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High-voltage pulse sharpening using corrugated NLTLs with ferrites

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Abstract. This article presents a method for reducing the duration of the leading edge of a high-voltage pulse. A model of a 20 Ohm coaxial transmission line with a corrugated inner conductor and ferrite rings was developed using the KARAT code. The conductor itself consists of four parts with different sizes, each of which is designed for different frequencies of excitation of damped oscillations. This made it possible to provide a subnanosecond rise time of the pulse of hundreds of kV at the output of the sharpening system.
Keywords: pulse sharpening, corrugated NLTL, ferrites, multi-section cascade.

1. Introduction

Research work on sharpening the rise time of high-voltage pulses (1 ns and less) remains relevant today. In particular, for a number of practical problems of high-power microwave electronics, it is required to provide a subnanosecond rise times of a voltage pulse with an amplitude of several hundred kV [1]. To solve this problem, sharpening gas spark gaps or non-linear transmission lines (NLTL) with ferrite filling can be used. The sharpening of the high-voltage pulse rise time in an NLTL with ferrite is observed both in the case of unsaturated ferrite and in the case when it is preliminarily saturated in the magnetic field created by an external solenoid. For the problems of microwave electronics, NLTLs are more convenient, since, in addition to providing subnanosecond voltage pulse rise times, they allow one to control the pulse travel speed when using an external magnetic field that preliminarily saturates the ferrite filling. Today, NLTLs with ferrite make it possible to provide a voltage rise rate of a few MV/ns with a subnanosecond rise time for voltage pulses of hundreds of kV [2].

An external magnetic field is necessary not only to control the propagation speed of a high-voltage pulse, but its use in NLTL-based sharpeners makes it possible to further reduce the rise time. If a specific task does not require control of the delay time, then the problem of pre-saturation of the ferromagnetic material without the use of an external solenoid, which seriously increases the dimensions of the system, seems relevant. Moreover, long operation of the solenoid leads to heating of the transmission line and worsen sharpener parameters. As one of the ways to refuse the solenoid, it is possible to use a spiral transmission line in which the ferrites are located inside the spiral [3, 4]. However, the using of pre-unsaturated ferrite will dissipate some of the pulse energy.

Recently [5], the possibility of excitation of high-frequency oscillations in NLTLs with periodically spaced ferrites and permanent magnets has been demonstrated. In this work, the inner conductor of a coaxial transmission line was a corrugated conductor, inside of which a ferrite was located. The saturating magnetic field was created by rings of permanent magnets between which ferrite rings were located. It seems relevant to use a similar design of the transmission line for the tasks of sharpening the leading edge. In this paper, we have experimentally and numerically investigated a way to reduce the rise time of high-voltage pulses using the corrugated geometry of a coaxial transmission line with permanent magnets.

2. Experimental research

To study the sharpening of the leading edge of a high-voltage pulse, an experimental model was developed in the form of a corrugated non-linear transmission line of 19 cells with magnets and ferrites (Fig.1). Ferrite rings 200VNP are located in each cell of the corrugated line. The length of this NLTL is 261 mm, and the total length of the ferrite filling is 81 mm. The dimensions of the corrugated conductor were chosen such that the line impedance, together with the presence of ferrite rings, was 20 Ohms.

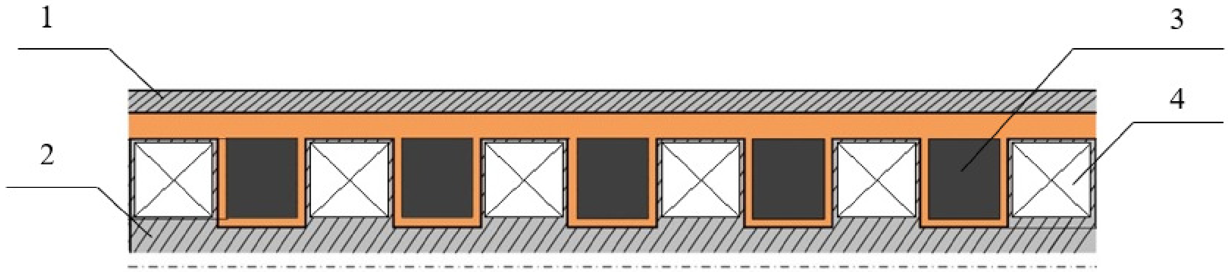

Fig.1. The geometry of a coaxial transmission line with a corrugated inner conductor with ferrites and magnets. 1 – outer conductor; 2 – inner corrugated conductor; 3 – filling with ferrites; 4 – permanent magnets inside the corrugated conductor.

The maximum operating voltage of the line due to electrical breakdown is 100 kV. Inside the corrugated conductor, ring permanent magnets were located with comparable sizes of ferrite rings for their uniform saturation. The diameter of the outer conductor of the NLTL was 20 mm. The scheme of the experimental setup is shown in Fig.2.

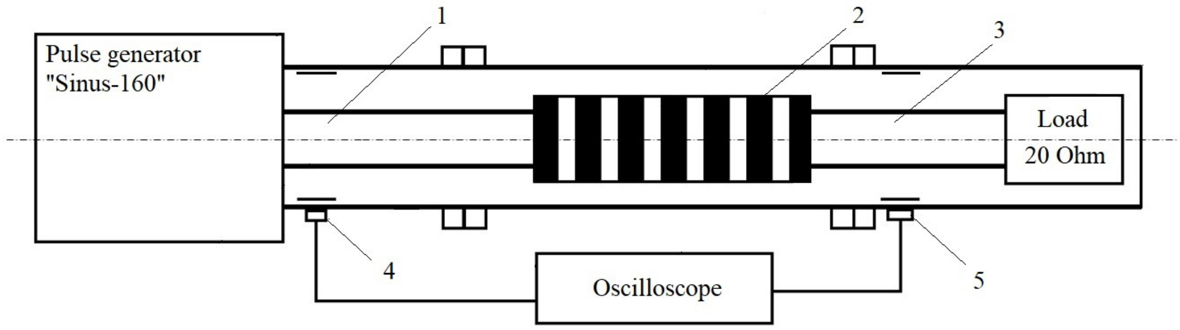

Fig.2 Experimental setup for studying the sharpening of the rise time of a high-voltage pulse. 1, 3 – line 20 Ohm; 2 – studied NLTL; 4, 5– d-dot sensors.

A high-voltage pulse from the Sinus-160 generator was fed through a high-pressure gas discharger to a 20-ohm transmission line, through which it entered the corrugated NLTL All transmission lines were filled with vacuum oil at a pressure of 10 atmospheres with a relative permittivity $\varepsilon = 2.2$. The pulses at the input and output of the corrugated line were recorded by an oscilloscope using d-dot sensors that record the derivative of a high-voltage pulse and have a time resolution of tens of picoseconds. In the experiment, the amplitude of the voltage pulse could vary from 20 to 100 kV.

Fig.3 shows typical waveforms of voltage pulses at the input and output of the NLTL. The incident pulse had an amplitude of 100 kV and a rise time of 3 ns.

In this corrugated NLTL, oscillations with a frequency of approximately 2.5 GHz are observed behind a sharp drop, which corresponds to a stationary rise time of 200 ps. Apparently, because of this, the rise time of 3 ns does not have time to sharpen, and at the output there is a short section of fast voltage rise, which is determined by the time of the transient process in the line.

In order to obtain a complete sharpening of the voltage leading edge, and not its short section, it is proposed to use a sequence of several corrugated NLTLs with different frequencies of excited oscillations, starting from the line at hundreds of MHz to sharpen the initial rise time in a few nanoseconds. The maximum frequency of the last line will be determined by the rise time to be obtained after the sharpening. The length of each line must be such that there are no high-frequency oscillations at its output.

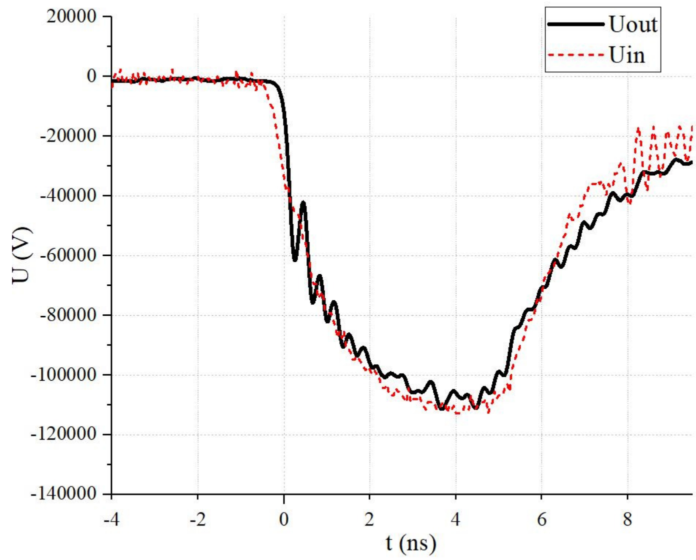

Fig.3. Waveforms of the incident (solid line) and output (dashed line) pulses of the transmission line with ferrites

3. Simulation of the voltage pulse sharpener

Verification of the concept outlined above was carried out using numerical methods. For modeling lines with saturated ferrite, the non-stationary KARAT code has proven itself well.

In the simulation, a sequence of corrugated NLTLs with different frequencies of excited oscillations was developed. The length of each line was chosen in such a way that the amplitude of high-frequency oscillations at its output was small or absent. The dielectric component of the coaxial line between the inner and outer conductors is vacuum oil with a dielectric constant of 2.2. In Table 1 the parameters of each line with ferrite are given.

The length of the lines can also be made shorter, since each subsequent section will reduce the already sharpened pulse rise time from the output of the previous one to the required values. The result at the output of the NLTL cascade is shown in Fig.4. The incident pulse was an ideal trapezoid with an amplitude of 300 kV and a rise time of 2 ns. The specified value of the longitudinal magnetic field strength was 40 kA/m.

As a result, the duration of the pulse leading edge of the multisectional cascade was reduced from 2 ns to 500 ps. The electric field strength between the corrugation and the outer conductor does not exceed the breakdown level.

Table 1. Parameters of corrugated NLTLs with ferrites

Section number	Dimensions of ferrite rings, mm	Line length, mm	Oscillation excitation frequency, GHz	Output pulse rise time duration, ns
1	45×11×8	36	0.7	1.32
2	45×20×8	31	1.3	1.3
3	45×25×8	26	1.6	1.37
4	40×25×8	44	2	1.34

The non-ideal input pulse from the experiments described above was also used in the KARAT code to investigate leading edge reduction. However, four sections were not enough to completely sharpen the rise time of the incident pulse, which is approximately 3 ns. Therefore, another section was added at the input of the cascade, which excites oscillations at a frequency of 300 MHz.

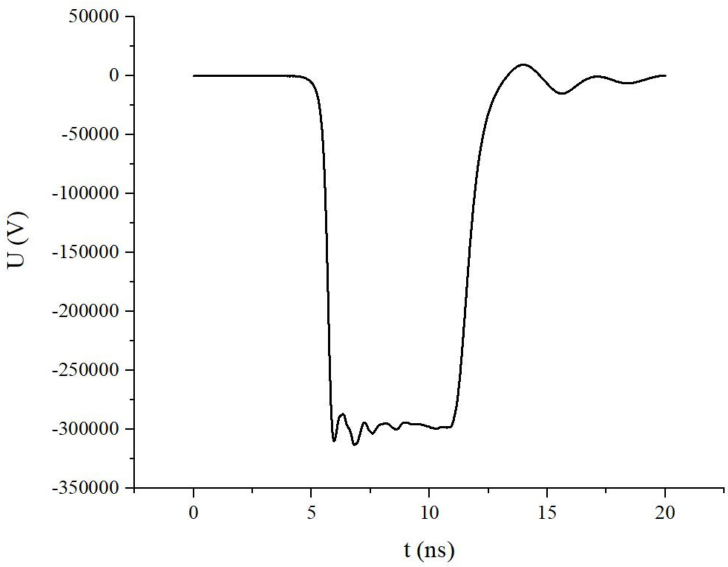

Fig.4. High voltage pulse at the output of the NLTL model in KARAT.

The obtained results were compared with the results of the four-section model and the model of the experimental sample made earlier (Fig.5). The duration of the pulse rise time at the output of the cascade of four parts and the experimental layout turned out to be the same at a level of 0.1 to 0.9. However, a short section at the leading edge of a multi-section transmission line reaches 80 kV, and at the output of the experimental line – 60 kV.

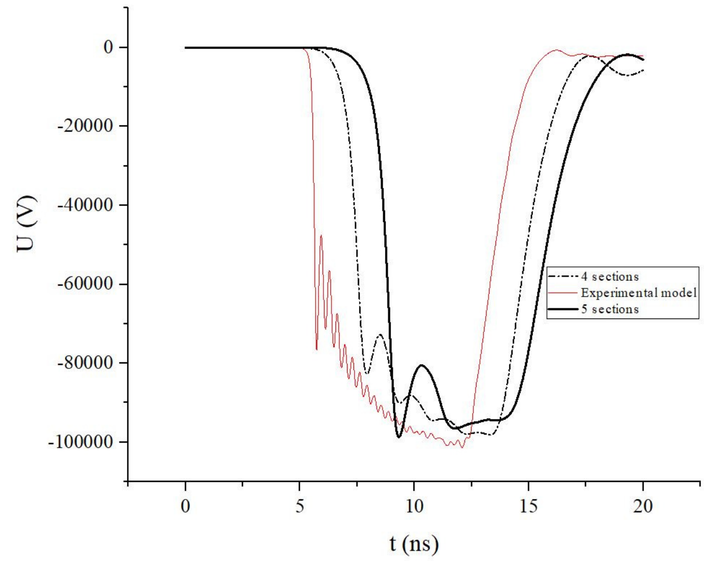

Fig.5. Comparison of the output pulses of the models of the studied sharpeners from 4 (black dash-dotted line) and 5 (black solid line) sections and the experimental sample (red line) in the KARAT code.

A cascade of 5 sections managed to achieve a complete sharpening of the pulse rise time, the duration of which was 1 ns. The observed losses in the pulse amplitude after the leading edge are associated with a small mismatch inside the prototype and require additional optimization of its geometry in the manufacture of an experimental model.

4. Conclusion

In the course of the work done, an effective method for sharpening the duration of the rise time of a high-voltage nanosecond pulse was proposed and studied. Using the KARAT code, a model of a multi-section corrugated transmission line with ferrite filling has been developed, which has a number of advantages over previously studied nonlinear systems. The 300 kV perfect trapezoid pulse rise time has been reduced from 2 to 0.53 ns, which is a very good result for a line of appropriate size. With the addition of the fifth low-frequency section of 300 MHz to the cascade, it was possible to sharpen a non-ideal experimental pulse of 100 kV with a rise time of 3 ns to 1 ns at a level of 0.1–0.9. The results obtained showed that the concept presented in the paper works, and it definitely makes sense to move further in this direction. When implementing fabrication, it will be necessary to optimize the geometry of sharpeners to eliminate existing losses. The longitudinal magnetic field to saturate the ferrites will be provided by permanent magnets located inside the corrugated conductor. This will make it possible to eliminate the use of an external solenoid in the development of high-power nanosecond pulse generators, as well as various systems in solving practical problems of high-power microwave electronics.

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5. References

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