STACKED, PARALLEL-PLATE SOLID-DIELECTRIC BLUMLEIN LINES FOR COMPACT PULSED POWER

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Abstract

The stacked Blumlein line is a concept that has been touted as a highly compact pulsed power system because it combines the functions of energy storage, voltage scaling, and pulse shaping into a single sub-system. As a result, two single stage Blumlein lines have been fabricated and tested using a polymer-ceramic composite dielectric. Examination of the breakdown of the dielectric near the DC voltage specification led to the understanding of the degree of voltage reversal experienced by the lines. Voltage reversal is compounded in a stacked arrangement. The voltage reversal and transients induced by the switch jitter in a stacked configuration require significant derating of the dielectric strength. Consequently, the system must be operated much below the intrinsic dielectric energy density, compromising efforts to design a compact pulsed power system. This paper presents the conclusion that for derating below 0.72, as is likely necessary, a stacked Blumlein line will contain more dielectric than a comparable stacked transmission line.

I. INTRODUCTION

Design solutions for compact, repetitive pulsed power generators integrate a multitude of considerations including output current, output voltage, pulse length, pulse flatness, pulse rise-time and fall-time, average power, duty cycle, lifetime, consumables, environment, and of course the size and weight. Historically these considerations have driven designers to Marx banks, Marx-PFNs, or some variant of a stacked, or Marxed, pulse forming line (PFL). PFLs are attractive because of their intrinsic pulse shaping. Polymer-ceramic composites can be fabricated over large areas, and the dielectric constant of the composite material can be tuned to reduce the propagation speed in a transmission line to 4 cm/ns.[1] Consequently, polymer-ceramic composite dielectrics show promise for compact pulsed power systems based on solid dielectric transmission lines. The Blumlein arrangement is considered attractive for compact systems because, for fixed charge voltages, it requires half the switches of a stacked transmission line to erect the load voltage.[2,3] The stacked transmission line also requires additional inter-stage insulation. As a result of these considerations, AFRL has begun to investigate the use of Blumlein lines fabricated with ceramic loaded polymers (CLP) as a compact pulsed power driver.

This paper reports the progress to date in fabricating and testing single and two-stage Blumlein lines. The design considerations involved in pulse forming line systems are also examined with an expanded discussion[4] of the stresses experienced by the dielectric and the switches.

II. CERAMIC LOADED POLYMER BLUMLEIN LINES

Two single-stage and two two-stage Blumlein lines were fabricated using a ceramic loaded polymer (CLP) composite dielectric. The single stage lines have been tested, and the results of those tests are presented here.

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14. ABSTRACT

The stacked Blumlein line is a concept that has been touted as a highly compact pulsed power system because it combines the functions of energy storage, voltage scaling, and pulse shaping into a single sub-system. As a result, two single stage Blumlein lines have been fabricated and tested using a polymer-ceramic composite dielectric. Examination of the breakdown of the dielectric near the DC voltage specification led to the understanding of the degree of voltage reversal experienced by the lines. Voltage reversal is compounded in a stacked arrangement. The voltage reversal and transients induced by the switch jitter in a stacked configuration require significant derating of the dielectric strength. Consequently, the system must be operated much below the intrinsic dielectric energy density, compromising efforts to design a compact pulsed power system. This paper presents the conclusion that for derating below 0.72, as is likely necessary, a stacked Blumlein line will contain more dielectric than a comparable stacked transmission line.

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A. *Single-Stage Blumlein Line Tests*

The single stage Blumlein lines shown in Figure 1 were designed to drive a load of 6.9 Ω based on a dielectric constant of 50. Due to fabrication limitations, the lines were limited to approximately 1.02 m from the switch to the load, giving a two-way transit time of 48 ns. Variations in the loading fraction of ceramic during the casting process resulted in the two lines having dielectric constants of 32 and 52 for lines 1 and 2, respectively. The resultant as-fabricated line characteristics are listed in Table 1. Custom miniature railgap switches, shown in Figure 2 were designed and fabricated to commutate the lines. The switches used pressurized SF_6, Ar-SF_6 (85/15), or N_2 depending on the test. The primary reason for varying the gas was to adjust the resistive phase of switch operation.

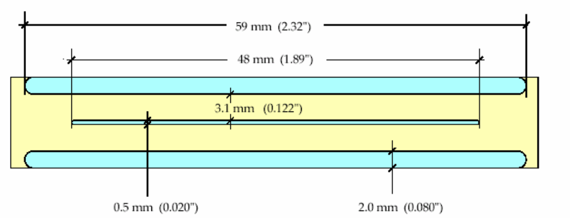

Figure 1. Schematic Cross-Section of a Single-Stage Blumlein Line

Table 1. Circuit Parameters for the Single-Stage Blumlein Lines as Fabricated

	Z_o (Ω)	τ_p (ns)
Line 1	8.6	38
Line 2	6.8	49

The lines were DC and pulse charged for various tests. The charge voltage was monitored using a 1000:1 high voltage probe. The switch was either allowed to self-break or command triggered using a 50 kV trigger supply to the mid-plane trigger. The pulse voltage near the load was measured using a custom 380:1 voltage probe. The pulse current was measured using a current viewing resistor (CVR) of approximately 5 mΩ.

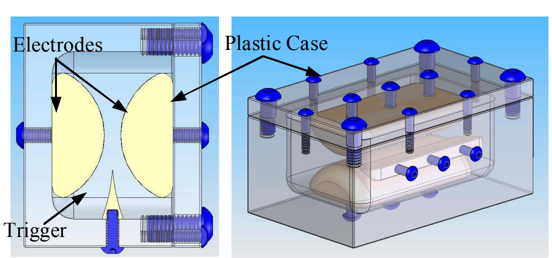

Figure 2. Side and Perspective Views of the Miniature Railgap Switch with Mid-Plane Trigger for Blumlein Line Testing.

B. *Single-Stage Blumlein Dielectric Breakdown*

Line 1 originally failed at a triple-point at the switch end of the line while being DC charged to -35 kV. The affected dielectric was removed, shortening the line, and additional dielectric was cast to mitigate the severity of the triple point. Subsequent testing of Line 1 focused on the use of pulse charging to alleviate some of the stress placed on the dielectric. The line ultimately failed at a charge voltage of -41 kV. The failure shown in Figure 3 occurred on the switch side of the line at the load end, as would be expected due to the voltage reversal at this location. Based on PSPICE circuit analysis, the peak-to-peak voltage during the last healthy shot was 58.8 kV. While the visual evidence indicates a crack, it was undetermined whether the crack contributed to or was a result of the dielectric breakdown.

Line 2 was also tested to the full extent of the pulse charging system before DC charging was implemented. Line 2 failed after eight successful shots at 50 kV charge. Based on the PSPICE circuit analysis, the peak-to-peak voltage during the 50 kV charge shots was 71 kV, in excess of the 62.5 kV acceptance specification.

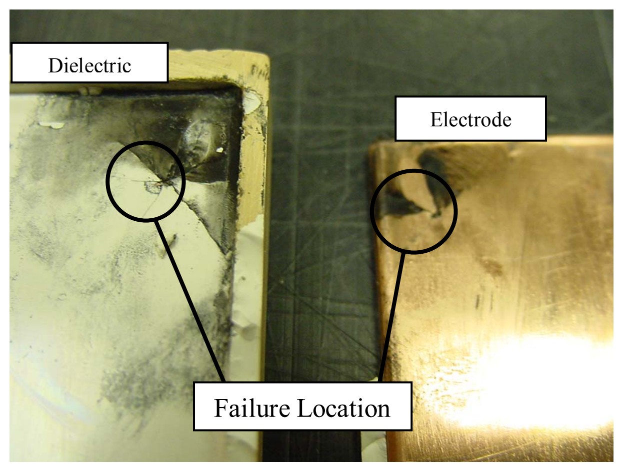

Figure 3. Photograph of the Dielectric Failure of Line 1 at the Load End. The Dielectric Failed After a Charge to -41 kV Which Applied a Peak-to-Peak Voltage of 58.8 kV at This Location.

III. Stacked Blumlein Line Operation

Figure 4 depicts a schematic of a four-stage Blumlein line. Depending on the dielectric and the length of the line, the relevant pulse lengths range from a few ns to a few hundred ns for compact systems. The center electrode of each stage is charged to V_{CH}, and each stage is commutated by a switch. Smith [5] provides a detailed description of Blumlein line operation into a matched load. Stacked Blumlein operation with ideal switches and a matched load delivers a square voltage flat-top with a magnitude equal to the number of stages times the charge voltage with a duration of 2τ. In reality, the switches will have jitter, inductance, a finite rate of commutation, and some residual resistance when closed. The load Z_0 is treated as purely resistive in this paper, but will generally contain inductive and capacitive components.

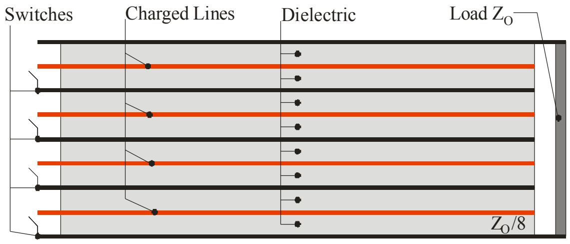

Figure 4. Schematic Illustration of a Four-Stage Vertically Stacked Blumlein.

Proper operation of a stacked Blumlein imposes several requirements[4] on the switch operation: 1) the triggering jitter between the switches should be minimal, 2) the inductance should be small compared to the stage inductance, 3) the resistive phase should be short compared to the pulse length, 4) the closed-state resistance should be small compared to the stage impedance, and 5) each switch must conduct at least twice the load current. The switch-to-switch jitter must be small compared to the pulse length to preserve the performance of the line. Additionally, the switch-to-switch jitter must be small compared to the time required to breakdown the dielectric at expected field stresses induced by the jitter. Inductance in the switch causes the output voltage to be rounded off, reducing the quality and duration of the flat-top. Both the resistive decay time and the closed-state resistance decrease the performance of the line by slowing the voltage rise across the load and consuming some of the stored energy. The effects of switch performance on Blumlein operation are elaborated below.

Switch jitter alters both the output voltage and the voltage stress on the dielectric in the line. Jitter results in temporally staggered wave fronts in the lines. Only when all of the waves have reached the load will the output voltage stack to the desired value of $n*V_{CH}$ where n is the number of stages. Consequently the duration of the voltage flat-top is reduced by twice the spread in the switch closure times. The switch jitter also leads to extreme voltage transients on the dielectric. Given that a goal of compact pulsed power design is to minimize insulation margins, switch jitter adversely impacts system size.

Figure 5 shows the normalized voltage within a four-stage stacked Blumlein. The voltage is normalized to the charge voltage, and the time is normalized to the one-way transit time for the line. The switch for each of the four lines has ideal behavior, but the closing times are staggered. The result is excessive transient voltage excursions in the lines. The line whose switch triggers last experiences the largest voltage extremes. As the waves initially approach the load end of the line, the last line to trigger experiences a voltage of

$$V_\tau = \left(1 + \frac{n-1}{2n}\right) V_{CH} \qquad (1)$$

Similarly, after the waves complete their roundtrip to the switch end of the line, the line whose switch triggered last experiences a voltage of

$$V_{3\tau} = -\left(\frac{1}{2} + \frac{3(n-1)}{2n}\right) V_{CH} \qquad (2)$$

The resulting upper and lower limits of voltage experienced by a stage are plotted in Figure 6. For purely resistive loads, reduction of the number of stages helps to minimize the margin of dielectric strength required, although the number of stages is usually determined by the desired output voltage and the available power supply. In the limit as the number of stages becomes large, the transients extend to +1.5 to -2 V_{CH}. Even if the switch jitter is tightly controlled, fault conditions will result in Blumlein lines experiencing large voltage transients, and designs should accommodate this feature.

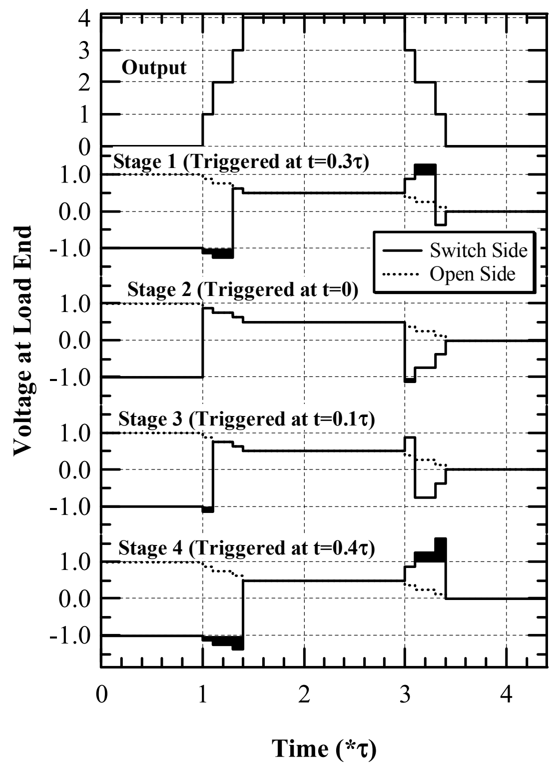

Figure 5. Four-Stage Stacked Blumlein Response with Specified Switch Jitter (Shaded Regions Indicate Voltage Excursions Beyond the Charge Voltage Magnitude)

IV. Marxed Transmission Line Operation

The Marxed transmission line operates very similarly to a conventional Marx bank where the capacitors have been replaced by transmission lines as shown in Figure 7. The eight-stage line drives the same load with the same current as the four-stage Blumlein line illustrated in Figure 4. Like a Marx bank, the transmission lines are charged in parallel, and discharged in series, providing the voltage multiplication. Like the Blumlein, the transmission line elements shape the voltage and current output. All of the switches must close to provide continuity, and like the Marx bank, once a couple of stages have been triggered, the subsequent stages and the output switch are driven to an over-voltage condition which closes them. Further, for a matched load, the transmission line elements are discharged without voltage reversal. Consequently switch jitter requirements are somewhat alleviated in the case of the Marxed transmission line, although fault conditions must still be taken into account. The stage-to-stage insulation can be optimized for dielectric strength alone to minimize volume.

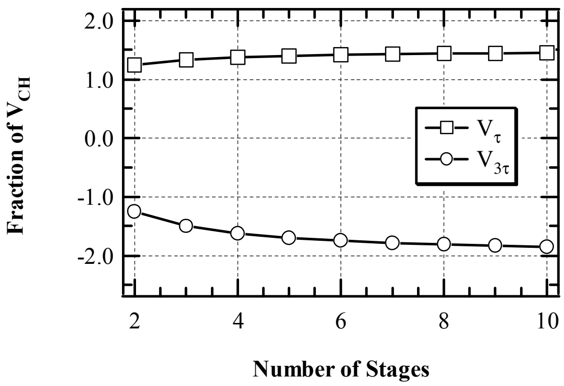

Figure 6. Maximum Voltages Experienced within the a Stacked Blumlein with Individually Commutated Switches as a Function of the Number of Stages

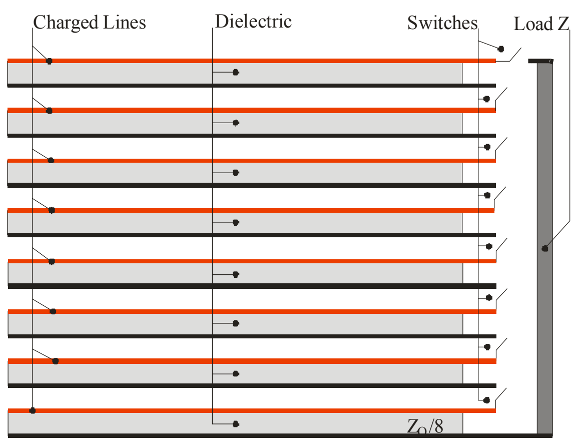

Figure 7. Schematic of an Eight-Stage Stacked Transmission Line with Switches and Load.

V. Compactness of PFL Concepts

In order to assess the impact of dielectric strength derating on the energy density of a Blumlein line, it can be compared with an electrically equivalent transmission line. For a given load Z_L, load voltage V_o, and pulse length τ_p, the ratio of volumetric energy density of the dielectric in a Marxed transmission line to that in a stacked Blumlein line is just the inverse ratio of their volume.

$$R_\upsilon = \frac{\mathcal{V}_B}{\mathcal{V}_T} \tag{3}$$

where $\mathcal{V}_B$ is the Blumlein dielectric volume and $\mathcal{V}_T$ is the transmission line dielectric volume including the inter-stage insulation. For the parallel plate geometries considered in this paper the Blumlein dielectric volume is

$$\mathcal{V}_B = \frac{4V_o^2}{\delta^2 k_1^2}\frac{\tau_p c}{\varepsilon_r Z_L}\sqrt{\frac{\mu_o \mu_r}{\varepsilon_o}} \tag{4}$$

where c is the speed-of-light, δ is the derating fraction for the Blumlein dielectric, k_1 is the dielectric strength of the high energy density dielectric, and ε_r and μ_r are the relative permittivity (dielectric constant) and permeability, respectively.

The expression for the dielectric volume in a Marxed transmission line includes the inter-stage insulation. Ideally, the dielectric used in the transmission line elements will have a much higher dielectric constant than the inter-stage insulation but a similar dielectric strength. The high dielectric constant will reduce the length of the line and make it more compact. In practice, the inter-stage insulation can and should have a much higher dielectric strength to further minimize volume. For a Marxed transmission line, the volume is

$$\mathcal{V}_T = \frac{4V_o^2 \tau_p c}{k_1 \varepsilon_r Z_L}\sqrt{\frac{\mu_o \mu_r}{\varepsilon_o}}\left[\frac{k_2 n_T + k_1 n_T - k_1}{k_1 k_2 n_T}\right] \tag{5}$$

where k_2 is the dielectric strength of the inter-stage insulation, and n_T is the number of stages in the Marxed transmission line.

Assuming that the same charge voltage and the same high energy density dielectric are used in the Blumlein and transmission lines, Equations 3-5 yield the following expression for the volumetric energy density ratio in terms of design parameters.

$$R_\upsilon = \frac{k_2 n_T}{\delta^2\left[k_2 n_T + k_1 n_T - k_1\right]} \tag{6}$$

The volumetric energy density ratio scales with the inverse square of the derating factor. The number of stages and the ratio of dielectric strengths (k_1/k_2) have a more modest impact on R_v. As shown in Figure 8, the Blumlein is the most compact option only for $\delta>0.72$. Figure 8 also reveals the modest improvements in the energy density of a transmission line system achieved by reducing the number of stages or increasing k_2.

Solid dielectric failure is stochastic in nature and is dependent upon the electric field and weakly dependent upon the volume.[6] Assessment of the derating necessary for operating a stacked Blumlein may be derived from capacitor data. For polymer film dielectric, voltage reversal has a highly nonlinear effect on the life of the dielectric.[7] For the highly ideal case where the switch jitter is negligible, the derating factor for a dielectric rated to 10 percent reversal but experiencing 50 percent reversal is 0.775, barely resulting in the Blumlein line being the most compact option. Reference [7] also points out that “slow” polarization mechanisms within the dielectric will not reverse in phase with the applied voltage resulting in electric field stresses that may further curtail dielectric life. A simple design guideline for ceramic dielectrics[8] states that the design voltage should equal the peak-to-peak voltage of the circuit. With the idealized Blumlein line operation, this results in a derating factor of 0.67, and as Figure 8 shows derating to this degree clearly indicates that a Marxed transmission line concept will be more compact than a stacked Blumlein line. When the fault mode of operation or significant jitter is considered, any remaining advantages of stacked Blumlein lines in terms of compactness evaporate. Since nearly all composite dielectrics are formed from a combination of polymers and ceramics, the required derating in a stacked Blumlein line is expected to fall between the two cases (0.67 to 0.775) considered here. This is consistent with observed breakdown of the single-stage Blumlein lines which for lines 1 and 2, broke at 0.66 and 0.8 times the DC acceptance voltage, respectively.

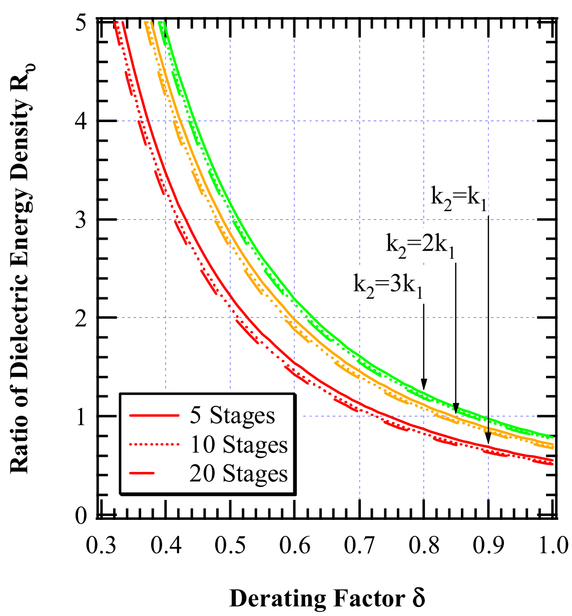

Figure 8. Ratio of Marxed Transmission Line to Stacked Blumlein Line Energy Density. The Blumlein Is More Compact Only for Modest Derating.

The analysis presented here neglects the switch volume, partly because its effect on system volume cannot be generalized in the same manner as that of the dielectric. A stacked transmission line system requires twice as many switches as a stacked Blumlein line. The switches in a stacked Blumlein line must conduct twice the load current, and more under fault conditions, and each switch must be triggered. Any differences in the system energy density due to the switches have more to do with the peripheral features of the switch technology than with number of switches in a particular design.

VI. Conclusions

The suitability of the stacked Blumlein lines for compact pulsed power was compared with stacked or Marxed transmission lines. Under ideal circumstances, the Blumlein experiences a 50 percent voltage reversal. Under fault conditions or significant jitter in a low loss line, segments of the stacked Blumlein experience as much as +1.5 to -2.0 V_{CH}. Since the dielectric in a Blumlein line must be derated, the stacked or Marxed transmission line configuration was shown to be the more compact option except for the cases where a very small voltage derating is applicable.

Additionally, test results for two single stage lines fabricated with a ceramic loaded polymer dielectric were presented. The two lines had different ceramic loading fractions and consequently different dielectric constants. The test results showed only a minimal degradation of the dielectric constant at 50 kV charge in Line 2. The lines experienced dielectric failures when the peak-to-peak voltage was 58.8kV and 71 kV for lines 1 and 2, respectively. The failures occurred reasonably close to the DC acceptance voltage of 62.5 kV. The root cause of the failure could not be determined based on the visual evidence, although cracking of the dielectric due to mechanical stress or simply the application of too high an electric field are the primary candidates. Fabrication of two-stage Blumleins was also discussed.

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