High-voltage pulse rise time decreasing using transmission coaxial and spiral lines with ferrite

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Abstract. This article presents the results of a study of the formation of a short rise time of a powerful nanosecond 410 kV pulse. Ferrite filled coaxial transmission lines with standard inner conductor and construction in the form of a spiral are designed. The sharpening of the pulse occurs due to the appearance of an electromagnetic shock wave in the ferrite. The value of the rise time at the level of 0.1 - 0.9 has been decreased from 4.5 to 2.5 ns.

1. Introduction
The task of reducing the duration of the leading edge of a high-voltage pulse in the development of microwave generators in high-current electronics is still actual today. Excitation of oscillations in such systems arises due to the interaction of the sharpened shock front of the pulse with a line with dispersion properties. Elements with a material with nonlinear dielectric or magnetic properties are usually used for our purpose implementation. The use of a ferrite-filled sharpening transmission line is one way of decreasing the rise time of the high voltage pulse. [1, 2].

This paper presents a sharpening system in the form of a coaxial transmission line filled with ferrite rings. A spiral line was also developed as an inner conductor with ferrites placed inside the spiral. To solve our problem, an experimental setup with 90 Ohm electrodes leading to the dispersion transmission line was assembled.

2. Theory and experimental setup
As is known, the reducing of the rise time of a high-voltage pulse is associated with the dissipation of electromagnetic energy at the leading edge due to energy losses due to magnetization reversal of ferrite. At the beginning of wave propagation along the line, a sharp section appears at the base of its front, called the shock front [3]. The value of the duration of the rise time of a stationary shock wave in a line with ferrite at a level of 0.1 - 0.9 is calculated by the following equation:

\[ t = \frac{1 + \alpha^2}{2\alpha(gf)} f(m_0), \]

where \( \alpha \) – the dissipation coefficient, which depends on the physical properties of ferrite, \( m_0 \) – the ratio of the initial magnetization to the saturation magnetization of ferrite \( (M_s / M_i) \), \( g \) – the gyromagnetic ratio for an electron, \( H_f \) – the magnetic field strength developed in the ferrite behind the pulse leading edge.
According to this formula, with an increase in the value of the magnetic field strength transmitting into the ferrites, the duration of the leading edge of the voltage pulse decreases. This magnetic field strength developed in the ferrite is related to the dispersion line impedance and pulse amplitude in the sharpening system by the following formula.

\[ H_f = \frac{U_f}{\pi D_\Sigma \rho_f} \]

where \( U_f \) – the amplitude of the line voltage pulse, \( D_\Sigma \) is determined by the geometry of the coaxial transmission line, \( \rho_f \) – impedance of the ferrite-filled line.

The maximum slope of the pulse rise when it is formed by the method of an electromagnetic shock wave is limited by the dispersion properties of ferrite. These properties of a nonlinear transmission line with ferrite make it the main element in the generation of extremely short powerful pulses [4, 5]. The above equations do not take into account the inductive component of the spiral transmission line.

A schematic of the experimental setup for studying the formation of a short rise time of a high-voltage pulse is shown in figure 1.

**Figure 1.** Schematic of the experimental setup. 1 – pulse generator, 2 and 4 – 90 Ohm transmission lines, 3 – ferrite rings, 5 – 90 Ohm resistive load, 6 and 9 – voltage dividers, 7 – oscilloscope, 8 – solenoid.

A generator based on a Tesla transformer, through a high-pressure gas spark gap, sends a pulse to a 90 Ohm transmission line with an inner conductor diameter of 27 mm and an outer conductor diameter of 250 mm. The input voltage pulse has an amplitude of 410 kV, a duration of 22 ns, and a rise time at a level of 0.1 - 0.9 is approximately 4.5 ns. Two voltage dividers installed after the generator are required to determine the impedance of the ferrite line. The signal from the second divider will go to the oscilloscope with a pulse reflected from the dispersion line superimposed on the input one. The problem of matching with the impedances of the lead electrodes was solved by placing an outer conductor with a diameter of 150 mm inside the line. In addition to the azimuthal magnetic field created by the incident pulse, the ferrites will also be affected by the external longitudinal field reached by the solenoid. The solenoid itself was installed on the outer conductor of the coaxial transmission line. Ferrite rings with external and internal diameters of 45 and 28 mm were used, and the filling length was 500 mm. The system is also filled with transformer oil to prevent unwanted breakdown voltage.

3. Simulation and experimental results

3.1. Coaxial transmission line with standard inner conductor

A model of a 90 Ohm coaxial transmission line with ferrite filling was built using CAD CST Studio Suite. Figure 2 shows the results of modeling the propagation of the azimuthal magnetic field and the values of its strength.
Figure 2. Propagation of a magnetic field in a 90 Ohm transmission line with a ferrite (the model is shown in cutting plane section). 1 - filling with ferrite rings; 2 - inner conductor of the coaxial line.

The value of the magnetic field strength created by the incident voltage pulse with an amplitude of 410 kV and penetrating into the ferrites is 42 kA/m. The values of the rise time of high-voltage reverse voltage pulses are shown in figure 3.

Figure 3. Oscillograms of the values of the leading edge of voltage pulses.
The differences between these three output pulses, shown in the figure above, are the addition of an external magnetic field to the transmission line with ferrite, created by an external solenoid. As a result, with a leading edge of the incident pulse of 4.5 ns, the output value at a level of 0.1 - 0.9 was 3.2 ns without an external MF, 2.9 ns at 7.5 kA/m of the external field, and 2.7 ns at 15 kA/m. The duration of the input pulse is 22 ns, and the output pulse is about 20 ns with a difference of up to one hundred picoseconds. Using the first two voltage dividers, the dispersion line impedance was determined to be 115 Ohm.

3.2. Coaxial TL with an inner conductor in the form of a spiral

Figure 4 shows a CST model of a spiral transmission line. The strength of the longitudinal magnetic field of the incident pulse inside the spiral is 52 kA/m. It should be noted that the longitudinal magnetic field is evenly propagated inside the spiral line.

![Figure 4. Propagation of a magnetic field in a spiral line with a ferrite inside (the model is shown in cutting plane section) 1 – spiral line. 2 – filling with ferrite rings.](image)

The line consists of 17 enamelled copper wires with a diameter of 1.4 mm, connected in parallel (see figure 5). This number of spirals is due to the need to match the 90 Ohm lead electrodes.

![Figure 5. Photo of the manufactured spiral transmission line.](image)

The number of turns of each spiral is 6. It was chosen based on the search for an optimal solution between impedance matching, the level of magnetic and electric fields [6]. A caprolon frame was also used for an even arrangement of the spirals. Ferrite rings with outer and inner diameters of 32 and 20
mm and filling length of 460 mm are placed inside the line [7]. The results of reducing the leading edge of the pulse are shown in Figure 6.

![Figure 6](image.png)

**Figure 6.** Comparison of the pulse rise time of the spiral TL with the rise time of the line pulse of the previous design (without additional bias).

An input voltage pulse with unchanged parameters was applied to the transmitting spiral line. As a result, the rise time was 2.5 ns, which is 200 ps less than the value using the previous version of the line with an external magnetic field of 15 kA/m. The duration of the output pulse remained unchanged and equal to approximately 20 ns.

4. Conclusion
In the course of work and research into the decreasing of the front of a powerful nanosecond pulse, the designs of dispersive transmission lines filled with ferrite were developed and applied. As a result, the line with a standard conductor was able to reduce the value of the pulse rise time from 4.5 to 3.2 ns, and with the addition of an external longitudinal magnetic field, to 2.7 ns. Using a spiral transmission line, this value has been improved by reducing the front to 2.5 ns without adding an external magnetic field. It should be noted that the volume of ferrite filling in the spiral transmission line is less than in the standard coaxial line, by almost 50%, and the level of the magnetic field in the ferrite, created by the incident pulse, is 20% higher. The use of a spiral line can eliminate the need to design and manufacture an external solenoid for additional ferrite magnetization. And this, of course, will affect the cost of the system for the better in the design and manufacture of generators of powerful nanosecond microwave pulses. This work was supported by IHCE State task by the Ministry of Education and Science of the Russian Federation (Grant No. 0291-2019-0001).

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