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Optimization of the numerical model of the triggerable LTD spark gap switch

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Abstract. In LTD generators, one of the main parts of the primary discharge circuit is the triggerable spark gap switch. For the cavities with oil insulation, the OrCAD switch model was developed [1–3] by taken into account the effect of the trigger pulse on the triggering time of these switches and its spread. According to the real design, the switch in this model is simulated as a block consisting of six independent spark gaps connected in series. However, because of such detailed description of the switch structure this initial model is quite complex causing significant complications in simulation of the full generator in case it includes numerous switches. To avoid that complexity, in the given paper we investigate the possibility to optimize the initial complex model, and present at the output much less complicated switch model with acceptable simulation error.

1. Introduction

LTD generators are actual areas of development of the pulse power generators, because LTD generator can form sub microsecond pulse without any additional compression system [1, 2]. The generator consists of several of LTD cavities and vacuum transmission lines. The cavity is a toroidal inductor, inside of which is located a capacitive storage with a small time of energy output. Capacitive storage involves the simultaneous triggering of all switches of the cavity for correct operation. The asynchronous triggering leads to the "spreading" of the output pulse of the cavity and, accordingly, to a decrease maximum of power [3]. Therefore, value of jitter of the switch is important for the cavity. Detail study of HCEI switch shows significant dependency value of jitter from voltage rise rate at trigger plate [4, 5]. So, parameters of triggering of the switch are depended from parameters of triggering generator and triggering circuit [6]. This makes it necessary to have a model of the switch, having a calculation of the statistical parameters of triggering of switch with dependency on shape of voltage pulse at triggering plate.

Early we development the numerical model named oLTD, which into account dependency value of jitter from rate of rise voltage at triggering electrode of the switch. Main disadvantage of the oLTD model is significant complexity. In addition, it is necessary to reduce the accuracy of numerical simulation to ensure the convergence in the OrCAD [7] using the PSpice computational code. Even a small decrease in the number of elements in the switch model can significantly reduce the duration of simulation. In this paper, two simplify models are proposed based on investigation of the process of triggering of the numerical model the switch.



2. Analysis of triggering process of the switch

The oLTD switch model is presented in figure 1. According geometry, the switch consists of six equal gaps, are presented by Gap blocks. All electrodes and covers have parasitic capacitance on ground and nearby electrodes. Voltage distribution between electrodes is calculating with accounting parasitic capacitance.

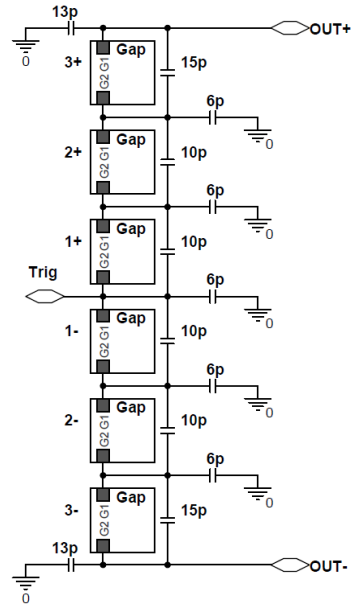


Figure 1. The oLTD switch model with simulation each of six gaps.

Design of Gap block of the oLTD switch model is presented in figure 2.

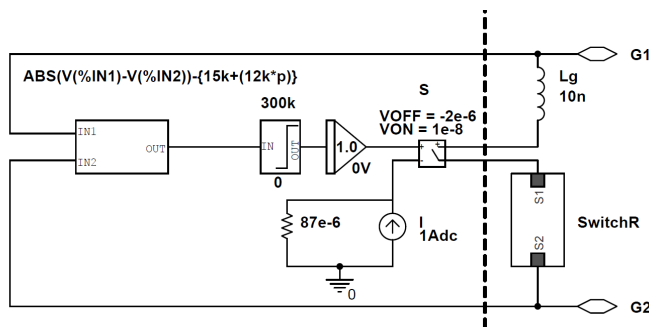


Figure 2. Gap block of the oLTD switch model.

Gap block may be functionally divided into two parts (shown by dashed line). Left part – calculation of breakdown time of the gap based on integral criteria of breakdown [4, 5]. Right part – simulation of discharge channel after breakdown with constant inductance (L_g) and variable resistance (SwitchR block), based on [8].

In order to simplify, reducing the number of simulated gaps is supposed in the switch model, namely either grouping the three gaps of each one-half into one, or replacing all six gaps with one, while keeping all the parameters of the oLTD switch model. To study the possibility of such a simplification, process of triggering of the switch model was investigated in detail. One brick, consisting of two storage capacitors and the switch, was simulated for two charging voltages (± 80 kV and ± 100 kV) and two values of the triggering resistor resistances (300 Ohms and 1000 Ohms). For each combination of parameters 1000 runs were performed, after which measured the statistical parameters of breakdown for each gap.

The simulation results are shown in figure 3. It can be seen, that the gaps of the switch breakdowns in series: the gap “1+”, located closest to the triggering electrode in the positive one-half of the switch,

closes first; then the gaps “2+” and “3+” closes in series; and only then is the sequential breakdown of the gaps of the negative one-half of the switch – “1-”, “2-” and “3-”. It should be noted that the “1+” gap has the lowest voltage rise rate and, accordingly, it will have the biggest jitter. On the remaining gaps, the voltage increases much faster and the spread of the breakdown time for these gaps will significantly decrease.

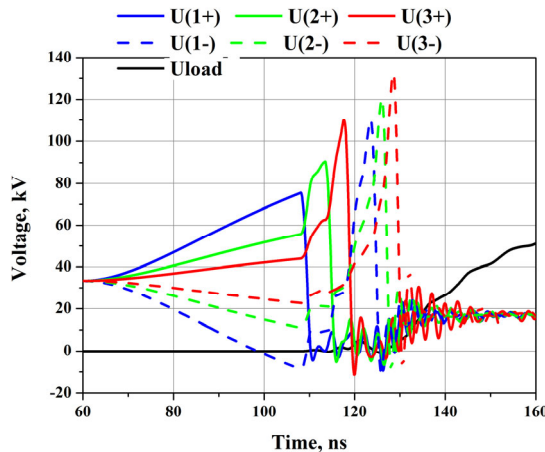


Figure 3. Voltage on gaps of the switch and load voltage.

Results of measure statistic parameters of gap breakdown of the switch are presented in table 1 and table 2.

Table 1. Mean value of time intervals in ns, measured in 1000 runs of simulation of the brick at various value of the charging voltage (U_{ch}) and trigger resistor resistance (R_{trig}).

U_{ch} (kV)	R_{trig} (Ohm)	+	-	All
80	300	9.4	9.0	30
80	1000	10.9	9.3	29
100	300	8.3	5.1	20
100	1000	9.5	4.8	20

Table 2. Coefficient variations of time intervals in %, measured in 1000 runs of simulation of the brick at various value of the charging voltage (U_{ch}) and trigger resistor resistance (R_{trig}).

U_{ch} (kV)	R_{trig} (Ohm)	+	-	All
80	300	5.2	10.6	8.9
80	1000	5.3	6.3	3.8
100	300	5.4	5.9	3.2
100	1000	5.9	5.7	3.4

The column “+” correspond to time interval from breakdown of gap “1+” to breakdown “3+”. The column “-” respectively describes the time interval of negative half of the switch. The column “All” correspond to time interval from breakdown of gap “1+” to breakdown “3-”

From tables 1–2 it follows that, the statistical parameters of the “+” interval weakly depend on value of the charging voltage and the resistance of the trigger resistor. For the “-” interval, the mean strongly depends on the charging voltage, and the coefficient of variation strongly depends on the resistance of the trigger resistor at a reduced charging voltage. For the “All” interval, there is a significant change in both the mean and the coefficient of variation at a reducing charging voltage.

This means that it is necessary to accurately take into account the limits of applicability of the model when simplifying the switch model. In this case, further work will be done only with a charging voltage of ± 100 kV, since it is the main value of charging voltage for the LTD generator. We will consider two options to simplify the switch model: to two half and to whole.

Must be taken account, it is necessary to leave the full Gap model for the “1+” gap for any options to simplify the switch model. This is necessary to ensure voltage fall on the triggering electrode after the breakdown of the first gap, observed in the full model of the spark gap, and affecting the pulse shape in the LTD triggering system of the stage. Thus, in the simplified oLTD switch model with two Gaps, the moments of first gaps breakdown in each half will be calculated by Gap model. The remaining gaps in one-half will close as one gap with a certain time delay. The simplified switch model with one Gap assumes that the moment of breakdown of only the first gap will be calculated by Gap model. Other gaps of the switch will close as one gap with some time delay.

3. Simplified oLTD model with two Gaps

The oLTD model takes into account the following factors: the voltage distribution over the switch's electrodes, calculating the time of breakdown of each gap depending on the voltage applied to it, taking into account the inductance of the discharge channel and calculating the resistance of the discharge channel depending on the current flowing through it. Thus, functionally, the switch model can be represented in the form of three blocks: voltage distribution, breakdown moment, and discharge channel. Consider a way to simplify each function separately.

The system of parasitic capacitances of the electrodes affects the voltage distribution in the switch, and, accordingly, the voltage applied to the “1+” and “1-” gaps. Therefore, to completely abandon the consideration of parasitic capacitances will not work. But we can simplify the system, since it is necessary to monitor the voltage at one gap instead of three. A simplified system of parasitic capacitances is presented in figure 4 (left).

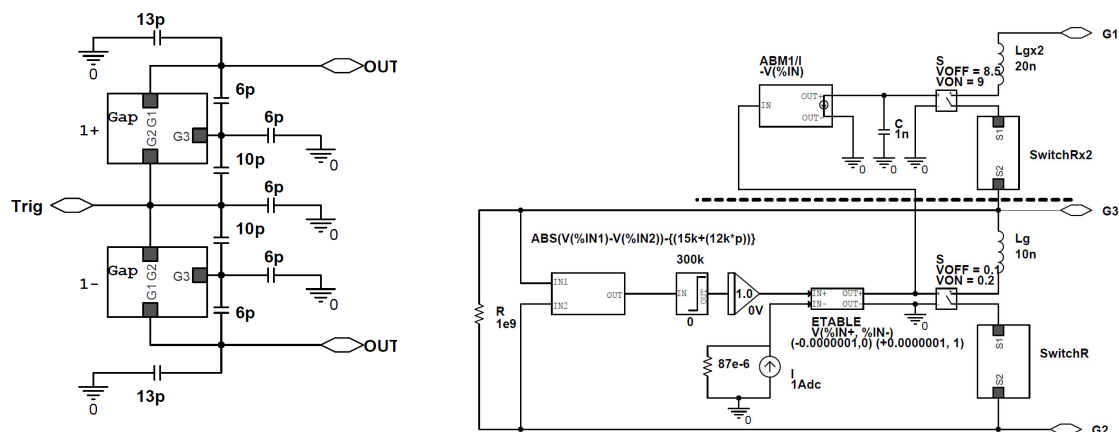


Figure 4. Simplified oLTD model with two Gaps (left) and circuit of Gap block (right).

Simplification of the calculation of the moment of breakdown will be as follows. In each one-half of the switch there will be a serial connection of the standard Gap block of oLTD model and the model of the discharge channel of two gaps with a delay line. The parameters of the delay line are determined by the column in tables 1–2, corresponding to one-half the switch. The implementation of this circuit is shown in figure 4 (right).

The calculation of the parameters of the discharge channel for several gaps is not difficult, since the gaps are connected in series. In this case, it is necessary to sum up the inductance and resistance of the required number of gaps.

The Gap model is located between the G3–G2 pins. ETABLE element added to the Gap model. This element generates a signal to trigger the key S (lower) of the first gap and, through the delay line, generates a signal to trigger the key S (upper) for the remaining two gaps. The block for calculating the resistance of the spark channel of two SwitchRx2 gaps is similar to the SwitchR block, taking into account the formation of the spark channel of two series-connected gaps. Thus, the main simplification of the model is that the calculation of the moment of breakdown is determined for only one gap.

4. Simplified oLTD model with one Gap

A further simplification of triggering of the switch model assumes to account only two points: the moment of breakdown of the first gap and the moment of triggering of the whole switch. To determine the moment of breakdown of the first gap, it is necessary to account the voltage on it. Accordingly, the system of parasitic capacitances of the electrodes is not possible to simplify significantly. Therefore, it remains unchanged, as in figure 4. The add resistors R1 and R2 in figure 5 are necessary for the correct operation of the OrCAD program. The GapALL block has 4 pins: the electrodes of the first gap and the caps of the switch.

The circuit of the GapALL block is shown in figure 5. In comparison with figure 4, a model of the discharge channel of the three gaps of the negative one-half of the switch (the lower third of the circuit) was added to the block circuit. The addition of elements, and not the correction of the coefficients in the existing ones, is connected with the need to ensure the connection of the triggering electrode with the caps of the switch when it triggered. This connection is necessary for correct modeling of the impact of the switch on the triggering circuit of the LTD cavity.

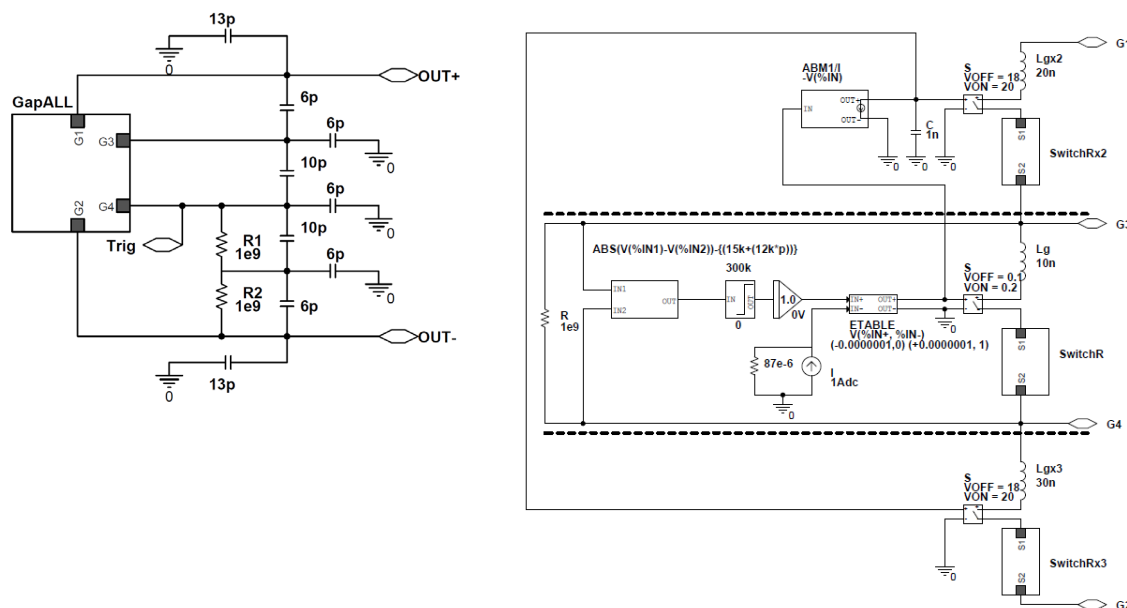


Figure 5. Simplified oLTD model with one Gap (left) and circuit of GapALL block.

5. Analysis of results of numerical simulation with using different type of oLTD models

Initially, the accuracy of calculations in simplified models was verified via full oLTD model. Diagrams of voltages at triggering electrode and matched load are shown in figure 6.

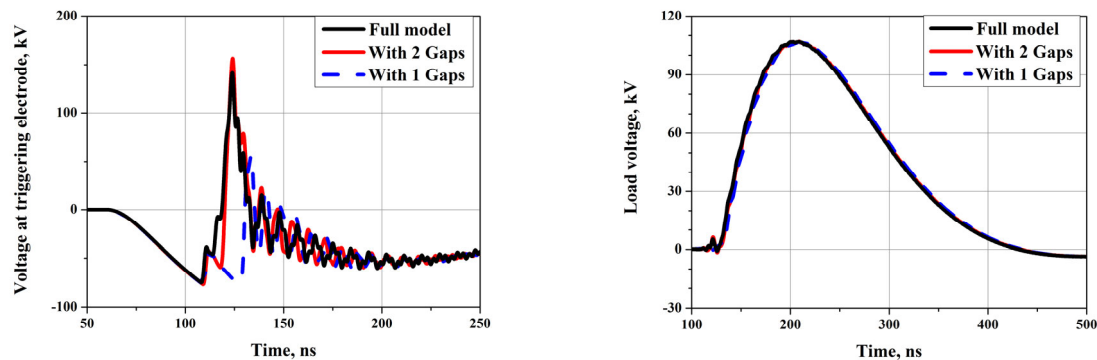


Figure 6. Comparisons diagram of triggering electrode voltage and load voltage at the full oLTD model (black), Simplified oLTD model with two Gaps (red) and with one Gap (dash blue).

From the diagrams it can be seen that calculated voltage fall while breakdown of first gap with different switch models are congruent. Also, the load voltage shape very similar for different models.

Further, the statistical parameters of the brick delay time were determined. This is the time interval from the appearance of the triggering pulse on the triggering electrode to the appearance of voltage on the load. For each variant, 1000 simulation runs were performed. The results of the calculations are given in table 3.

Table 3. Comparisons of statistical parameters of triggering of the brick.

	$U_{ch} = 100 \text{ kV}, R_{trig} = 1 \text{ kOhm}$			$U_{ch} = 100 \text{ kV}, R_{trig} = 300 \text{ Ohm}$		
	Full	Two Gaps	One Gap	Full	Two Gaps	One Gap
Mean (ns)	64.0	64.5	66.0	55.0	56.7	58.6
Variation coefficient (%)	1.04	1.14	1.18	1.07	1.07	1.12

From table 3 it can be seen that the simplification of the switch model leads to a slight increase (of the order of 10%) of both the mean and the coefficient of variation of the delay time. That reliability of the simulation by simplified models remains at an acceptable level. A much more important parameter characterizing the simplification of the model is the execution time of 1000 simulation runs. It is represented in figure 7.

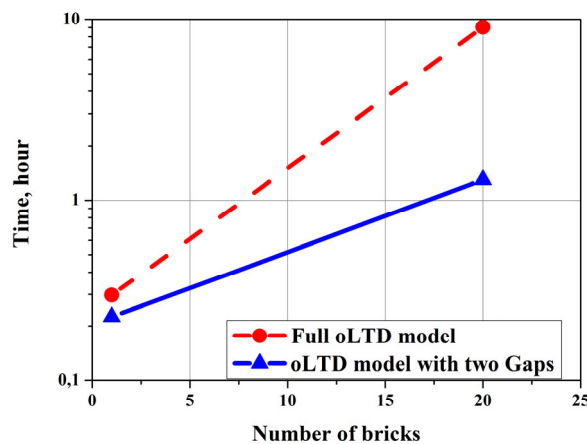


Figure 7. Voltage on gaps of the switch and load voltage.

When using the switch model with two Gaps, the time to perform calculations with one brick is reduced by 10% compared with the full model. When using the switch model with one Gap, the time for performing calculations with one section is reduced by another 10%. However, the situation changes significantly when simulation the LTD cavity with 20 bricks. In this case, the use of a simplified model with one gap allows to reduce the time for performing calculations ~ 7 times. Also, if about 10% of the runs were lost due to not convergence in the OrCAD with full model, then with a simplified model such problems are not observed. Thus, the use of simplified switch models allows to significantly accelerating the simulation of an LTD generator with a large number of switches.

6. Conclusion

Features of triggering process of the switch were investigated for oLTD model. As results, two variants of simplify of the model was proposed. Necessary parameters of simplified models were measured. Numerical simulation shows satisfactory coincidence of simulation results of between full model and simplified models. Computing time slightly decrease for simulation one brick by simplified models, but this decreasing will be significant with rising quantity of bricks. For LTD cavity with 20 bricks this time decreases in seven times.

Acknowledgments

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