Developments in resonant power converters for RF tube modulators

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Presentation

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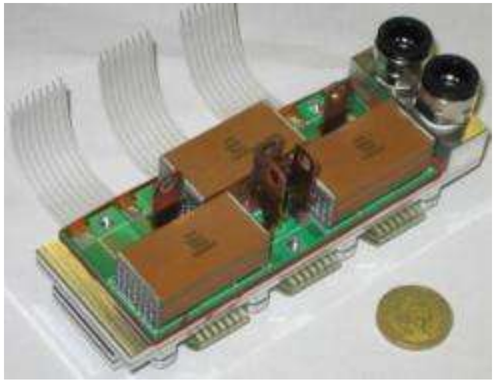
- PEMC Group at Nottingham
- Resonant power converter concepts for RF modulators
- Experimental tests on efficiency and thermal performance
- Some related technologies (if time permits)

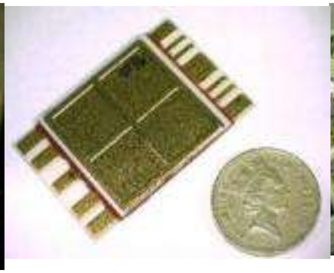
PEMC GROUP at Nottingham
Overview

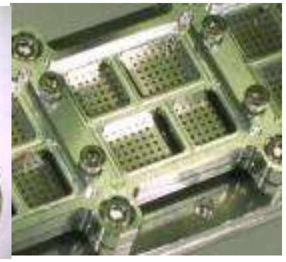
- One of the largest research groups in this field worldwide
- 9 academics (4 Professors)
- 40 PhD students, 35 Postdoctoral researchers
- Close links with industry
- £18M research portfolio

Current Research Technology Focus Areas

- Electrical Energy Conversion, Conditioning and Control
- Power Electronics Integration, Packaging and Thermal Management
- Motor Drives and Drive Control
- Electrical Machines







Current (main) Research Application Areas

- Electrical Energy Systems
- Aerospace (More Electric Aircraft)
- Marine Systems
- Industrial Drive Systems
- High Voltage Power Converters

High Power RF Power Supplies
Research Overview

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- Research started under "High Power RF Faraday Partnership" aimed at developing new power supply technologies for driving RF tubes
  - Klystrons, Magnetrons, Travelling Wave Tubes (TWT), Inductive Output Tubes (IOT), Gyrotrons etc
- Applications
  - High energy physics experiments
  - Industrial processing
    - » Mineral extraction for example
  - Military
  - Medical
  - Spin-off applications: capacitor chargers, electrostatic precipitators
- Main support
  - PPARC, STFC, DSTL, EPSRC, TSB, e2v, TMD

Technical Requirements

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- Generally two types of requirement
- CW (DC)
  - High voltage DC power supply (typ 100kV+)
  - High stability and low ripple
    - » Voltage variations affect phase of RF produced – critical for some applications
  - Low stored energy in output filter
    - » In the event of tube "arc-down", the energy deposited in the tube must be small – otherwise tube destroyed (expensive!)
  - High input power quality (from the grid)
  - Small size
- Long-Pulse (considerations as above +)
  - High voltage pulsed power supply
  - Typically 100kV+, 1-2ms pulses (MW power levels)
  - High pulse stability, flat top and short rise-time
  - Power smoothing for supply ("flicker" mitigation at the grid)

Long Pulse
Existing Technology

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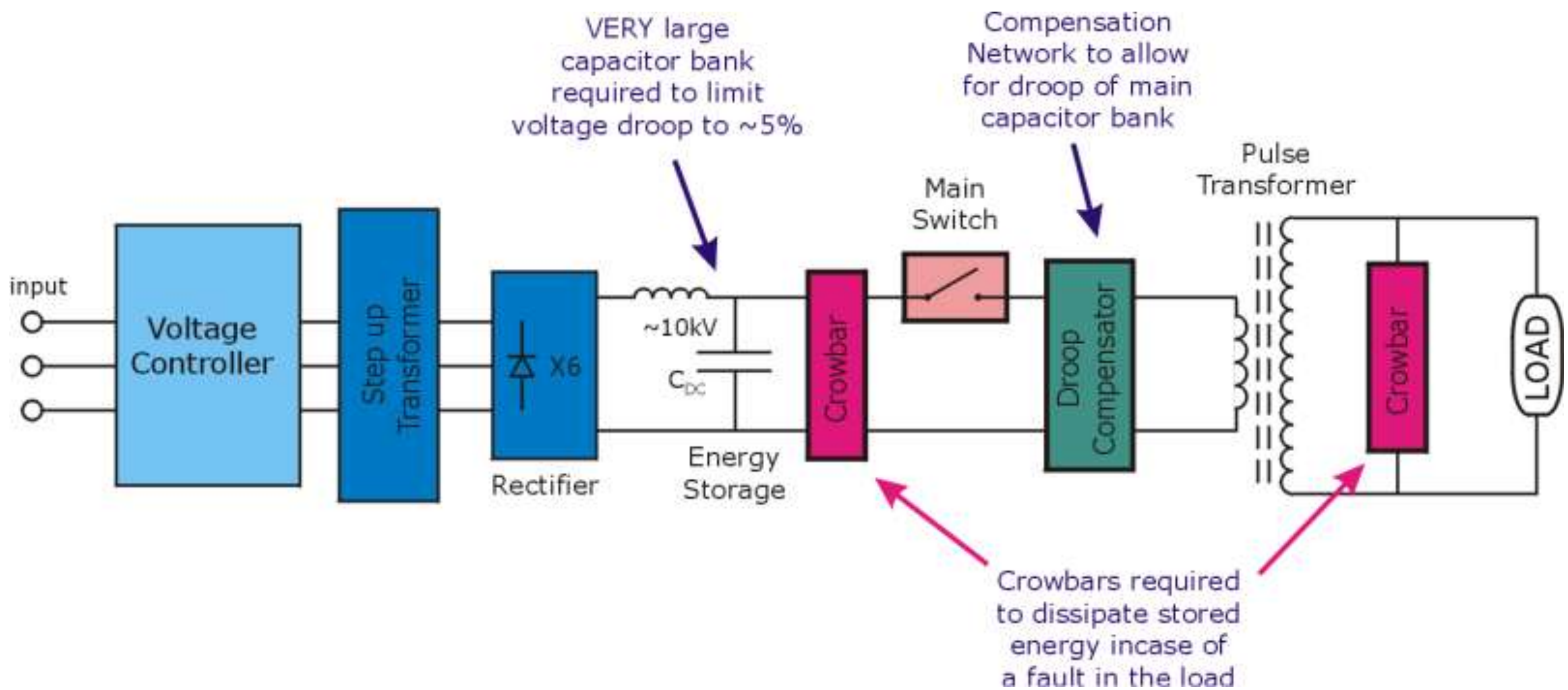

Disadvantages

- Very large capacitor bank (energy storage ~80kJ)
- Crowbars Required
- Large filter components required to limit "flicker"
- Pulse transformer size $\propto$ pulse length

Long Pulse

Existing Technology - example

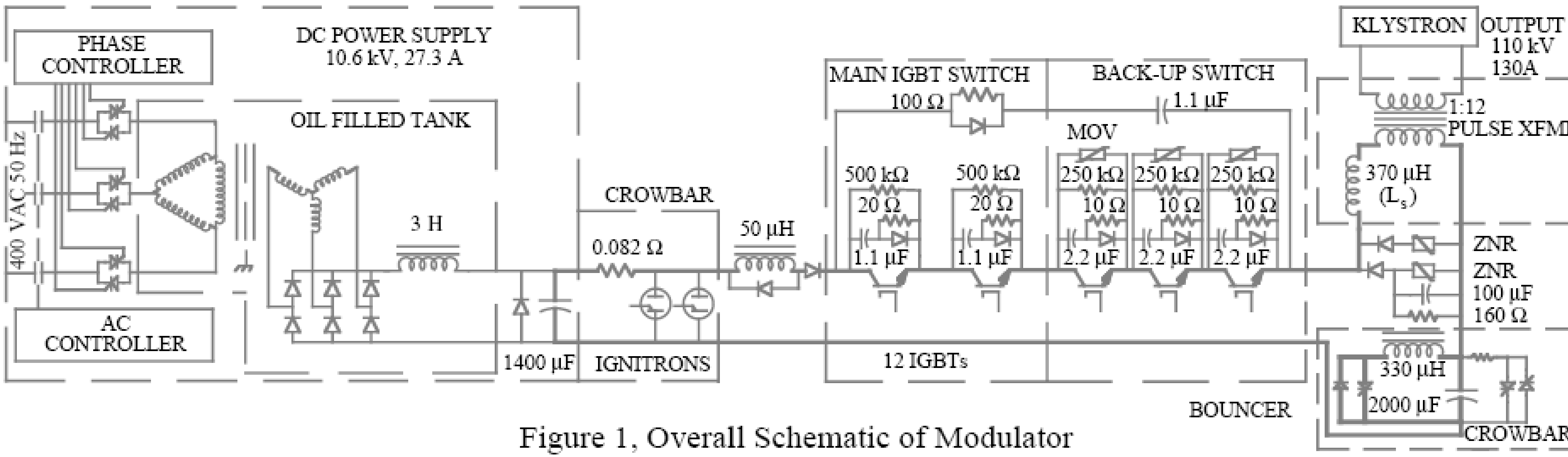

Figure 1, Overall Schematic of Modulator

- Large Utility frequency transformer and rectifier
- Poor input quality
- Huge DC capacitor bank (need low voltage droop during pulse)
- 2 “Crowbars”
- High voltage series switch

Long Pulse

New Technology – High Freq Power Supply

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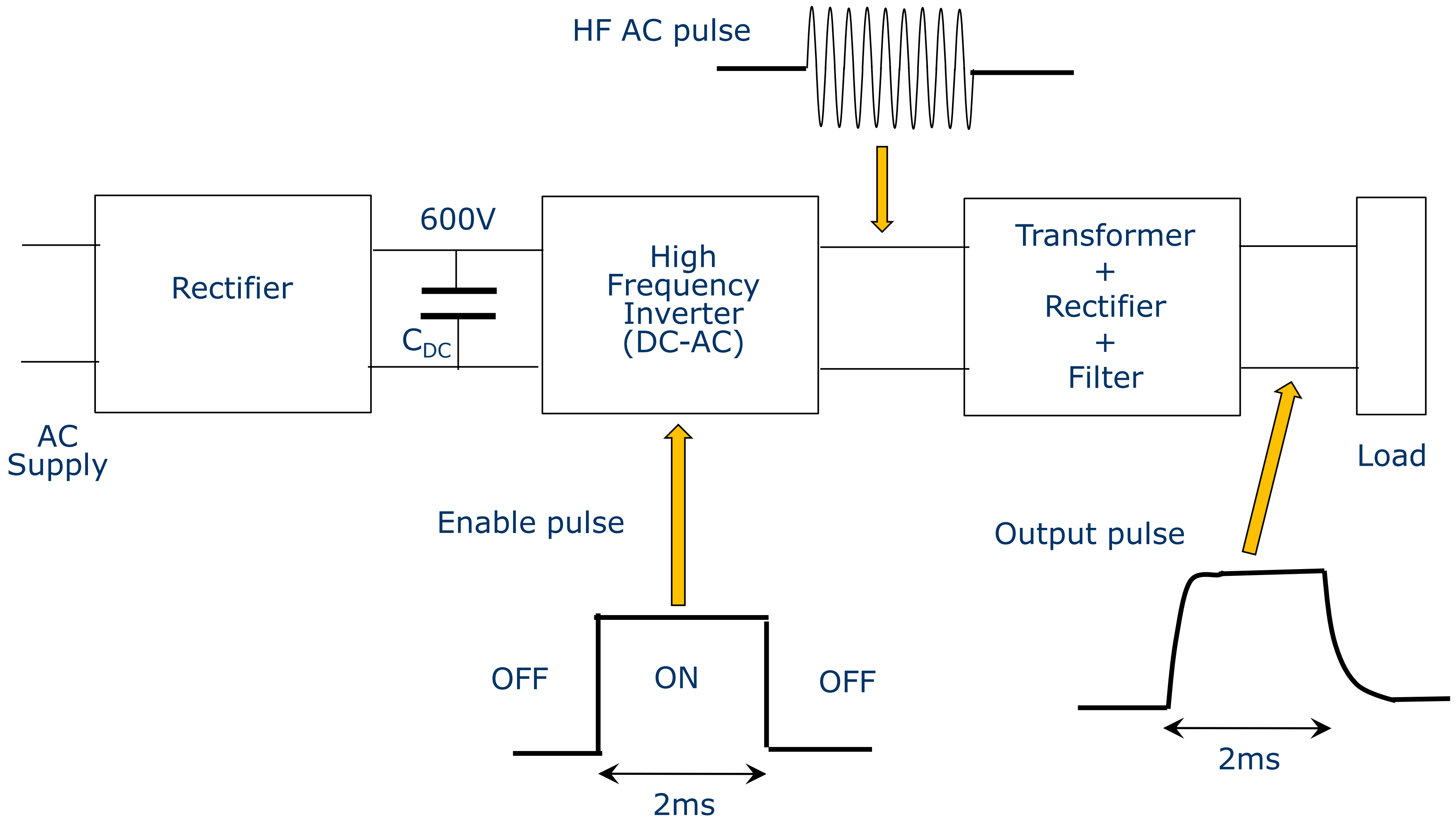

Long Pulse
High Freq Power Supply

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Advantages

- "Voltage gain" of the inverter stage can be controlled during the pulse
  - Much larger droop in the DC capacitor voltage possible whilst keeping output pulse flat
  - Much smaller capacitor (20 times)
- Transformer size not proportional to pulse length
  - Can operate with longer pulses or continuously
  - Limitation is thermal, not transformer core saturation
- If operating frequency is high enough (see challenges), output filtering components can be made very small
  - Low stored energy – eliminate need for crowbar
  - Small HF transformer

Long Pulse

High Freq Power Supply

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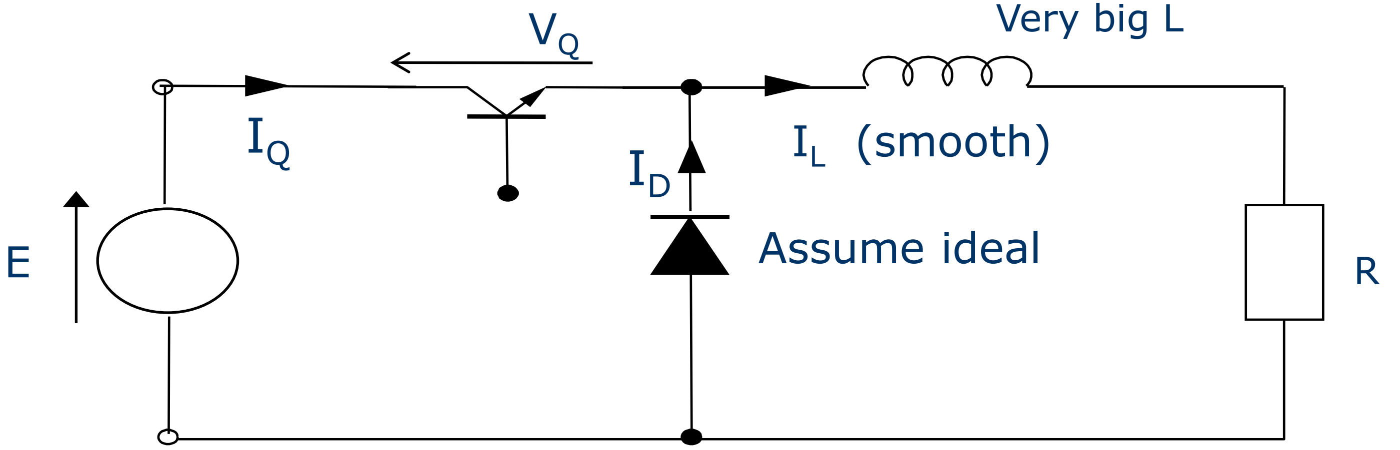
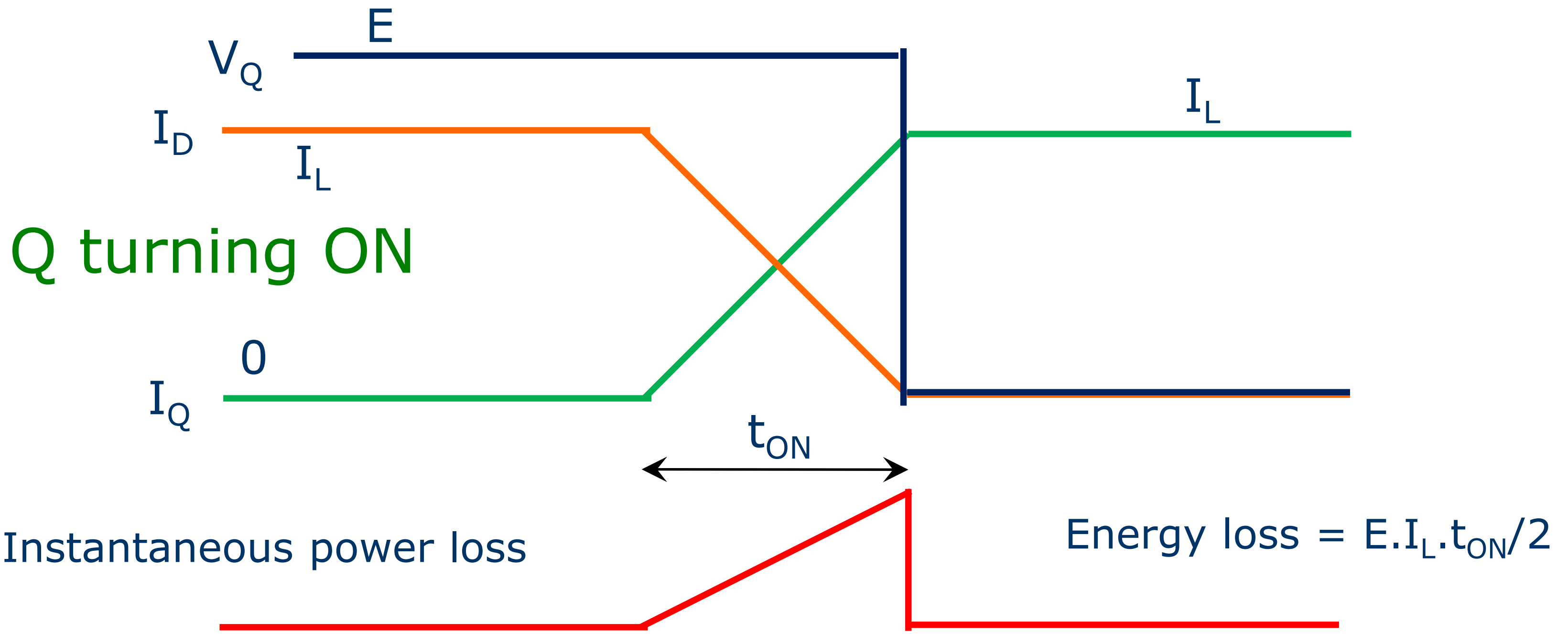
Challenges

- Need to operate inverter at “high” frequency (typ 20kHz+)
  - To get desired size and energy storage reduction
  - To get sufficient speed of response for acceptable pulse risetime (<100us)
- High frequency operation of high power inverters is not straightforward
  - Typical 100kW inverter for an industrial motor drive would switch at 4kHz – lower at higher powers – need to do much better than this
  - Limitation is due to the energy loss in the semiconductors each time they switch
  - Need to use “resonant converter” techniques to reduce loss
- Control of inverter switching to get flat output pulse
  - DC voltage droops by up to 25% during pulse

Switching energy loss
(hard switching)





Switching energy loss
(hard switching)

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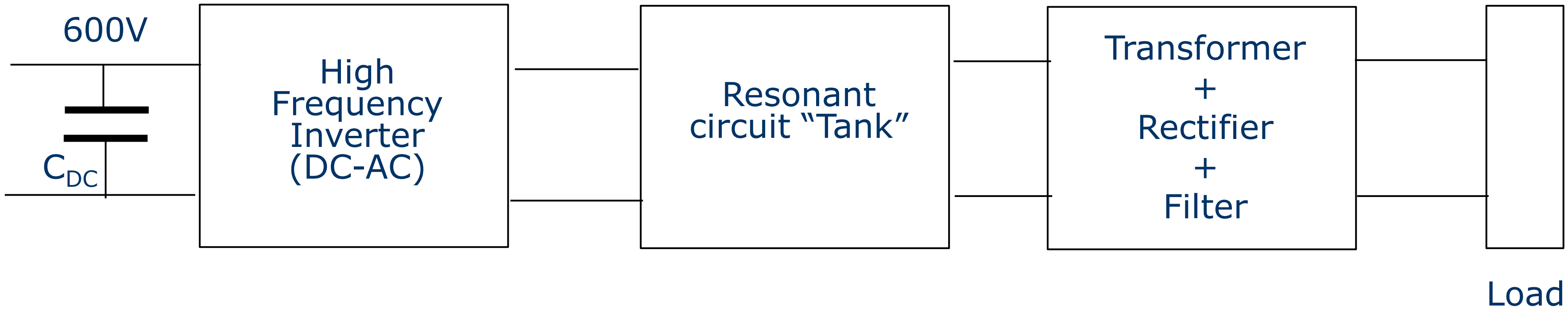
Hard switching

- Abrupt commutation of current from one device to another
  - Accompanied with abrupt change in voltage across device
- Each switching transition causes energy loss
- Average power loss = (energy).(switching frequency)
  - Implies switching frequency limitation for acceptable efficiency
- High power semiconductors have longer switching times
  - Impossible to operate high power devices at high frequencies in hard switched circuits
- Most “common” power electronic circuits are hard switched
- Need different approaches for high power, high frequency operation
  - $\Rightarrow$ soft switching

Soft switching
Resonant converters

- Modify circuit (usually through some resonant behaviour) so that either the voltage and/or current is zero at each switching instant
  - Zero voltage switching (ZVS)
  - Zero current switching (ZCS)
- Theoretically reduce switching loss to zero
  - Much reduced in practice – not zero
- Many types of resonant converter proposed
- For this application, we are interested in "load resonant converters"
  - Insert resonant circuit between inverter and rectifier/filter.

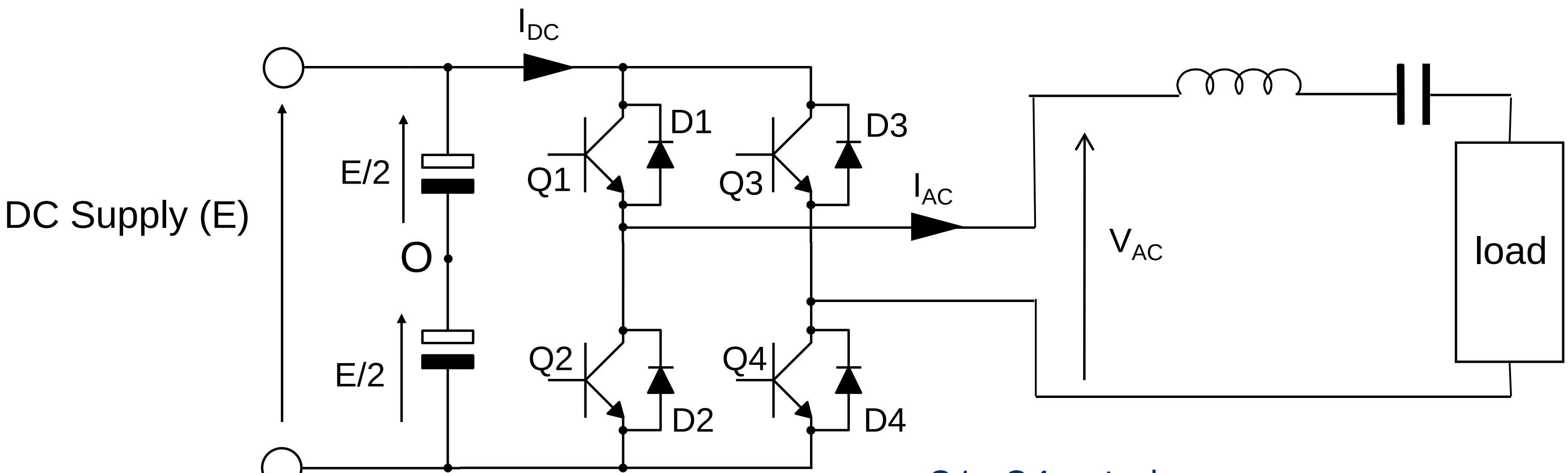
Load resonant converter

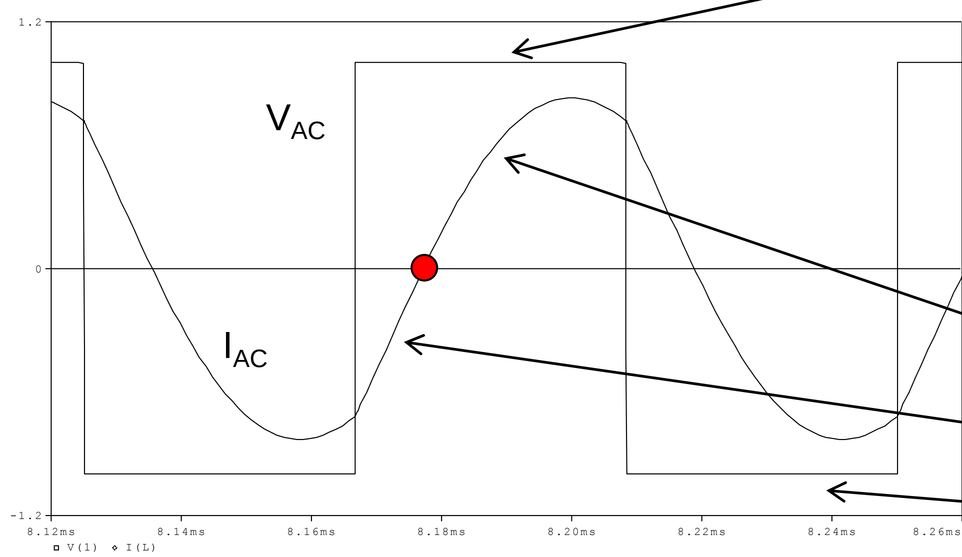


- Addition of "resonant tank", coupled with a suitable control regime allows soft switching of all the semiconductor devices in the inverter
  - ⇒ High power, high frequency operation possible

Soft switching

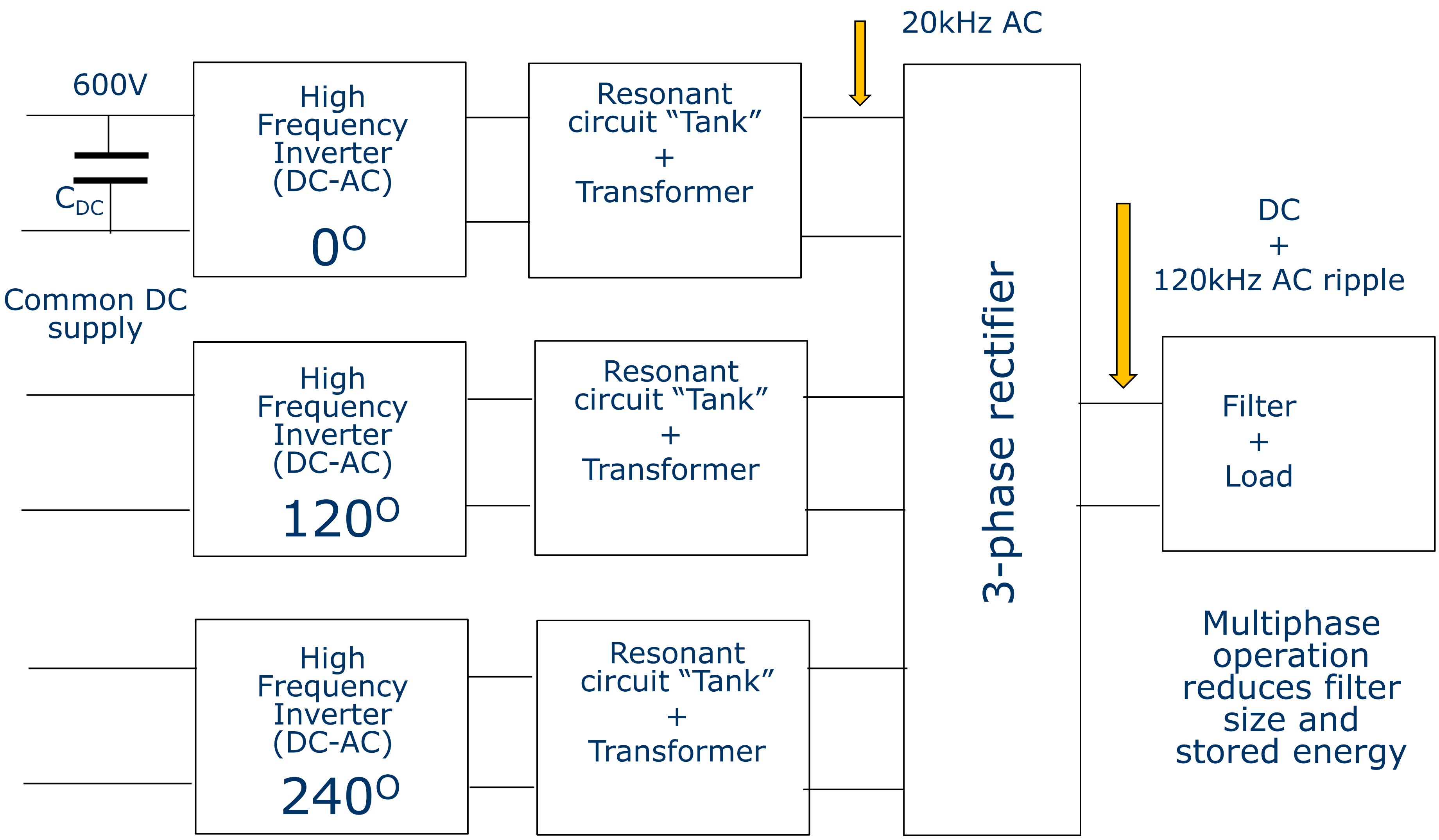
Illustration





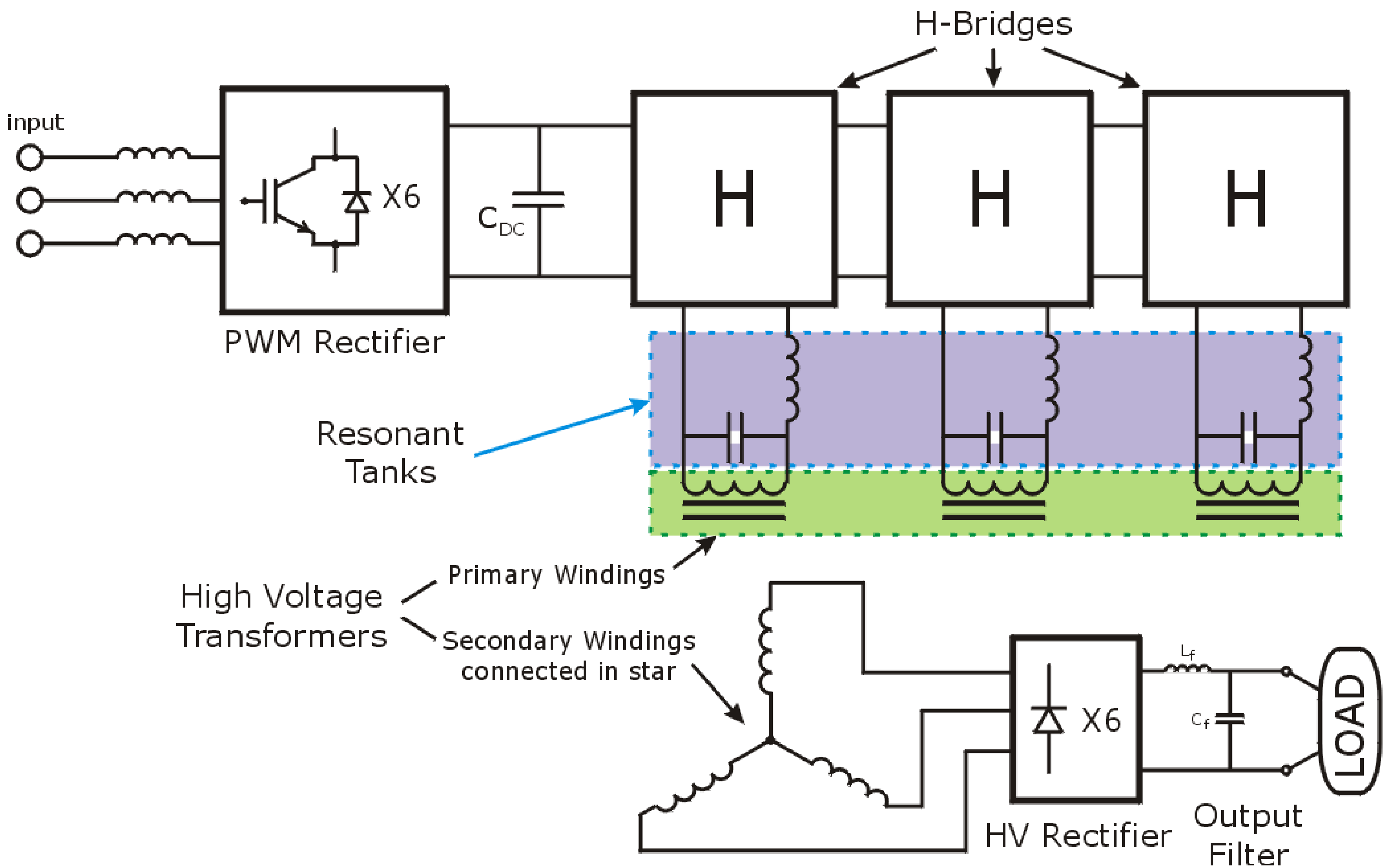
- Current passes from D1/D4 to Q1/Q4 with zero loss

Multiphase resonant converter
(increasing ripple frequency)



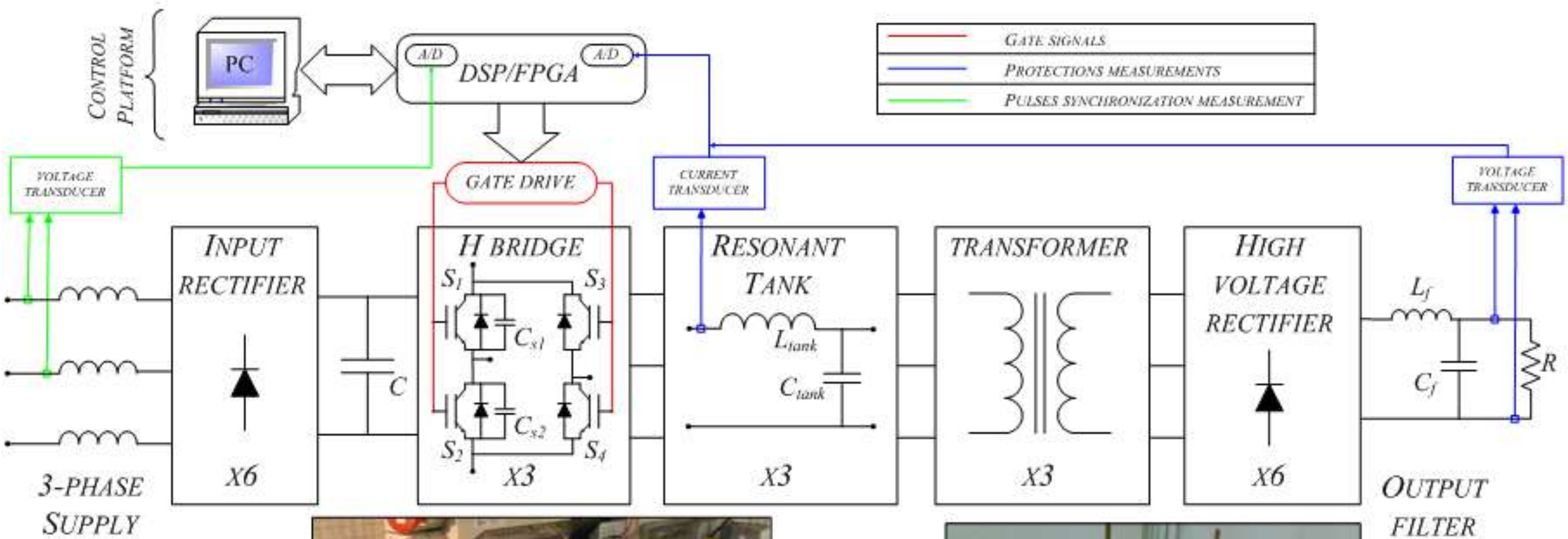
Multiphase operation reduces filter size and stored energy

Pulsed power supply
(Overview)



Three-phase Series Resonant Parallel Loaded (SRPL) power supply

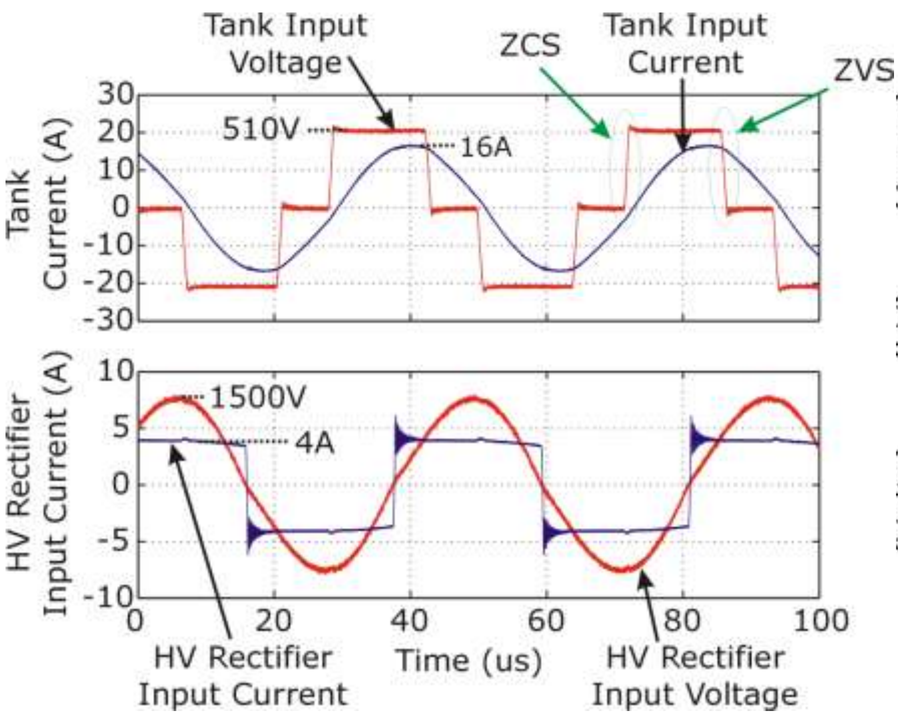
Schematic of the three-phase SRPL power supply control platform and experimental setup.



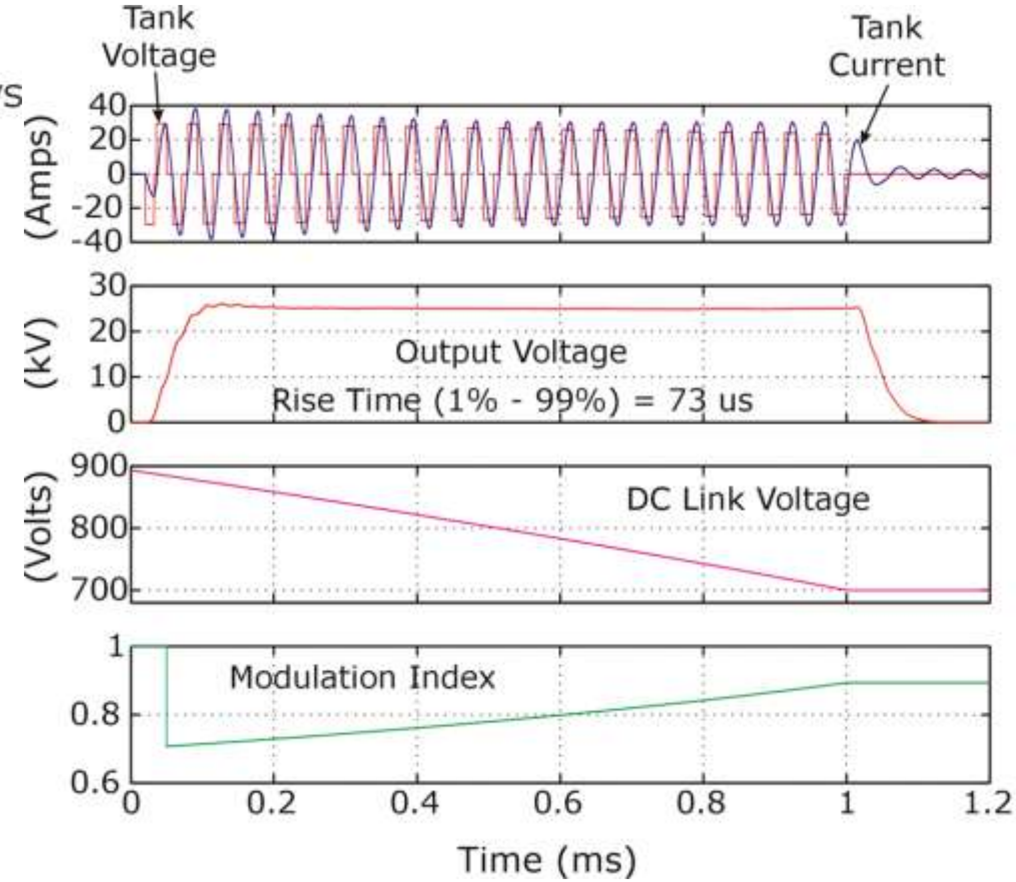
3-PHASE RESONANT CONVERTER

3-PHASE TRANSFORMER/RECTIFIER

Long Pulse Converter
Soft Switching and Pulse Output

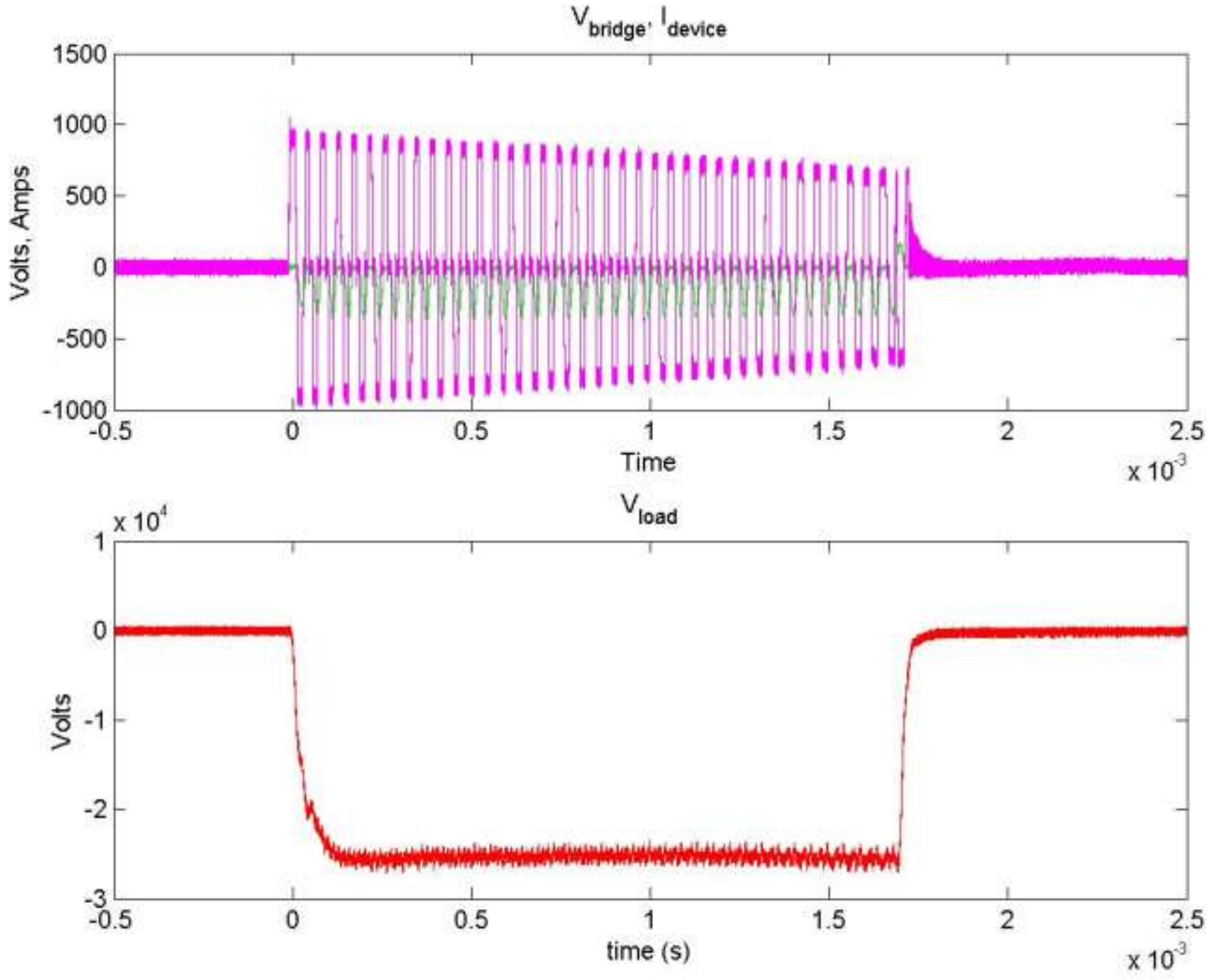


Experimental result, combined frequency/phase control



Simulation result, combined frequency/phase control

Long Pulse Converter
315kW pulse



Long Pulse Converter
(Tube tests)


Converter in test enclosure at e2v

Three-phase SRPL power supply
Tube results (150kW)

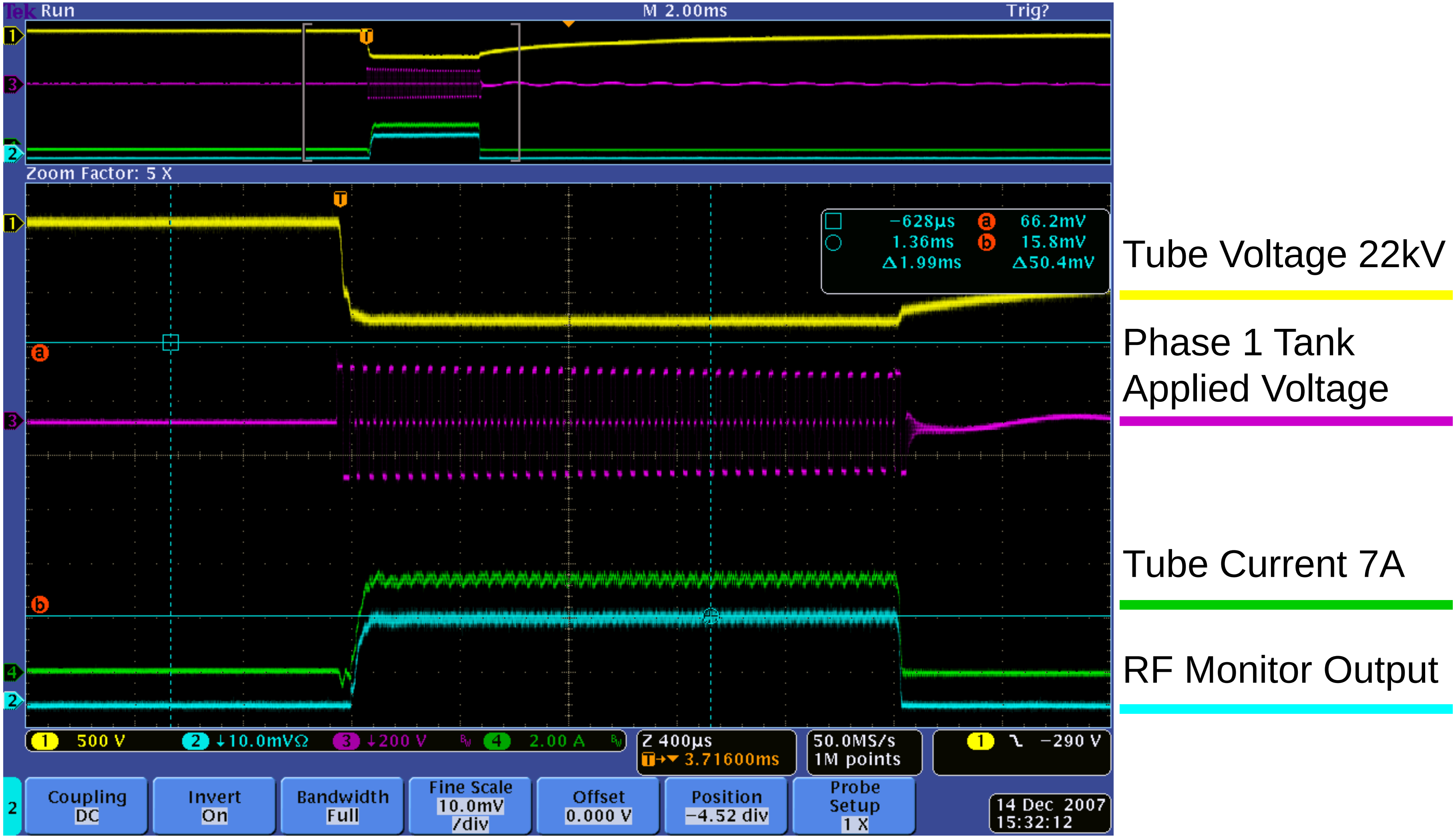
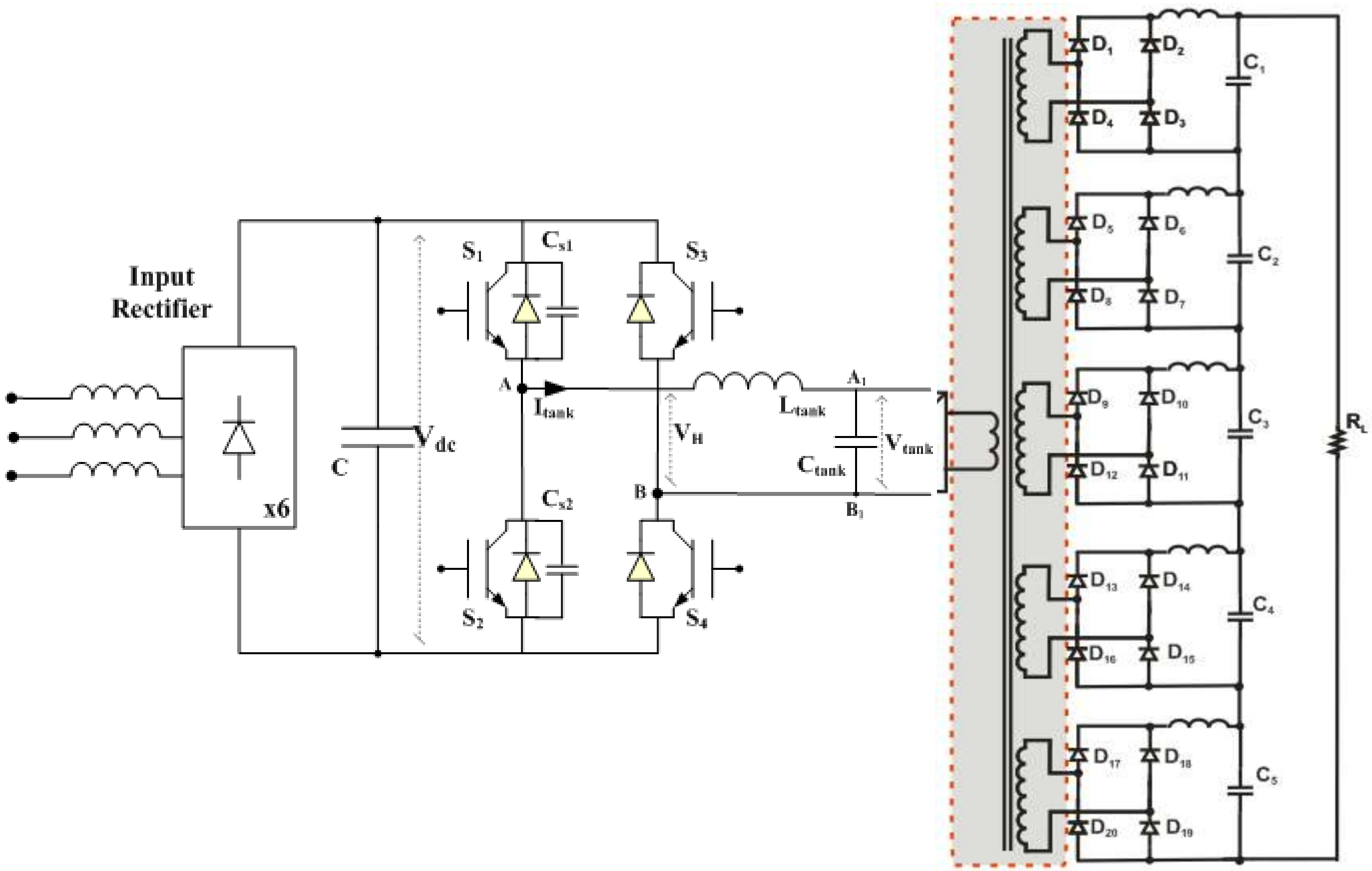


Figure 1: Experimental results (Tube 150kW) .

Some current work

(high voltage, high frequency transformers)



Intermediate voltage transformer:

Specifications:

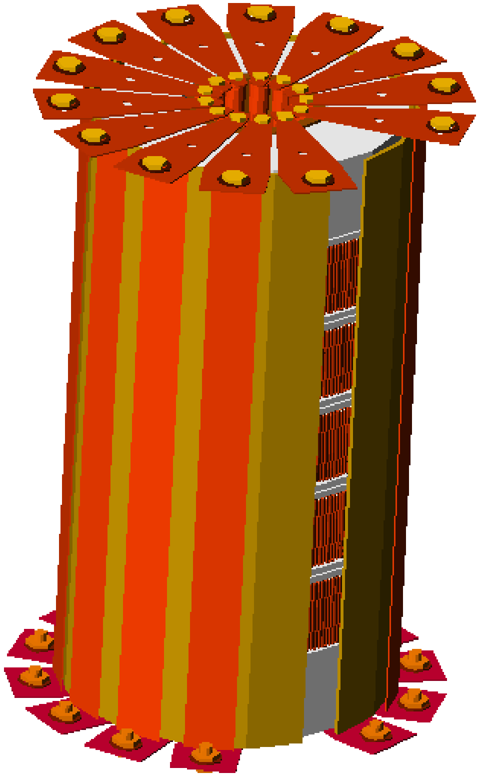
- Vout= 50kV
- Iout= 1.66A

Sectionalised modular transformer/rectifier concept for high voltage operation

50kV prototype under test, 150kV version designed

Some current work

(high voltage, high frequency transformers)



50kV version

Each section of the transformer uses a toroidal nanocrystalline core

Common primary winding passes through all cores

Resonant Converter Modulators (summary)

- Long Pulse (1-2ms) or CW (Continuous Wave) operation
- Soft switching ➔ high power, high frequency operation
- Combined phase shift and frequency control to control output voltage at the same time as minimizing the semiconductor losses ➔Allow up to 25% droop on V_{DC} – dramatic reduction in energy stored
- High Frequency very compact design <1/10 the size of conventional technology
- Absence of Crowbars and High voltage series switch
- High Frequency + multiphase operation gives high ripple frequency
  - Small output filter
  - Low energy storage – small energy dump during load arc fault
- Current work is directed towards optimising transformer and filtering arrangements

Losses and Reliability Assessment

Losses and Reliability

- Prospective users are nervous about operating IGBTs at high powers and high frequency under pulsed conditions
- Possibility that repeated thermal cycling may impact reliability
- Hence we have spent some effort experimentally investigating the losses and thermal behaviour

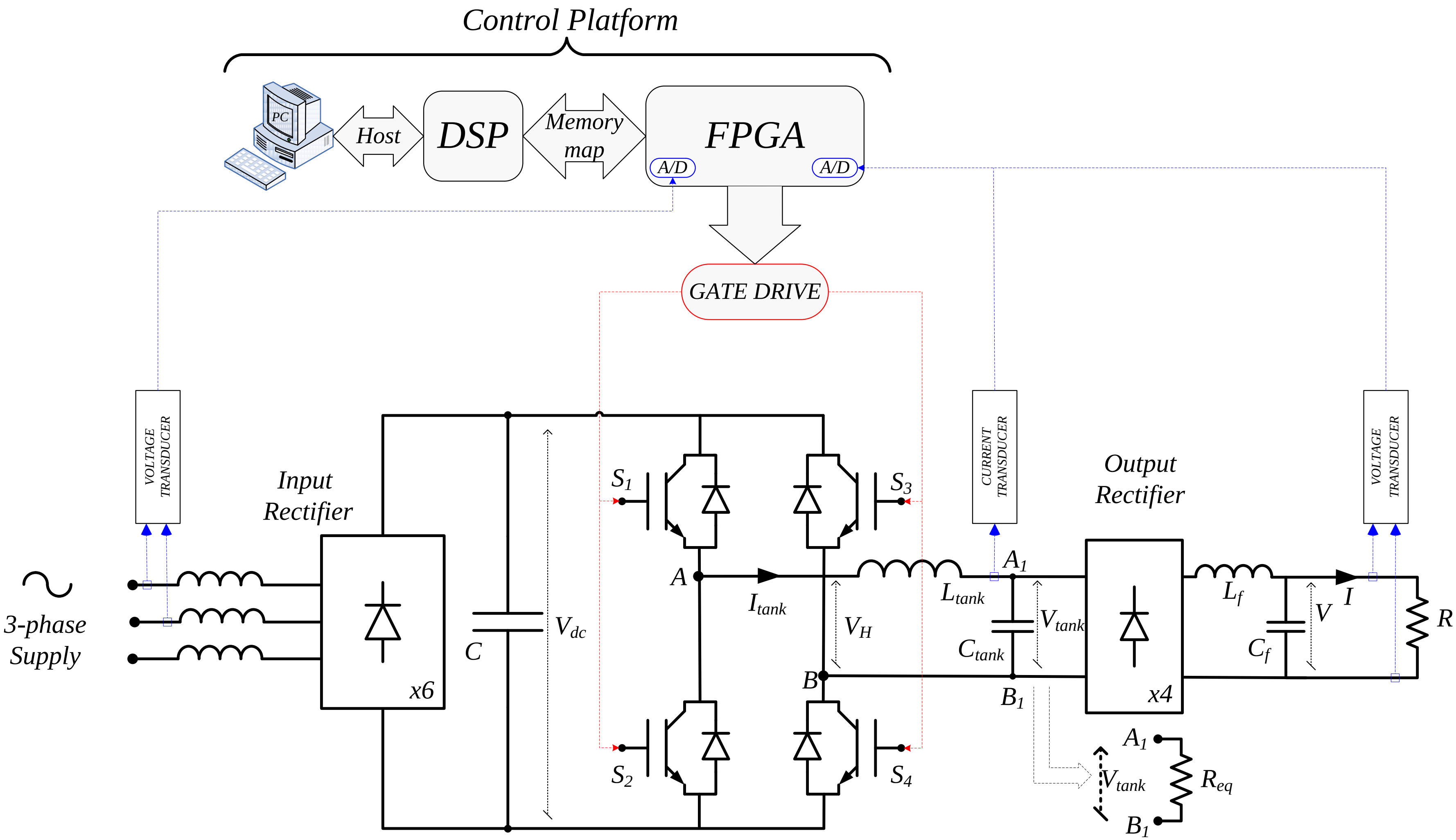
Wire-bond lift off in a power module due to thermal cycling

Losses and Reliability
Approach

Dedicated 250 kW single-phase Series Resonant Parallel Loaded power supply built in order to:

- Monitor semiconductor losses in the IGBT modules through calorimetric measurements
- Monitor transient device temperature using high speed thermal imaging
- Determine how good our soft-switching is
- Very difficult to do this from measurements of the electrical variables

Losses and Reliability
Test rig



Schematic of the single-phase SRPL power supply and control platform.

Losses and Reliability

Test rig electrical design

The electrical design of the power supply is based on 800 A dual switch IGBT Dynex module

High voltage output not required – hence no transformer

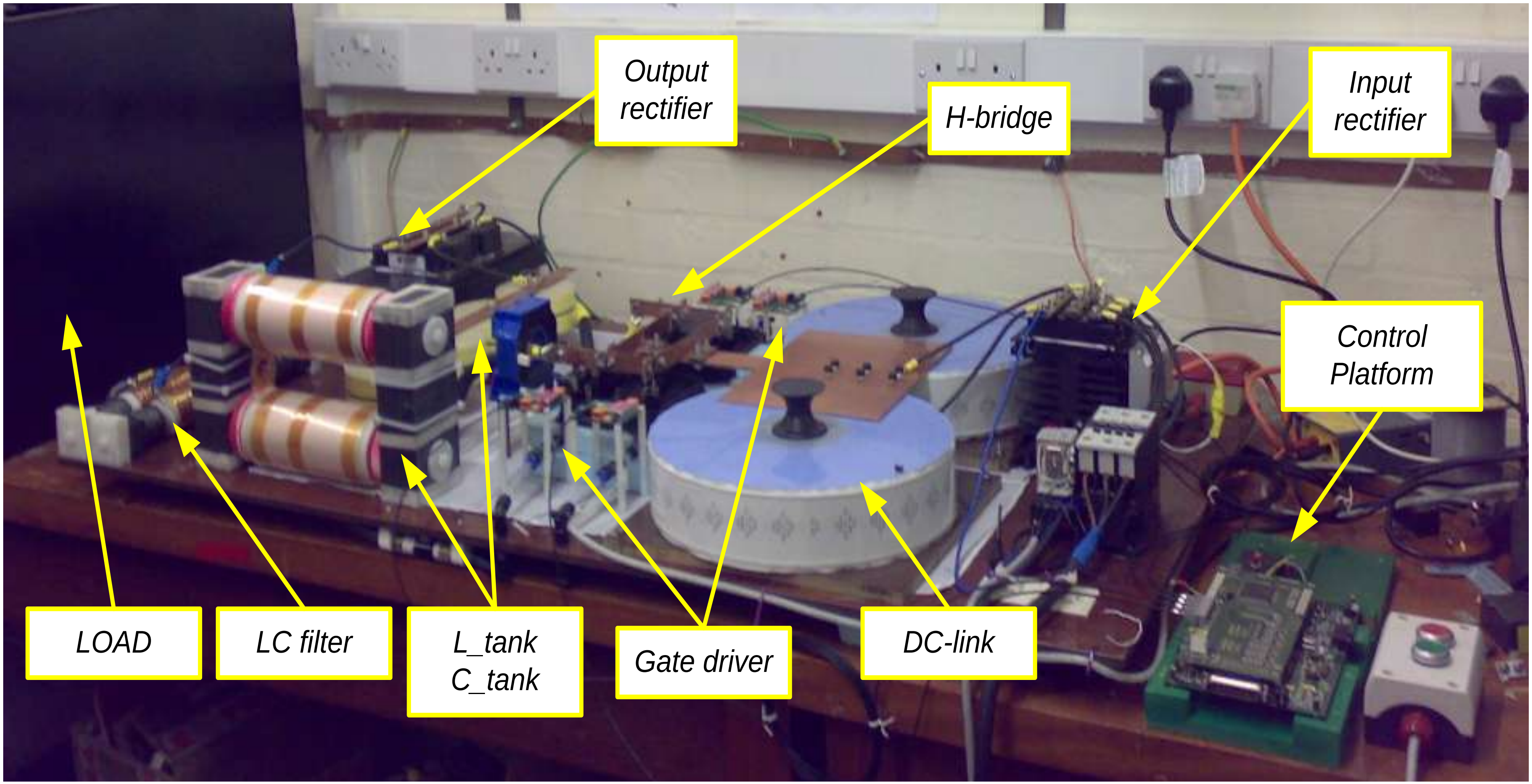
Description	Symbol	Value
Pulse length	T_p	*1 ms*
DC-link	V_{dc}	*560 V*
Duty Ratio	d	*10 %*
Quality Factor	Q	*2.5*
Resonant tank output current	I_{tank}	*800 A*
IGBT modules continuous collector current	I_c	*800 A*
Switching frequency	f_{sw}	*20 kHz*
Voltage droop during the pulse	ΔV_{dc}	*15%*
Pulsed Output power	P_x	*250 kW*
Average Output power	P_{av}	*25 kW*

POWER SUPPLY SPECIFICATIONS

Description	Symbol	Value
Load Resistance	R	*4 Ω*
Pulsed load current	I	*250 A*
Pulsed load voltage	V	*1 kV*
Dc-link capacitance	C	*5.8 mF*
Natural frequency	f_0	*21.8 kHz*
Tank inductor	L_{tank}	*0.0145 mH*
Tank Capacitor	C_{tank}	*3.66 μF*
Filter inductor	Lf	*0.06 mH*
Filter capacitance	Cf	*6 μF*

CONVERTER SPECIFICATIONS RESULTING FROM THE DESIGN

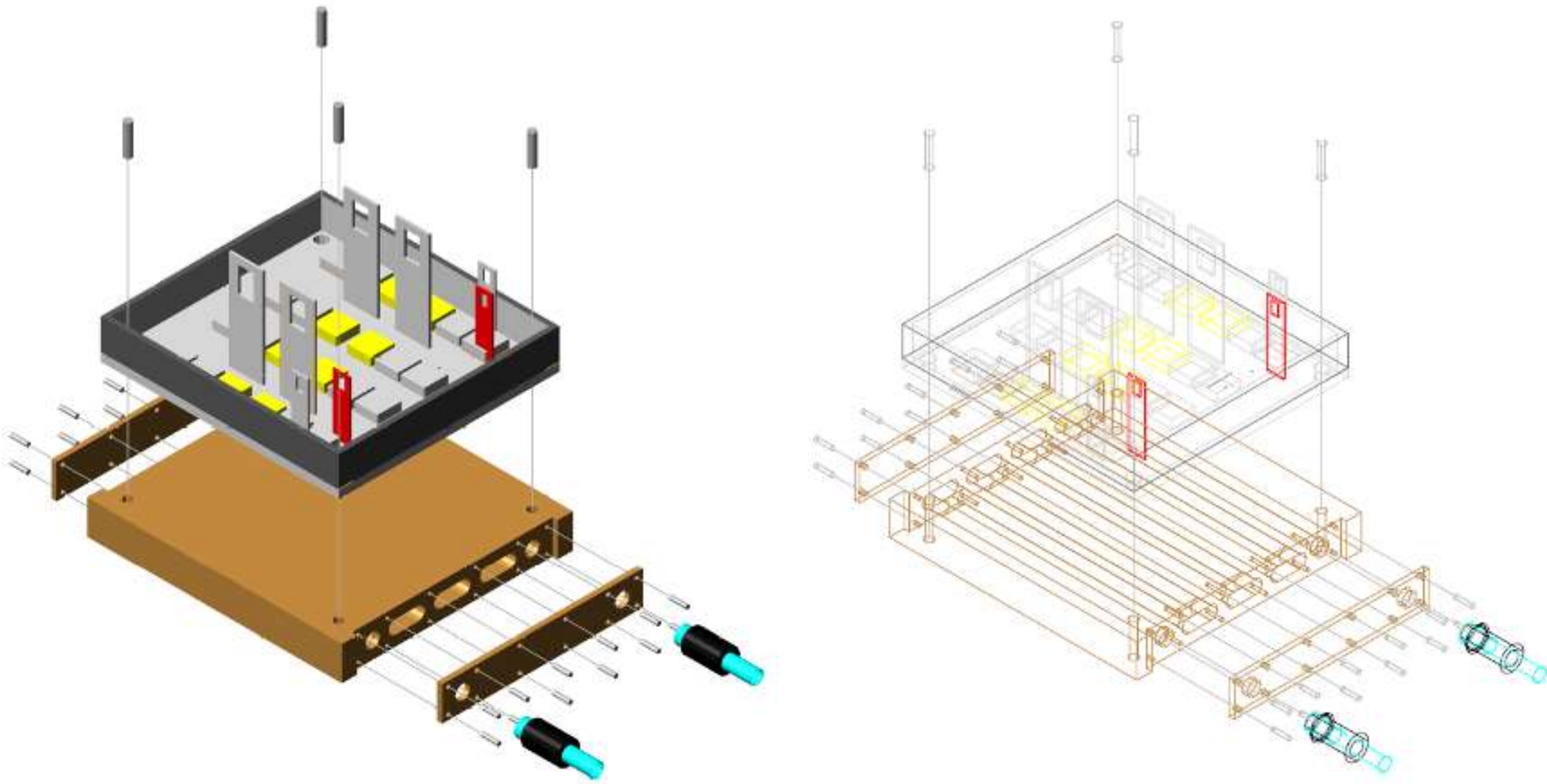
Losses and Reliability
Test rig implementation



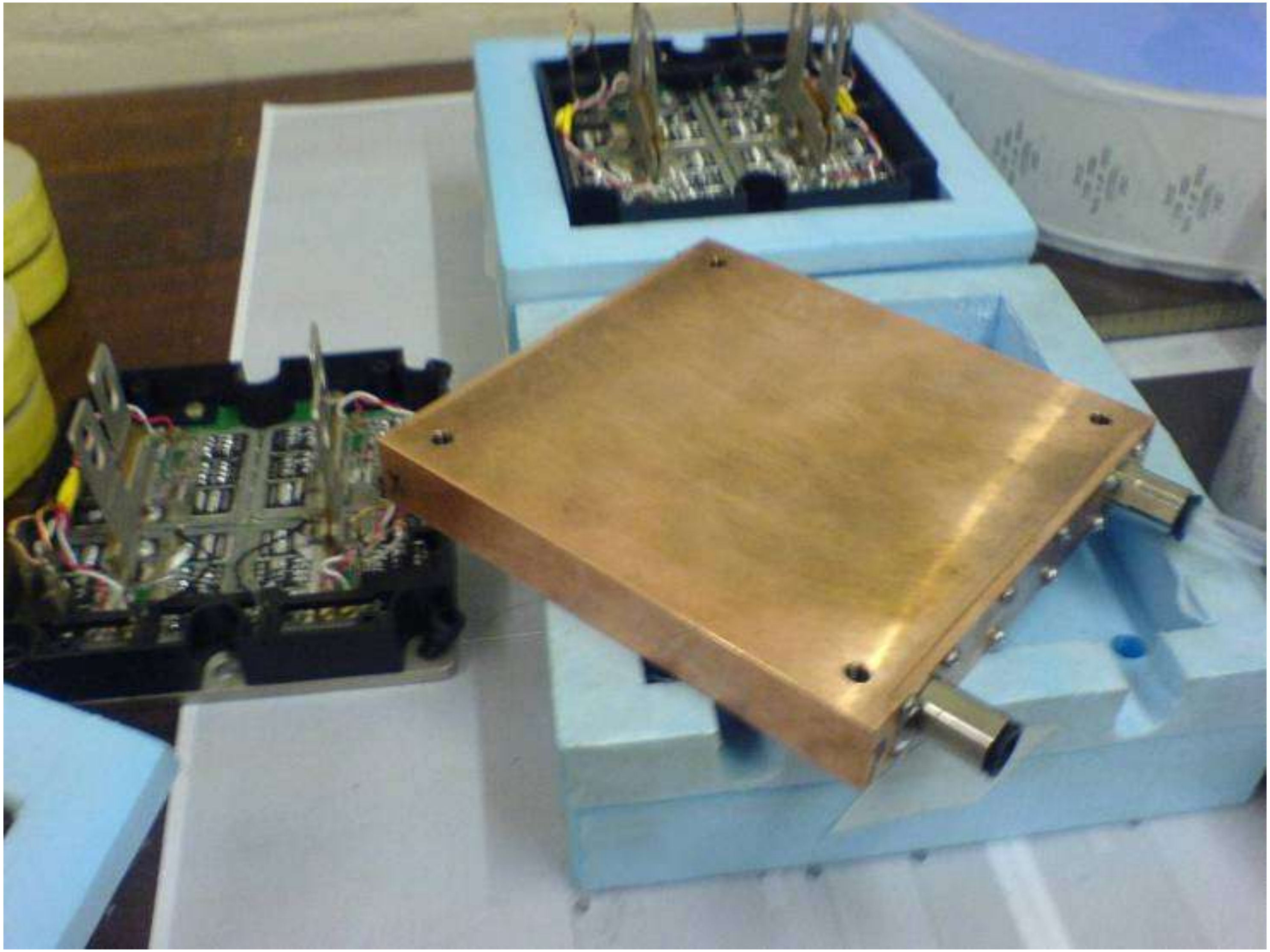
Losses and Reliability

Calorimetry set-up

Water cooled copper cold plates to measure the losses of leading and lagging arms independently



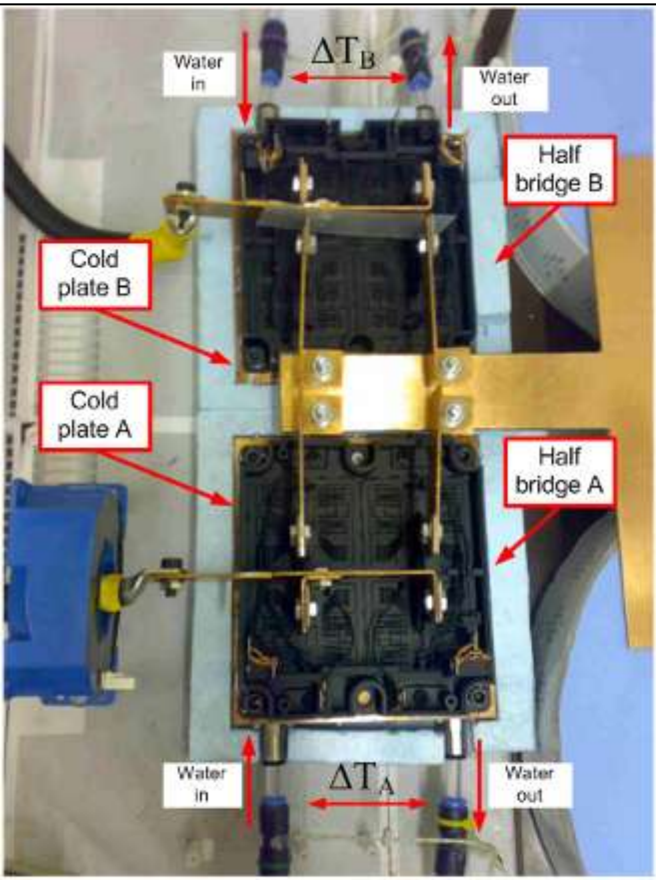
Losses and Reliability
Calorimetry set-up

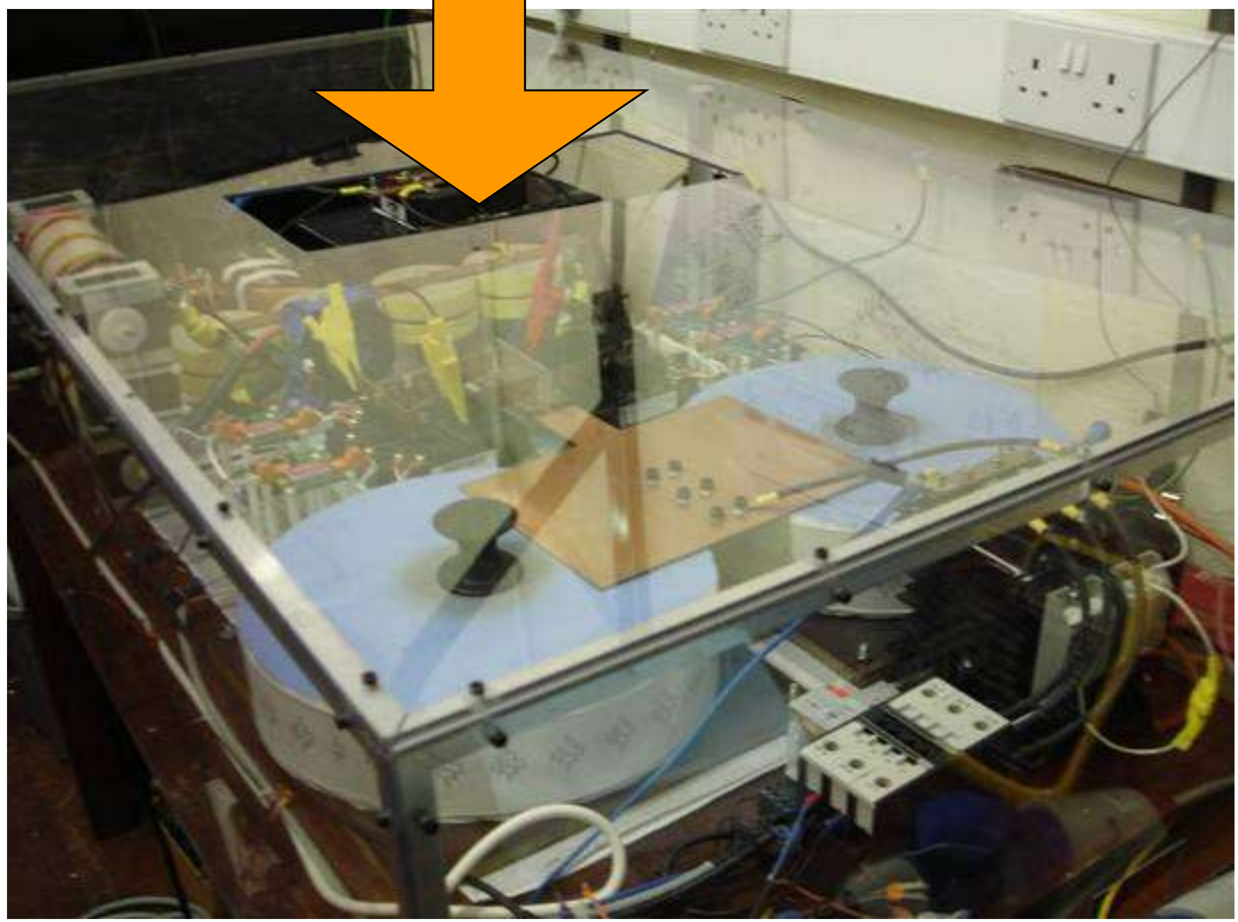


Copper cold plates

Losses and Reliability

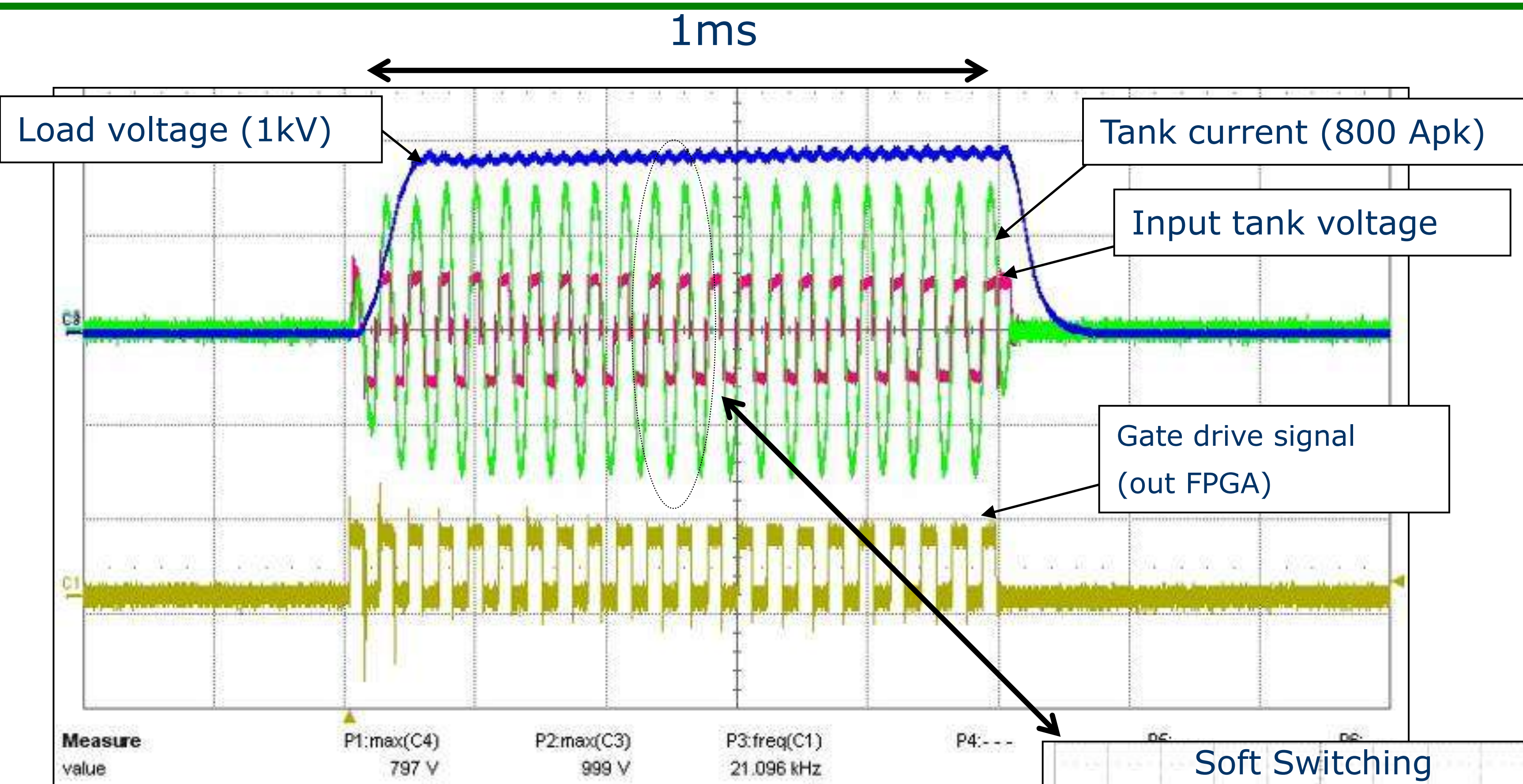
Set-up for high speed thermal imaging

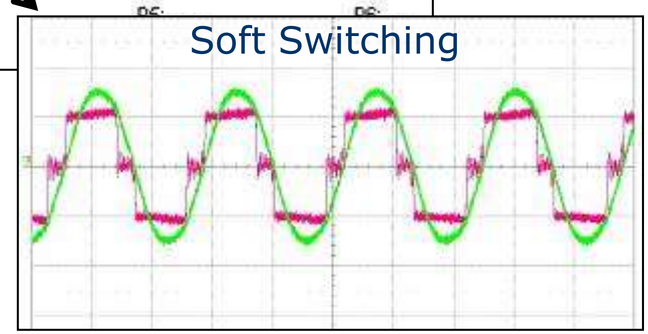




Losses and Reliability

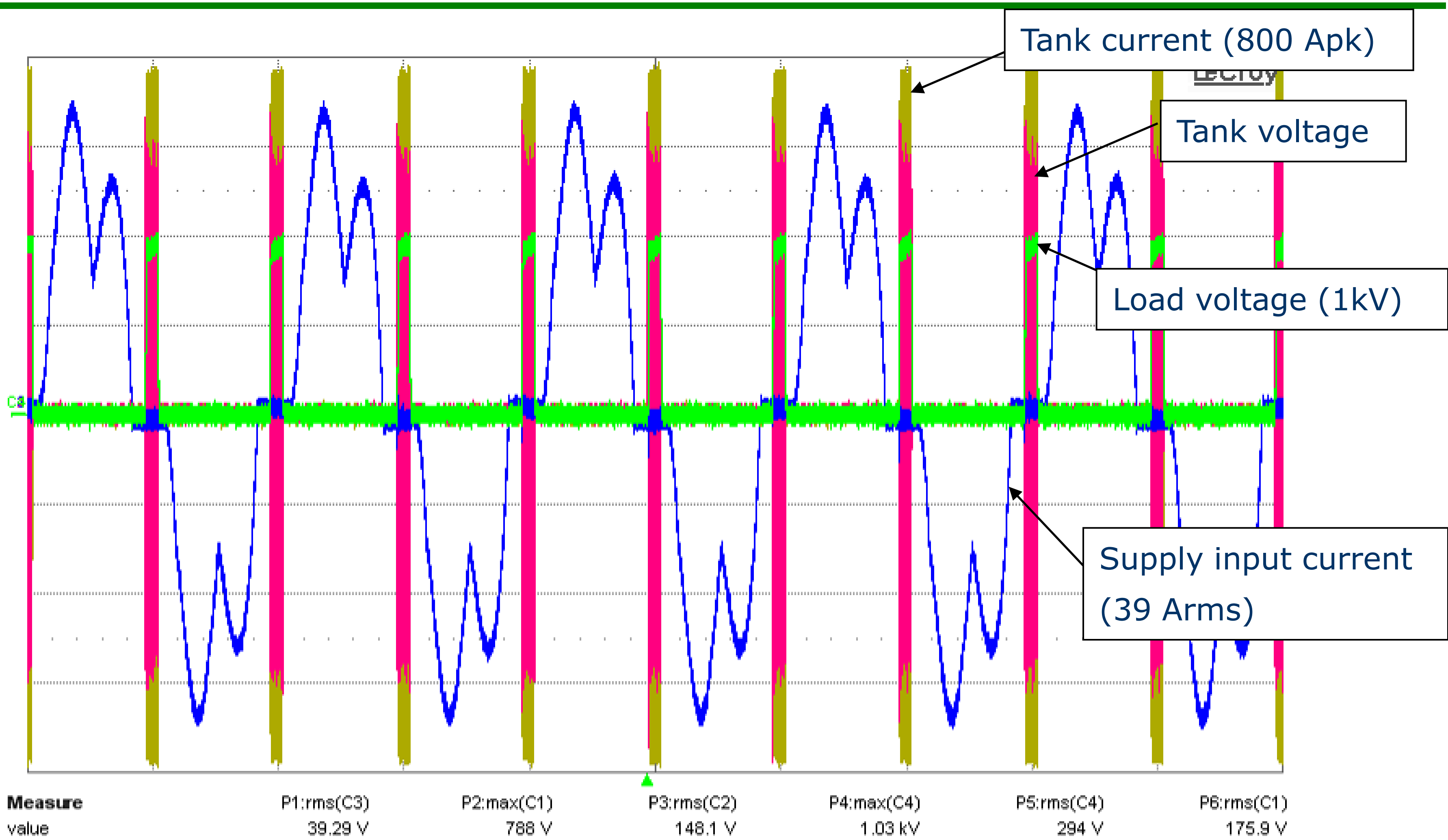
Full power experimental 1ms pulse





DC-link=560V

Losses and Reliability
Continuous pulsing



250kW, 10% duty cycle pulses, pulsing synchronised to the mains supply

Losses and Reliability

Calorimetry tests (8 minute)

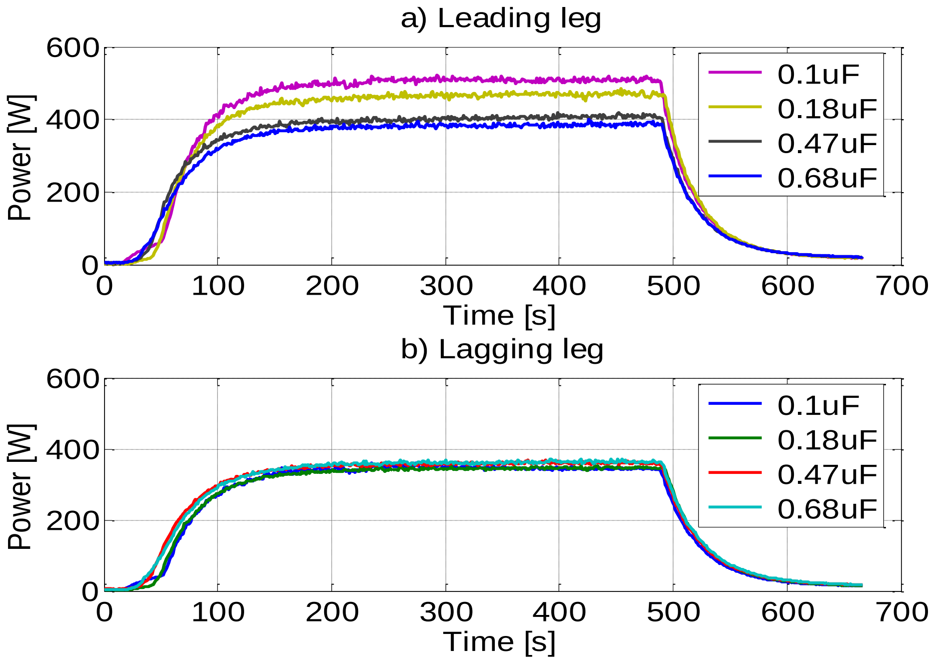


Figure 1: Power losses at full power for different turn-off snubber capacitor values, for the leading a), and lagging leg, b), respectively .

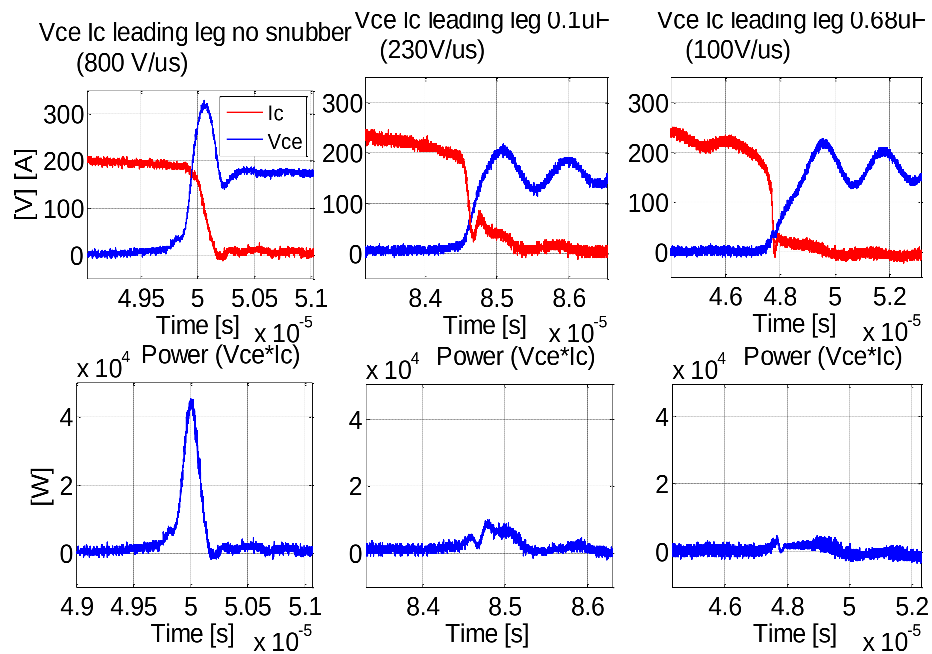


Figure 2: Leading leg turn-off waveforms with different turn-off snubber capacitors values.

- Lagging leg power losses are constant during each test since the devices switch at zero current for all commutations;
- Significant reduction (about 25%) of the leading leg power loss as the snubber capacitor is increased from 0.1uF to 0.68uF (**Turn-off waveforms illustrate the reduction in the turn-off power loss**);

Losses and Reliability

Calorimetry tests– Semiconductor Losses

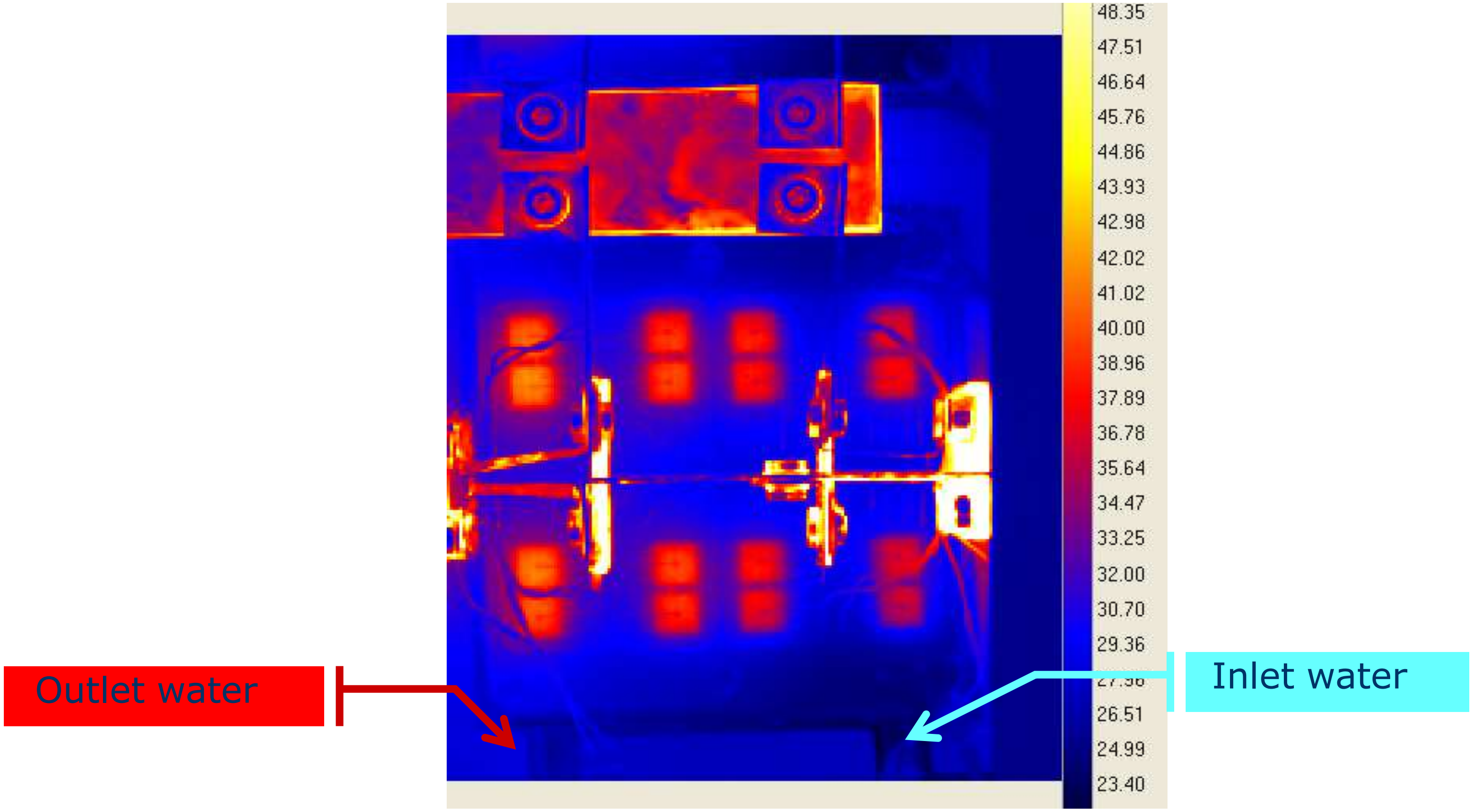
Leg	Soft-switching (measured)				Hard-switching (predicted)	
	Module losses measured with 0.68μF snubber capacitor [W]	*Average conduction losses [W]*	*Average switching losses [W]*	*Total semiconductor loss % of the average output power*	*Average switching losses [W]*	*Total semiconductor loss % of the average output power*
Leading	383	127	256	1.53	2248	9.5
Lagging	350	127	223	1.40	2248	9.5
Total	733	254	479	2.93	4496	19

Table I: Soft and Hard-switching comparison.

Clearly it would be impossible to use these devices at these conditions in a hard switched converter

Electro-Thermal characterisation

High speed thermal imaging test **(1072 frames per sec., 45 sec)**



IGBT infrared thermal imaging

The observed average temperature distribution agrees with the measured temperature difference, **5.7°C**, between inlet and outlet of the cold plate water loop

Electro-Thermal characterisation

High speed thermal imaging test **(1072 frames per sec., 45 sec)**

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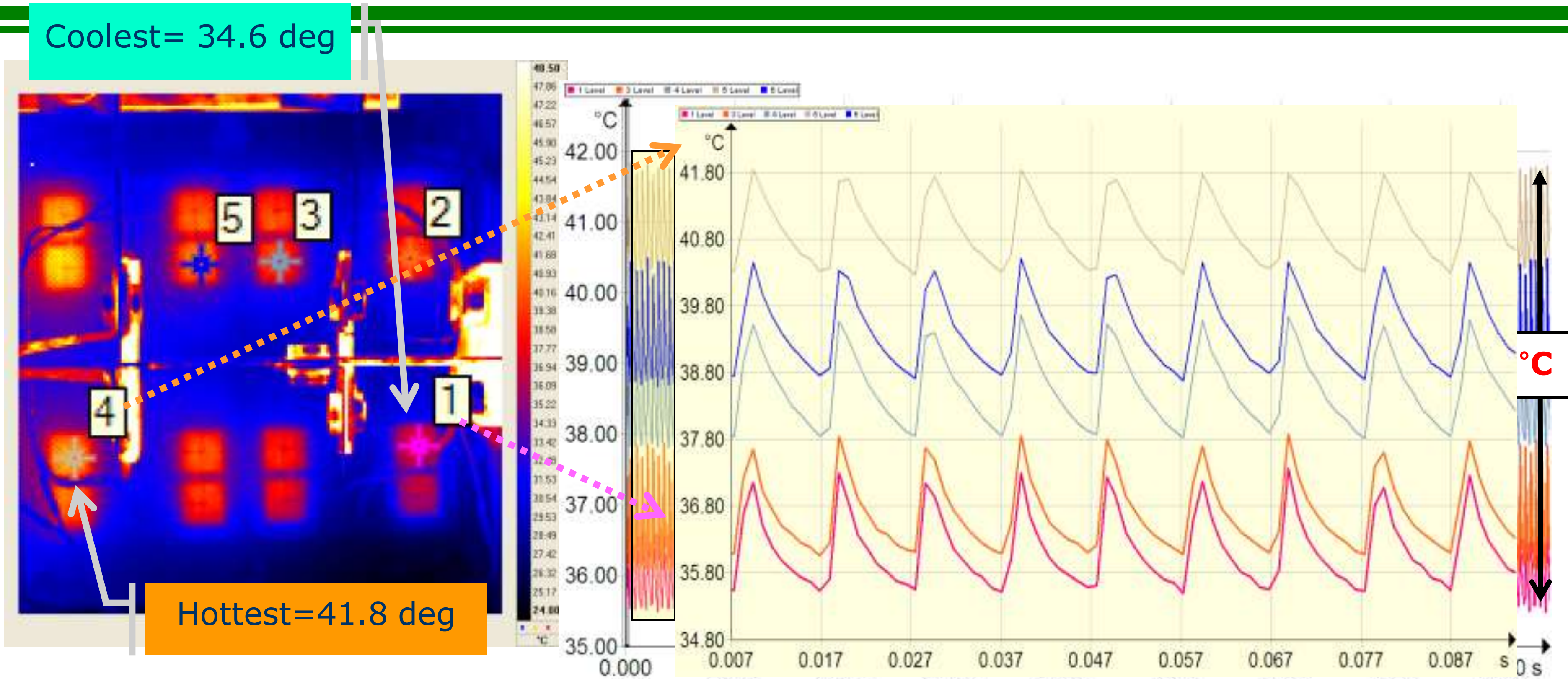

IGBT infrared thermal imaging, Sampled thermal transient during the test.

- Maximum junction temperature of **41.8°C** obtained from the experimental results, during steady state cold plate temperature conditions.
- During the 1ms pulse (i.e., the low-frequency waveform), a maximum temperature rise < **1.4°C** is observed..

Reliability - summary

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- ✓ *The results* presented indicate that pulsed power resonant conversion incorporating overall soft-switching of the modulator active devices is not, or very little, affected by IGBT module thermal cycling failure mechanisms
- ✓ Such topologies can be built employing standard commercially available power module technology.
- ✓ We can expect high semiconductor reliability in pulsed power supplies using these techniques.

Related technologies – an example

Electrostatic precipitator

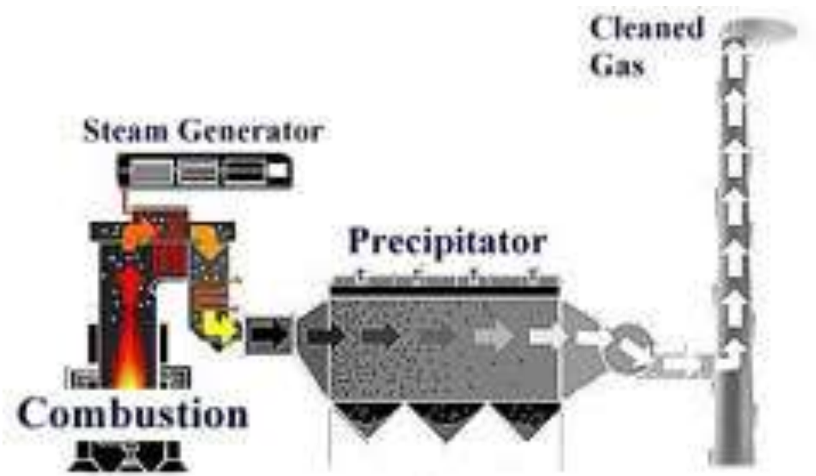


Figure 1: Electrostatic precipitator

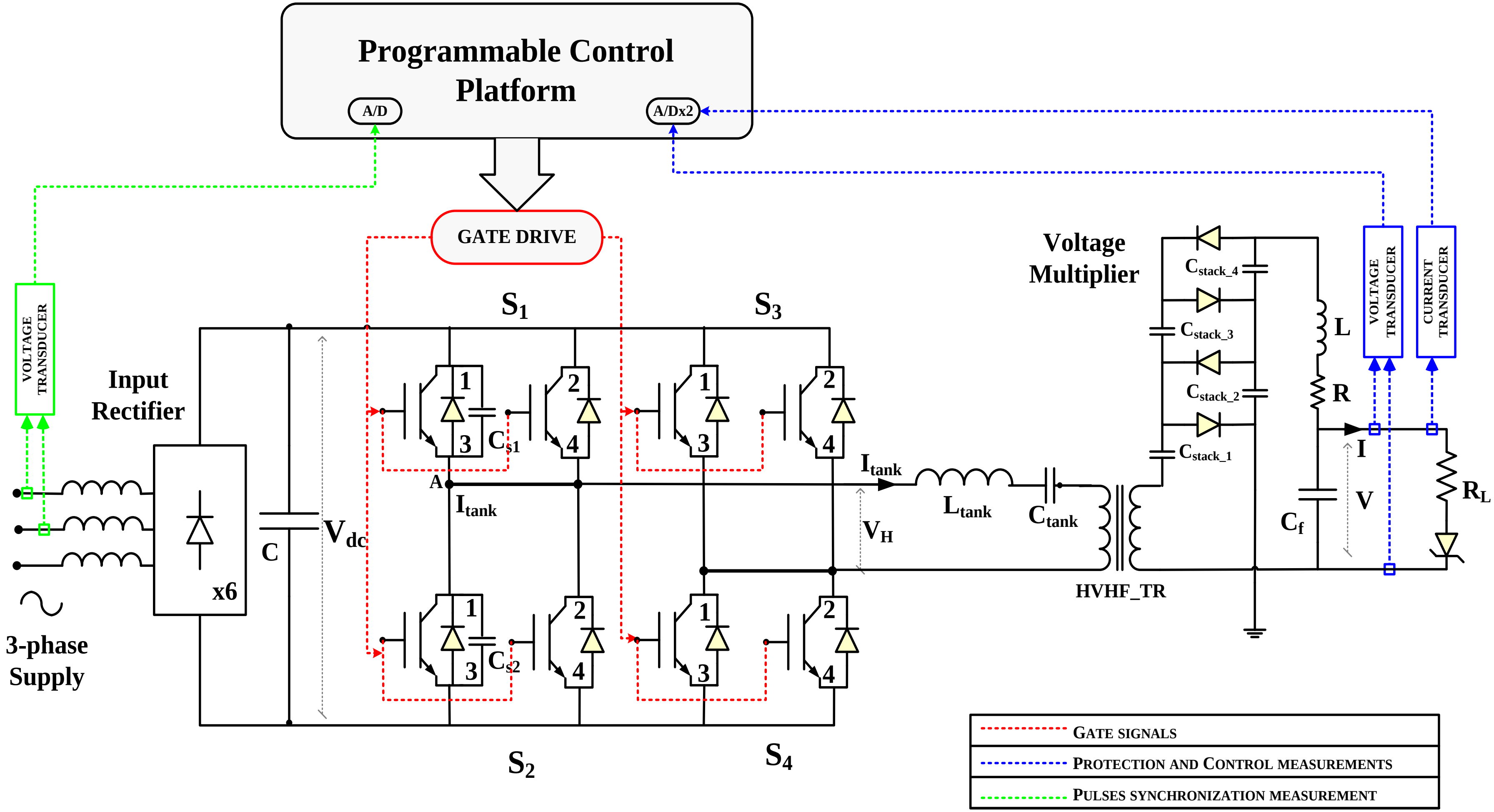
An electrostatic precipitator is a large, industrial emission-control unit. It is designed to trap and remove dust particles from the exhaust gas stream of an industrial process. Precipitators are used in these industries:

- Power stations (coal fired)
- Cement
- Chemicals
- Metals
- Paper

For most precipitators, a power supply with a high voltage output of 50kV to 100kV with high short-circuit capability is required to achieve the best efficiency of dust removal

Traditional power supplies in use for high voltage EPS systems are based upon 50/60Hz line frequency technology, which results in quite cumbersome designs

Resonant converter implementation
200kW (100kV 2A)



Test Rig

Test rig implementation

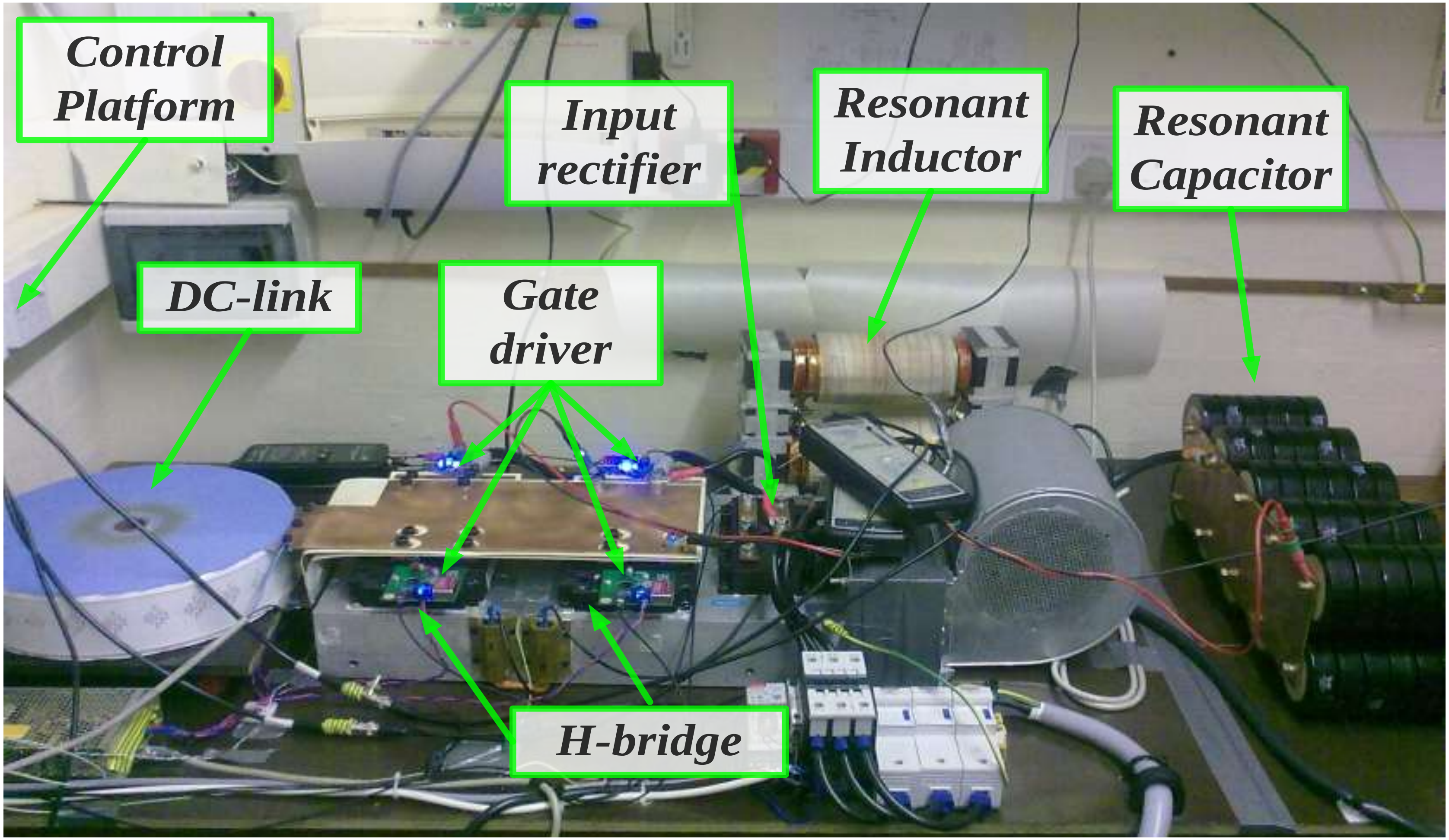


Figure1: Experimental setup of the single-phase power supply.

Test Rig

High Voltage transformer and load arrangement

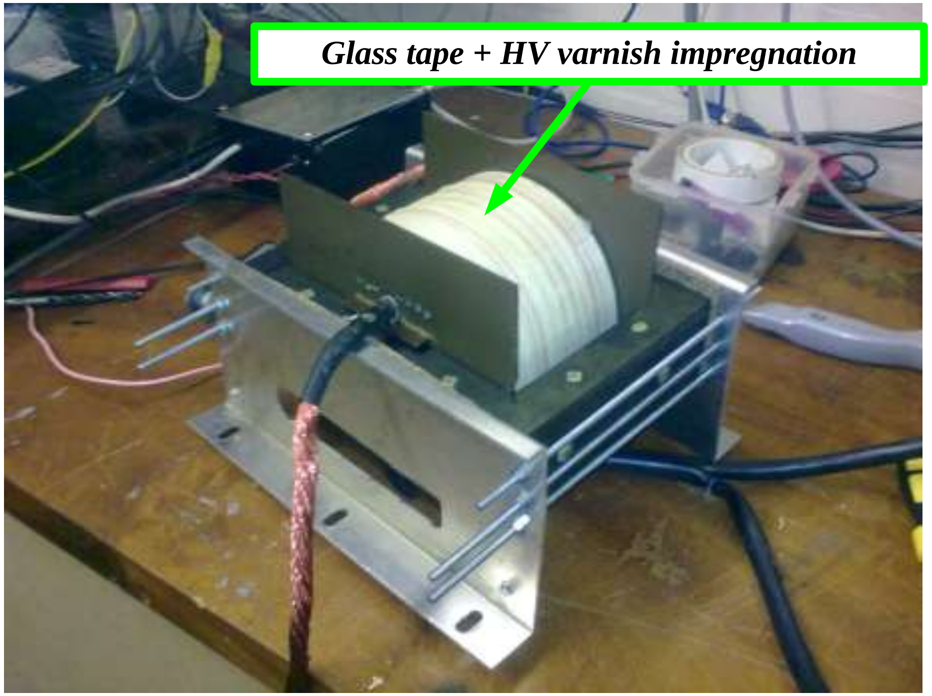


Figure1: High Voltage transformer.

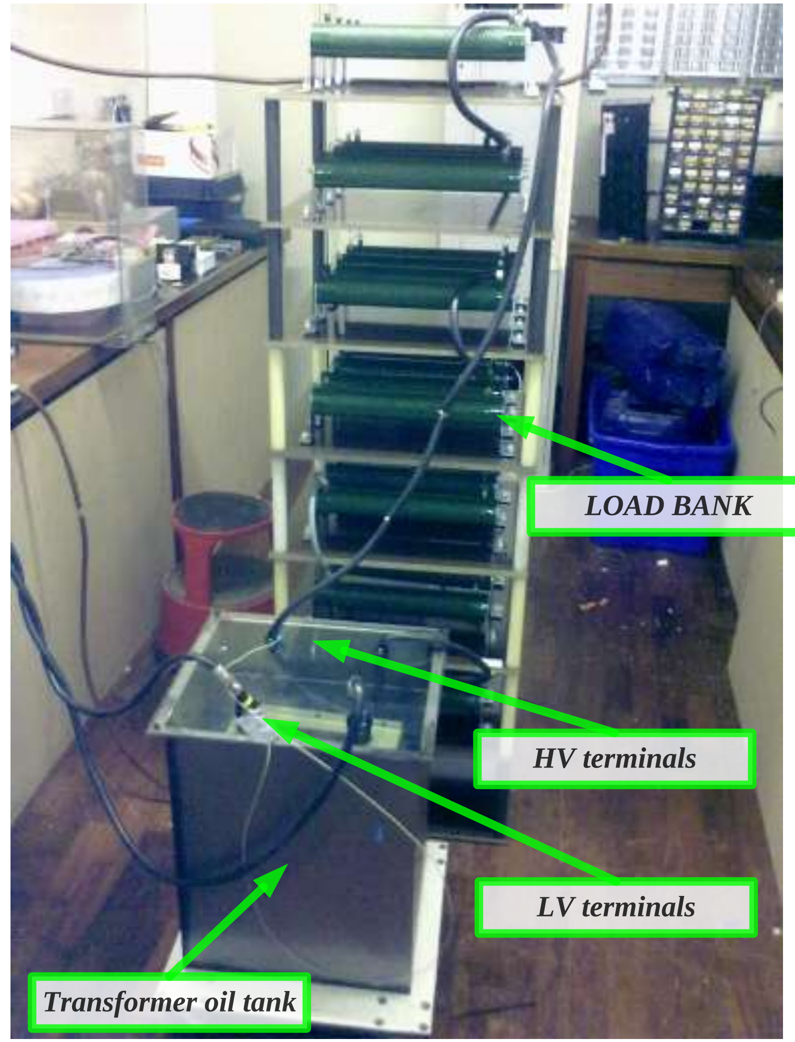
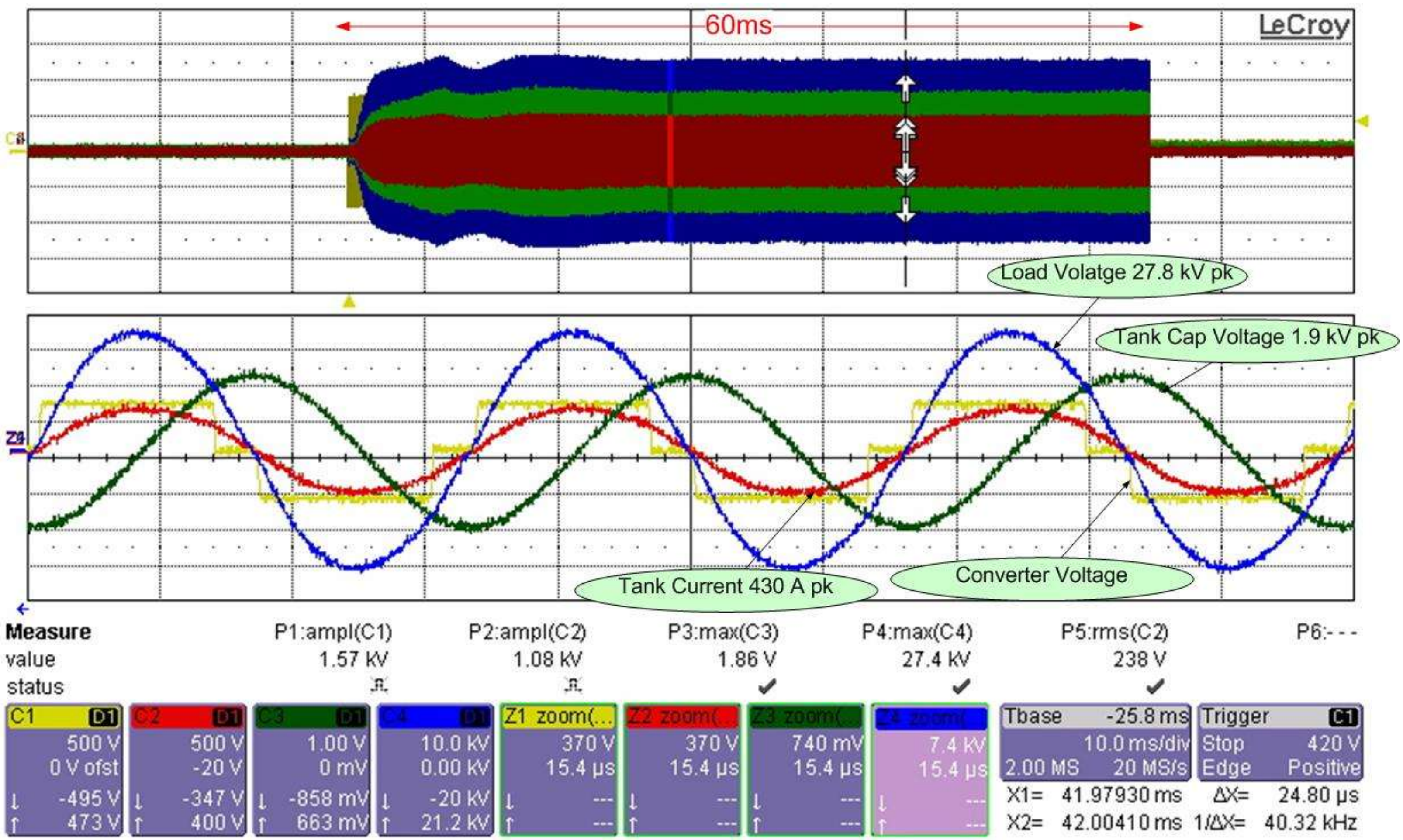


Figure 2: High Voltage transformer and load bank.

Test Rig Results

(Final results without multiplier)



Experimental waveforms at full power

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Thank You