Developments in resonant power converters for RF tube modulators

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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
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

- 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)
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

- 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

Rectifier

High Frequency Inverter (DC-AC)

Transformer + Rectifier + Filter

AC Supply

C_Dc

600V

HF AC pulse

Enable pulse

OFF

ON

OFF

2ms

Output pulse

Load

ON

OFF

2ms
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
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)*

Instantaneous power loss

Energy loss = \( E.I_L.t_{ON}/2 \)
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
  - $\Rightarrow$ High power, high frequency operation possible
Soft switching

**Illustration**

- **Current** passes from D1/D4 to Q1/Q4 with zero loss
- Q1+Q4 conducting
- D1+D4 conducting
- Q2+Q3 gated

**Diagram Details:**
- DC Supply (E)
- Q1, Q2, Q3, Q4
- D1, D2, D3, D4
- I_{DC}, I_{AC}, V_{AC}
- Current passes from D1/D4 to Q1/Q4 with zero loss
- Q1+Q4 conducting
- D1+D4 conducting
- Q2+Q3 gated
Multiphase resonant converter
*(increasing ripple frequency)*

- **Common DC supply**
- **600V**
- **C<sub>DC</sub>**
- **High Frequency Inverter (DC-AC)**
  - **0°**
  - **Resonant circuit “Tank” + Transformer**
  - **20kHz AC**
- **High Frequency Inverter (DC-AC)**
  - **120°**
  - **Resonant circuit “Tank” + Transformer**
  - **DC + 120kHz AC ripple**
- **High Frequency Inverter (DC-AC)**
  - **240°**
  - **Resonant circuit “Tank” + Transformer**
  - **Filter + Load**

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.
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).
Sectionalised modular transformer/rectifier concept for high voltage operation

50kV prototype under test, 150kV version designed

Some current work
(high voltage, high frequency transformers)

Intermediate voltage transformer:

Specifications:
- Vout = 50kV
- Iout = 1.66A
Some current work
(high voltage, high frequency transformers)

Each section of the transformer uses a toroidal nanocrystalline core
Common primary winding passes through all cores

50kV version
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
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.
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
Schematic of the single-phase SRPL power supply and control platform.
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.

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

### Converter Specifications

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Resistance</td>
<td>$R$</td>
<td>4 $\Omega$</td>
</tr>
<tr>
<td>Pulsed load current</td>
<td>$I$</td>
<td>250 A</td>
</tr>
<tr>
<td>Pulsed load voltage</td>
<td>$V$</td>
<td>1 kV</td>
</tr>
<tr>
<td>Dc-link capacitance</td>
<td>$C$</td>
<td>5.8 mF</td>
</tr>
<tr>
<td>Natural frequency</td>
<td>$f_0$</td>
<td>21.8 kHz</td>
</tr>
<tr>
<td>Tank inductor</td>
<td>$L_{tank}$</td>
<td>0.0145 mH</td>
</tr>
<tr>
<td>Tank Capacitor</td>
<td>$C_{tank}$</td>
<td>3.66 $\mu$F</td>
</tr>
<tr>
<td>Filter inductor</td>
<td>$L_f$</td>
<td>0.06 mH</td>
</tr>
<tr>
<td>Filter capacitance</td>
<td>$C_f$</td>
<td>6 $\mu$F</td>
</tr>
</tbody>
</table>

**POWER SUPPLY SPECIFICATIONS**

**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

Load voltage (1kV)

Tank current (800 Apk)

Input tank voltage

Gate drive signal (out FPGA)

1ms

DC-link = 560V

Soft Switching
Losses and Reliability

Continuous pulsing

250kW, 10% duty cycle pulses, pulsing synchronised to the mains supply
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);
## Calorimetry tests—Semiconductor Losses

### Table I: Soft and Hard-switching comparison.

<table>
<thead>
<tr>
<th>Leg</th>
<th>Soft-switching (measured)</th>
<th>Hard-switching (predicted)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Module losses measured with 0.68 μF snubber capacitor [W]</td>
<td>Average conduction losses [W]</td>
</tr>
<tr>
<td>Leading</td>
<td>383</td>
<td>127</td>
</tr>
<tr>
<td>Lagging</td>
<td>350</td>
<td>127</td>
</tr>
<tr>
<td>Total</td>
<td>733</td>
<td>254</td>
</tr>
</tbody>
</table>

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

- 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.
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
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

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**Figure 1:** Experimental setup of the single-phase power supply.
Test Rig
High Voltage transformer and load arrangement

**Figure 1:** High Voltage transformer.

**Figure 2:** High Voltage transformer and load bank.
Test Rig Results
(Final results without multiplier)

Experimental waveforms at full power
Thank You