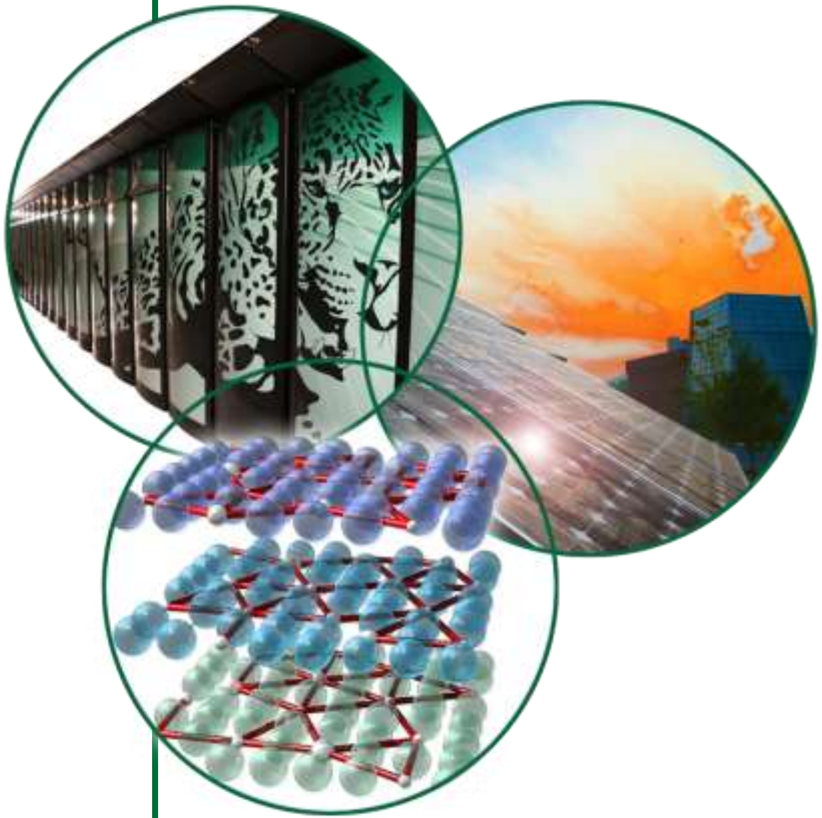
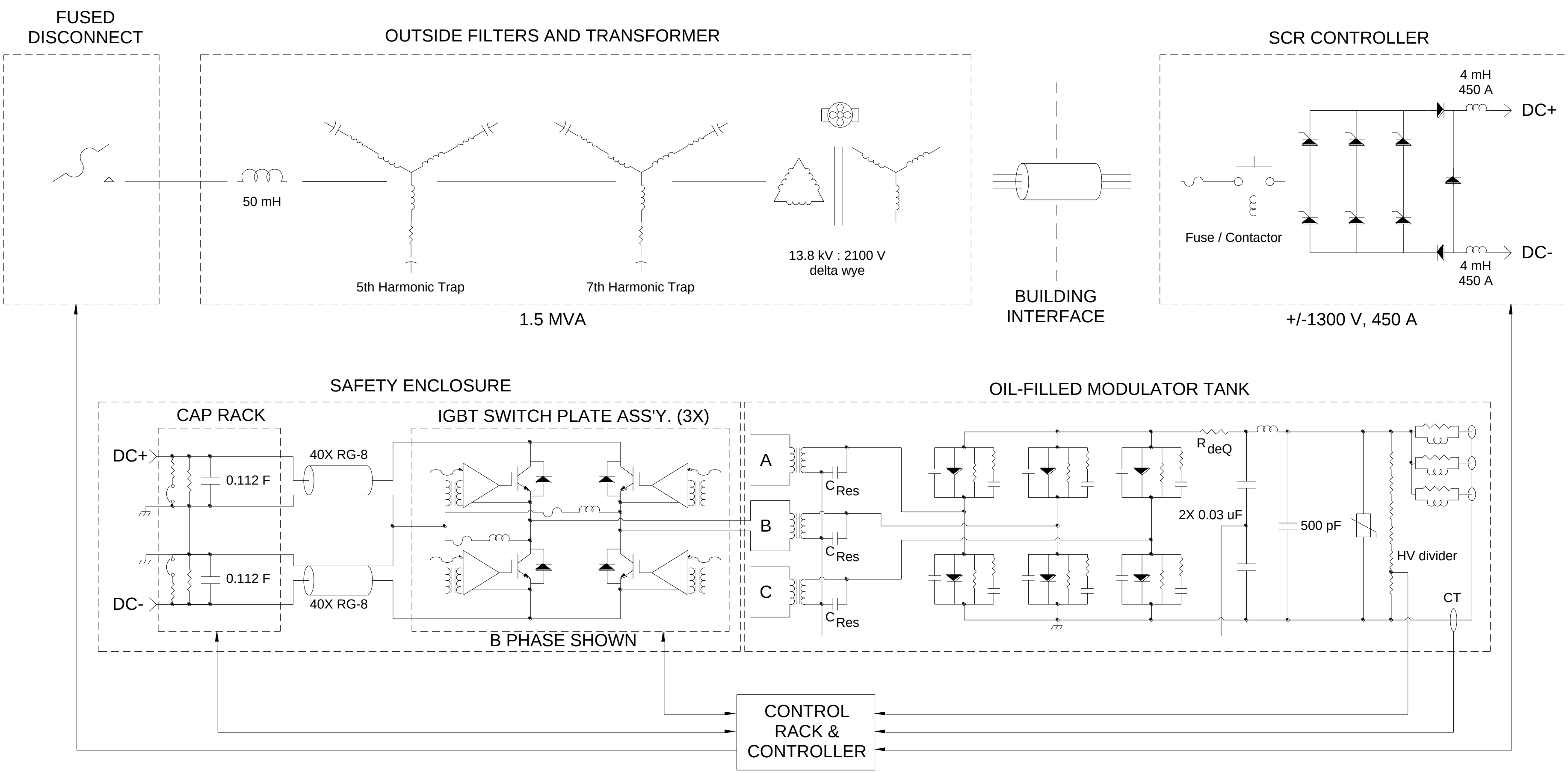
SNS Accelerator Advisory Committee Meeting

HVCM Modulator Upgrades & Plans

David E. Anderson



Modulator Block Diagram

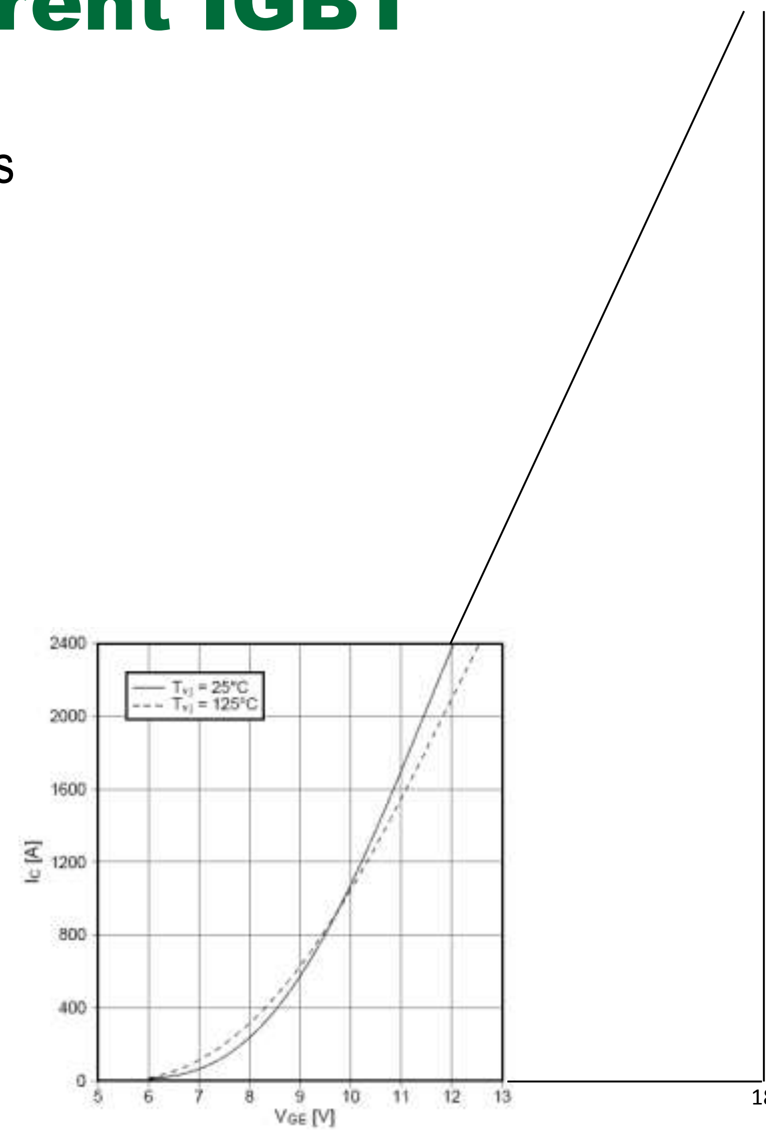


Outline

- Previous Action Items
- New IGBT drivers
- Controls
- PWM vs. PSPWM vs. FM w/ tradeoffs to power electronics
- IGBT snubbers
- Improved tank cooling
- JEMA modulator testing
- IGBT Test Stand
- Series fusing switch
- Alternate topology

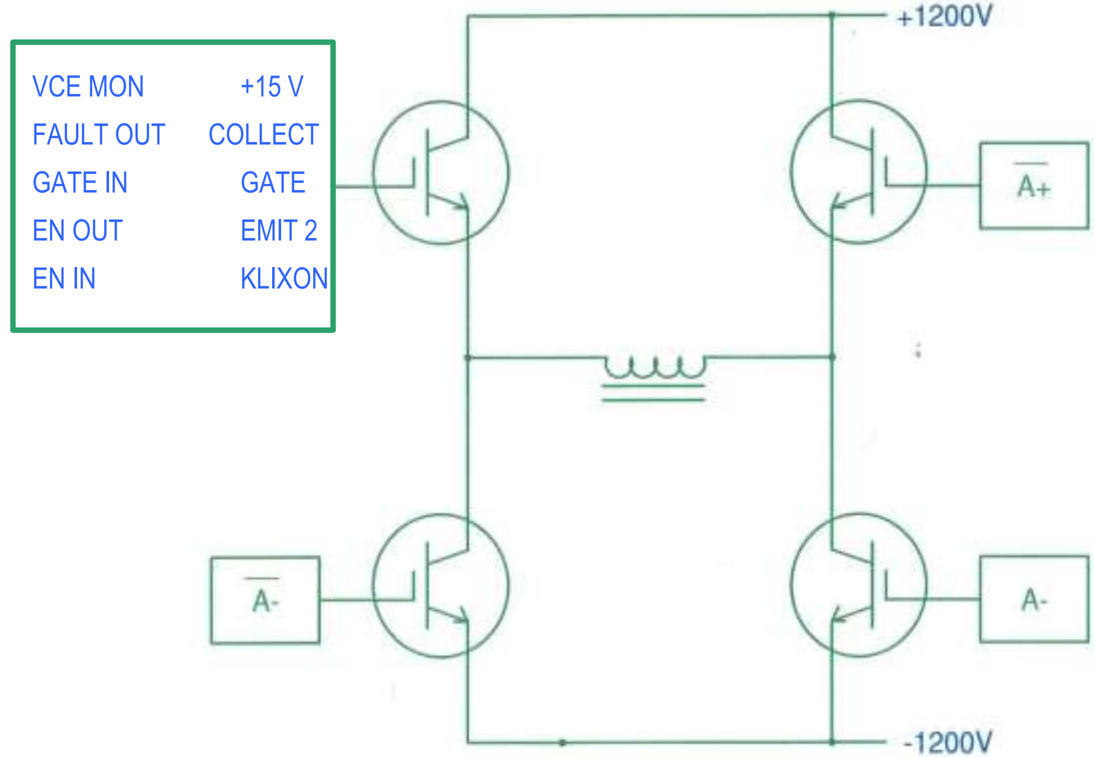
New IGBT Drivers – Current IGBT Driver Woes

- Severe overdrive increased saturated current levels
- Fault currents higher
- Jitter = higher shoot-thru probability
- Slow drift of electronic delays
  - Leads to timing skew
  - May lead to flux saturation
- No on-board IGBT fault detection
- 120 V ac distribution safety/reliability concerns
- Insufficient isolation derating for operating voltages
- Not connectorized, poor MTTR
- Poor EMI shielding



New Driver Features

- Totem pair shoot-thru protection
- Gate volt monitor for out-of-tolerance
- On-board over-current (OI) monitoring
- V_{SAT} monitor for tracking IGBT health (requires new controller)
- Over voltage monitor (IGBT protection)
- Dual 6 kV-isolated power distribution – evaluating 10 kV isolation due to faulty 6 kV units
- EMI enclosure
- LED display for fault troubleshooting
- Connectorized for low MTTR



New IGBT Gate Driver Current Status

- >2000 operational hours at full power, full duty cycle on RFTF, ran in RFQ during last operating period
- Several hundred “forced” hard arcs bus-to-bus, bus-to-ground, forced transformer saturation – faults cleared
- Engineering documentation complete
- Small redesign in works for revision to address voltage isolation on some 6 kV isolated converters
- 250 production units in-house, installed in RFQ, HEBT and RFTF
- Begin additional install Summer shutdown, resources & priorities permitting

Controls – Next Generation Controller

The new controller has been designed to address all of the previous controllers shortcomings, speed trouble-shooting & allow for future changes.

The new controller supports the New IGBT gate driver cards turn on/off feedback and VCE monitoring signals

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OAK RIDGE National Laboratory

Next Generation Controller

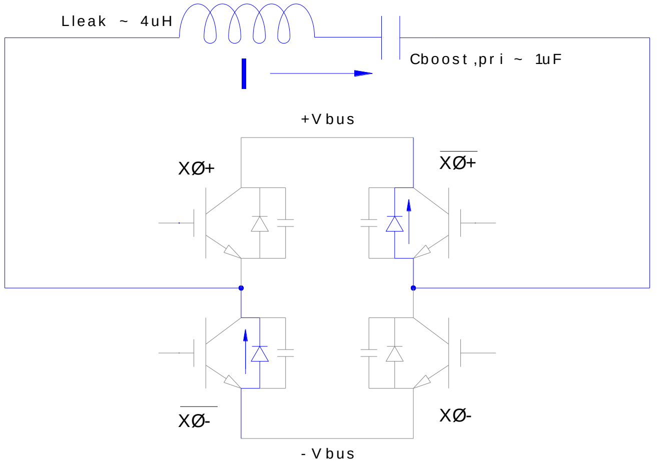
The new controller prototypes provide:

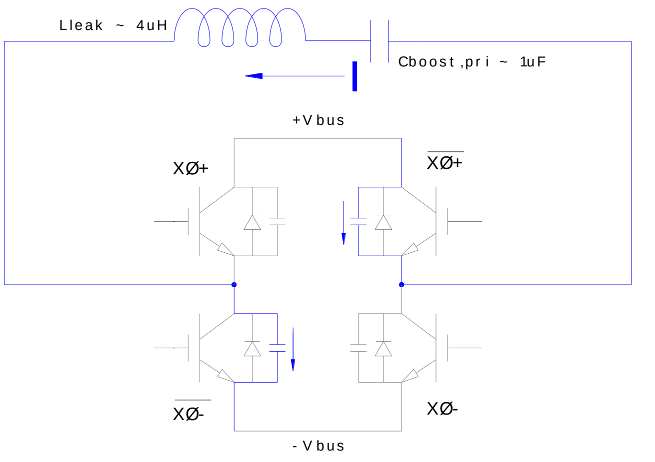
- Waveform capture & data logging, incl. first fault detection
- Flux monitoring, compensation & warnings
- IGBT V_{CE} monitoring & warnings
- Variable frequency operation & modulation
- Phase shifted pulse width modulation
- Complete control of start pulse width, position & phase
- Programmable fault & warning thresholds for all Inputs
- SCR power supply waveform monitoring and warnings
- EPICS interface

Future versions of the new controller will provide:

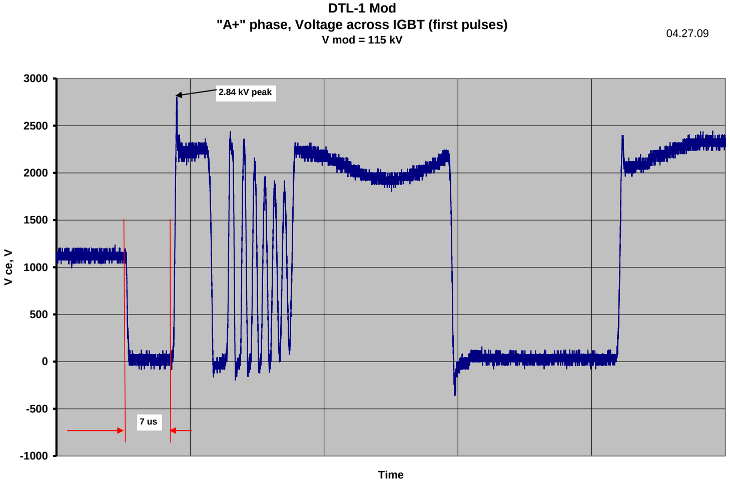
- Flexible smoke detector logic
- Control of series switches for IGBT fault isolation
- 3 & 4 phase operation with semi automatic IGBT fault recovery
- IGBT shoot-through monitoring & warnings
- IGBT turn on & turn off monitoring, compensation & warnings

Modulation Techniques – Why PWM Isn't Ideal Here





- Dead band $>\pi(L_{leak}C_{boost,pri})^{1/2}/2$ and free-wheel through IGBT parasitic capacitance, increasing switching losses in all devices
- If dead band too short OFF devices don't have sufficient time to recover
- RESULT→ Very narrow allowable operating dead band for the H-bridge in this topology



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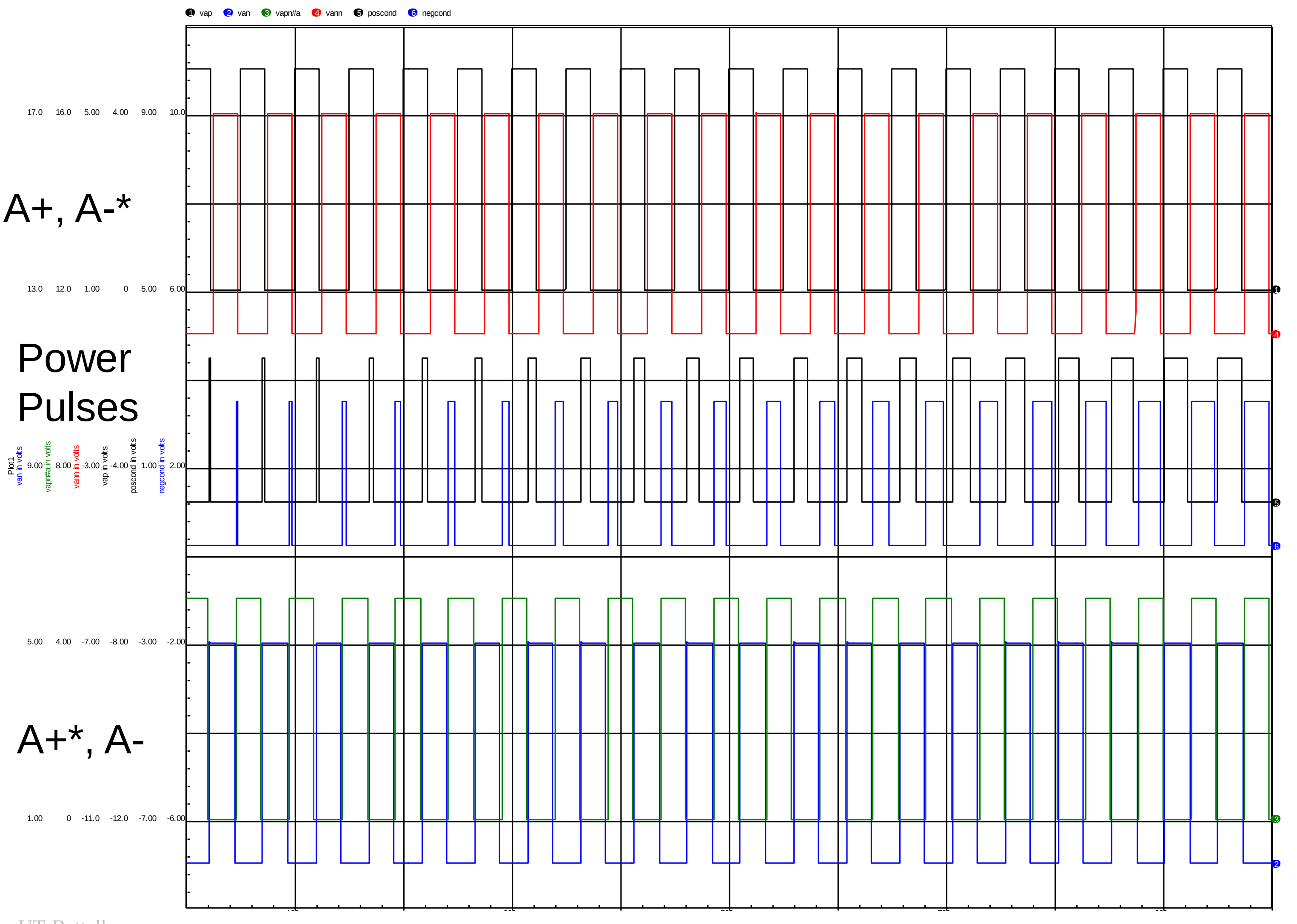
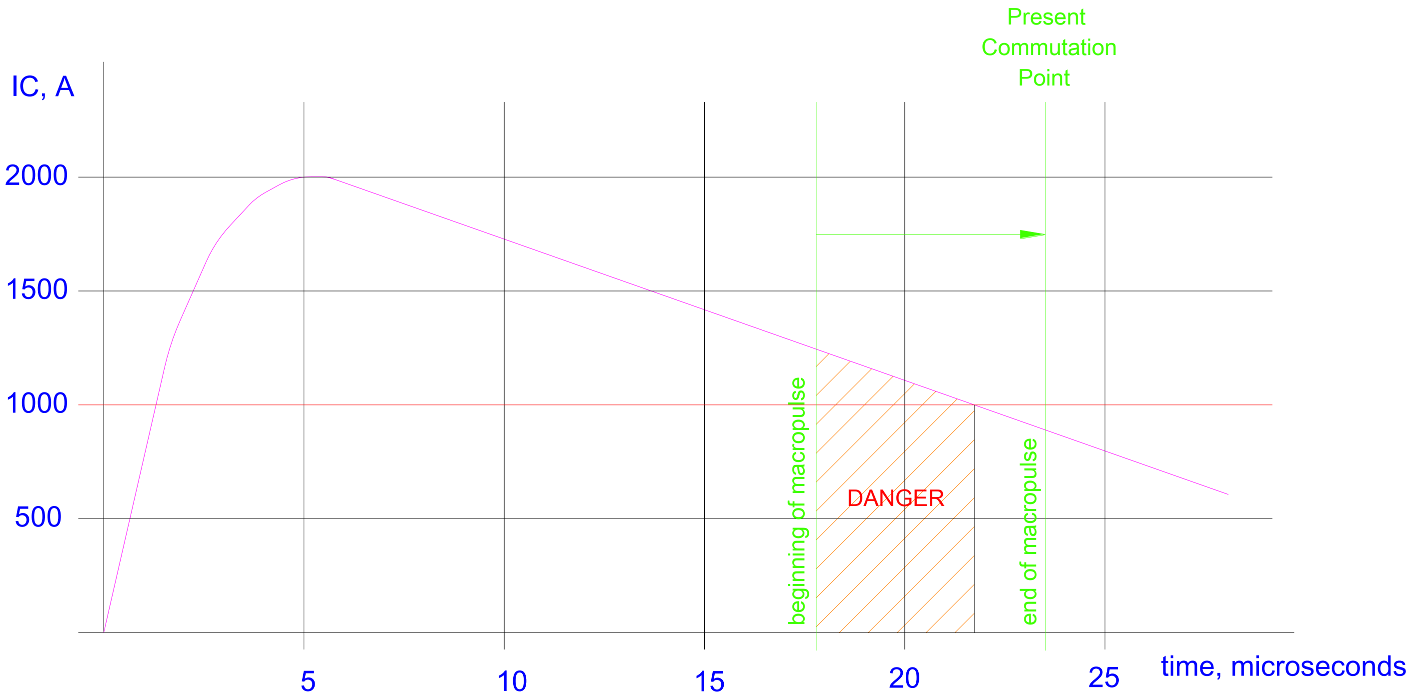
One Solution – Phase Shift Pulse Width Modulation (8°/cycle shown for clarity, much less required)



Phase Shift Pulse Width Modulation Limitations



•Too little commutation current results in insufficient energy stored in leakage inductance, non-zero voltage switching at turn-on
•Previous operational experience indicates commutating in excess of 1 kA dangerous (anti-parallel diode limitations, di/dt problems)
•Phase shift used exclusively forces excessive commutation current at beginning of macro pulse which may lead to IGBT failure
•Combined with frequency modulation, can maintain nearly constant commutation current

Phase Shift Pulse Width Modulated Summary

PROS:

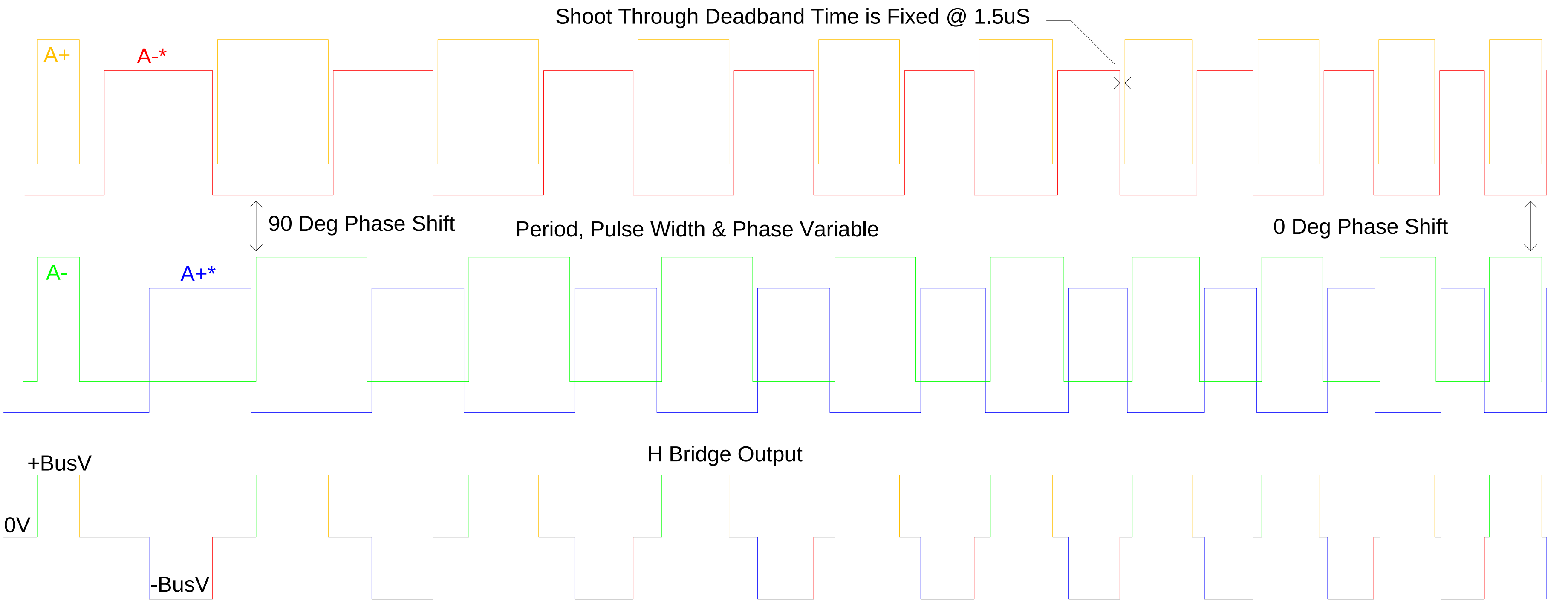
1. Maintains fixed dead band, minimizing problems with PWM
    1. Reduced device oscillations due to excessive dead band
    2. Reduced switching losses
2. “Shoot-thru” pairs held in constant timing relationship, phase shifting performed between LHS and RHS of bridge
3. Allows for droop correction

CONS:

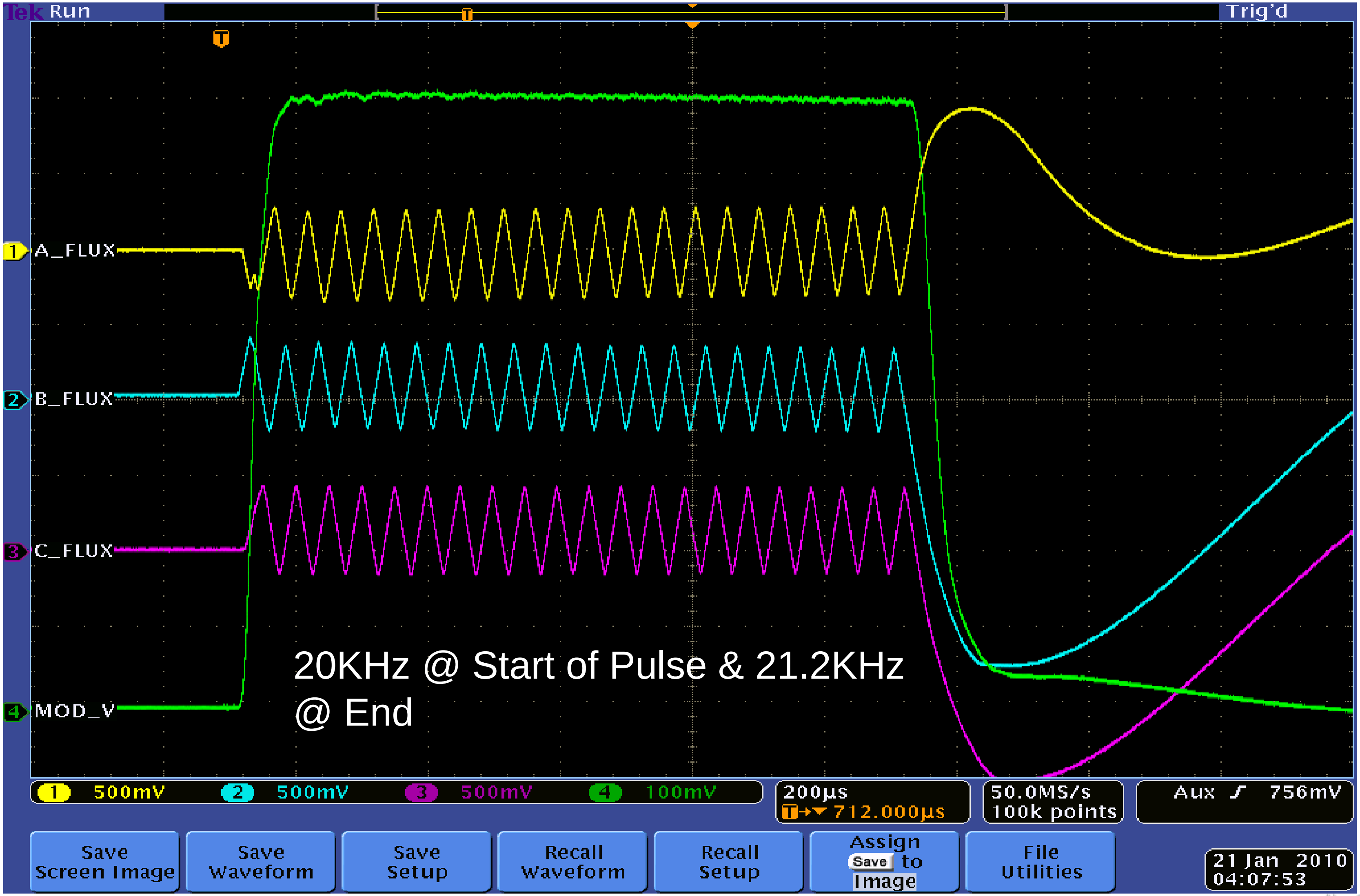
1. Collector current commutated at different levels
    1. Shorter power pulses result in higher commutation currents
    2. Combining with frequency modulation can minimize
2. Losses different on LHS and RHS of bridge (can alternate to alleviate)

Initial Low-voltage Results with Representative Gate Pulse Signals

Start Pulse Position , Phase Modulation, Frequency Modulation & Flux Compensation



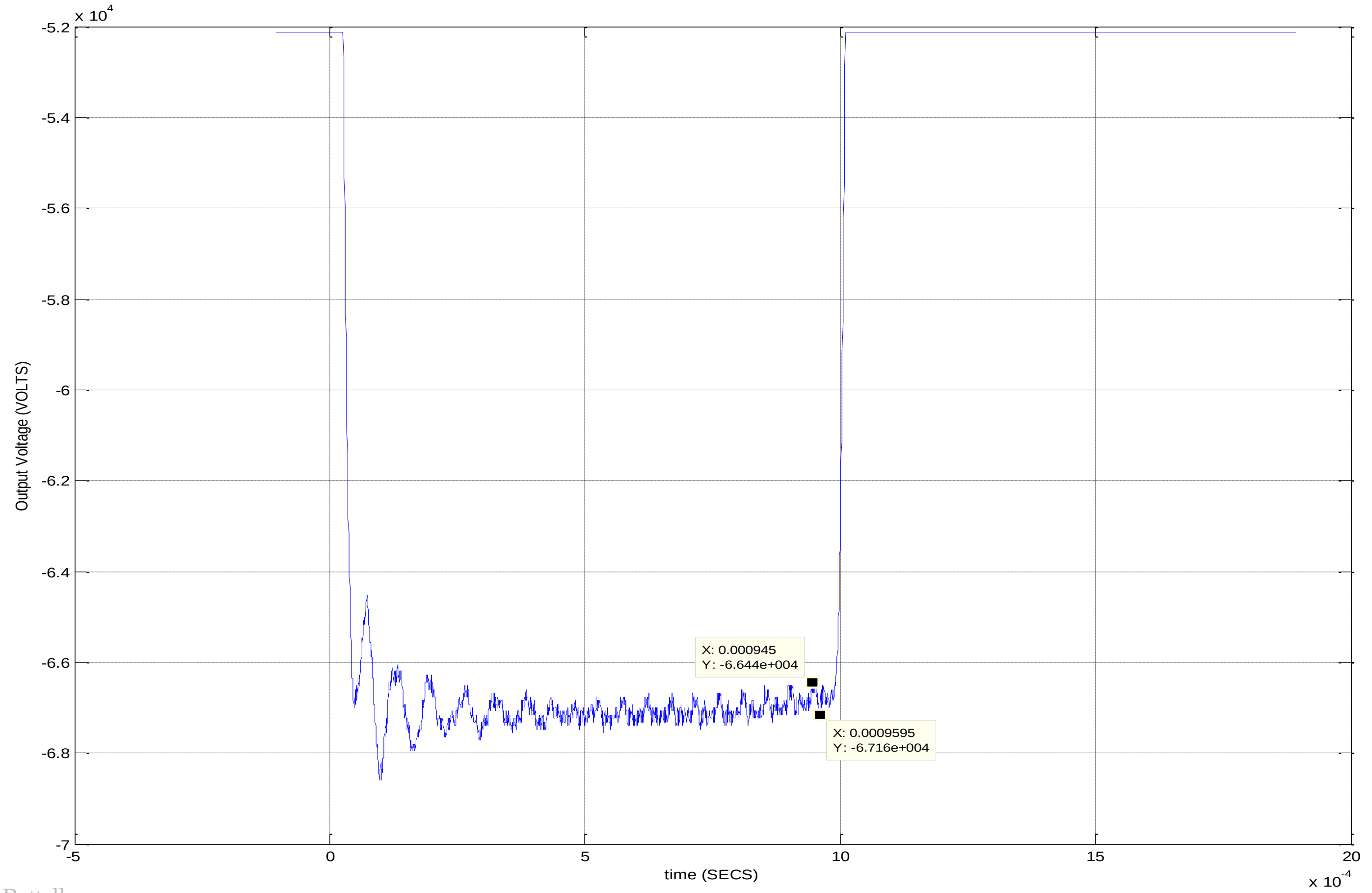
Frequency Modulation Turned On to Further Correct Slope of Modulator Output Voltage



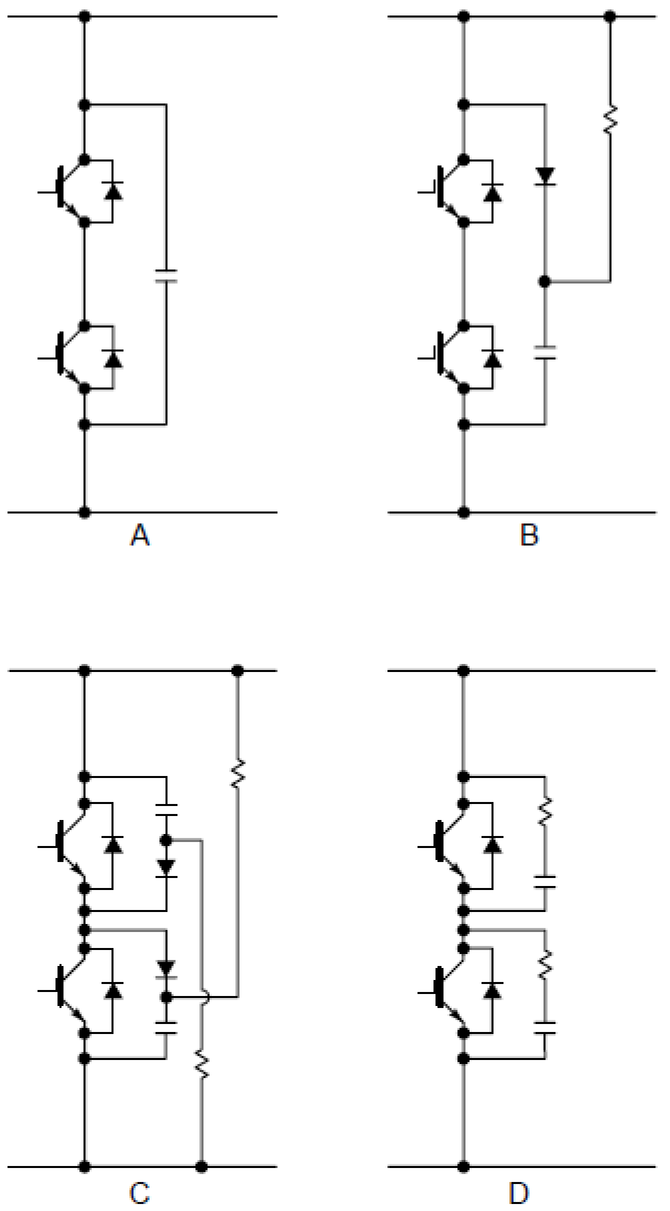
60 Hz Full Power Operation Test for 1 hour using Phase Shift and Frequency Modulation (start pulses not optimized)

Output Voltage= 61.8 kV
Bus Voltage= +/- 1004 V
FM = 20 kHz to 22 kHz
PSM = 95% to 100%

$\Delta Vdroop$ = 304 V/ms
$\Delta Vripple$ = 664 V



IGBT Snubbers – the Options



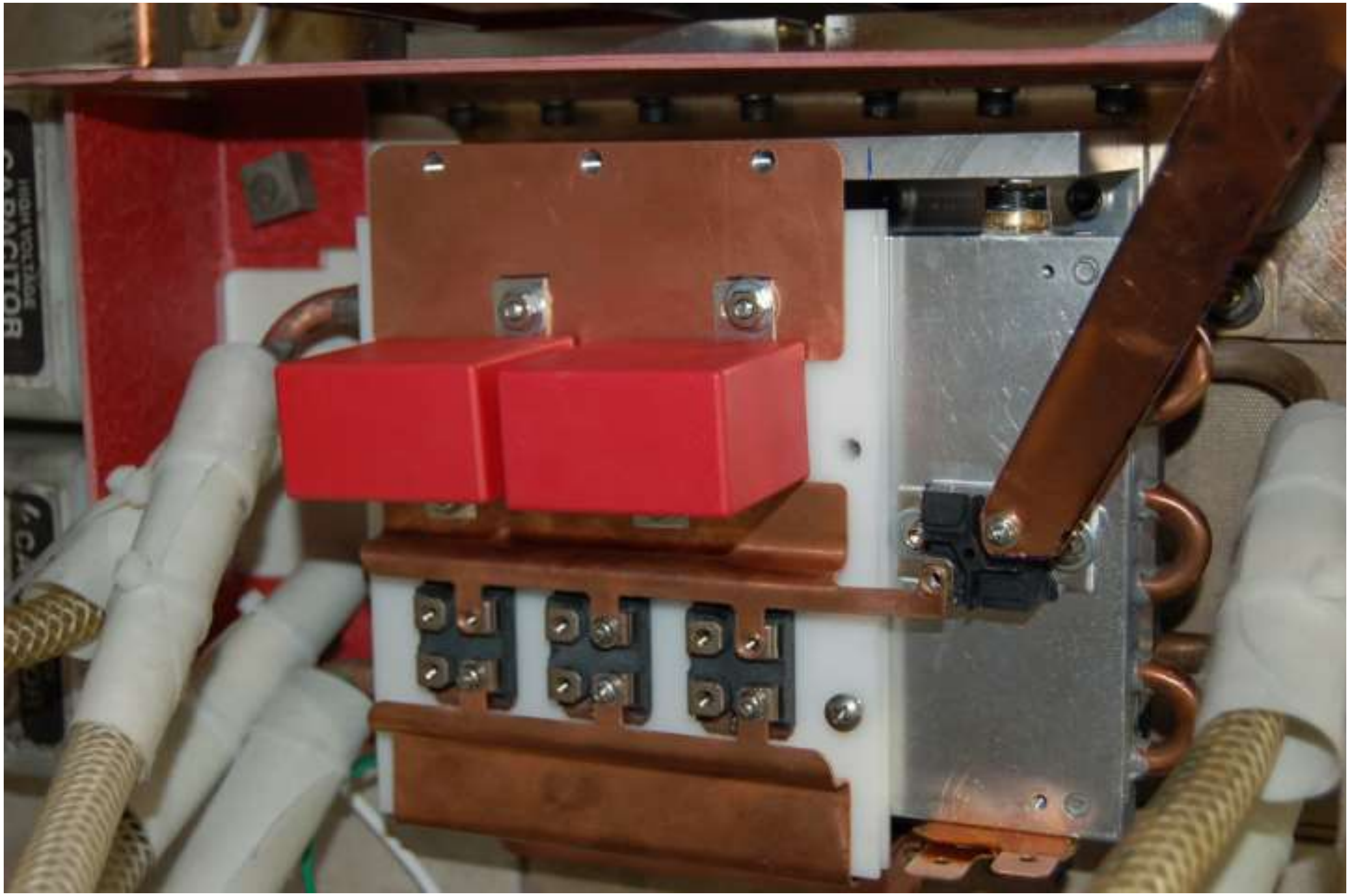
A – creates oscillations with resonant circuit, can be applied to single IGBT

B – effective snubbing requires low loop inductance

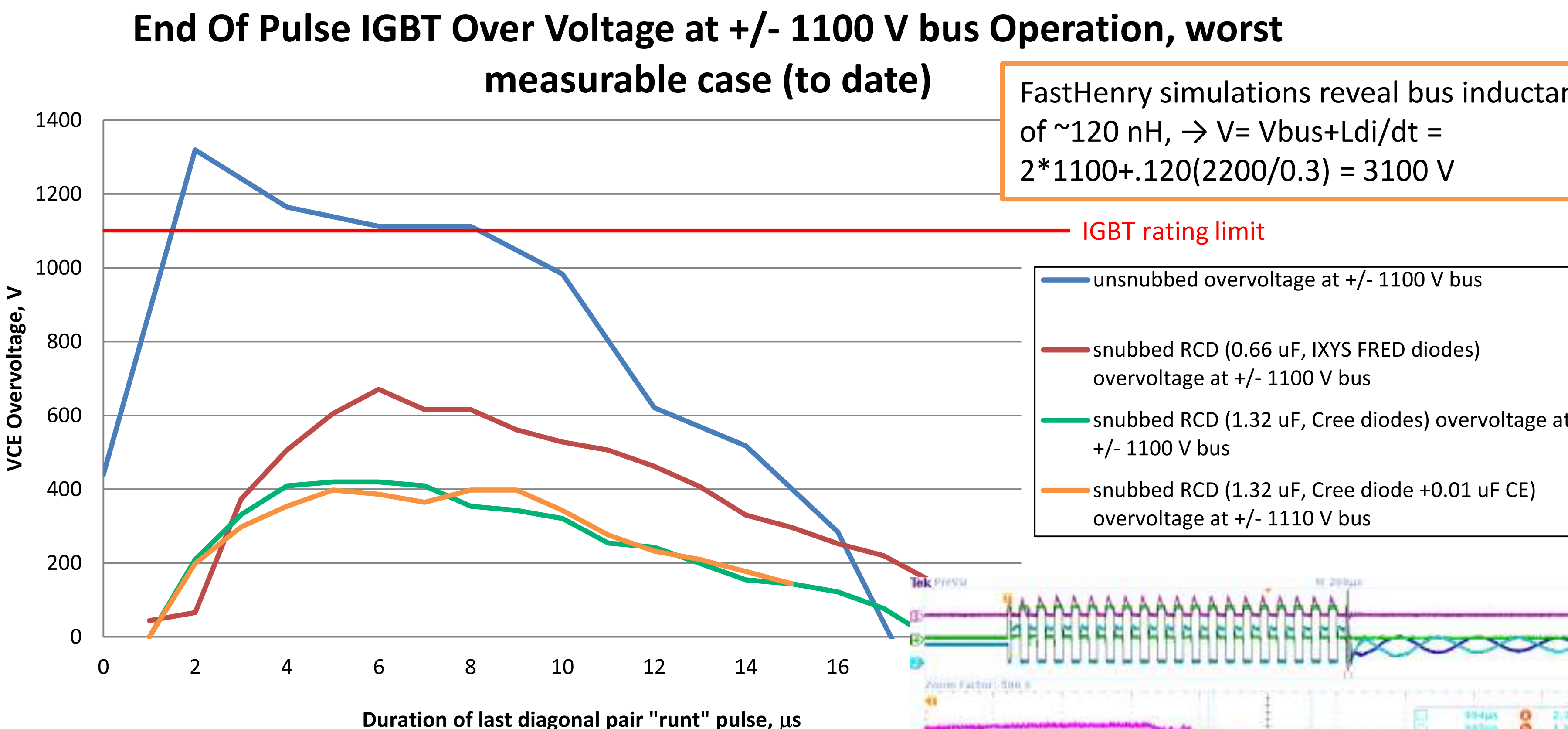
D – capacitor charges and discharges each switching cycle, resistor losses very high, efficiency compromised

C – voltage clamp, resistor only dissipates power when capacitor clamps over voltages – does require ultra-fast diode and very low loop inductance in CD loop

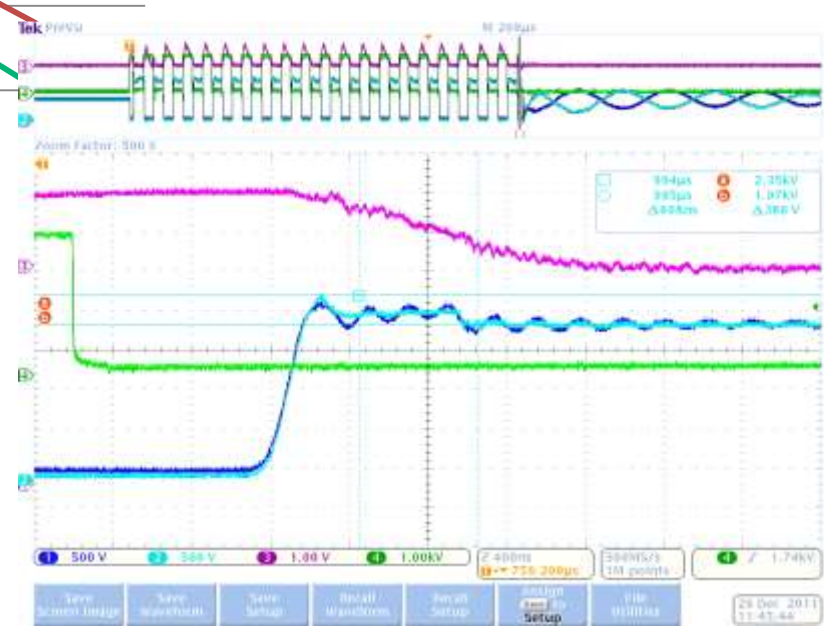
IGBT Snubber – the Prototype



IGBT Snubber – the Problem



FastHenry simulations reveal bus inductance of ~120 nH, → V= Vbus+Ldi/dt = 2*1100+.120(2200/0.3) = 3100 V



IGBT Snubber – absence of is a hindrance going forward

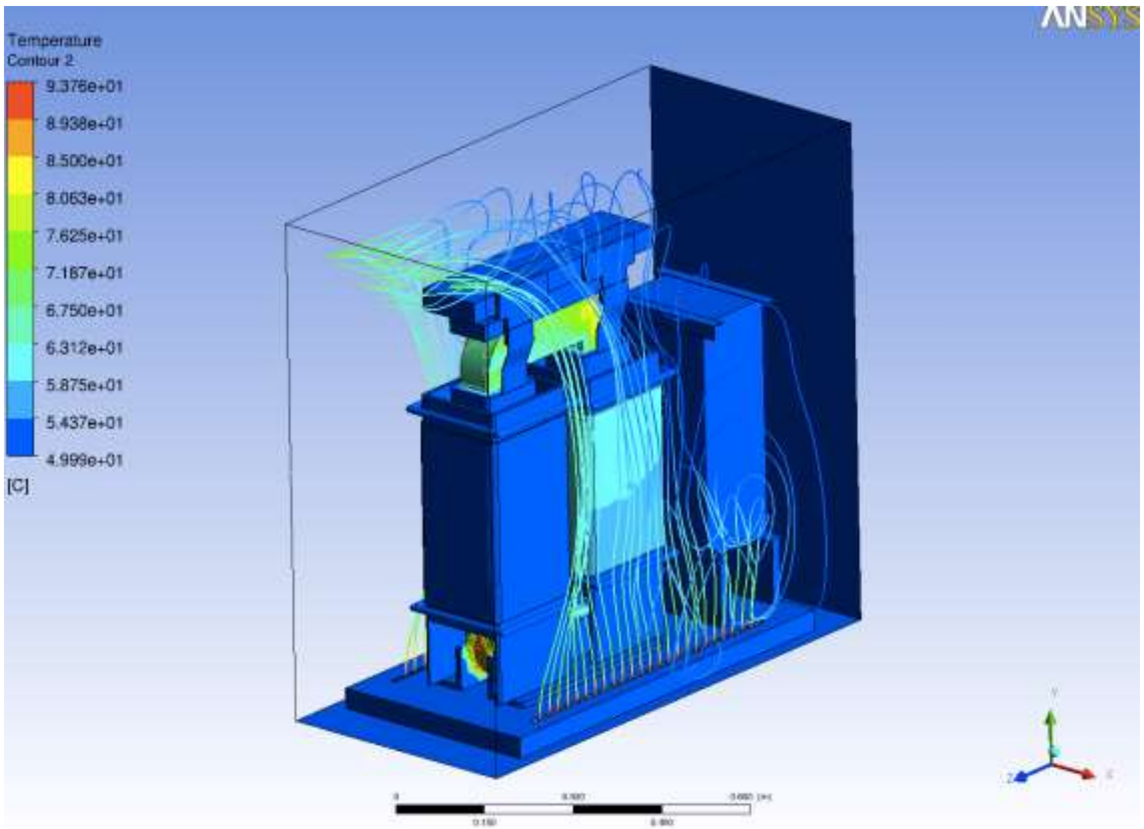
Current lack of a snubber presents other system limitations:

- Load fault events can generate uncontrolled voltage transients on IGBTs
- Having them may permit longer pulse width at present modulator output voltages without additional upgrades
  - Presently limited by bus voltage which is restricted due to voltage transients
  - Reducing transients should allow for higher DC operating levels

Tank Thermal Issues – explain cap failures and other anomalies?

- Tanks clearly run hot if filter plugged or due to other blockages, up to 160°F observed in RFQ modulator
- Current flow interlock insufficient given oil properties and failure to shut system down, evaluating submergible oil flow meters
- Submerged heat exchanger / pump makes replacement time consuming
- Submerged voltage divider electronics also increases MTTR
- Cap mfgr. concerned about high ambient temperature and stresses on case causing weld failure, lifetime ~doubles for every 10°C temp. reduction
- 2605-SA1 max. continuous operating temperature 150°C
- 155°C for nanocrystalline, although 10% degradation in saturation flux density at 140°C and μ_r degrades over time at >100°C
- Like to keep diode junctions <100°C for long lifetime
- Lots of visual evidence of thermal hot spots in RFQ modulator
- New system could be built with pressure bypasses, redundant filters, redundant pumps, etc.
- Oil distribution system should also be redesigned – **no current AIP funds!**

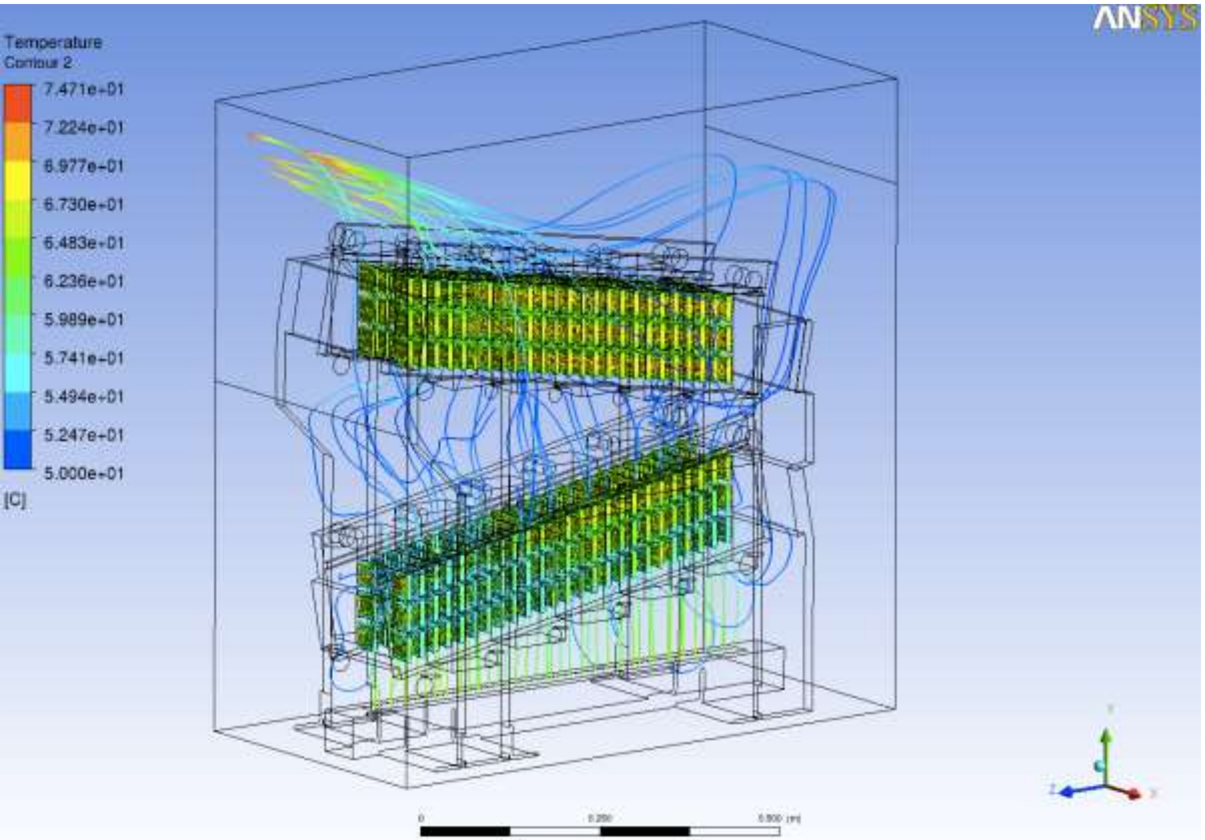
Examples of Improved Oil Distribution System Transformer – ANSYS



Simple 1D conduction

- v_{oil} = 1 m/s
- P_{core} = 6 kW (~2 kW used in ANSYS analysis)
- For a 10 mm "slice" of the core, P/lamination = 7.5 mW
- Heat flux is 6.7 kW/m^2
- Core interior temp. 25ºC higher than surface temperature
- 110ºC approaches the manufacturer's max recommended operating temperature

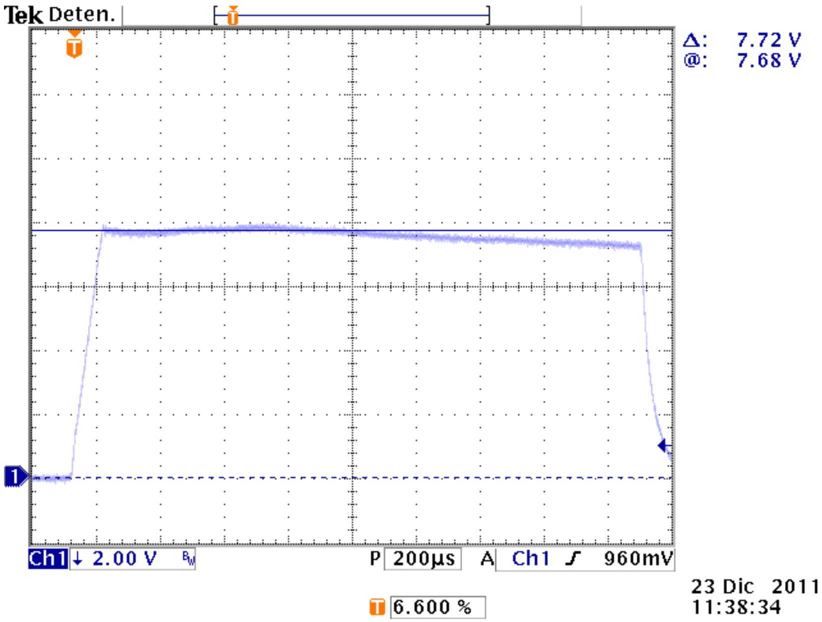
Examples of Improved Oil Distribution System Rectifiers – ANSYS



v_{oil} = 0.25 m/s
$R_{th,JC}$ = 0.35 K/W
$R_{th,CS}$ = 0.25 K/W
P/diode = 6.1 W

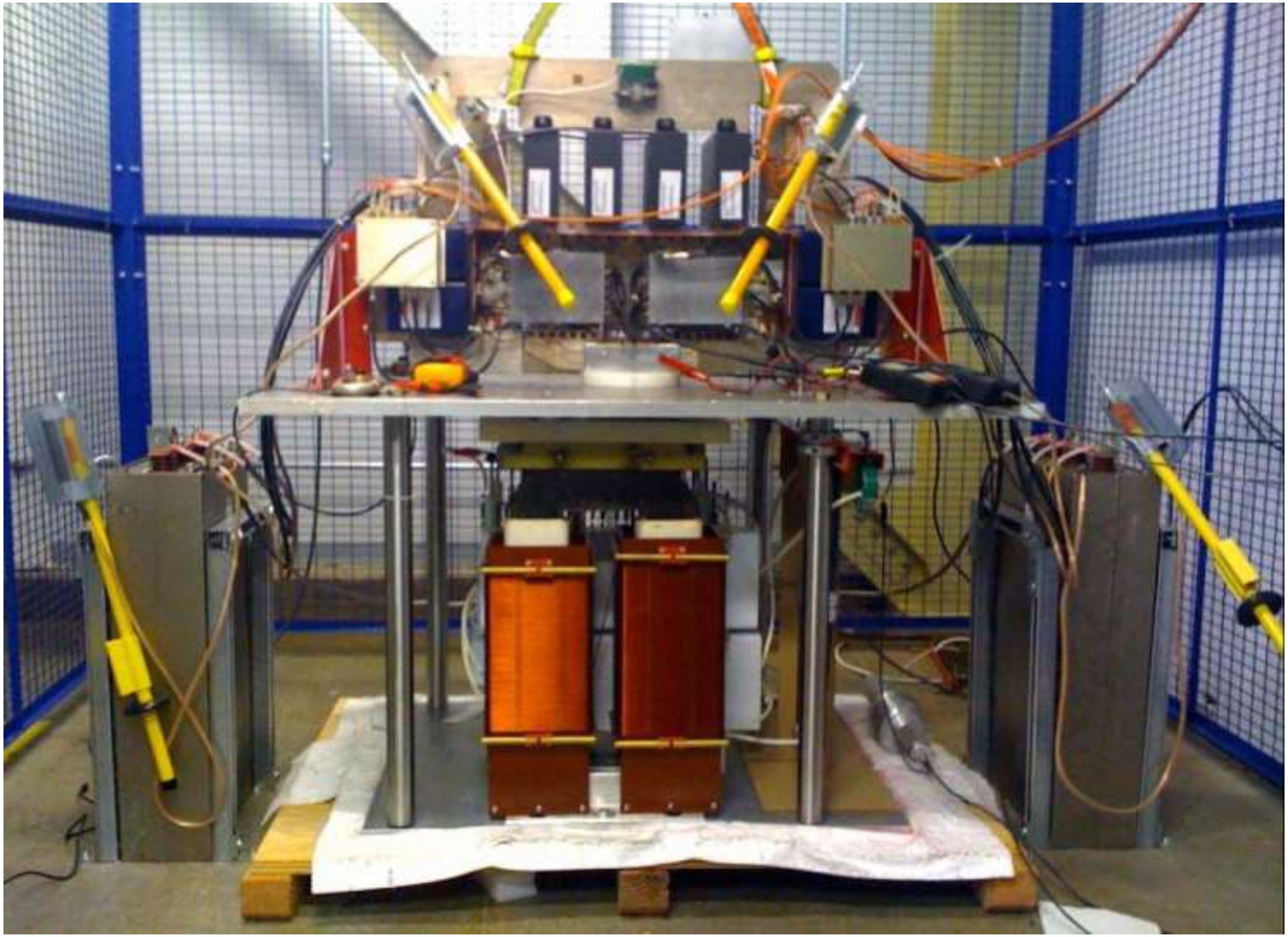
Max. junction temp. = 80°C

JEMA Modulator Test Plans

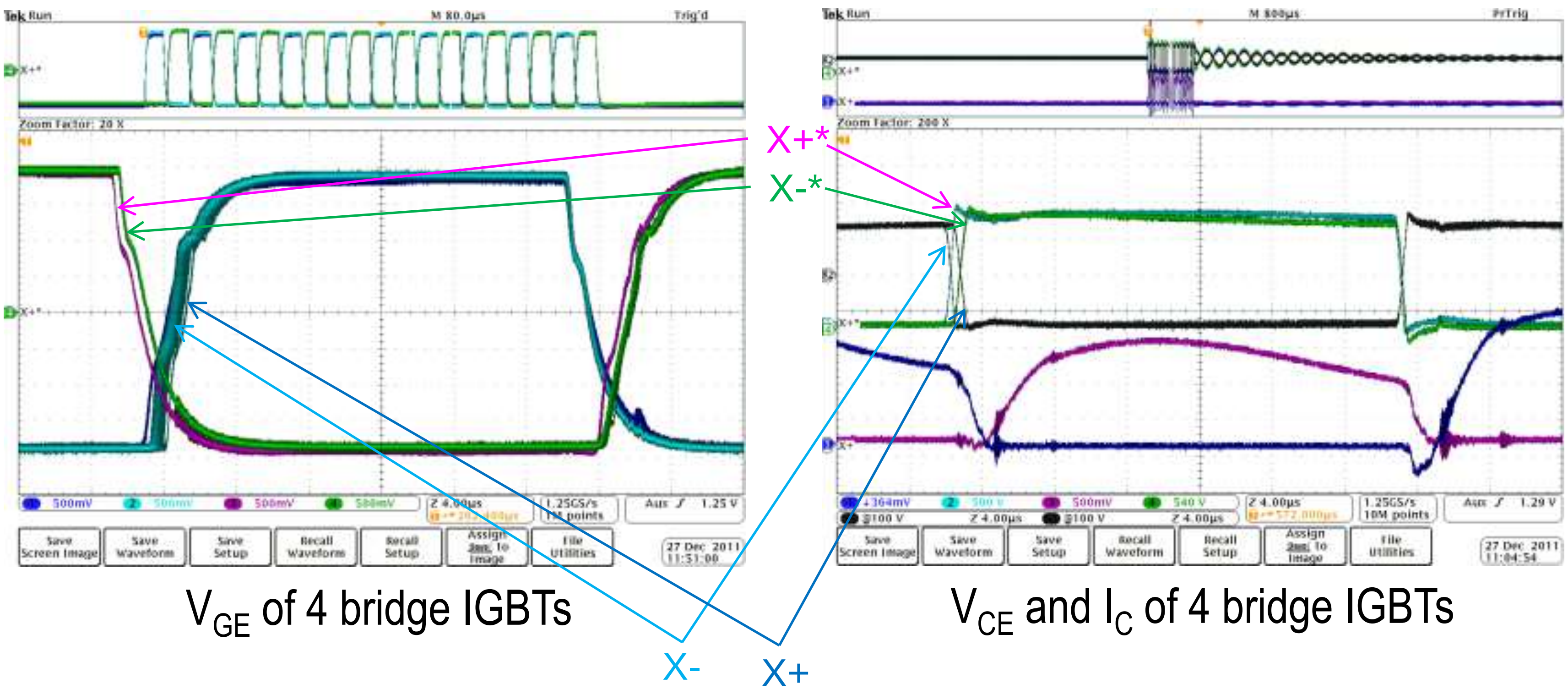


- Open loop operation demonstrated to 115 kV, 57 A (ESS-Bilbao version)
- SNS version due to ship March 1 – rated for up to 85 kV, 160 A
- Could be reconfigured for RFQ test stand operation, other applications

IGBT Test stand located in gallery



IGBT Test Stand Purpose



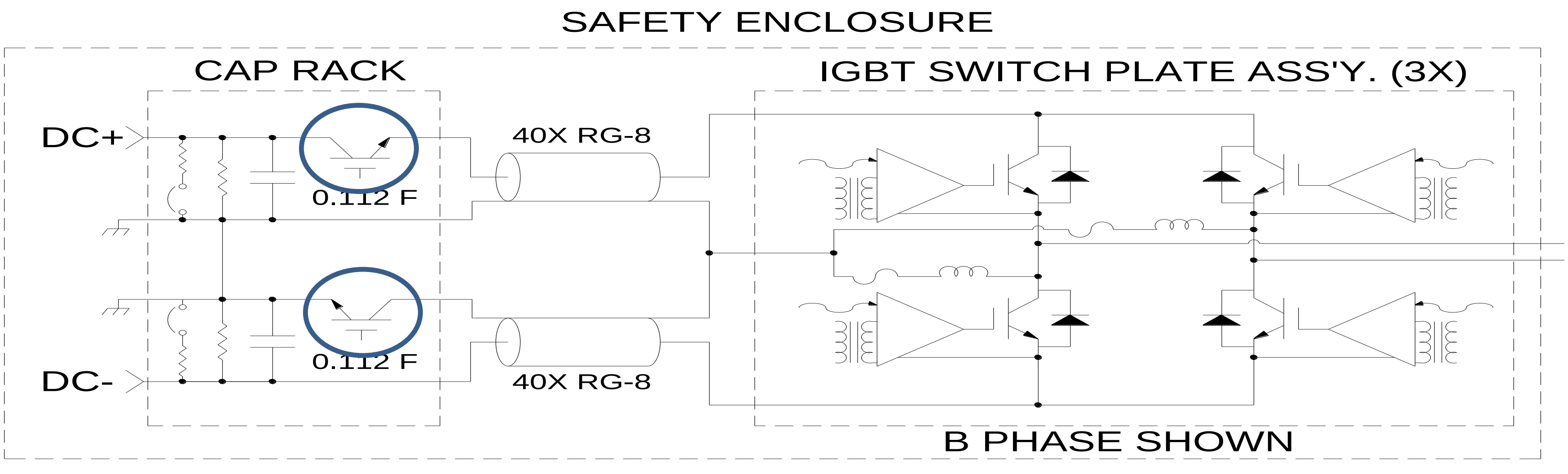
V_{GE} of 4 bridge IGBTs

V_{CE} and I_C of 4 bridge IGBTs

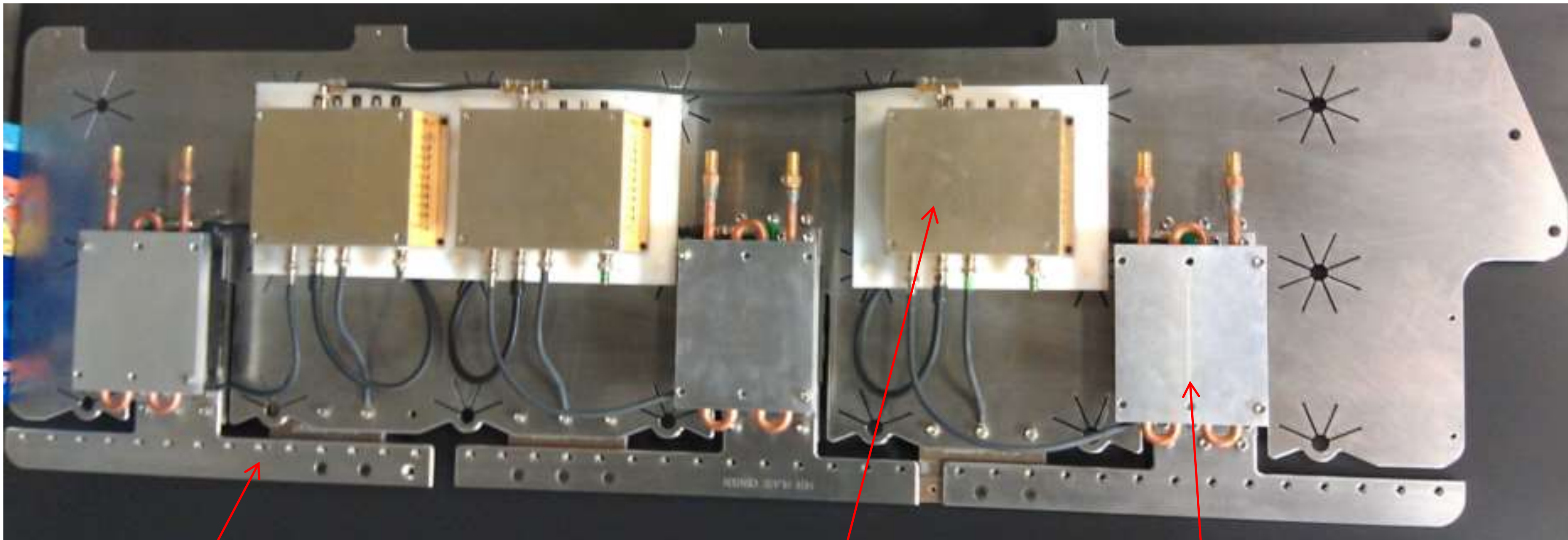
- **Locate jittery drive cards (X- shows ~ 1 μs of turn on jitter)**
- **Identify asymmetrical H-bridge operation (as on the right-hand side)**
- **Match drive / IGBT pairs to produce symmetric operation, minimizing possibility of shoot-thru (X+* and X-* clearly not matched) & providing flat flux vs. time response**
- **Can run for up to 1 hour at 1-2 pps, full pulse width to characterize device behavior at ambient and max. IGBT operating temperature**

Series Fusing Switch

- Installed between main energy storage capacitor and H-bridges
- Limits the amount of energy available to a “downstream” fault
- Can limit available fault current
- May reduce and/or eliminate collateral damage
- May prevent fires in catastrophic events
- Can be used to detect over currents in a single phase
- Can isolate phase if redundant phases are incorporated at some future time



Series Fusing Switch Prototype Hardware

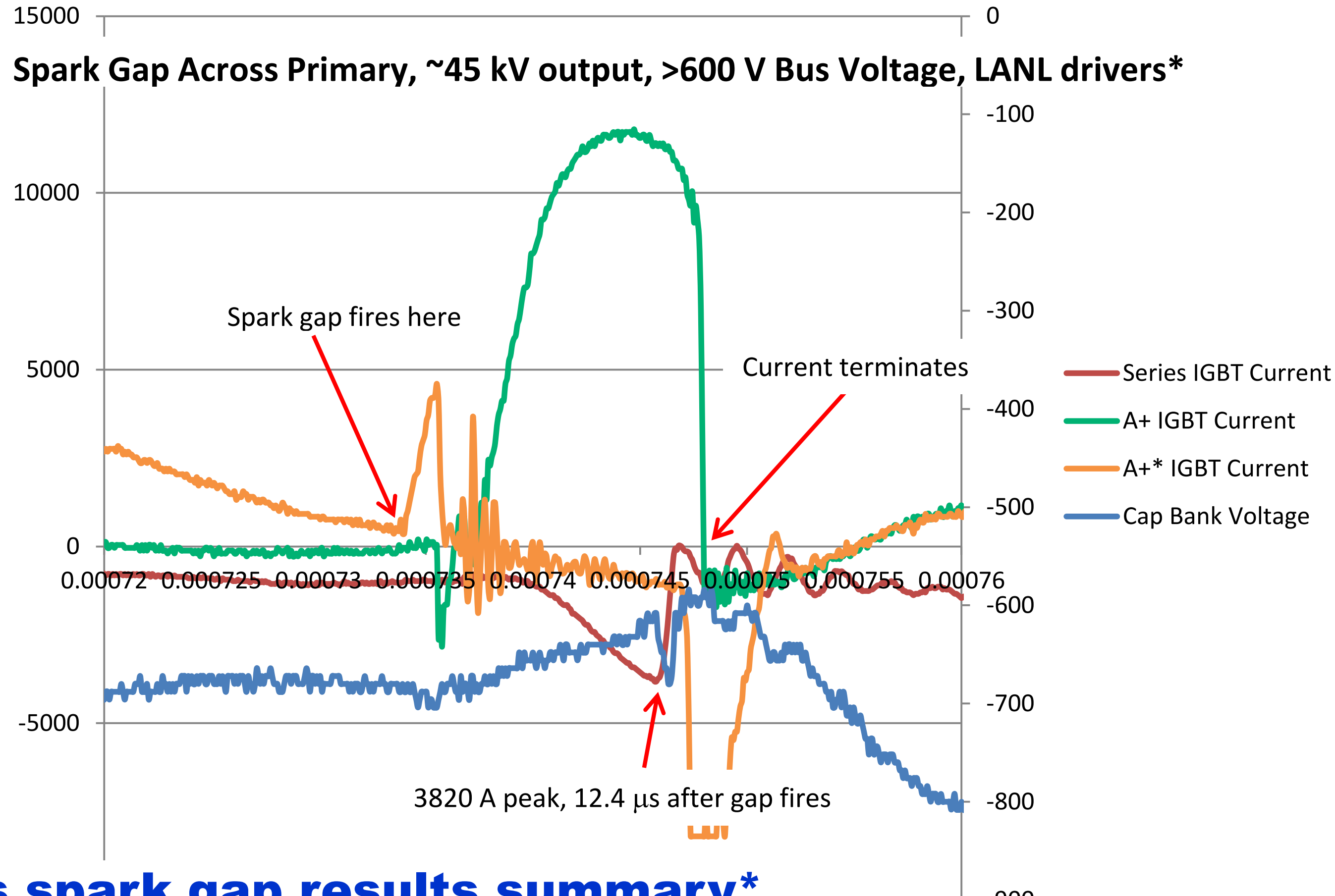


Segmented DC bus

IGBT driver

IGBT and cold plate

Series Fusing Switch Results, installed on one cap bank only



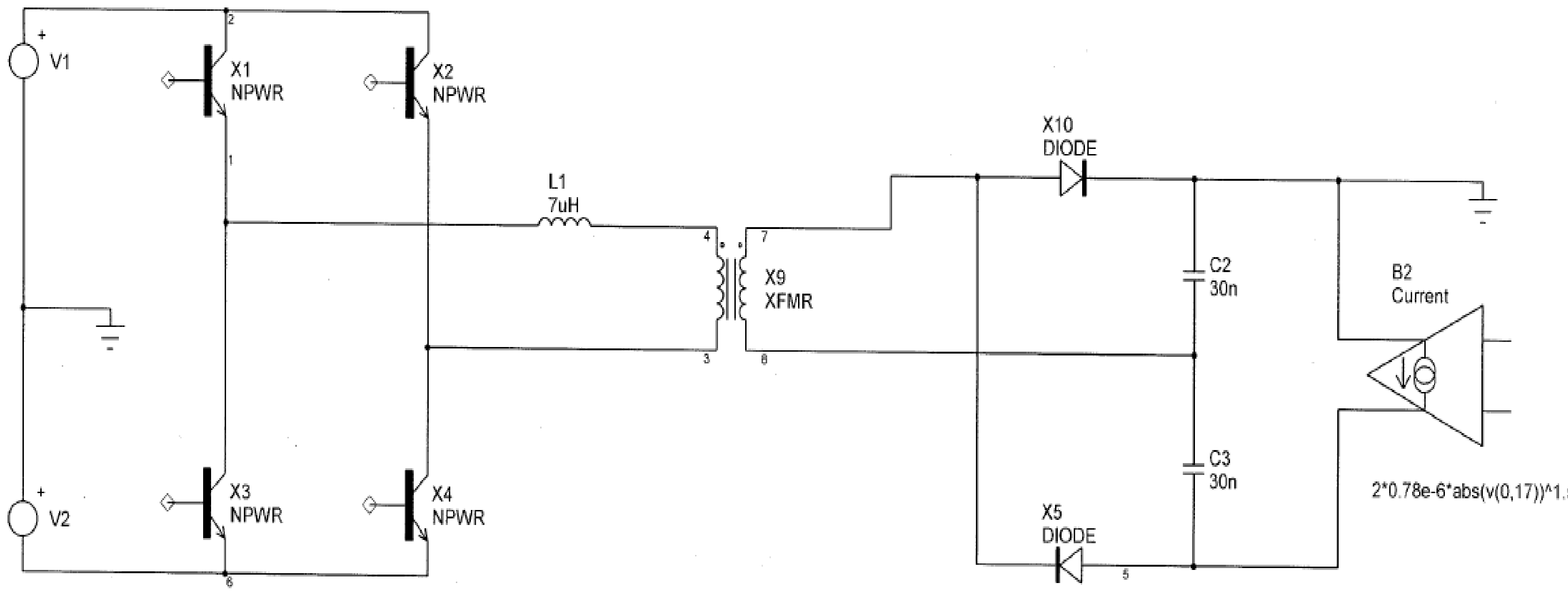
Bus-to-bus spark gap results summary*

Vbus(V)	Toff_SW(us)	ISG_pk(kA)
800	~2.33	6.25
1000	1.44	8.5
2000	1.44	13

*Simulated primary arc relied on energy storage cap bank Rogowskis for detection, simulated bus-to-bus arc utilized over current detection incorporated in new IGBT driver circuits

Alternate Topology – modification

Analysis for a NC linac HVCM with 2 DTL 2.5 MW klystrons
Three phases in series. Transformer 13:1 step up ratio



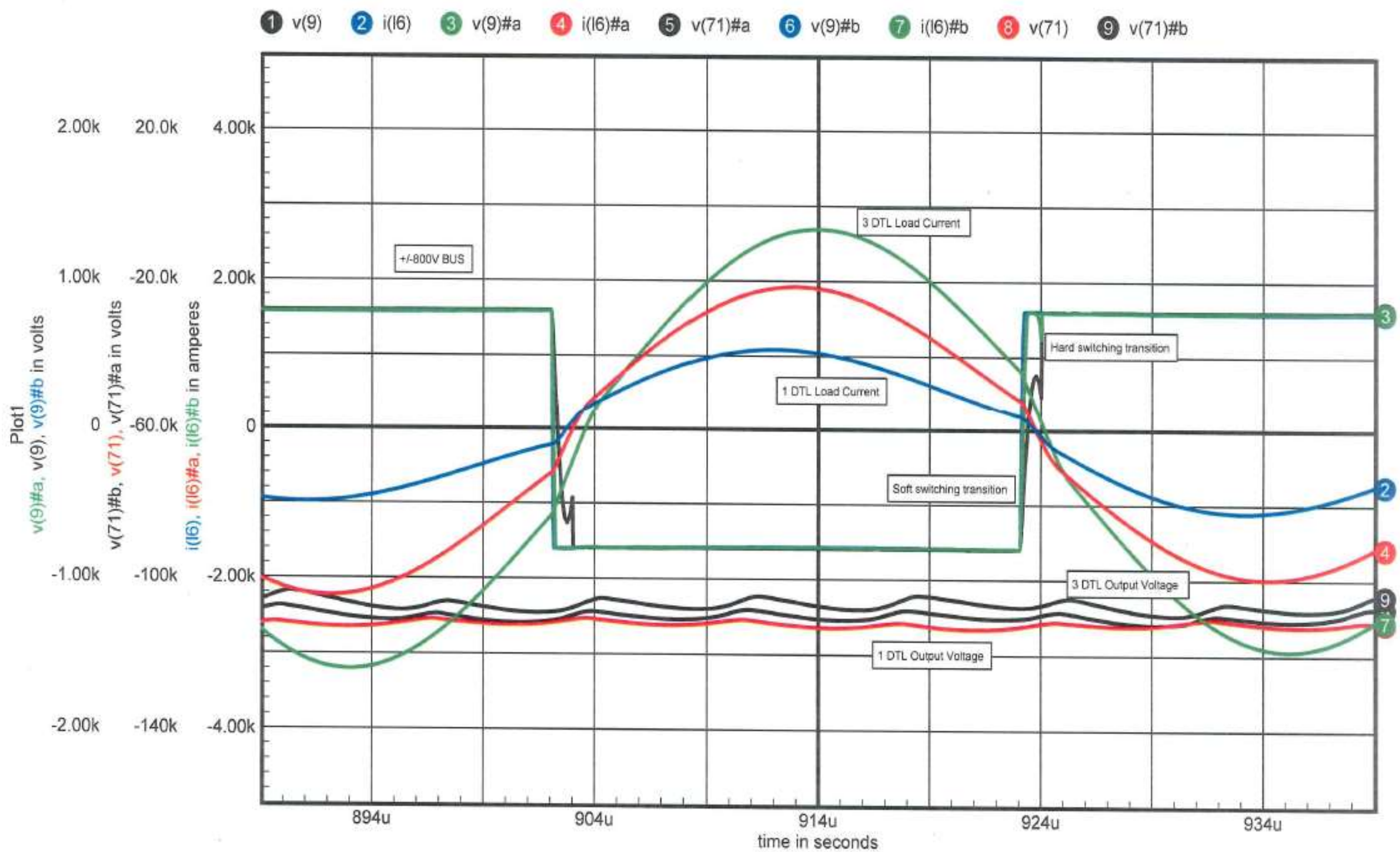
Resonant Period $T_{RES} = 2\pi \sqrt{L_{RES} C_{RES}}$

Characteristic Impedance $Z_C = \sqrt{L_{RES} / C_{RES}}$

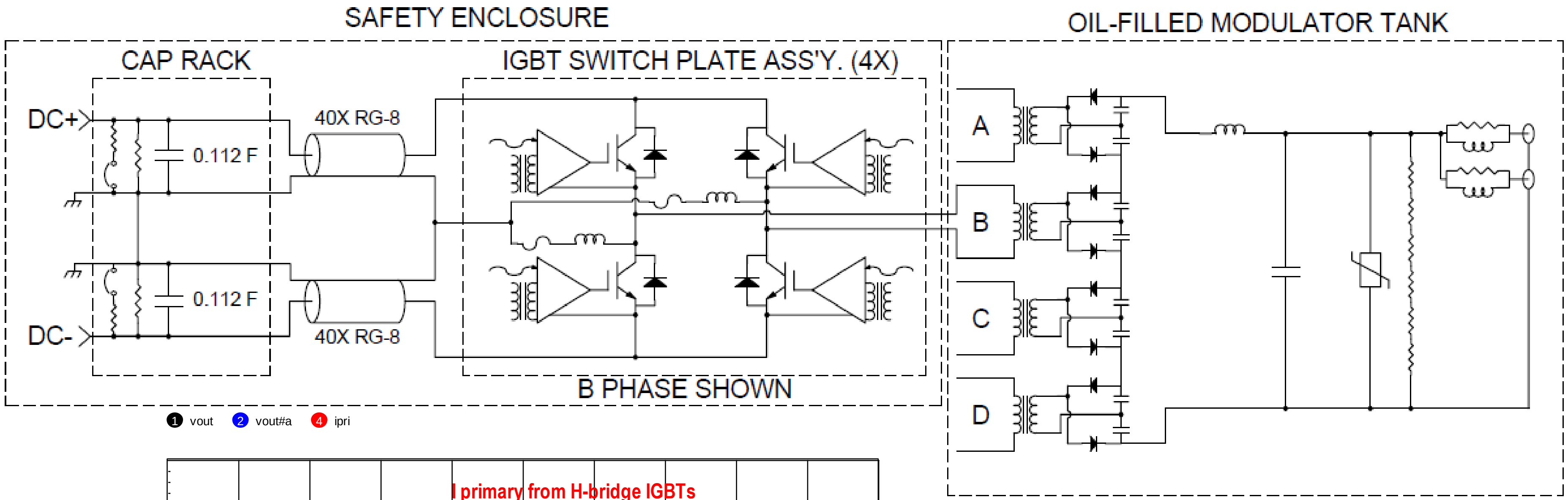
Voltage swing across resonant capacitor $\Delta V C_{RES} = I Z_C$

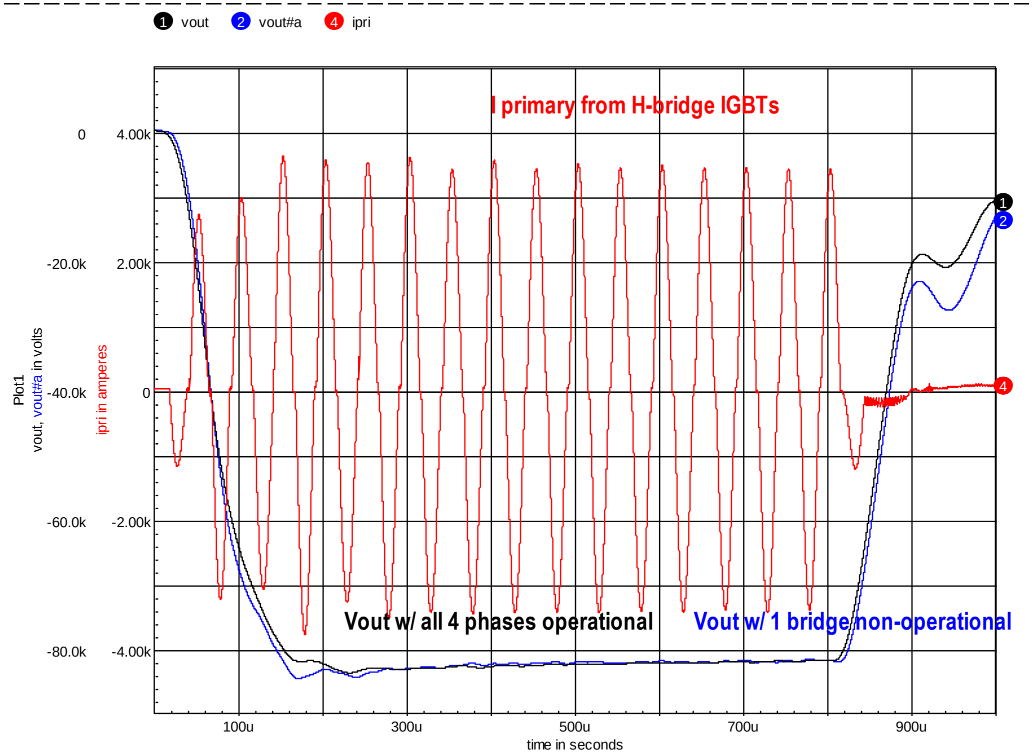
Load change on QRFB

DTL / 2DTL / 3DTL loading comparison



Series-stacked Redundant System





- 4 phase ▶ ±750 V DC
- 3 phase ▶ ±990 V DC
- Timing and circuit values not optimized
- Controller reconfigures system for 3 phase operation

Future Direction in QRFB / alternate topology

- A simple topology modification to reduce stress on IGBT and output capacitors, extends HVCM flexibility and performance.
- Demonstrated the topology on the test stand in air at 1 MW and 94.5% efficiency single phase.
  (1% efficiency gain = 100 kW peak power saving/modulator)
- Resonant capacitors and transformers cores ordered and received.
- Next steps : build new transformers with appropriate turns ratio for > 80kV operation (STS upgrade) and configure for three phase operation in test modulator.

Retain focus on resolution of modulator issues.

- Significant improvements in HVCM reliability a strong indicator of our commitment to this principle

Re-evaluate the criteria required by the Change Control Board for modifying the modulators to convert them to an industry-standard configuration.

- Alternate topologies under consideration and development that are more consistent with modern modulator architectures – could be done for ~$100k per system plus labor
- A thorough evaluation of the HVCM with emphasis on standard practices has been conducted

Implement snubbers or equivalent devices across the IGBT's to reduce the overvoltage due to diode "snap off".

- Covered

Implement the new IGBT driver circuit to improve the monitoring and protect the IGBT's from "shoot thru" pulsing.

- Covered

Implement the energy storage capacitor bank fast disconnect switch to improve failure diagnostics and prevent explosive faults under IGBT/capacitor failure.

- Covered

Proceed with procurement of the new control driver to provide improved monitoring and control.

- Covered

Procure, test, and replace all of the resonance capacitors for warm section modulators, and monitor all resonance capacitors.

- Done and continuing

Continue evaluating the IGBT failure problems.

- Ongoing, but lack for IGBT failure for ~2 years indicates problem may be resolved (<u>under current operating conditions</u>)

Develop a new modulator topology using series connected output rectifiers to reduce voltage stress on high voltage components.

- Covered

Reduce ground loops and develop damping for the energy storage capacitor bank.

- Oscillations are due to multiple cable inductance and switch plate bypass capacitors, adds 60 and 120 kHz harmonics
- Developing laminated bus with industry but need funds – low priority

Develop automatic methods to insure minimum power loss in IGBT’s.

- Will be investigated when prototype controller is available.
- Covered

Study automatic core saturation and output voltage droop compensation techniques to reduce the RF requirements and adjustment requirements.

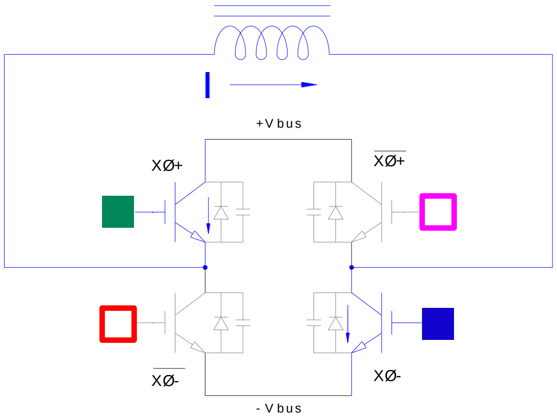
- Started, will be performed on prototype controller when available.

Conclusion

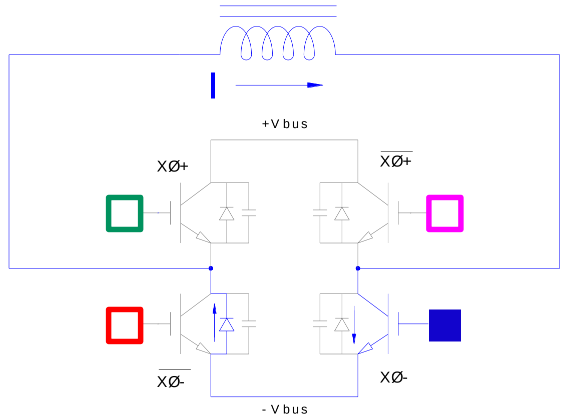
- **HVCM availability improved substantially to almost 99% since last meeting**
- Synergistic solutions in development to address major shortcomings of HVCM
  - IGBT failures and reliability
  - H-bridge component damage and collateral damage
  - Control scheme to implement advanced features, extend useable pulse width, remove clumsy legacy control interfaces
  - All proposed improvements intertwined
- Implementation allows for future expansion, possibly major subsystem redundancy
- Parallel investigations of alternate architectures provide even more robust and reliable solutions with minimal perturbations to existing system
- Recent reorganization should make more resources available for these efforts; recent modulator reliability improvements have helped tremendously

Back Up Material

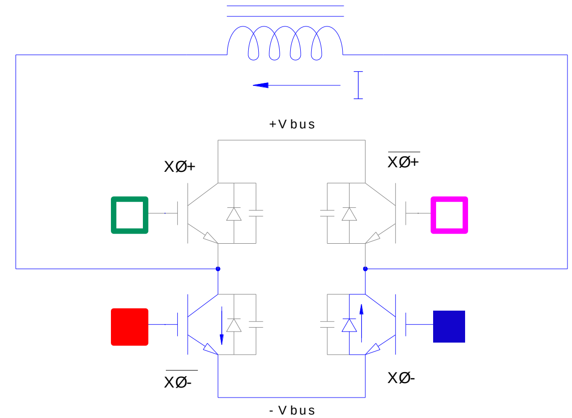
Modes of Operation for Phase Shift Modulation



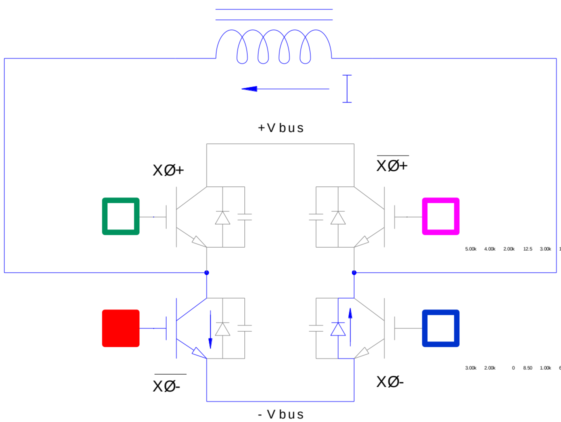
Mode 1 – Power



Mode 2 – Freewheel



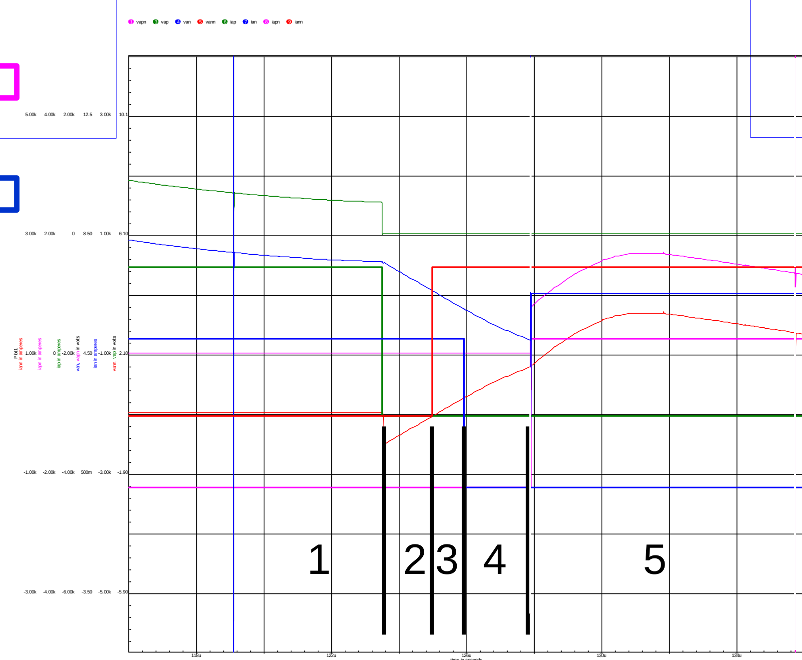
Mode 3 – Switch Closure

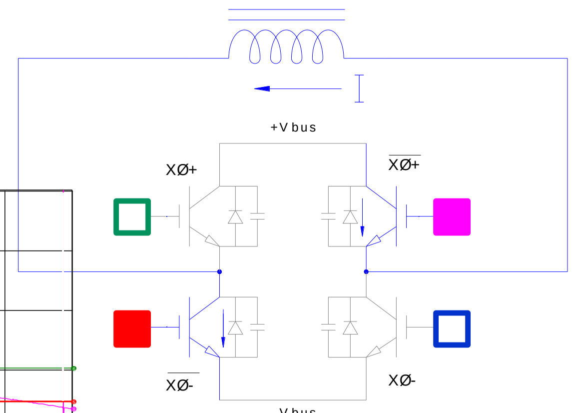


Mode 4 – Freewheel

■ = ON

□ = OFF

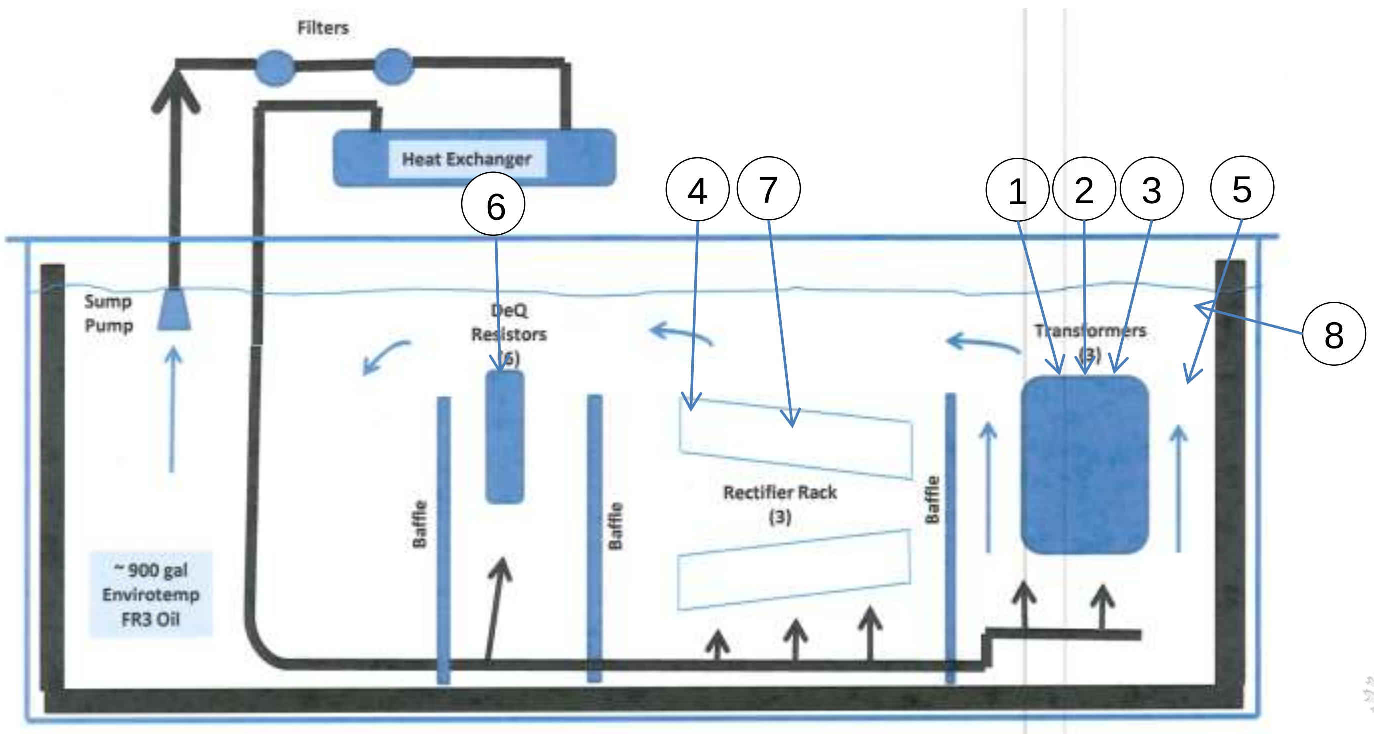




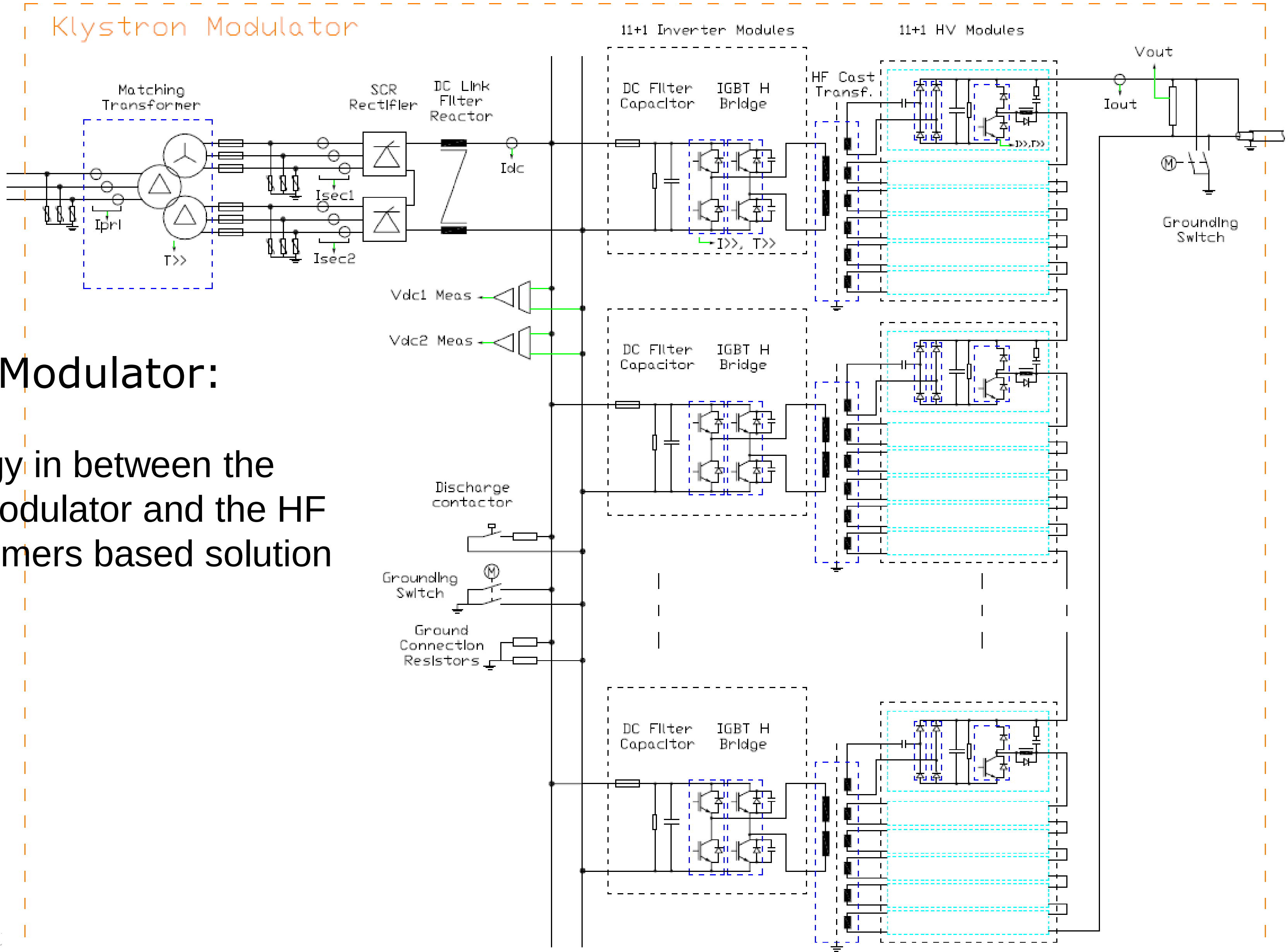
Mode 5 – Power

Key Component Temperature Measurements pending

Location	A transformer core adjacent to primary winding	B transformer core adjacent to primary winding	C transformer core adjacent to primary winding	Diode heat sink surface	A boost capacitor	deQing resistor surface	Resonant capacitor	Oil away from pump
	1	2	3	4	5	6	7	8



JEMA Modulator



JEMA Modulator:

Topology in between the Marx Modulator and the HF transformers based solution