# DOE Office of Electricity TRAC

## Peer Review

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

# Intelligent Power Stages (IPSs)

PRINCIPAL INVESTIGATORS
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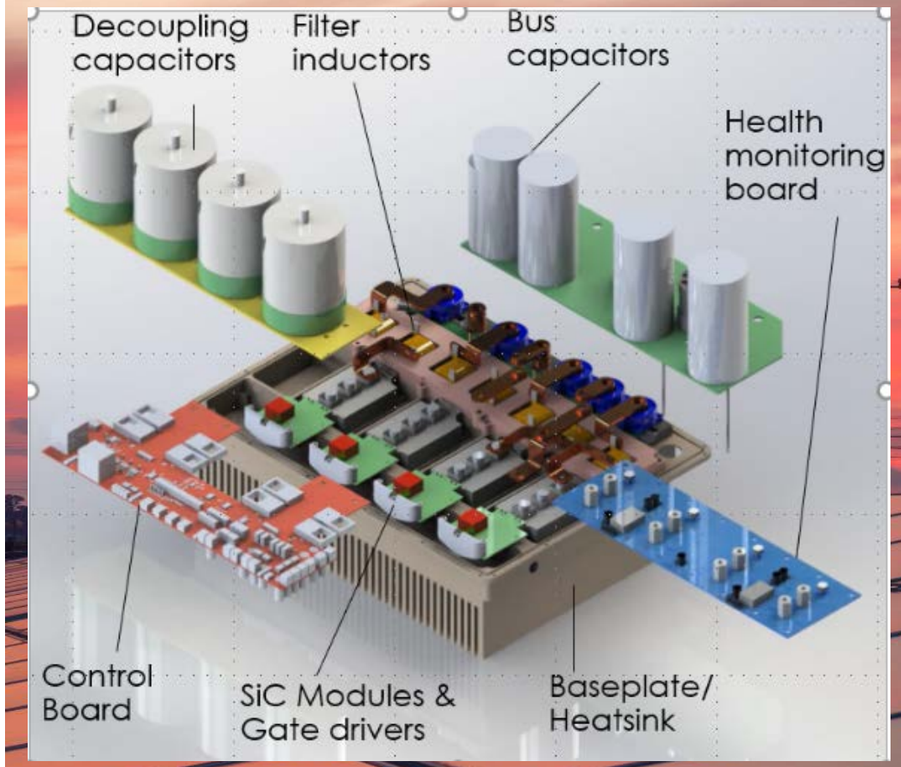
PROJECT SUMMARY

# Smart Universal Power Electronic Regulators (SUPERs) & Intelligent Power Stages (IPSs)

The project focuses on developing and validating an intelligent power stage (IPS) incorporating system interoperability, diagnostics, and prognostics features.

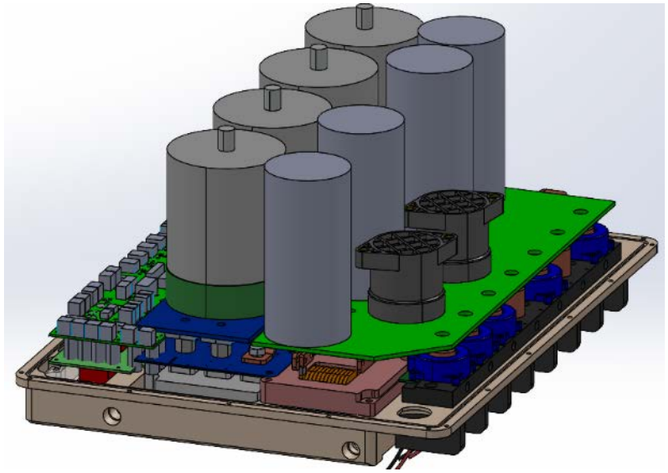
# Innovations

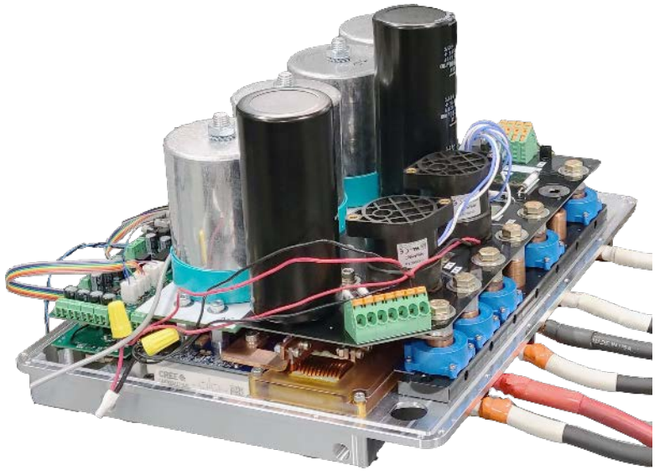
- Development of an interoperable inverter with a secondary controller (IPS-SUPER)
  - Operation of the IPS with an emulated SUPER with less than 1 switching cycle delay
- Development of key elements/sensors/modules to monitor and report on status of the IPS (Diagnostics and Prognostics)
  - Key feature for diagnostics: Shoot-through detection of SiC power modules
  - Key feature for prognostics: resistance change and characterization of SiC semiconductor power modules

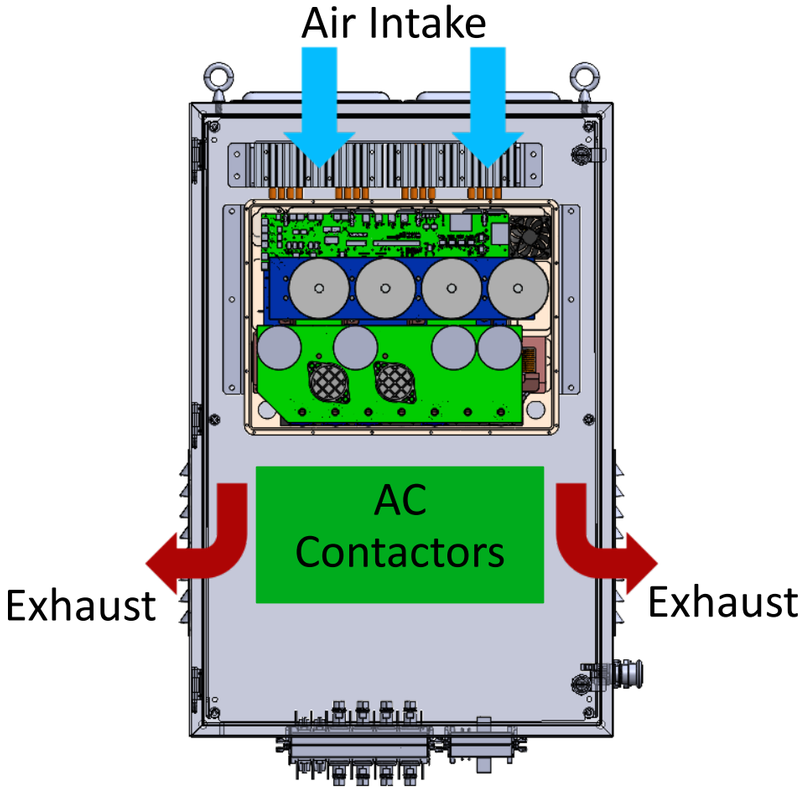


# Innovation Update: IPS-SUPER Hardware

- *Interoperable Intelligent Power Stage (IPS)*

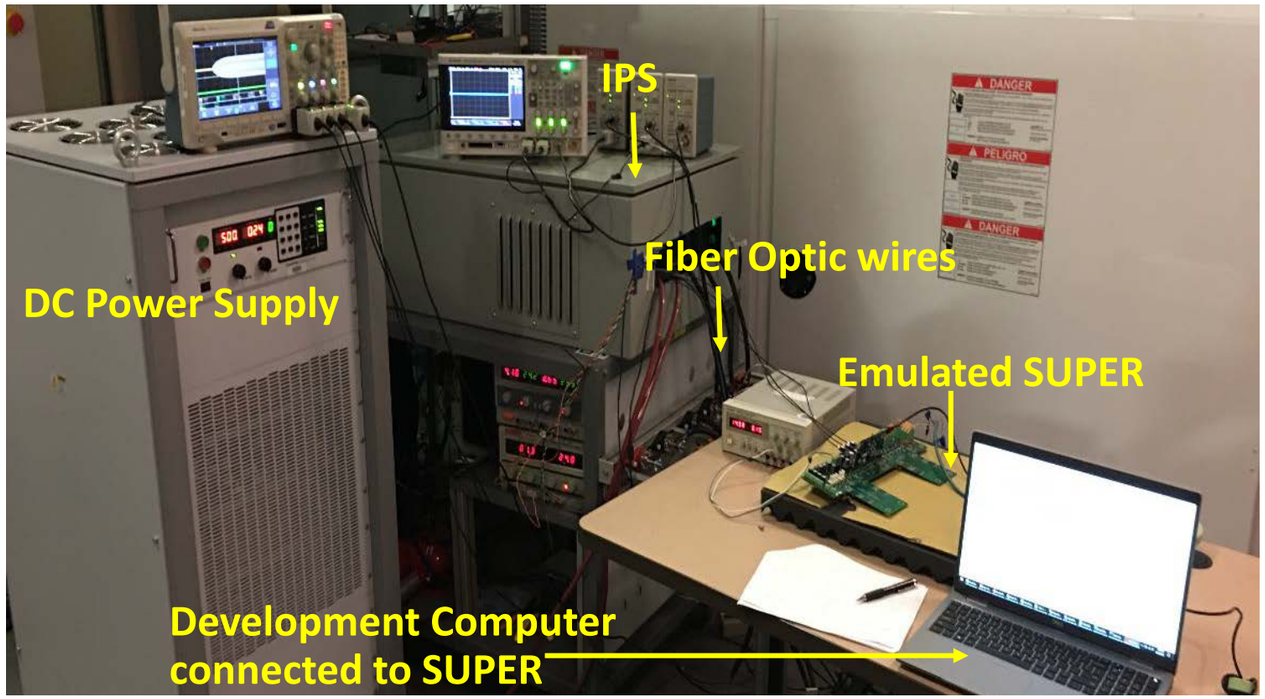


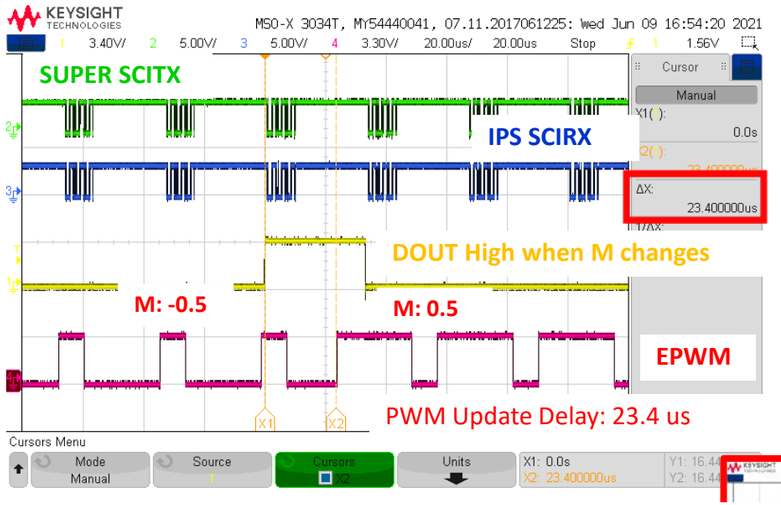


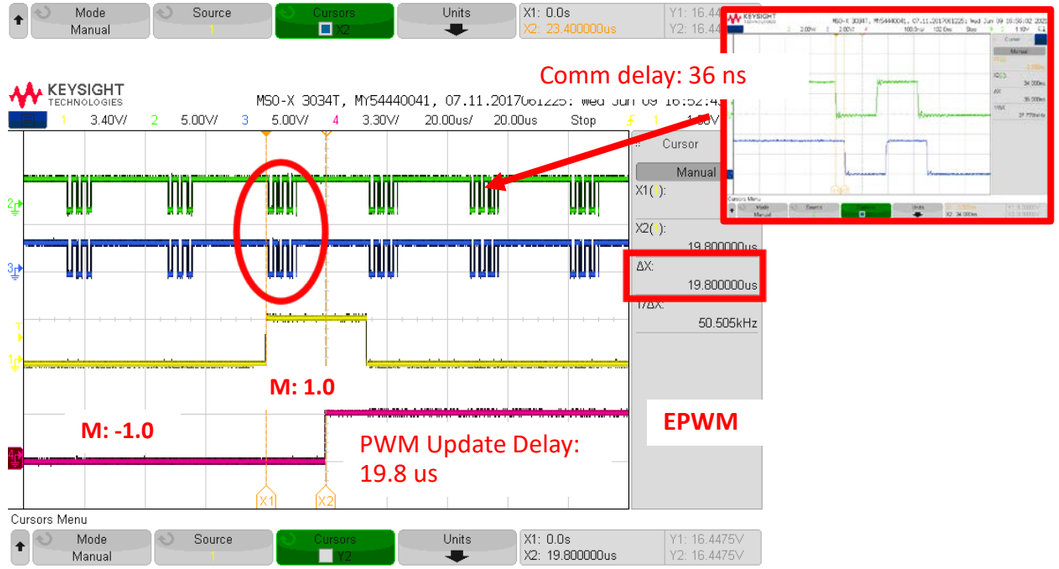



# Innovation Update: Control Concept -1

- *Interoperable Intelligent Power Stage (IPS)*
  - Control Channel Communication Characterization
    - Verified the delay is within one switching cycle

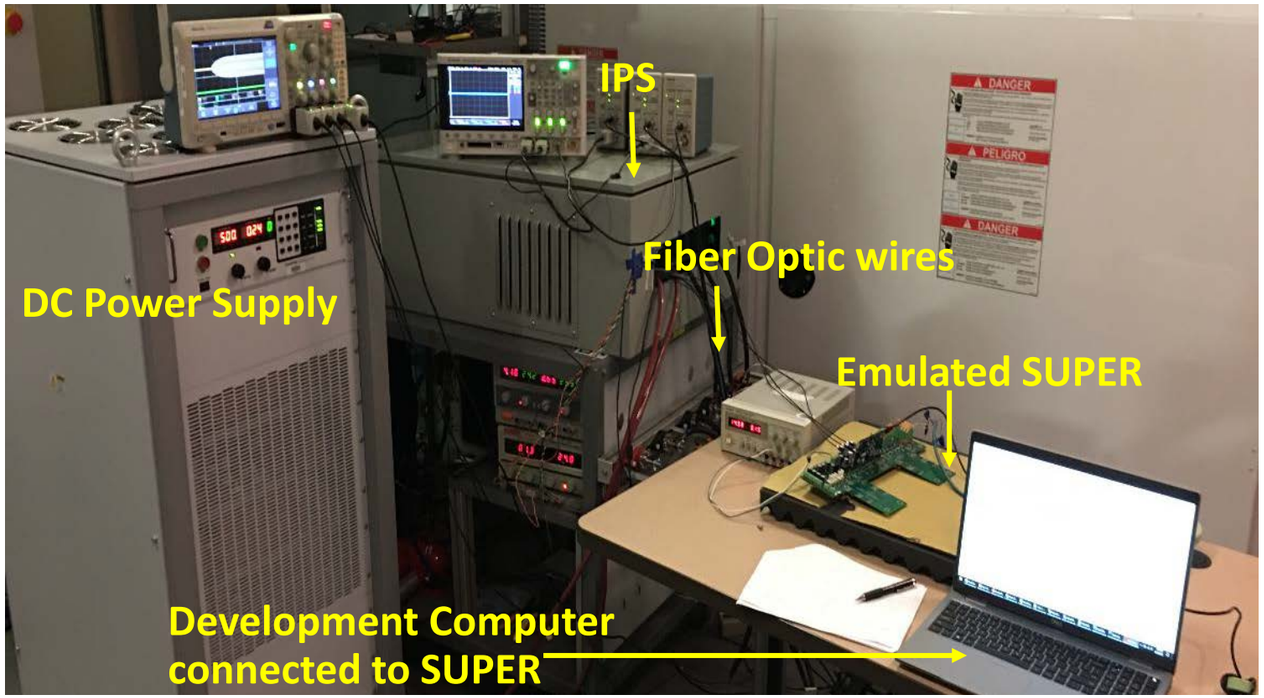


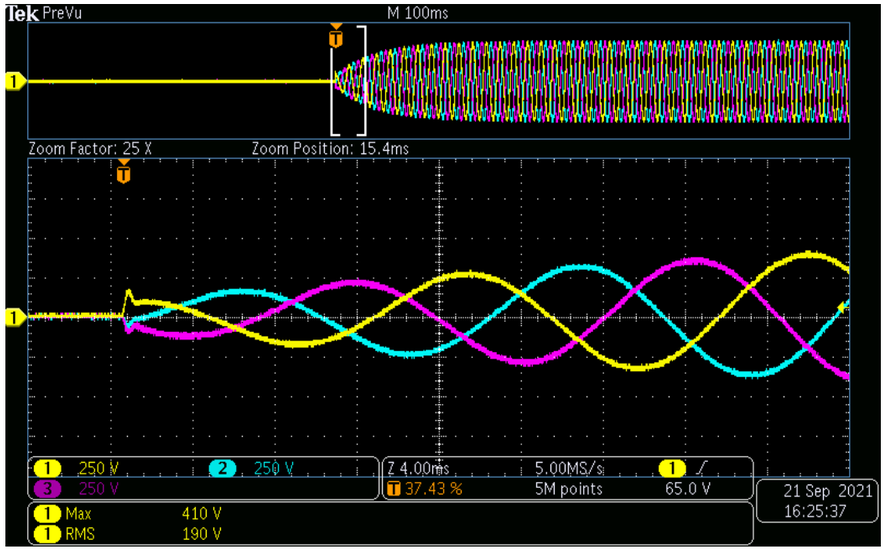



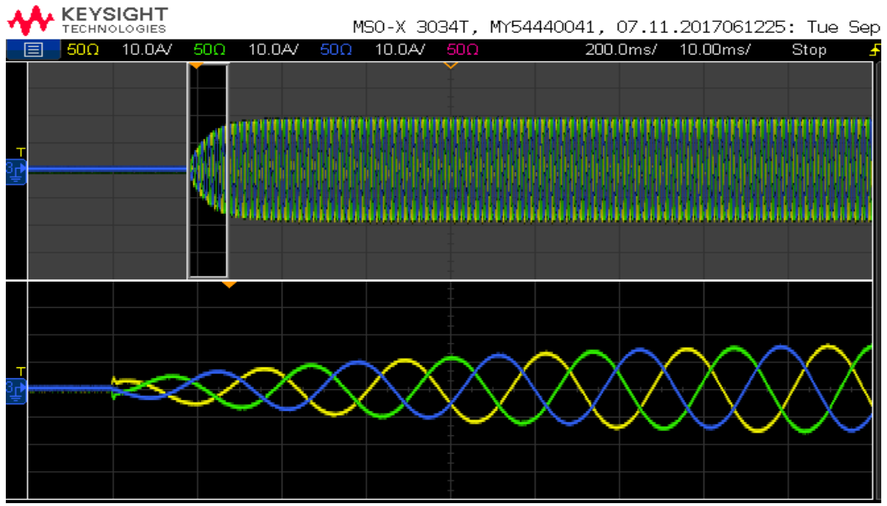
# Innovation Update: Control Concept-2

- *Interoperable Intelligent Power Stage (IPS)*
  - Closed-loop (voltage-mode) at 10kW, 480VAC, 800VDC




3ϕ L-L voltages




3ϕ phase currents

# Innovation Update: Robustness

- *Interoperable Intelligent Power Stage (IPS)*
  - Open-loop Control through Emulated SUPER at 75kW, 480VAC, 900VDC


- 98.36% efficiency was obtained

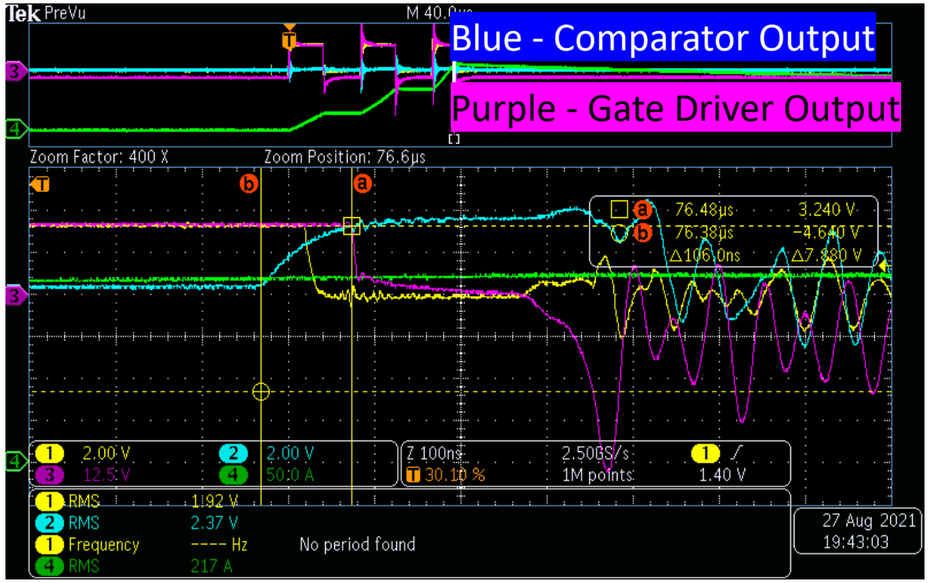
| $P_{IN}$ | $P_{OUT}$ | η | $P_{LOSS}$ |
|---|---|---|---|
| 77.13 kW | 75.87 kW | 98.36 % | 1.26 kW |

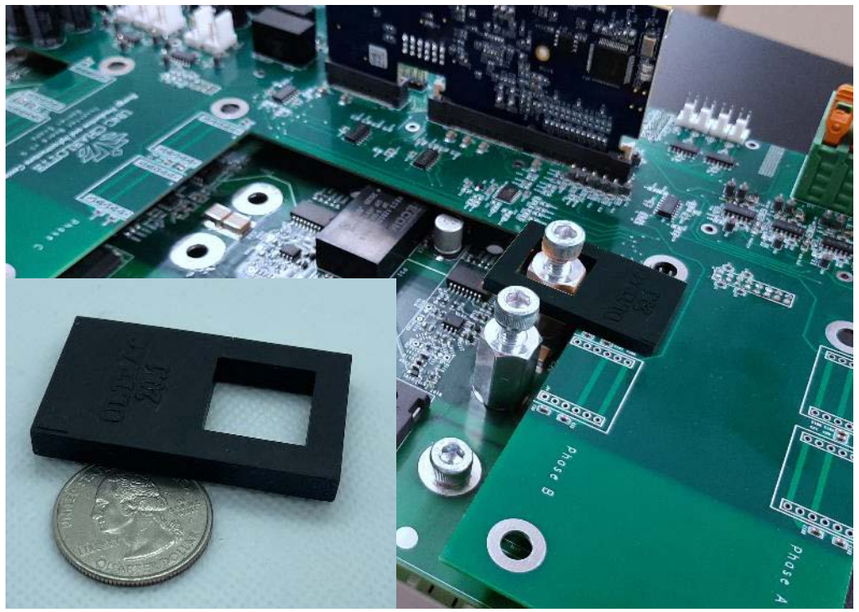
- Waited until the equilibrium temperature point (saturation point)

| Module-PhA | Module-PhB | Module-PhC | Module-PhN | Ambient |
|---|---|---|---|---|
| 49.7 °C | 52.9 °C | 46.8 °C | 32.0 °C | 25 °C |

# Innovation Update: Shoot-Through Sensor

- *Diagnostics: Shoot-Through Protection*
  - Typical de-saturation technique delay is greater than 2 microseconds and highly depends on temperature.
  - Shoot-through alarm & protection in less than 400 nsec.
  - Inverter tripped at 220 Apeak.

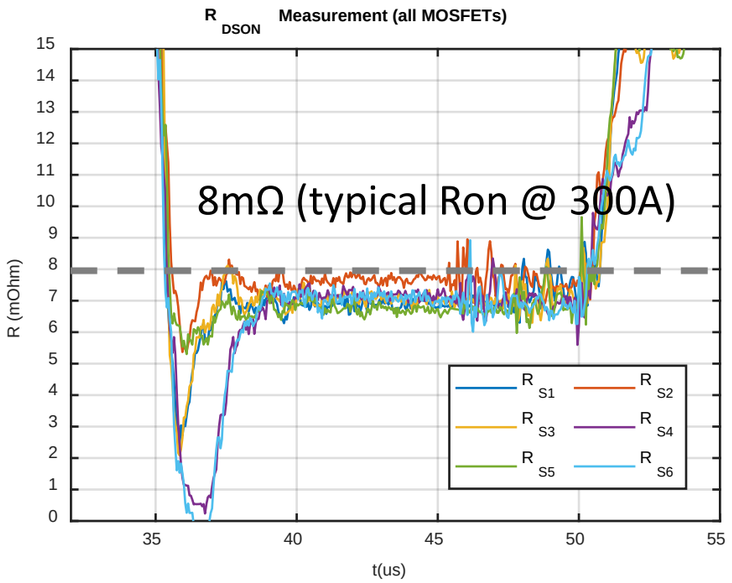


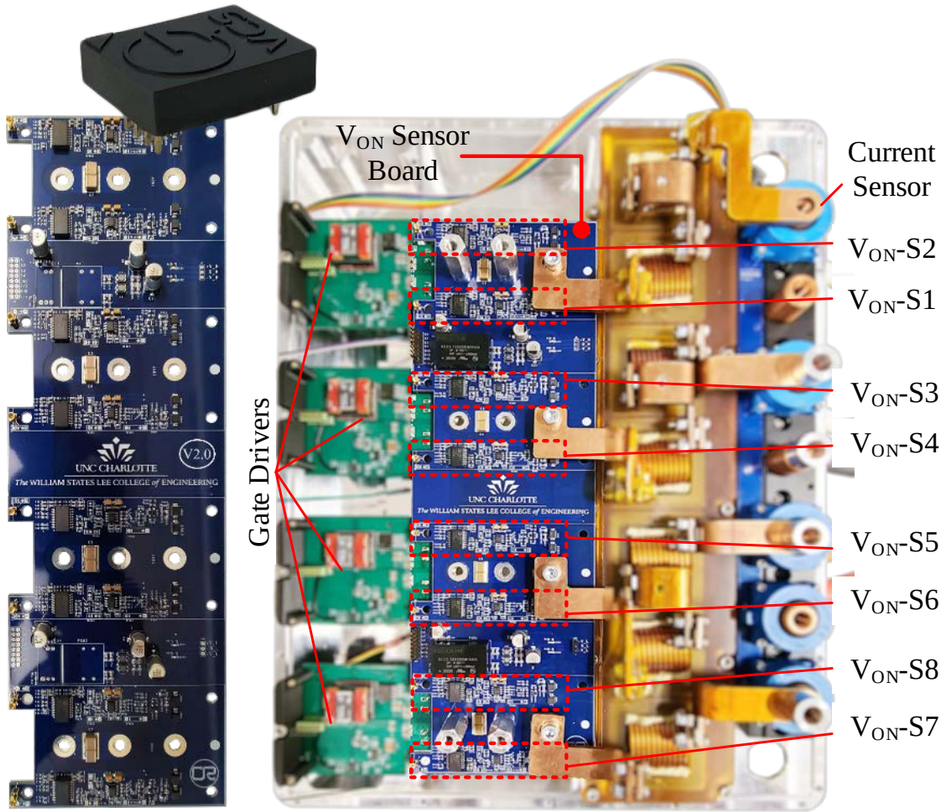
| Symbol | Description | Time |
|---|---|---|
| $T_{comp}$ | Comparator Propagation Delay | 76 ns |
| $T_{GPIO}$ | GPIO Input – RC Pullup Time | 32 ns |
| $T_{MCU}$ | ePWM Trip Latency | 20 ns |
| $T_{GD}$ | Gate Driver Delay | 53 ns |
| $T_{SiC}$ | SiC Module Turn Off time (datasheet) | 219 ns |
| **$T_{total}$** | **Shoot-through protection delay** | **400 ns** |

# Innovation Update: $R_{ON}$ Sensor

- *Prognostics: In-situ real-time $R_{ON}$ Estimation*
  - Developed isolated sensors and an algorithm to monitor the on-state resistance of SiC power modules,
  - Average reporting, one value/second to SUPER: two-four samples per switching cycles, > 30 A.
  - Relative parameter (value) to each device baseline value will be reported to SUPER or IPS-edge processor



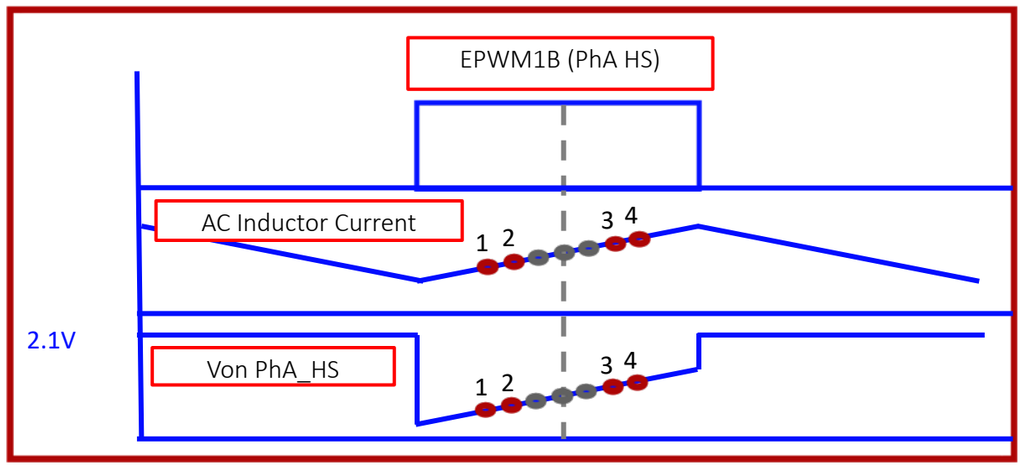

| Device | RON Measured (mΩ) |
|---|---|
| S1 | 6.88 |
| S2 | 7.69 |
| S3 | 7.09 |
| S4 | 7.27 |
| S5 | 6.81 |
| S6 | 7.14 |

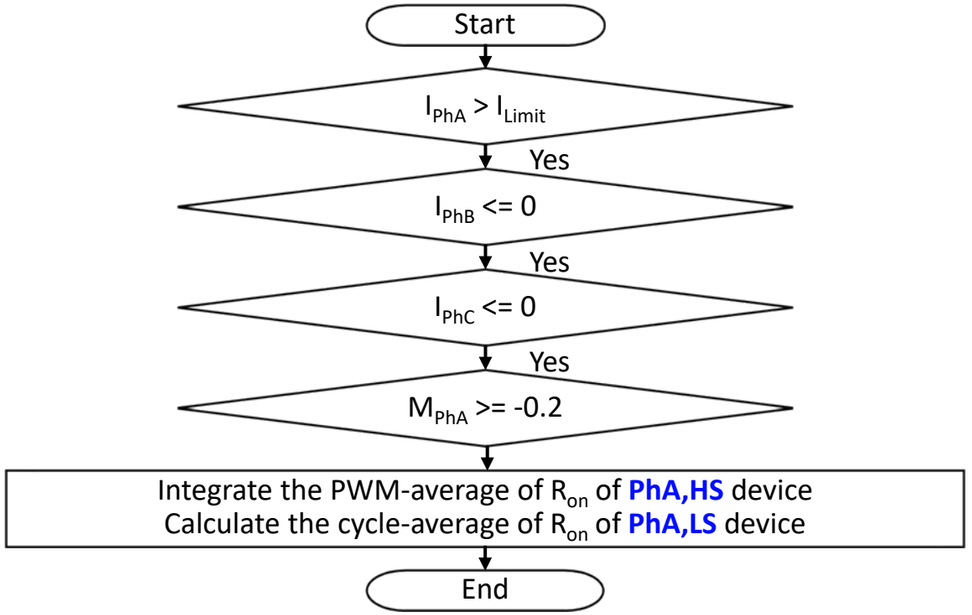


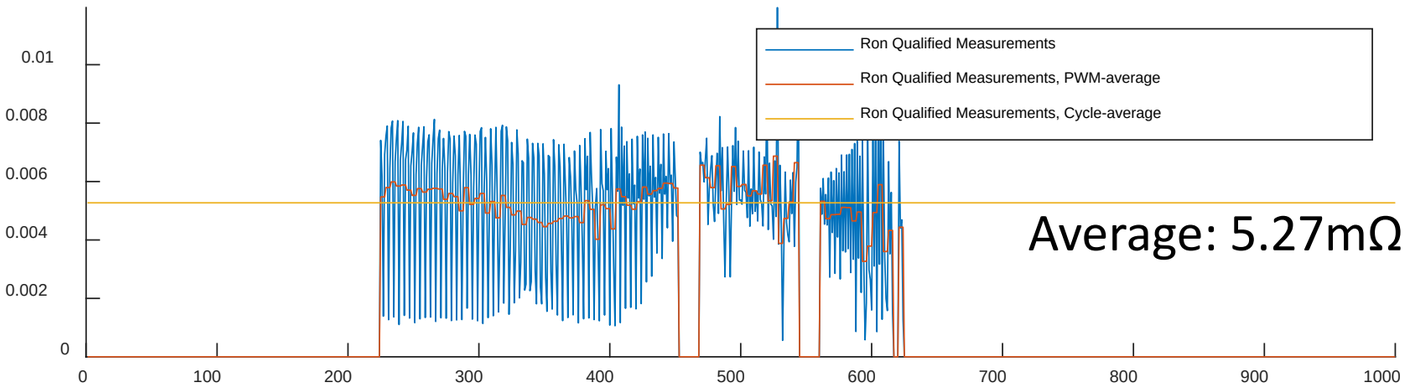

Conditions: 1kVDC, 140Amax, DPT (Second pulse)

# Innovation Update: $R_{ON}$ Algorithm

- *Prognostics: In-situ real-time $R_{ON}$ Estimation - 2*
  - Multi-sample averaging approach

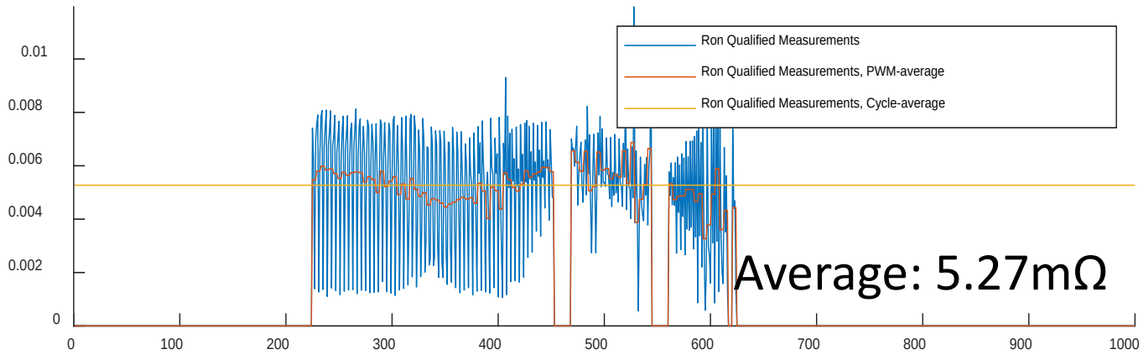


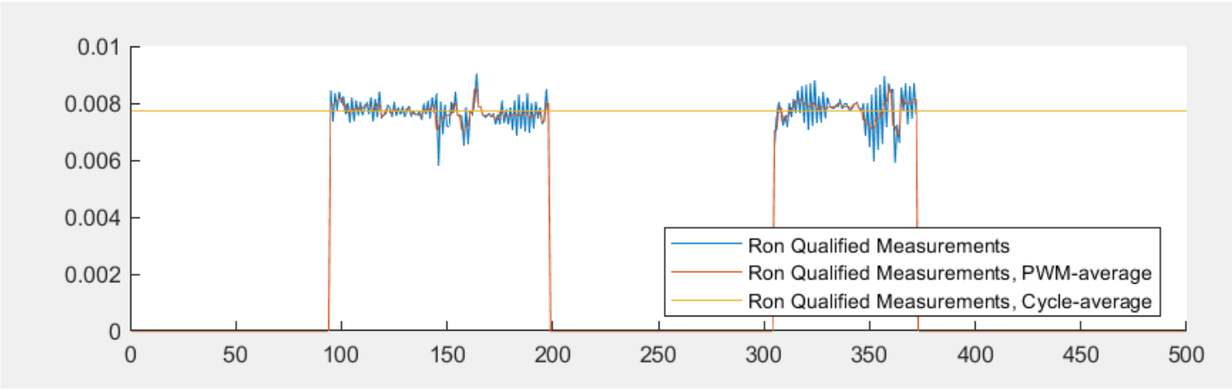



# Innovation Update: $R_{ON}$ Consistency

- *Prognostics: In-situ real-time $R_{ON}$ Estimation - 3*
  - To improve the consistency: hardened the sensing hardware and developed a data qualification algorithm



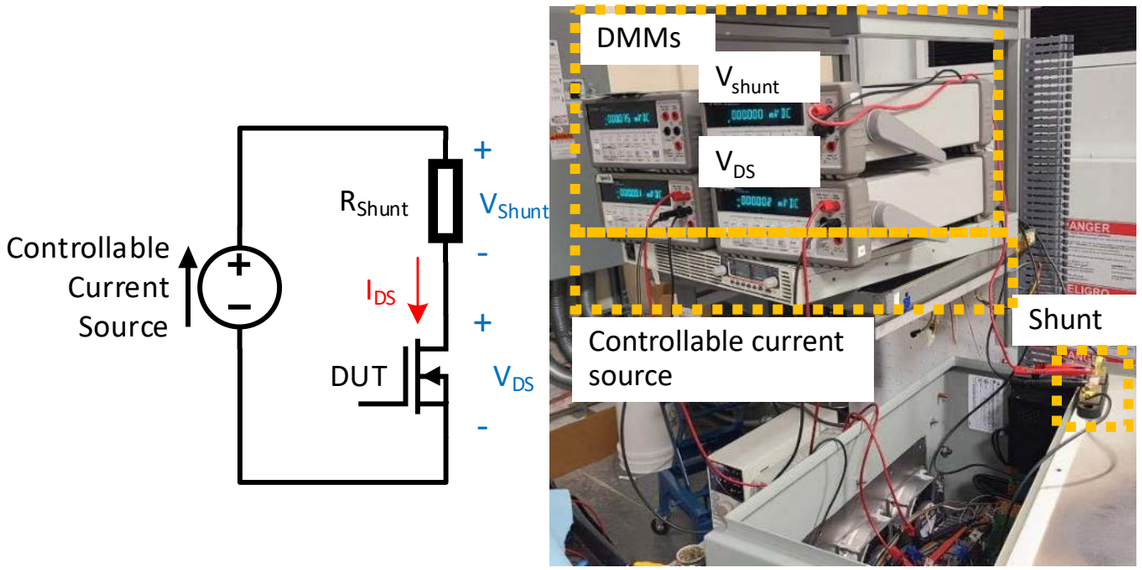

After Data Qualification

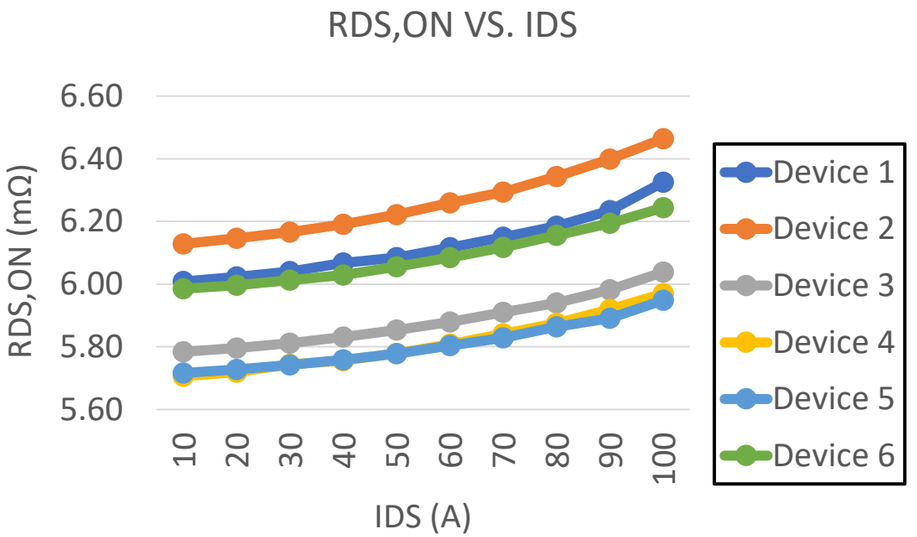


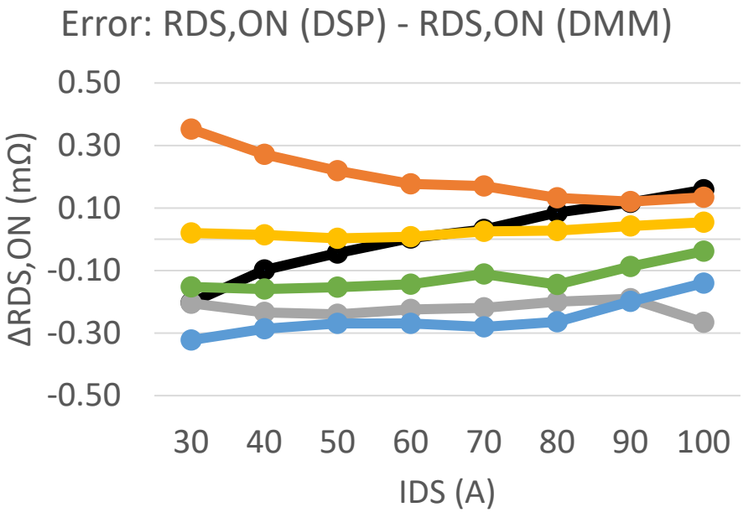

| Cycle-Avrg | PhA,HS | PhA,LS | PhB,HS | PhB,LS | PhC,HS | PhC,LS |
|---|---|---|---|---|---|---|
| MATLAB | 7.72 | 7.67 | 6.01 | 6.83 | 7.03 | 6.59 |
| IPS DSP | 7.71 | 7.67 | 6.02 | 6.82 | 7.02 | 6.58 |

# Innovation Update: $R_{ON}$ Accuracy

- *Prognostics: In-situ real-time $R_{ON}$ Estimation - 4*
  - A true (offline) on-resistance set up developed to measure the reference values for six devices
  - Observed differences from -0.32mΩ to +0.35mΩ which is equivalent to 5%-7%



# Innovation Update : Future

- Calibration of the relative $R_{ON}$ based on the current value and temperature
- Health monitoring of electrolytic DC link capacitors in IPS.
- Development of algorithm identifying the health status of the DC link capacitors.

# Impact/Commercialization

- Include the impact/commercialization status here:

With our industrial partners, an LOI is submitted to DOE SBIR program under DE-FOA-0002555 to commercialize and demonstrate the developed sensors and features in a commercial inverter

## IP STATUS

**Provisional patent application:**
**Title:** On-State Voltage Measurement of High-Side Power Transistors in Three-Phase Four-Leg Inverter for In-Situ Prognostics
**No.**: 63/203,405
**Inventor(s)**: Chondon Roy, Namwon Kim, James Gafford, and Babak Parkhideh
**Status:** Filed new provisional patent application.

# THANK YOU

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