Radiopulse generation in dispersive nonlinear transmission lines with gas dischargers

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Abstract. The problem of excitation of high-frequency oscillations in a transmission line with gas dischargers is considered. The main patterns of the generation of radio pulses during the propagation of a shock electromagnetic wave in lines with dispersion and gas dischargers are revealed. The conditions for the most efficient conversion of energy of a video pulse into energy of a radio pulse are found.

1. Introduction
The study of nonlinear transmission lines for pulse front sharpening and generating of radio pulses has been going on for almost 50 years, and the lines themselves are used in a number of different applied problems. At present, nonlinear transmission lines (NLTLs) used to generate radio pulses can be divided into lines with lumped parameters and lines with longitudinal filling [1-3]. As for lumped lines, circuits using nonlinear capacitances and inductances are currently being actively developed, which energy characteristics are significantly lower in comparison with lines with uniform filling, but at the same time, they are very compact devices [4-6]. Of practical interest is the creation of new NLTL schemes with lumped parameters with improved characteristics.

The generation of radio pulses in lumped NLTLs using nonlinear capacitances, inductances, or combinations thereof occurs during the propagation of a sharpening voltage pulse in a dispersive line. One of the disadvantages of such nonlinear elements is that the front of the pulse sharpening in the line occurs at a certain length of the line, which imposes certain restrictions on the size of the lines. For the formation of a shock wave in the transmission line, it is possible to use gas dischargers capable of providing subnanosecond current rise times. The use of dischargers in each cell of an LC-line can allow the formation of a voltage pulse with a short front after each cell of the line. The formation of an equally short front in a line with non-linearity on capacitors or inductances occurs after several cells of the line. Earlier, the generation of high-frequency pulses was demonstrated in a model of an NLTL with gas dischargers [7].

2. RF excitation in a line with gas dischargers

2.1. LC lumped line
When a pulse propagates in a line in which each LC cell contains non-linear elements, the formation of oscillations occurs when the duration of the voltage rise time becomes less than the time determined...
by the cutoff frequency of the artificial line. The critical frequency in the line is due to dispersion in the LC-line. The dispersion ratio for the LC line has the form

$$\omega^2 = 4\omega_0^2 \sin^2(lk / 2),$$

where $\omega_0 = 1 / \sqrt{LC}$, $L$ is the inductance of a link of the line, $C$ is the capacitance of a link of the line, $l$ is the period of the system. The line cutoff frequency $\omega_c = 2 / \sqrt{LC}$ is the frequency at which the group velocity of the wave in the line is equal to zero.

It is not analytically possible to consider the process of excitation of oscillations in artificial lines with gas dischargers representing nonlinear resistances in the line equivalent circuit analytically. To solve this problem, it is necessary to use the numerical integration of the Kirchhoff’s equations together with the equation describing the nonlinear resistance represented by the discharger. The Rompe-Weizel model for the resistance of the spark channel [8] was chosen as the model for describing the dischargers, since this model describes the one-spark dischargers quite well and is convenient for use in numerical simulation. Using the Rompe-Weizel formula, we can write a differential equation to describe the conductivity of the spark channel of a spark gap with $a$ gap $d$ and pressure $p$. Parameter $a$ determines the type of gas of the spark gap.

$$R(i, t) = d / \sqrt{2a / p \int i^2(t) dt}, \quad \frac{d\sigma(i, t)}{dt} = \frac{a}{d^2 p} \frac{i^2(t)}{\sigma(i, t)}. \quad \text{(1)}$$

A scheme of an LC line with gas arresters is shown in figure 1 a. The dimensionless Kirchhoff equations for the n-th link of the line have and equation for conductivity have the form

$$\frac{di_n}{d\tau} = u_{n-1} - u_n - \frac{i_n}{\sigma_n}, \quad \frac{du_n}{d\tau} = i_n - i_{n+1}, \quad \frac{d\sigma_n}{d\tau} = A \frac{i_n^2}{\sigma_n}. \quad \text{(2)}$$

Here $A = aU_0^2 \sqrt{LC} / d^2 p$ is a dimensionless parameter that determines the properties of the gas discharge gap in the LC circuit. Typical values for parameter $A$ realized in the experiment range from hundreds to several thousands, depending on the type of gas. All calculations were performed for the value of the parameter $A = 1000$. Figure 2 shows the transformation of a semi-infinite pulse during its propagation in an LC line with gas dischargers of 60 cells.

It can be seen from the results that, since the sharpening of the front of the incident pulse occurs in each cell of the line, already after the pulse travels a certain length in the line, a train of oscillations is formed. It should be noted that the generated oscillations train has small amplitude and fixed oscillation frequency. The frequency is 0.8 of $\omega_0$. The limitation associated with significant losses in the line caused by the residual resistance of the dischargers is imposed on the number of oscillations in the radio pulse and on the maximum number of cells in the line. For this model, the residual resistance of a discharger in the line is in the range from 0.1 to 0.2 of the impedance of the line.

$$\frac{d\sigma}{d\tau} = A \frac{i^2}{\sigma}, \quad \text{(3)}$$

Figure 1. Schemes of transmission lines with gas dischargers. a - LC line, b - line with spatial dispersion in the form of capacitive links, c - line with spatial dispersion in the form of cross link capacitators.

To increase the modulation depth and the length of the oscillation train, one can switch to lines with stronger dispersion. If we consider the case when a finite duration pulse is applied to the line input, in this case the efficiency of converting the energy of a video pulse into a radio pulse does not exceed 5%.
The main advantage of using such a line to excite high-frequency oscillations is the simplicity of its design.

![Graph showing transformation of a semi-infinite pulse in an LC line with gas dischargers. Waveforms in 20, 40 and 60 cell of the line.](image)

**Figure 2.** Transformation of a semi-infinite pulse in an LC line with gas dischargers. Waveforms in 20, 40 and 60 cell of the line.

2.2. **LC-line with spatial dispersion in the form of capacitive links**

If we consider a line with a more complex dispersion, then it is obvious that when a shock wave propagates in it behind its front, those waves whose phase velocity is equal to the velocity of the shock wave front and the group velocity must be less than the front velocity for effective energy outflow will be excited. The difference between the group velocity and the velocity of the shock wave front determines the line length necessary to generate a given oscillation train.

An example of a line with spatial dispersion can be the line shown in figure 1 b. This line is a line with spatial dispersion in the form of capacitive connections of line cells. The dispersion expression for this line has the form

$$\omega^2 = \frac{4\omega_0^2 \sin^2 (lk / 2)}{4\gamma \sin^2 (lk / 2) + 1},$$

where $\gamma = C' / C$ is a parameter that determines the dispersion of the line. One of the advantages of this line is the possibility of changing the frequency of the excited oscillations when changing the value of the parameter $\gamma$. Kirchhoff equations in dimensionless form for the nth cell of the line have the form

$$\frac{d\sigma_n}{d\tau} = \frac{i_n}{\sigma_n} - i_{n+1} \frac{d}{d\tau} (u_n - 2u_{n+1} + u_{n+2}), \frac{d\sigma_n}{d\tau} = A \frac{i_n^2}{\sigma_n}.$$  

The results of calculations of a typical transformation of a semi-infinite pulse in a line of 100 cells at $\gamma = 0.5$ are presented in figure 3.
At the beginning, the pulse from the generator is sharpened on the dischargers, then due to the presence of dispersion in the line, when the duration of the shock wave front becomes comparable to the period of the synchronous wave in the line, oscillations begin to be excited and the front becomes longer. Such a process occurs along the entire length of the line, which leads to the transformation of the video pulse into a radio pulse. Compared with the LC line, in the presence of capacitive links, a slightly longer oscillation train with a slightly larger amplitude is formed in the line. As a result, the efficiency of converting a video pulse of finite duration into a radio pulse in these calculations is approximately 7%. By changing the parameter $\gamma$, the frequency of the excited oscillations can be changed in the interval from 0.4 to 0.8 of $\omega_0$. When the parameters were varied in the calculations, the formation of a quasistationary wave train was not observed. When the line length is not too long, several oscillations of the same amplitude are formed, but then the waveform ceases to be quasistationary. This is because the pulse propagates in a lossy line because the dischargers have residual resistance. Because of this, the amplitude of the shock wave (in other words, the amplitude of the pulse itself) decreases as it propagates in the line, therefore, its spectrum changes, and in this case it is no longer possible to talk about the formation of a quasistationary generation mode and synchronism with a wave of a certain frequency.

2.3. LC line with spatial dispersion in the form of cross link capacitors

Another example of a spatial dispersion line is an LC-line with cross capacitive links. Such a line has been well studied both theoretically and experimentally for the case of nonlinear inductances [6, 9]. A cross-link line scheme is shown in figure 1 c. The dispersion ratio for the line has the form

$$\omega^2 = \frac{4\omega_0^2 \sin^2 lk / 2}{4\gamma \sin^2 lk + 1}.$$ 

The Kirchhoff equations for a given line have the form
The results of calculations of a typical transformation of a semi-infinite pulse in a line with 100 cells with cross link capacitors at $\gamma = 0.1$ are presented in figure 4.

Figure 4. Transformation of a semi-infinite pulse in a line with cross link capacitors. Waveforms in 20, 40, 80, 100 cells of the line.

In the case of cross capacitive links, the formation of a quasi-stationary oscillation train is also not observed. A significant increase in the amplitude of the excited oscillations is observed in comparison with other configurations. The maximum value of the efficiency of converting the energy of a video pulse into a radio pulse in a line with cross link capacitors can be 10%. This fact makes this line configuration energetically more advantageous. The frequency of the excited oscillations with $\gamma$ changes in the interval from 0.2 to 0.8 of $\omega_0$. Due to the presence of significant losses in the line, a limitation is imposed on the number of oscillations obtained in this way.

3. Conclusion
Using numerical simulation, three configurations of transmission lines with gas dischargers for generating nanosecond radio pulses are considered. The results showed that all the configuration allow for direct transformation of videopulse into RF pulse. The estimated frequency range of generation of such lines is in the range from hundreds of megahertz to several gigahertz. The calculation results show that the cross capacitive coupling configuration can be energetically favorable. However, from the point of view of practical implementation, it may turn out to be more complex than a line with capacitive couplings. The main advantage of using gas dischargers is the reduction in the number of line cells needed to generate a radio pulse of the required duration. At the same time, the presence of residual resistance imposes a limit on the maximum line length. Today, for nanosecond pulse sharpening, there is an alternative to gas dischargers, which can greatly reduce the dimensions of the devices and, judging by some publications, are more effective in use since they have low residual resistance - these are semiconductor switching diodes (GaAs, Si) operating on a self-breakdown, called solid state arresters in some literature. The use of such devices instead of gas dischargers can increase the efficiency of the considered oscillation excitation scheme.
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