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Title:

CAPABILITIES, PERFORMANCE, AND FUTURE POSSIBILITIES OF HIGH FREQUENCY POLYPHASE RESONANT CONVERTERS

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Capabilities, Performance, and Future Possibilities of High Frequency Polyphase Resonant Converters*

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Abstract

High Frequency Polyphase Resonant Power Conditioning (PRPC) techniques developed at Los Alamos National Laboratory (LANL) are now being utilized for the Oak Ridge National Laboratory (ORNL) Spallation Neutron Source (SNS) accelerator klystron RF amplifier power systems. Three different styles of polyphase resonant converter modulators were developed for the SNS application. The various systems operate up to 140 kV, or 11 MW pulses, or up to 1.1 MW average power, all from a DC input of +/- 1.2 kV. Component improvements realized with the SNS effort coupled with new applied engineering techniques have resulted in dramatic changes in RF power conditioning topology. As an example, the high-voltage transformers are over 100 times smaller and lighter than equivalent 60 Hz versions. With resonant conversion techniques, load protective networks are not required. A shorted load de-tunes the resonance and little power transfer can occur. This provides for power conditioning systems that are inherently self-protective, with automatic fault "ride-through" capabilities. By altering the Los Alamos design, higher power and CW power conditioning systems can be realized without further demands of the individual component voltage or current capabilities. This has led to designs that can accommodate 30 MW long pulse applications and megawatt class CW systems with high efficiencies. The same PRPC techniques can also be utilized for lower average power systems (~250 kW). This permits the use of significantly higher frequency conversion techniques that result in extremely compact systems with short pulse (10 to 100 us) capabilities. These lower power PRPC systems may be suitable for medical Linacs and mobile RF systems. This paper will briefly review the performance achieved for the SNS accelerator and examine designs for high efficiency megawatt class CW systems and 30 MW peak power applications. The devices and designs for compact higher frequency converters utilized for short pulse, lower average power applications will also be presented.

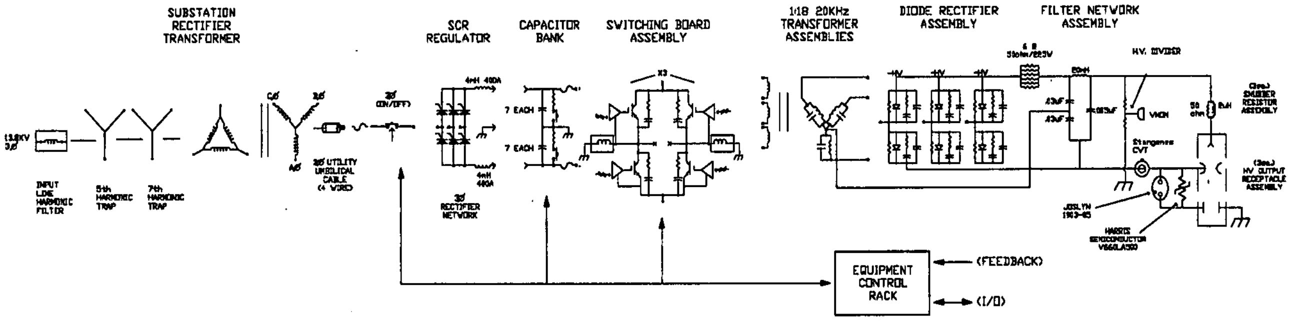

Figure 1: System Block Diagram

HARDWARE REVIEW

The system block diagram of the SNS converter-modulator is shown in Fig. 1. Each converter modulator derives its buss voltage from a standard 13.8 kV to 2100 Y (1.5 MVA) substation cast-core transformer. Each substation is followed by an SCR pre-regulator to accommodate system voltage changes from no load to full load, in addition to providing a soft-start function. The nominal output voltage at full power is +/- 1200VDC. Energy storage and filtering is provided by specially developed low inductance self-clearing metallized hazy polypropylene traction capacitors. These capacitors do not fail short, but clear any internal anomaly, providing a calculated lifetime of over 300,000 hours. As in traction application, these capacitors are hard-bussed parallel. Three "H-Bridge" IGBT switching networks are used to generate the polyphase 20 kHz transformer primary drive waveforms. The 20 kHz drive waveforms are gated the appropriate duration to generate the desired klystron pulse width. Other transformer tuning conditions, switching frequencies, and interlacing (e.g. pentaphase vs. three phase) can be considered to optimize CW and short pulse configurations. The nanocrystalline boost transformers are wound with a ratio of 1:19, but the output is about 1:60. Unlike previous power transformers with the same "volts-per-turn" for both the primary and secondary, this design generates multiple volts-per-turn on the secondary. These transformers are designed for leakage inductance, not turns ratio. In addition, the core flux expended is that of the primary. It would seem that the secondary leakage inductance isolates the core from the voltage swing

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generated on the secondary. The zero-voltage-switching characteristic (determined from the tuning of the leakage inductance and the overall secondary capacitance) minimizes the IGBT switching loss, turn on is soft without forced commutation (and losses) of the opposite IGBT free-wheeling diode.

To provide six pulse rectification of the 20 kHz, ~140 kV line-line voltages, resonant rectification techniques are used. Capacitors are placed in parallel with groups of rectification diodes. However, low loss, fast recovery diodes are still necessary for this design. The circuit effect of the added rectification capacitance is that it acts like the transformer shunt peaking capacitors and must be considered in the analysis of the transformer tuning. The resonant rectification capacitors have the desirous effect to bypass diode switching transients and swamp "Miller" (ground) capacitance from the diodes. The Miller capacitance (to ground) will cause significant over-voltage of diodes high in the stack. Output filtering is provided by a standard "Pi-R" network, and now also include harmonic traps (not shown on schematic). The input resistance damps the ringing of the rectifier circuits. Filter capacitance values are chosen to provide adequate filtering yet minimize stored energy. The stored energy is wasted power that is lost at the end of the klystron pulse. With 120 kHz ripple frequency, high efficiency with good filtering can be attained. The additional harmonic traps are required due to subtle timing differences of the IGBT's, which then generate fixed frequency ripple.

CONVERTER MODULATOR ASSEMBLY

A view of the completed converter modulator assembly is shown in Figure 2. The oil tank, safety enclosure, and water distribution panel are the prominent features that can be noted in this figure. This is the only configuration for the three different kinds of modulators required for the SNS accelerator. The RFQ/DTL modulator operates 3 parallel 402 MHz klystrons at 116 kV. The 140 kV modulator operates either 2 parallel 402 MHz klystrons or one large (5MW), 805 MHz klystron. A 75 kV modulator operates up to 12 parallel 550 kW, 805 MHz klystrons. A view of the converter-modulator assembly connected to the 12 parallel 550 kW, 805 MHZ klystrons is shown in Figure 3.

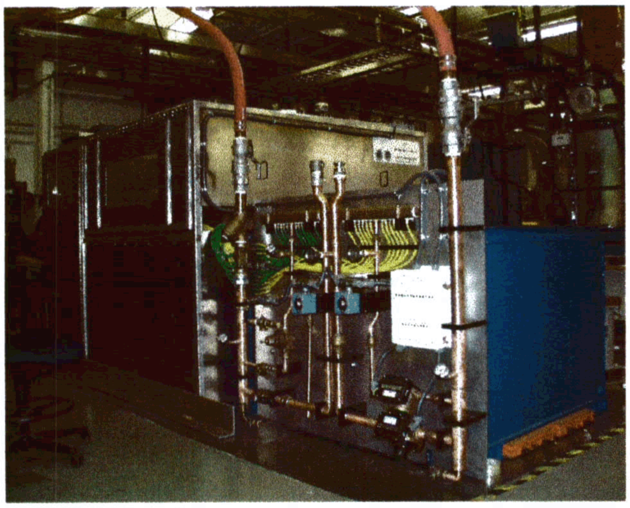

Figure 2: Converter Modulator Assembly

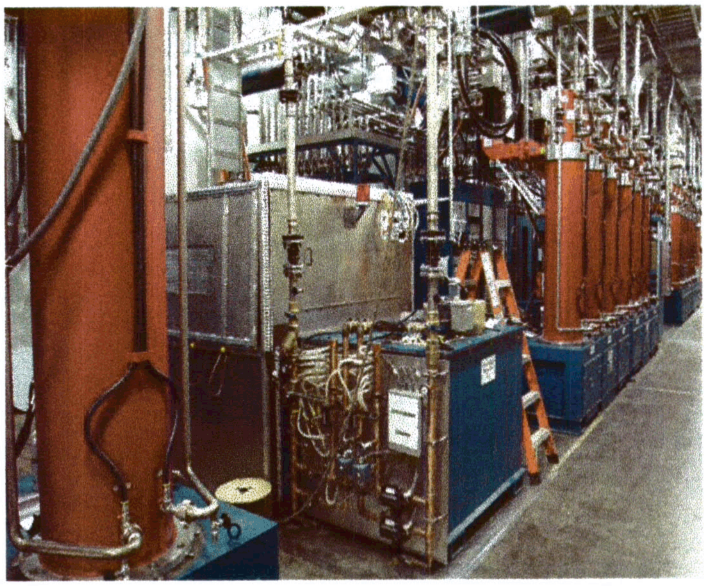

Figure 3: ORNL 75 kV Modulator Connected to 12-Pack

OPERATIONAL PERFORMANCE

All converter modulator system have been delivered to Oak Ridge National Laboratory. System operations to full average power have been performed both at LANL and ORNL. LANL has been operating the 140 kV, 805 MHz klystron system to full power. The output voltage waveform for this system can be seen in Figure 4.

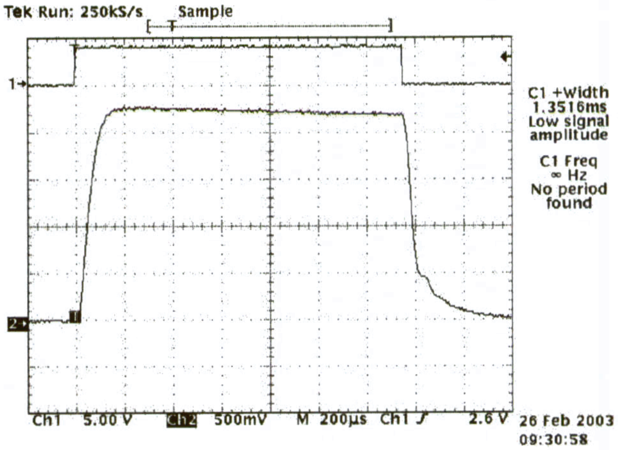

Figure 4: Full Average Power, 136 kV Waveform

For the 125 kV converter-modulator, operating a pair of 2.5 MW, 402 MHz klystrons, the output waveform operating at full average power (from ORNL) is shown in Figure 5.

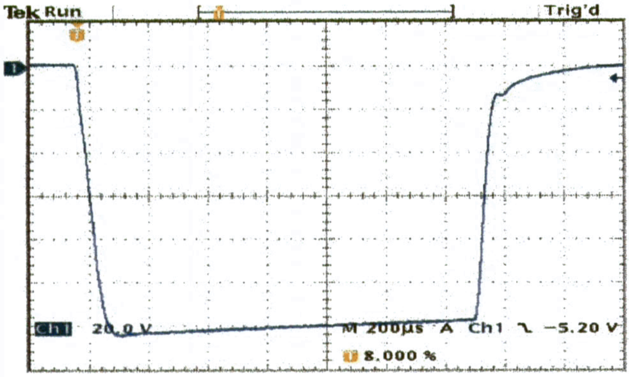

Figure 5: Full Average Power, 125 kV Waveform

Both the 125 kV and 140 kV modulators share the same design, and both exhibit better than 93% efficiency at full power. The IGBT power loss is less than 2 kW each, and is an important consideration to minimize thermal cycling from each power pulse. Although IGBT's do have anomalous switching characteristics such as dynamic saturation and tail current affects, it is important to note that zero-voltage-switching does improve efficiency considerably, and is mandatory to maintain long-term reliability. The operational results of the recently installed 12 pack, 75 kV system is shown in Figure 6. The output voltage, upper trace, ~75 kV and the IGBT current waveforms operating at full peak voltage and power. Full average power testing will commence in early June 04.

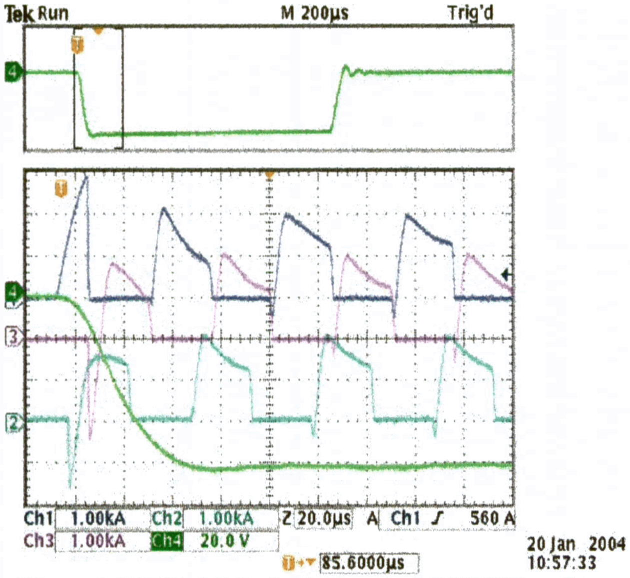

Figure 6: 75 kV, 12 Pack Voltage and IGBT Waveforms

The lower trace shows details the voltage risetime (~40 uS) and the IGBT current waveforms (1 kA/div). The current waveforms show some hard switching for the first few pulses and then zero-voltage-switching by the onset of free wheel diode conduction, the small negative current at the beginning of each pulse. The electrical efficiency of the 75 kV converter-modulator seems to be better than 92%.

HIGH POWER FUTURE POSSIBILITIES

The long-pulse capabilities of polyphase resonant power conditioning techniques have already been demonstrated. In order to generate the 10 MW pulses, the semiconductor components must be rated at the appropriate (10 MW) current and voltage levels. To attain CW operation at the 10 MW level, no further demands in current or voltage are required for any of the components, just a continuous "on" time. The design issue then becomes one of thermal transfer and efficiency. A 10 MW CW system would have a different set of optimizations than a 10 MW pulse system. An examination of the long-pulse 10 MW technology seems to indicate that a lower frequency "pentaphase" converter (72° timing offset) is a viable design option that could also be packaged in similar foot-print as the SNS design. The CW system would maintain many of the desirable properties of the SNS design such as: no crowbar requirements, automatic fault ride-through capabilities, remote location, and long output cable lengths (> 1 kM). For this system, as shown if Figure 7, we would estimate efficiencies greater than 96%.

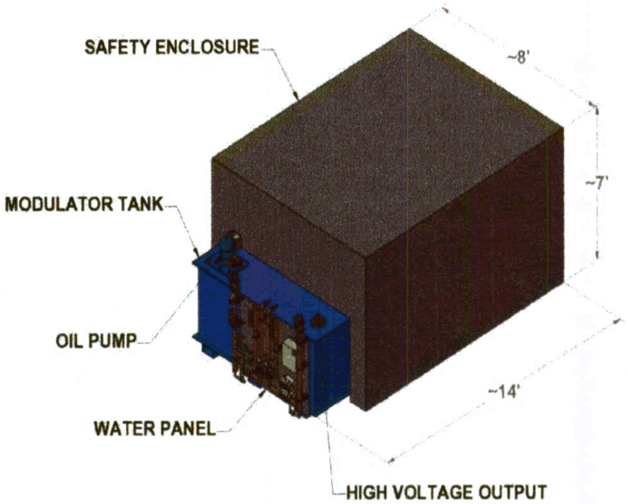

Figure 7: 10 MW CW Pentaphase Converter (Estimate)

In a similar size, a pentaphase converter could easily power at remote length, a pair of 15 MW pulsed klystrons, and still maintain appropriate fault energies.

LOWER POWER CONVERTERS

Lower power resonant converters, whether cw or pulse, are also easily viable. We have performed a design study on what we thought was a reasonable capability with fast switching 1,000 volt class MOSFETS. One can envision polyphase systems operating directly from a line rectified 480 V, 3ϕ power source. Operating at what we thought would be the maximum reasonable load and a maximum average power, our design study resulted in a 250 kW average power system as shown in Figure 8.

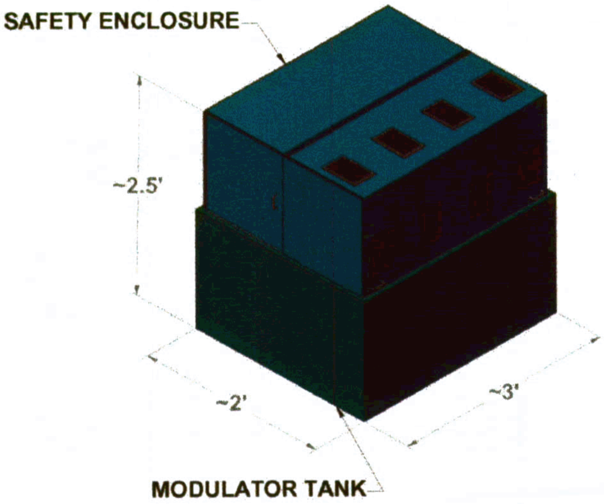

Figure 8: 250 kW Average MOSFET Converter

This design is based on available components and can be optimized for various uses such as mobile and/or airborne applications. This topology, with efficient MOSFET switches would have good pulse width variability, kilohertz rep-rates, and output voltage agility. The modeled output of this system, operating at a maximum pulse load (2.5 MW), is shown if Figure 9. This voltage and current may be typical of many tube type loads. Higher load impedances (lower peak power) would result in improved rise and fall times (sub-microsecond).

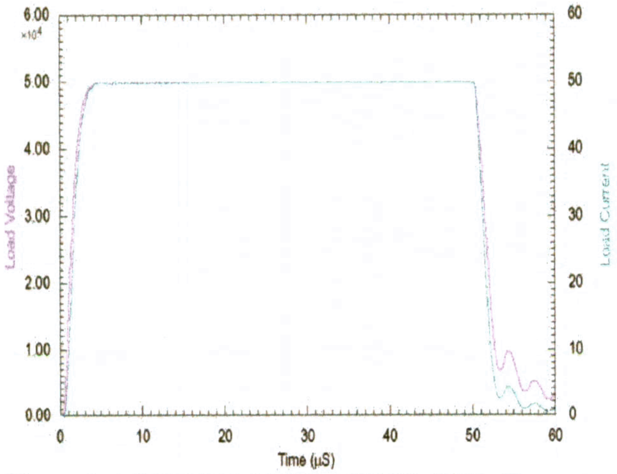

Figure 9: MOSFET 2.5 MW, 250 kW, 2 kHz Converter

CONCLUSION

The polyphase resonant converter-modulator has demonstrated several new design methodologies that are expected to revolutionize long-pulse, medium pulse, and CW power conditioning designs. These new technologies include special low inductance self-clearing capacitors, low inductance high frequency and high voltage power capacitors, large amorphous nanocrystalline cut-core transformers, polyphase resonant voltage multiplication, resonant rectification, and snubberless IGBT switching. The design is fault tolerant, a shorted load detunes the resonance and maintains power flows that do not damage itself or the load. This then provides for systems that have automatic fault "ride-through" capabilities. By generating high-voltage when needed, system reliability and personnel safety is greatly enhanced. We believe that this is a significant change in power conditioning topology and has many ideal attributes for military, medical, and scientific applications.

AKNOWLEDGEMENTS

There are many people who have contributed to the overall success of this technology. These contributing individuals came from both industry and the national laboratories. Some of the initial polyphase resonant topologies and the resonant rectification idea were initiated by Jan Przybyla of E2V (old Marconi), jan.przybyla@eev.com. George Schoefield, of Titan Pulse Sciences contributed to overall system topology. Claude Vincent of Thomson Passive Components (AVX), successfully oversaw the development of the high density, low inductance self-healing capacitors, claude.vincent@tpc.fr . Bob Cooper of General Atomics Energy Products (bob.cooper@ga-esi.com) developed many capacitor styles that operate at high frequency and high voltage. For the resonant converter application, one of the most important capacitor developments was the high power IGBT bypass capacitors that obviate the need of the IGBT R-C snubbers. The 3.5 MVA, 20 kHz, 140 kV HV transformer resonating capacitors were also a successful development. Although small size, uncut nanocrystalline alloy products were available, Bill Jahnke (bjahnke@mkmagnetics.com) of MK Magnetics (owned by Stangenes) developed the processing and manufacturing techniques for the "large" SNS nanocrystalline alloy cut-core transformers. This is a significant component for the high-frequency polyphase resonant conversion technology. The system linear and non-linear circuit models were developed and implemented by Danny Doss (jddoss@taosnet.com) and Robin Gribble (rf.gribble@worldnet.att.net). These models were critical in making design decisions and trade studies that resulted in the overall success of the implemented hardware.

The authors appreciate the hard work and dedicated efforts of the engineers, mechanical, and electrical fabrication technicians, both at LANL and ORNL. Dave Anderson (deanderson@ornl.gov) has led the ORNL converter-modulator installations and has provided key input the design and fabrication process.