

Trigger circuit optimization of the oil-insulated LTD cavity

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Abstract. The goal of the research was to reduce the number of external trigger cables needed to trigger the oil insulated LTD cavity. The usual trigger circuit inside LTD cavity is a single wire O-ring and the minimum number of the external trigger cables connected to this O-ring is determined as 1 cable per 10 switches. In recent article LTD cavity of 34 bricks with novel trigger system and special internal trigger brick was represented. In our tests similar trigger system was used but without the internal trigger brick. The LTD cavity of 16 bricks was tested in more than 3000 shots. In all these shots no malfunction was observed. Numerical simulation has shown that up to 40 switches might be successfully triggered by 1 external trigger cable by using both the novel trigger system and a simple wire O-ring. This last prediction was tested in experiment with LTD cavity of 16 bricks in 600 shots and no malfunction was observed also. The results of this research have shown that previous requirement can be reduced to less strict claim of 1 trigger cable per 16 switches.

Keywords: LTD cavity, trigger circuit.

1. Introduction

Pulse power generators based on LTD cavities with oil insulation is leading-edge technology and wide-used at now. LTD cavity has endured significant development since their development more than 20 years ago. Numerous parts of LTD cavity were changed both to improve parameters of output pulse of a generator and to improve the generator lifetime. One of the important points in the generator operation is the triggering of the switches, the number of which in the generator can reach several hundred, with a minimum time spread. However, despite considerable attention paid to the development of gas switches with minimal jitter, the distribution system of the triggering pulse inside the LTD cavity (hereinafter referred to as the distribution system) has not been changed.

The standard distribution system is a single wire O-ring. Switches are connected to the O-ring at uniform intervals in pairs. Cables from the trigger generator are connected to the ring also. The minimum number of the external trigger cables connected to the O-ring is determined as 1 cable per 10 switches. It means, for example, that to trigger the switches of the LTD cavity of 30 bricks there must be at least 3 external trigger pulses. This ratio was determined empirically in the study of the first prototypes of LTD cavity and remains unchanged to the present. Reducing of the number of external trigger cables is important for building the LTD generator from many LTD cavities, since this simplifies the triggering scheme of the generator.

The paper [1] describes an LTD cavity of 34 bricks and a novel trigger system. In this work, the modification consisted of two parts: first, the triggering pulse was formed by a special trigger brick inside the LTD cavity; secondly, in addition to the standard distribution system, a circuit for distributing the pulse from the trigger brick to four evenly distributed points on the O-ring system has been added. Thus, one trigger cable was used to launch the LTD cavity.

The purpose of this work is to study the possibility of triggering more than 10 switches of the LTD cavity from one external trigger cable. In numerical simulation, the LTD cavity model with up to 40 bricks was studied, taking into account the effect of the applied trigger pulse both on the average response time and on the jitter of the switches. In experiments, both the O-ring distribution system and the novel one similar to that described in [1] were studied. Experimental studies were carried out on the LTD cavity of 16 bricks.

2. Numerical model of LTD cavity

The numerical model of the LTD cavity was based the Spice code. The brick model is described in [2, 3]. The switches are connected to the distribution system through a solenoids with an inductance of 5.4 μH. Losses in magnetic core were neglected. The load of the LTD cavity is resistive with a value of 0.8 from the matched load.

Wire of the distribution system was described as uniform transmission line (hereinafter referred to as the Line). The Line parameters as the linear capacitance and inductance of the wire were calculated with account of the design of the LTD cavity. The influence of the LTD cavity housing and capacitors was accounted only. The influence of other elements of LTD cavity was neglected. From Fig.1 it can be seen that a part of the distribution system wire is located between the storage capacitors, which affect the parameters of the Line.

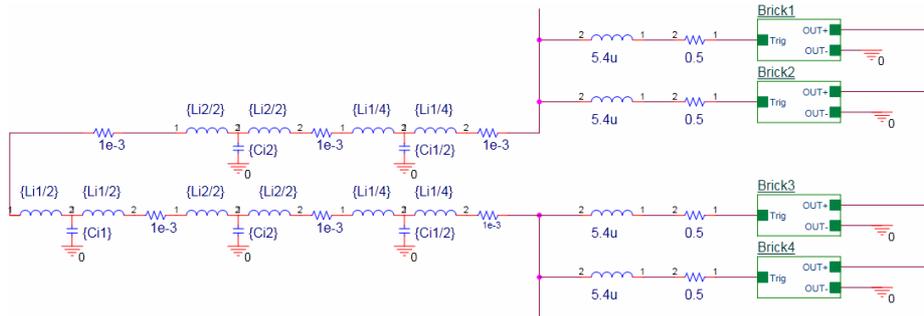


Fig.1. Numerical model of part of the O-ring distribution system between two adjacent points of connection of switches.

Thus, the Line will have a periodically changing impedance. In the section between bricks, this will be the geometry of the wire passing between two endless walls with zero potential, and according to [4], the linear capacitance in this case is determined by the formula:

$$C_0 = \frac{2\pi\epsilon\epsilon_0}{\ln\left(1.27 + \frac{b}{2r}\right)}, \quad (1)$$

where $b = 2h$, h – distance between the wire and the wall, r – radius of the wire.

For transformer oil in LTD cavity $\epsilon = 2.3$. In usual LTD cavity, the distance between wire and the housing wall is $h = 89.5$ mm, and the wire radius is $r = 1$ mm. Then the linear capacity of the distribution system wire is $C_0 = 2.83 \cdot 10^{-13}$ F/cm. Since the Line is considered as uniform, the following relation holds:

$$v = \frac{1}{\sqrt{L_0 C_0}} = \frac{c}{\sqrt{\epsilon}} \quad (2)$$

Taking into account (1) and (2), the value of the linear inductance of the wire in this section is $L_0 = 9 \cdot 10^{-9}$ H/cm. To determine the capacitance of the wire located under the capacitors, it was using formula that takes into account the location a wire near the edge of a wall, and given in [4]:

$$C_0 = \left[\ln\left(4R \sin\left(\frac{\gamma}{2}\right) / a\right) \right]^{-1}. \quad (3)$$

At an angle $\gamma = 90^\circ$ (the wire passes along the edge of the capacitors), $R = 8$ mm, $a = 1$ mm, the linear capacity is $C_0 = 4.10 \cdot 10^{-13}$ F/cm, and the linear inductance, according to (2), is $L_0 = 6.24 \cdot 10^{-9}$ H/cm.

The final model (shown in Fig.1) has five parts between the connection points of the switches: two parts under the bricks, one part as full section between the bricks and two parts as half sections between the bricks. The connection point of the trigger cable divide *LC* chain between bricks into two equal parts.

3. Simulation results

LTD cavities with 20 and 40 bricks were investigated by numerical simulation. For LTD cavity with 20 bricks, the distribution system has three variants: O-ring with one or two trigger cables and a modified distribution system with two connection points on O-ring. For the LTD cavity with 40 bricks, the distribution system has five variants: O-ring with one/two/four trigger cables and a modified distribution system with two or four connection points on O-ring.

The trigger pulse had trapezoidal form with an amplitude of 80 kV and was applied independently to the input of each trigger cable. From Fig.2, the average voltage rise rate is about 1 kV/ns. The trigger pulse with three rise rates of 0.5, 1, and 2 kV/ns was used.

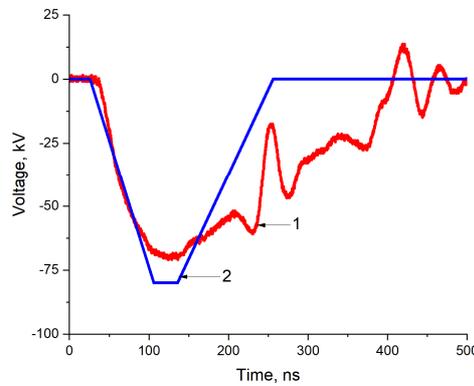


Fig.2. Trigger pulse in experimental (1) and in simulation (2).

Table 1 shows the measurements of the amplitudes of the output pulse of the LTD cavity without taking into account the jitter of the switches. Simulation results of the LTD cavity with the modified distribution system and the LTD cavity with O-ring and ratio 1 trigger cable per 10 switches are matched. Rising of quantity switches up to 20 per 1 trigger cable led to a slight decrease in amplitude of output pulse. Whereas increasing the ratio up to 40 switches per 1 trigger cable already leads to a noticeable decrease in the amplitude of the output pulse.

Table 1. Amplitude of output pulse of the LTD cavity

| | Number of bricks | Distribution system | Number of cables | Amplitude, kV | | |
|---|------------------|---------------------|------------------|--------------------------|--------------------------|--------------------------|
| | | | | ($dU_{tr}/dt = 0.5$ kV) | ($dU_{tr}/dt = 1.0$ kV) | ($dU_{tr}/dt = 2.0$ kV) |
| 1 | 20 | O-ring | 1 | 96 | 96 | 95 |
| 2 | 20 | O-ring | 2 | 96 | 96 | 95 |
| 3 | 20 | Modified | 1 | 96 | 96 | 96 |
| 4 | 40 | O-ring | 1 | 96 | 96 | 93 |
| 5 | 40 | O-ring | 2 | 96 | 96 | 95 |
| 6 | 40 | O-ring | 4 | 96 | 96 | 96 |
| 7 | 40 | Modified 2 points | 1 | 96 | 96 | 96 |
| 8 | 40 | Modified 4 points | 1 | 96 | 96 | 96 |

To estimate the influence of the distribution system on the output pulse jitter of the LTD cavity, the *S* parameter is introduced:

$$S = \frac{\sigma^*}{\sigma_{est}}, \tag{4}$$

where σ^* – the output pulse jitter of the LTD cavity in 600 simulation runs, σ_{est} – the estimated jitter of the output pulse of the LTD cavity. The estimated jitter is calculated by formula in [5]:

$$\sigma_{cavity} = \frac{\sigma_{switch}}{N^{0.5}}, \tag{5}$$

where σ_{switch} – the switch jittering in unit brick, N – number of bricks in the LTD cavity.

The simulation results for the LTD cavity with 20 bricks are shown in Fig.3. The using of a ratio of 1 trigger cable to 10 switches allows to get the lowest S parameter. Reducing the number of trigger cables increases S parameter. Using of the modified distribution system is similar to using O-ring with one trigger cable.

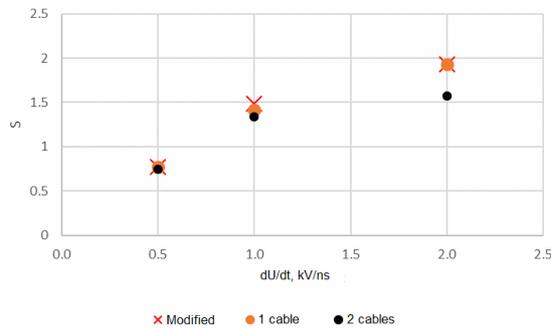


Fig.3. S parameter for LTD cavity with 20 bricks.

The simulation results for the LTD cavity with 40 bricks are shown below. While using O-ring distribution system, reducing the number of trigger cables to two does not practically change the S parameter. But using one trigger cable with O-ring leads to a noticeable increase of S parameter at large values of dU/dt . The transition to a modified distribution system is not unambiguous. In the region of small dU/dt , S parameter will be greater than for O-ring with any number trigger cables. However, in the high dU/dt region, the jitter will be less than for O-ring with one trigger cable.

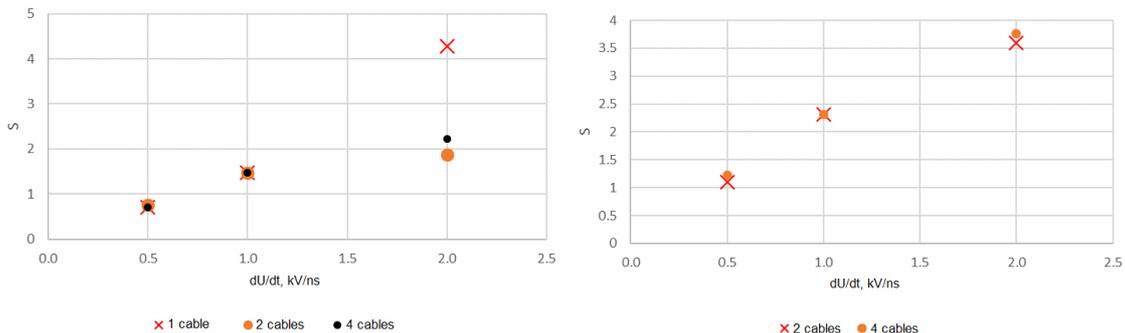


Fig.4. S parameter for LTD cavity with 20 bricks and using O-ring (left) or modified (right) distribution system.

4. Test stand

The oil-insulated LTD cavity of 16 bricks was used for experimental study. The layout elements of the LTD cavity are shown in Fig.5. A distinctive feature of this cavity is a composite central insulator, which allows the use of both O-ring distribution system and a modified one. 16 identical bricks are installed inside the cavity. Each brick consists of two 40 nF capacitors (Part

35426M of General Atomic) (brown in Fig.5) and a Fast LTD switch (orange in Fig.5). Charging voltage up to 100 kV. The magnetic core (blue in Fig.5) consists of 6 rings made of electrical steel ET3425 with a thickness of 50 μm . The total core cross section is $6.12 \cdot 10^{-3} \text{ m}^2$, the average length is 2.16 m. According to [6], the equivalent loss resistance is $\sim 45 \text{ Ohm}$. The load is liquid with an active resistance of 0.22 Ohm, which is close to the match load.

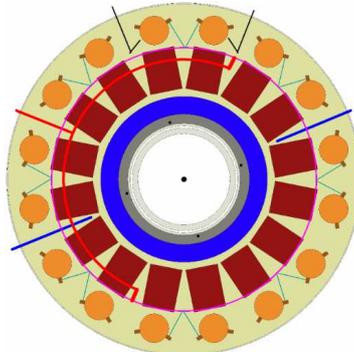


Fig.5. The layout of the elements inside the LTD cavity with 16 bricks.

In Fig.5 the modified distribution system is shown, which, in addition to O-ring (shown in pink), additionally includes additional system (shown in red) for dividing the trigger pulse into two and feeding them to diametrically located points on O-ring. Thus, this system is similar to connecting two trigger cables to O-ring and there are ratio 1 trigger cable per 8 switches. O-ring with one trigger cable has ratio 1 cable per 16 switches. The switches are connected to the distribution system through individual solenoids [2].

The trigger generator consists of a storage capacitor with a capacity of 20 nF, charged up to 100 kV, and a gas switch that connects storage to 4 output cables (KVI-120). One of them was connected to the LTD cavity. The second one was connected to an external divider for recording oscillograms (shown in Fig.2). Unused cables were connected to a dummy load (resistance $\sim 20 \text{ Ohms}$). The registration system included four B-dot sensors for recording output current and external divider for recording output voltage. The locations of the sensors and point connected with divider are shown in Fig.5.

5. Experimental results

The LTD cavity with O-ring distribution system and one trigger cable was tested in up to 800 shots. The LTD cavity with modified distribution system was tested in more than 2500 shots. In all these shots no malfunction was observed. In Fig.6, the output voltage oscillograms are compared for the LTD cavity with O-ring and one trigger cable and the LTD cavity with modified distribution system. When using both the O-ring distribution system with one trigger cable and the modified one, the output pulse has no signs of shape distortion. However, the amplitude of the output pulse of the LTD cavity with O-ring is 8% less than when using the modified distribution system. Since the simulation results assumed a decrease in the amplitude of the output pulse of the LTD cavity with 20 bricks by 1%, then with linear extrapolation, the expected amplitude decrease for the LTD cavity with 40 bricks will be more than 20%. Such a significant decrease of amplitude can be considered a malfunction of the LTD cavity, but it requires experimental confirmation.

A comparison of the delay time of the output pulse of the LTD cavity is shown in Fig.7. Jitter of the delay time depends little on the type of the distribution system. This allows it to say that the decrease in the amplitude of the output pulse is due to the difference in the arrival time of the trigger pulse at the switches, due to the propagation of the trigger pulse along the wire of the O-ring distribution system.

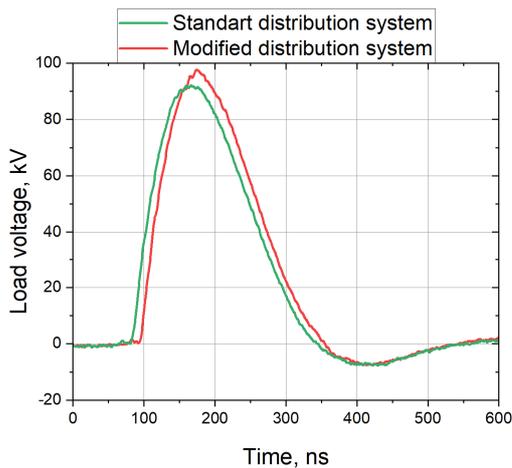


Fig.6. Oscillograms of the output voltage pulse of the LTD cavity with different distribution systems and one trigger cable. The charging voltage is 100 kV, the load resistance is ~ 0.22 Ohm.

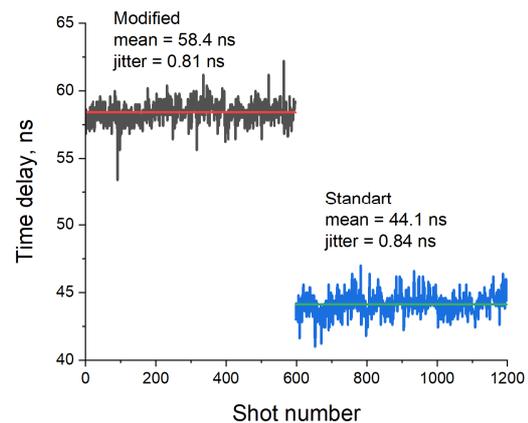


Fig.7. Comparison of the operation delay time of the LTD cavity different distribution systems and one trigger cable for 600 consecutive runs for each option. The charging voltage is 100 kV, the load resistance is ~ 0.22 Ohm.

6. Conclusion

The possibility of launching the LTD cavity with 16 bricks from one trigger cable was experimentally shown using both O-ring distribution system of the trigger pulse and a modified one. This makes it possible to reduce the number of trigger cables required to launch the LTD cavity by a factor of 1.5. However, the using of O-ring distribution system results a decreasing of the output pulse amplitude without changing the jitter.

Numerical modeling of the LTD cavity showed the possibility of triggering up to 40 switches from one trigger cable using a modified distribution system without changing the parameters of the output pulse. Using O-ring distribution system with one trigger cable for triggering 40 bricks is also possible, however, in this case, a significant decrease in the amplitude of the output pulse of the LTD cavity is expected.

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7. References

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