CIRCUIT MODELING AND COMPONENT TRIMMING TO ACHIEVE PERFORMANCE REQUIREMENTS FOR THE DARHT PROTOTYPE INJECTOR

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Abstract

To produce an acceptable electron beam, the Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility accelerators require high-voltage pulses that are flat to within ±1% for 65±5 ns. Achieving this accuracy and pulse duration in operation on the Integrated Test Stand (a full-scale prototype of the DARHT 4-Mev injector and first eight linear induction accelerator cells) has required fine-tuning selected components in the injector pulsed power circuits. Several circuit analysis codes are used to analyze circuit performance and to predict the effects of component changes. Four cases are presented. (1) The center conductor of an ethylene glycol transmission line was tapered to compensate for a 4-5% tilt of the flat-top portion of the injector voltage waveform. (2) The mixture of water-glycol solution used in the Blumlein "peaking" section was changed to compensate for a 2% hump in the flat-top portion of the voltage waveform. (3) Confirmation was provided that observed changes in pulse shape could be caused by changes in dielectric constant of the ethylene glycol used in the Blumlein, caused by hygroscopic absorption of water vapor. (4) A damping resistor was added in series with the Blumlein center conductor to reduce the amplitude of low-frequency, post-pulse oscillations that were causing late-time flash-overs of the vacuum insulator.

Introduction

The Dual-Axis Radiographic HydroTest (DARHT) facility at Los Alamos will use two 16- to 20-Mev electron beam accelerators to produce high-resolution flash radiographs of hydrodynamic experiments. Each accelerator will use a 4-Mev injector and a series of 250 kV linear induction cells to produce a 3 kA electron beam lasting 60 ns. An Integrated Test Stand (ITS) has been constructed to test the first injector and eight induction cells. It has been in operation since January 1991, and has successfully achieved six milestones to demonstrate system performance prior to final construction approval.

To generate a high quality electron beam in the DARHT Facility imposes very high performance requirements on the pulsed power systems. For example, the injector circuits must produce a 4-MV pulse of 100 ns duration, with a risetime of 17 ns and a falltime of 20 ns. The flat-top portion of the pulse must be flat to ±1%, and have duration 65±5 ns. The overall system jitter must be less than 5 ns.

The vendor of the injector pulsed power system achieved these stringent specifications, verified by an acceptance test program conducted into a dummy load [1]. Since installation in the ITS at Los Alamos, the pulsed power system has operated with high reliability and repeatability [2]; however, it came as no surprise that it was necessary to trim the system to meet the required performance specifications, once the complete system was assembled. This paper describes several modifications made to the injector, and circuit simulations performed prior to the modifications to predict system performance. Two of the modifications involved trimming components to produce pulse shapes within the ±1% tolerance. Another investigation involved finding the reason for a mysterious change in the waveforms following an extended system shut-down. The fourth modification was to insert a damping resistor in the Blumlein changing circuit to reduce the amplitude of a late-time reversed voltage that was contributing to flashovers of the diode insulator.

Injector Circuit Models

Figure 1 is a diagram of the ITS injector. A 2.8 μF capacitor bank is charged to 112 kV and discharged through a 15:1 step-up transformer to pulse charge the 14 Ω ethylene glycol Blumlein

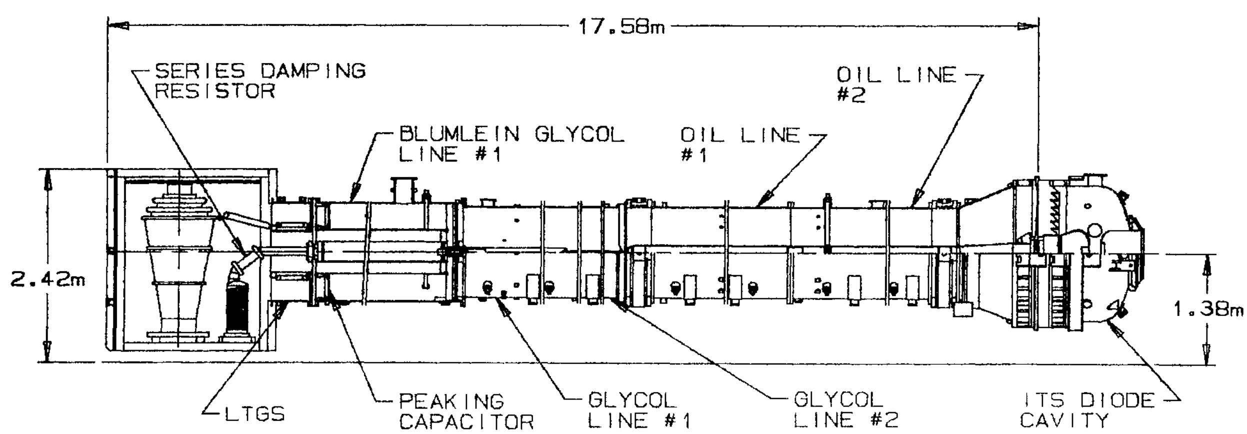

Figure 1. Overall ITS Layout, showing Blumlein and Transmission Lines.

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14. ABSTRACT
To produce an acceptable electron beam, the Dual-Axis Radiographic Hydrodynamic Test (DARHT) Facility accelerators require high-voltage pulses that are flat to within ±1% for 65±5 ns. Achieving this accuracy and pulse duration in operation on the Integrated Test stand (a fullscale prototype of the DARHT 4-Mev injector and first eight linear induction accelerator cells) has required fine-tuning selected components in the injector pulsed power circuits. Several circuit analysis codes are used to analyze circuit performance and to predict the effects of component changes. Four cases are presented. (1) The center conductor of an ethylene glycol transmission line was tapered to compensate for a 4-5% tilt of the flat-top portion of the injector voltage waveform. (2) The mixture of water-glycol solution used in the Blumlein "peaking" section was changed to compensate for a 2% hump in the flat-top portion of the voltage waveform. (3) Confirmation was provided that observed changes in pulse shape could be caused by changes in dielectric constant of the ethylene glycol used in the Blumlein, caused by hygroscopic absorption of water vapor. (4) A damping resistor was added in series with the Blumlein center conductor to reduce the amplitude of low-frequency, post-pulse oscillations that were causing late-time flashovers of the vacuum insulator.

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to 1.43-MV in 4.3 μs. The Blumlein discharges through four laser-triggered (SF_6) gas switches (LTGS) to produce a 1.8-MV output pulse. The voltage is transformed up as the pulse propagates through two glycol transmission lines (45 ns long, with impedance 23 Ω and 37 Ω) and an oil-filled transmission line (43 ns long and 75 Ω), to the diode. The diode has a radial liquid resistor of 174 Ω in parallel with the impedance of the A-K diode (about 1500 Ω) to produce a 150 Ω load. The voltage at the input to the second glycol line is 2.3-MV; at the input to the oil line, 3.0-MV; and at the diode, 4.0-MV.

Careful attention was given in the design to the component impedances, and to the effect each has on the pulse length and flatness. Detailed circuit models were developed which gave particular attention to transmission lines, as this is a component that is particularly difficult to model in most circuit codes. The principal circuit code used in the design phase was TLCODE [3], because of its particular efficacy in handling transmission lines.

Development of circuit models has continued during operation at Los Alamos. TLCODE is still used, but we also use MicroCap-III and -IV [4], which are commercially available SPICE-based programs with transmission line models. When results are compared from the two codes, they generally agree to within 1-2%.

A typical circuit model for the injector circuits contains over 50 components, including 12 transmission lines, and is too complex to reproduce here. We have gradually included more refinements in the model, but it is still difficult to reproduce details of the experimental waveforms to within 4%. We believe that some of this is due to effects, such as dispersion and multiple modes, that are difficult to model with circuit codes.

We are continuing to develop more refined models for the system and for components, including frequency-dependent models for transmission lines to account for skin-effect and dielectric dissipation, using MicroCap-IV. We have successfully modeled the skin-effect attenuation of small-signal cables; however, the model is still too cumbersome and slow when the circuit contains more than three transmission lines.

Despite the difficulty of the present models to reproduce the details of the waveforms to within ±1%, it is still possible to make useful predictions of proposed system changes. The following sections describe four simulations which were successful enough to produce the desired result.

Tapering of Center Conductors of Glycol Lines

In early 1991, the ITS facility was down for several months to repair damage done by a Blumlein breakdown and to make mechanical improvements to prevent a repeat occurrence. The shut-down was an opportunity to improve the waveshape of the voltage on the diode. It had been observed that the flat-top portion of the anode voltage had about 6% ramp from start to finish. This was producing too much spread in energy in the electron beam.

Several solutions were considered, but it was decided to taper the center conductors of the two glycol transmission lines, because this pulse shaping technique had been used before on a similar machine [4]. Rather than machining a linear taper onto the center conductors, we produced a one step reduction in diameter at the middle of each conductor. Numerous simulations were run to determine how to perform the taper.

In the configuration selected, the conductor of the first line, which had been 10.16 cm diameter and 556.3 cm long (45.5 ns), was stepped in the middle from 12.07 cm to 10.16 cm diameter, producing an impedance change from 22.3 Ω to 23.2 Ω. The conductor of the second line, which had been 2.54 cm diameter and 556.3 cm long, was stepped from 2.9 cm to 2.54 cm diameter, producing an impedance change from 35.3 Ω to 36.6 Ω.

This step-taper produced the desired change in waveform, but it was not as much as predicted. Simulations indicated no ramp in voltage; experimentally, it was measured to be 1.5%. In this case, the circuit simulations were very useful, allowing us to evaluate many possible ways to produce the taper, although the final accuracy was not as close as we would like.

Trimming of Peaker Section

The inductance of the LTGS's causes the leading edge of the output voltage pulse to be rounded. The possible need to compensate for this rounding was anticipated, and adjustment was provided in the design by making the first 10 cm of the outer Blumlein section a "peaking" section. This is a separate chamber that can contain a different solution from the 100% glycol used in the Blumlein. Filling this chamber with water produces the maximum "peaking" of the leading edge, thereby providing maximum compensation. The dielectric constant of the solution can be trimmed by mixing water and glycol to tailor the profile of the leading edge.

While the experiment was down for mechanical modifications, the length of the peaking section was increased from 10 cm to 20 cm. Later, when the experiment began operating, it was found that this change, together with other changes that had been made, produced a beam energy pulse (measured by spectrometer) rolling off too soon on the trailing edge of the pulse, such that the beam energy was within ±1% for only 50 ns. We decided to correct for this by changing the peaking solution, since this could be done without disassembling the system.

It was assumed that the dielectric constant of the solution varies linearly between the dielectric constant of glycol (38) and that of water (78) proportional to the percentage of water in the solution. From this assumption, the impedance and delay of the peaker section was calculated and simulations were run until the desired correction to the waveform was obtained.

The simulations indicated that a mixture of 80% water-20% glycol would have the desired effect of depressing the first half of the pulse by about -0.8% and boosting the final part by about +0.8%. When this was tried experimentally, it worked perfectly, adding welcome credibility both to the model and to the modeler.

Contamination of Glycol

Another instance of predicting circuit performance occurred inadvertently when it was observed that the voltage at the diode was 4% lower than before and that the pulse was arriving about 5 ns later. This could be caused by a 4% increase in source impedance. It was hypothesized that during a recent lengthy shut-down, when the glycol was pumped from the system into a holding tank where the surface was exposed to atmosphere, water vapor was absorbed by the glycol, producing a change in dielectric constant.

Several simulations were run to determine how large a change had to be made to impedances and delays of the Blumlein and two glycol transmission lines to produce such a change in pulse amplitude. We found that an 8% increase in dielectric constant would produce the changes observed. Under the assumption that dielectric constant varies linearly with the percentage of water in the mixture, this corresponds to 8% water in the glycol.

In this case, it was not necessary for the codes to be very accurate in order to confirm what had happened. It is remarkable that the injector system has been so stable and reproducible, even over long periods of time, that these small changes in the waveforms were very noticeable.

Damping of Late-time Positive Post-Pulse

When the diode was operated at higher voltages (above 3.5-MV), late-time breakdowns in the diode would often be seen by open shutter cameras and by photomultipliers. Traces of the anode voltage showed that the breakdowns were occurring at late times, typically 2-5-μs after the 100 ns main voltage pulse was over. At the time of the breakdowns, the voltage was positive, and there was a low-frequency oscillation occurring between the inductance of the system and the capacitance of the prime energy storage capacitor. The positive post-pulse was quite large, typically +1.0-MV for a -4.0-MV main pulse. (See Fig. 2.)

Most of the breakdowns appeared to be surface flashovers of the diode insulator, and the insulator was able to recover. The final breakdown, however, was inside the insulator and left a carbonized arc channel which forced a shut-down. Examination of the insulator revealed numerous dendrites which, from the direction of branching, appeared to be produced when the voltage on the diode was reversed.

Various ways to reduce the late-time oscillations were investigated. It was decided to try using a series damping resistor in the Blumlein charging circuit, between the center conductor of the Blumlein and the isolation inductor. Numerous simulations were run to determine where to place the resistor and the best value of resistance to use. A compromise was necessary because the resistor produced a positive pre-pulse on the diode during the 4.3 μs Blumlein pulse charge. Since the resonance is a series LC circuit, increasing the resistance produces increased damping. However, increased resistance produced an increased pre-pulse voltage. A limit of 150 kV was placed on this pre-pulse, to avoid breakdowns before the main pulse.

A value of 50 Ω was selected as the best compromise. The resistor reduced the oscillations to about 0.4-MV peak, and also reduced the time that the voltage was positive. (See Fig. 2.) The experimental changes were very close to the predicted changes.

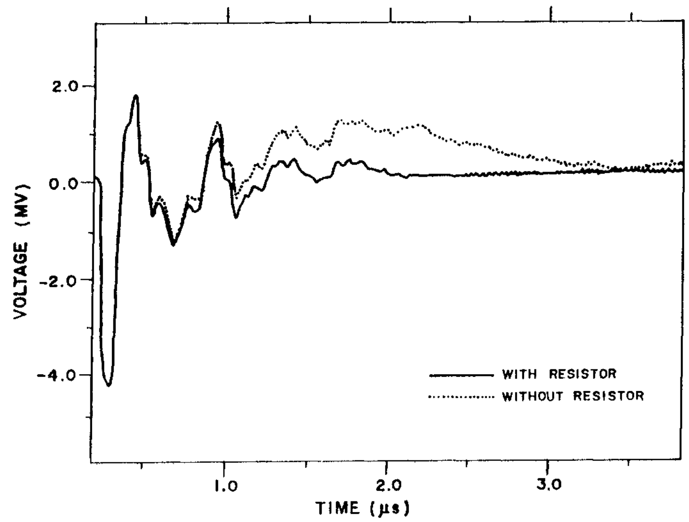

Figure 2. Injector Voltage, with and without Series Damping Resistor.

Summary

Several circuit codes have been used to model the performance of the ITS diode and its pulsed power drivers. Although the accuracy of the models used are not within the ±1% performance requirement placed on the ITS system, they have been valuable tools to allow the system to meet the ±1% requirement.

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