

MODELING OF A COMPACT, PORTABLE TRANSMISSION LINE FOR PULSED-POWER APPLICATIONS *

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Abstract

In this paper, we present a computational approach to the research of designing high-power microwave systems as compact and portable units. We discuss the motivation to run a comprehensive computational study as an alternative to the, more common, experimental set-ups. We further elaborate on the differences between a physical set-up of the experiment vs. a computational model. The differences between the ideal theoretical settings and the current computer model are contrasted as well as the current challenges encompassing the computational modeling.

I. INTRODUCTION

Historically, high-power microwave (HPM) systems, due to their large size, have been mainly employed in a laboratory environment. However, recent trends in HPM research are focusing towards the reduction of the overall dimensions of HPM systems. A component where such a reduction in size seems to be possible is the pulse-forming section of the HPM system.

The pulse-forming section typically comprises some kind of a transmission line. While there is more than one configuration that can serve as a pulse-forming unit, a Blumlein-configuration of the line shows advantages over the other types. The essential advantage for this choice is in the fact that the Blumlein line can deliver a pulse of the same magnitude as the magnitude of the pulse that was used as the input to the line, while a simple transmission line will be able to produce only half of that value. However, regardless of the line configuration being chosen, the goal is to reduce the line dimensions to make the line compact and portable, but on the other side retain power-bearing capabilities of the “original-size” line. Some attempts to achieve this goal are essentially based on folding the line structure [1] to accommodate for the dimensions requirement, and exploring various dielectrics to support power-handling requirements.

While various research efforts are based on experimental set-ups and such an approach has its advantages, it cannot provide an insight into the structure and also has some other inherent limitations. That is why

we began to study the structure and the nature of the pulse-forming process by running a comprehensive computational model. This approach gives an insight into the structure, and enables better understanding of the process from ‘inside’ by analyzing the field distributions and propagation. Unlike the experimental approach, it enables quick and easy redesign of the structure in terms of materials, geometry, dimensions etc. Thus, new materials, and geometries can be tested in a very time-efficient and cost-effective way, simply by modifying the computer model, rather than manufacturing a new sample of the structure for every desired modification in the experiment. In fact, the two approaches are very complementary, and the overall research on this subject may gain an ultimate benefit by combining both of them.

On one side, the experimental set-up can realize the experiment closely to the theoretical description. However, the downside of this is that one can measure merely the physical outcome of the experiment, i.e. the dielectric breakdown at a certain moment. Whereas, in order to improve the characteristics of the line, we need to better understand the internal behavior of the transient process. With the experimental set-up, the line under test behaves as a ‘black box’ to which a desired input pulse is applied, and the maximum field value and the breakdown is recorded. On the other hand, the computational analysis enables us to study the field creation and temporal enhancement throughout the line. Consequently, such an insight into this process, and accompanied analysis can help us better understand the nature of the process, and search for a solution to improve the design in terms of the dielectric strength and the overall power-handling capabilities of the line.

II. COMPUTATIONAL MODELING

In this section we will discuss the challenges of the computational modeling of a folded Blumlein line, and some difficulties currently accompanying this task. For this purpose, the ‘original’ requirements on the experiment will be recalled first. Secondly, we will address the present substitutes and equivalents involved in the computational model.

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A. Requirements for a Blumlein line simulation

Ideally, there is an initial voltage present along the line. At some moment, a switch closes toward the grounded conductor plate, producing a negative voltage step [2] that starts propagating along the line, annihilating the initial voltage. When that propagating effect hits the load, a portion of the impinging wave will reflect from the load, due to the (desired) mismatch of the load against the single line, while another portion will pass through the load propagating toward the end of the second line. At this point, the front end of the first line is short-circuited, while the end of the second line stays an open end. The reflected and transmitted parts of the original wave ideally pass the same distance, hitting the short- and open- end at the same time. The open end will reflect the wave with the same polarity, while the short end will reflect it with a reversed polarity. When they hit the load again, they will cancel each other if the load impedance is exactly twice the value of the impedance of the single line [2]-[3], thus ending a pulse-forming process with a pulse of the duration twice as long as the time the wave needs to pass the line once. In short, this transient process involves one biased conductor, one grounded conductor (short-circuit termination) and one ‘open’ conductor (open-circuit termination). It includes an initial voltage, which is then taken off by the above-described transitional effect.

In our work, we use CST Microwave Studio™ (MWS) software. MWS is a very capable code for various electromagnetic problems, but presently it cannot support all the specified requirements encountered in this problem. This is a strongly transient problem, and, quite likely, no commercial code at this point can completely model this system since most of the codes are made to deal with a stationary type of a problem. In that context, we try to substitute the original requirements and settings with the equivalent ones, as closely as possible using the MWS.

For example, we cannot specify initial conditions along the line for $t = 0^-$, and it is not possible to directly model a switch that will create a short circuit when it closes toward the grounded plate. Instead, we try to model those effects by adequately shaping the input pulse. It is also hard to dynamically produce a short-end termination of the line after the pulse was sent into the structure. In contrast, the open-end termination is an easier task to model. In this particular case, that the line impedance is low (about 5Ω), even free space impedance makes a satisfactory approximation to the open end. Another subtlety is related to the proper modeling of the load. Namely, given the characteristic line impedance, the load in the Blumlein line has to be twice that value. Since we deal here with distributed elements, it is not possible to simply assign some desired impedance value to the load. Instead, it must be modeled in a way to have a good physical match with the line, and, in addition, to have such electromagnetic properties that will ultimately represent the necessary impedance value, taking into account the whole volume of the 3D load. While it can seem to be simple at first, it turns out not to be that simple

to realize. And any offset of the load impedance from the desired value will not ultimately result in a clean single output pulse, but there will also be undesired additional reflections and oscillations. Nevertheless, our major difficulty in this moment is modeling of the switch effect.

The first thing we want to test is the effects of dielectric size (dielectric wider than the width of line) and any fringing effects that appear. Furthermore, we would like to investigate how applicable the well-known equation for the characteristic line impedance Z_c , given by Eq. (1), is to the case of the folded line, as well as to the case when the dielectric is wider than the plate.

$$Z_c = \frac{Z_0 * d}{\sqrt{\epsilon_r} * (w + d)} [\Omega] \quad (1)$$

where Z_0 is free space impedance, d is thickness of the dielectric, w is width of the plate, and ϵ_r is relative permittivity of the dielectric. Namely, Eq. (1) implicitly assumes that the dielectric is as wide as the plate, and that the line is straight. The curvature of the line might, indeed, affect the permittivity (whether in actuality or just in the numerical computation), and thus have the influence on the other parameters as well. Since the success of the process is strongly dependent on the matching between the load impedance and the line impedance, it is worthwhile to study the effect of the bending of the line.

B. Current Capabilities of Analysis

At this point, we can analyze the aforementioned effects on a straight line as well as on the folded line. The rationale for doing separate analyses of the straight line and the folded line is in the fact that a curved line may introduce additional effects, which are not present in the straight line configuration. Simultaneously, we have a Blumlein line configuration modeled, as shown in Fig. 1, and any experience acquired on the research of a straight- and folded- (simple) line will be included in the final design of the Blumlein line.

We are interested in the analysis of the maximum field value with respect to the input pulse being applied, the type of the dielectric material, and the geometry of the line. Different durations and shapes for the input pulse will not produce the same effect, and it is interesting to see how the line responds to different stimuli. In addition to that, we want to explore the distribution of the electric field throughout the line, and which points in the line are critical for the breakdown.

To do that, we record the field distribution along the line. Fig. 2 shows one such example. In such a plot, every point on the line can be inspected for the value of the electric field, as well as other parameters of interest. To monitor a pulse propagation along the line, we place probes on the desired locations in the line. Fig. 3 illustrates the line with seven probes placed on characteristic locations.

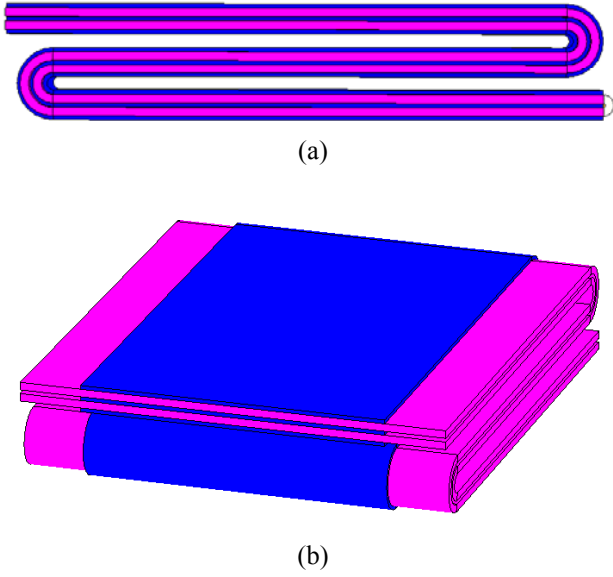


Figure 1. Folded Blumlein line computational model: a) side view; b) angle view

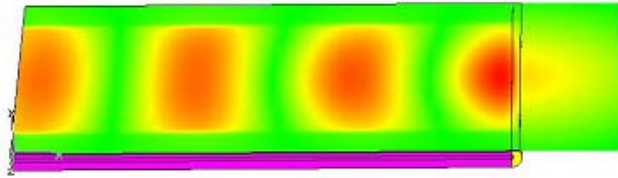


Figure 2. Field distribution recorded on the line

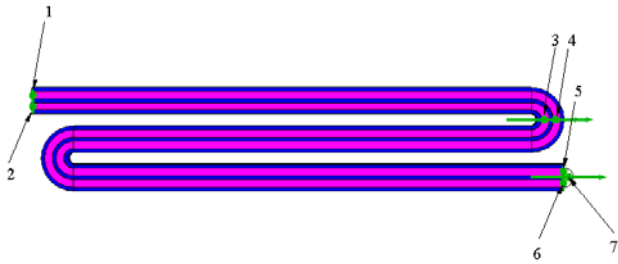


Figure 3. Probes inserted in line to record field variation

These probes record the temporal variations of the field (or voltage) and enable exact reading of the field on the load versus the field (or voltage) at the input. That way we can check the magnitude, shape and duration of the pulse on the load, and see if it satisfies the requirements. An example of one such analysis is presented in Fig. 4, which shows the recorded values corresponding to the probes from Fig. 3. In this case, however, the input pulse

was set to be a Gaussian pulse, instead of a rectangular pulse that may be preferred in general.

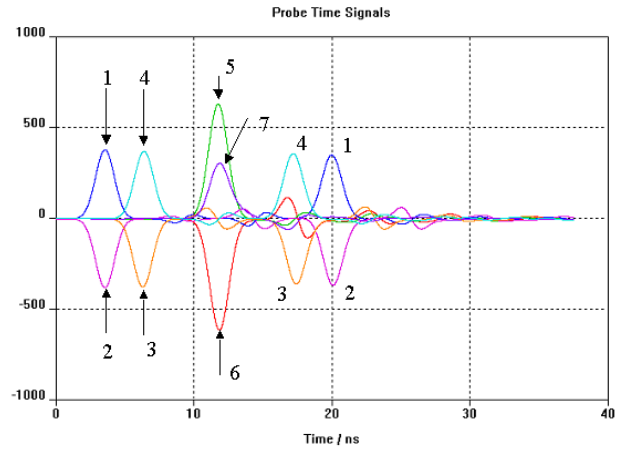


Figure 4. Probe time signal recorded on the probes

C. Future Work

We have already mentioned the fundamental research we would like to perform in order to eliminate uncertainties of the effects of line bending on the characteristic impedance and the breakdown strength of the line. In that context, the validity of Eq. (1) can also be verified in terms of the non-standard designs that we deal with in this project.

We have not explicitly stated it throughout the text, but the dielectric so far is assumed to be homogeneous. However, in the forthcoming research, we will also experiment with an inhomogeneous dielectric. For example, one type of the material may be used to bring benefit in terms of the propagation velocity, characteristic impedance, and losses, while another kind may be used on critical spots along the transmission line to improve the breakdown strength of the line. Certainly, in configurations with inhomogeneous materials, which can be arbitrarily distributed over the volume of the line, the use of the computer code seems to be the only effective way to simulate such non-standard solutions and predict the quantitative effects of that.

Yet another goal of this research will be the use of dielectrics with anisotropic properties. This may be either an alternative to the use of inhomogeneous dielectric, or be used together with it. Should the analysis of the temporal and spatial distribution of the electric field imply it, we may also experiment with different distribution functions of the dielectric.

As far as the geometry of the structure is concerned, we accepted the line configuration described in [1] as the starting point in the moment of joining this project. As our work will be developing, a handful of other competitive solutions may be explored and offered as an alternative to the current one. Naturally, the trend will be toward the reduction of the volume of the line, but compromised with the desired pulse duration, and the dielectric strength

against the breakdown. For example, to prolong the output pulse, there are basically two mechanisms available. We can either extend the overall length of the line or increase the permittivity of the dielectric. Extending the line practically opposes the aim to reduce dimensions of the line. The downside of having a longer line can be somewhat alleviated by employing multiple bends. That will keep the straight section of the line arbitrarily short, but increase the overall height of the line. Perhaps more perspective approach is to use a high-permittivity dielectric. In the future work, we look forward to testing novel dielectric materials [4]-[6] that may be suitable for pulsed high-power applications.

III. SUMMARY

We have discussed the characteristics and benefits of the computational research approach as a complementary alternative to the experimental set-ups in this context. We illustrated some of our current capabilities of analysis and addressed the subtleties of the computational modeling encountered in this phase of the work. Finally, some prospects of further work have been pointed out.

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