FIRST RESULTS OF THE LOS ALAMOS POLYPHASE BOOST CONVERTER-MODULATOR

W.A. Reass, J.D. Doss, R.F. Gribble, M.T. Lynch, D.E. Rees, and P.J. Tallerico [*]
Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico, 87544, USA

Abstract
This paper describes the first full-scale electrical test results of the Los Alamos polyphase boost converter-modulator being developed for the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The converter-modulator provides 140 kV, 1.2 ms, 60 Hz pulses to a 5 MW, 805 MHz klystron. The system, which has 1 MW average power, derives its +/- 1250 Volt DC buss link voltages from a standard 3-phase utility 13.8 kV to 2100 volt transformer. An SCR pre-regulator provides a soft-start function in addition to correction of line and load variations, from no-load to full-load. Energy storage is provided by low inductance self-clearing metallized hazy polypropylene traction capacitors. Each of the 3-phase H-bridge Insulated Gate Bipolar Transistor (IGBT) Pulse-Width Modulation (PWM) drivers are resonated with the amorphous nanocrystalline boost transformer and associated peaking circuits to provide zero-voltage-switching characteristics for the IGBT's. This design feature minimizes IGBT switching losses. By PWM of individual IGBT conduction angles, output pulse regulation with adaptive feedforward and feedback techniques is used to improve the klystron voltage pulse shape. In addition to the first operational results, this paper will discuss the relevant design techniques associated with the boost converter-modulator topology.

1. INTRODUCTION

The simplified bock diagram of the converter/modulator system is shown in Figure 1. This system minimizes costs with the utilization of many standard and proven industrial and utility components. The substation is a standard 3 phase 13.8 kV to 2100 V vacuum-cast core transformer with passive harmonic traps and input harmonic chokes. These components are located in an outdoor rated NEMA 3R enclosure that does not require secondary oil containment or related fire suppression equipment. The Los Alamos prototype is manufactured by *Dynapower Corporation* in Burlington, Vermont. The power transformer is followed by an SCR pre-regulator that accommodates incoming line voltage variations and other voltage changes resulting from transformer and trap impedances, from no-load to full-load. The SCR pre-regulator also provides the soft-start function. The SCR regulator provides a nominal +/- 1250 Volt output to the energy storage capacitor banks. The SCR pre-regulator utilized in the Los Alamos prototype is manufactured by *NWL* in Bordentown, New Jersey. The energy storage capacitors are self-clearing metallized hazy polypropylene traction motor capacitors. As in traction application, these capacitors are hard bussed in parallel. These capacitors do not fail short, but fuse or "clear" any internal anomaly. At our capacitor voltage rating (1.5 kV) there has not been a recorded internal capacitor buss failure. In this application, as in traction motor applications, the capacitor lifetime is calculated to be 1e9 hours, before de-rating factors are included. A special low inductance design for these capacitors has been developed by *Thomson Components* in Saint-Apollinaire, France. The Insulated Gate Bipolar Transistors (IGBT's) are configured into three "H" bridge circuits to generate a three phase 20 kHz square wave voltage drive waveform applied to the transformer primaries. The IGBT's are "chirped" the appropriate

Work supported by the U.S. Department of Energy

duration to generate the high voltage klystron pulse, typically 1.2 ms. Due to the IGBT switching power levels, currents, and frequencies involved, low inductance busswork and bypassing is of paramount importance. The IGBT's are 3300 volt, 1200 amp devices (*FZ1200R33KL2)* manufactured by *EUPEC* of Hanau, Germany. The boost transformers utilize amorphous nanocrystalline material that has very low loss at the applied frequency and flux swing. Operating at 20 kHz and about 1.6 Tesla bi-directional, the core loss is about 1.2 watts per pound in our application, or 320 W per core. Each of the "C" cores (one for each phase) weigh 260 lbs. and has a 3.5" by 5" post. The nanocrystalline material is manufactured by *AMET,* located in Asah, Russia. By appropriately spacing the secondary from the primary, the transformer leakage inductance can be resonated with secondary shunt peaking capacitors to maximize voltage output and tune the IGBT switch current to provide "zero-voltage-switching" with IGBT turn-on. The zero-voltage-switching occurs when the IGBT gate drive is positive, but reverse transformer primary circulating current is being carried by the IGBT internal freewheel diode. We have tuned for about 4 μs of freewheel current before the IGBT conducts in the normal quadrant. This tuning provides for about 15% control range (4/25 μs) for IGBT pulse width modulation (PWM). Further transformer design optimizations can change IGBT commutation (turn-off) current for control range and coupling coefficient for IGBT peak current. As transformer design characteristics interact with other circuit parameters, optimization may be performed for various klystron loads and voltages. IGBT PWM of the active klystron voltage pulse enables us to use adaptive feedback and feedforward techniques with digital signal processors (DSP's) to regulate and provide "flat" klystron voltage pulses, irrespective of capacitor bank "start" voltage and related droop. The DSP adaptive feedback/feedforward processor used in the Los Alamos prototype was manufactured by *Z-TEC Inc.*, of Albuquerque, New Mexico. Line synchronization is not absolutely required as the adaptive DSP can read bank voltage parameters at the start of each pulse and calculate expected droop. The output high-voltage rectification circuit is a standard six-pulse rectification circuit with a "pi-R" type filter network. The diodes are high-voltage fast recovery ion-implanted types, manufactured by *IXYS*, which are series connected with the appropriate compensation networks. The diodes have the second highest total power loss (after the IGBT's) and are forced oil cooled. The filter network must attenuate the 120 kHz switching ripple and have a minimal stored energy. The stored energy is wasted energy that must be dissipated by the klystron at the end of each pulse. With the parameters we have chosen, the ripple is very low (~300 volts) and the klystron fault energy (in an arc-down) is about 10 joules. Even if the IGBT's are not turned off, the transformer resonance is out of tune in a fault condition, and little difference in klystron fault energy will result. If the IGBT's fail short, through the transformer primary winding, the boost transformer will saturate in about 30 uS, also limiting any destructive faults to the klystron. In a faulted condition, the klystron peak fault current is about twice nominal, with low dI/dT's.

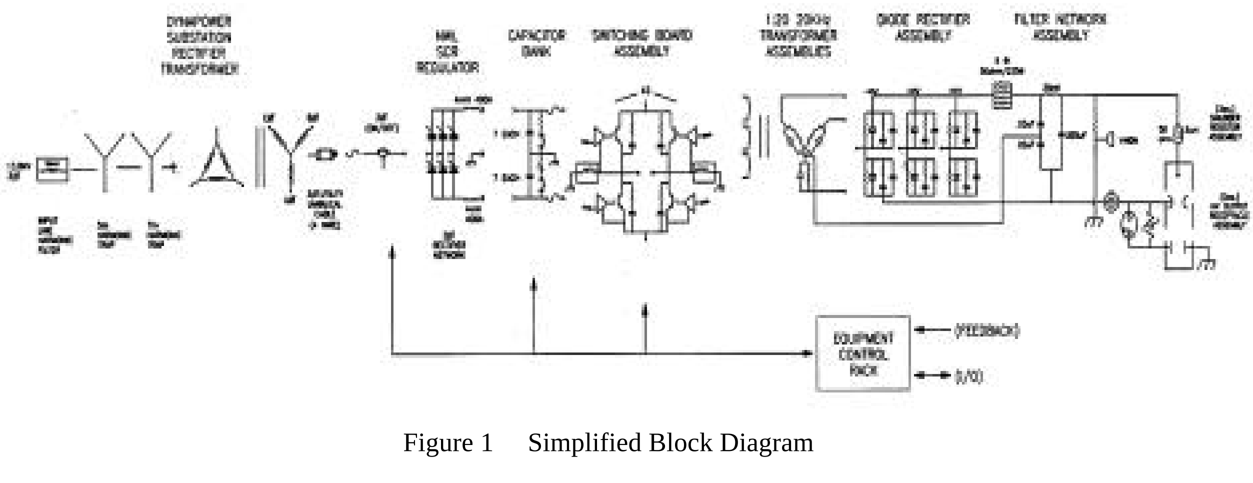


Figure 1 Simplified Block Diagram

2. MODELING

The complete electrical system of the converter/modulator system has been modeled in extreme detail. This includes design studies of the utility characteristics, transformer and rectification methodology (e.g. 6 pulse vs. 12 pulse), IGBT switching losses, boost transformer parameters, failure modes, fault analysis, and system efficiencies. Various codes such as SCEPTRE, MicrocapIV, Flux2D, and Flux3D have been used to perform these tasks. SCEPTRE has been primarily used to examine IGBT and boost transformer performance in great detail to understand design parameters such as switching losses, IGBT commutation dI/dT, buss inductance, buss transients, core flux, core flux offset, and transformer Eigen frequencies. Flux2D and Flux3D have been used to examine transformer coupling coefficients, leakage inductance, core internal and external flux lines, winding electric field potentials, and winding field stresses. The Flux2D and Flux3D were particularly useful to examine transformer secondary winding profiles that gave the desired coupling coefficients with minimized electrical field stresses. Micro-CapIV has been used to examine overall design performance of the system. This includes the utility grid parameters such as power factor, line harmonics, and flicker. We have optimized the design to accommodate the IEEE-519 and IEEE-141 harmonic content and flicker standards. Micro-CapIV uses simplified switch models for the IGBT's, which does not accurately predict their losses. However, the code has been very useful to examine tradeoffs of circuit performance with the lumped elements such as the boost transformer, shunt peaking capacitance, the filter networks, and the input energy stores. Micro-CapIV is also adept at making parametric scans to determine component sensitivities and tolerances. Comparisons between the SCEPTRE and MicrocapIV codes show no significant differences in the system operational performance such as switching currents, switching voltages, and output voltage.

3. FIRST RESULTS

The converter-modulator made its first high voltage pulse on January 17, 2001. After 10 days of testing and replacement of defective dummy load components, full pulse output voltage (140 kV), pulse width (~1.2 ms), and peak power (11 MW) were obtained. As shown in Figure 2, the 140 kV risetime is about 20 µs with about a 6% bank droop. The risetime compares favorably to other long-pulse modulator topologies. Additional high-voltage tests were made at 80 kV, as this voltage will be used in the SNS linac superconducting portion. The 80 kV operations are shown in Figure 3. 80 kV operations with the DSP adaptive feedback/feedforward processor is shown in Figure 4. The DSP processor removes all overshoot and bank voltage droop.

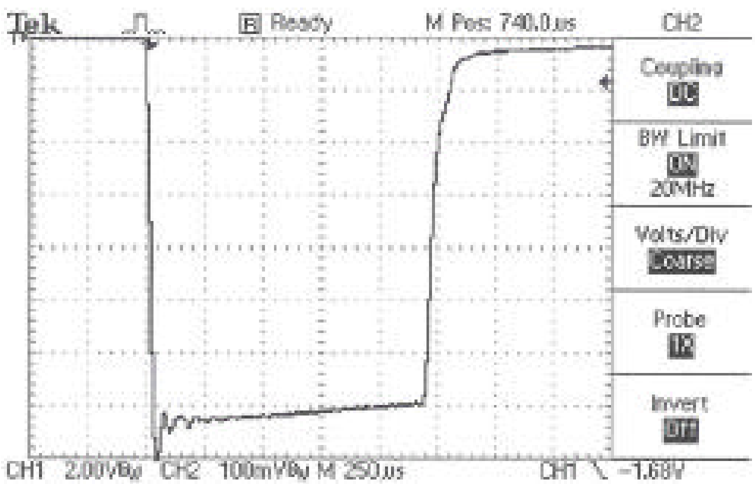


Figure 2 140 kV Output Pulse, 20 kV/Division

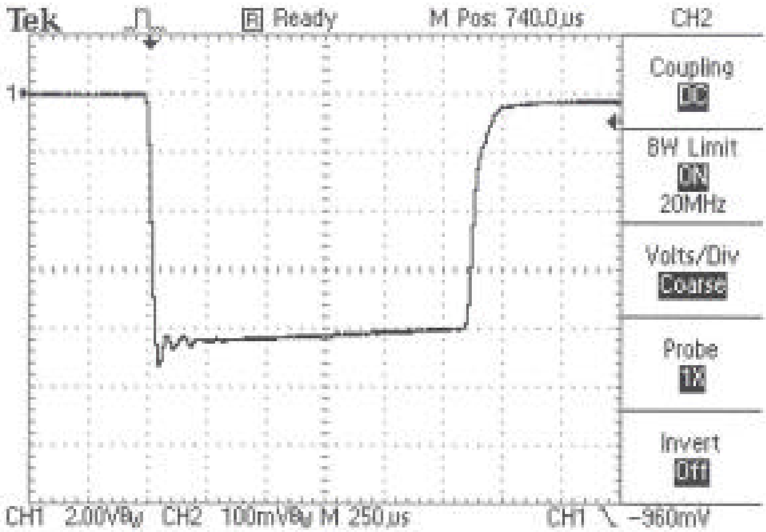


Figure 3 80 kV Output Pulse, 20 kV/Division

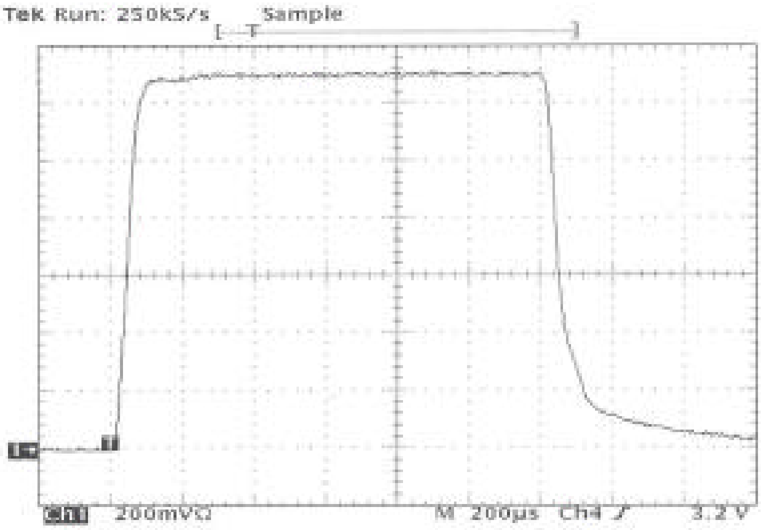


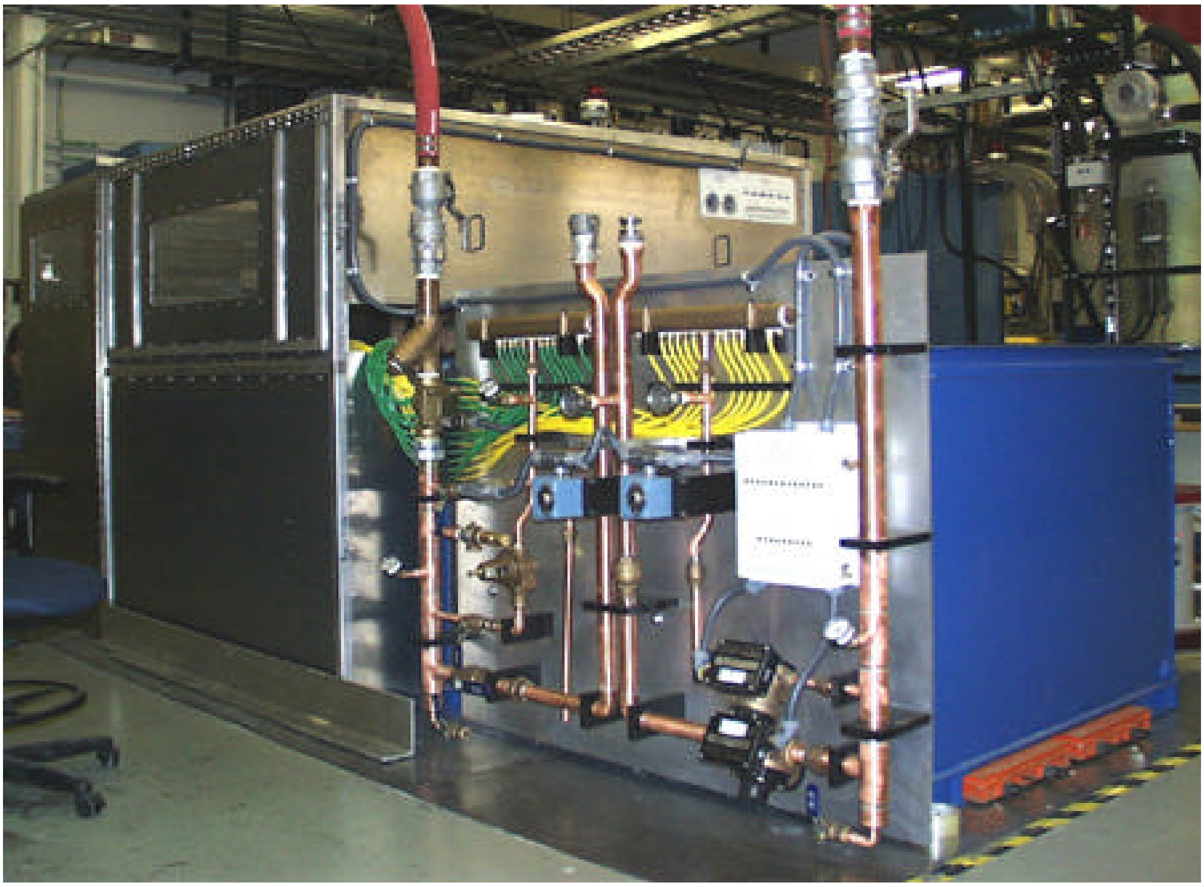
Figure 4 80 kV Output with Adaptive Feedback/Feedforward

2. PROJECT STATUS

The low average power testing of the first article has been completely successful. The substation construction work is nearing completion and it is anticipated that high average power testing will begin in May.

3. CONCLUSION

The converter/modulator has demonstrated several new design methodologies that are expected to revolutionize long-pulse klystron modulator design. These items include special low-inductance self-clearing capacitors, large amorphous nanocrystalline cut-core transformers, high-voltage and high-power polyphase quasi-resonant DC-DC conversion, and adaptive power supply control techniques. The first test results on the initial design were achieved in about a year after conception. Design economies are achieved by the use of industrial traction motor components (IGBT's and self-clearing capacitors) and standard utility cast-core power transformers. The compact and modular design, Figure 5, minimizes on-site construction and a simplified utility interconnection scheme further reduces installation costs. The design does not require capacitor rooms and related crowbars. By generating high-voltage only when needed, reliability and personnel safety is greatly enhanced. This approach provides design flexibility to operate klystrons of different voltages primarily by changing the boost transformer turns ratio. Other optimizations also permit "CW" operation of the polyphase boost converter topology. All testing of the full-scale system have been completely successful and all results agree with modeling efforts to date, which indicate the design methodologies will be imminently successful.



ACKNOWLEDGEMENTS

The authors would like to especially thank the talented contributions and efforts of David Baca, David Miera, Jeff Griego, Gabriel Roybal, Marvin Roybal, Sean Apgar, and Jacqueline Gonzales. Industrial consultations have been very fruitful with help and guidance from Jan Przybyla of *Marconi* in Chelmsford, England and George Schoefield of *Maxwell Systems Group* in San Diego, California.