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Study of High Energy Storage Blumlein Transmission Lines as High Power Microwave Drivers

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ABSTRACT

The evolution of high power microwave (HPM) sources into practical systems requires the development of compact pulsed power that can be integrated into mobile platforms. One approach to pursuing this objective, developed by researchers at Sandia National Laboratories (Sandia) [1], is to utilize parallel-stacked Blumlein transmission lines energized with a compact Marx generator. Such a configuration would be capable of driving low impedance HPM sources with a long pulse waveform. One of the limitations of this approach is field enhancement-induced breakdown at the edges of the line. Another limitation is percolation of, and subsequent breakdown of the liquid dielectric that is used in the system. This paper describes a research program that, both computationally and experimentally, is studying electrical breakdown in such transmission line configurations for a variety of dielectric materials and substrate geometries. In this collaborative study calculations are being performed using various electromagnetic simulation tools at the University of New Mexico. Liquid breakdown investigations are being performed at Old Dominion University. The goal of this research is to better understand the properties of solid and liquid dielectrics to facilitate the development of compact pulsed power.

INTRODUCTION

High Power Microwave (HPM) systems require compact, portable pulsed power in order to operate on mobile platforms. To-date the emphasis in HPM research has been on sources, with modest attention being paid to the pulsed power. Figure 1 presents a typical block diagram representation of an HPM system.

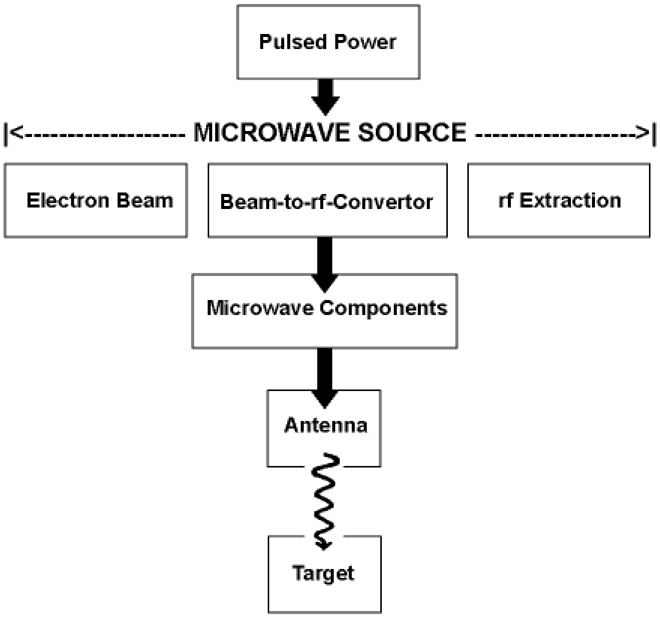

Figure 1. A block diagram of an HPM system. Pulsed power is used to energize an electron beam diode. The HPM source itself comprises the electron beam, the beam-to-rf converter (typically termed the interaction space), and the rf extractor. Once rf is extracted from the interaction space, components are used to couple the rf to an antenna, which ultimately radiates the energy towards some target. ***(Figure originally appeared in [2], used with the permission of the authors.)***

Capacitive storage-based pulsed power systems are typically used as HPM source drivers. The requirements on such drivers include maintaining a constant impedance (typically of the order of 10-100 Ω) at 0.1-1.0 MV voltages for time scales on the order of 100's ns. Capacitive energy storage-based systems are well-suited to meet these requirements. A block diagram representation of such a system is depicted in Fig. 2. The primary energy source (or "prime power") in the laboratory is the electrical transformer. (Outside the laboratory this could be turbines on an aircraft, or a diesel generator on the ground or on board a ship.) We focus on the capacitive energy store and pulse forming sections, since these occupy the greatest volume and comprise the largest mass in the system.

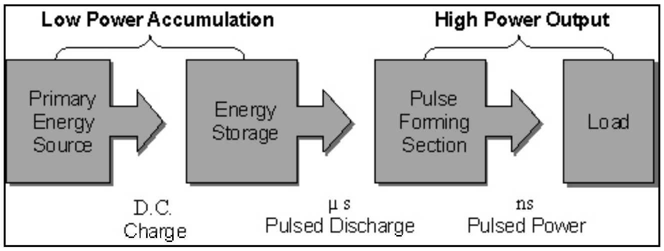

Figure 2. A capacitive energy storage-based pulsed power system. The prime power charges a capacitor bank on a long time scale. This output is then conditioned to meet the needs of the load.

BLUMLEIN TRANSMISSION LINE-BASED PULSER

A Blumlein transmission line [3] consists of two or more coupled transmission lines. Rapidly-shorting switches cause voltage reversal in half of the lines for a time given by the double transit of an electromagnetic pulse. The resulting characteristic feature of a Blumlein transmission line is that the output pulse is roughly equally to the charge voltage of the line. In contrast, traditional transmission lines are characterized by the matched pulse at the load having only half the charge voltage at the input to the line.

Researchers at Sandia have been developing a 600 kV, 50 ns, 5 Ω compact pulse-shaping driver that is significantly lighter than comparable coaxial water transmission line systems. Studies by Alexander *et al.* [1] demonstrated that propylene carbonate-impregnated Kapton™ sheets are attractive for constructing high average field striplines that can be folded into a compact geometry. Such a compact pulsed power source can potentially be used to drive low impedance HPM sources (such as a Vircator, MILO, or Radial Acceletron [2]) on a portable platform. The research at the University of New Mexico (UNM), in collaboration with Old Dominion University (ODU) seeks to support this work and advance it through studies of other dielectric materials to be candidates for this transmission line configuration, as well as through a careful study of the breakdown characteristics of propylene carbonate.

KAPTON™ DIELECTRIC IMMERSED IN PROPYLENE CARBONATE: ELECTRIC FIELD CALCULATIONS AND LIQUID BREAKDOWN STUDIES

The initial Blumlein transmission line configuration that is being studied is the system described in [1]. The pulser that was used to charge the pulse-shaping section is a 6-stage bipolar charged Marx system. The capacitors in the Marx are 0.2 μF, 100 kV cans and the switches are Maxwell™ midplane-triggered pancake spark gaps. The pulse shaping section comprises the Blumlein transmission line and its switch (triggered rail gap).

The Blumlein transmission line section utilized 10” wide copper strips with 2” Kapton™ margins in a 48” line that was folded into a 15” long unit. The dimensions were selected to achieve the design line impedance Z utilizing

$$Z \approx \frac{377 * d}{w * \sqrt{\varepsilon_r}} \ \Omega, \tag{1}$$

where d is the thickness of the dielectric medium, w is the width of the line (assuming $d/w < 0.1$), and ε_r is the dielectric constant. The parameters utilized yield an impedance of 5 Ω.

Electromagnetic Modeling

The approach at UNM is to first model the actual folded Blumlein configuration electromagnetically. In Fig. 3 we present the results of an HFSS™ (Agilent/Ansoft) calculation to explore the electric field distribution between the center and outer conductors of the Blumlein configuration. In this configuration a voltage waveform is launched between the top and center conductors. A portion of the waveform is transmitted and propagates between the center conductor and the bottom conductor. A portion of the waveform reflects back upstream in the top section. Finally, after a double transit time, the full line charge voltage appears at the load (shown to be the at the end of the line where the coordinate axes are defined in the sketch).

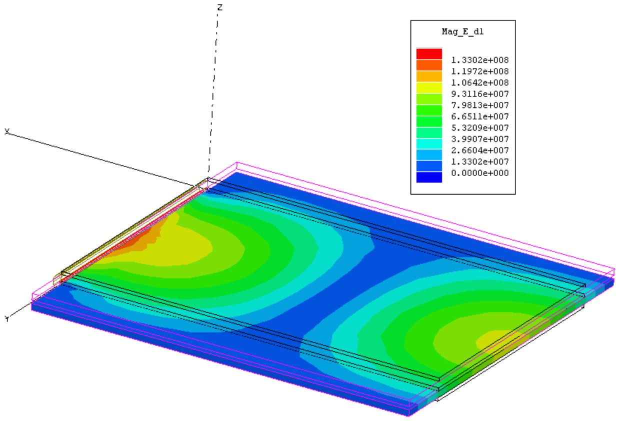

Figure 3. Calculation of voltage distribution at the load (defined by the position of the coordinate axes in the sketch). The red indicates full charge voltage at the load.

The importance of such calculations is to ultimately include the effects of resistivity grading at the outer ends of the line (where the dielectric and liquid interact) and to propose tailored dielectrics.

Liquid Breakdown Studies

In order to achieve the output parameters in this pulser, considerable electrical stress is placed on the liquid dielectric, in the Blumlein transmission line, propylene carbonate [4,5]. In fact, after many shots of testing, fine bubbles were being generated in the propylene carbonate, well in advance of any visible corona or electrical breakdown [1]. The bubbles were generated at electric fields exceeding 1.0 MV/cm, even though expectations were that breakdown would not be a problem until the 1.4 MV/cm field level was approached. Attempts at utilizing salts diluted in the propylene carbonate to adjust the electrical conductivity of the liquid dielectric did not greatly alter the situation.

This observation motivated the studies of liquid breakdown at Old Dominion University through experimentation and modeling [6]. The recent modeling work utilized a percolative approach, where the dielectric is treated as a network of resistors having random values and breakdown characteristics based on a specified statistical distribution. The model successfully characterized the fractal structure found in dielectric breakdown. It was shown that the overall breakdown process consists of the successive breakdown of individual elements, leading to the formation of a percolation cluster. The relationship between this modeling result and the experimental observations of the percolation of the propylene carbonate is not yet clear, although is presently under intensive scrutiny.

HIGH DIELECTRIC CONSTANT CERAMICS FOR USE IN BLUMLEIN TRANSMISSION LINES

Although the folded Blumlein pulser confriguration described thus far is compact, it is widely recognized that high energy density ceramic dielectrics can further decrease the volume of such pulser systems and this is what motivates our interest in breakdown in solids. The particular aspect of breakdown in solids that is of interest is a study of breakdown in high dielectric constant ceramics with spatially-varying permittivity (leading to a graded resisitivity) [7,8]. High dielectric constant ceramics are being developed for a wide variety of applications in electrical engineering, including as a dielectric for high energy density capacitors [9]. Although the dielectric constant of electronic ceramics typically range from a low value of 2.2 for pure SiO_2 up to 30,000 for relaxor ferroelectrics, the parameters of interest to the Blumlein pulse-shaping driver application include high dielectric constant ($\varepsilon_r > 100$) and high breakdown strength (>400 kV/cm).

The energy density γ (in J/m^3) of a ceramic under the influence of an applied electric field is given by

$$\gamma = \varepsilon_0 \varepsilon_r E^2/2 \qquad (2)$$

where ε_0 is the permittivity of free space, ε_r is the dielectric constant of the ceramic, and E is the applied electric field strength. Typical candidate materials that are being studied in this regard are TiO_2 and $BaTiO_3$.

The development of high dielectric constant ceramics is led by the ceramists, who are concerned with the microstructure and processing techniques used in fabricating samples. We have begun an experimental and computational effort to study high dielectric constant ceramics for use in Blumlein transmission lines. The experimental program utilizes a simple DC breakdown set-up using a variety of electrode geometries and materials. The experimental set-up was developed by Sandia National Laboratories and is located on-site in the laboratory facility utilized for the Blumlein pulser studies. Some ceramic material is available for investigation, fabricated under the auspices of an earlier Sandia collaboration with the University of Missouri-Rolla [7,8]. Continued interaction with ceramists from the University of Missouri-Rolla is anticipated.

CONCLUSION

A promising approach to developing compact pulsed power drivers of High Power Microwave (HPM) sources utilizes a Blumlein transmission line as the pulse shaping element. Such a pulser configuration can be charged by a capacitor storage-based pulsed power system, and deliver the line impedance and pulse length characteristics required to drive the electron beam diode of HPM sources. We described progress in the understanding of folded Blumlein configurations that utilized propylene carbonate-impregnated Kapton™ sheets as the dielectric between planar copper conductors. Electromagnetic modeling, coupled with liquid breakdown studies, is seeking to understand the limitations of such a configuration. An even more attractive approach would utilize a short section of Blumlein transmission line with a very large dielectric constant ceramic substrate material. Preliminary research on this subject is seeking to understand how one can optimize a spatially-varying permittivity distribution to extend the breakdown characteristics of the dielectrics in the Blumlein configuration. Much additional work needs to be performed in understanding how candidate tailored ceramics would behave over time in this application. Mechanical and electrical effects of stresses could be a fundamentally limiting property of the ceramics.

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