Progress In Electromagnetics Research M, Vol. 16, 95–104, 2011

ELETROMAGNETIC SIMULATION OF INITIALLY CHARGED STRUCTURES WITH A DISCHARGE SOURCE

J.-H. Ryu

Agency for Defense Development
Yuseong, P. O. Box 35-5, Daejeon 305-600, Korea

Abstract—A methodology for electromagnetic simulation of initially charged structure with a discharge source (ICSWDS) has been investigated. The ICSWDS can be applied to a lot of areas such as high power electromagnetic (HPEM) radiators. As a method of electromagnetically simulating the ICSWDS, converting initially charged structures into equivalent transient structures and modeling discharge sources by using step voltage sources have been found. A Blumlein pulse forming line (PFL) has been simulated, manufactured and tested to validate this approach. A measured waveform from the test has a good agreement with a simulated waveform.

1. INTRODUCTION

HPEM radiators are of interest for a variety of potential applications such as high power radars, directed energy weapons, power beaming, and so on. Over the past few decades, there has been progress in the development of HPEM radiators [1]. These HPEM radiators can be categorized into narrow band radiators and wide band radiators including ultra-wideband (UWB) [2]. Both of these radiators mostly employ ICSWDS such as PFL. Electrostatic discharge (ESD) is also a physical phenomenon occurred in the ICSWDS.

HPEM radiators using the ICSWDS feature generally complicated electromagnetic structure and very fast pulse formation. For this reason, a lot of time and cost on manufacturing are required to develop them. In order to reduce the time and the cost, computer simulations could be a good alternative. Indian Institute of Science,

Received 25 October 2010, Accepted 1 December 2010, Scheduled 9 December 2010
Corresponding author: Ji Heon Ryu (ryujiheon@gmail.com).

India simulated a pulsed power system for a high power microwave (HPM) source using Pspice program [3]. Institute for Plasma Research, India also employed the Pspice program to simulate a GW pulsed power source for intense electron beam generation [4]. Giri et al. used the Pspice program to simulate switched oscillators to develop a HPEM radiator with a helical antenna [5]. Electric circuit simulators such as the Pspice program are helpful for investigating the principle of the overall systems but there is a limit on predicting accurately electromagnetic performances of the ICSWDS. This is because it is much more demanding to find precise equivalent circuits for high-voltage and ultra-short pulse generators with large size.

To improve the accuracy of simulating ICSWDS with fast rise time and large size, consideration for parasitically capacitive and inductive elements is essential. For this reason, three dimensional electromagnetic simulators are more appropriate for accurate prediction. Though there are a variety of commercial electromagnetic simulators, they have some difficulties in simulating the ICSWDS because their applications focus on low-voltage electronic circuits such as wireless communication devices.

There are two challenges to apply the electromagnetic simulators to the ICSWDS. The first is how to represent the initially charge structures in these simulators. The second is how to model discharge sources in the simulators. In this paper, in order to solve these two challenges, we will discuss a method of converting initially charged structures into equivalent transient structures and substituting discharge sources with step voltage sources. We will mention a simulation method of the ICSWDS by a FDTD simulator, CST®Microwave Studio. A Blumlein PFL has been built, simulated and tested to validate this approach. The simulation results will be compared with the measurement results.

2. CONVERSION OF INITIALLY CHARGED STRUCTURES

High voltage pulses in HPEM radiators are mostly produced by switching initially charged devices. A closing circuit with a charged capacitor or a charged transmission line as shown in Figure 1 generates a pulse into the load. For ultra short pulse generation in HPEM radiators, initially charged transmission lines with a discharge source are generally used to produce rectangular pulses with short duration of nanosecond or even sub-nanosecond. As shown in Figure 2, a simple pulse forming line (PFL) composed of an initially charged transmission line generates a square pulse. Ideally, a square pulse with pulse width

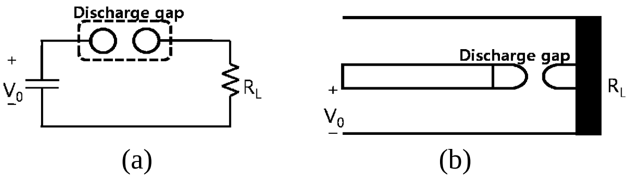


Figure 1. (a) Capacitor discharge source and (b) coaxial PFL discharge source.

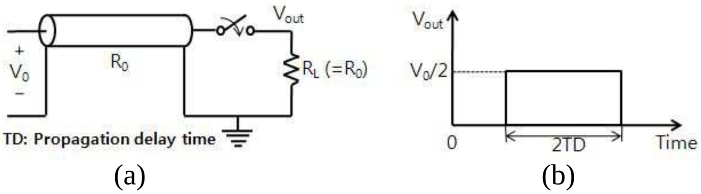


Figure 2. (a) Simple PFL circuit and (b) generated pulse.

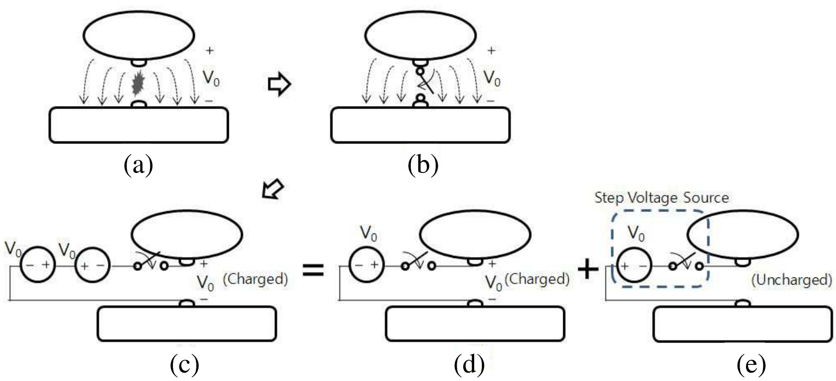


Figure 3. Conversion of initially charged structure with discharge source.

as two times of the propagation delay time is generated from the simple PFL circuit. Pulse shapes obtained from actual experiments are distorted by the effects of parasitic elements existing in the structures.

Unlike general electromagnetic structures, the initially charged structures cannot be modeled in the electromagnetic simulators. Reference [6] provides us with a good approach to convert initially charged structures into uncharged structures. Let us explain this approach by using an example as shown in Figure 3.

Generally, ICSWDS is symbolized by two electrodes with a

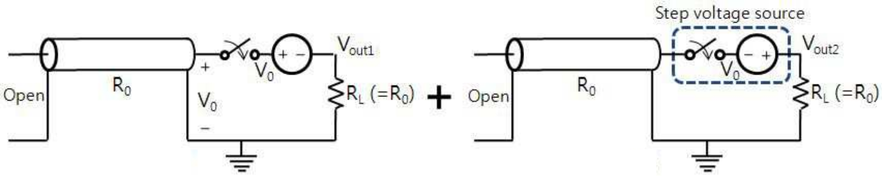


Figure 4. Converted circuits for the simple PFL circuit in the Figure 2.

discharge gap. Figure 3(a) shows an arbitrary ICSWDS, which can be converted to charged electrodes with a closing switch as shown in Figure 3(b). The switch is equivalent to a switch with two voltage sources of opposite polarity as shown in Figure 3(c). This circuit is the same as the superposition of the circuit in Figure 3(d) and the circuit in Figure 3(e). The circuit in Figure 3(d) does not give rise to transients so the circuit in Figure 3(e) is the only one whose transient behaviors are needed to be analyzed. Because this equivalent circuit in Figure 3(e) doesn't have a charged device, it can be modeled in electromagnetic simulators. The circuit in Figure 3(e) is an uncharged structure with a step voltage source. The switch closure doesn't make any changes in the circuit of Figure 3(d). All electromagnetic parameters in Figure 3(d) are constant before and after closure of the switch. If these constant parameters are superposed onto the calculated parameters from the transient electromagnetic simulation of Figure 3(e), we can get the final results for the primary structure in Figure 3(a). If the load is an antenna, radiated field from the antenna is the same as field calculated from the transient electromagnetic simulation for the circuit in Figure 3(e) because the circuit in Figure 3(d) doesn't make any radiation by the closure.

The simple PFL circuit in Figure 2 can be converted as shown in Figure 4. Output voltage at the load in Figure 4(a) is zero before and after closure. The output voltage at the load is the same as output voltage achieved from transient electromagnetic simulation of the circuit in Figure 4(b).

3. MODELING DISCHARGE SOURCES

Discharge sources can be converted into step voltage sources by the conversion method in Figure 3. If we have information of discharge sources from experiments just for them based on theoretical analysis, it is possible to describe the step voltage source and to simulate

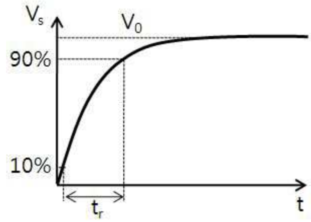


Figure 5. Step voltage waveform with amplitude (V_0) and rise time (t_r).

the entire electromagnetic structures including a discharge source as well. There are many experiments to investigate the characteristics of discharge sources [8, 10]. These discharge sources are analyzed theoretically to determine equivalent circuits or to find relationships between achievable rise time and amplitude [7, 11]. Bojovschi et al. simulated the electromagnetic radiation from partial discharge by using an approximated Gaussian impulse [12].

While the discharge source is modeled using a step voltage source, it is not essential to determine the precise voltage waveform of the discharge channel because electromagnetic structure of the discharge region strongly affects the waveform generated from the discharge. Rise time and amplitude are dominant parameters to model the switching channel. Though there are various equations to represent the step function, we used Equation (1) to describe it. While the rise time (t_r) is defined as time corresponding to amplitude change from 10% to 90% over the maximum voltage (V_0), the step voltage (V_s) is expressed by Equation (1). A waveform plotted by this equation is shown in Figure 5.

$$V_s = V_0 \left(1 - e^{\frac{-2.2t}{t_r}}\right) \tag{1}$$

4. TRANSIENT ELECTROMAGNETIC SIMULATION

Based on conversion of initially charged structures and model of discharge sources, ICSWDS can be analyzed by electromagnetic simulators. FDTD simulators which use time domain solvers are more appropriate to simulate the transient electromagnetic structures. We chose CST®Microwave Studio among them. A Blumlein PFL using parallel plate transmission lines as shown in Figure 6 was simulated. The switched parallel plate transmission line can be a pulse source of a HPEM radiator with a TEM horn antenna [9].

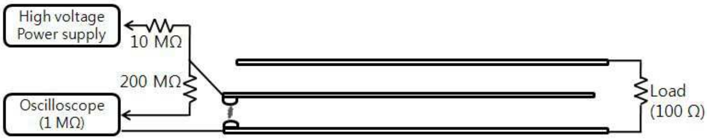


Figure 6. Blumlein PFL using parallel plate transmission lines.

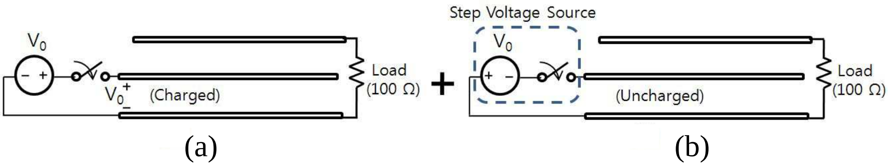


Figure 7. Converted circuits of the Blumlein PFL.

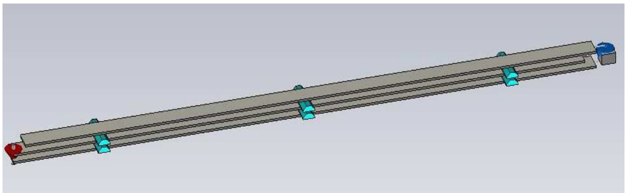


Figure 8. Blumlein PFL drawn in the electromagnetic simulator.

The Blumlein PFL has an advantage that the pulse generated into the load is equal to the charged voltage at the transmission line, while the pulse generated into the matched load in the simple PFL is half the charged voltage at the transmission line. Width and length of the parallel plates are 30 mm, 1000 mm. Resistors with resistance of 10 MΩ, 200 MΩ are installed to limit the charged current and to measure the charged voltage. The impedance of the resistors is much greater than that of the transmission line so the circuits located in the left of the discharge gap can be ignored in the transient electromagnetic simulation. Using the method in Figure 3, the Blumlein PFL is converted into the circuits in Figure 7. The circuit in Figure 7(b) is the only circuit to be simulated electromagnetically. This circuit consists just of a step voltage source and an uncharged transmission line so it can be modeled by electromagnetic simulators.

Figure 8 illustrates the Blumlein PFL drawn by using CST®Microwave Studio A discrete port is substituted for the discharge source. The load is modeled using a resistor among lumped elements. A current monitor to measure the pulse generated into the

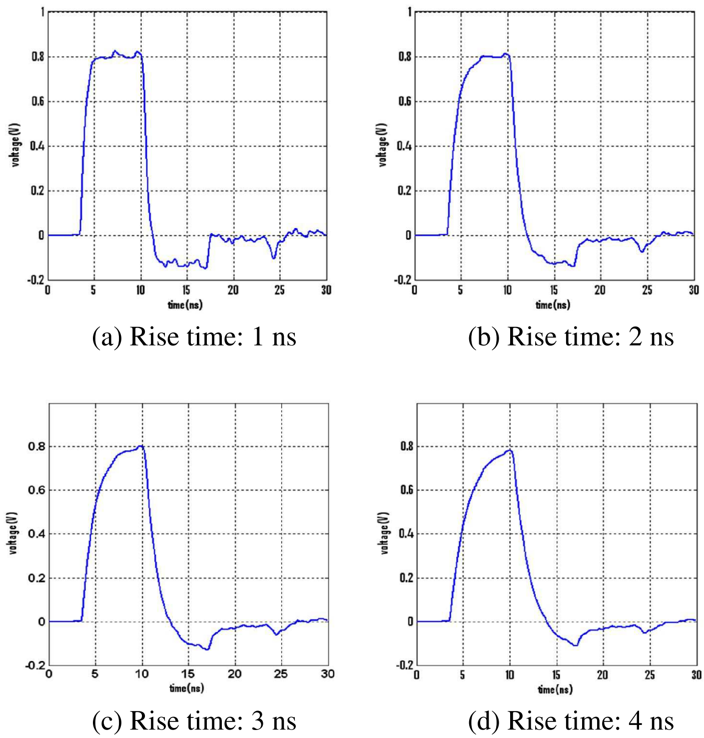


Figure 9. Pulses generated into the load for rise times of 1 ns, 2 ns, 3 ns and 4 ns.

load is drawn as well. The discrete port is a voltage port with a step voltage waveform described by the Equation (1). The amplitude of the waveform is a unit. The Blumlein PFL is simulated for rise times of 1 ns, 2 ns, 3 ns and 4 ns. Pulses in Figure 9 were calculated. As the rise time is faster, the pulse at the load is more similar to a rectangular pulse.

5. COMPARING THE MEASUREMENTS WITH THE SIMULATIONS

The Blumlein PFL was manufactured to check the validity of this approach to simulate electromagnetically ICSWDS. Figure 10 is illustrations of the experiment setup and the discharge. The voltage charged at the transmission line is measured by a resistive voltage divider. The pulse waveform generated into the load is measured by a current monitor which is a Berguz Instrumentation CT-B2.5 current

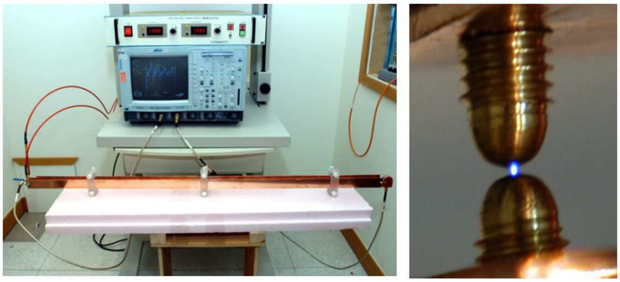
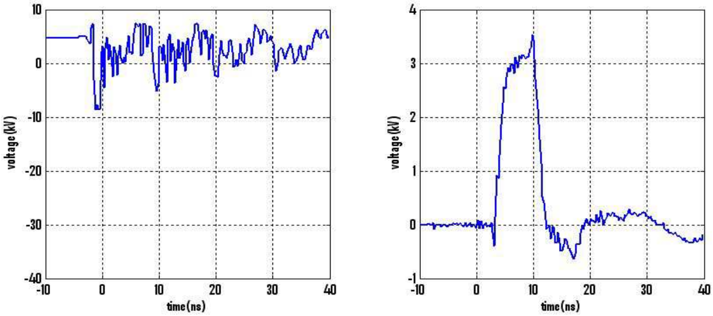


Figure 10. Illustration of experiment setup and discharge.



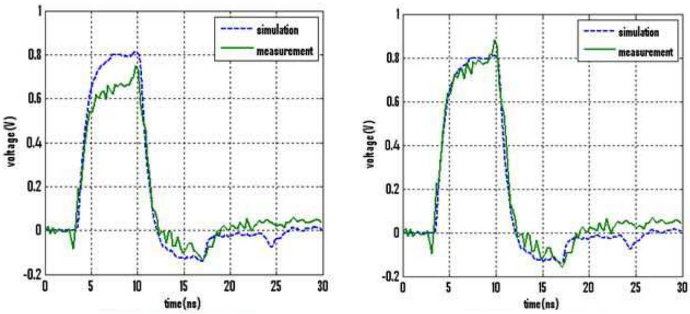
(a) (b)

Figure 11. (a) Measured signals of charged voltage and (b) pulse waveform at the load.

transformer.

Discharge is started at the voltage of 4.7 kV as shown in the left of Figure 11. The pulse at the load has an amplitude of 3.2 kV and a full width at half maximum (FWHM) of approximately 7 ns.

Let us compare the measured waveform with the simulated. The simulated waveform for rise time of 2 ns is the most similar to the measured. This comparison is shown in Figure 12. The measured waveform is normalized by the voltage where the discharge is started. Figure 12(a) is the simulated waveform and the measured waveform. Both waveforms are very similar. If the measured waveform is scaled by 17%, the two waveforms are almost overlapped as shown in Figure 12(b). This agreement of the waveforms implies that this simulation can predict precisely the waveforms generated from ICSWDS. It is valuable because it is possible to estimate waveform and tendency of an overall system including discharge source by using information from experiments just for the discharge source. It is



(a) Without scaling (b) With scaling

Figure 12. Comparing the measured waveform with the simulated waveform.

suggested that the amplitude difference between the simulated and the measured results from simulation condition that the discharge source is lossless. If we know equivalent resistance by experiments, it can be reflected in the simulation. In CST®Microwave Studio program, the loss of discharge source can be represented by using a scattering parameter port with a source resistance instead of a voltage port. In conclusion, using information of discharge source and this simulation method, it is possible to simulate HPEM radiators composed of a discharge source, transmission line circuits, an antenna and so on.

6. CONCLUSION

A methodology for electromagnetic simulation of ICSWDS has been addressed. Because the ICSWDS is not directly modeled in electromagnetic simulators, a new method has been found to simulate the ICSWDS. This method is to convert the initially charged structures into equivalent transient structures and to model the discharge sources using step voltage sources. Using this method, it has been possible to electromagnetically simulate the ICSWDS. A Blumlein PFL has been manufactured to verify the validity of this approach. The measured waveform has a good agreement with the simulated. This was deemed sufficient for the simulation method to predict performances of the ICSWDS.

A current area of research is investigating the characteristics of discharge sources including rise time and resistance by experimental and theoretical methods.

REFERENCES

1. Giri, D. V., *High Power Electromagnetic Radiators*, Harvard University Press, 2004.
2. Benford, J., J. A. Swegle, and E. Schamiloglu, *High Power Microwave*, 2nd Edition, Taylor & Francis, 2007.
3. Senthil Kumar, D. and M. Joy Thomas, "Design and development of a pulsed power system for a vircator based HPM source," *INCEMIC Proceedings*, 2006.
4. Verma, R., A Shyam, S. Chaturvedi, R. Kumar, D. Lathi, V. Chaudhary, R. Shukla, K. Debnath, S. Sharma, J. Sonara, K. Shah, B. Adhikary, R. Thakkar, and B. Chauhan, "Portable & low cost giga-watt pulsed power source for intense electron beam generation," *IEEE Pulsed Power Conference*, 2005.
5. Giri, D. V., F. M. Tesche, M. D. Abdalla, M. C. Skipper, and M. Nyffeler, "Switched oscillators and their integration into helical antennas," *IEEE Transactions on Plasma Science*, Vol. 38, June 2010.
6. Cheng, D. K., *Field and Wave Electromagnetics*, 2nd Edition, Addison-Wesley Publishing Company, 1992.
7. Istenic, M., I. R. Smith, and B. M. Novac, "Dynamic resistance calculation of nanosecond spark-gaps," *IEEE Pulsed Power Conference*, 2005.
8. Frostm, C. A., T. H. Martin, P. E. Patterson, L. F. Rinehart, G. J. Rohwein, L. D. Roose, J. F. Aurand, and M. T. Buttram, "Ultrafast gas switching experiments," *9th IEEE International Pulse Power Conference, Digest of Technical Paper*, 1993.
9. Ahn, J. W., S.-Y. Song, J. H. Ryu, and M.-S. Jung, "A marx-type electromagnetic pulse generator," *Ultra-wideband, Short-pulse Electromagnetics*, Vol. 7, Springer, 2007.
10. Carboni, V., S. Leandro, H. Lachner, D. Giri, and J. Lehr, "The breakdown fields and risetimes of select gases under the codition of fast charging ($\sim$ 20 ns and less) and high pressures (20–100 atmospheres)," *Pulsed Power Plasma Science, PPPS-2001, Digest of Technical Papers*, 2001.
11. Lehr, J. M., C. E. Baum, W. D. Prather, and F. J. Agee, "Aspects of ultra fast spark gap switching for UWB HPM generation," *Pulsed Power Conference, Digest of Technical Papers*, 1997.
12. Bojovschi, A., W. Rowe, and A. K. L. Wong, "Electromagnetic field intensity generated by partial discharge in high voltage insulating materials," *Progress In Electromagnetics Research*, Vol. 104, 167–182, 2010.