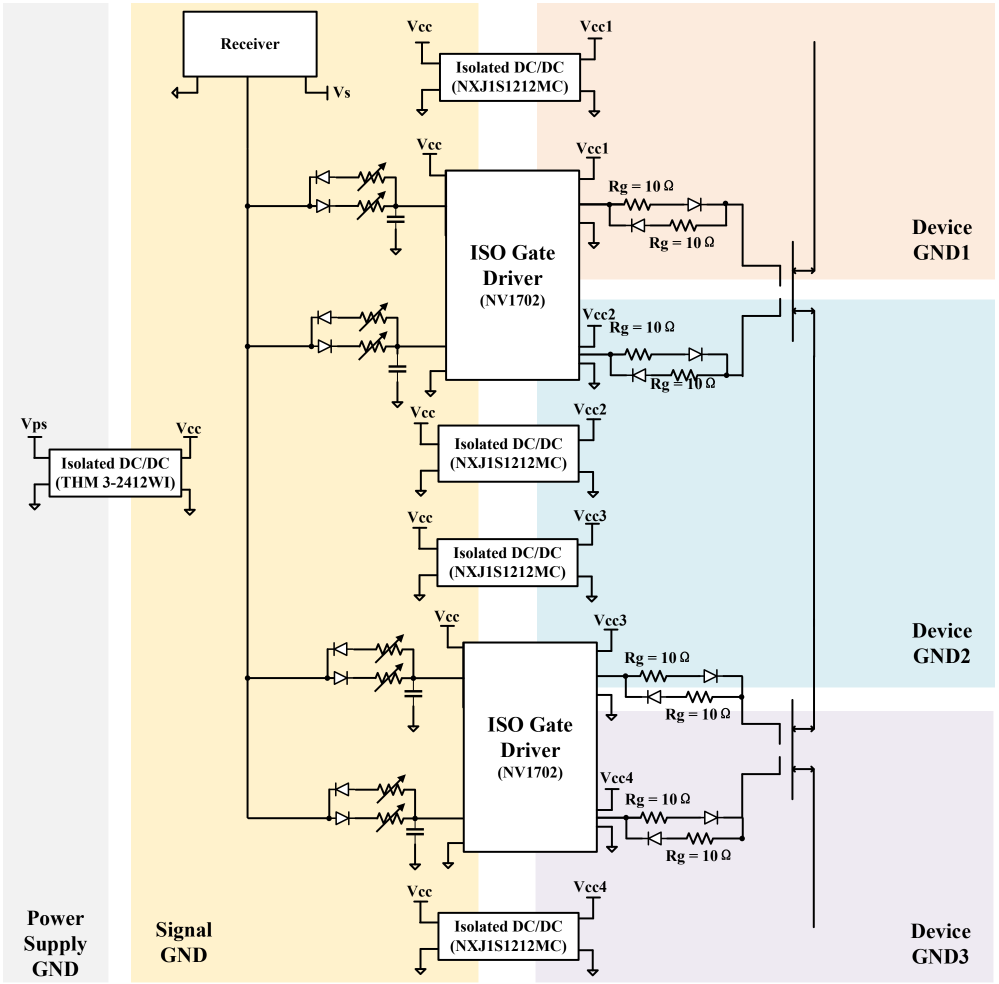
  Determines gate signal matching during switching transients

Device preselection is required to achieve voltage balance.

Test Setup for Two GaN MBDS Devices Connected in Series

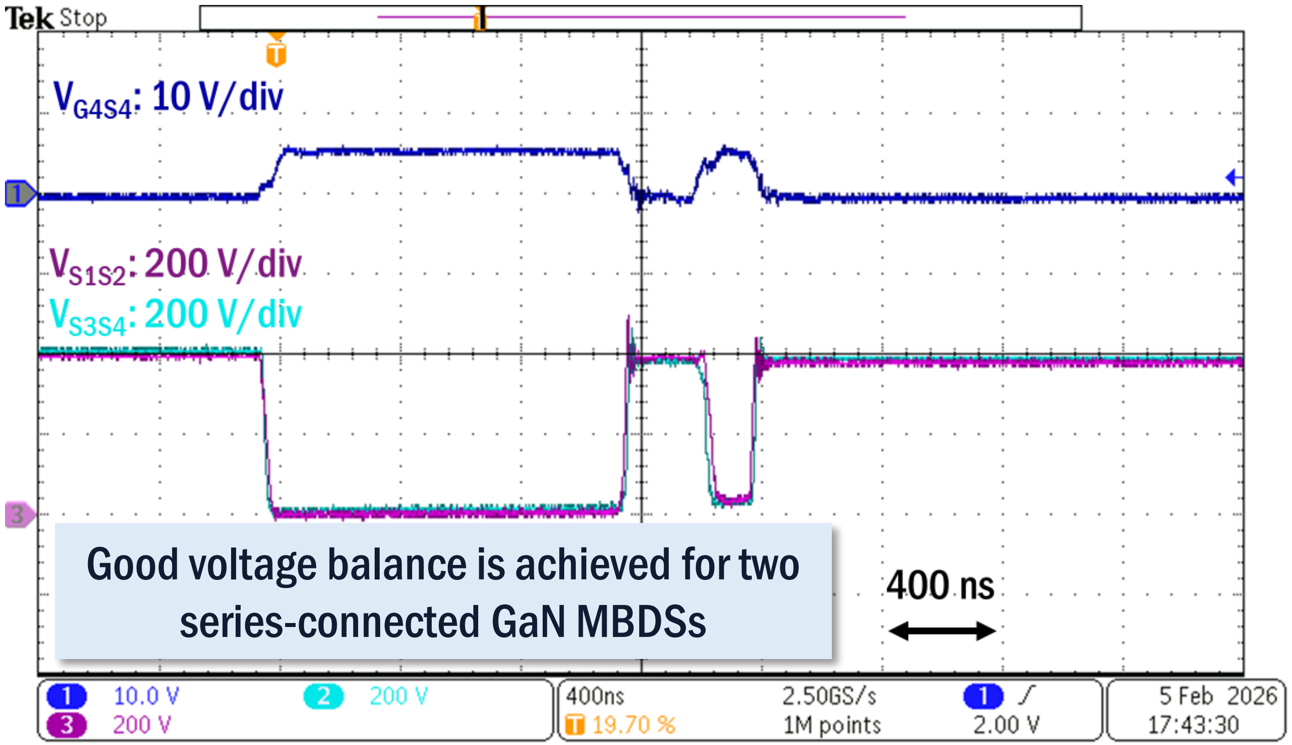


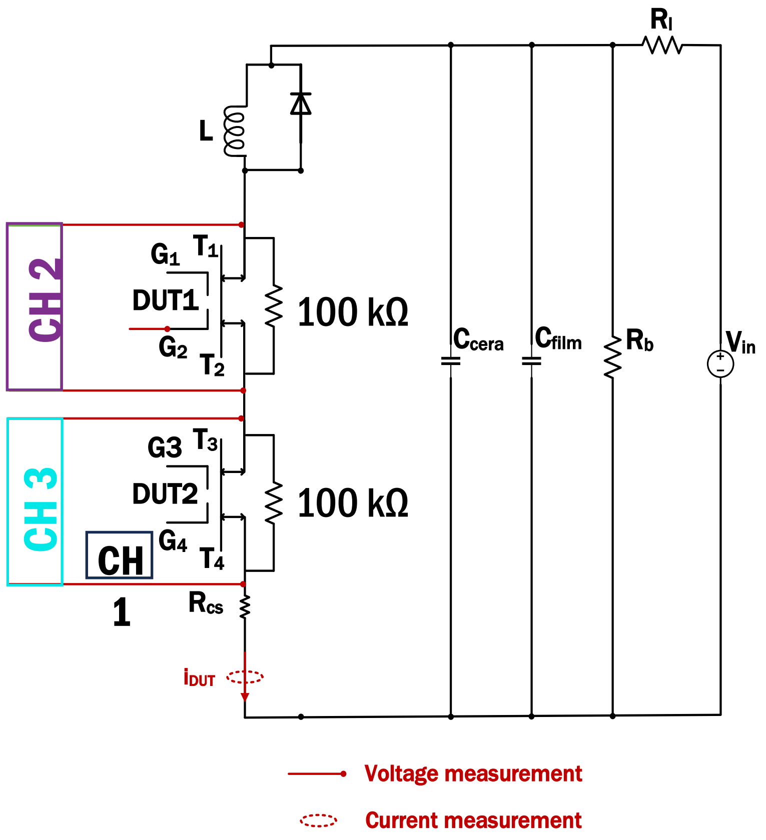
Double pulse tester for series operation of GaN MBDS



Circuit diagram

Test Results for Series Connection





CH 1: device gate to source voltage V_{G4T4}

CH 2: device source to source voltage V_{T1T2}

CH 3: device source to source voltage V_{T3T4}

Excellent short circuit capability and the feasibility of series operation show that series-connected GaN MBDS can be implemented for 800-V rated circuit breakers and converters!

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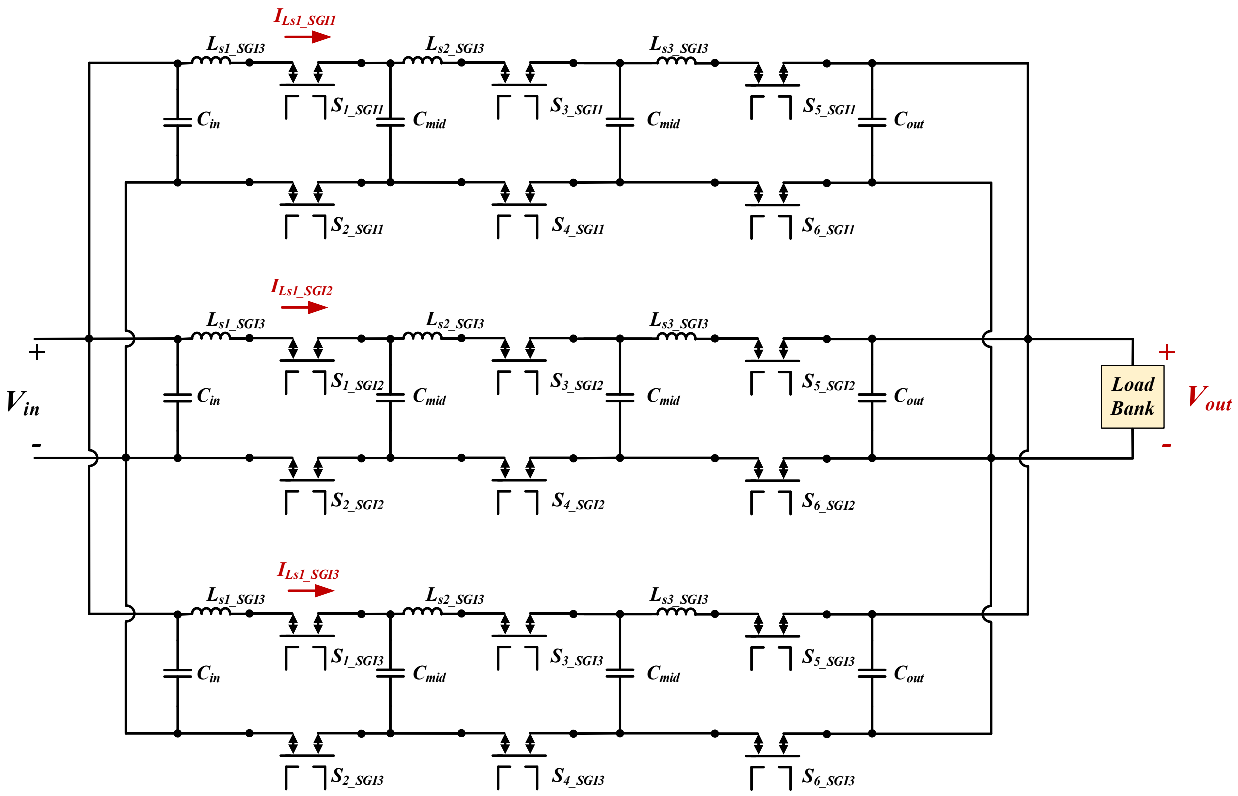
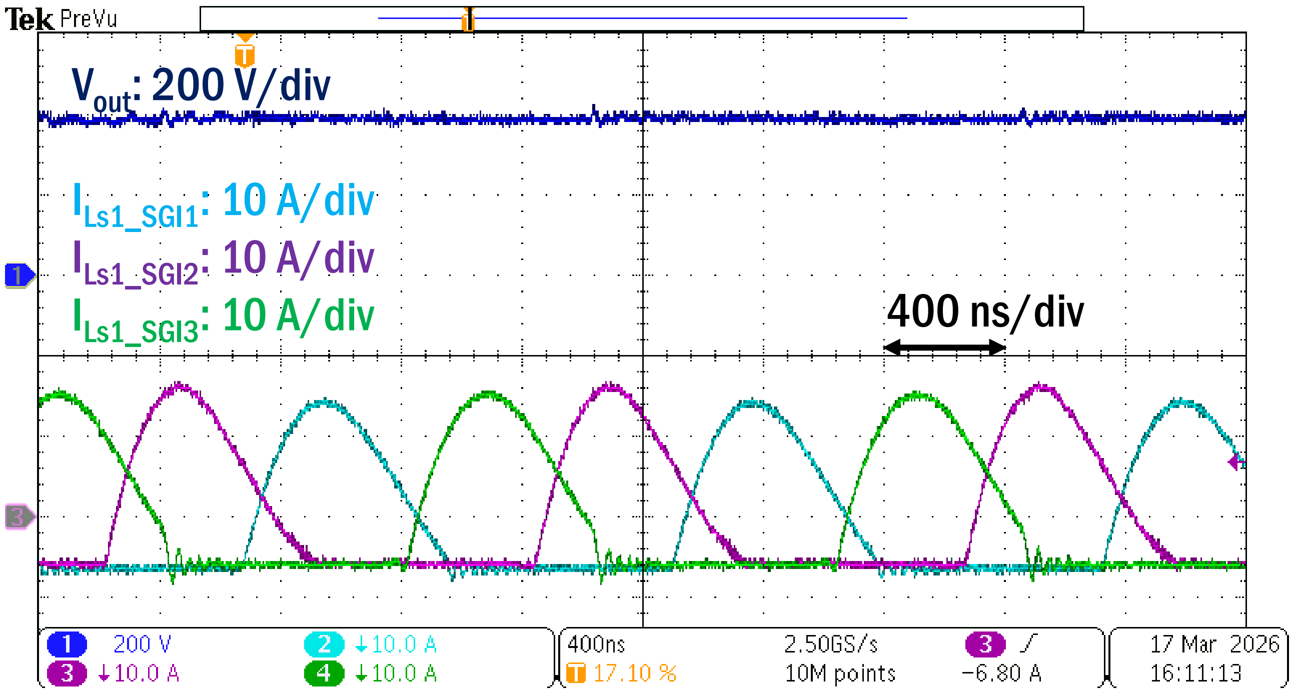
Parallel Operation of 3 SGI Modules



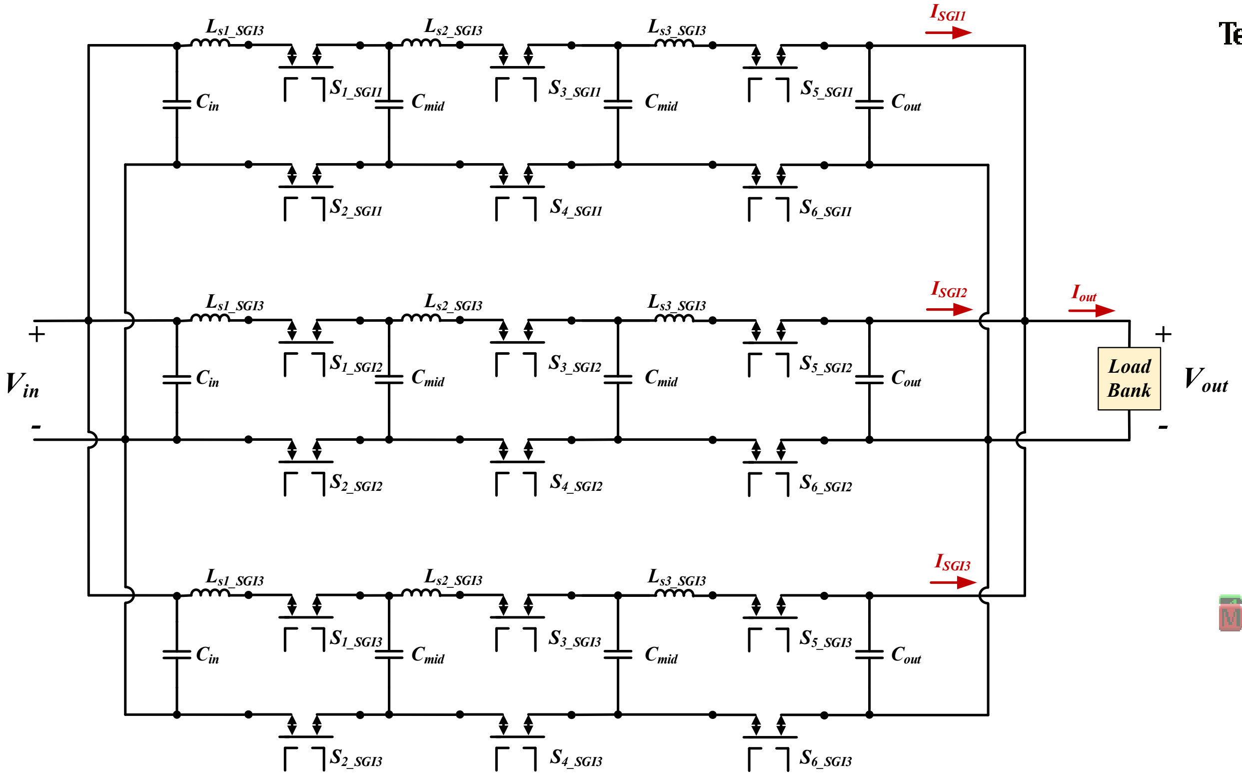
7.5 kW paralleled SGI converter circuit diagram



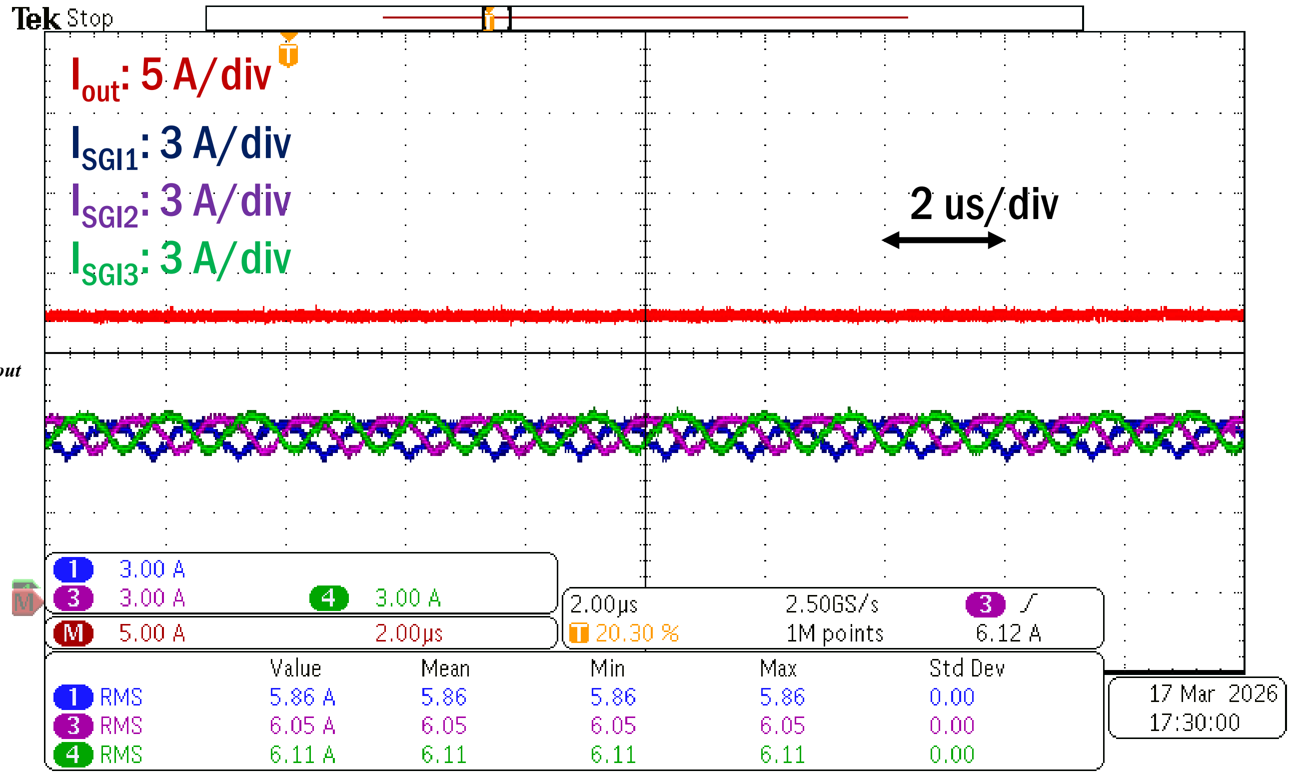
Experimental waveforms of the cell currents.

- The output voltage stables at 400 V
- The phase shift between each converter is $\frac{2\pi}{3}$

Current Sharing between Paralleled SGI Modules



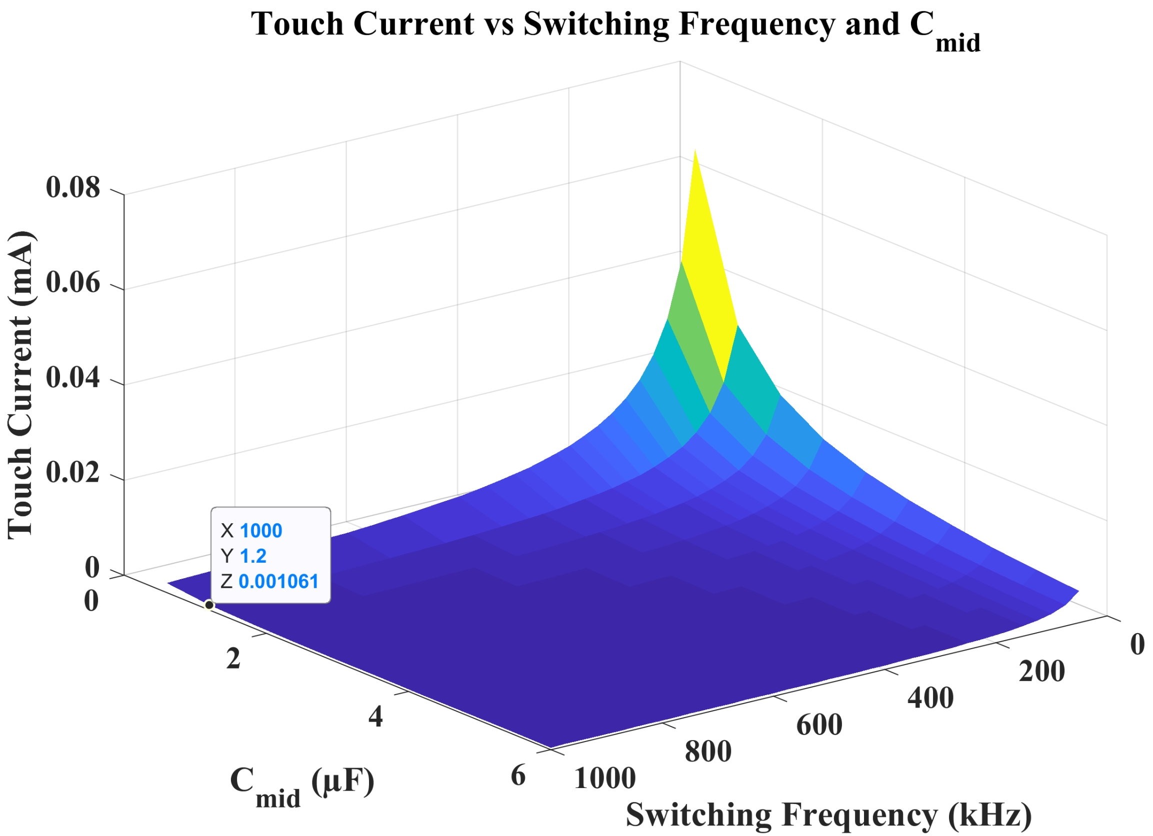
7.5 kW paralleled SGI converter circuit diagram

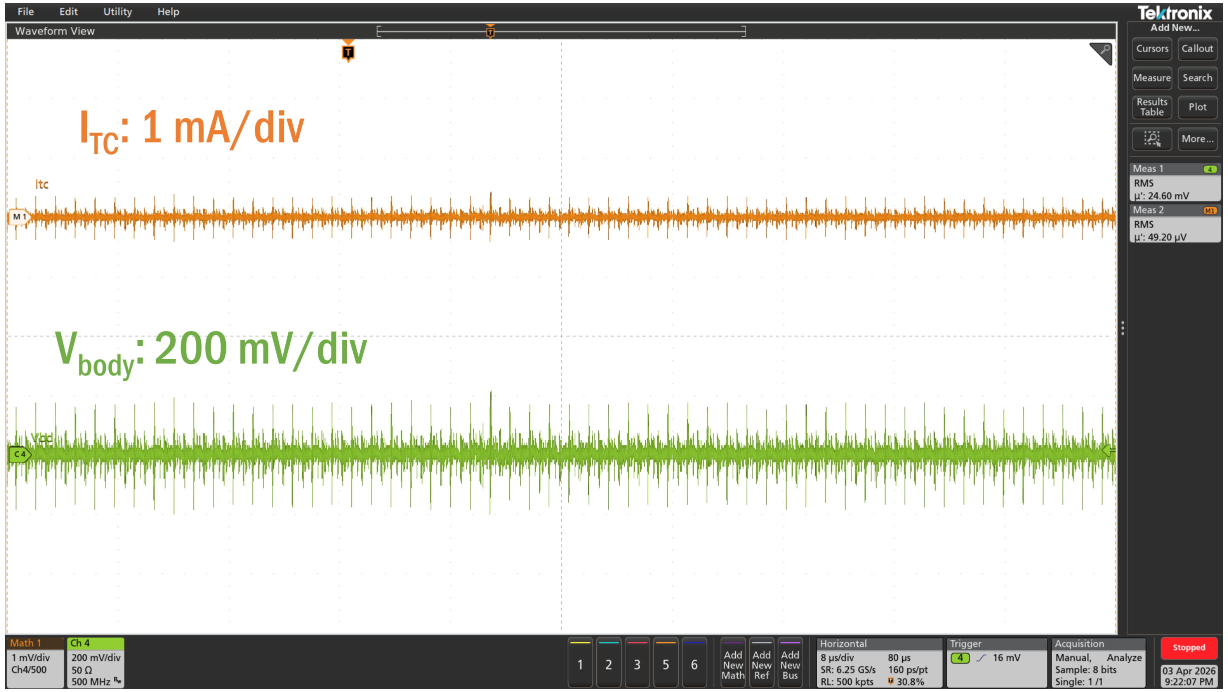


Experimental waveforms of output currents.

$$Current\ Sharing\ Error = \frac{\max(|I_{SGIi} - I_{avg}|)}{I_{avg}} = 2.4\ \%$$

Touch Current Calculation and Test Results





Touch current measurement

- The calculated touch current is at 1 MHz is 1.06 µA, which is lower than the single SGI touch current (1.46 µA).
- The measured touch current of three paralleled SGI converters is 0.049 mA (<0.5 mA, IEC Standard)

Conclusion

- GaN MBDS could further improve the efficiency and power density.
- The long short-circuit withstand time of GaN MBDS improves system reliability.
- Series operation study enables higher voltage application of GaN MBDS.
- SGI is an effective and safe solution to realize galvanic isolation with no magnetics components.
- Two-layer, MHz SGI prototype offers a simple, low-cost design, significantly reducing manufacturing costs.
- Parallel operation of the SGI enables higher-power applications and reduces touch current.

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

Thank you!

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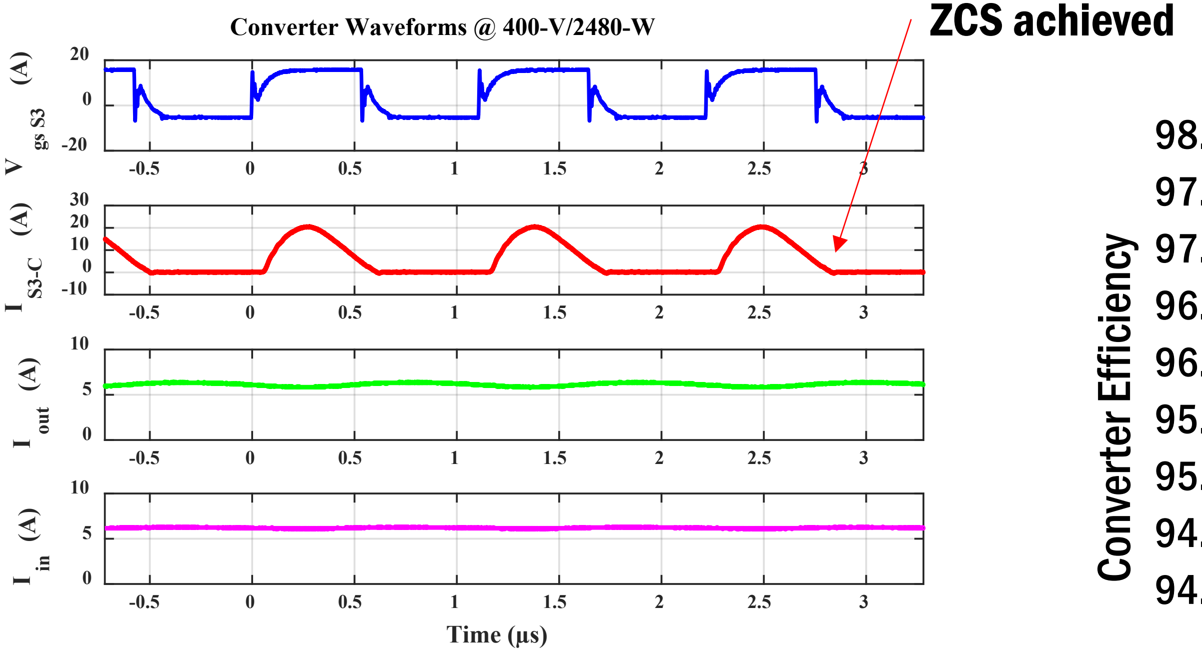
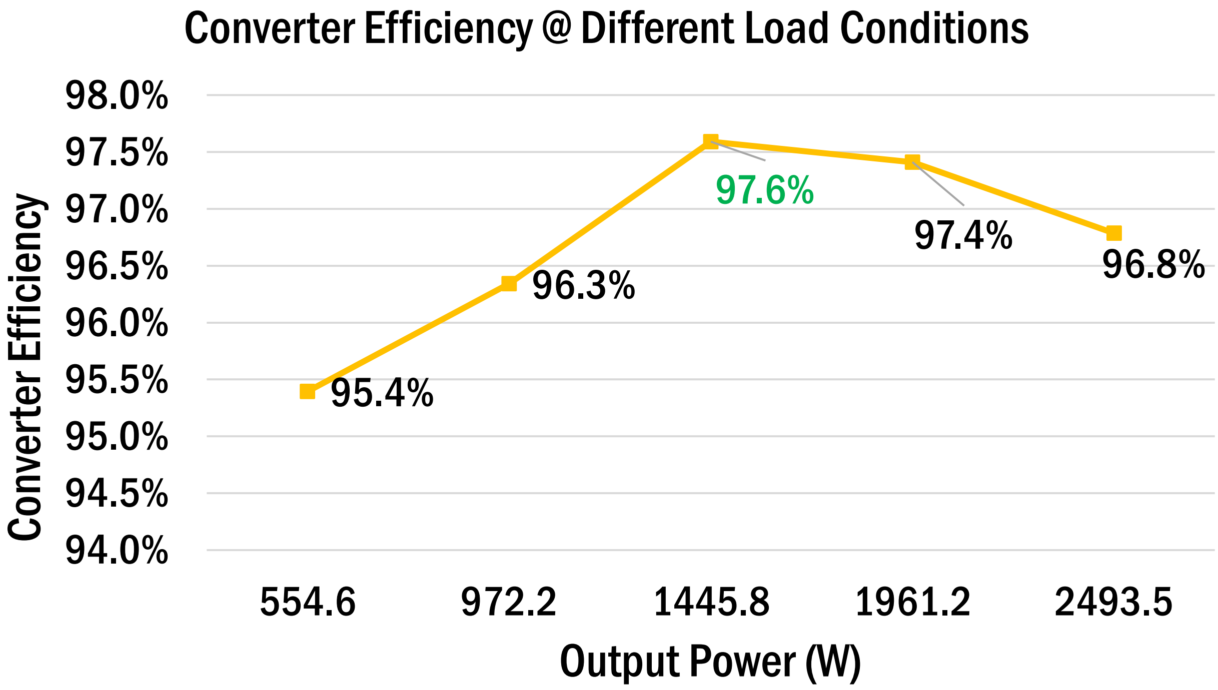
Jin Wang: wang.1248@osu.edu

Backup

2.5-kW 3-Cell SGI Prototype Validation and Efficiency





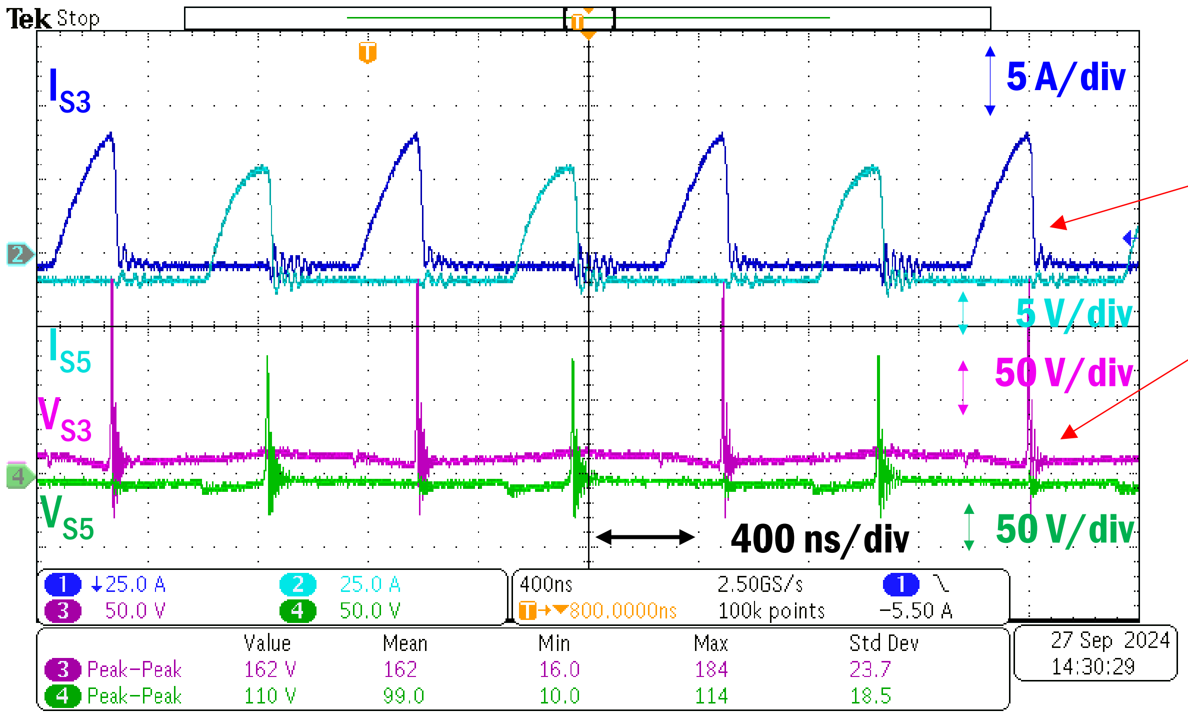

2.5-kW, 400-V, 0.9-MHz SGI Module

- Converter power loss includes a 16.5-W power consumption for driving and control circuit

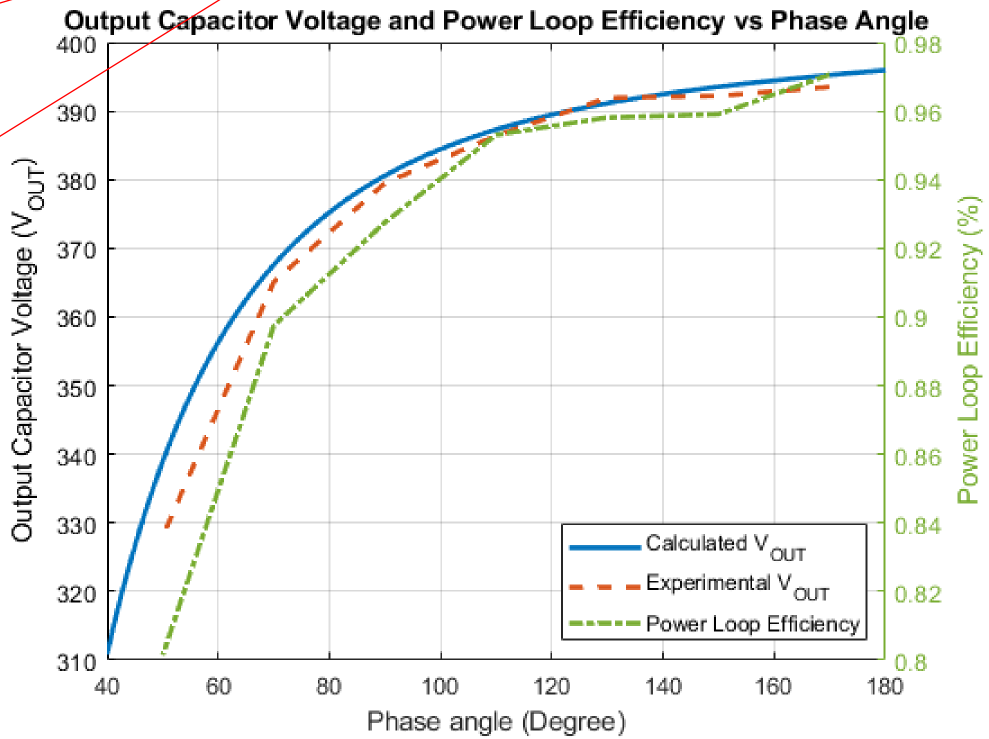
When considering power loop efficiency only, a 98.7% peak efficiency is achieved.

2.5-kW 3-Cell SGI Voltage Regulation

70° phase angle (213-ns t_{ON})



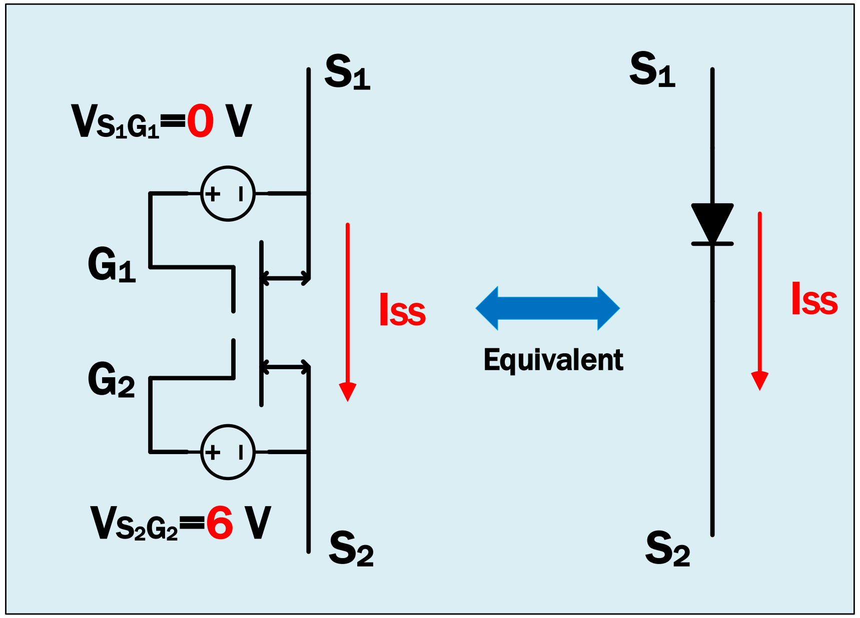
Hard switching for SC cells

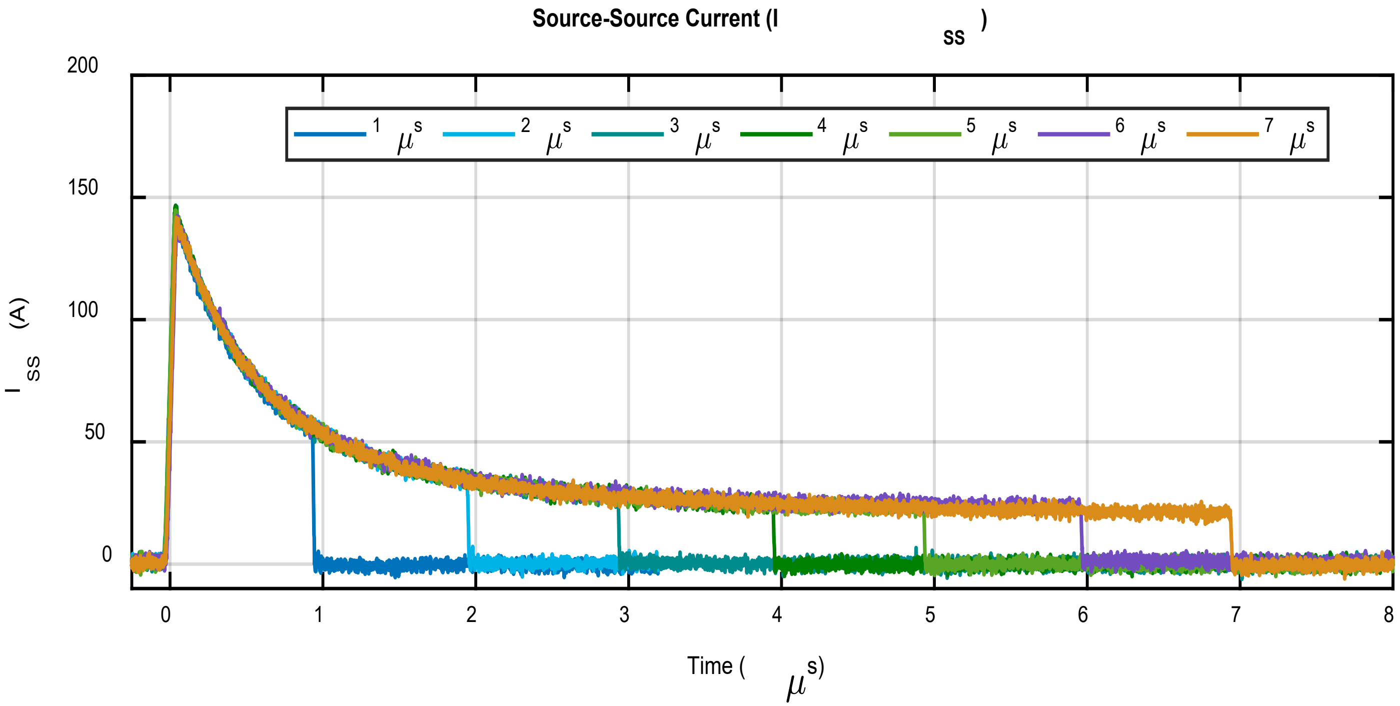


- Forced resonant current cut-off regulates output voltage
- Hard switching increases device switching loss and converter loss

Voltage regulation is achieved with adjustable turn-off angle with certain compromise on efficiency.

Short Circuit Withstand Time of with One Gate On





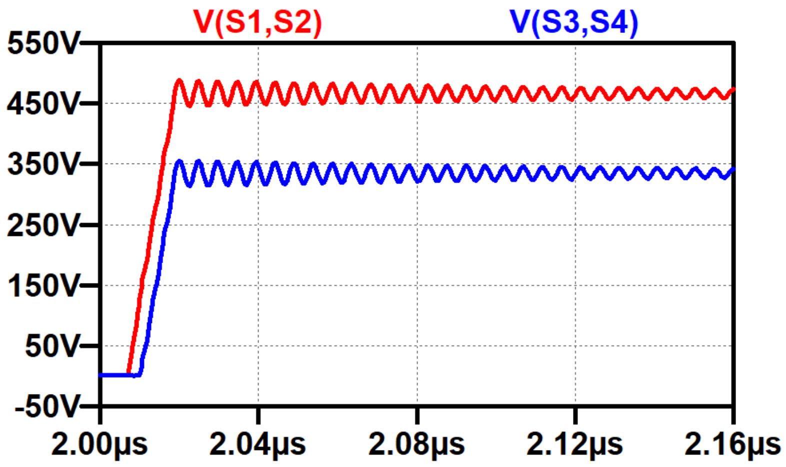
Device	DC Bus	I_{pk}	SC Energy	SCWT	Breakdown
Navitas GaN MBDS	400 V	141 A	85.78 mJ	7 μs	7.25 μs

Challenges for Series Operation of GaN MBDS: Driving Circuit Variation

Differences in gate driver propagation delay, gate resistance, or parasitic inductance could cause asynchronous switching transitions.

Comparison of Gate Driver Solutions for GaN MBDS

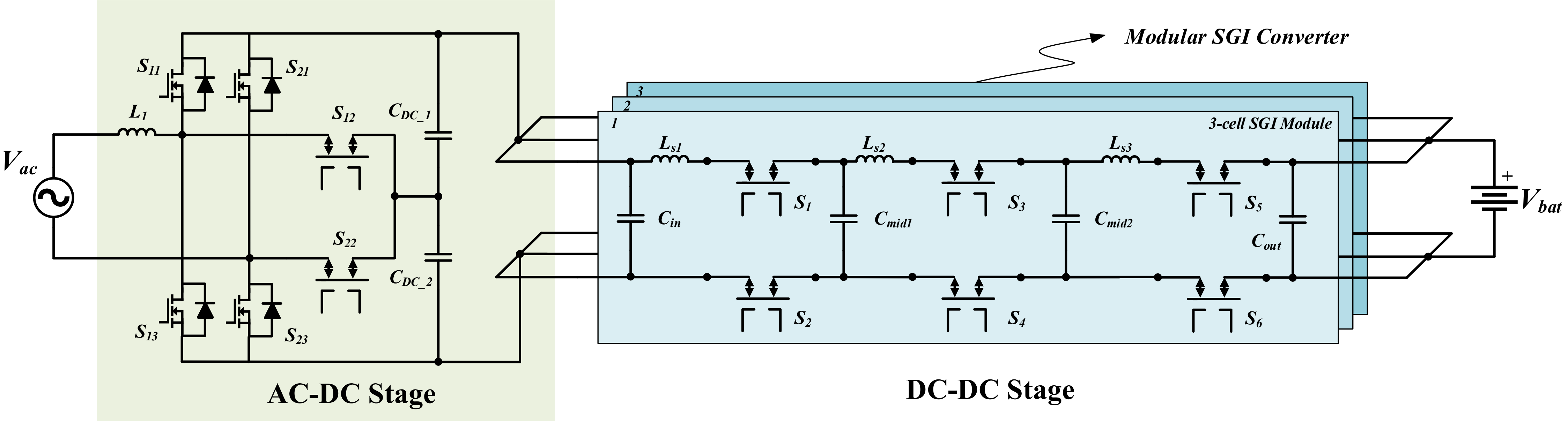
Part Num.	CMTI	Barrier capacitance	Channel	Propagation delay
MAX22701EASA+	300 V/ns	1 pF	1	2 ns (part to part)
NV1702	200 V/ns	0.2 pF	2	0.34 ns (channel to channel)



Simulated turn-off transient with 3 ns gate signal mismatch

Symmetric layout and low-tolerance components in driving circuits are required to achieve voltage balance.

Proposed 7.5-kW Magnetic-less Galvanically Isolated AC-DC Converter



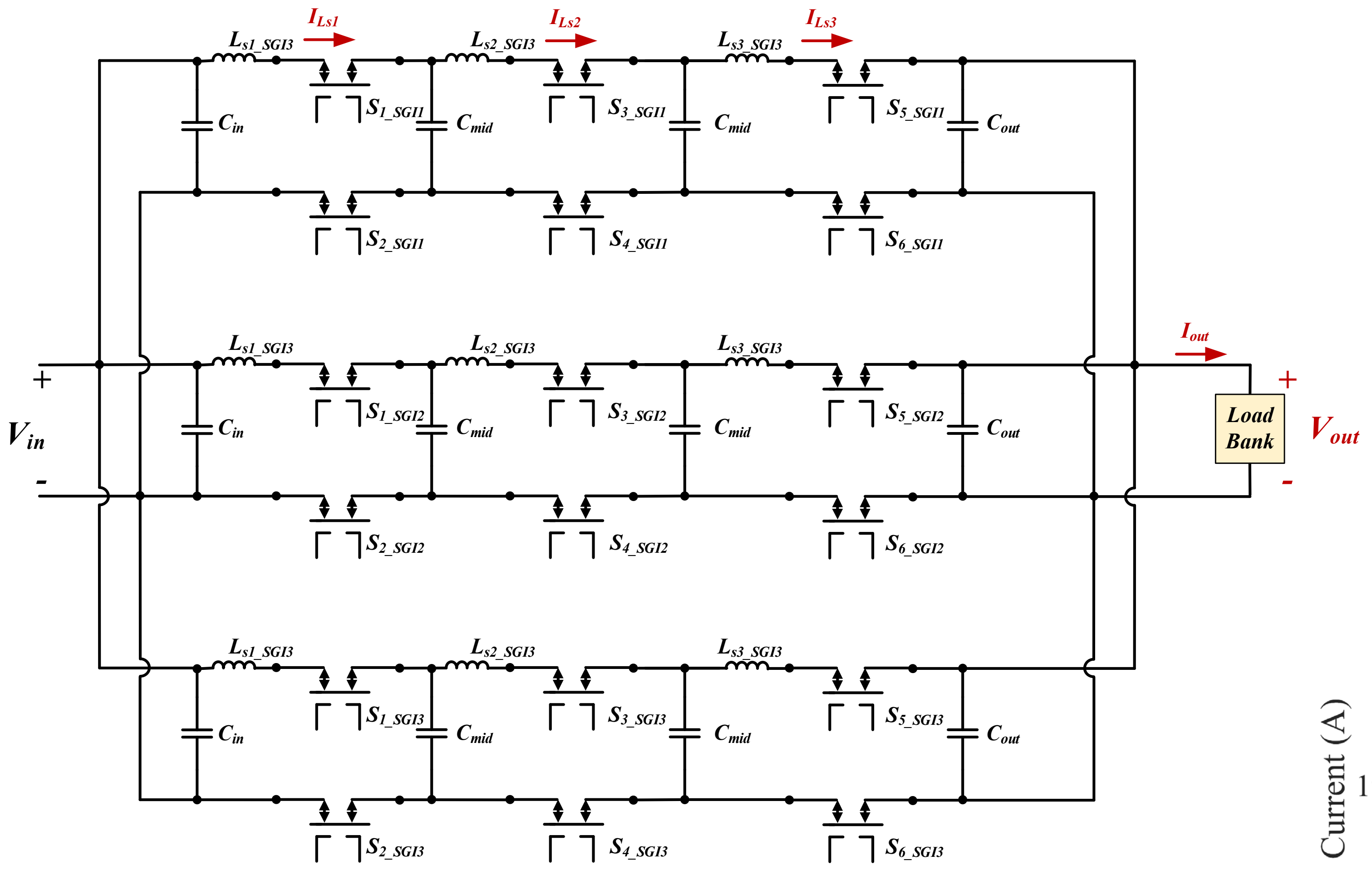
Ac-Dc stage

Parameters	Value
Switching frequency	25 kHz
Input ac voltage (RMS)	240 V
Output dc voltage	400 V
Power rating	7.5 kW

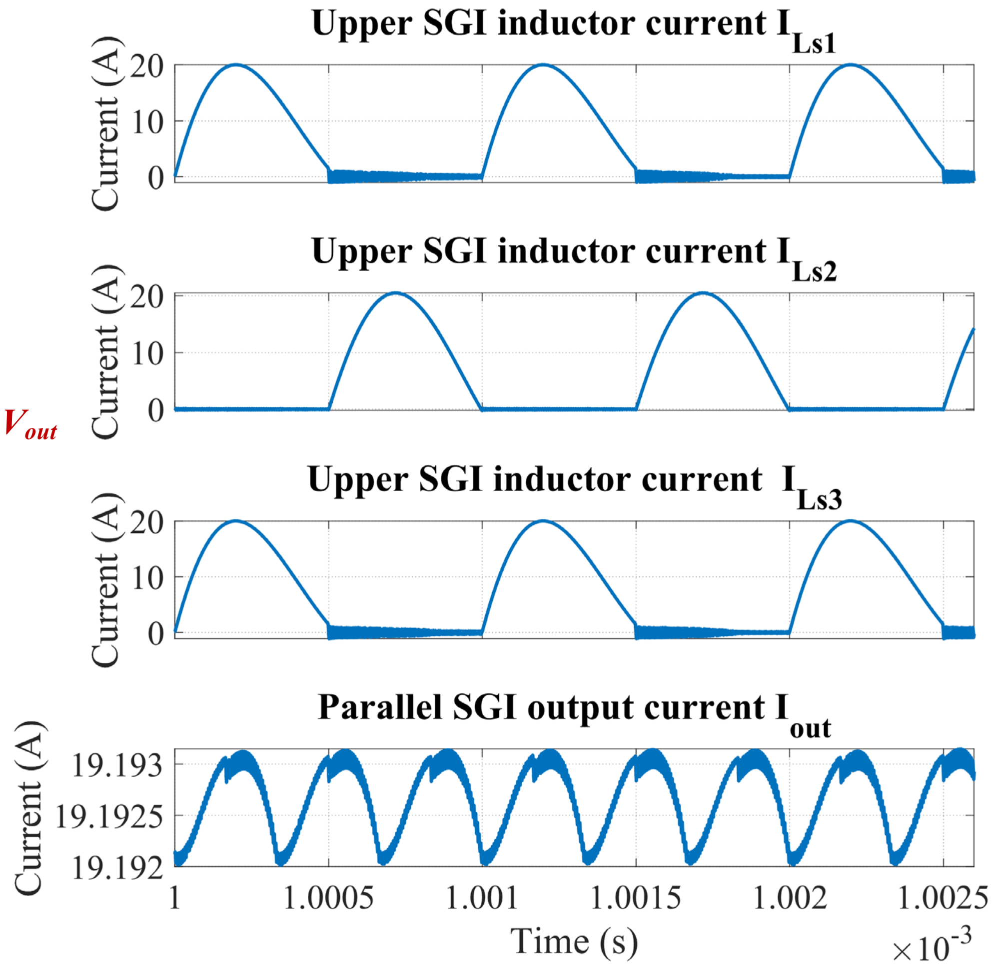
Dc-Dc stage

Parameters	Value
Switching frequency	900 kHz
Input dc voltage	400 V
Output dc voltage	400 V
Power rating	7.5 kW

Parallel Configuration of Three SGI Modules with Interleaved Strategy

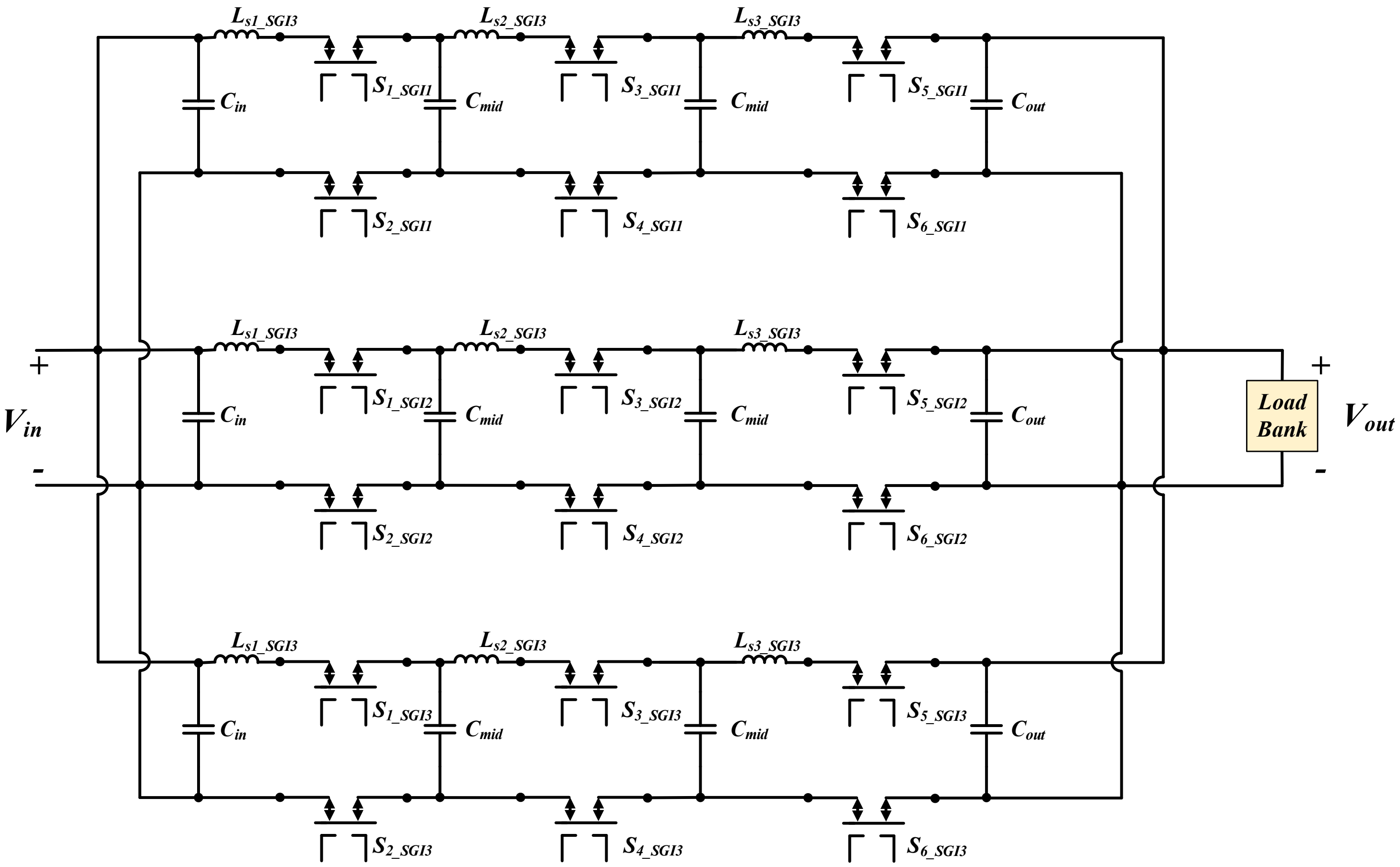


3 paralleled SGI modules circuit topology



The effective switching frequency observed in the output currents is $N_{SGI}*f_s$, which is 3 MHz in this case.

Parallel Configuration of Three SGI Modules



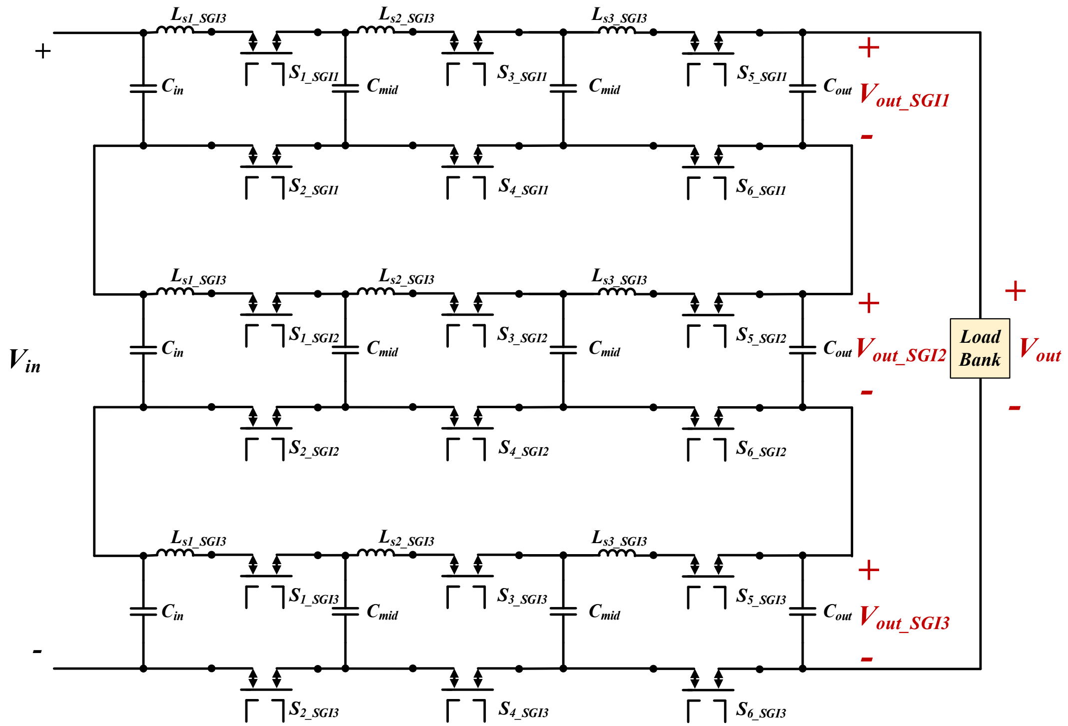
Three SGI modules connected in parallel

Parameters	Variables	Values
DC Input voltage	V_{in}	400 V
Input power	P	7.5 kW
Switching frequency	f_s	1 MHz
Input dc link capacitance	C_{in}	6 µF
Mid capacitance	C_{mid}	1.2 µF
Output dc capacitance	C_{out}	1.2 µF
Resonant Stray Inductance	$L_{s1/3}/L_{s2}$	20 nH/ 40 nH

Withstand Voltage for the Paralleled SGI Modules

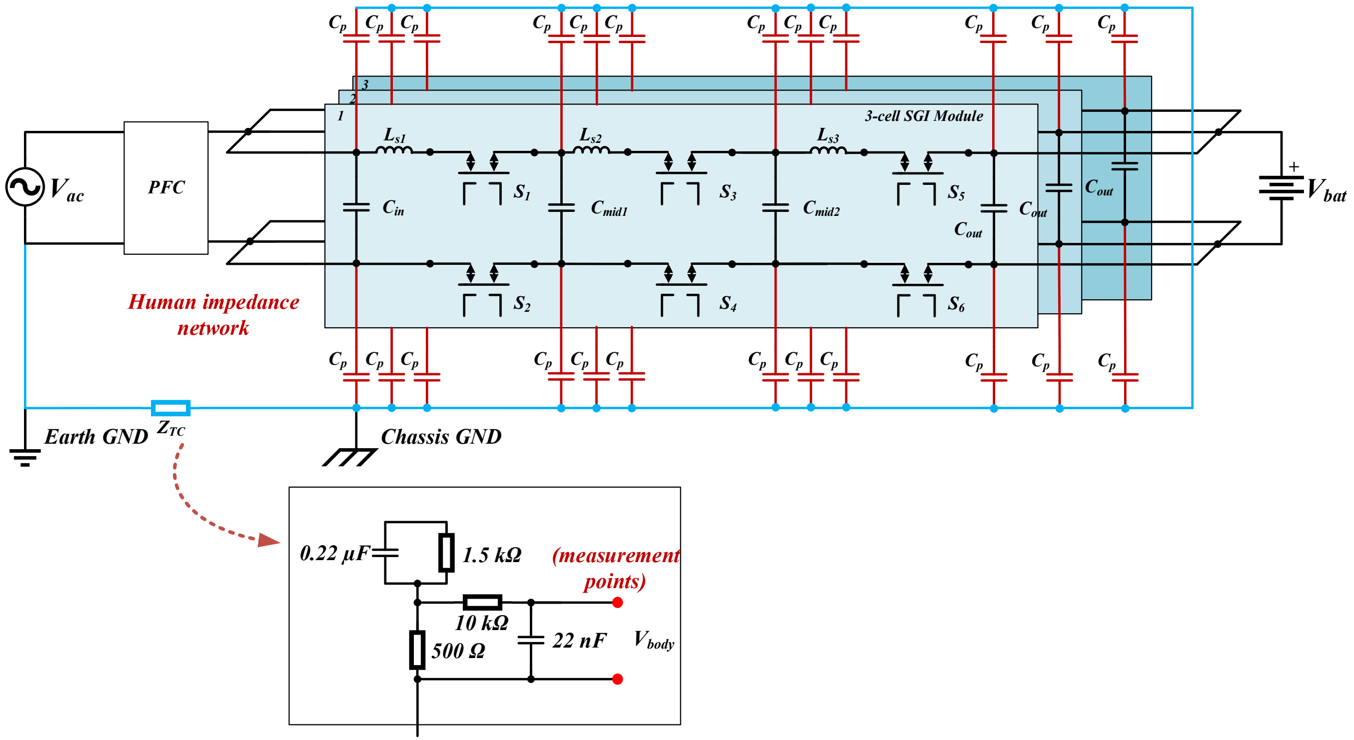
UL 1741: inverters and converters for distributed energy resources are required to withstand one thousand volts plus twice the maximum operating voltage for one second.

- Input voltage: 450 V
- Required withstand voltage: 450 V × 2 + 1000 V= 1900 V
- SGI withstand voltage: 650 V × 3 = 1950 V √



Touch Current Analysis

IEC 61558-1: Touch current of galvanic isolated converter needs to be less than 0.5 mA.



- The voltage ripple on the DC-link capacitors determines the touch current flowing through the human impedance network Z_{TC}

$$I_{tc} = \frac{V_{ripple}}{Z_{chassis} + Z_{TC}}$$

- Voltage ripple across the DC-link capacitors (C_{mid}):

$$V_{ripple} = \frac{I_{avg}}{f_s \cdot C_f \cdot \left(1 - e^{-\frac{t_{on}}{(R_{dson}+ESR)\cdot C_f}}\right)}$$

- Due to interleaving of three SGI modules, the effective switching frequency observed from Z_{TC} is 3 times of the individual switching frequency.