Synchronization of Multiple Magnetically Switched Modules to Power Linear Induction Adder Accelerators

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JUL 02 1996

Abstract

In applications where multiple magnetic modulators are used to drive a single Linear Induction Voltage Adder (LIVA) or Linear Accelerator (LINAC), it is essential that the outputs of the modulators be synchronized. Output rise times are typically in the 10ns to 20ns range, often making it necessary to synchronize to within less than 1ns. Microprocessor and electronic feedback schemes have been developed and demonstrated¹⁻⁶ that achieve the required level of synchronization, however, they are sophisticated and potentially complex. In a quest for simplicity, this work seeks to determine the achievable level of modulator to modulator timing jitter that can be obtained with simple design practices and passive techniques. Sources of output pulse time jitter in magnetic modulators are reviewed and some basic modulator design principles that can be used to minimize the intrinsic time jitter between modulators are discussed. A novel technique for passive synchronization is presented.

Introduction

A number of industrial applications requiring continuously operating pulse powered X-ray and electron beam generators necessitate power levels approaching 1MW. Food irradiation to eliminate pathogens, waste water treatment applications, and hazardous waste treatment require accelerating potentials in the 5 MV to 10 MV range to maximize efficiency and treatment depth as well as high power levels to provide high throughput. Linear induction voltage addition allows the output voltage to be increased by simply adding more stages; however, the power required for this increased voltage necessitates multiple, parallel pulse forming and modular networks. The Repetitive High Energy Pulsed Power (RHEPP) program yielded a 2 MV accelerator with an average output power of 300 kW from a single magnetic compressor and pulse forming line. Using the RHEPP technology to produce 5 MV would require 700kW, and 10 MV for 1.4 MW. Impedance constraints prohibit achieving these power levels from a single module. In order to combine the outputs of multiple pulsed power modules using a linear induction voltage adder or induction Linac, it is necessary to synchronize the outputs to within a fraction of the output rise time.

This work was supported by the United States Department of Energy under contract DE-AC04-94ACAC85000.

Dos Lineas Modulator Pair

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A pair of identical magnetic modulators were built and christened "Dos Lineas" at Sandia to test simple jitter control techniques. Each modulator was designed to run continuously at 100 Hz, with 25 kW input power and 77% efficiency to the load. A two stage SCR prime switch powers a 10:140 pulse transformer that drives a two stage magnetic compressor, Fig. 1. The output voltage pulse is a $\frac{1}{2}V_0[1-\cos(\pi t/\tau)]$ charging waveform on a 24.5 nFd capacitor, with a charge time of 1 μ s.

Fig. 1. Circuit for each half of the Dos Lineas magnetic modulator pair. The two modulators are respectively designated "A" and "B".

To minimize the number of magnetic stages required, the second SCR was designed to discharge as quickly as possible (40 μ s), subject to the di/dt limits of the device. The switches are equipped with cooling manifolds and channels, Fig. 2, but we began taking data before the plumbing was completed. Without coolant flow, synchronization experiments were conducted using 1 sec, 100 Hz bursts. All the data include the effects of a 20% voltage droop on the first capacitor during the start-up transient.

Reasonable Design Techniques

The two-stage prime switch topology has been employed by others to drive magnetic modulators using thyatrons^{2,3,4,7}. This circuit helps reduce timing variations in the magnetic modulator section. The pair of switches form a "charge lock" that allows the first switch to recover before the second switch is triggered. Resistor-like magnetic switch losses and the resistive losses in the water insulated PFL produce reflections in a typical magnetic modulator that preserve the forward direction of the current in the original pulse. At the time of the reflection, the magnetic switches have just switched in the forward direction, so reflections return

Fig. 2. Typical Dos Lineas magnetic switch (MS2). Large outside windings are the coupling windings, main windings are barely visible inside the cooling manifold.

very quickly to the beginning of the modulator with no switch delays. The second primary switch is not allowed to commute before the reflected energy arrives at the intermediate storage capacitor, C1, so the reflected charge is trapped on the negative side of C1. This charge is transferred to the positive side of C1 when the first switch closes during the next shot, but it is then at a higher potential, so the reflected energy is recovered along with additional energy that is extracted from the reservoir capacitor, C0. Trapping the reflections between the *non-magnetic* primary switches prevents them from stagnating on any of the *magnetic* switches and causing timing variations.

Sources of Timing Jitter in Magnetic Modulators

Significant work has been done by others¹⁻⁶, investigating the types and sources of jitter in magnetic modulators. Timing variations between the trigger and the output of a modulator, or between the outputs of two or more modulators can be classified as *slow and monotonic* or *fast and usually random*. Slow timing variations due to temperature rise or main power supply drift, are easily corrected by slow charge voltage or trigger timing adjustments. Fast, random jitter in the prime switch can be reduced to well below $1\sigma = 1\text{ ns}$ by

proper choice of the switch and its operating parameters (thyratrons and SCRs can achieve this). Fast, random jitter due to ripple on the magnetic switch biases can be held to acceptable levels by using reasonable bias current filtering (usually in the form of a bias isolation inductor) and by providing sufficient bias to drive the cores well into saturation, where the available ΔB is less sensitive to current variations. The toughest magnetic switch jitter mechanism to deal with is fast, random voltage variations on the switch terminals, caused by reflections. Voltage variations influence magnetic switch timing through the volt-second product and through the change in operating point on the B-H curve at saturation, which changes the discharge inductance. Effects of reflections, and power supply transients and ripple can be handled with electronic feedback circuitry controlling a first primary switch, that can be commutated when C1 has reached a specific voltage²⁻⁴. This scheme can be implemented on the Dos Lineas modulators by replacing the first SCR with a GTO or an IGBT. The approach hinges on a circuit topology that captures all of the voltage variations due to reflections and power supply ripple in one location, C1, away from the magnetic switches, that can be monitored and controlled just before a shot. Where sub-nanosecond output timing stability is required, practical limitations on voltage regulation necessitates additional electronics to control the trigger delay.

Results of Dos Lineas Experiments

The trigger-to-output timing variations on the Dos Lineas modulators were measured by comparing the load voltage to a fiducial ramp that was generated by delaying and integrating the square trigger pulse. The comparison used an algorithm that time shifted one of the waveforms so as to minimize the mean squared difference between the output waveform and fiducial ramp. Steady state was reached for shots 70-99, where the 1σ jitter was calculated, Table 1.

Table 1. Steady-State timing jitter for shots 70 through 99 for various cases (Error bars are $\pm 0.5\text{ ns}$).

Case	(Load)	Range of 1σ Std. [ns]
Machine A vs Fidu	(200 Ω)	2.1 to 2.5
Machine A vs B	(200 Ω)	1.9 to 2.3
Machine A vs B	(200 Ω , 24.5 nFd)	0.7 to 1.0
Machine A vs B	(200 Ω , 24.5 nFd)	≈ 0.1
with Magnetic Coupling		(All Tests)

Relative timing variations between the outputs of the two machines were measured by comparing the A and B output current pulses using the same algorithm. Although it is impossible to say with $\pm 0.5\text{ ns}$ error bars, the slightly smaller 1σ jitter between machine A and B (Load: 200 Ω) compared to that between the fiducial and machine A, may indicate that voltage ripple effects

on the *common* reservoir capacitor, C0, tend to cancel when the outputs are compared to one another. A better matched load (200Ω, 24.5 nFd) reduced the reflections and yielded even lower output jitter. In any case, the 1σ steady state time jitter seems to be remarkably small for a pair of modulators that have no jitter compensation circuits and are running from an unregulated power supply. This performance is attributed to ample, well filtered magnetic switch biases and the reflection trapping primary switch topology. The only likely source of time variation in the outputs of the machines is voltage variations on C1. These voltage variations are due to a combination of power supply ripple, start-up transients and the captured load reflection. The voltage was measured on C1 just before the second SCR switched and then converted to the output time change that it would cause using,

$$\Delta t_{out} = \Delta V_{C1} \sum_n \frac{-[t_{sw} - (\tau/\pi) \sin(\pi t_{sw}/\tau)]_n}{V_{C1} [1 - \cos(\pi t_{sw}/\tau)]_n}$$

n = compression stage index

τ = time to peak

t_{sw} = time to switch

Δt_{out} = output time shift

V_{C1} = voltage on C1

ΔV_{C1} = change in V_{C1} causing output time shift.

yielding a scale factor of Δt_{out}/ΔV_{C1}=2.6 ns/volt. The time jitter calculated from the voltage ripple on C1 from two different burst runs was 1σ = 1.6ns & 2.0ns compared to the measured time jitter of 1σ = 2.1ns & 2.1ns. Furthermore, the decay time constant of 2.6×V_{C1} matched the time constant of the output delay exactly. This indicates that to within our ability to measure, the output time variations are due to voltage variations on C1. If there are other jitter components such as trigger jitter in the SCRs, they are very small.

A typical plot of the timing variation between the output of one of the modulators and the fiducial is shown in Fig. 3. The initial advancement in the output

Fig. 3. Output timing variation on machine A relative to the fiducial. Inset is detail of shots 70 to 100.

time corresponds to an increase in the charge voltage on C1 at the onset of repetitive operation, due to energy recovery. The voltage on C1 increases most between the first and second shots and then continues to increase more slowly as the higher input charge causes a proportionate increase in the reflection. The voltage and hence the output timing advance falls off as the voltage drop in the wires between C0 and the charging power supply begin to dominate.

Fig. 4. The Magnetic Coupling Technique

Synchronization by Magnetic Coupling

A simple, passive, maintenance free technique for synchronizing independent magnetic switches and modulators has been developed. Two similar magnetic switches can be made to switch together by applying *equal* windings to both and then interconnecting them symmetrically, Fig. 4. No current flows in the coupling winding if the switches charge together and switch together. If one switch starts to charge before the other, the transformer action of the coupling winding causes the other switch to begin to charge as well. This tends to equalize the charge voltage on corresponding stages of both modulators. If then for any reason at all one switches before the other, the coupling winding acts as a shorted secondary on the slow switch and forces it into a low inductance or switched state. Ten-turn coupling windings were installed between machines A and B on corresponding switches of both magnetic compression stages. The output timing offset between the Dos Lineas modulators is compared *with* and *without* magnetic coupling in Fig. 5. The start-up timing transient *without* magnetic coupling is mainly due to the voltage transient on C0 varying the output timing via the constant volt-second product. There is a small residual start-up transient *with* magnetic coupling that is believed to be caused by modulation of the saturated inductance's in the output switches due to the variation in the operating point. The varying inductance's change the widths of the output current pulses that we are comparing resulting in the timing offset. Since minimizing the RMS difference yields the time shift that *centers* the current pulses on each other, a relative width change on pulses that are forced to start at the same time by the magnetic coupling, causes an apparent time shift to result from our algorithm.

Fig. 5. Effect of magnetic coupling on transient and on random jitter between Dos Lineas outputs. Inset shows expanded view of shots 50-100. (Uncoupled data was shifted up in inset)

In addition to comparing transients and jitter with and without coupling, two additional tests were conducted to evaluate magnetic coupling effectiveness. *First*, trigger offsets were introduced between the two machines of $\pm 1\mu\text{s}$ and *second* a 6.5% difference in charge voltage was introduced at the inputs of the two machines. As indicated in Table 1, in all of these tests the measured time shifts between the outputs *with coupling* were identical to the baseline results, *with coupling*, in Fig. 5.

With magnetic coupling, we found that in all of our tests the timing on the A output is locked to 70 ns before the B output. This fixed time shift is due to the round-trip propagation delay in the coupling circuit. This was determined by calculations for a helical transmission line with the ground housing far from the helical winding, yielding an approximate round-trip delay of 62 ns for the coupling winding⁸. The saturated inductance of the *first* magnetic switch on the A side is slightly less than that on the B side. Since these switches are coupled, they switch together and the A side always reaches the volt-second product of the A output switch first. Thus, regardless of whether machine A is triggered before or after B, the A output always leads the B output by the fixed geometrical delay in the coupling winding between the output switches -- give or take the apparent delay caused by modulation of the saturated inductance's in the output switches. On different days, our operating point varied enough to make this time shift between machine A and B vary by a total spread of 3.5 ns across all of our data.

When there is an imbalance between the two machines, the first stage to be affected by the imbalance transmits a small current (15 A in the first coupling network for a $1\mu\text{s}$ trigger offset) through the coupling network to the next down stream stage. If the next stage is magnetically coupled this current has *no effect* and it is shunted through that stages coupling network, and so on. To test the effect on the timing of

an uncoupled switch being driven by the modulator, we uncoupled the second magnetic switch pair (its hold-off time is $6.7\mu\text{s}$), leaving the first pair coupled and introduced a trigger offset between the machines that ranged from -100ns to 100ns. In response to the foot, the timing variation at the output of the uncoupled switch ranged from -4ns to 4ns. This timing represents 0.06% of the hold-off time of the uncoupled switch, to which it is proportional. In an actual application, the first switch that might be difficult to couple would be a closed geometry switch with a hold-off time of about $1\mu\text{s}$. Thus, the $\pm 100\text{ ns}$ trigger offset would result in $\pm 0.6\text{ ns}$ output timing variation. PSPICE simulations indicate that this offset can be greatly reduced by increasing the bias on the uncoupled switch to compensate for the volt-seconds applied by the foot.

Conclusions

The Dos Lineas modulator pair has been used to demonstrate that it is possible to build a pair of magnetic modulators that have less than $1\sigma = 1\text{ ns}$ steady-state timing jitter between their outputs, with no special jitter compensation provisions. Attainable jitter is a function of the load. If start-up transients are an issue, they can be compensated using voltage regulation as shown by others or magnetic coupling. Magnetic coupling shows promise as a simple maintenance-free way to control *all types* of machine-to-machine jitter in magnetic switches and modulators.

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