Module Level and System Level Challenges for Integrations of WBG Devices for High Power Applications

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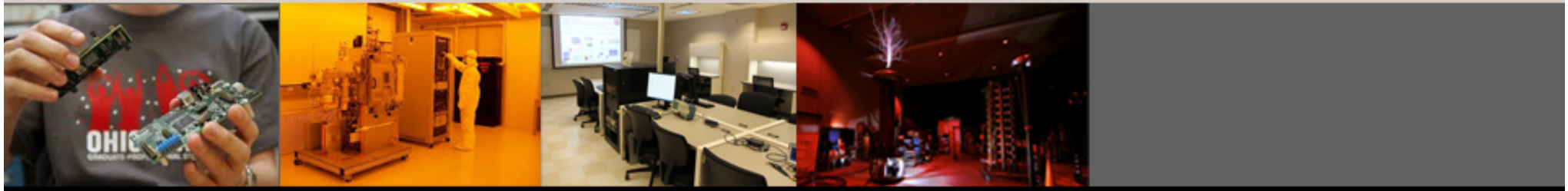
April 24th , 2019



HPPE Center for High Performance Power Electronics

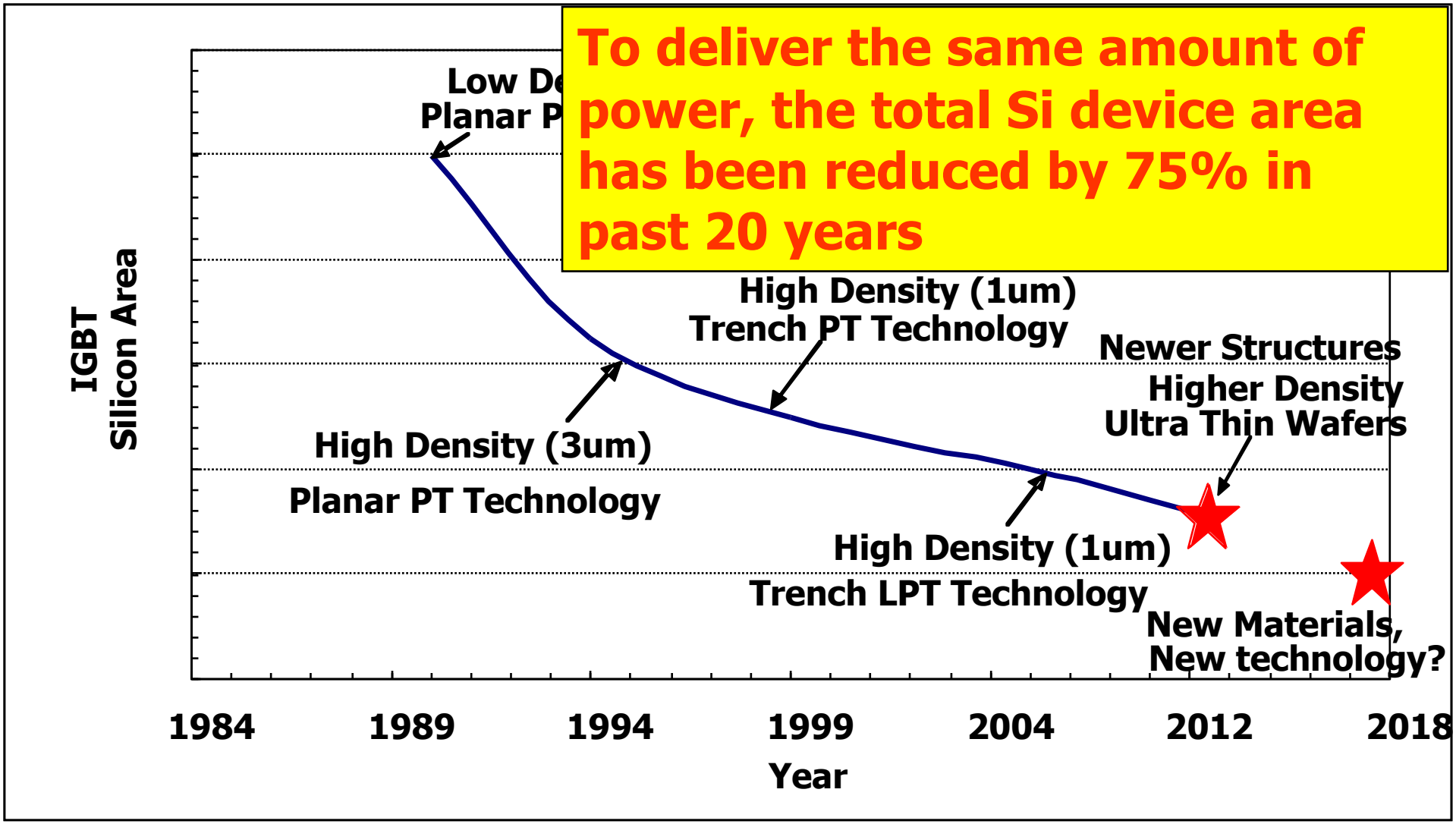
IWIPP

THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

Presentation Outline

- Introduction and high power application examples
- Overview of high dv/dt induced problems in high power applications of WBG devices
- Partial discharge with PWM waveforms with fast rise time
- Summary

Power Module Technology Evolution



Picture Courtesy from Dr. Lihua Chen at the Ford Motor Company

Wide Bandgap Material

	Silicon	Gallium Nitride	Silicon Carbide	Property
Bandgap	1.1 eV	3.4 eV	3.3 eV	Operating temperature
Critical Electric Field Strength	0.3 MV/cm	3.0 MV/cm	2.0 MV/cm	Breakdown voltage On-resistance
Saturation Velocity	1.0×10^7 cm/s	2.5×10^7 cm/s	2.0×10^7 cm/s	Switching Speed

Relevance to Commercial Applications

Higher operating temperatures → Smaller heatsinks
→ Smaller die sizes
→ Lower costs

Faster switching speed → Reduced size of passive elements
→ **A series of new or signified challenges**

High Power SiC Three Phase Inverter

Commercially Available SiC Inverter:

- 250 kW Peak Power
- 800 V_{DC} Bus (1.2 kV SiC)
- (3) 325 A SiC Half Bridge Modules

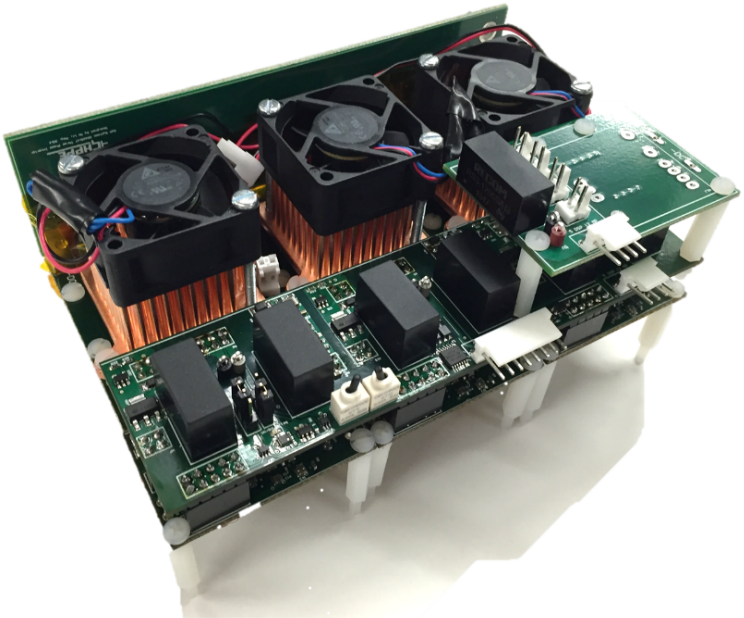
250 kW Three Phase Inverter*

325 A SiC Phase Leg*

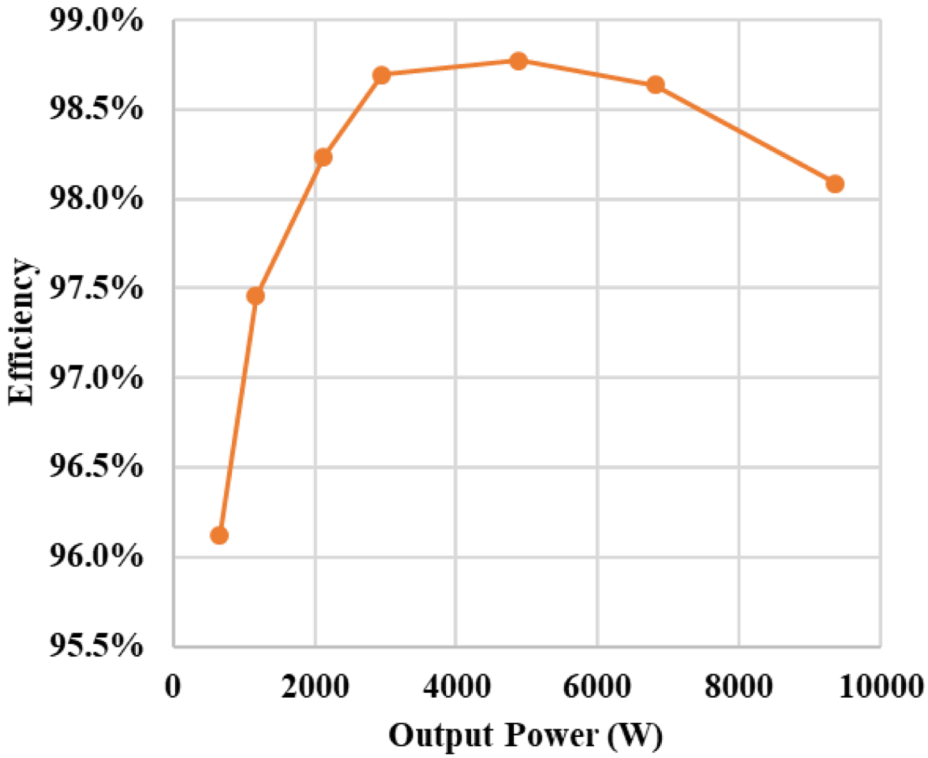
Gate Driver for SiC Phase Leg*

http://www.all-electronics.de/250-kw-wechselrichter-mit-sic-mosfets/2/

10 kW GaN based High Power Density Three phase Inverter



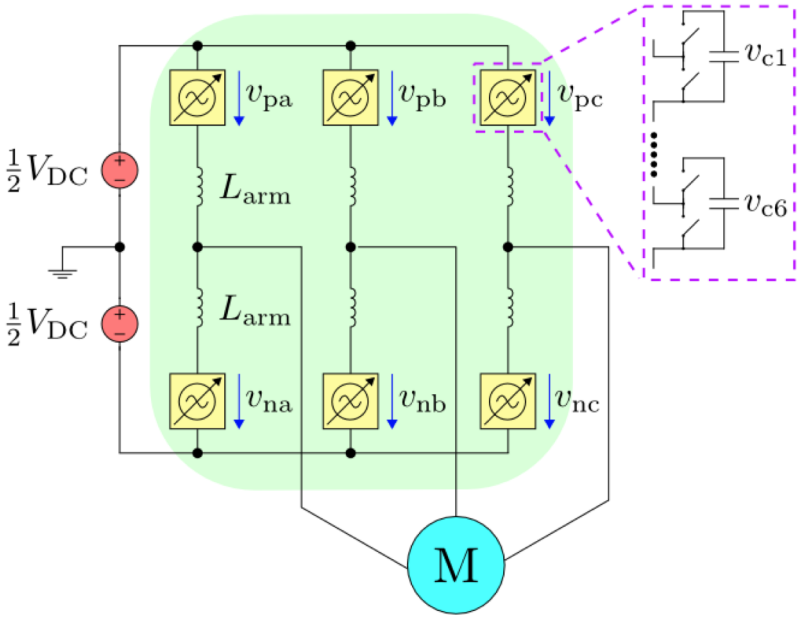
Total box volume: 14.6 cm * 9.3 cm * 5.2 cm = 0.706 Liter

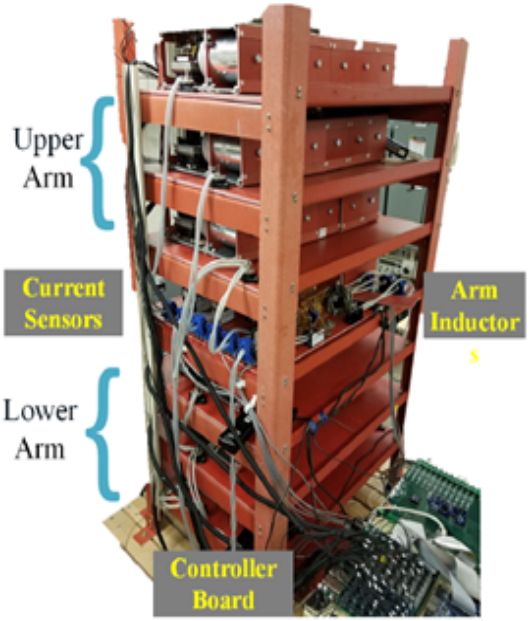


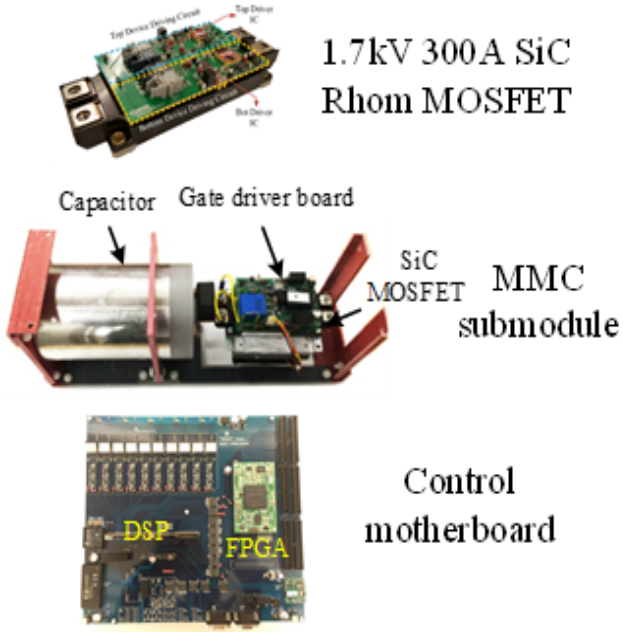
- No free-wheeling diode
- High switching frequency (50 kHz) enabled small dc link capacitor (ceramic)
- Top side cooled device with small heatsink and low power fan

Vdc = 400 V, Vac_{L-L} = 208 V, Fsw = 50 kHz, PF > 0.99

A 7 kV, 1 MVA SiC based Modular Multilevel Converter







- Transformerless
- Thirty six 1.7 kV rated SiC power module based submodules

- Efficiency >99.3%
- Inversed power density of 1.2 m³/MW
- Almost 3 times of loss reduction and 4 times power density improvement
- Reduced submodule capacitance benefited from high frequency switching capability

7 kV 1 MVA SiC-based MMC Test Video

0-1000 Hz Variable Frequency Operation

Capacitor voltage & arm current

Output voltage & current

Test condition: 7kV DC bus voltage, constant 200 A load current

High dv/dt Induced Obstacles

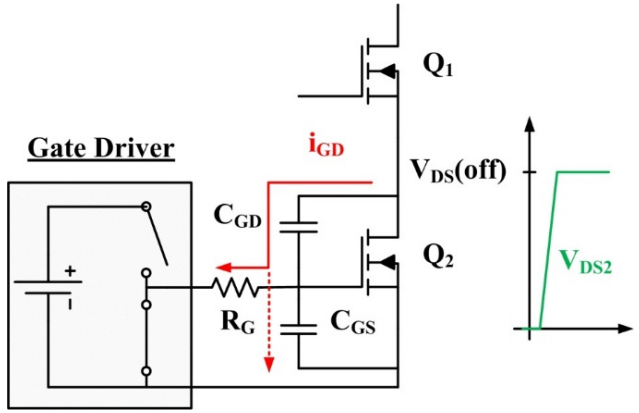
High dv/dt introduces or signifies the following challenges

- Miller plateau
- Gate drive design and auxiliary power supply
- Reflective wave
- EMI
- Insulation degradation and partial discharge in power modules and loads

Miller Capacitance Effect

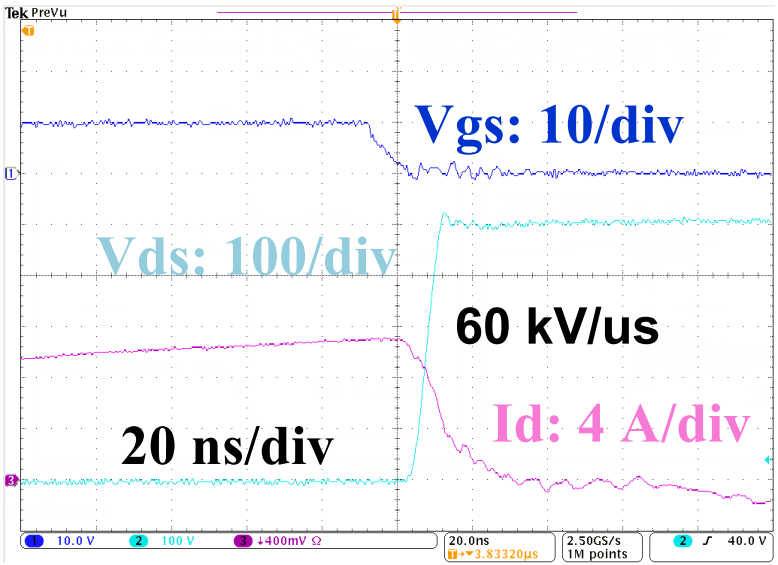
Potential for Shoot Through:

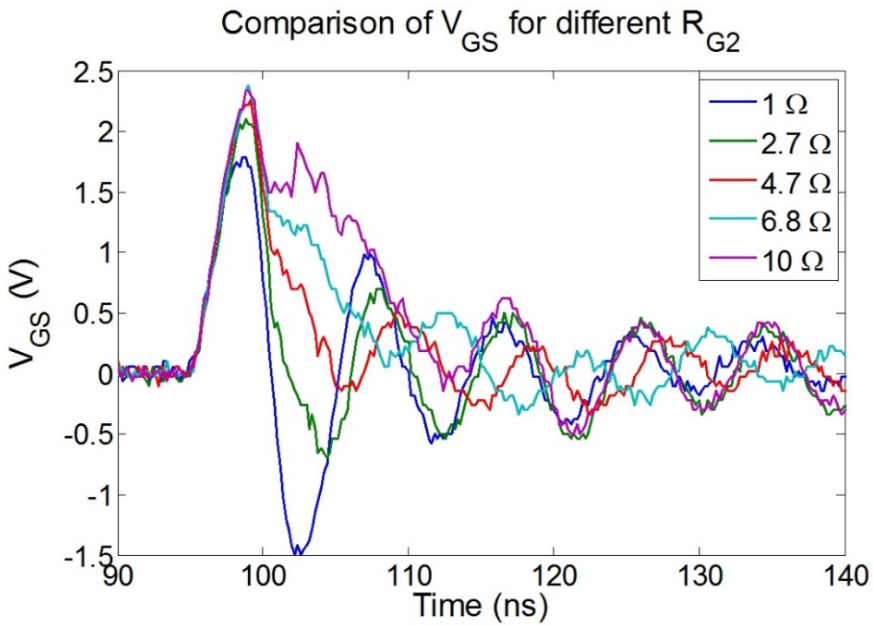
- Upper device in phase leg causes transients to appear on gate-source terminals of lower device.
- If VRG is higher than the VTH, the device will turn on momentarily.



Miller Capacitance Related Shoot- Through

$$V_{GS\_MAX} \approx R_G C_{GD} \frac{dV_{DC}}{dt}$$

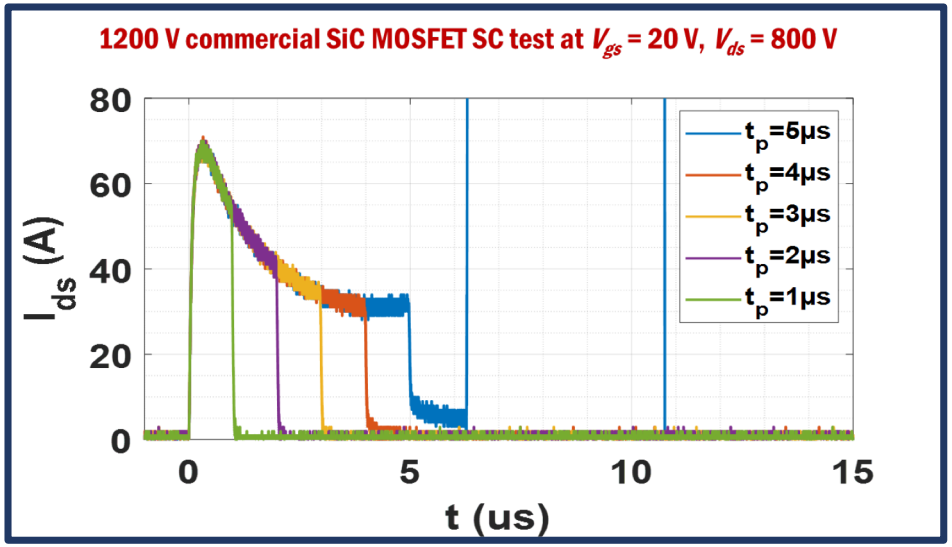


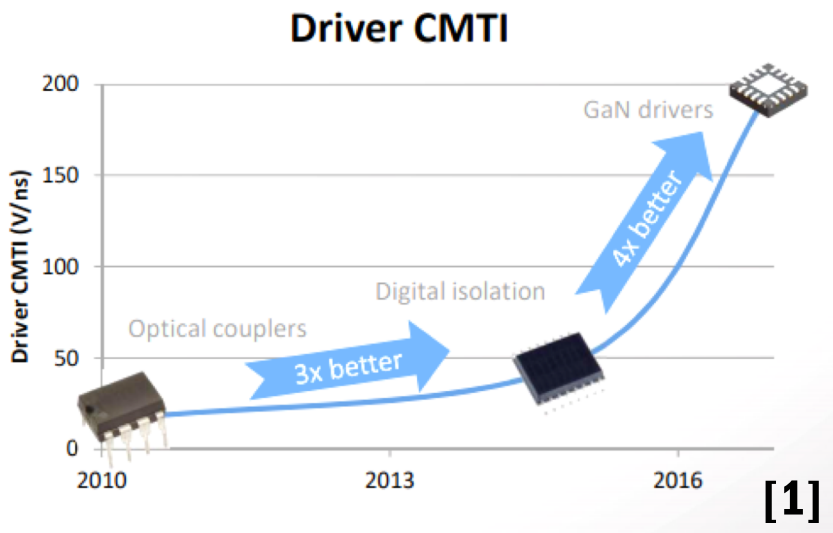


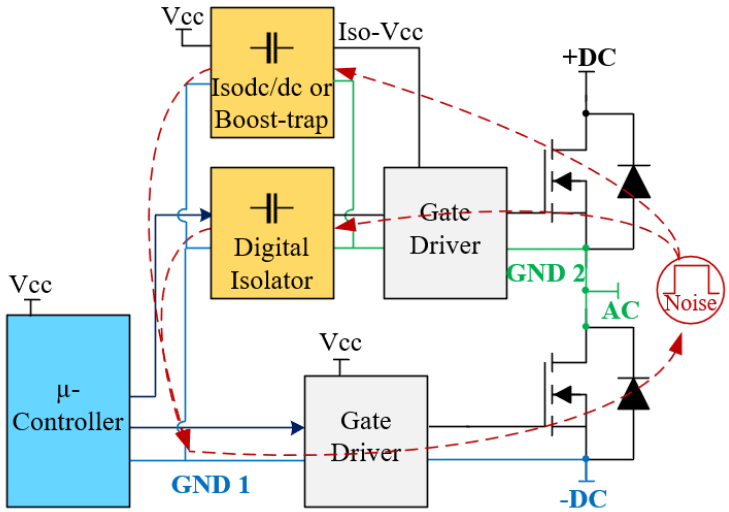
Basic Requirements on WBG Device Gate Drive Circuit Design

Requirements on gate drive circuit:

- **Accurately** drive the device based on μ-controller command;
- **Low coupling** capacitance iso-dc/dc, high CMTI gate drive are necessary for WBG device based converter;
- Provide **sufficient protections** to WBG device.

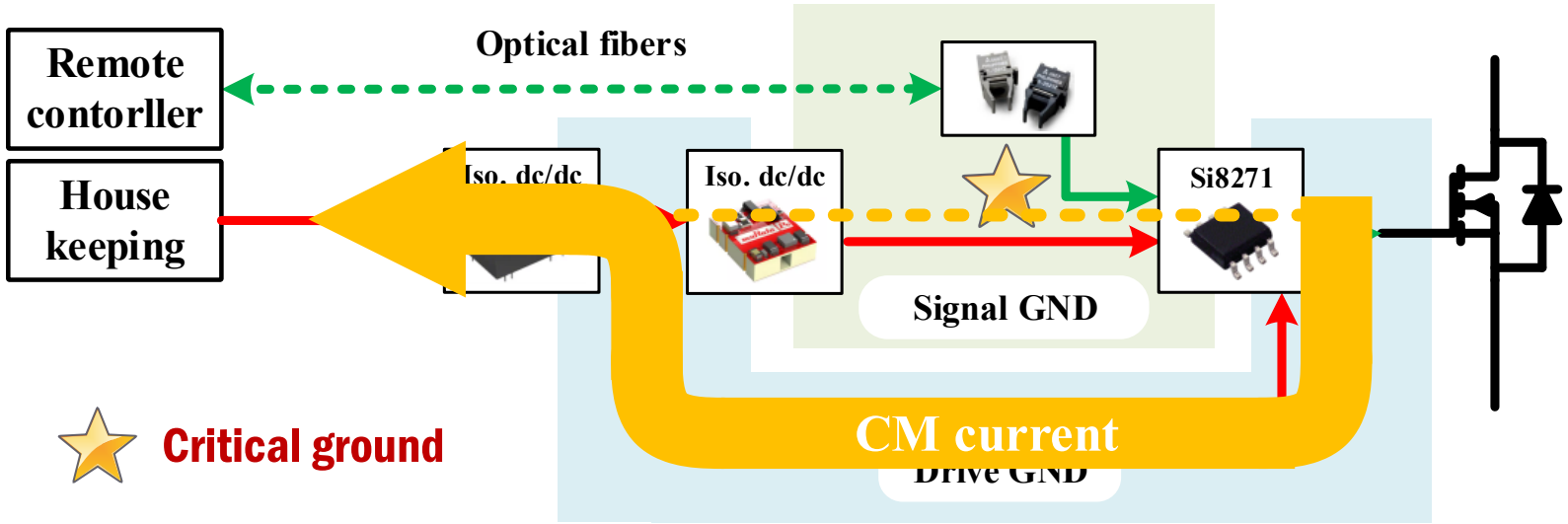






[1] Jim Witham, "Designing with GaN", Presentation, PCIM 2017

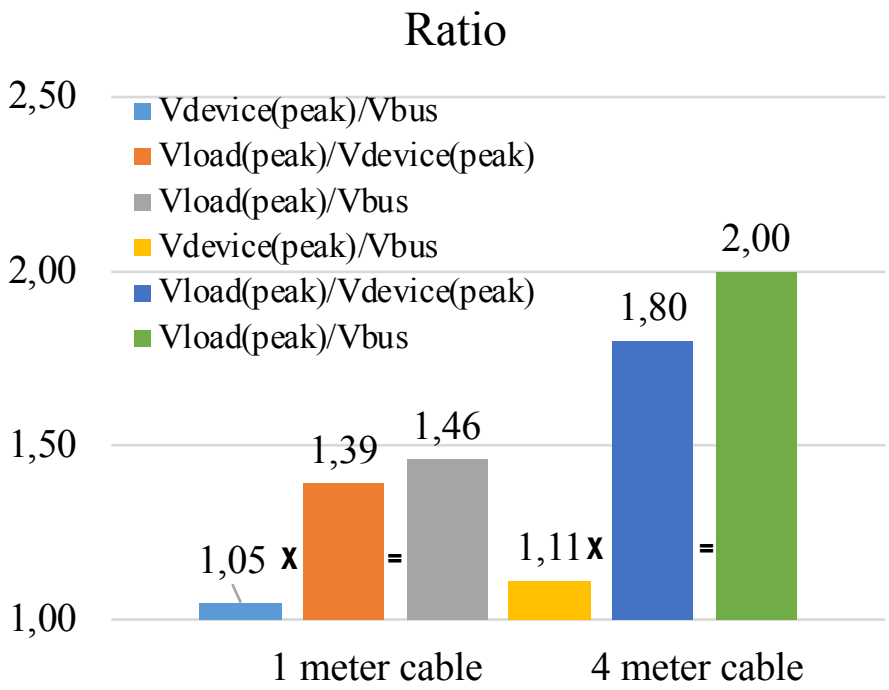
Grounding Arrangement Example for High Power Converters

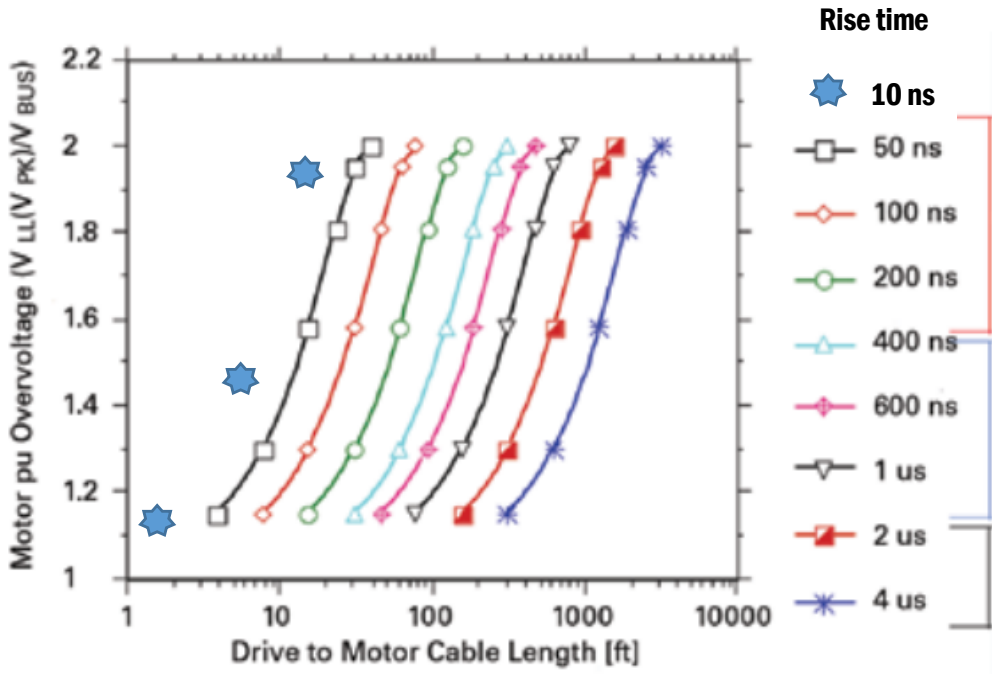


In this grounding arrangement, a bypass route is created for the common mode current. Thus, the critical ground for gate drive chip is stable.

Reflected Wave in Motor Drives

For a motor drive with a cable connection between power electronics and the electric machine, if the propagation time of the cable is greater than 1/3 the rise time, a full reflection will occur at the motor terminals*.



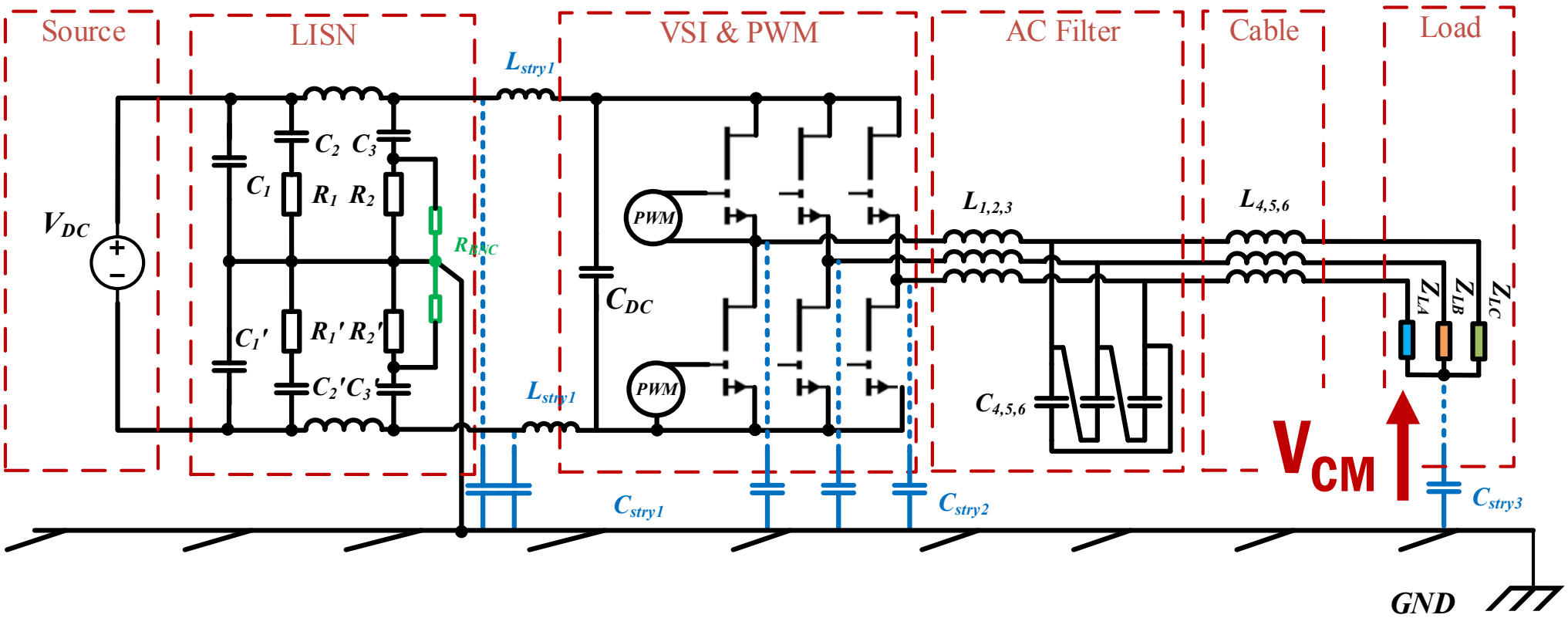


Vdc: 400 V, Trise: 10 ns, IL: 10, 20, 30 and 40 A, cable length: 0, 1 and 4 m

* A. von Jouanne, et al., "Application Issues for PWM adjustable speed AC motor drives", *IEEE Ind. Appl. Mag.*, vol. pp. 10-18, Sept/Oct. 1996.

Typical Time Domain EMI Modeling for Inverter

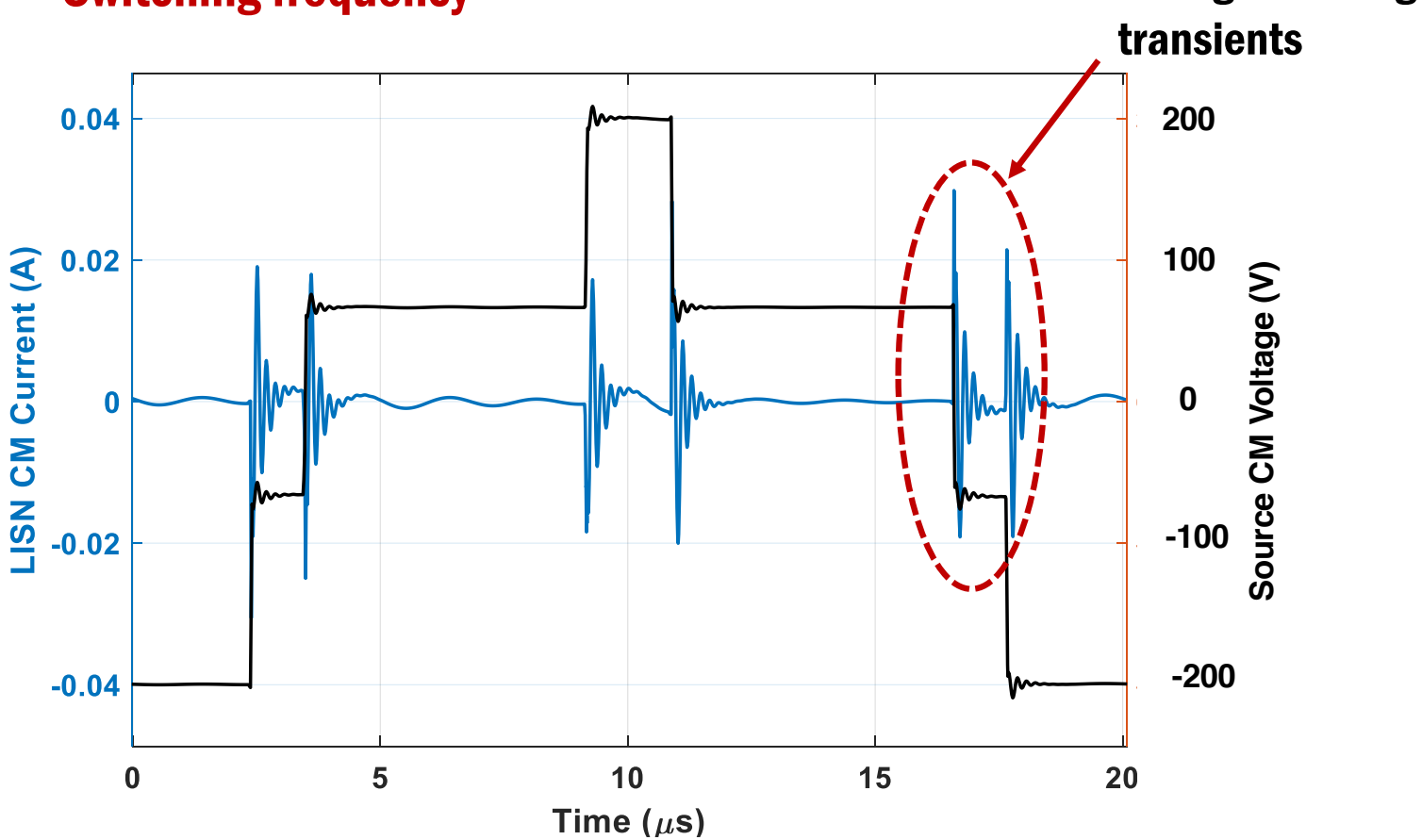
Schematic:



Factors Affecting CM Voltage

Factors affecting CM Noise (Cont'd)

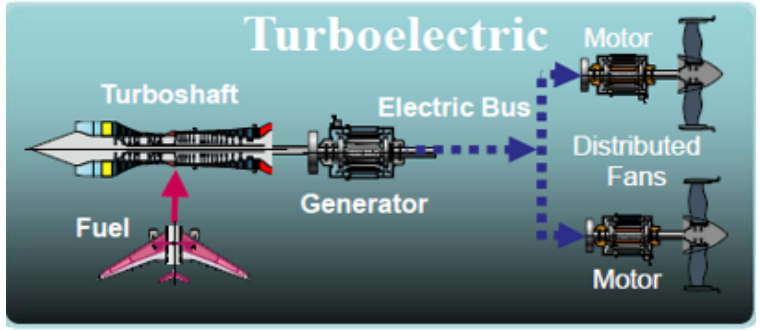
- Turn on/off slew rates $(\frac{dv}{dt})$
- Switching frequency

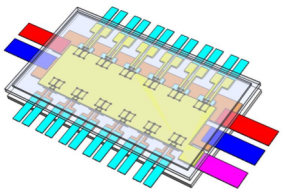


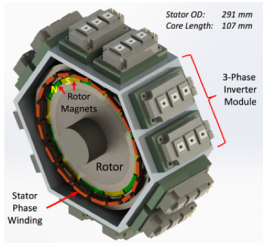
Electric Propulsion: Challenges and Opportunities

Challenges:

- Power Electronics and Electric Machines: 25 kW/kg for power electronics and 14 kW/kg for electric machine.
- Energy storage devices: battery technologies need to be significantly improved in terms of power density, safety and reliability.
- Aircraft Electrical Power Systems: electric power systems onboard aircrafts also present a number of system level challenges, e.g. stability and thermal management.
- Hybrid systems: the turbines, together with the battery assisted electrical power systems form a hybrid system that requires multi-levels of optimization.
- Research Infrastructure for Electric Technologies: the research and development of large megawatt class machines is hampered by the lack of development testing facilities.



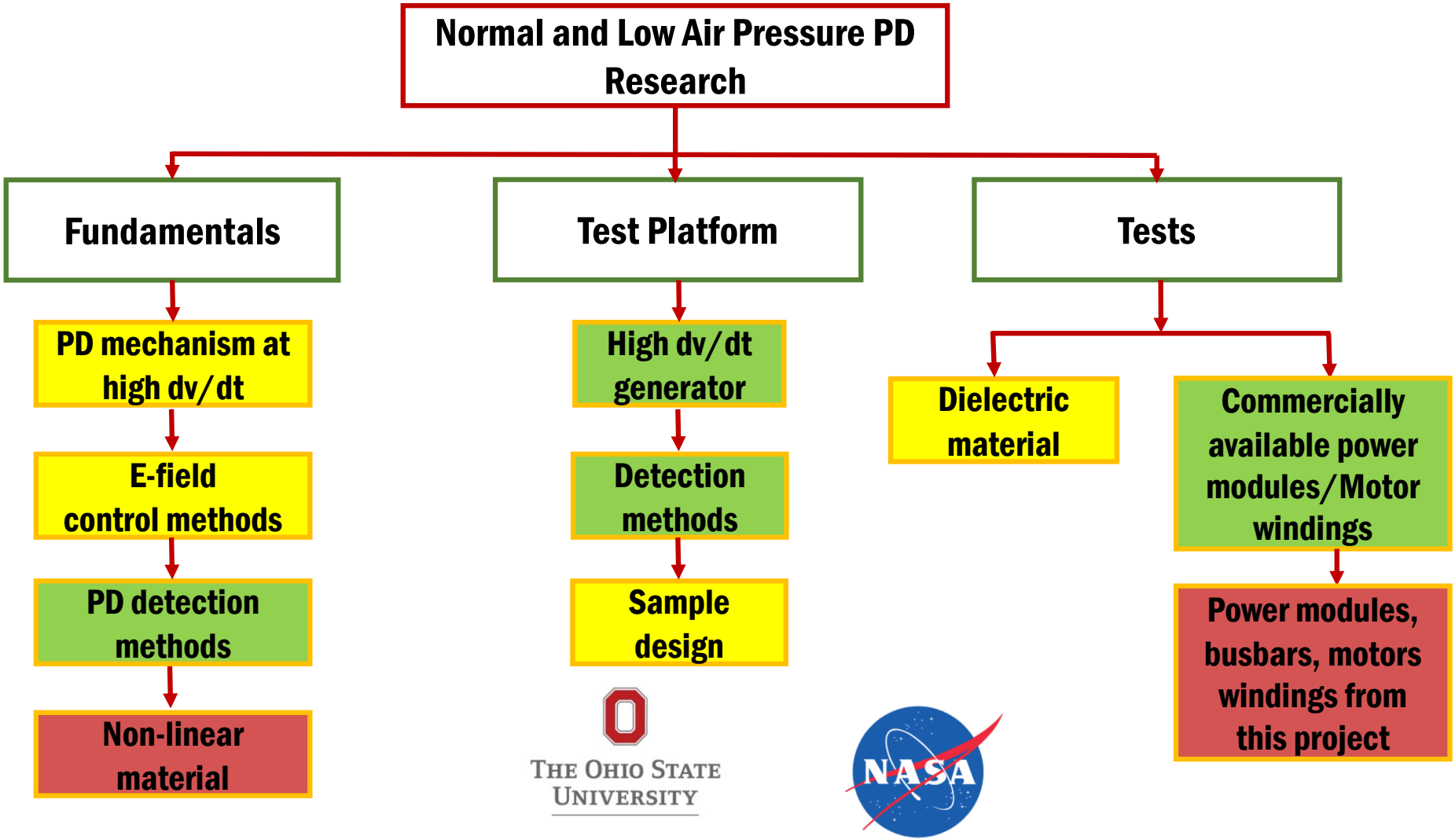




Team:

- Ohio State University
- University of Wisconsin
- University of Maryland
- Case Western Reserve University
- Georgia Institute of Technology
- North Carolina A&T University
- GE Aviation and Global Research
- NASA Glenn (NEAT testbed)

Partial Discharge for Power Modules and Systems



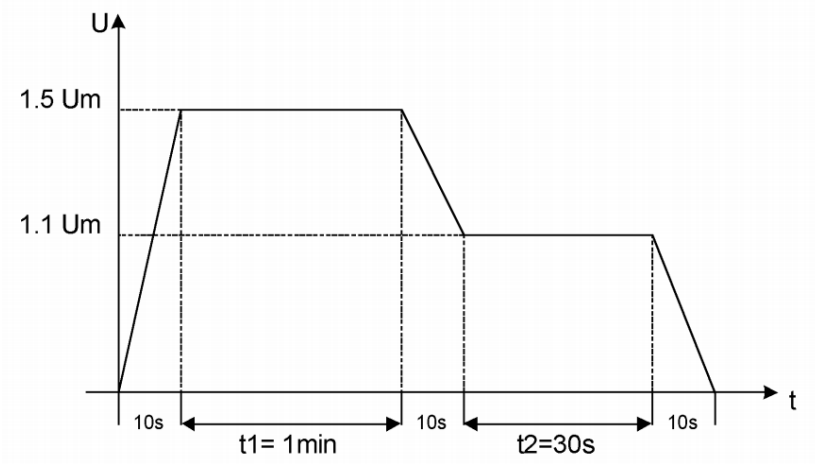
A NASA ULI Panel on Aug. 22 2019 at the AIAA/IEEE Electric Aircraft Technologies Symposium (EATS)

https://www.aiaa.org/propulsionenergy/EATS/

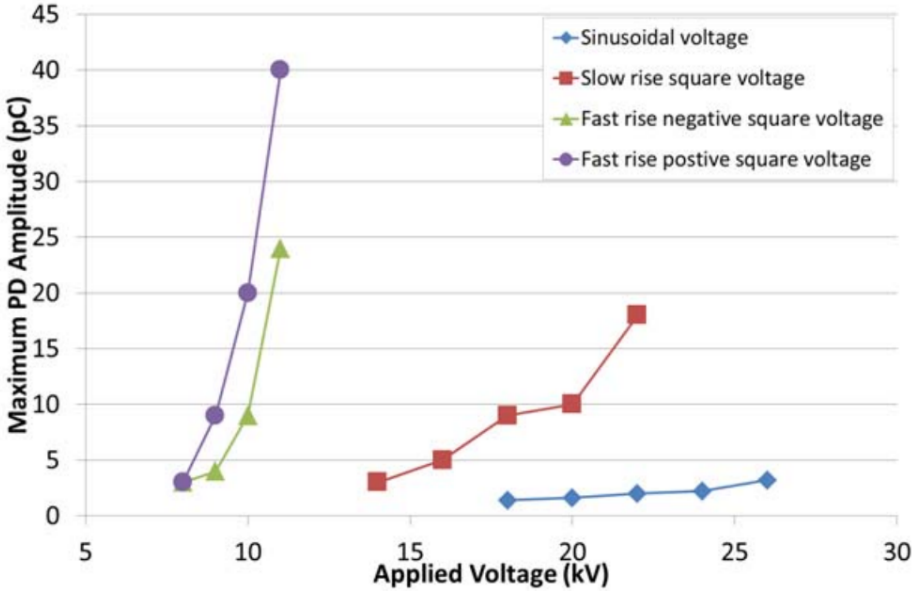
Power Module PD Test Standards & Past Results

Power modules are tested for Partial Discharges (PD) with IEC 1287 and IEC 60270 normalized tests [1]

Standard Test Profile (60 Hz ac)



Standard and non-standard test results



Peak value of the voltage applied to the power modules during the normalized test.

- **The voltage is increased up to 1.5 Vm (Vm being the maximum voltage during normal operation)**
- **The voltage is then decreased to 1.1 Vm.**

PD for different voltage excitations [2]

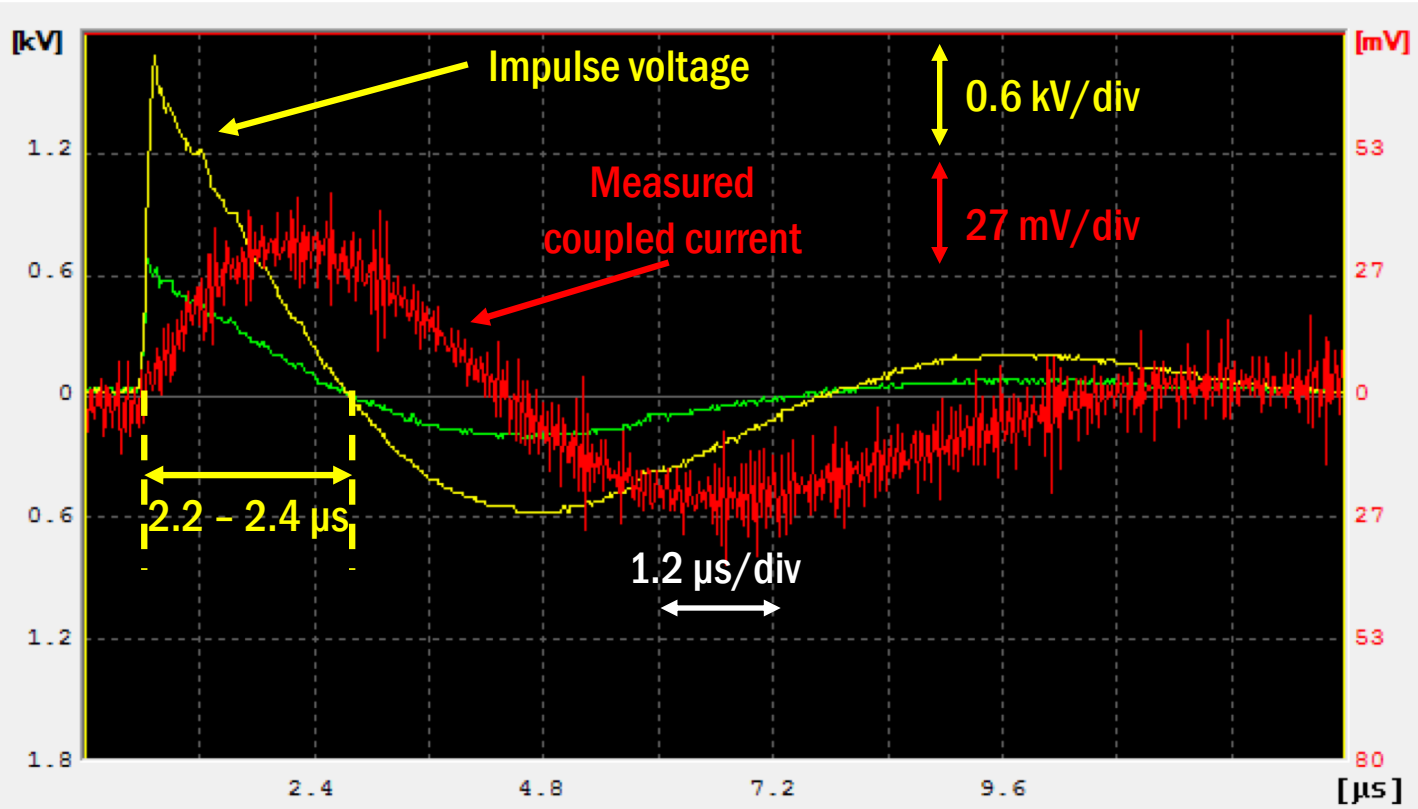
[1] Int. Elect. Commission: "Electronic power converters", IEC 1287, 61-287-1, 2005.
[2] Abdelmalik, A. A., A. Nysveen, and L. Lundgaard. "Influence of fast rise voltage and pressure on partial discharges in liquid embedded power electronics." IEEE Transactions on Dielectrics and Electrical Insulation 22.5 (2015): 2770-2779.

High dv/dt will lower the partial discharge voltage in power modules and loads!

Why New Testers Need to be Built for PD Studies

Existing PD testers either do not have high dv/dt to represent the fast switching of SiC devices or do not have controllable pulse width and duty ratio.

Test Results on a Motor Winding from a State-of-the-art PD Tester

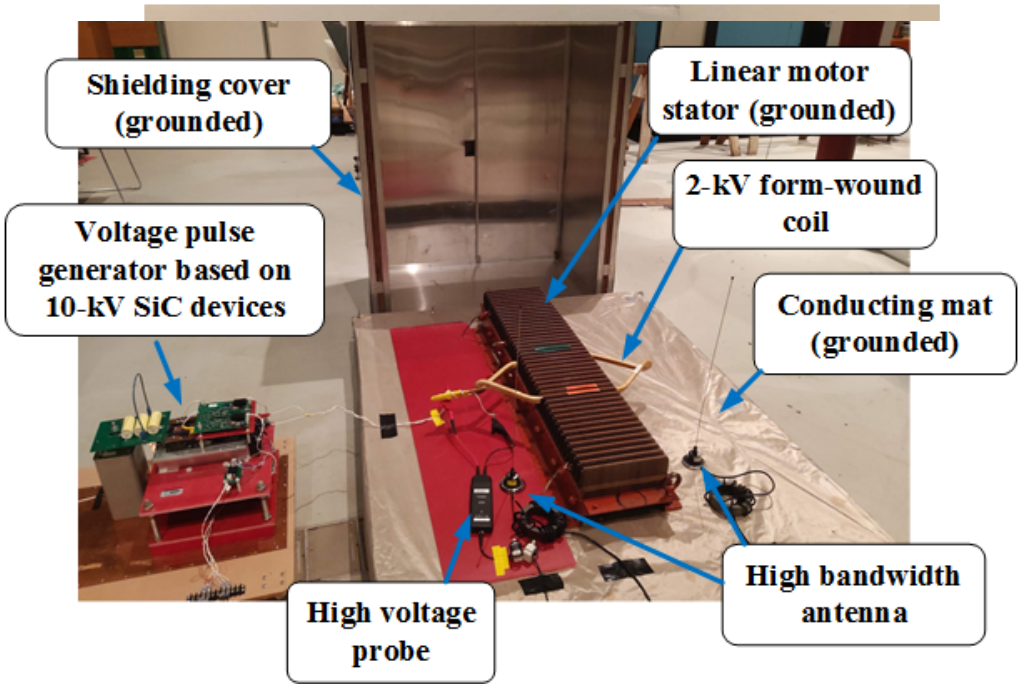


Previous test records and publications show that most PD pulses happen between 3 – 60 µs after a rising edge of a pulse voltage is applied.

A 10 kV Partial Discharge Test Platform

A unique high dv/dt (up to 105 kV/μs) test platform has been designed and built.

- An ac-dc rectifier
- A 10 kV SiC-based pulse generator
- Shielded test chambers
- Multiple low pressure chambers that can be placed in shielded test chambers



Multiple types of PD detection sensors can be placed in shielded chambers, including a Photon Multiplier Tube (PMT), a High Frequency Current Transducer (HFCT), a high bandwidth antenna, and a Shunt Resistor are used together for PD detection.

PD Tests with the 10 kV Test Platform

Partial discharge inception voltage (PDIV) tests with 10 kV pulse width modulated (PWM) waveform generator for direct bond copper (DBC) and twisted pairs and samples

- DBC samples are used to emulate power electronics modules
- Twisted pairs are used to emulate motor windings

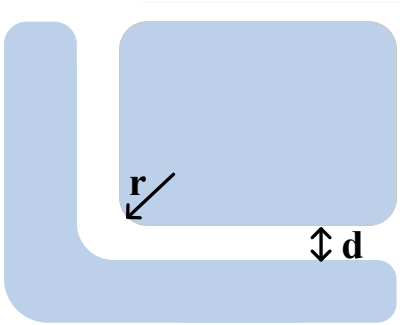
Test approaches:

- Step 1: single pulse tests to identify the impact from rise time and pulse width
- Step 2: repetitive pulse tests to identify the impact from duty ratio and switching frequency
- Step 3: Sinusoidal waveforms to test the impact from modulation index and fundamental frequency

Test Samples: DBC

Test sample: direct bond Copper (DBC) (to study the PD in the power module)

- Widths of trench d: 0.3 mm, 0.5 mm, 0.7 mm
- Rounding chamfer r: right angle, 0.3 mm, 0.5 mm, 0.7 mm

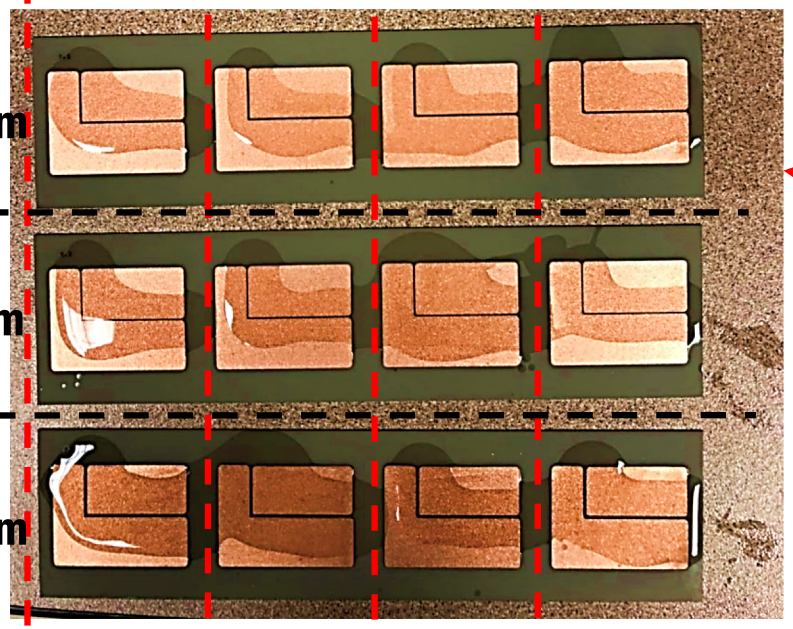


r: right angle 0.3 mm 0.5 mm 0.7 mm

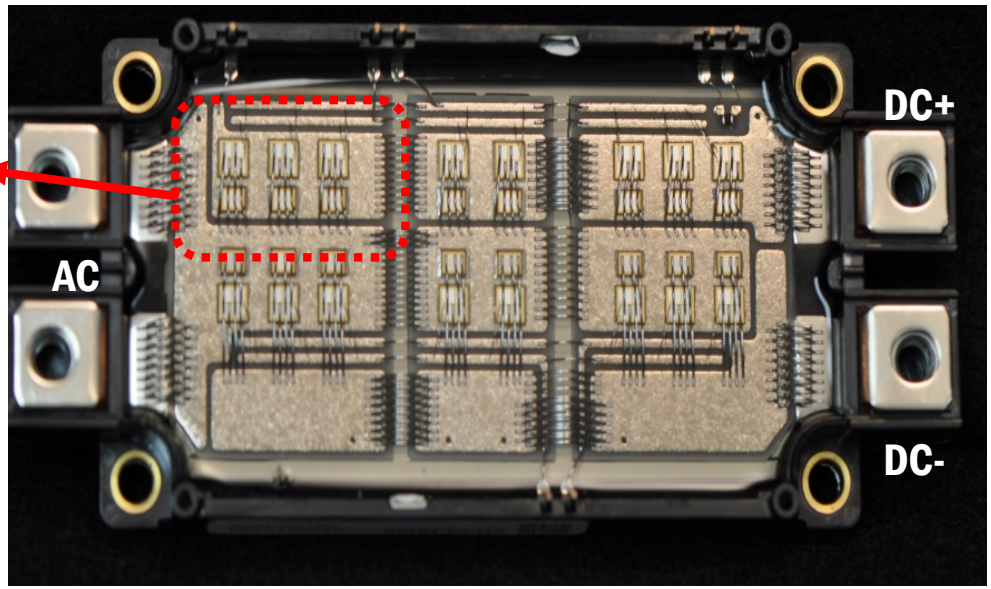
d: 0.3 mm

d: 0.5 mm

d: 0.7 mm



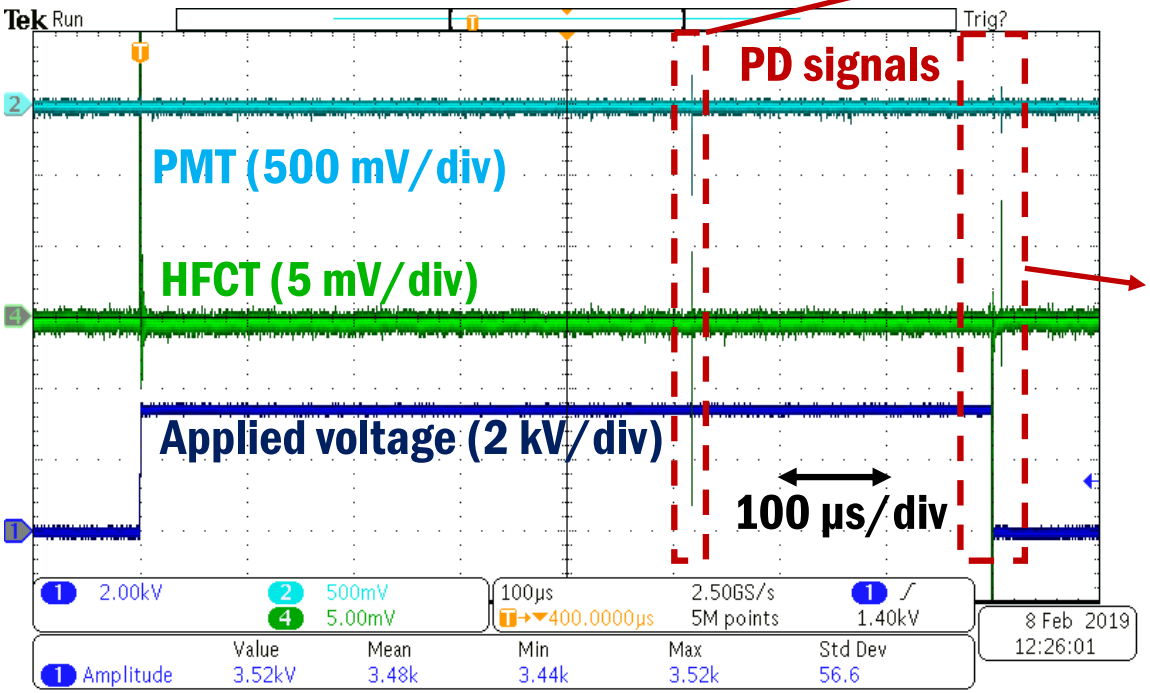
Sample structure



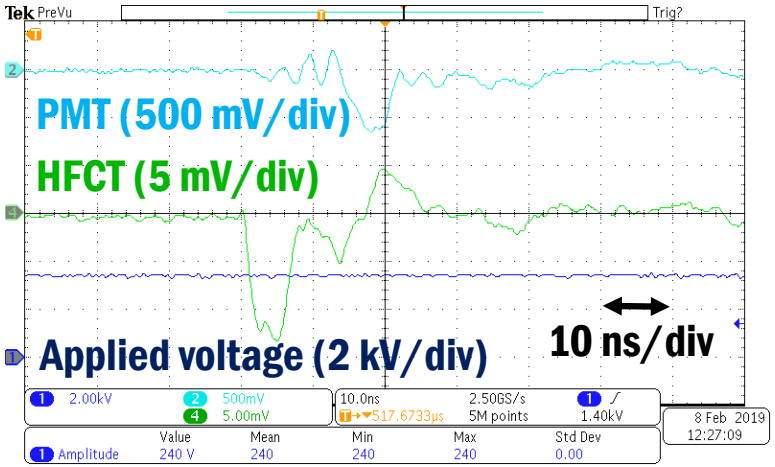
Single Pulse Tests of DBC Samples

DBC Single Pulse Tests

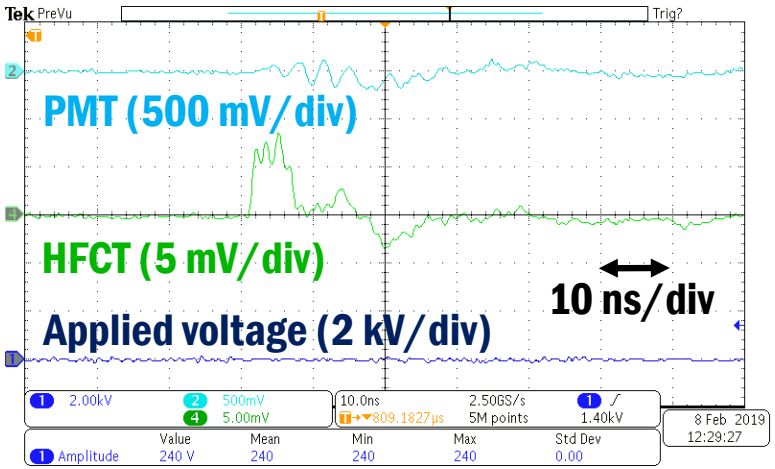
- Typical PD test waveforms
  - PD happens at high voltage plateau and falling edge



Rise time: 200 ns, pulse width: 500 µs



Zoomed-in at the voltage plateau

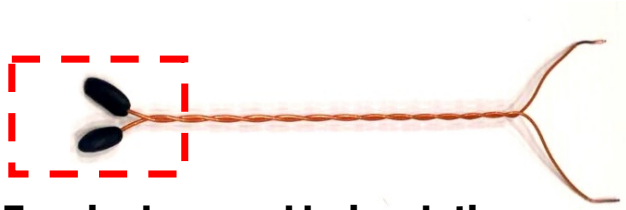


Zoomed-in at the falling edge

Test Sample: Twisted Pair

Twisted Pair (to emulate motor winding insulation)

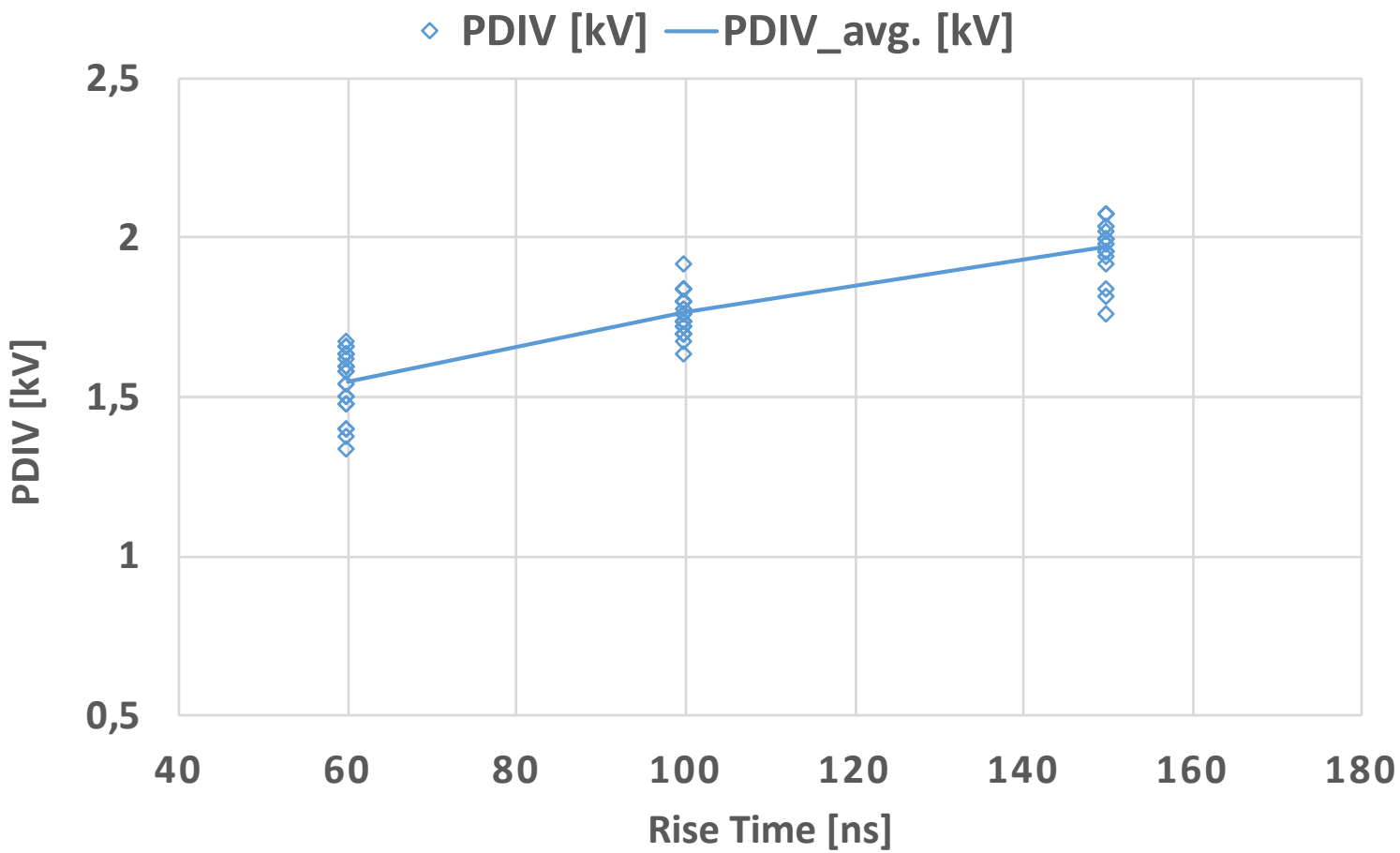
- Two Von Roll FO 180 wires fabricated according to IEC 60851-5:2008
  - 8 twists with 13.50 N force applied on one end
- 1 mm diameter
- Approximately 125 mm long



Terminal covered by insulation compound

Sample of Test Results: Repetitive Tests of Twisted Pair

Partial discharge voltage vs. rise time

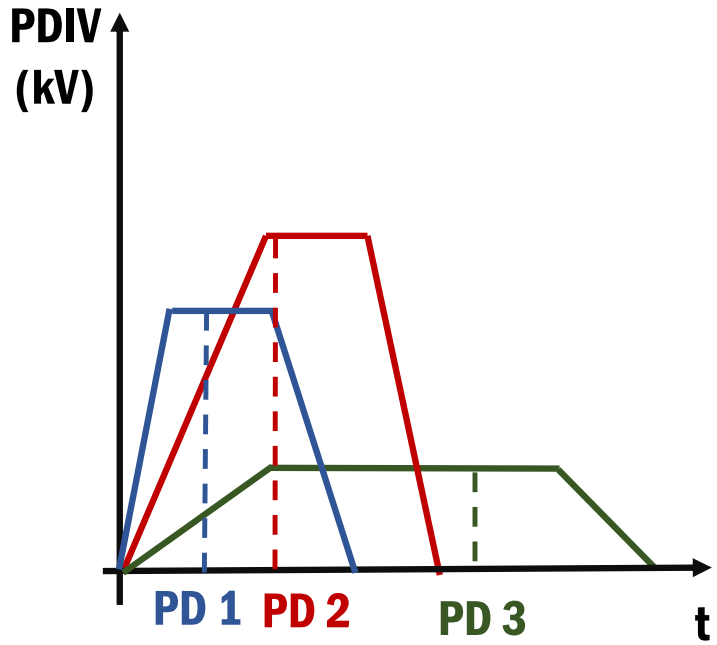


Switching frequency: 1 kHz Duty Ratio: 0.5

Initial Findings

Summary of initial findings

- PDIVs for both twisted pairs and DBC samples decrease with longer pulse width
- PDIVs at short pulse width (<5 μs) is heavily influenced by the rise time of the waveform



Significance of the findings:

These findings means that SiC and GaN based inverter will introduce higher insulation stress to motor windings because of the higher stress caused by ultra-fast rise time in short PWM pulses.

Thoughts

Research on WBG based applications need address

- Enable technologies of new devices such as smart short circuit protection, high voltage gate drive, partial discharge mitigation for motor windings and power electronic devices/circuits
- Most high dv/dt related issues are either being addressed or will be addressed soon
- Application oriented failure modes and reliability studies
- Packaging!

Thank You!