SAND2012-4364C

SQUARE PULSE LTD DESIGN AND EXPERIMENTS

A.A. Kim , M.G. Mazarakis*, V.A. Sinebryukhov, S.N. Volkov, S.S. Kondratiev, V.M. Alexeenko, F. Bayol, G. Demol**, W.A. Stygar***

Institute of High Current Electronics
Tomsk 634055, Russia
**Sandia National Laboratories*
Albuquerque, New Mexico 87185, USA
***International Technologies for High Pulsed Power*
Thegra 46500, France

Abstract

The usual LTD architecture [1, 2, 3] provides sine shaped output pulses that may not be suitable in flash radiography, high power microwave production, z-pinch drivers, and certain other applications. A more suitable driver output pulse would have a flat or inclined top (slightly rising or falling). In this paper, we present the design and first test results of an LTD cavity that generates this type of the output pulse by including within its circular array some number of the third harmonic bricks in addition to the standard bricks.

I. INTRODUCTION

The idea of the Square Pulse LTD is based on the Fourier theorem, which states that any waveform can be duplicated by the superposition of a series of sine and cosine waves. In particular, the constant function *f(x)* defined as

$$f(x) = \frac{\pi}{4} \tag{1}$$

at $0 \le x \le \pi$, can be duplicated by

$$f(x) = \sum_{p=1}^{\infty} \frac{\sin(2p-1)x}{2p-1} . \tag{2}$$

Figure 1 shows how the equation (2) transforms into (1) depending on *p*. For the case *p* = 2 the equation (2) gets the form

$$f_2(x) = \sin x + \frac{\sin 3x}{a} , \tag{3}$$

where *a* = 3. If *a* increases from 3 to ~9, the top of the pulse flattens, as this is shown in Fig. 2.

If the function $f_2(x)$ is the current in the load, then to square the pulse at *p*=2, the driving circuit has to deliver to the load two sine pulses with different frequencies, ω_1

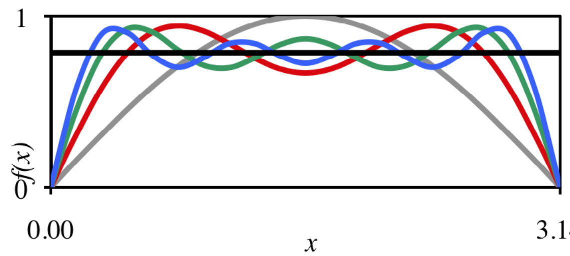

Figure 1. The function *f(x)* given by Eq. (2) at *p* = 1 ÷ 4 compared to *f(x)* =*π*/4 (black line), P=1 gray, p=4 blew.

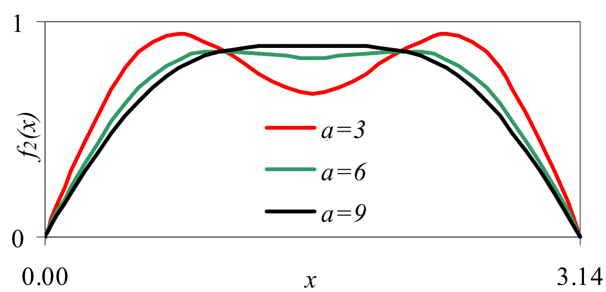

Figure 2. The function $f_2(x)$ depending on *a*.

and ω_2~3ω_1, and the amplitude of the current pulse with the frequency ω_2 has to be ~9 times less than the one with the frequency ω_1, depending on the requirements to the shape of the pulse. The LTD architecture is convenient for such kind of pulse shaping because its discharge circuit is composed of multiple separate bricks connected in parallel. The output LTD pulse can be squared as in Fig. 2 if the bricks in the cavity are of two different kinds: part of them are standard "1*ω*" bricks that deliver the main energy into the load, and the other part are modified "3*ω*" bricks that flatten the top of the output pulse.

Work supported in part by the Sandia National Laboratories (USA) under contract number PO#1016856 and by International Technologies for High Pulsed Power (France) under contract number ITHPP/HCEI/11-C01.

e-mail: kim@oit.hcei.tsc.ru

II. ESTIMATION OF THE SQUARE PULSE LTD PARAMETERS

The simplified electrical circuit of the square pulse LTD is shown in Fig. 3. It consists of s standard and m modified bricks. Each brick includes two capacitors charged in opposite polarity and connected in series with the switch. The two buses (metal plates) connect the capacitors with the load. In Fig. 3, C_1 and L_1 are respectively the total capacitance and inductance of the standard brick that generates the current pulse with the frequency ω_1. Similarly C_2 and L_2 denote the same parameters of the modified brick generating the current pulse with the frequency $\omega_2 \sim 3\omega_1$. All bricks are connected in parallel and triggered simultaneously at t = 0. The load resistance is R_L. We assume that both standard and modified bricks are charged to the same charge voltage U_0, as this is preferable in an actual cavity.

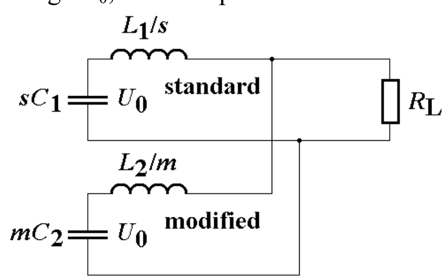

FIG. 3. Simplified electrical circuit of the Square Pulse LTD.

For an arbitrary set of the parameters, the equations describing the circuit of Fig. 3 cannot be solved analytically. Fortunately, for our purposes, the approximate solution to these equations derived by taking into account a number of simplifying assumptions, can adequately describe the above circuit behavior. These assumptions are:

i) since the standard bricks store the main energy, they should be matched to the cavity load, i.e. the following condition must be satisfied:

$$\sqrt{\frac{L_1/s}{sC_1}} = \frac{1}{s}\sqrt{\frac{L_1}{C_1}} = \frac{1}{s}\rho_1 \sim R_L\,, \quad (4)$$

where $\rho_1 = \sqrt{\dfrac{L_1}{C_1}}$ is the circuit impedance of the standard brick.

ii) to flatten the output pulse top, the circuit frequency of the modified brick must be ~3 times that of the standard brick, resulting in

$$\sqrt{L_1 C_1} \sim 3\sqrt{L_2 C_2}\,. \quad (5)$$

iii) in the standard fast LTDs, the bricks are designed in such a way that for a given capacitor and switch the inductance L_1 is reduced to its minimum possible value. This means that the inductance L_2 is limited, at least from below, by the value

$$L_2 \sim L_1\,. \quad (6)$$

Equation (5) approximates the matched load of the square pulse LTD, whereas Eqs. (6)-(7) give the estimate for the capacitance of the modified brick as a function of the capacitance of the standard brick

$$C_2 \sim \frac{1}{9}C_1\,. \quad (7)$$

Simulations show that if the conditions (5)-(7) are satisfied, the standard and modified bricks discharge into the load R_L as if they were almost independent of each other. Then the amplitude of the current delivered by s standard bricks into the *matched* load R_L is

$$I_1 \sim 0.5\frac{U_0}{\rho_1}s\,. \quad (8)$$

While the amplitude of the current I_2 delivered by the m (< s) modified bricks into the load

$R_L \sim \dfrac{\rho_1}{s} \sim \dfrac{m}{3s}\dfrac{\rho_2}{m} < 0.33\dfrac{\rho_2}{m}$, is

$$I_2 \sim 0.9\frac{U_0}{\rho_2}m\,. \quad (9)$$

This is because the load that the modified bricks see, R_L, is much smaller (under matched) than their characteristic impedance $\rho_2 = \sqrt{\dfrac{L_2}{C_2}}$.

Equations (6)-(10) indicate that the shape of the load pulse (defined by the coefficient a in Eq. (3), see Fig. 2) depends on the ratio of the number of standard and modified bricks in the cavity, because

$$, a = \frac{I_1}{I_2} \sim 0.55\frac{\rho_2}{\rho_1}\frac{s}{m} \sim 1.65\frac{s}{m}\,. \quad (10)$$

III. DESIGN OF THE SQUARE PULSE LTD

The square pulse LTD was designed containing s = 4 standard bricks each consisting of two capacitors GA 35460 (100 kV, 8 nF) connected in series, and m = 2 modified bricks each consisting of four TDK ceramic capacitors type UHV-12A (50 kV, 1.7 nF) connected in series. The layout of this cavity is presented in Fig. 4, showing the bottom row of the capacitors in the bricks. In the tests described below the number of standard bricks was varied in order to compare the results with simulations.

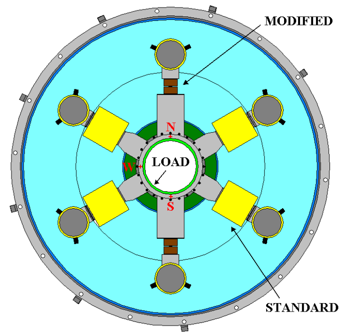

FIG. 4. Square pulse LTD with 4 standard and 2 modified bricks. The outer diameter of the cavity is 140 cm. The location of the cavity core is indicated in dark green.

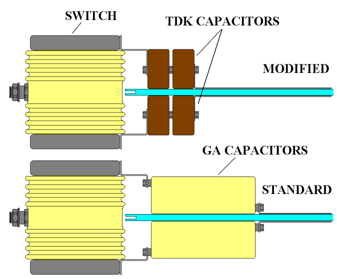

FIG. 5. Modified brick with TDK ceramic capacitors and standard brick with GA 35460 oil-filled capacitors.

The current flowing in the load was measured by using 3 differential-output B-dot monitors. Red crosses in Fig. 4 marked as N, W, and S indicate the location of these monitors relative to the position of the modified bricks in the cavity. The resistance of the load was defined as $R_L=U_L/I_L$, where U_L is the load voltage measured by the external voltage divider, and I_L is the load current calculated as

$$I_L = 0.5 I_W + 0.25 I_N + 0.25 I_S, \tag{11}$$

where I_W, I_N, and I_S are integrated signals from the corresponding B-dot probes. Equation (12) assumes that the current between the two right standard bricks is the same as that between the two left standard bricks.

IV. SIMULATION

The behavior of the square pulse LTD was simulated in PSPICE[1] by using the circuit presented in Fig. 6. It includes s=4 standard and m=2 modified bricks. The capacitors C_1 and C_2 have capacitance equal respectively to the total capacitance of the standard and modified brick, and they are charged to same charge voltage U_0. The inductors L_{11} and L_{21} represent the inductance of the capacitors and the switches in the bricks, and L_{12} and L_{22} represent the inductance of the strip lines connecting the capacitors with the AK gap of the cavity. The load inductance is L_L, and its resistance is R_L.

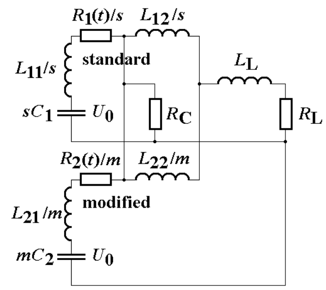

FIG. 6. Square Pulse LTD circuit used in PSPICE simulations.

Each of the resistors R_1(t) and R_2(t) consist of two parts connected in series, one of them represents the constant resistance of the capacitors and the other the current-dependent resistance of the gas switches [4]. The model of reference [4] was used to simulate the brick switch resistance in order to separately take into account the influence of the different currents flowing in the standard and modified bricks.

The resistance R_C connected in parallel to the inputs of the strip lines simulates the energy loss in the cavity core due to generation of the Eddy current in its material [5].

V. EXPERIMENTAL RESULTS

The installation of the modified bricks into the cavity squares the shape of the output pulse, as this is shown in Fig. 8, where the recorded and simulated load voltage traces for s=4, m=2, R_L~1.6 Ohm, and U_{CH}=±100 kV are plotted. This shot was made also without the core and was simulated with $R_C=10^6$ Ohms in the circuit of Fig. 6.

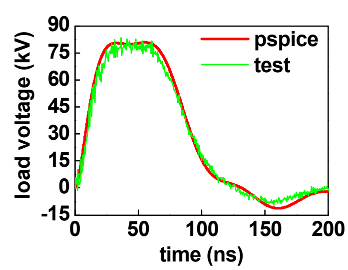

FIG. 8. The recorded and simulated load voltage in a shot without of the current loop around the core, at s=4, m=2, R_L~1.6 Ohms, and U_{CH}=±100 kV.

The top of this pulse at s/m=2 is almost flat; this means that Eq. (11) must be modified

$$a \sim 3\frac{s}{m}. \tag{12}$$

[1] PSPICE is a registered trademark of MicroSim Corporation.

The need for such modification appears because of relatively high resistance of the TDK ceramic capacitors, which was measured to be ~0.3 Ohms per capacitor (resulting in ~1.2 Ohms per each modified brick). This resistance damps the amplitude of the second current peak produced in the load by the modified bricks.

Figure 10 presents the total load current I_L calculated by using Eq. (11) in comparison with the currents measured in this shot by separate B-dot probes. The current I_W measured between the standard bricks is larger than I_N and I_S measured opposite the modified bricks, indicating that the current flow in our circular load cavity is not homogeneous.

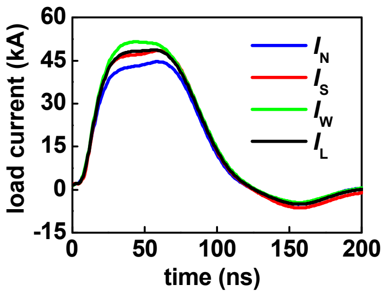

FIG. 10. Load current measured by separate B-dot probes, and total load current I_L calculated by using Eq. (12). Same shot as in Fig. 8.

The installation of the core reduces the load voltage amplitude (Fig. 11), indicating an energy loss associated with the core. Figure 11 shows the load voltage trace recorded with the same conditions as that in Fig. 8; the only difference between these two results is the presence of the top metal cover closing the current loop around the core and the installation of the core in the shot presented in Fig. 11. The voltage amplitude in Fig. 11 is ~10% less than that in Fig. 8, and the same reduction is observed in the PSPICE trace which was calculated with self consistent values of VS_{PULSE} =5.2 mVs and R_C=8.99 Ohms. The energy loss (during the main pulse, before the voltage becomes negative) in R_C=8.99 Ohms is ~35 J or ~10% of total energy stored in the capacitors at ±100 kV charge voltage.

VI. CONCLUSION

The results presented in this report definitely indicate that the shape of the output LTD pulse can be squared if the cavity is assembled with some number of modified bricks with ~10 times less capacitive storage capacitors than in the standard bricks. Relative number of the modified bricks determines the shape of the output pulse.

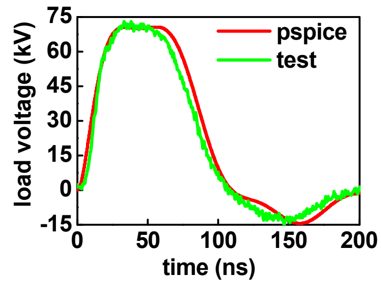

FIG. 11. Recorded and simulated load voltage in a shot with the core, at s=4, m=2, R_L~1.6 Ohm, and U_{CH} =±100 kV. Compared with Fig. 8, the installation of the core reduces the voltage amplitude from ~77 kV to ~70 kV because of energy loss in the core.

VII. ACKNOWLEDGEMENTS

The authors would like to thank Academician RAS B.M. Kovalchuk for the support of this work. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy under Contract No. DE-AC04-94-AL85000.

VIII. REFERENCES

[1] A. A. Kim, M. G. Mazarakis, V. A. Sinebryukhov, et.al., "Development and tests of the 1-MA linear transformer driver stages", Phys. Rew. ST Accel. Beams **12**, 050402 (2009).

[2] M. G. Mazarakis, W. E. Fowler, A. A. Kim, et.al., "High-current, 0.5-MA, fast, 100-ns, linear transformer driver experiments", Phys. Rev. ST Accel. Beams **12**, 050401 (2009).

[3] A. a. Kim, M. G. Mazarakis, V. A. Sinebryukhov, S. N. Volkov, S. S. Kondratiev, V. M. Alexenko, F. Bayol, G. Demol, W. A. Stygar, "Square Pulse LTD", Phys.Rev. ST Accel. Beams, **15**, 040401 (2012).

[4] A.A. Kim, V.G. Durakov, S.N. Volkov, et. al., "Gas switch performance depending on current in the circuit", in Proc. 14th Symp. High Current Electronics, Tomsk 2006, p.297.

[5] A.A. Kim, M.G. Mazarakis, V.I. Manylov, et.al., "Energy loss due to eddy current in linear transformer driver cores", Phys. Rev. ST Accel. Beams, **13**, 070401 (2010).