High MegaWatt MV Drives

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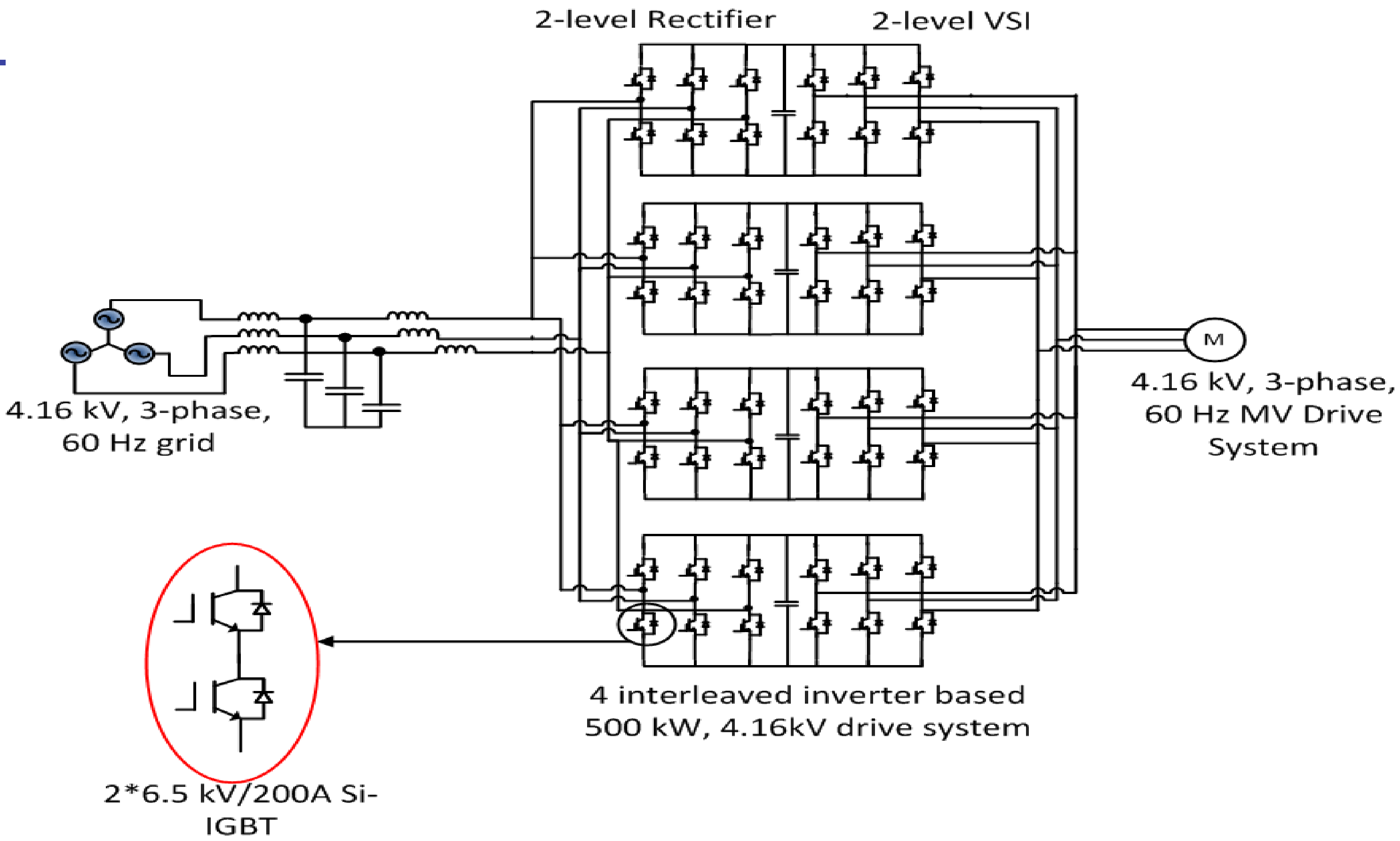
MV drives issues and needs

- 60-70% of the MV motors are not driven by drives – why?
- Estimate yearly energy savings
- Capital cost requirement – payback period
- Space important ? – match footprint of soft-starter ?
- MV motors are used typically in critical processes – steel mills, cement kilns, air-handling, compressors, pumps
- Reliability is key; downtime is allowed with concept of "modular replacement" possible by semi-skilled people

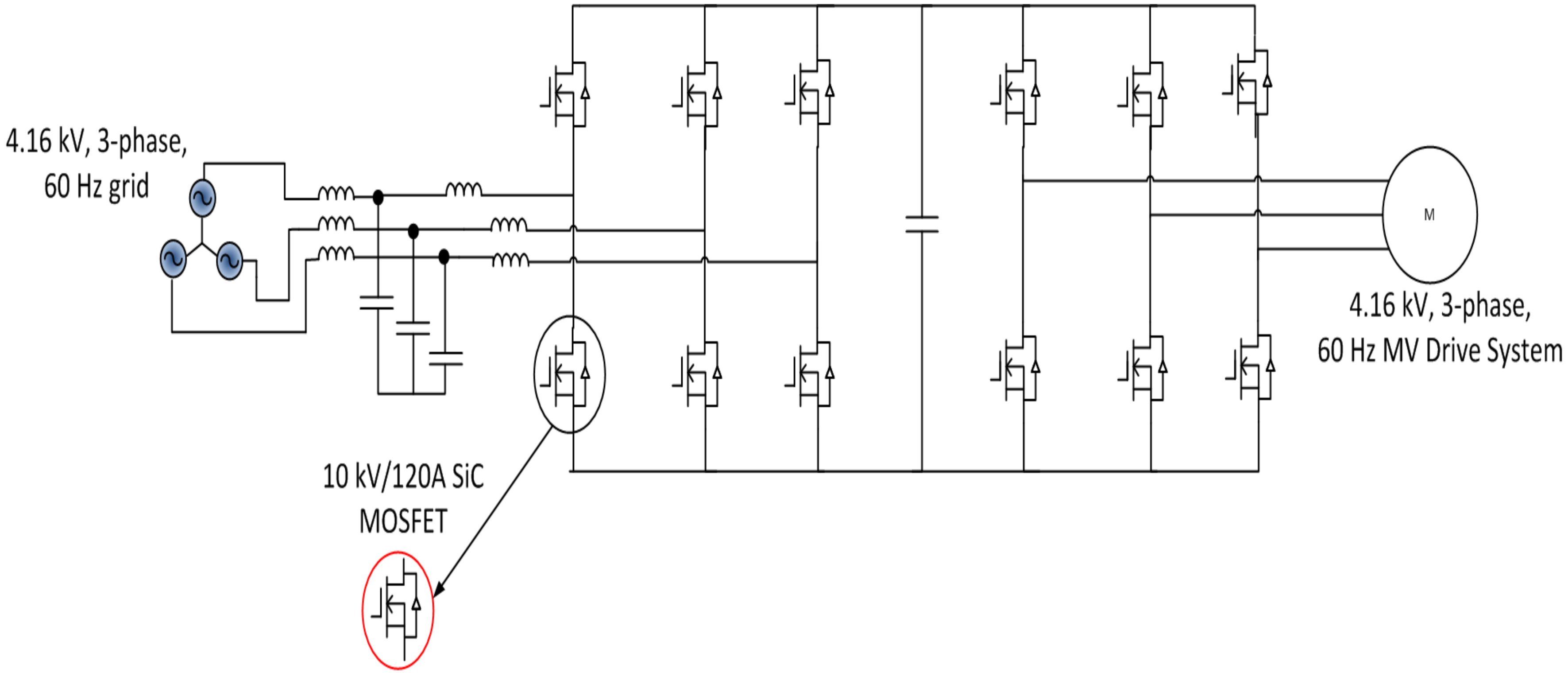
- MV Motor energy efficiency – what does higher NEMA energy efficiency standards mean – lower losses -> lower damping – need for higher current bandwidth control required?
  - Can SiC play a real role? Enable high speed motor designs (future)

500 kW Si-IGBT based drive



For 4.16 kV, 500 kW system, line rms current = 69A, peak current of each phase = 98 A. Peak of line to line voltage is 5.88kV. Hence, two 6.5kV/200A Silicon IGBT devices are required to be in series to block forward voltage. However, Si-IGBTs cannot be switched at high frequency while conducting high current. Hence, around 4 interleaved inverters are required to switch at around 1.5 kHz. Each inverter block is switched at 300-400Hz.

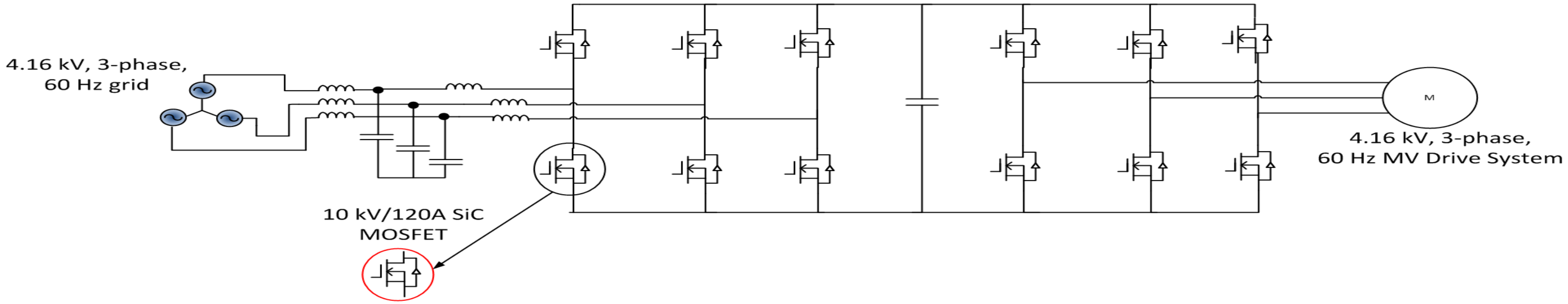
500 kW SiC Mosfet based drive



SiC MOSFET kV rating? 10kV, 12kV, 15kV

For the same 4.16 kV, 500 kW drive system, using 10 kV/120A SiC-Mosfet, it is possible to have a 2-level topology. The SiC devices can be switched at 5 kHz, for 69A rms (98A peak) current, and a single device can withstand the forward blocking voltage of Vdc = 6kV.

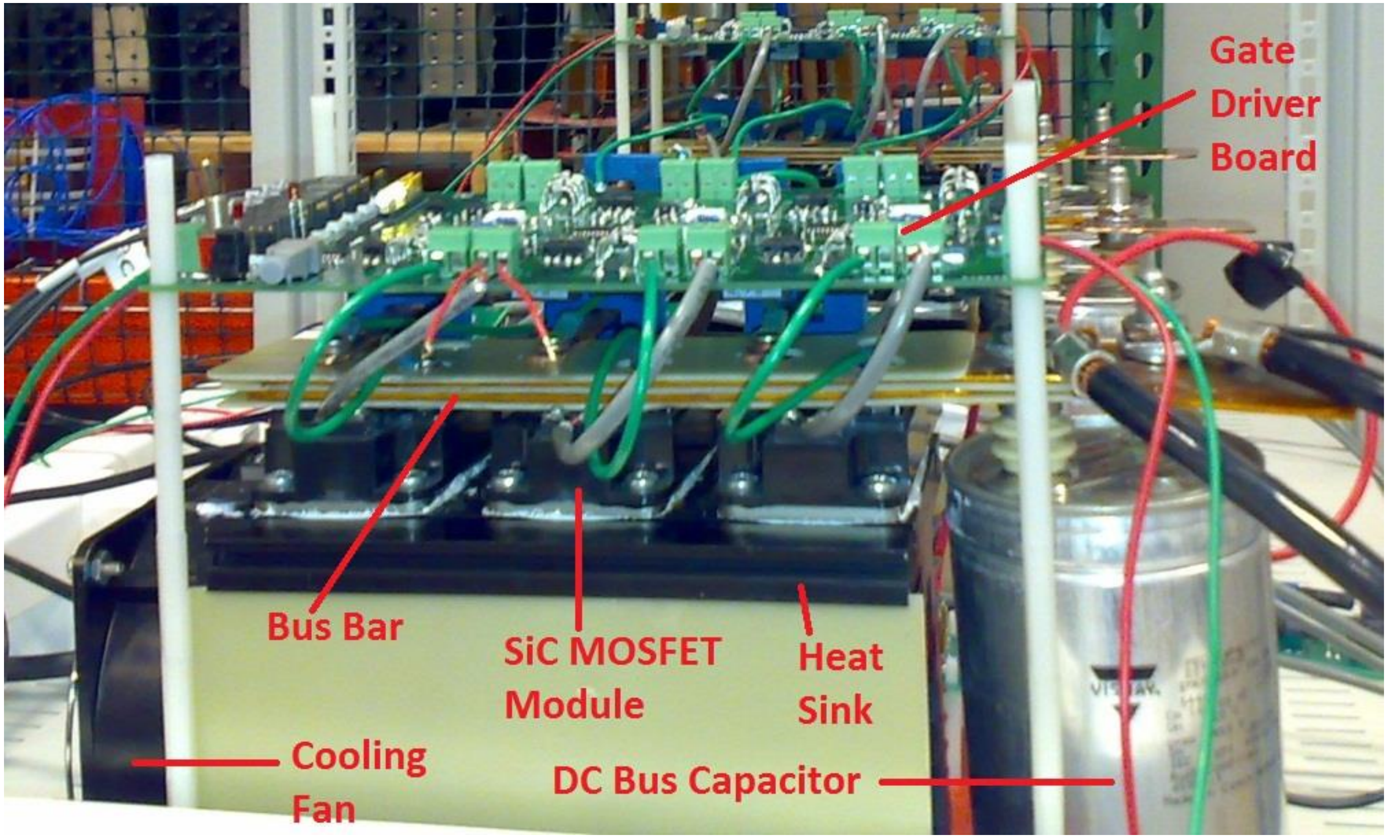
500 kW SiC Mosfet based drive



SiC MOSFET kV rating? 10kV, 12kV, 15kV

- Rds(on) vs Vdc, Temp. upto 125-150 deg C
- J (A/cm2), die size -> packaging issues, thermal, overload current rating, device short circuit protection and time, inductance, non-wire bond packaging (for thermal, not only fail-short), maximum module current rating
- SiC device designed for short-circuit capability – what does this mean for Vce(sat), Eon and Eoff, positive temp. coeff.
- Characterization of switching frequency vs. thermal, Voltage
- Eon and Eoff vs. I, V and temp. [function of V important]
- Dv/dt and its management – active gate driving, ZVS (?)

50 kW SiC-Mosfet based Inverter



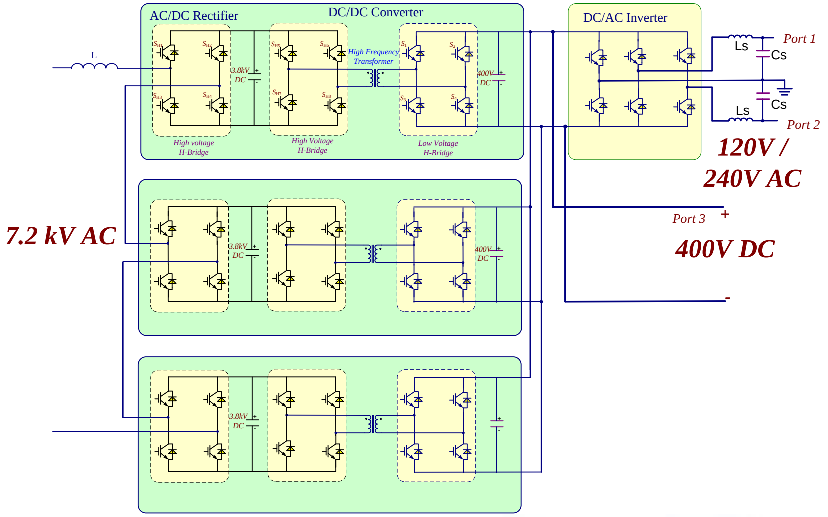
50 kW drive system, using 1200 V/100A SiC-Mosfet.

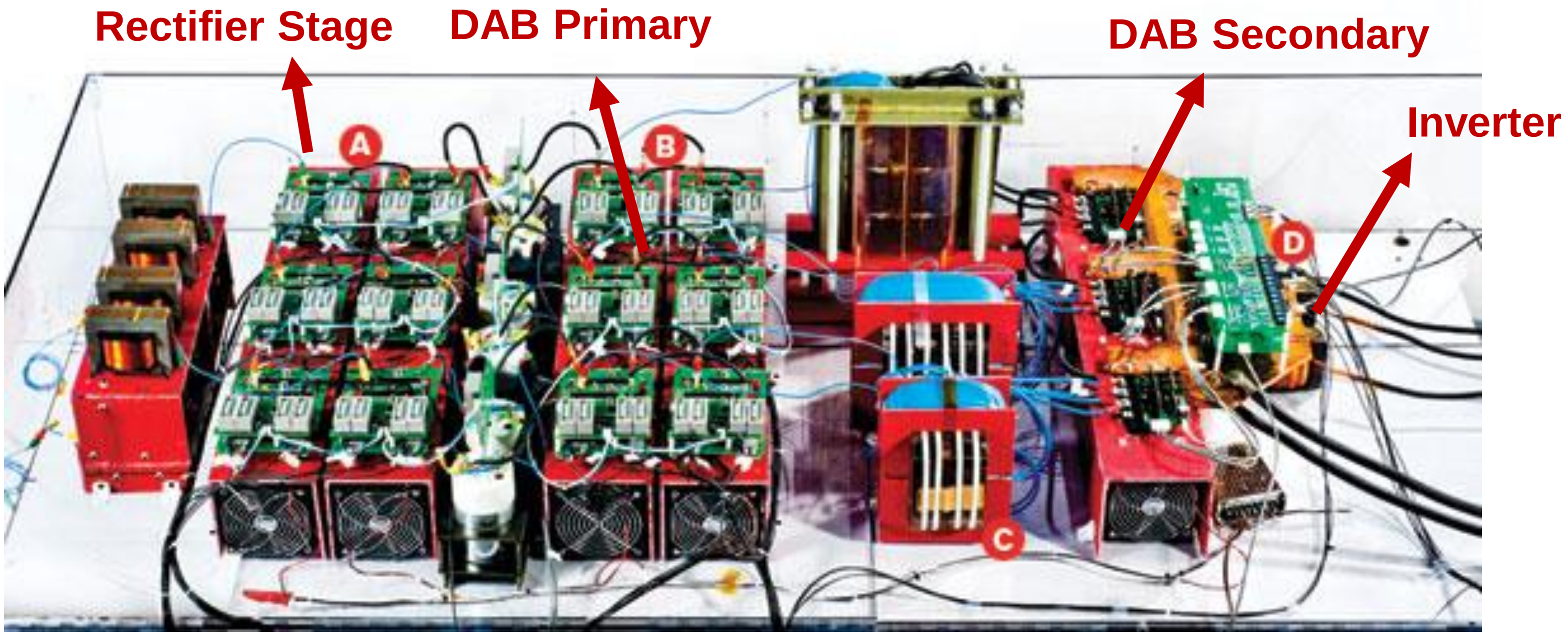
The SiC devices can be switched at 20-40 kHz, Vdc = 800V.

Gen-I SST : Topology and Prototype

Specifications:

- **Input: 7.2kV**
- **Output: 240Vac/120Vac; 400Vdc**
- **Power rating: 20kVA**

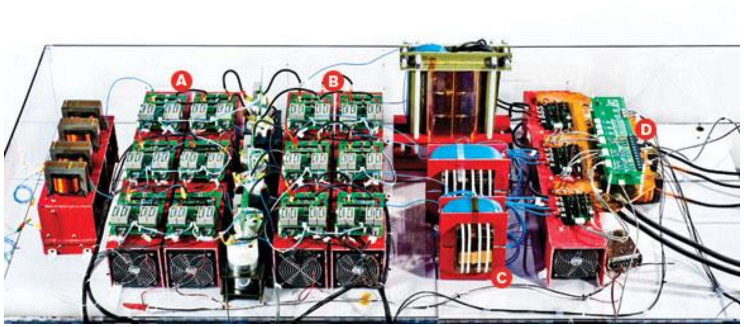


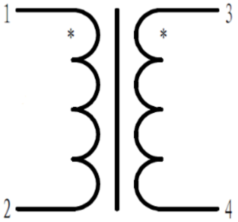


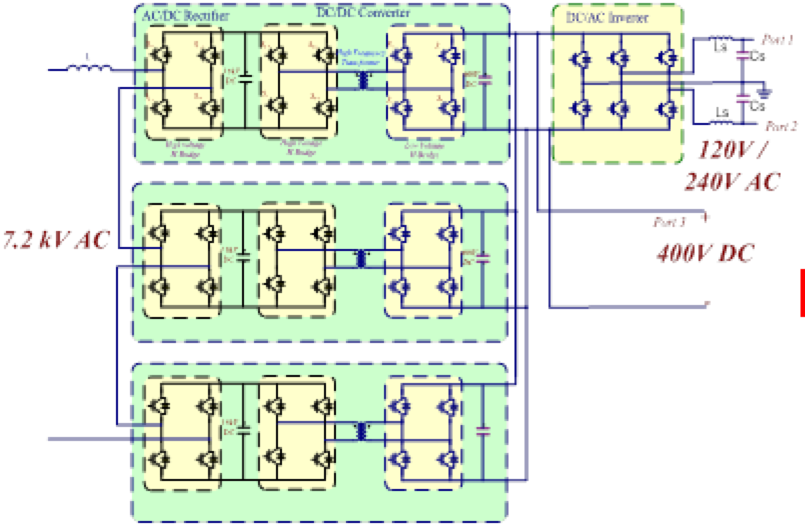
Named to MIT Technology Review's 2011 list of the world's 10 most important emerging technologies

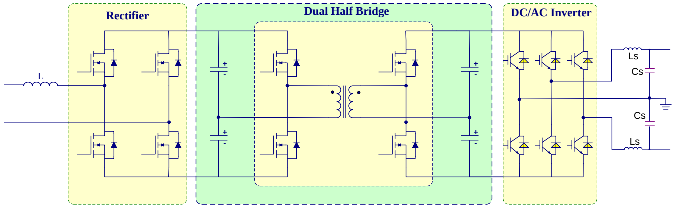
FREEDM SST: Two generations (Si *vs* SiC)

Input: 7.2kVac Output: 240Vac/120Vac; 380Vdc Power rating: 20kVA









Pole mounted transformer

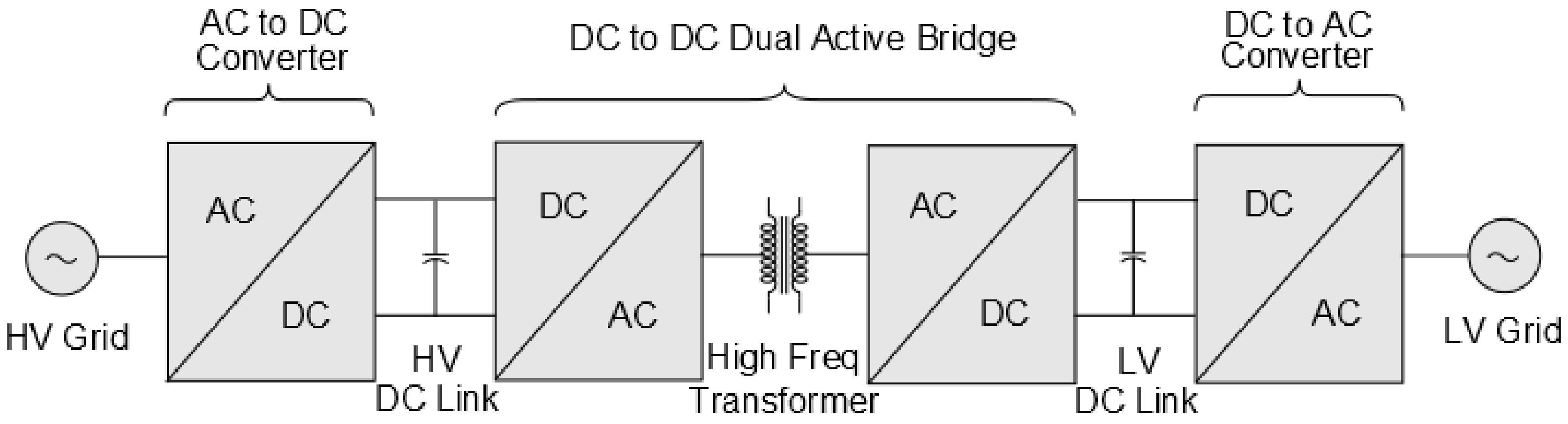
Gen-I SST 6.5kV Si IGBT based

Gen-II SST 15kV SiC MOSFET based

Solid State Transformer (SST) – MV drives relationship

Three stage SST

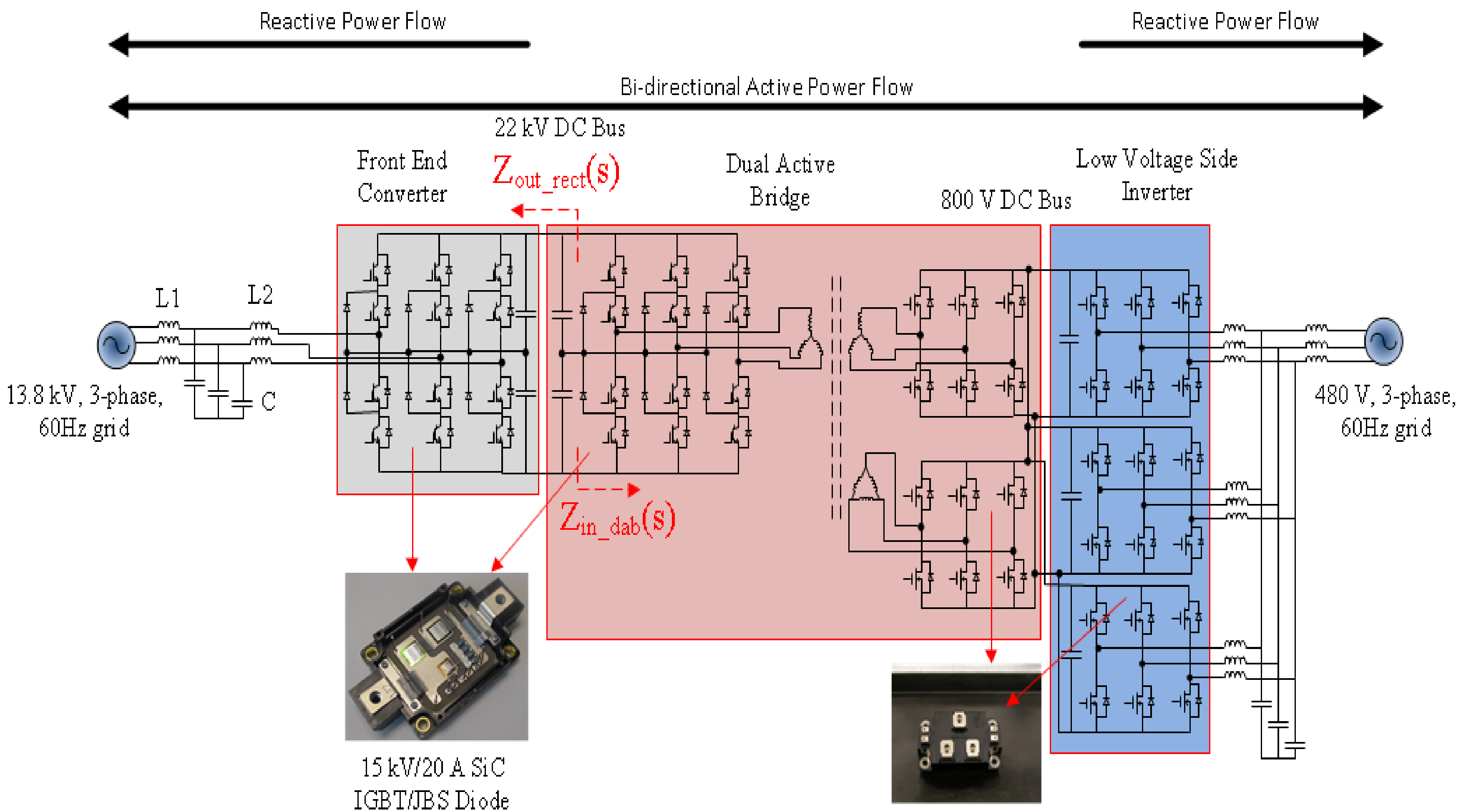
- AC to DC converter,
- DC to DC converter with high frequency transformer
- DC to AC converter



Features:

- Active/Reactive power control at both HV and LV side grids
- Integration of both AC and DC renewable energy sources
- High frequency isolation – most MV drives are 1:1 in terms of voltage input/output
- SiC devices are key enabler for DC-DC transformer

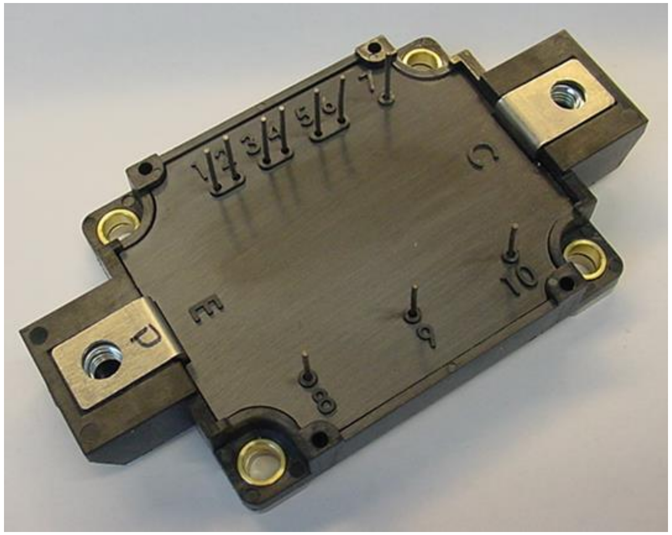
Transformerless Intelligent Power Substation (TIPS) – 3 phase SST

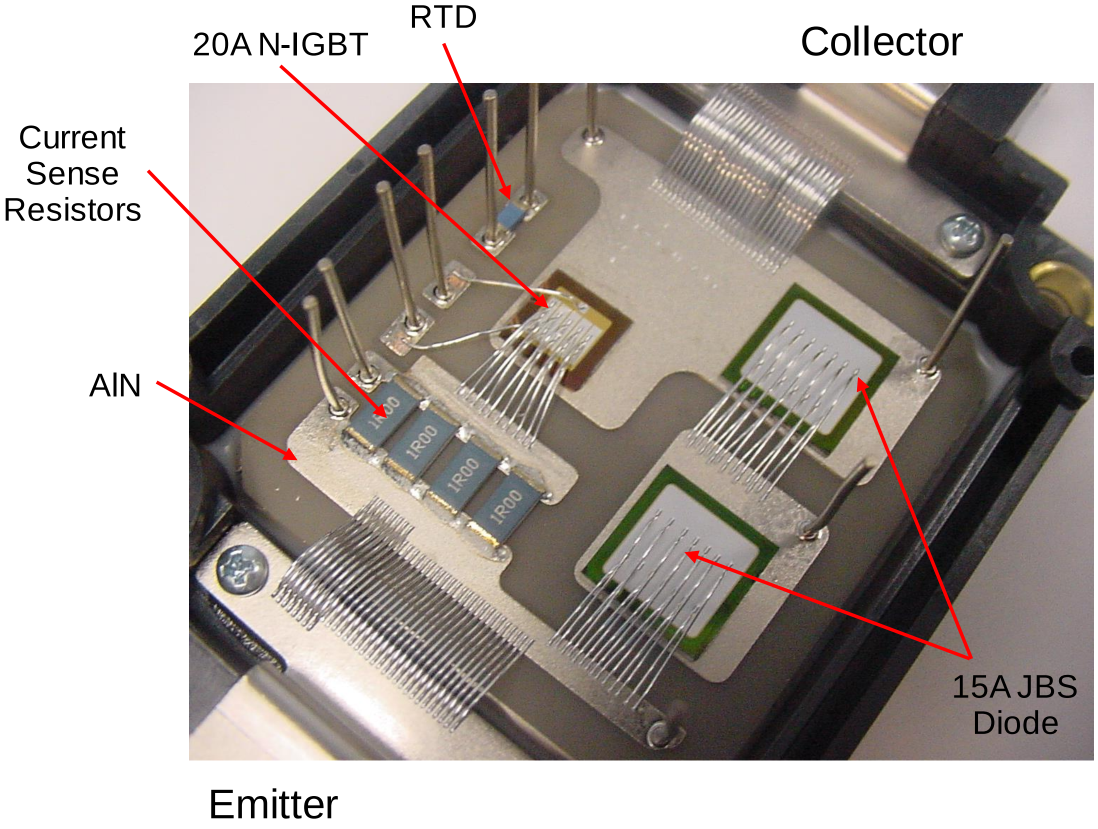


15 kV/20 A SiC
IGBT/JBS Diode
Co-pack module

1200 V/100 A SiC
MOSFET/JBS Diode
Co-pack module

15 kV, 20 A SiC IGBT Co-pack Modules



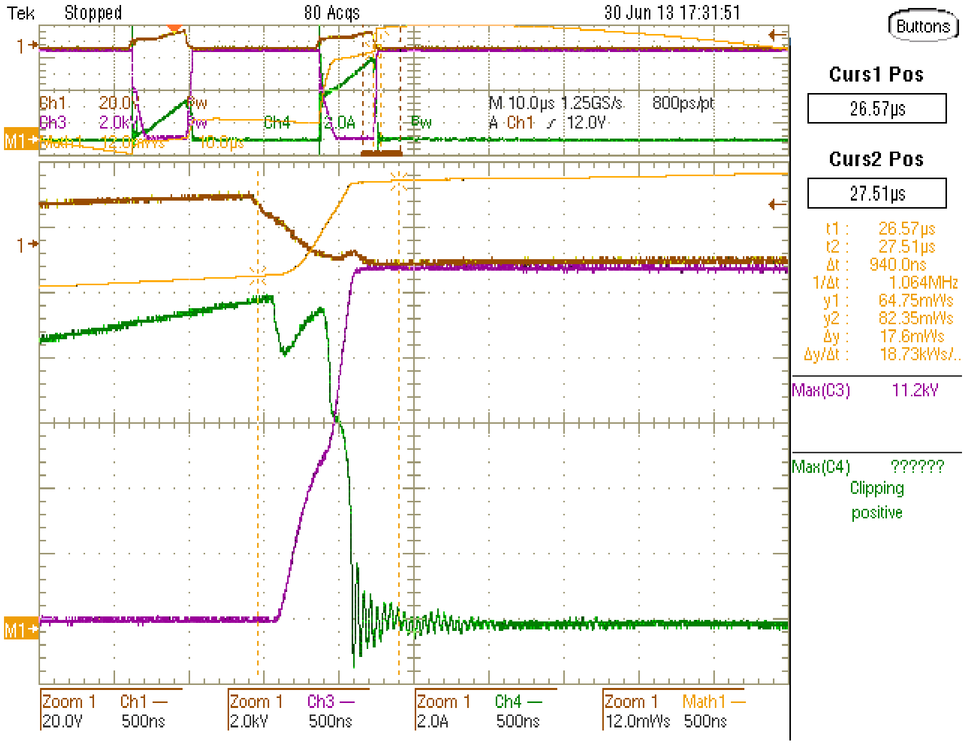


The module includes:

- 15 kV, 20 A SiC IGBT
- 20 kV (10*2), 10 A SiC JBS Diodes
- Current sense resistors
- Thermistor

Characteristics of 15 kV, 20 A, SiC IGBT

Turn-off transition at 11 kV, 5 A, 25^{o}C



V_{GE} (20 V/div); V_{CE} (2 kV/div);

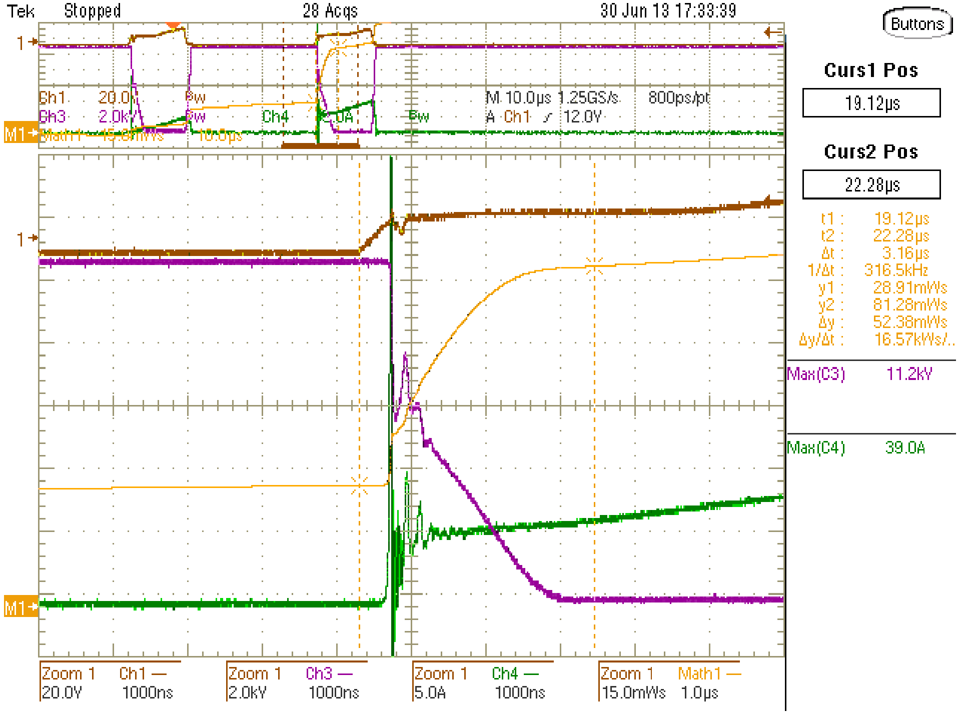
I_C (5 A/div); E_{OFF} (15 mJ/div);

Time scale: 1000 ns/div

- $R_{G(OFF)}$ = 10 Ω.
- Voltage has two different slopes. (punch-through design)
- Current bump; tail ringing.
- Total duration of the transition = 650 ns.
- Energy loss = 17.6 mJ

Characteristics of 15 kV, 20 A, SiC IGBT

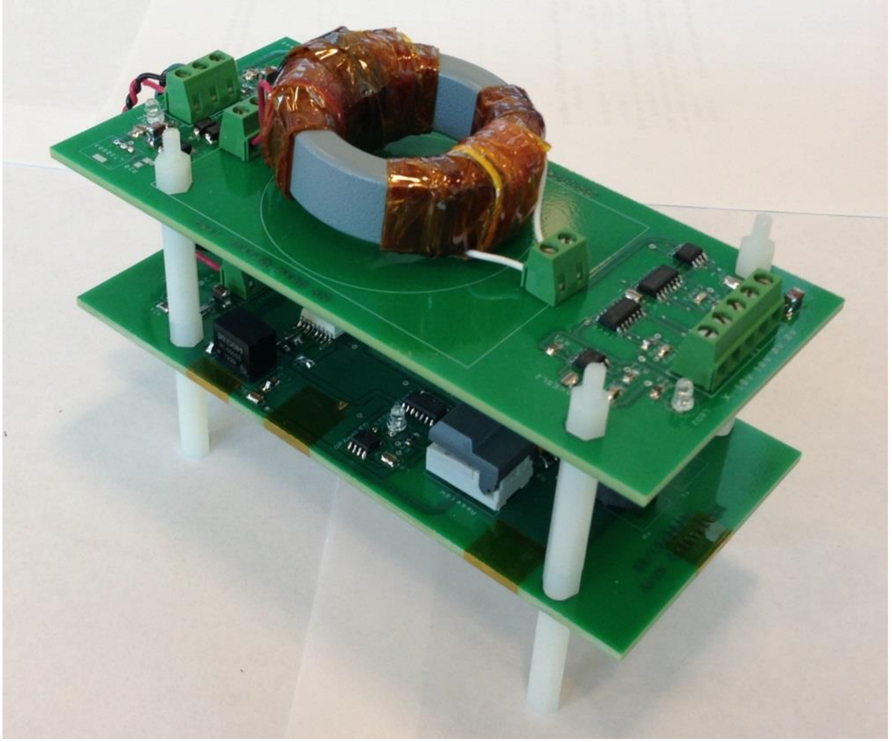
Turn-on transition at 11 kV, 10 A, 25°C

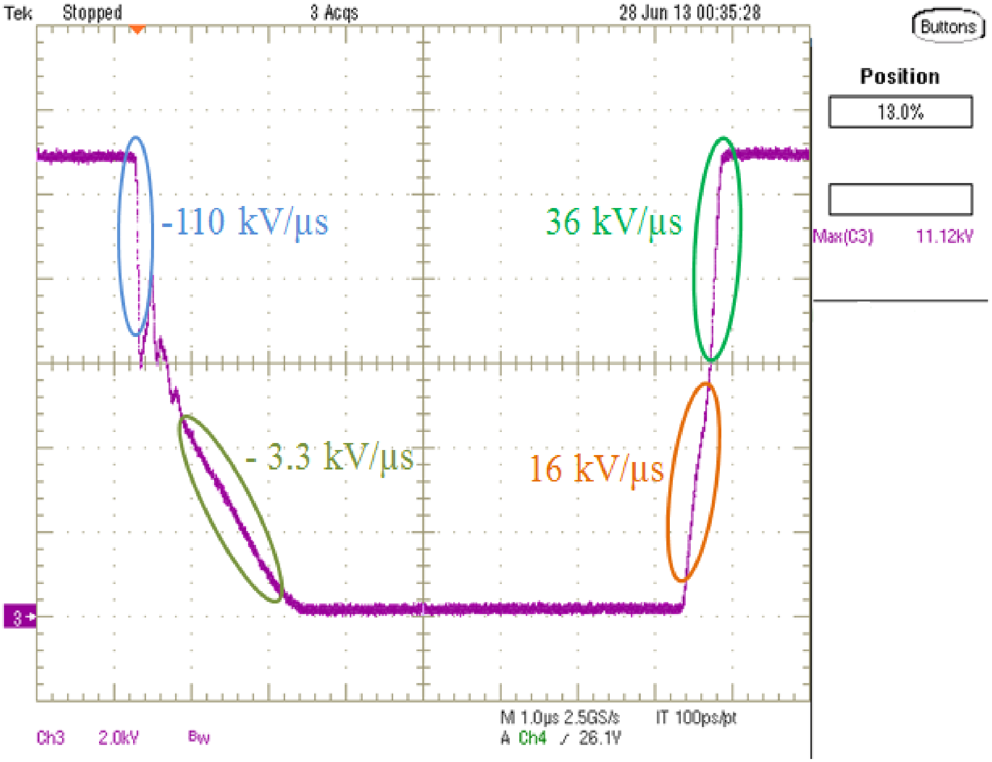


V_{GE} (20 V/div); V_{CE} (2 kV/div);
I_C (2 A/div); E_{OFF} (12 mJ/div);
Time scale: 500 ns/div

- $R_{G(ON)} = 200\ \Omega$.
- Voltage has two different slopes. (very high dv/dt at the beginning of the transition)
- Current spike; followed by ringing.
- Total duration of the transition = 2.2 μs.
- Energy loss = 52.4 mJ.
- High $R_{G(ON)}$ is used to limit the initial dv/dt.

HV Gate Driver





High Isolation Gate Driver

11 kV, high dv/dt switching voltage of the IGBT

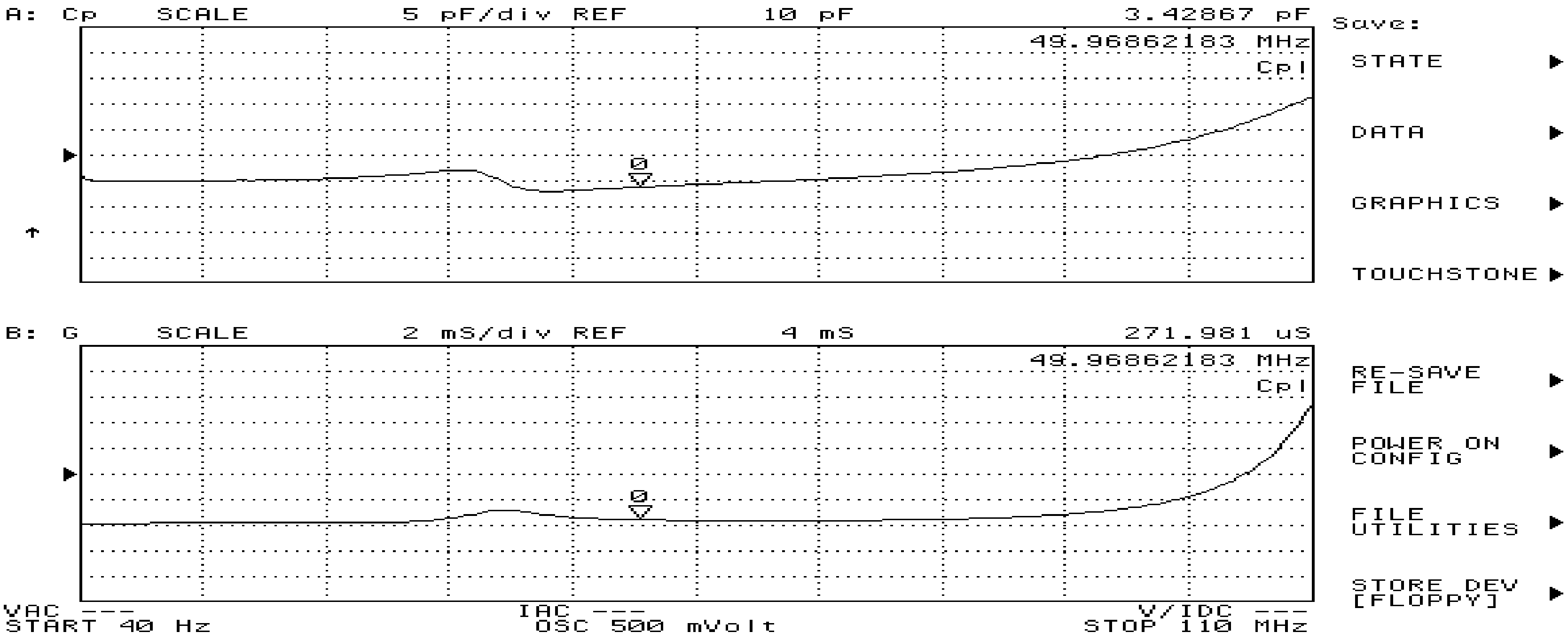
Device maximum Turn ON and Turn OFF dv/dt

- Turn ON dv/dt = 100.6 kV/µs, Turn OFF dv/dt = 28.29 kV/µs

The Gate driver has been exposed to 100 kV/µs at 11 kV

Gate Driver Isolation Transformer

- Isolation transformer inter-winding coupling capacitance (a crucial element for high dv/dt immunity) w.r.t frequency.



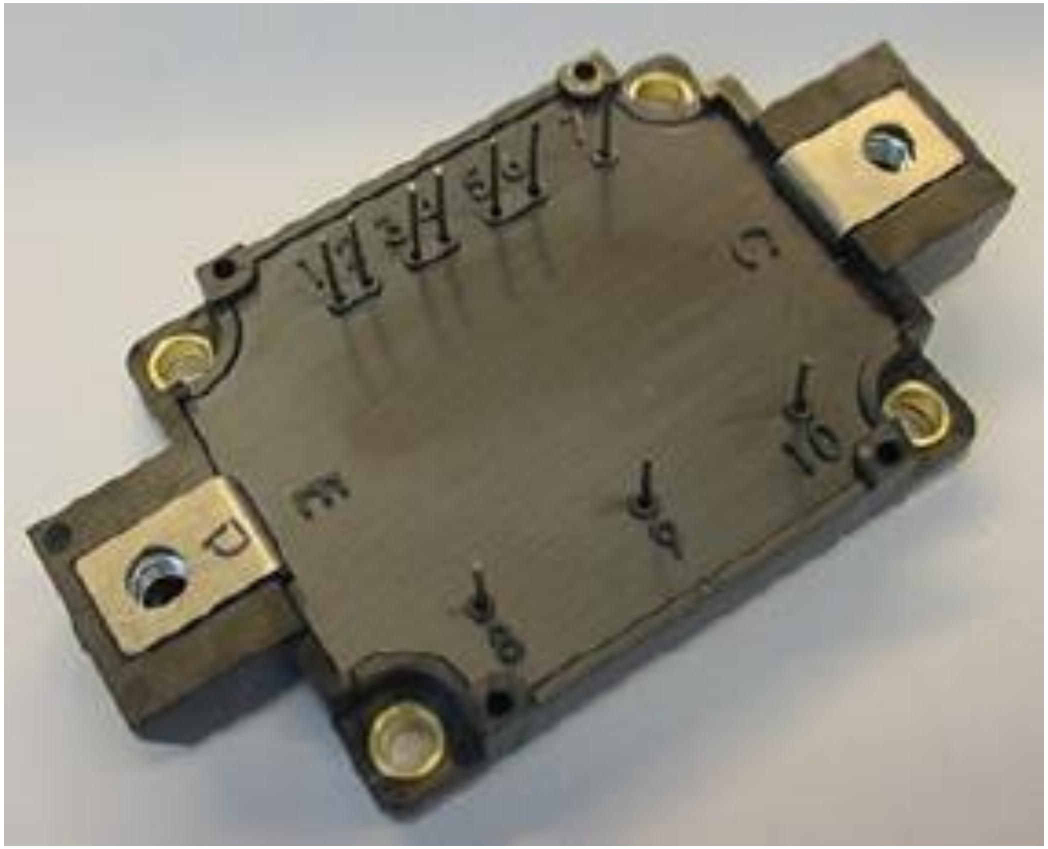
A: Cp SCALE 5 pF/div REF 10 pF 3.42867 pF
49.96862183 MHz
Cp!

B: G SCALE 2 mS/div REF 4 mS 271.981 uS
49.96862183 MHz
Cp!

VAC --- START 40 Hz
IAC --- OSC 500 mVolt
V/IDC --- STOP 110 MHz

- Measured up to 110 MHz using Agilent Impedance Analyzer.
- 3.4 pF at 50 MHz; 13 pF at 100 MHz.

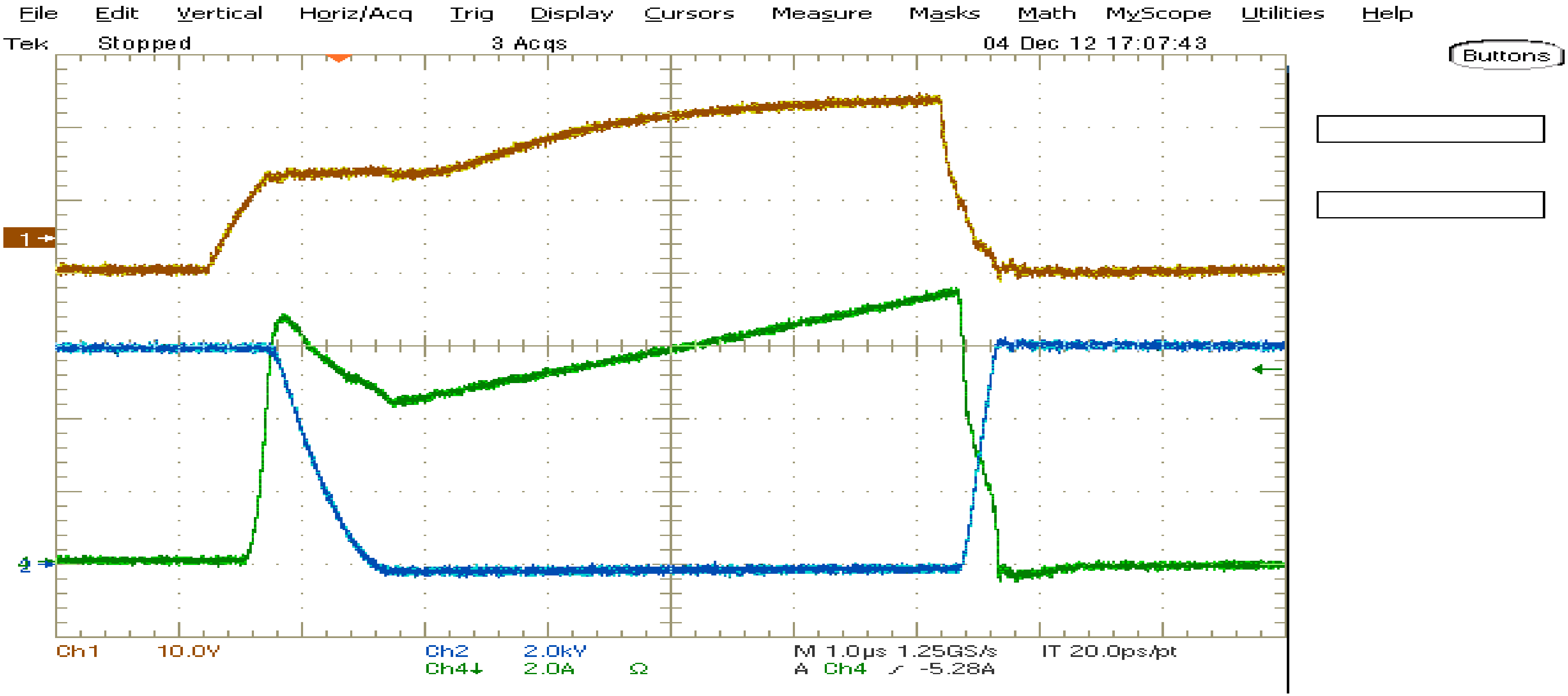
10kV SiC MOSFET



Single 10kV SiC MOSFET Module

10 kV/10 A SiC MOSFET switching characteristics

10 kV, 10 A SiC MOSFET Characteristics at Vdc = 6kV



Tek Stopped 3 Acqs 04 Dec 12 17:07:43

Ch1 10.0V

Ch2 2.0kV

Ch4↓ 2.0A Ω

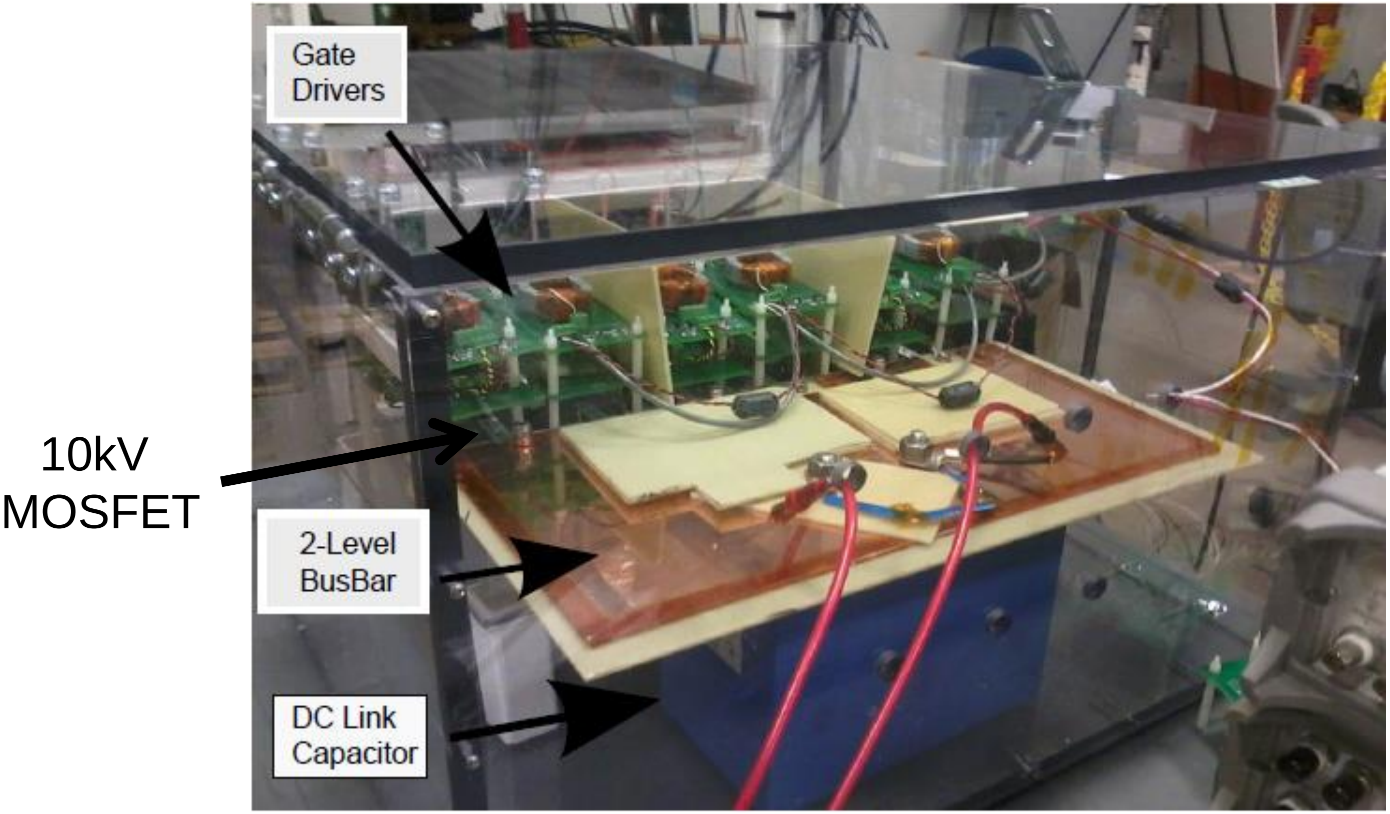
M 1.0µs 1.25GS/s IT 20.0ps/pt

A Ch4 ⟋ -5.28A

V_{GE} (10 V/div); V_{CE} (2 kV/div);

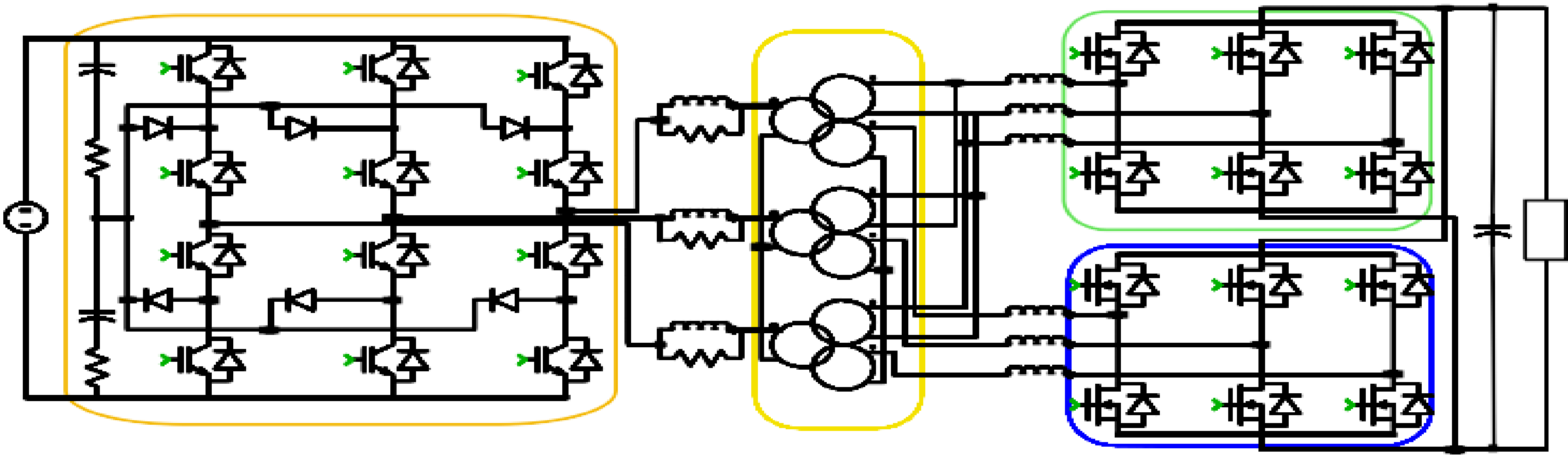
I_C (5 A/div); Time scale: 1000 ns/div

10kV SiC MOSFET based Inverter



2-level 3-phase Inverter built using 10kV SiC MOSFET

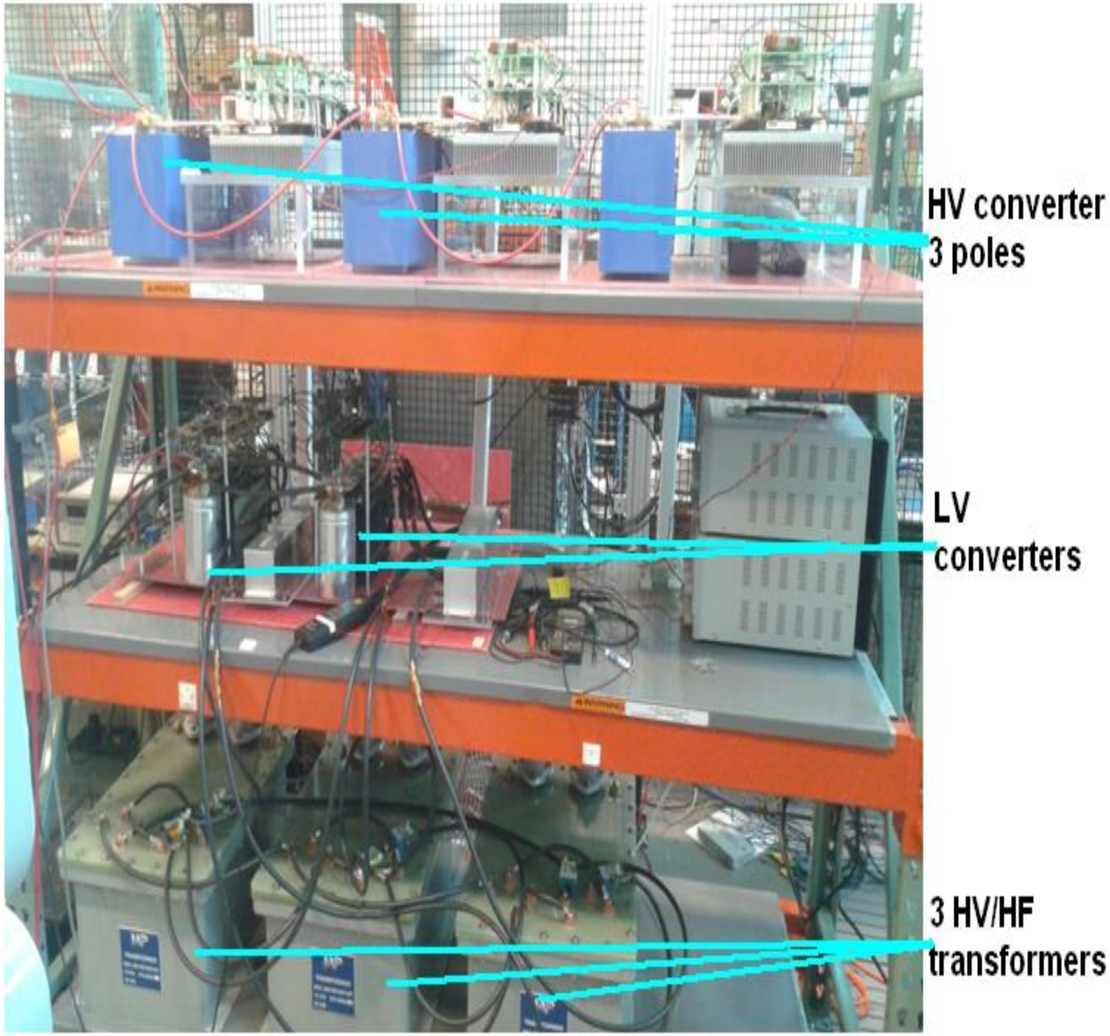
TIPS DAB DC-DC Converter



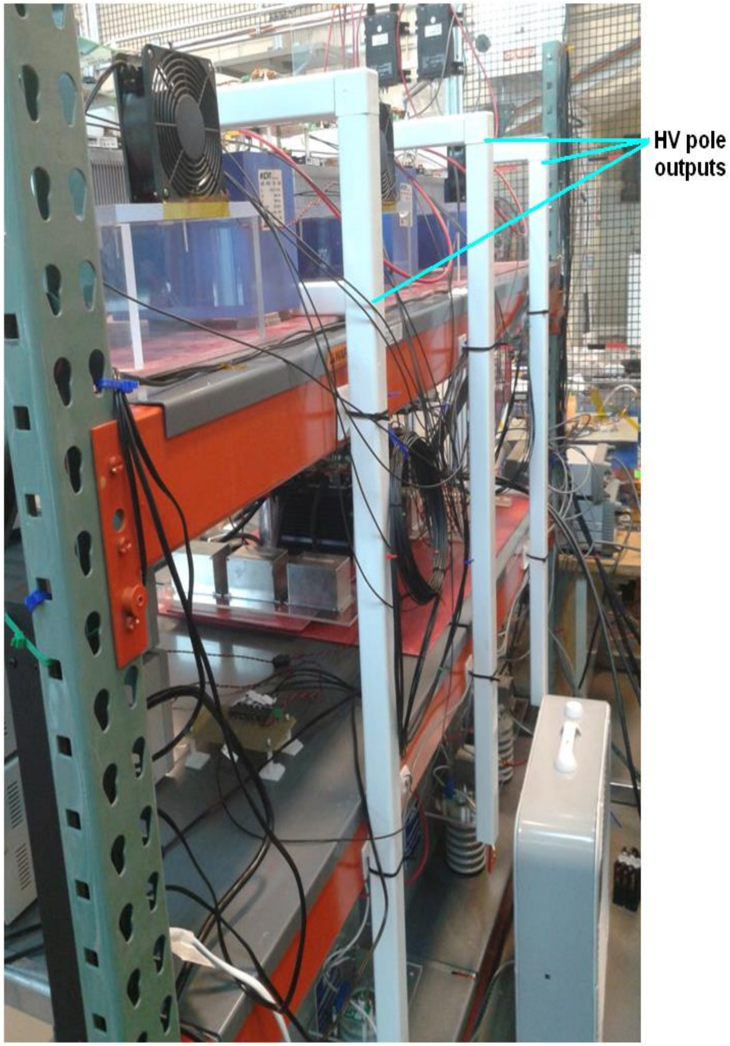
Circuit Diagram Three-phase Y:Y/Δ DAB

- ☐ **Three HF single phase transformer**
- ☐ **Cancellation of 3rd, 5th and 7th Harmonics**
- ☐ **Predominantly sinusoidal current and flux**
- ☐ **Lower Step Voltage on MV winding**

HV 3-phase DAB DC-DC Converter

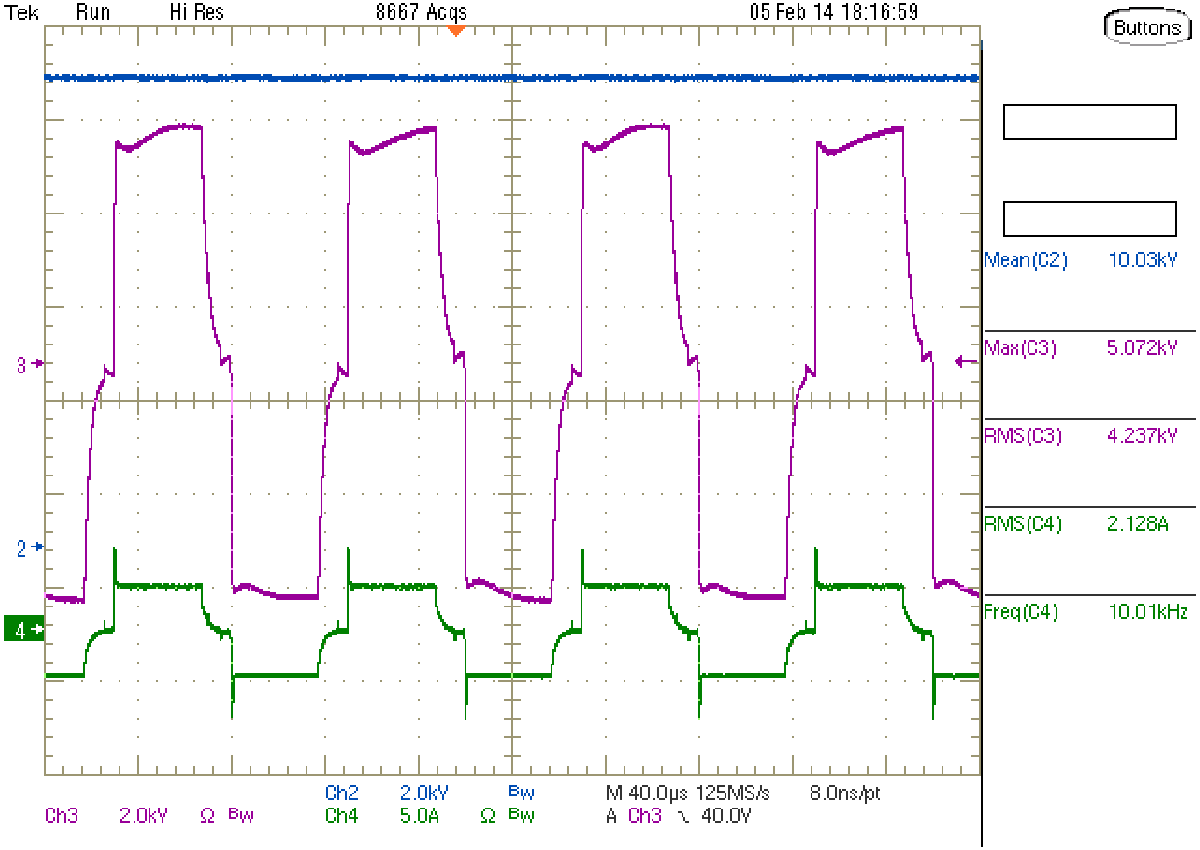


The front view of the DAB converter



Back view of the DAB converter

3-level Pole tests at 10 kV, 10 kHz (9 kW Power Level – on single phase pole)



Input Voltage - 2 kV/div;

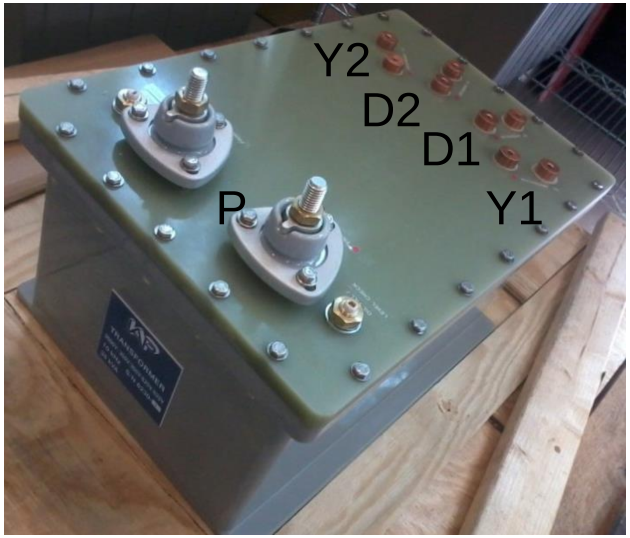
Output Voltage - 2 kV/div;

Load current - 5 A/div;

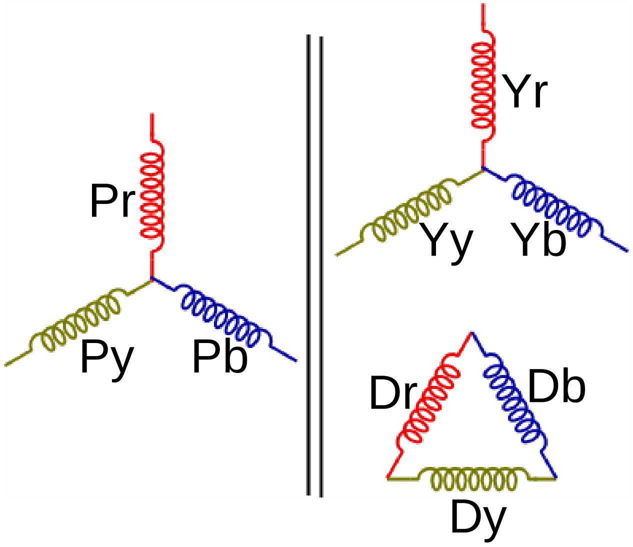
Time scale - 40 µs/div.

- The 3-level converter pole is tested up to 10 kV, 10 kHz with 9 kW Resistive loading.
- This serves as validation up to 27 kW with three-phase converter (3-poles in parallel)

High Frequency Transformer for DAB

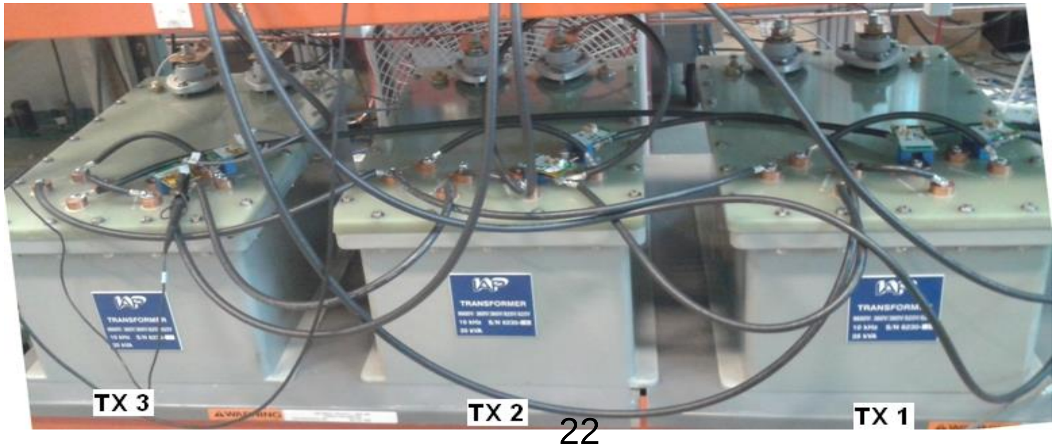


Transformer Connections

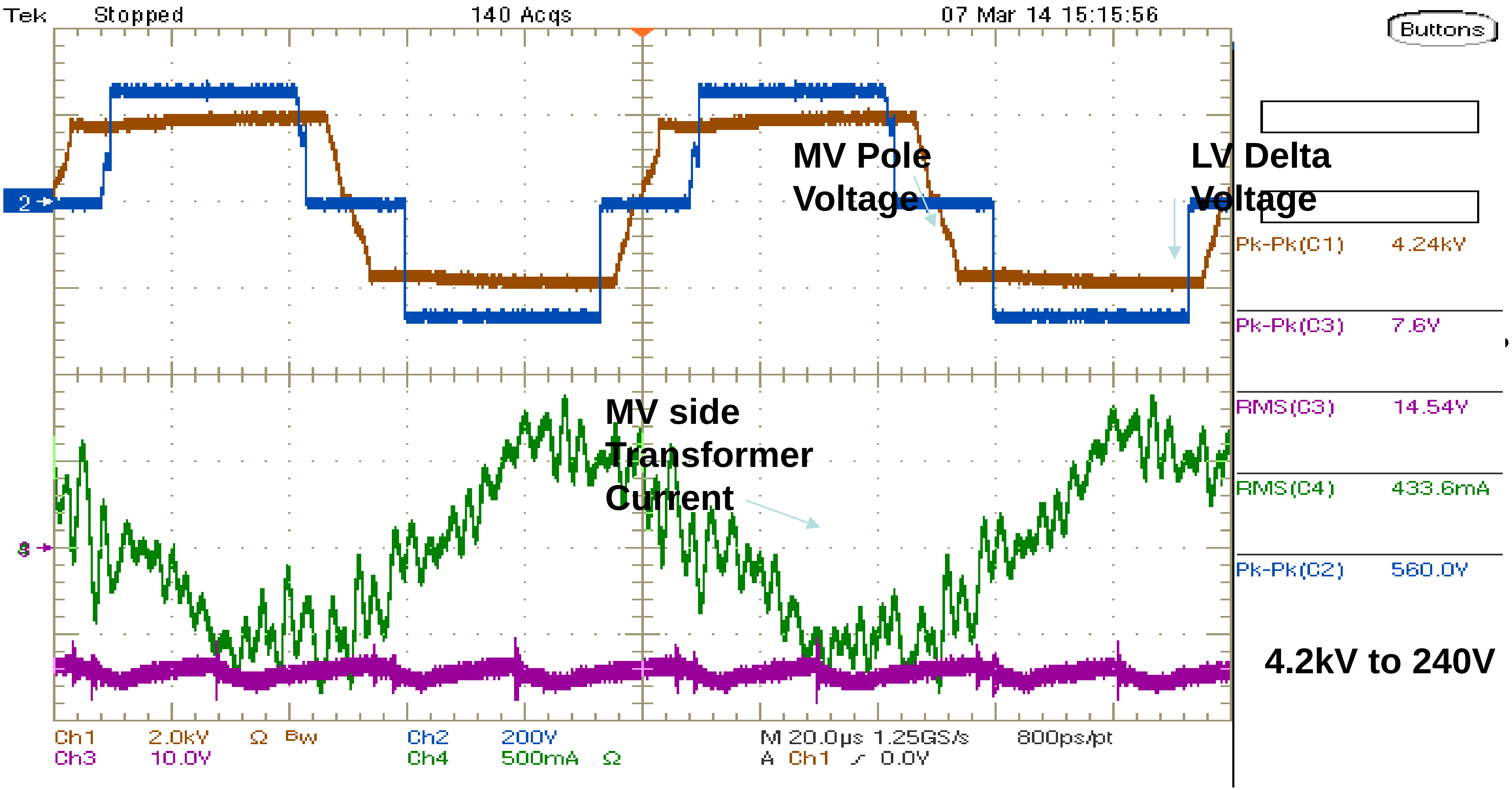


22/11 kV : 800V, 10 kHz, 35 kVA 1-Φ Transformer

- **Insulation tested up to 22kV**
- **Oil filled transformer**
- **Three 1-Φ transformers are connected in Y/Y-Δ for 3-Φ DAB**



DC-DC Converter DAB 4kV Operation



MV Pole Voltage

LV Delta Voltage

MV side Transformer Current

Pk-Pk(C1)	4.24kV
Pk-Pk(C3)	7.6V
RMS(C3)	14.54V
RMS(C4)	433.6mA
Pk-Pk(C2)	560.0V

4.2kV to 240V

Smoothing Effect of Lagging Current (ZVS) on HV Converter Noise Magnitude due to high dV/dt

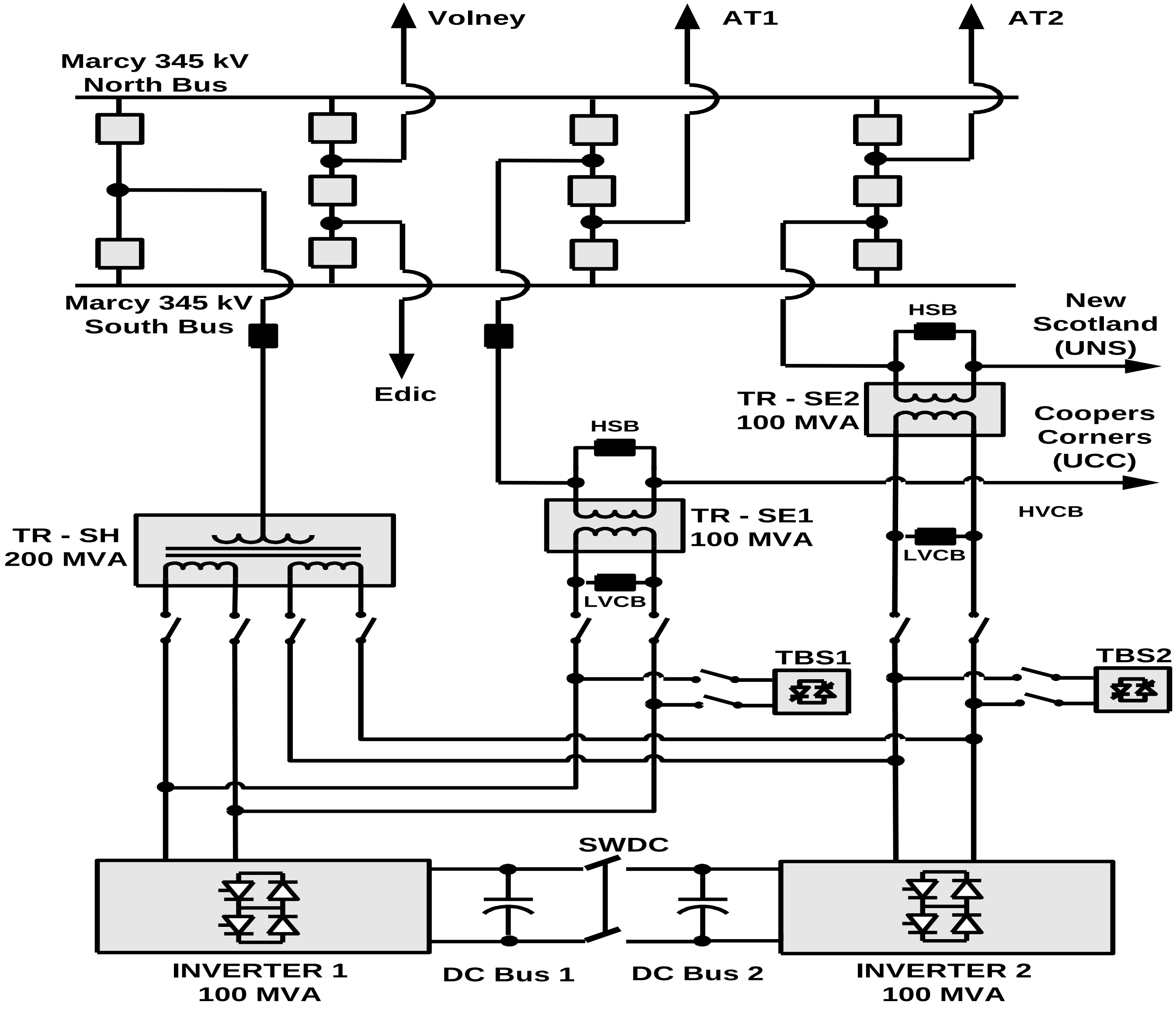
FACTS

Convertible Static Compensator (CSC) - Marcy Substation FACTS Applications

Marcy 345kV SC is 18,000 MVA

There are 11 possible configurations

- STATCOM
- SSSC
- UPFC
- IPFC

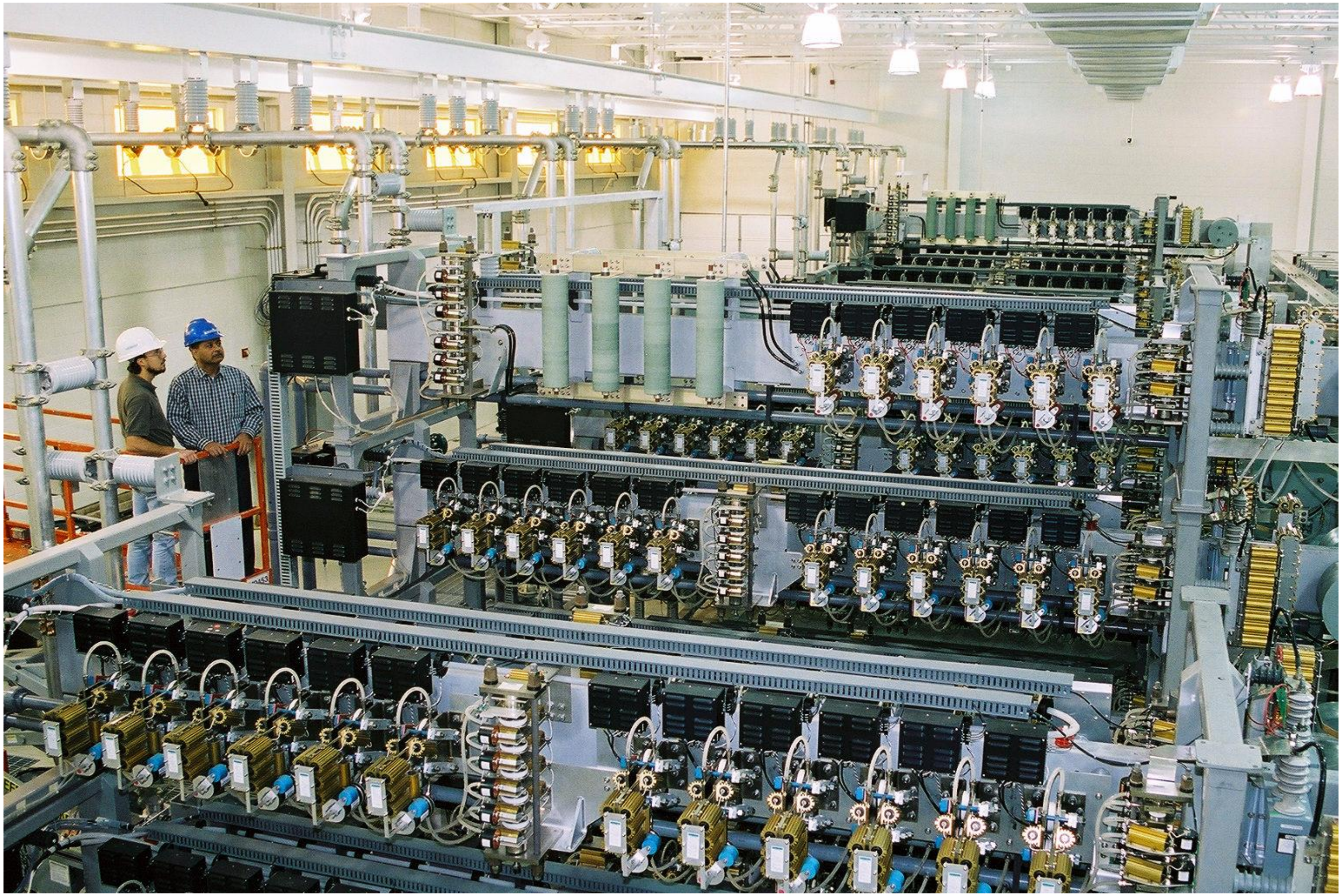


Convertible Static Compensator (CSC) Inverter Hall

Each 100MVA VSC has four 3-phase 3-level NPC converters

Two 100 MVA VSC in the valve hall

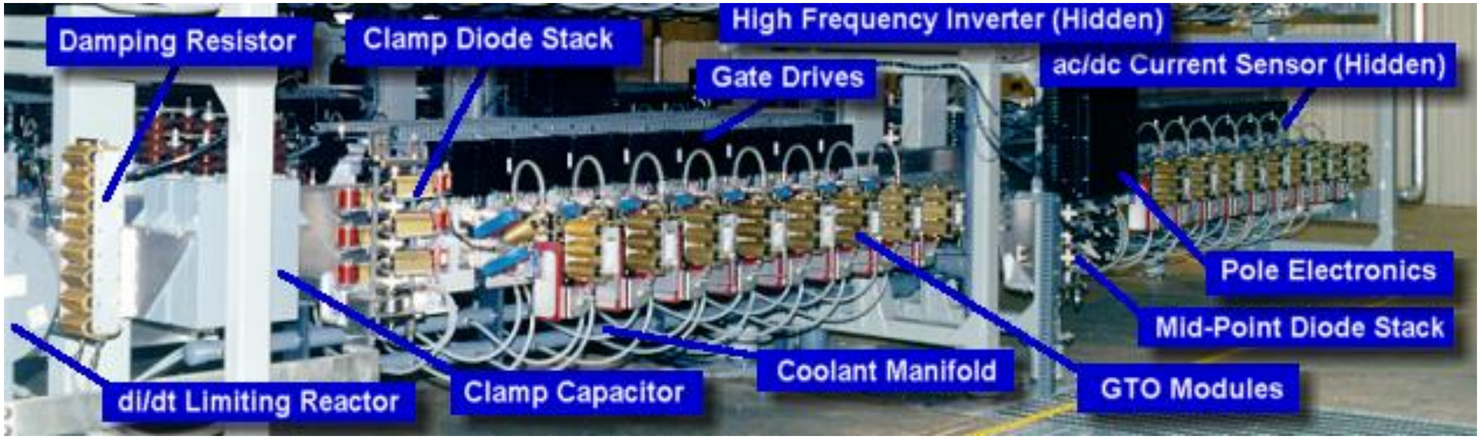
Series connected GTO based 3-level NPC poles

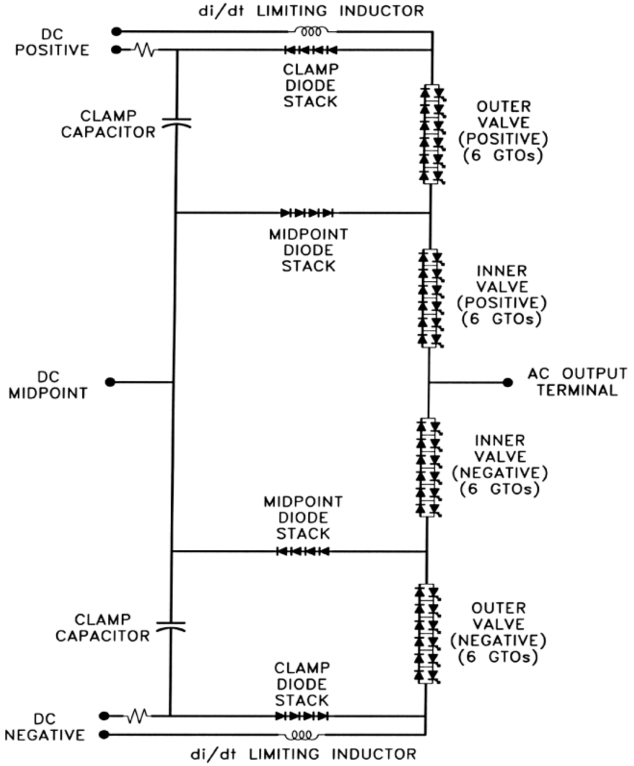


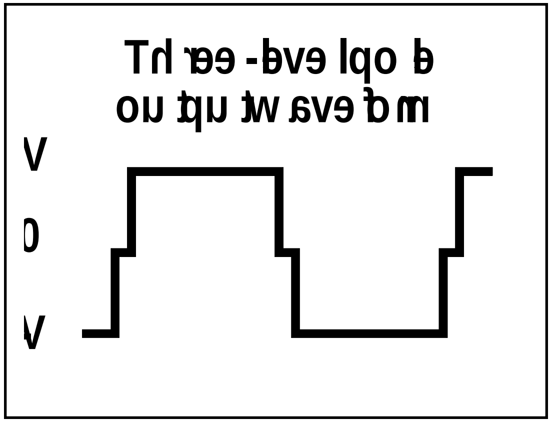
FACTS

Main Components of 3-Level NPC Inverter Pole

Series connected GTO based 3-level NPC poles







IGCT based 3-level NPC inverter pole

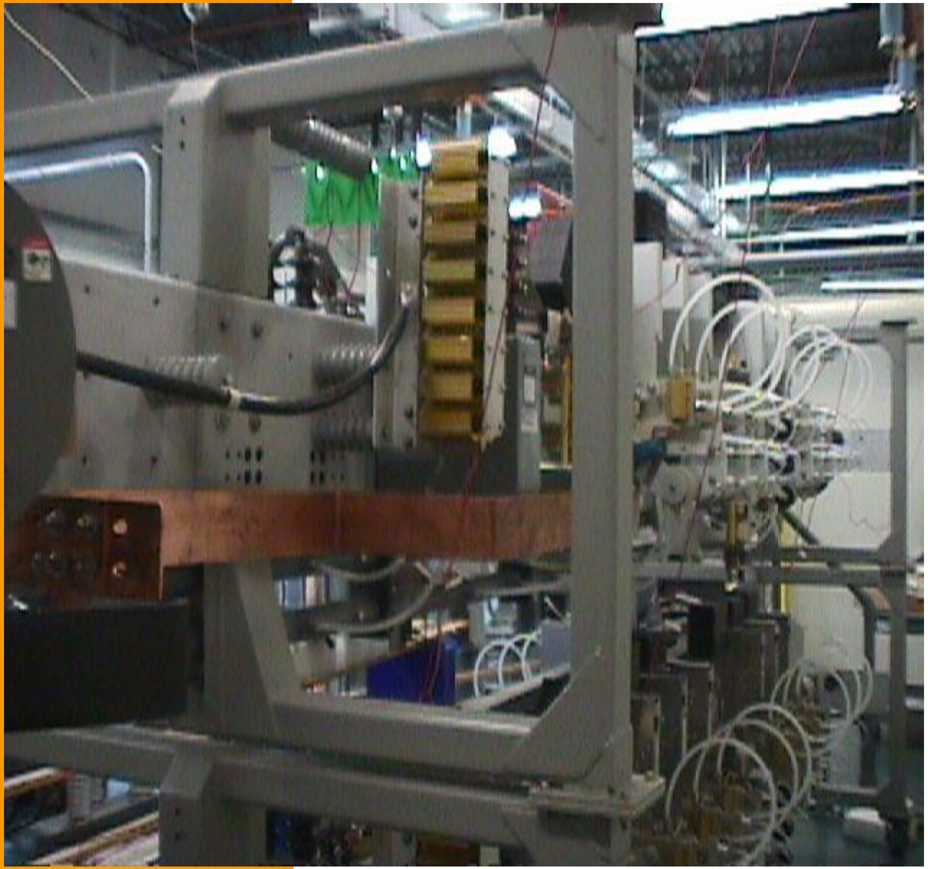
3 series IGCTs per valve

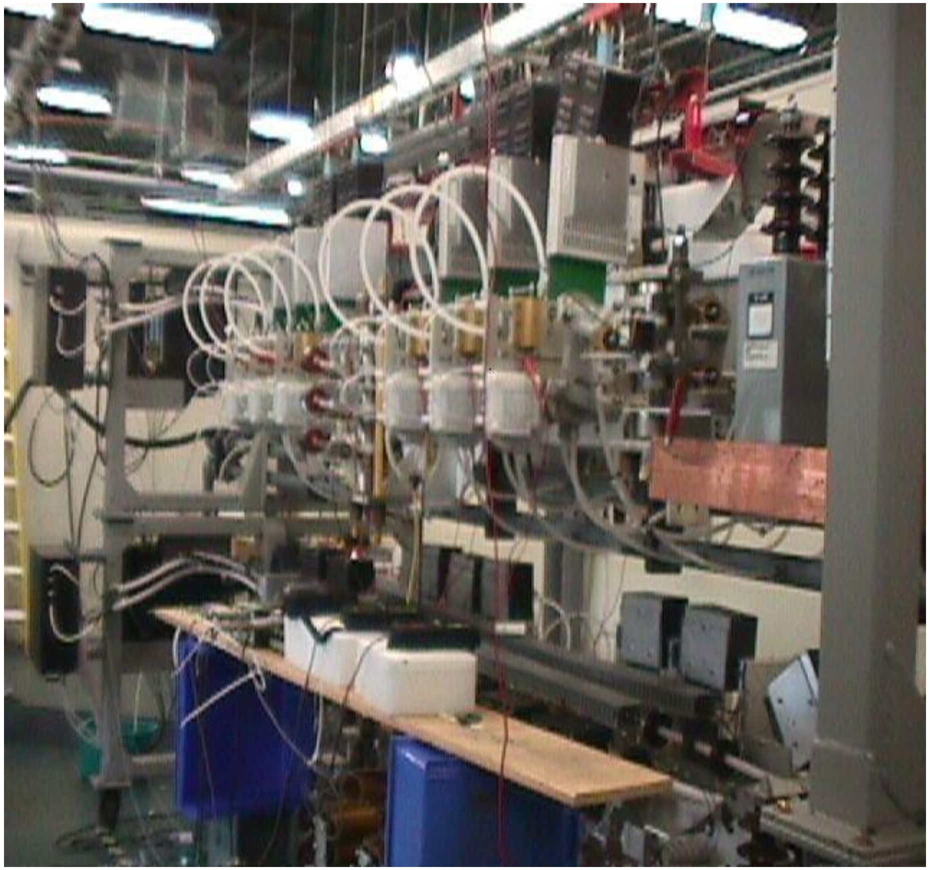
IGCT pole A1

IGCT pole A2

H-bridge test - IGCT based 3-level NPC poles

IGCT pole A1 (top)





IGCT pole A2 (bottom)

High MegaWatt MV Drives

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