A 50 kV SOLID STATE MULTIPULSE KICKER MODULATOR*

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Abstract

Performance requirements, design concepts, and test results for a prototype multipulse kicker modulator based on solid-state switches and a voltage-adding transformer topology are described. Tape-wound cores are stacked to form the transformer primary windings and a cylindrical pipe that passes through the circular inner diameters of the cores serves as the secondary winding of the step-up transformer. Boards containing MOSFET switches, trigger circuitry, and energy-storage capacitors plug into the core housings. A 50 kV prototype modulator that meets most of the facility requirements has been designed, fabricated, and tested at LLNL. More recent work has been concerned with designing and testing cores and boards with the full volt-second capability needed for 24-pulse operation. Results of the 50 kV prototype tests, preliminary tests of the full-volt-second cores and boards, and future development needs are described.

INTRODUCTION

In the Advanced Hydrotest Facility (AHF) proposed by Los Alamos National Laboratory, individual proton bunches will be extracted from a 50-GeV synchrotron by bunches will be extracted from a 50-GeV synchrotron by two 50-ohm parallel-plate transmission-line kickers that each produce an arbitrary time sequence of up to 24 kicks. In order to maximize the kick while minimizing the pulser voltage, the kickers are operated in a push-pull mode, a positive voltage pulse being applied one side and a negative pulse with equal magnitude to the other. The vertical plane between the two plates is a virtual ground when the pulses on the two sides are identical except for sign. Each side of the kicker separately represents a 50-ohm load and is separately terminated with a 50-ohm resistor. A kicker modulator capable of generating a string of approximately 25 pulses at arbitrary times within a total time of 100 microseconds or more is needed. Pulses with a 50 kV flattop of ±1% flatness and 75 ns duration, together with rise and fall times of 65 ns or shorter are required. Allowable after-pulse ringing and modulator output baseline changes are defined by the requirement that the circulating beam bunches remaining in the ring after a bunch pair has been kicked out not be disturbed; the maximum allowable baseline shift in AHF is 300 V, 300 ns after the trailing edge of the pulse, although less baseline shift would be desirable. The requirements cannot be met with the commonly used pulse-forming cables or networks (PFNs) switched with thyratrons. Accordingly, an ED&D program to build and test a solid-state modulator using a voltage-adding transformer was started at LLNL in the year 2001.

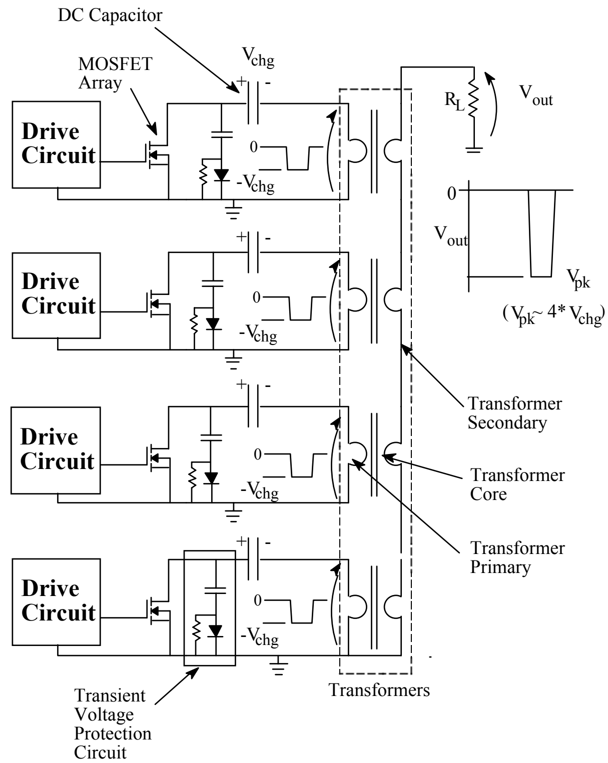

Fig. 1: Simplified circuit schematic for the voltage-adder concept.

THE VOLTAGE-ADDER CONCEPT

The present voltage-adder kicker modulator concept (see Fig. 1) is an outgrowth of solid-state pulsed-modulator development for induction accelerators at Livermore and is based on that of an existing 20 kV modulator built by the Lawrence Livermore National Laboratory for the DAHRT facility at LANL[1]. The voltage adder is basically a step-up transformer with many separately powered parallel single-turn primary windings and a series-connected secondary winding that couples to all of the cores. The transformer is formed from a stack of annular magnetic cores wound from Metglas or other high-permeability magnetic tape material. The output circuit is formed by a center cylinder that passes through the center of the core stack. Pulses of either positive or negative polarity are produced depending upon which end of the stack is grounded, a feature that is useful in powering push-pull kickers. Circuit boards with 12 parallel MOSFET switches plug into the spaces between the core housings. Energy for the pulses is stored in capacitors on the boards. Intrinsic switching times for the MOSFETS are approximately 15

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ns. Rise times for output pulse of the entire stack are considerably longer than 15 ns, due to a combination of various effects, including the MOSFET switching time, circuit inductances, and the finite length of the modulator. For a 50-kV pulser that is 10 feet tall, the two-way transit time of a TEM pulse from the top of the stack to the bottom and back to the top is approximately 20 ns. The actual 0-100% rise time for a 50-kV prototype pulser turned out to be approximately 40 ns, not including some overshoot at the front of the pulse. Each core provides approximately 700 V to the output pulse; for 50 kV output, cores are sized to provide the required volt-seconds for the output pulse train, which for AHF is 0.35 V-s for the entire stack. Additional circuits can be switched in to compensate for capacitor voltage droop in a long pulse train.

THE 50 KV PROTOTYPE MODULATOR

Fig. 2: Single-stack 50 kV modulator

A staged hardware development plan for the modulator was described in a paper given at the 2001 Particle Accelerator Conference [2]. The objective of the 2001 Stage 1 effort was a proof-of-principle demonstration of a 50 kV solid-state modulator that could meet most of the pulse requirements for the AHF extraction kicker except the full volt-seconds of the 24-pulse burst. To minimize cost and expedite the demonstration, the modulator used many parts designed to meet DARHT requirements. The modulator was fabricated and tested with a dummy 50-ohm load in 2001. The prototype kicker modulator consisted of 70 toroidal transformer modules with drive circuits. Initially, the cells were arranged in two columns with a crossover conductor connecting the center rods of the two stacks together. In initial tests of the prototype, a peak voltage of ~ 43kV into a 50Ω load was achieved. This was the maximum output voltage that could be achieved without over stressing the MOSFETs with regard to their drain-to-source voltage (the devices used have a maximum drain-source rating of 1000V and ~ 970 volts was measured during the turn-off of the devices). The voltage stress was due to the inductive voltage spike generated as a result of the very fast turn-off of the MOSFETs (< 10ns) and the subsequent dI/dt (~86kA/µs). The circuit boards were therefore modified to slow down the fall time of the gate drive pulse and the turn-off time of the power MOSFETs. After the making the above and other modifications to circuit boards, the modulator stack was rebuilt. In the rebuilding, changes were made to the output cable connections and the double-stack configuration was changed to a single-stack configuration to reduce impedance mismatch effects on the output pulse. The reconfigured modulator, shown in Fig. 2, is a structure approximately 10 feet tall. The reconfigured modulator was tested at 50 kV into a 50-ohm load at a 5 MHz burst frequency. A five-pulse burst is shown in Fig. 3.

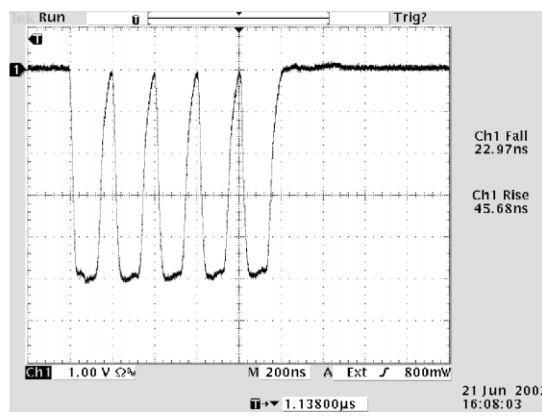

Fig. 3: 50 kV five-pulse burst from the prototype modulator

The ripple/droop over the entire flattop of the pulse of Fig. 3 is ~ ±1.2%. The pulse rise time is well within AHF requirements (measured at ~23ns at 10%-90%) and the pulse fall time is close to the maximum allowed (~46ns at 10-90% but closer to 70ns at 0%-100%). The pulse fall time was observed to increase substantially (from ~20ns to ~ 50ns) as the output voltage increased from 40kV to 50 kV. Measurements indicated that some of the MOSFETs were turning back on during turn-off due to energy coupled through the Miller capacitance into the gate drive circuit. Discussions with the MOSFET vendor indicated that newer devices are now available that have a smaller Miller capacitance. Slight changes to the gate drive circuit would also reduce the susceptibility to turn-on. Eliminating device turn-on by either of these options could reduce the output pulse fall time to the range of 20-30ns and easily exceed AHF pulse requirements. The inter-pulse voltage drops to less than 250 volts within approximately 300ns and meets requirements. Most of the voltage that appears on the output after the main pulse is due to the transformer magnetization current, which increases with each pulse of the burst and reaches maximum value after the last pulse of the burst. The voltage that is generated in the primary circuit by the magnetization current decay is coupled into the secondary circuit and appears as a voltage (opposite polarity to main pulses) on the output. The duration of the voltage is determined by the L/R time-constant where L is the transformer's primary inductance and R is the resistance in the path of the magnetization current. Another contributor to the intra-pulse voltage is the very slight impedance mismatch between the adder stalk and the cable. The prototype modulator has demonstrated the capability of meeting most of the AHF pulse parameters. Two parameters that cannot be met due to hardware limitations are the full 24-pulse burst and voltage droop over the entire burst. The transformer therefore needed to be redesigned to have more volt-seconds to satisfy the burst requirement and the drive boards redesigned to have a much larger storage capacitance to satisfy the droop requirement.

DEVELOPMENT OF IMPROVED CORES AND DRIVE BOARDS

As the number of pulses in a burst increases, it becomes more difficult to meet the intra-pulse voltage requirement because magnetization current increases with each pulse of the burst. Therefore, in addition to increasing pulse number and quality, one of the goals of the drive board design and transformer design is to better dampen the magnetization current and/or reduce the magnetization current.

Core Development for the 24-pulse modulator

The objective of the core development effort of 2002 was to increase the magnetic core cross-sectional area to handle 24-pulse burst requirement and to reduce the magnetization current. The baseline design approach was to use for the core material Metglas™ SA1. With a mean pulse width of 150ns, 24 pulses in the burst, and a charge voltage of 750 volts, each core must provide a minimum of 2.70×10^{-3} V-s. Empirical data indicate that the useable ΔB for SA1 is ~ 1.46 T. Adding a 20 % safety factor gives a minimum core area of 4 in^2. However, As the magnetic core is not the major cost driver (~25% of total modulator costs), there is little incentive to minimize the core volume other than to keep the modulator reasonable in size. On the other hand, there is a strong motivation to have more core volume than required; the transformer should never saturate under any reasonable/normal operating condition and any extra core material serves to reduce the peak magnetization current. Metglas™ SA1, and annealed nanocrystalline and transverse annealed nanocrystalline cores of the same geometry as the new SA1 cores were procured and tested. The measurements showed that due to its higher permeability, the nanocrystalline material has substantially lower magnetization current (~40% of SA1 for the same core geometry), but has approximately 70% of the available volt-seconds. In view of these results, some type of nanocrystalline core is the preferred approach for future work.

Improved Drive Board Design

The most efficient approach to meeting the full AHF V-s requirement is to incorporate as much capacitance as possible on a board layout that is reasonable in size and cost and to incorporate extra adder cells into the final pulser design. Using boards with a new high energy-density 12 μF capacitor, the load voltage will have drooped 1% (500 volts) by the 13th pulse. To compensate for this droop, additional adder cells charged to can be brought on line at various times through the pulse train. A new drive board incorporating the new capacitors, improved MOSFETS, and some other improvements was designed and successfully tested together with the new cores in a four-cell stack. Based on these results, a modulator with four extra compensation drive circuits/cells is expected to meet the AHF requirements.

SUMMARY AND PLANS FOR FUTURE DEVELOPMENT

A 50 KV, 1000 A pulsed kicker modulator meeting the objectives of Stages 1 and 2 the original development plan [2] has been designed and successfully tested. At present, due to lack of funding, execution of Stage3 (a full-scale modulator capable of producing the entire pulse train for AHF) has been postponed indefinitely. Nevertheless, a highly promising new modulator technology has been demonstrated. It is likely that the demonstrated voltage-adder approach will find use in accelerator technology and will eventually displace PFNs switched by gas-filled thyratron tubes in many applications.

REFERENCES

[1] J. A. Watson et al., “A Solid-State Modulator for High-Speed Kickers”, Proc. PAC 2001, Chicago, IL, p. 3738.

[2] P. L. Walstrom and E. G. Cook, “Extraction Kickers and Modulators for the Advanced Hydrotest Facility”, Proc. PAC 2001, Chicago, IL, p. 3735.