Advanced Topologies – Converter Topology Systems

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Converter Topologies in Pulsed Power Systems

- Useful in longer pulse applications where $\tau >> 1/f_s$ ($\tau > 100 \mu s$ to DC)
- Enabled by high voltage ($\leq 10$ kV) high current (multi-kA) semiconductor power modules
- Pulsed power applications often require use of transformers to achieve required voltage levels (or series-stacked modules)
- Typical converter topologies utilized shown – there are several other options and various switching schemes

\[ V_{\text{out}} = D \cdot V_{\text{in}} \] (continuous conduction)

\[ V_{\text{out}} = 1/(1-D) \cdot V_{\text{in}} \] (continuous conduction)

D = $t_{\text{on}}/T_s$
Converter Topologies Benefits

• Evolution of solid-state switching modules to relevant power and voltage levels enabled this technology in 1990s
• Draws heavily on Power Electronics field of Electrical Engineering

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<tr>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>High efficiency (&gt;90%) achievable due to soft switching</td>
<td>Often use many solid-state switching devices and diodes</td>
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<td>Reduces stored energy requirements</td>
<td>Large number of components may lead to less reliable design</td>
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<td>Can eliminate need for crowbar circuit</td>
<td>Complex controls with multiple feedback loops and precise device timing</td>
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<td>Modular architectures</td>
<td>Not feasible for short pulse applications</td>
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<td>Can incorporate redundancy in some topologies</td>
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<td>Can mitigate PF and harmonics on utility grid</td>
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<td>Overall system volume can be reduced compared to traditional topologies</td>
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Ampegon Pulse Step Modulator

• Line frequency diode rectifiers with isolation transformers to create unregulated DC power
• Series-stacked boost converters to create HV in individual modules
• Add redundancy with additional modules, diode/switch to bypass inactive modules
• Modulator configuration with reduced MTTR

• Developed for the European Spallation Source
• Inverters charge series-stacked capacitors through transformer
• Add redundancy with additional modules, diode/switch to bypass inactive modules
• Modulator configuration with reduced MTTR

ESS-Lund Modulator

- Developed for the European Spallation Source
- Active front end and constant power charging maintains stringent Swedish PF, harmonics and flicker requirements
- Inverters drive step-up transformers to charge series-connected capacitors

Parallel Resonant Converter-Modulator

- Parallel resonant converter
  - Chopping at solid-state switch voltage
  - AC transformer steps up to high voltage
  - Soft (zero-voltage switching) ZVS achievable
- Poly-phase for high power operation within safe operating area of switches
- Resonant circuit
  - Transformer leakage inductance
  - Tuning capacitor
- Rectification
- Filtering
  - LC circuit

High Voltage Converter Modulator System Overview

- Provides up to 135 kV, 1.35 ms pulses at 60 Hz to amplify RF up to 5 MW
- Variable pulse widths 0.3- 1.4 ms
- IGBTs chop at 20 kHz nominal
- Powers multiple klystrons up to 11 MW peak power, 1 MW average
- 15 operational modulators, 3 test stand modulators
- Approximately $1.5 \times 10^6$ combined hours
HVCM Substation Power Transformer

- Operates at 13.8 kV distribution voltage
- Meets IEE-519 harmonics standard
  - $h=5$, 7.8% measured
  - $h=7$, 5.2% measured
- Cast coil construction
- Over 225 years combined operation, no major failures
HVCM SCR Controller

• Converts $2100 \ V_{RMS}$ to ±1300 V, 450 A DC
• Voltage stability ≤0.1% at constant load
• Regulation ≤2% from 25-100% full load
• Simple 6-pulse system with thyristor control
• System self-contained with rudimentary remote interface capability
HVCM Modulator System

- Energy storage capacitors and IGBT H-bridge switch plates located inside Safety Enclosure
- HV boost transformers, rectifiers and filter components inside oil-insulated tank
- Ancillary systems for cooling water distribution, oil circulation, CO$_2$ fire suppression system and diagnostics/controls
HVCM Control System

• New controller developed at ORNL using National Instruments FlexRIO FPGAs and analog/digital I/O
• Enhanced capabilities over previous controller
  • First Fault detection to 25 ns resolution
  • Pulse Flattening
  • Full waveform capture
  • Set warning/trip levels
  • Additional operational modes
  • Enhanced IGBT functionality integrated
  • Intellectual property ownership
  • Expandable
SNS HVCM Advantages

- 20 kHz inverter frequency
  - Small transformers
  - Small output filter
    - Fast risetime (<100 μs)
    - Low stored energy: minimize arc fault energy
- Low inverter voltage (~2 kV)
  - H-bridge is air insulated
  - Only low maintenance HV components are in oil
- The resonant peaking capacitors allow fault “ride-through” capabilities.
  - Load impedance changes (such as klystron discharges) de-tune the resonant circuit.
- Modulator utilizes frequency modulation (FM) operation to obtain a well-regulated output pulse
- Excellent fault detection, equipment protection and troubleshooting tools
SNS HVCM Disadvantages

• IGBTs operation exceeds intended application(s) and with reduced engineering safety margins
  • 20 kHz operation requires careful attention to IGBT gate drivers
  • Nominal operation at ~70% of device rating requires fast snubbers and low parasitic inductance in H-bridge
• Load-sensitive topology requires variations for variety of klystron load configurations at accelerator facility
• Resonant capacitor sees full voltage reversal – difficult to design high reliability capacitor
• 6-pulse controller rectifier converter generates harmonics and variable PF on utility grid
HVCM under test with Safety Enclosure removed and partial storage capacitor array
Energy Storage Capacitors

- 112 mF (16 mF × 7) at up to ±1300 V
- 75 kJ nominally each, rated for up to 95 kJ each
- Large metallized film units provide self-clearing capabilities in the event of an internal fault
- Bus work to H-bridge switch plates consists of 40 parallel fire-retardant RG-8 coaxial cables
- Safety circuitry, bleeder resistor, DC voltage diagnostics mounted on top
**H-bridge Operation Fundamentals**

- Four solid-state switches create bipolar square voltage pulses across the load
- Dead-time necessary to allow switches to recover
- If switches don’t recover, shoot-thru event can occur and destroy switches on left- or right-hand of bridge

![H-bridge Diagram](image)

![Graph](image)
HVCM IGBT H-bridge switch plate

- Four H-bridge 3300 V, 1200 A Infineon IGBTs switching nominal 20 kHz mounted on discrete cold plates with bus work towards center.

- Unipolar and bipolar capacitors provide high frequency bypass

- Gate drivers located remotely with low impedance cabling to IGBT terminals

- Gate driver power supply distributes 24 V DC

- RCD snubbers incorporated to eliminate IGBT overvoltage
New IGBT gate drivers also lower losses & reduce ripple

- Uses commercial Power Integrations 30 A driver
- Demonstrated IGBT switching loss reduction of 30%
- ~5X reduction in RF forward power ripple due to reduced dead band
High voltage components inside oil-filled tank
Pulse flattening to compensate for capacitor droop

- Reduces voltage stress on klystrons & modulator components
  - Utilizing frequency modulation only
  - Phase shift pulse width modulation effective but increases switching losses in right-hand side of H-bridge
- IGBT commutation currents increase by 40% but still acceptable – hard switching in some cases
- Reduces LLRF bandwidth requirements
Alternate Topology (AT)-HVCM Developed to Reduce Component Stress and Achieve Soft Switching
Necessary Conditions to Achieve zero voltage switching (ZVS)

Conditions for ZVS in resonant converter

1. Inductive load impedance for bridge
   Insures current is circulating at turn-on
2. Sufficient energy stored in resonant tank inductor
   \( \frac{1}{2} L_i^2 > C_{OSS} V_{CE}^2 \)
3. Sufficient dead-time

In the AT-HVCM topology, the transformer magnetizing inductance provides the stored energy.

Q1 and Q4 have just been gated off. \( I_L \) stored energy charges \( C_{OSS} \) of Q1 and Q4. Current then transfers to the freewheeling diode of Q2 and Q3 allowing zero voltage at turn on of those transistors.
AT-HVCM Frequency Modulation Performance

- Transfer function peaks at 23kHz and falls off below and above resonance.
- Gradient is 2x greater when operating below resonance.
- A 5% droop in capacitor bank voltage (equivalent to 2/37 gain change) compensated by 2kHz frequency sweep.

- Operating below resonance provides minimum IGBT switching loss and minimum frequency sweep for pulse flattening.
- Typical AT-HVCM IGBT losses are 30 J/macropulse (1.8kW) compared with 50 J/macropulse (3.0kW) for the present HVCM, further improving system efficiency.