Gas Switch Performance Depending on Current in the Circuit[*]

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Abstract – In the report, we describe the test results obtained on a single RLC circuit, called brick, which is the main component of the fast LTD technology. The brick was tested at varying charge voltage and resistance of the load. The results are compared with circuit simulation to define the equivalent resistance and inductance of the switch as a function of current. It is shown that in case the brick is simulated as a simple RLC circuit, to fit the test data, both the resistance and inductance of the switch have to be increased when the current reduces. In case the resistance of the switch is simulated by a resistive model similar to the one of Braginsky [1], simulation fits the experiment without of any other changes in the circuit for all test conditions.

1. Introduction

Fast LTD technology providing ≤100 ns rise time of the output pulse in direct drive mode is promising for number of applications where usually only traditional water line technology is possible. The essence of the fast LTD technology is the discharge in a single RLC circuit (called brick) where C is the capacitance of the two serial storage capacitors, L and R are the inductance and resistance of the brick circuit including the gas switch. The time constant of this RLC circuit, $(LC)^{1/2}$, determines the width of the pulse. So, in fast LTD technology, fast rise time and short pulse width are provided mainly by reduced capacitance C. At the same time, the circuit impedance of the RLC circuit, $(L/C)^{1/2}$, increases when C reduces and therefore the current flowing in the switch also reduces. The reduction of the current in a gas switch may increase it's resistance and inductance to unacceptable level and thus limit the possibility to extend the fast LTD technology to shorter pulses.

In tests described below, a separate brick including two GA35436 (100 kV, 8 nF) capacitors and a gas switch type fast LTD was tested at varying charge voltage and resistance of the load. The goal was to investigate if such a brick could be used for the fast LTD stage providing in matched mode an output pulse with a FWHM of ~ 75 ns.

2. Design of the test bed

The design of the test bed is shown in Fig. 1. The switch type fast LTD (1), two capacitors (2) and the resistive load (3) locate in the middle of the grounded test cavity, the dimensions of the cavity are 83x63x18 cm^3. The capacitors are charged to ± (60-100) kV, the insulation is provided by polyethylene sheets (4) and transformer oil inside the cavity. The load is made of solid 20 W resistors connected in parallel. The inductance of the load loop including plane connectors and the resistors is ~20 nH.

The switch type fast LTD [2] consists of 5 intermediate stainless steel electrodes and 6 air gaps, each electrode is a ring with mean diameter of 56 mm. The width of each gap is 6 mm.

The voltage across the load was measured by resistive divider locating inside the test cavity in oil.

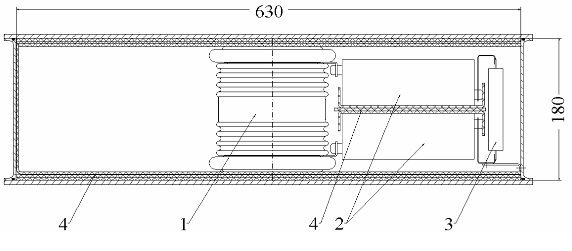

Fig.1. Design of the test bed: 1 – gas switch type fast LTD, 2 – GA35436 capacitors, 3 – resistive load, 4 – polyethylene insulation.

3. Test results

First, the capacitance C_C, the inductance L_C and the resistance R_C of the GA35436 capacitors were defined in a ringing discharge at ~500 V charge. The results are: $C_C \sim 8.35$ nF, $L_C = 35$ nH, $R_C = 0.3$ Ohm.

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[*] The work was supported by the contract CEA/ITHPP/IHCE/05-C02

Next, the brick was assembled as shown in Fig. 1, and the voltage across the load was recorded at different charge voltage, U_{CH}, and resistance of the load, R_L. The recorded load voltage traces were simulated with a simple RLC circuit in order to define how the equivalent resistance and inductance of the switch vary with current through the switch. The RLC circuit is shown in Fig. 2. Here C_2, R_2 and L_2 are capacitance, resistance and inductance of two serial GA35436 capacitors, R_{SW} and L_{SW} are the resistance and the inductance of the switch, L_L = 20 nH and R_L are the inductance and resistance of the load. The parallel resistance of 114 Ohm represents the voltage divider.

The results of the comparison are given in Table 1.

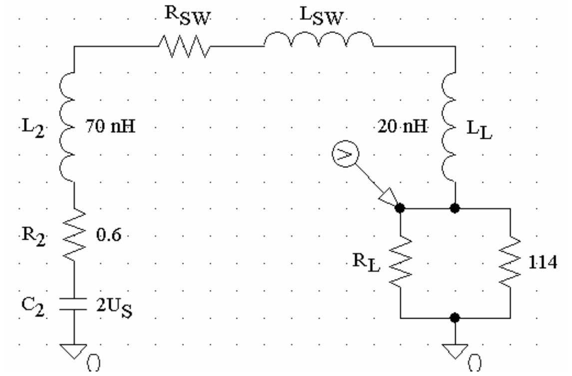

Fig. 2. Simple RLC circuit used for comparison with test data.

Table 1. Comparison between the test data and simple RLC simulation.

R_L, Ω/ C_2, nF	±Uch kV	P ata	I_{MAX} kA	FWHM ns	R_{SW} Ohm	L_{SW}, nH
5.09/4.17	100/92.5	3.4	16.9	59	0.5	60
8.7/4.21	100/95	3.4	13.9	62	0.2	70
	90/81.5	3.0	11.4	64	0.8	80
	80/72	2.6	9.44	65	1.2	100
12.77/4.21	100/91	3.4	10.7	68	0	100
	90/77	3.0	8.77	68	0.4	110
	80/70	2.6	7.72	72	0.8	123
	70/62	2.2	6.64	74	1.2	135
	60/55	2.0	5.78	72	1.7	130
15.02/4.21	100/100	3.4	10.5	69	0.4	100
	90/81	3.0	8.23	72	0.8	120
	80/73	2.6	7.16	75	1.2	130
	70/63	2.2	6.1	75	1.6	135
	60/55	2.0	5.22	76	2.0	140
18.9/4.17	100/106	3.4	9.7	76	0.2	120
	90/86	3.0	7.5	79	1.2	130
	80/76	2.6	6.49	82	1.6	140
21.4/4.21	100/101	3.4	8.49	81	0.4	120
	90/83	3.0	6.77	86	1.0	140
	80/73	2.6	5.79	87	1.6	150
	70/64.5	2.2	5.04	88	1.9	160
	60/55.5	2.0	4.2	91	2.2	200

In Table 1 the charge voltage is shown as U_T/U_S, where U_T appears from the test and U_S is the charge voltage in simulations providing the best fit to the particular shot. Usually $U_S<U_T$, this can be explained by small storage capacitance (~4 nF) resulting in it's fast discharge after the power supply was switched off before the shot. The current I_{MAX} is the peak current through the switch in the simulation at a given U_S. An example of how the simulation fits the recorded load voltage is given in Fig. 3.

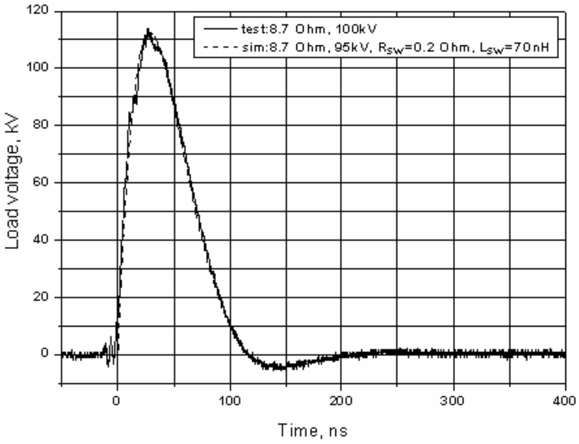

Fig. 3. Comparison between the test and the simulated load voltages at R_L = 8.7 Ohm, U_T = ±100 kV.

One may see in Table 1, that at any R_L both the resistance and the inductance of the switch increase when the charge voltage reduces. The width of the pulse varies between ~60 and ~90 ns. For R_L ≤ 15 Ohms it is less or equal to 75 ns.

General tendency for R_{SW} to increase when the current reduces is evident in Fig. 4, where R_{SW} is plotted versus I_{MAX}.

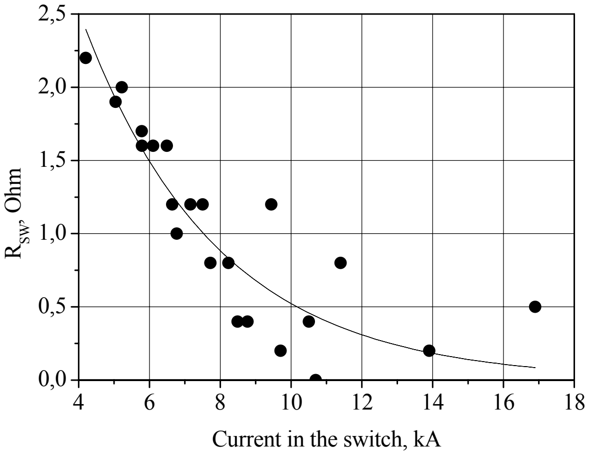

Fig. 4. Resistance of the switch versus current.

The inductance of the switch behaves in similar way (see Fig. 5). It increases ~3 times and reaches ~ (180-200) nH when the current in the switch reduces from ~18 to ~4 kA. Note, that at high current the inductance L_{SW} approaches ~60 nH.

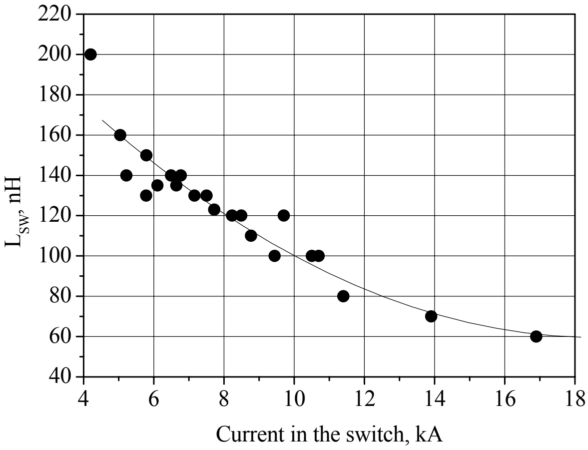

Fig. 5. Inductance of the switch versus current.

4. Discussion

The behavior of the switch resistance versus current is not surprising, many authors already noted and explained this feature. In the same time, it is rather difficult to explain the threefold variation of the switch inductance. In our test the switch locates in the middle of the relatively large cavity and the inductance of the switch can't change significantly with diameter of the spark channel or if the discharge switches from single to multi channel mode within ~28 mm around the axis of the switch.

In attempt to explain our test results another set of Pspice simulation was performed by using S. Braginsky's model of the spark channel [1] for the resistance of the switch.

According to Braginsky, the cross section, *S*, of the spark channel in air is given by the following relation:

$$S = 4600\left(\frac{1}{p\xi\sigma}\right)^{0.33} \int I^{0.67} dt, \qquad (1)$$

where *p* is absolute pressure in ata, *I* is the current per channel in Amperes, $\xi = 4.5$, σ is conductivity in $(\mathrm{Ohm \cdot cm})^{-1}$, *S* is in cm^2, and time is in seconds. The resistance of the switch, R_{BR}, is given then by

$$R_{BR} = \frac{d}{S\sigma} = \frac{d}{4600}\left(\frac{p\xi}{\sigma^2}\right)^{0.33} \frac{1}{\int I^{0.67} dt}, \qquad (2)$$

where *d* is the length of the air gap in cm, R_{BR} is the resistance in Ohms.

The RLC circuit in Fig. 2 was modified, as shown in Fig. 6. The value of L_{SW} is assumed to be 60 nH (minimal inductance at high current in Fig. 5), the resistance R_{SW} is replaced with a block, RBR, which is the current dependent voltage source providing the voltage drop $U_{SW} = IR_{BR}$ between the outputs.

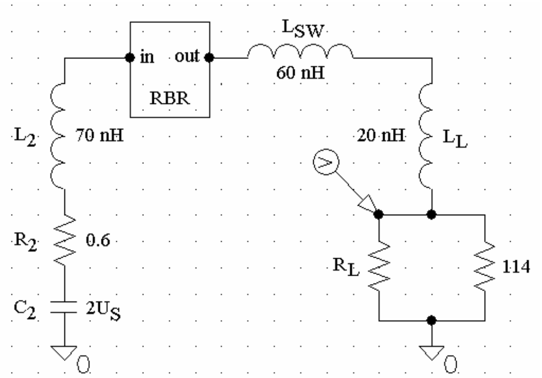

Fig. 6. Pspice schematic with the block RBR representing Braginsky's resistive model.

The example of such simulation is shown in Fig. 7 for R_L = 12.77 Ohm. One may see that to fit the observed voltage amplitude, the simulation requires U_S = ± 98 kV, higher than U_T = ±90 kV. The simulated rise and fall times are longer than in the experiment resulting in FWHM = 84 ns compared to 68 ns measured.

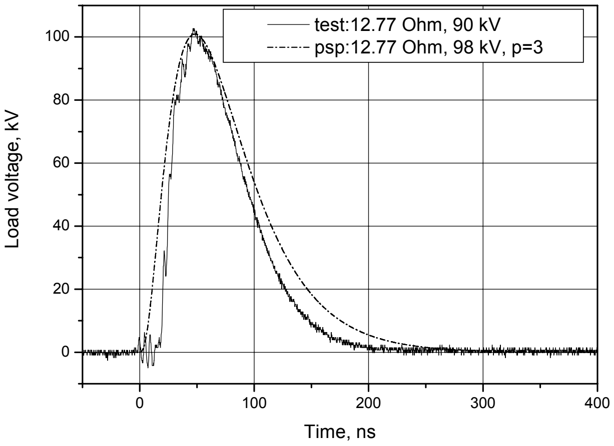

Fig. 7. Comparison between the test and the simulation by using the Eq. (1) with R_L = 12.77 Ohm and U_{CH} = ±90 kV.

There exist at least two possibilities to get better fit with our results by using modified expressions (1-2).

One possibility [3] is to change the coefficient $4600\left(\frac{\sigma^2}{p\xi}\right)^{0.33} \sim 1.2 \cdot 10^5$ for air in Eq. (2) (σ = 300 $(\mathrm{Ohm \cdot cm})^{-1}$, p = 1ata) to ~ $4 \cdot 10^5$. This means $\sigma \sim 1700$ $(\mathrm{Ohm \cdot cm})^{-1}$, that contradicts with Braginsky (σ = 180 $(\mathrm{Ohm \cdot cm})^{-1}$) and Andreev ($\sigma$ = 300 $(\mathrm{Ohm \cdot cm})^{-1}$) [4].

Other possibility is to change the scaling $I^{0.67}$ in Eqs. (1-2) to $I^{0.85}$, and to keep all other terms unchanged. Following T. Martin [5], one can estimate that in this case the energy dissipated in the switch is proportional to $(V_{PEAK}I_{PEAK})^n$, where n = 1.125. This value agrees with T. Martin's exponent of 1.1846±0.1.

Both modifications of Eqs. (1-2) allow fitting our test data in the whole range of R_L and U_{CH} presented in Table 1. Figs. 8-10 show some comparison examples between tests and simulations with modified $I^{0.85}$ scaling. Fig. 8 shows the shot at highest current in the switch with R_L = 5.09 Ohms and U_T = ±100 kV. The simulation fits the experiment with U_S = ± 97.5 kV. Fig. 9 is the shot at smallest current with R_L = 21.4 Ohm and U_T = ±60 kV. Here the simulation requires U_S = ±54 kV. Last shot in Fig. 10 is the same shot as in Fig. 7 at R_L = 12.77 Ohm and U_T = 90 kV. The determined U_S = ±78 kV is similar to the one obtained for a simple RLC circuit (see Table 1).

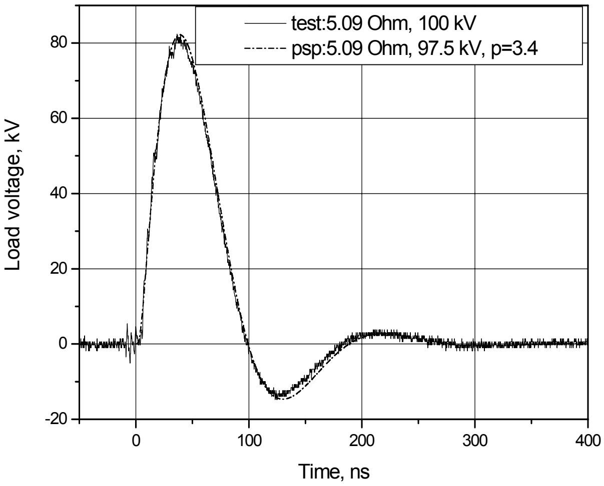

Fig. 8. Comparison between the test and $I^{0.85}$ resistive model at R_L = 5.09 Ohm and U_T = ±100 kV.

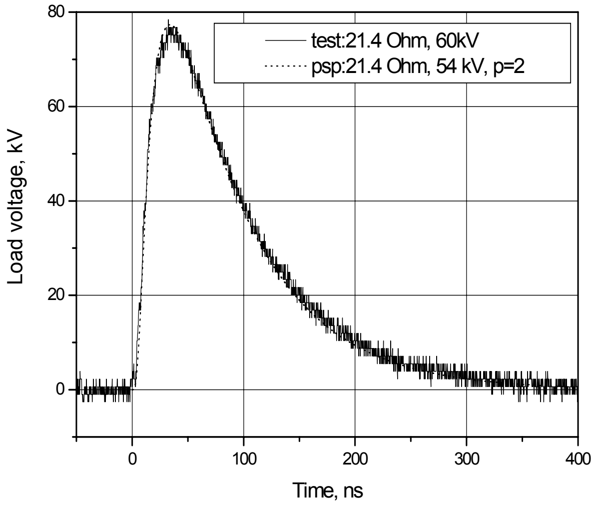

Fig. 9. Comparison between the test and $I^{0.85}$ resistive model at R_L = 21.4 Ohm and U_T = ±60 kV.

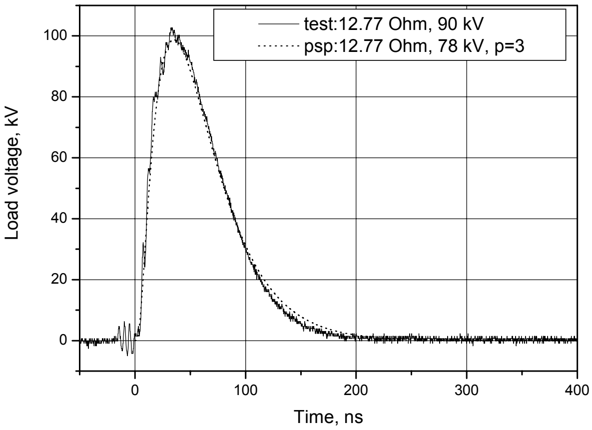

Fig. 10. Comparison between the test and $I^{0.85}$ resistive model at R_L = 12.77 Ohm and U_T = ±90 kV (to compare with Fig. 7).

5. Conclusion

A separate brick consisting of two serial 8 nF capacitors, a bipolar switch (fast LTD type) and a resistive load was tested at different charge voltage and resistance of the load providing fourfold variation of the current in the switch. In case the tests data are simulated as a simple RLC circuit, the resistance and the inductance of the switch have to be increased when the current through the switch reduces.

The modified Braginsky's resistive model allows fitting the test results with high enough accuracy in all conditions tested. It shows that the imaginary variation of the switch inductance with current can be explained as a time-dependent variation of the switch resistance only.

The modified resistive model, benchmarked on an already large current range (4 to 17kA), gives us a tool to simulate the output parameters of a brick consisting of different capacitors, for example with less capacitance if one would like to design an LTD with shorter pulse length.

References

[1] S.I. Braginsky, Rus. J. Exp. Tech. Physics **34**, No. 6, 1548 (1958).

[2] A.A. Kim, B.M. Kovalchuk, A.N. Bastrikov, etc, *in Proc. 13th IEEE Int. Pulsed Power Conf.,* 2001, pp. 1491-1494. See also the report of B.M. Kovalchuk in same Proc., pp. 1739-1742.

[3] A.A. Zherlitsyn, private communication, 2006.

[4] S.I. Andreev, B.I. Orlov, Rus. J. Tech. Physics **35**, No.8, 1411, 1965.

[5] T.H. Martin, J.F. Seamen, D.O. Jobe, *in Proc. 9th Int. Pulsed Power Conf.,* 1993, pp. 463-470.