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INVESTIGATION OF AMPLITUDE-TEMPORAL CHARACTERISTICS OF A HIGH-VOLTAGE RESISTIVE VOLTAGE DIVIDER

Purpose. Determination of the possibility of using the developed autonomous voltage divider for measuring high-voltage pulses with sharpened fronts (down to 1 ns). Methodology. We use the technique to determine the division ratio of the divider using a calibrated oscillator and oscilloscope. To determine the rise time of the transition characteristic of the divider, we use an experimental technique based on a high-voltage pulse generator with a steep front and computer simulation using circuit program Micro-Cap. Results. Oscillograms of high-voltage nanosecond pulses with subnanosecond fronts are experimentally obtained using an autonomous resistive voltage divider. A computer simulation of the operation of the created divider in various modes is carried out. Originality. We have shown that an autonomous shielded resistive high-voltage voltage divider can have a rise time less than 1 ns. The values of the parasitic parameters of the divider, which lead to a distortion of the sharpened pulse front with a rise time of ≈0.1 ns, are established. Practical value. The divider can be used to measure the characteristics of high-voltage pulses with a steep front (up to 1 ns as the lower limit). References 7, figures 15.
Key words: **voltage divider, high-voltage pulse generator, computer simulation, electrical circuit, rise time, transient response, pulse front.**

Мета. Визначення можливості використання розробленого автономного дільника напруги для вимірювання високовольтних імпульсів з загостреними фронтами (до 1 нс). Методика. Застосовано методику визначення коефіцієнта ділення дільника за допомогою каліброваного генератора і осцилографа. Для визначення часу наростання перехідної характеристики дільника використовувалась експериментальна методика на основі генератора високовольтних імпульсів з крутим фронтом і комп'ютерне моделювання з використанням програми схемотехнічного моделювання Micro-Cap. Результати. Експериментально отримано осцилограми високовольтних наносекундних імпульсів із субнаносекундними фронтами за допомогою створеного автономного резистивного дільника напруги. Проведено комп'ютерне моделювання роботи створеного дільника в різних режимах. Наукова новизна. Показано, що автономний екранований резистивний дільник високої напруги може мати час наростання менше, ніж 1 нс. Установлені величини паразитних параметрів дільника, що викликають викривлення загостреного фронту імпульсів з часом наростання ≈0,1 нс. Практична значущість. Дільник можна застосовувати для вимірювання характеристик високовольтних імпульсів з крутим фронтом (до 1 нс у якості нижньої границі). Бібл. 7, рис. 15.
Ключові слова: **дільник напруги, генератор високовольтних імпульсів, комп'ютерне моделювання, електрична схема, час наростання, перехідна характеристика, фронт імпульсу.**

Цель. Определение возможности использования разработанного автономного делителя напряжения для измерения высоковольтных импульсов с обостренными фронтами (до 1 нс). Методика. Применена методика определения коэффициента деления делителя при помощи калиброванного генератора и осциллографа. Для определения времени нарастания переходной характеристики делителя использовалась экспериментальная методика на основе генератора высоковольтных импульсов с крутым фронтом и компьютерное моделирование с использованием программы схемотехнического моделирования Micro-Cap. Результаты. Экспериментально получены осциллограммы высоковольтных наносекундных импульсов с субнаносекундными фронтами при помощи созданного автономного резистивного делителя напряжения. Проведено компьютерное моделирование работы созданного делителя в различных режимах. Научная новизна. Показано, что автономный экранированный резистивный делитель высокого напряжения может иметь время нарастания менее 1 нс. Установлены величины паразитных параметров делителя, приводящих к искажению обостренного фронта импульсов с временем нарастания ≈0,1 нс. Практическая значимость. Делитель можно применять для измерения характеристик высоковольтных импульсов с крутым фронтом (до 1 нс как нижней границы). Библ. 7, рис. 15.
Ключевые слова: **делитель напряжения, генератор высоковольтных импульсов, компьютерное моделирование, электрическая схема, время нарастания, переходная характеристика, фронт импульса.**

Introduction. In high-voltage pulse technology, the solution of the problem of measuring nanosecond differences (first of all, fronts) of high-voltage pulses at different loads is relevant [1-5]. In the work, the results of which are presented in [6], a compact autonomous resistive shielded low-resistive voltage divider (ARSLVD) is developed and tested to measure the record amplitude-temporal characteristics of high-voltage pulses from a generator in an apparatus for broadband electromagnetic pulse therapy (ABEMPT). The generator design is described in [6]. If the generator in ABEMPT operated without the use of a sharpening of the pulse front, then the voltage divider transmitted the expected pulse shape, including its front (≈2.5 ns), without distortion. If the mode of operation of the generator with the sharpening of the pulse front was used, then the divider introduced significant distortions at the front of the measured pulses. To register pulses from an ABEMPT generator, a C7-19 analog oscilloscope with a 5 GHz bandwidth was used. It is known [2] that for a satisfactory measurement of the amplitude-temporal characteristics of pulses, the rise time of the transient characteristic of a voltage divider (VD) should be noticeably shorter than the measured pulse front duration. Since the sharpening of the pulse front using spark gaps – sharpeners leads to a shortening of the front by about 10 times, the required rise time of the transient characteristic of the voltage divider used should be shorter than 0.2 ns for measuring pulses with sharpened fronts without significant distortion.

The definition of a scientific problem and the justification of its relevance with the identification of unsolved problems. In high-voltage pulse technology there is the problem of measuring the amplitude-temporal characteristics of high-voltage pulses with high accuracy [1]. Its relevance is determined by the fact that for different high-voltage electrical technologies, radars, high-voltage tests of various equipment high voltage pulses with a very steep front (units ns or less) are required [1-5].

The goal of the work is the determination of the possibility of using the developed autonomous voltage divider for measuring high-voltage pulses with sharpened fronts (up to 1 ns).

Tasks that need to be solved to achieve the goal:

- to determine the rise time of the transient response of an autonomous compact resistive voltage divider developed;
- to create a computer model of a two-stage resistive voltage divider;
- to determine what caused the appearance of high-frequency oscillations with large amplitude at the front of the measured high-voltage pulses with an extremely steep front (0.1 ns);
- to determine whether a combination of a short transient response (less than 1 ns) of the created autonomous voltage divider with a large division ratio (more than 500) is possible.

The circuit, the design of the divider and the experimental results to determine its division ratio and the rise time of the transient response. The first mention of the divisor considered in this paper is in [6]. The electric circuit of the divider is shown in Fig. 1.

According to measurements made with a multimeter M890G, R_1 = 73.8 Ω, R_2 = 3 Ω, R_3 = 23.9 Ω, R_4 = 1.7 Ω, R_5 = 47.2 Ω taking into account the uncertainty (error) in the readings of the multimeter of 0.4 Ω.

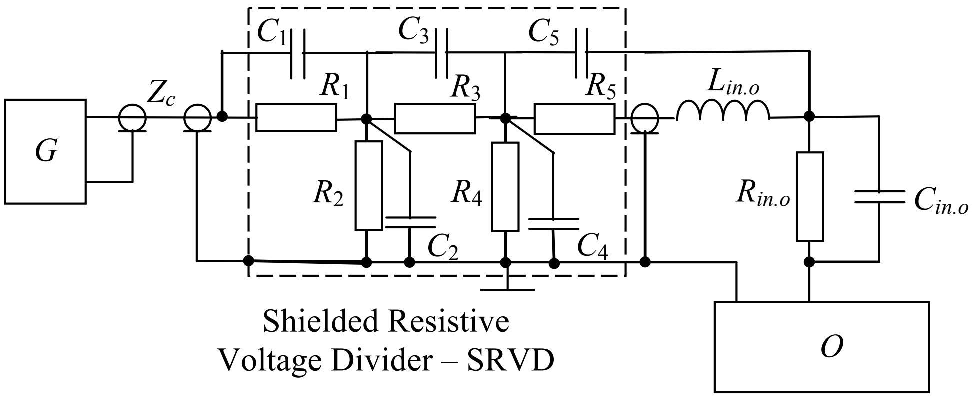


Fig. 1. The electrical circuit of the system of the generator G of pulses, resistive divider taking into account the parasitic capacitances and inductance $L_{in.o}$, coaxial broadband connecting cable with a characteristic impedance Z_c = 100 Ω and oscilloscope with input resistance $R_{in.o}$, input capacitance $C_{in.o}$

The divider is designed and manufactured as autonomous, collapsible in an aluminum case. At the input and output of the divider, coaxial connectors-sockets CP-50-165ФВ are applied, the pulsed electrical strength along the insulation surface of which determines the maximum allowable working voltage of the divider. Photo of the divider is presented in Fig. 2. The divider is made on the volume resistors TBO-1, TBO-0,5 and TBO-0,25 and is two-stage. The first stage is formed by the resistances R_1 (high-voltage arm of the first stage of the divider) and R_2 with a chain connected in parallel to it (the low-voltage arm of the first stage of the divider), if generator G is connected to the divider as in Fig. 1, i.e. to the 75-Ω input, and has a division ratio $K_{75.1}$.

Fig. 2. Photo of autonomous resistive shielded low-resistive voltage divider (ARSLVD)

The second stage is formed by the resistances R_3 (high voltage arm of the second stage of the divider) and R_4 (low voltage arm of the second stage of the divider) and has a division ratio $K_{75.2}$. Resistance R_5 in combination with the rest of the resistances of the divider forms a matching resistance equal to the characteristic impedance of 50 Ω of the coaxial cable, if one is connected between the output connector of the divider and the input of the oscilloscope. In this case, the input resistance of the oscilloscope can be either low-resistance (for example, 50 Ω) or high-resistance (for example, 1 MΩ): this does not lead to additional parasitic reflections in the cable as a long line. The total division factor of the divider can have two values: $K_{75high}=K_{75.1}K_{75.2}$, if the input of the oscilloscope is high-resistance, and $K_{75low}\approx 2K_{75.1}K_{75.2}$, if the input is low-resistance, i.e. oscilloscope input impedance $R_{in.o}$=50 Ω. This allows matching the coaxial cable (if used) with a wave resistance of 50 Ω connecting the 50-Ω output of the divider with the input resistance of the oscilloscope $R_{in.o}$=50 Ω from both ends. The body-screen of the divider can be conditionally divided into five component parts: two extreme cylindrical, each connected to its own coaxial connector CP-50-165ФВ, one central cylindrical, separated from the extreme cylindrical parts by two disk parts. In one extreme cylindrical part, the resistance R_1 = 73.8 Ω is located. In the other extreme cylindrical part – resistance R_5 = 47.2 Ω. In the central cylindrical part of the body, the resistance R_3 = 23.9 Ω is located. In the disk parts of the body there are resistors R_2 = 3.0 Ω and R_4 = 1.7 Ω. Resistance R_2 is formed by 7 TBO-0,25 resistors with nominal resistances of 22 Ω each, connected in parallel (see photo in Fig. 2). Resistance R_4 is formed by 4 TBO-0, 5 resistors with nominal resistances of 6.8 Ω each, connected in parallel.

If we do not take into account the influence of parasitic inductances and capacitances, then the division factor K_{75high} of the considered divider when applying a signal from the pulse generator to its 75-Ω input and using an oscilloscope with a high-resistance input can be defined as follows (see circuit in Fig. 1):

$$K_{75.1}=[R_1+R_2(R_3+R_4)/(R_2+R_3+R_4)]/[R_2(R_3+R_4)//(R_2+R_3+R_4)];$$

$$K_{75.2}=(R_3+R_4)/R_4.$$

Then:

$$K_{75high}=[R_1+R_2(R_3+R_4)/(R_2+R_3+R_4)]/[R_2(R_3+R_4)/(R_2+R_3+R_4)](R_3+R_4)/R_4 =$$

$$= [73,8+3(23,9+1,7)/(3+23,9+1,7)]/[3(23,9+1,7)/(3+23,9+1,7)](23,9+1,7)/1,7\approx$$

$$\approx (76,485/2,685)\cdot 25,6/1,7 \approx 28,5\cdot 15,1=430,35.$$

So,

$$K_{75high}=K_{75.1}K_{75.2}\approx 28,5\cdot 15,1 = 430,35.$$

Here $K_{75low} \approx 2K_{75.1}K_{75.2} \approx 2\cdot 28,5\cdot 15,1 = 860,7$.

The input and output of the divider can be reversed, since the same coaxial connectors CP-50-165ФВ, capable of withstanding pulse voltages up to 6 kV, are installed at the input and output. This changes the division ratio of the divider.

The division ratio K_{50high} of the considered divider when applying a signal from the pulse generator to its 50-Ω input and using an oscilloscope with a high-resistance input $K_{50high}=K_{50.1}K_{50.2}$.

$$K_{50.1}=[R_5+R_4(R_3+R_2)/(R_2+R_3+R_4)]/[R_4(R_3+R_2)/(R_2+R_3+R_4)];$$

$$K_{50.2}=(R_3+R_2)/R_2.$$

$$K_{50high}=[R_5+R_4(R_3+R_2)/(R_2+R_3+R_4)]/[R_4(R_3+R_2)/(R_2+R_3+R_4)](R_3+R_2)/R_2=[47,2+1,7(23,9+3)/(3+23,9+1,7)]/[1,7(23,9+3)/(3+23,9+1,7)]\cdot(23,9+3)/3 \approx$$

$$\approx (48,799/1,599)26,9/3 \approx 30,52\cdot 8,97 \approx 273,76.$$

Then $K_{50low}\approx 2K_{50.1}K_{50.2}\approx 2\cdot 30,52\cdot 8,97 = 547,52$, if the oscilloscope input resistance is $R_{in.o}$=75 Ω.

The input resistances of the divider are selected as low-resistance, since it is the low-resistance resistive voltage dividers that have the shortest rise time of the transient characteristic [2]. Specific values of 75 Ω and 50 Ω of input resistances are chosen based on the fact that the characteristic impedances of the most common coaxial cables in practice are 75 Ω and 50 Ω, and the input resistance of high-speed oscilloscopes with a wide (more than 1 GHz) bandwidth is, usually, 50 Ω.

As a generator in the experimental determination of the division factor of the divider, we used a C1-74 oscilloscope calibrator, which generates sinusoidal signals with known amplitude-frequency characteristics.

The division factor of the divider has been experimentally determined in two stages. At the first stage, we determined the $K_{75.1}$ division factor of the first stage of the divider as the ratio of the voltage amplitude from the calibrator at the 75- Ω input of the divider to the voltage at the low-voltage arm of the first cascade divider. At the second stage, $K_{75.2}$ has been defined as the ratio of the voltage amplitude from the calibrator at the input of the second stage of the divider (at series-connected resistances R_3 and R_4, $R_3+R_4 \approx$ 25.6 Ω) to the voltage at the low-voltage arm of the second stage of the divider (on resistance R_4).

At the first stage, the signal from the calibrator has been fed through a coaxial tee to the 75- Ω input of the divider and to the input (1 MΩ, 30 pF) of the C8-13 oscilloscope. At the same time, the 50-Ω input (output) of the divider has not been connected to external devices. Thus, the signal from the calibrator at the input of the divider has been measured. The oscillogram of this signal is presented in (Fig. 3).

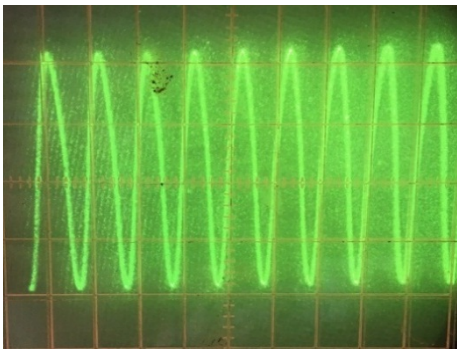


Fig. 3. Oscillogram of the voltage pulse from the calibrator of the C1-74 oscilloscope loaded on the input resistance $R_{in} \approx$ 75 Ω of the voltage divider (the scale along the time axis it is 1 μs/div, and along the signal axis is 0.1 V/div)

After that, the signal has been measured – the voltage on R_2 = 3 Ω in the disk part of the divider case with the remainder of the divider connected in parallel to R_2 – the low voltage arm of the first stage of the divider. The middle part of the body was removed from the voltage divider, the C8-13 oscilloscope input has been connected to R_2 using a coaxial cable, and The 75-Ω divider input has been connected to the calibrator with a separate coaxial cable. The result of measurements in the form of an oscillogram of voltage at R_2 – the output of the first cascade of this two-stage divider is shown in Fig. 4.

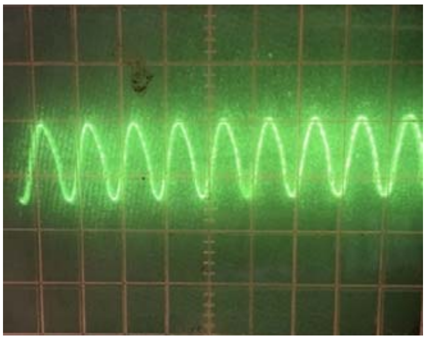


Fig. 4. Voltage pulse from a low-voltage arm the first stage of the voltage divider (the scale along the time axis is 1 μs/div, and along the process axis it is 0.01 V/div)

The ratio of the voltage amplitudes on the oscillograms in Fig. 3, 4 represents the experimentally determined division factor KE75.1 of the first cascade: $K_{E75.1} \approx 27.1$, which, taking into account the uncertainty (error) of measurements using oscillographs ≈ 10 %, is in good agreement with the value $K_{75.1} \approx 28.5$ obtained by calculation by the resistances of the divider elements $R_1 \ldots R_4$.

At the second stage, the voltage (signal) from the calibrator has been fed through a coaxial tee to the input of the second stage of the divider, i.e. for series connection of resistances R_3 and R_4, and to the input (1 MΩ, 30 pF) of the recording oscilloscope C8-13. The 50-Ω input (output) of the divider remained not connected to external devices, and the output of resistance R_3, initially connected to the corresponding pins of R_1 and R_2, has been disconnected from the connection point. This was done to ensure that the very low resistance R_2 = 3 Ω does not short the calibrator output. Thus, the signal from the calibrator at the input of the second stage of the divider has been measured. The oscillogram of this signal is presented in Fig. 5. Its amplitude is less than on the oscillogram in Fig. 3, because the calibrator in this case is loaded on the total resistance $R_3+R_4 \approx 25.6$ Ω, significantly less than the input resistance of the divider ≈ 75 Ω, which was the load of the calibrator in the first stage.

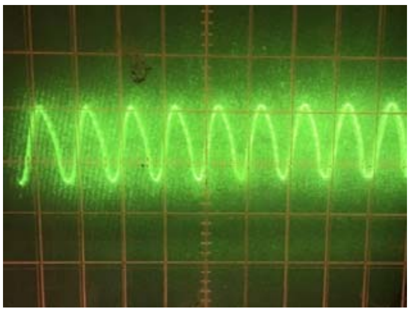


Fig. 5. The voltage pulse from the calibrator of the C1-74 oscilloscope at the input of the second stage of the divider (the scale along the time axis is 1 μs/div, and along the process axis it is 0.1 V/div)

Next, the signal has been measured – voltage on R_4 = 1.7 Ω (low-voltage arm of the second stage of the divider) in the disk part of the divider case. The CP-50 connector of the divider, connected by its central output to R_4 through R_5, has not been connected to external devices. The C8-13 oscilloscope input has been connected to R_4 with the help of a coaxial cable, and the input of the second stage of the divider has been connected to the calibrator with a separate coaxial cable. The measurement result in the form of the oscillogram of voltage on R_4 – the output of the second stage of this two-stage divider is shown in (Fig. 6).

Figure 7 shows an oscillogram of voltage from the low-voltage arm of the second stage of the divider for the mode in which in parallel to the high-resistance ($R_{in.o}$=1 MΩ) C8-13 oscilloscope input a 50 Ohm load has been connected.

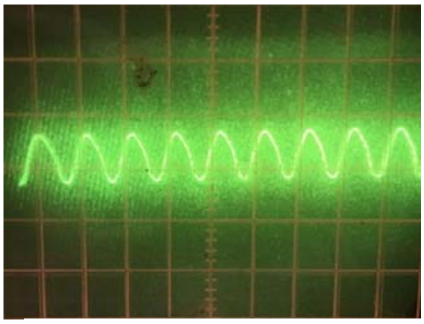


Fig. 6. The voltage pulse from the low voltage arm of the second stage of the voltage divider at the input resistance of the oscilloscope $R_{in.o}$ = 1 MΩ (the scale along the time axis is 1 μs/div, and along the process axis it is 0.01 V/div)

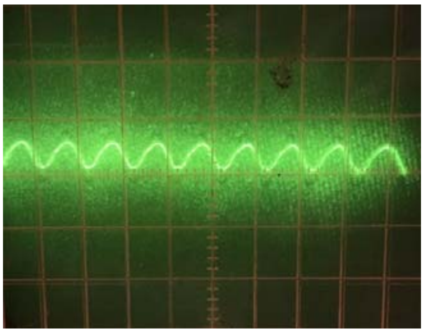


Fig. 7. The voltage pulse from the low-voltage arm of the second stage of the voltage divider when connecting a load of 50 Ω in parallel to the input resistance of the oscilloscope $R_{in.o}$=1 MΩ (the scale along the time axis is 1 μs/div, and along the process axis it is 0.01 V/div)

From Fig. 6, 7 it follows that connecting of a 50 Ω load in parallel to the input resistance of the oscilloscope $R_{in.o}$=1 MΩ reduces the voltage amplitude from the output of the second stage of the divider by about half, i.e. approximately doubles the division ratio of the divider.

The ratio of the voltage amplitudes on the oscillograms in Fig. 5, 6 represents the experimentally determined division factor $K_{E75.2}$ of the second stage: $K_{E75.2} \approx 15.5$, which, taking into account the uncertainty (error) of measurements using oscillographs ≈ 10 %, is in good agreement with the value $K_{E75.2} \approx 15.1$ obtained by calculation using the resistances of the divider elements R_3 = 23.9 Ω, R_4 = 1.7 Ω.

So,

$$K_{E75high} = K_{E75.1}K_{E75.2} \approx 27{,}1 \cdot 15{,}5 = 420{,}05;$$

$$K_{E75low} \approx 2K_{E75.1}K_{E75.2} \approx 840{,}1;$$

$$K_{75high}/K_{E75high} = K_{75low}/K_{E75low} = 430{,}35/420{,}05 \approx 1{,}0245,$$

i.e. the relative error (uncertainty) between the calculated value and the experimental value of the division factor for this divider does not exceed 2.5 %.

Determination of the rise time of the transition characteristics of the divider in the experiment. There are two main options for determining the rise time in the transmission system [2]. The first option implies as the rise time a period, during which the measured value (for example, voltage) increases from 0.1 to 0.9 of its maximum value. In the second variant, the rise time is the time during which the output signal reaches a certain percentage of the steady-state value when a rectangular pulse or voltage jump $u_1(t)$ of a given amplitude U_0 is input to the system

$$u_1(t) = U_0 1(t),$$

where $1(t)$ is the unit function:

$$1(t) = \begin{cases} 0 & \text{at} \quad t < 0; \\ 1 & \text{at} \quad t \geq 0. \end{cases}$$

If a jump occurs after a time interval τ after the origin, then the unit function is zero at $t<\tau$, equal to 1 at $t \geq \tau$, and is denoted by $1(t - \tau)$ [7].

The voltage $u_1(t)$ causes the voltage $u_2(t)$ – the response to a rectangular pulse in the output of the system (in our case, in the output of the voltage divider connected to the oscilloscope input and matched with it). The dimensionless function of time

$$h(t) = u_2(t)/U_0 \qquad (1)$$

is called a transition function or temporal characteristic of the system [2, p. 39], as well as the transient response of the circuit [7, p. 116].

In our case, $h(t)$ is represented as oscillograms. Here, the voltage at the output of the divider $u_2(t)$ can be determined using the Duhamel integral as a response to the input signal $u_1(t)$ of any form [2, p. 40]:

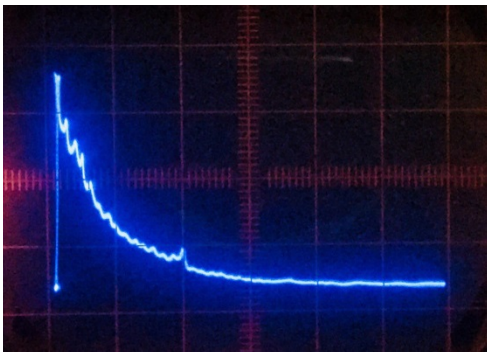
$$u_2(t) = u_1(+0)h(t) + \int_{\tau=0}^{\tau=t} u_1'(t-\tau)h(\tau)d\tau \,. \qquad (2)$$

Since in our case the duration of the pulse front from the generator, both when using sharpening and without sharpening, is much less than the half-drop time (drop to half the pulse amplitude) ≈ 50 ns, as far as in the first approximation, the pulse from the generator can be considered as a voltage jump (square pulse). Therefore, the time derivative $u'_1(t - \tau)$ in (2) can be taken equal to zero, since the function u_1 itself has only two values (two constants): 0 for $t<\tau$ and 1 for $t \geq \tau$ (taking into account the limits of integration – at $t = \tau$), and formula (2) is simplified to:

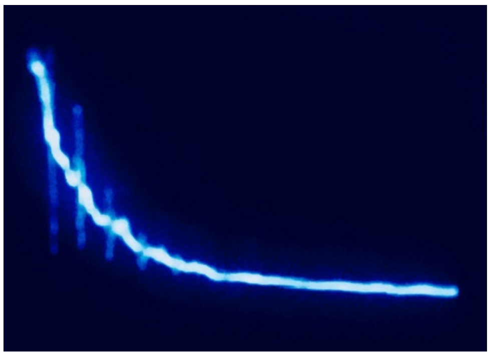
$$u_2(t) = u_1(+0)h(t). \qquad (3)$$

If we take into account that $u_1(+0) = U_0$ in (1), then (2) fully corresponds to (1).

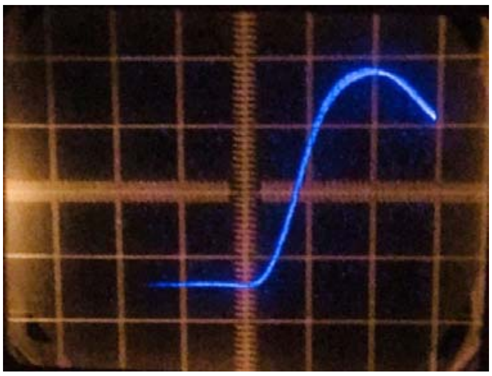
Fig. 8 shows the oscillograms of voltage pulses from the output of the voltage divider under study, connected to the input of C7-19 oscilloscope with 5 GHz bandwidth and an input active resistance of 50 Ω.



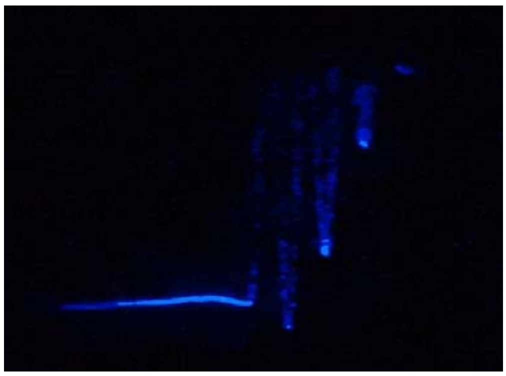
a



b



c



d

Fig. 8. Oscillograms of the pulses as a whole and of the front part of the pulses from the generator, measured by the divider and recorded with the C7-19 oscilloscope: *a*, *c* – without sharpening of the pulse front; *b*, *d* – using the sharpening of the front. On oscillograms *a*, *b* the scale along the time axis is 100 ns/div and 50 ns/div, respectively, on the oscillograms *c*, *d*, the scale along the time axis is 2.5 ns/div. The scale along the process axis is 1.5 V/div on all oscillograms, the division ratio of the divider $K_{75low} \approx 860.7$

The front of the pulses from the high-voltage generator [6] without sharpening is ≈ 2.5 ns. The divider transmits it without distortion (see the oscillogram in Fig. 8,*a*). From oscillograms in Fig. 8,*b*,*d* it can be seen that at sharpening (significant shortening) of the pulse front from the generator, parasitic oscillations occur on it (at the front). These oscillations are excited in this resistive voltage divider containing parasitic capacitances and inductances, by sharpened (subnanosecond) pulse front from the generator. Oscillogram in Fig. 8,*d* shows that the first voltage surge during sharpening of the front of measured and recorded pulses is significantly steeper than in the absence of sharpening, and in the rise time it is ≤0.5 ns.

To validate the experimental results and find out exactly which parasitic capacitances and inductances in the divider to the greatest extent affect its transient characteristic (function), computer simulation of the resistive voltage divider taking into account its parasitic parameters is carried out. The presence of a broadband coaxial cable with an impedance of 100 Ω and electrical length of 5-10 ns between the output of the high-voltage pulse generator and the input of the divider is also taken into account.

Computer simulation of the operation of the divider. The circuit used to model the operation of the divider when applying voltage pulses to the 75 Ω input with different fronts duration from the generator through a coaxial cable with an impedance of 100 Ω and an electrical length of 5 ns, is shown in Fig. 9. The values in the circuit elements varied. From the diagram in Fig. 1 it differs taking into account the parasitic inductances in the divider. In the diagram (Fig. 9), the pulse generator has the following characteristics. The amplitude of the pulses is 5 arbitrary units (for example, 5 kV). The delay before the start of the pulse is 10 ns. The duration (rise time) of the pulse front from the generator is 0.1 ns. The duration of the decay of pulses from the generator is 1000 ns. Pulse width (shelf on top) is 100 ns. The pulse repetition period from the generator is 5000 ns. The recording oscilloscope C7-19 in the diagram is represented by the input active resistance $R6$ = 50 Ω and included in parallel with the $R6$ input capacitance $C1$ = 15 pF. The parasitic inductance $L3$ at the point of connection of the divider output to the oscilloscope input during modeling varied in the range $L3$ = 0.1 ... 10.0 nH, and $L1$ – in the range $L1$ = 0.5 ... 10.0 nH. The values of inductances $L1$ and $L3$ have a significant effect on the shape of the front part of the pulse voltage at the output of the divider connected to the input of the oscilloscope.

The maximum step duration in modeling in Microcap-10 was 0.001 ns, the number of points in time was 100,000.

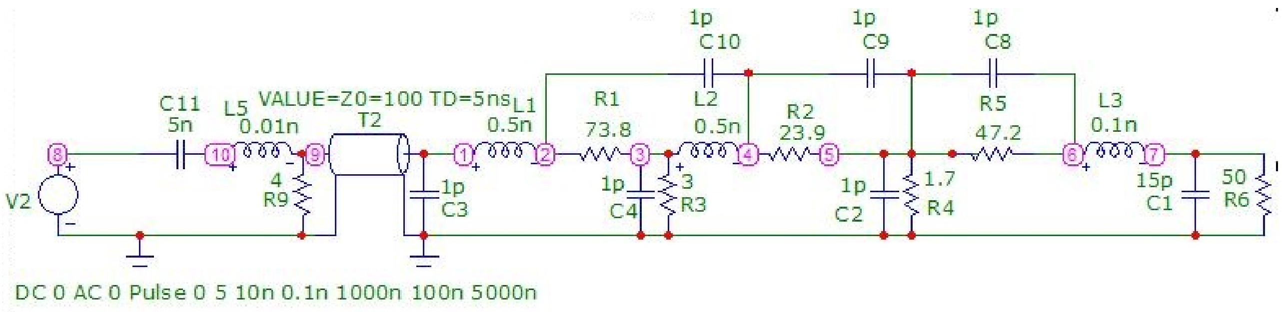


Fig. 9. Circuit for computer simulation of the voltage divider operation

The simulation results for the circuit (Fig. 9) are shown in Fig. 10. In Fig. 10,*a* the amplitude of the voltage $v(1)$ and $v(2)$ at points 1 and 2 is less than the amplitude $v(8)$, $v(9)$ and $v(10)$, because the characteristic impedance $Z0$=100 Ω of the cable line $T2$ is greater input resistance (≈75 Ω) of the divider. The division coefficient $K_{75.1}$ of the first stage of the divider can be determined from the graphs in Fig. 10,*a*,*b*, as $K_{75.1} \approx v_{max}(1)/v_{max}(3) \approx \approx 4270/150 \approx 28.5$ excluding the outlier, which corresponds to the above calculated value of $K_{75.1}$. From the graphs in Fig. 10,*c*,*d*, similarly, we determine $K_{75.2} \approx v_{max}(3)/v_{max}(5) \approx 150/9.95 \approx 15.1$, which also corresponds to the calculated value $K_{75.2}$.

Regular bursts with a repetition period of 10 ns on the graph (Fig. 10,*a*) of the voltage transient at point 2 (at the 75-Ω input of the divider) at the pulse front from the 0.1 ns generator are caused by the longitudinal capacitance in the divider $1/(1/C8+1/C9+1/C10)$ = 0.33 (pF). The repetition period is determined by the electric length of 5 ns of the cable $T2$ and is equal to twice the running time of the voltage wave from the generator through the cable to the input of the divider. Similar bursts were observed on oscillograms from the C7-19 oscilloscope. Only the period of these bursts was longer (approximately 20-25 ns) due to the longer cable length. If the longitudinal capacitance in the divider during modeling is reduced by an order of magnitude – to 0.033 pF, then the amplitude of bursts sharply decrease and become hardly noticeable. The bursts also decrease with increasing duration of the pulse front from the generator, which agrees well with the experimental data (see Fig. 8).

The numbers affixed to Fig. 9 are the numbers of the points at which the voltage was measured in the simulation (the voltage between this numbered point of the circuit and the grounded point of the circuit – the body of the divider). Filter $C11$-$L5$-$R9$ provides on the resistance $R9$, to which the input of a coaxial cable with an impedance $Z0$ = 100 Ω and an electrical length of 5 ns, is connected, the pulse shape in the form of a falling exponent with a steep front. If in the diagram in

Fig. 9 take $C1$ = 5 pF instead of 15 pF, the amplitude (range) of oscillations at point 6 at the input to the oscilloscope decreases slightly, and negative surges in oscillations disappear, as shown by the curves in Fig. 10,*d* and Fig. 11.

According to [2, p. 49] $t_f \approx 0.35/B$, where B is the bandwidth determined by attenuation 3 dB, t_f is the rise time for the system under study, in our case for the studied low-resistance resistive voltage divider or for a recording oscilloscope. Therefore, for a C7-19 oscilloscope with a 5 GHz bandwidth, the front t_f of pulses, which it transmits without significant distortion, $t_f \approx 0.35/5$ GHz = 0.07 ns.

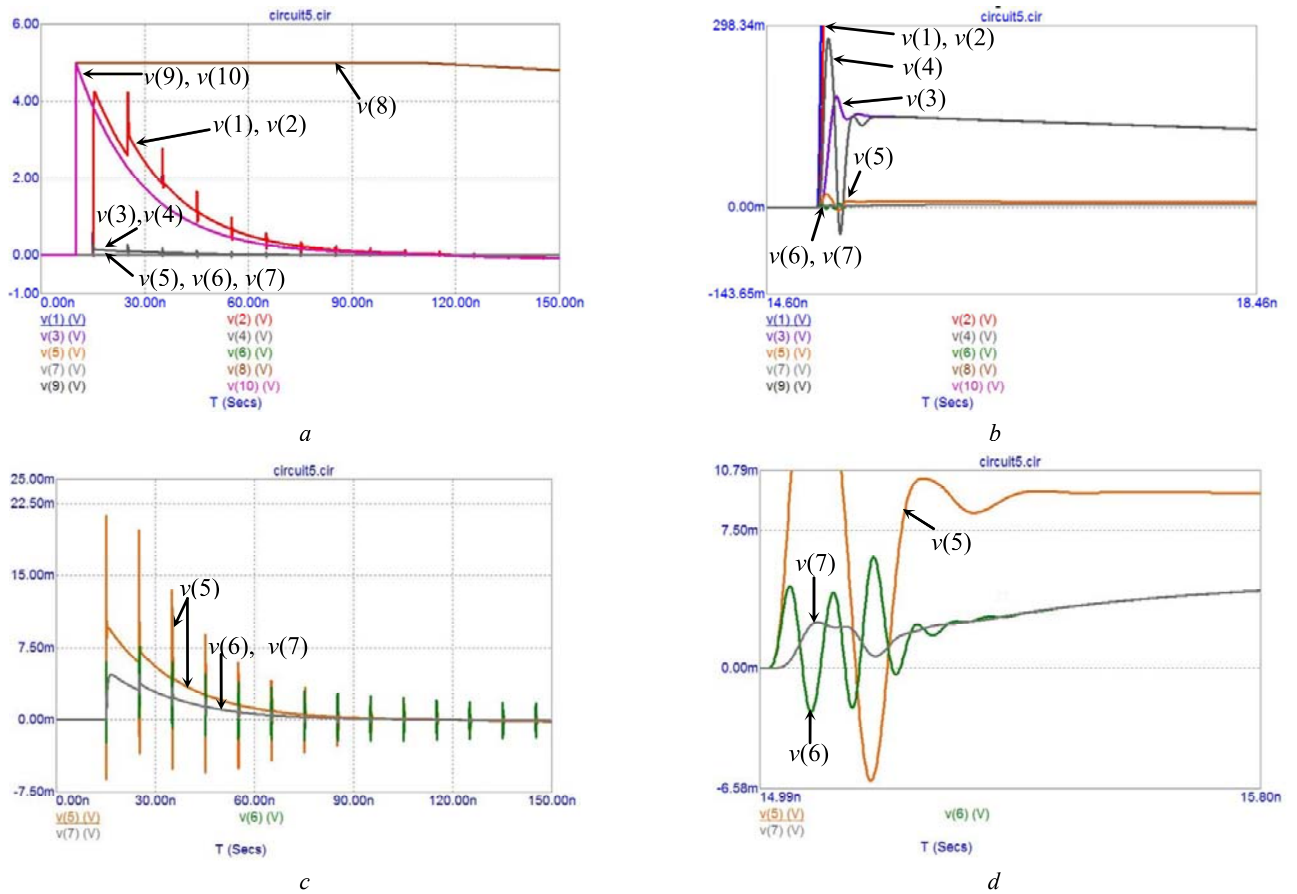


Fig. 10. The results of the simulation of transient in the circuit in Fig. 9

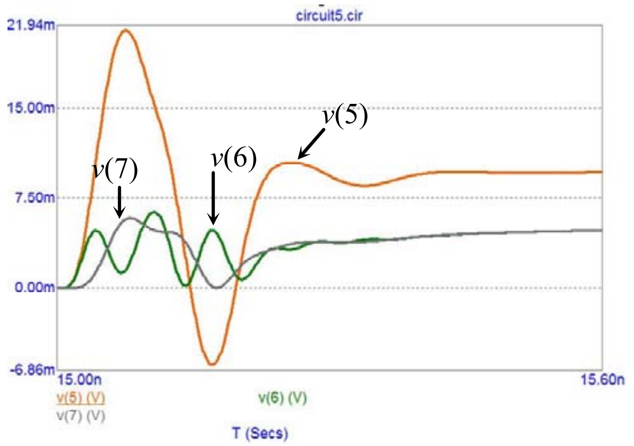


Fig. 11. The voltage at the output of the divider according to the circuit in Fig. 9 at $C1$ = 5 pF

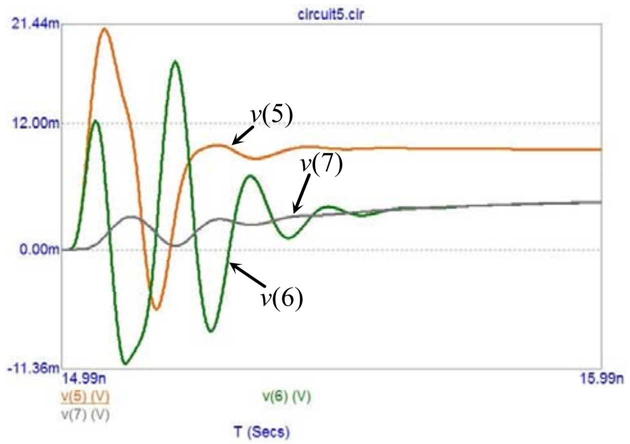


Fig. 12. The oscillations at the output of the divider according to the circuit in Fig. 9 at $L3$ = 0.5 nH

If in the circuit in Fig. 9 to increase $L3$ from 0.1 nH to 0.5 nH, then the amplitude of oscillations at point 6 at the pulse front from the generator increases by about 2.5 times, which illustrates the simulation result in Fig. 12.

Under these simulation conditions, the oscillations at point 6 at the front decay beyond ≈ 0.6 ns, which is less than in the experiment (see Fig. 8,*d*).

If in the simulation circuit in Fig. 9 set the duration of the pulse front from the generator not 0.1 ns, but 2.5 ns, which corresponds to the operation of a real pulse generator in the mode without sharpening of the front, as a result of the simulation we obtain the dependence of voltage on time at various points of the circuit, shown in Fig. 13.

Small fluctuations in the form of bursts and valleys at a front duration of 2.5 ns are caused by breaks in the initial pulse from the generator: at the beginning of the pulse and when going from the front to the flat top.

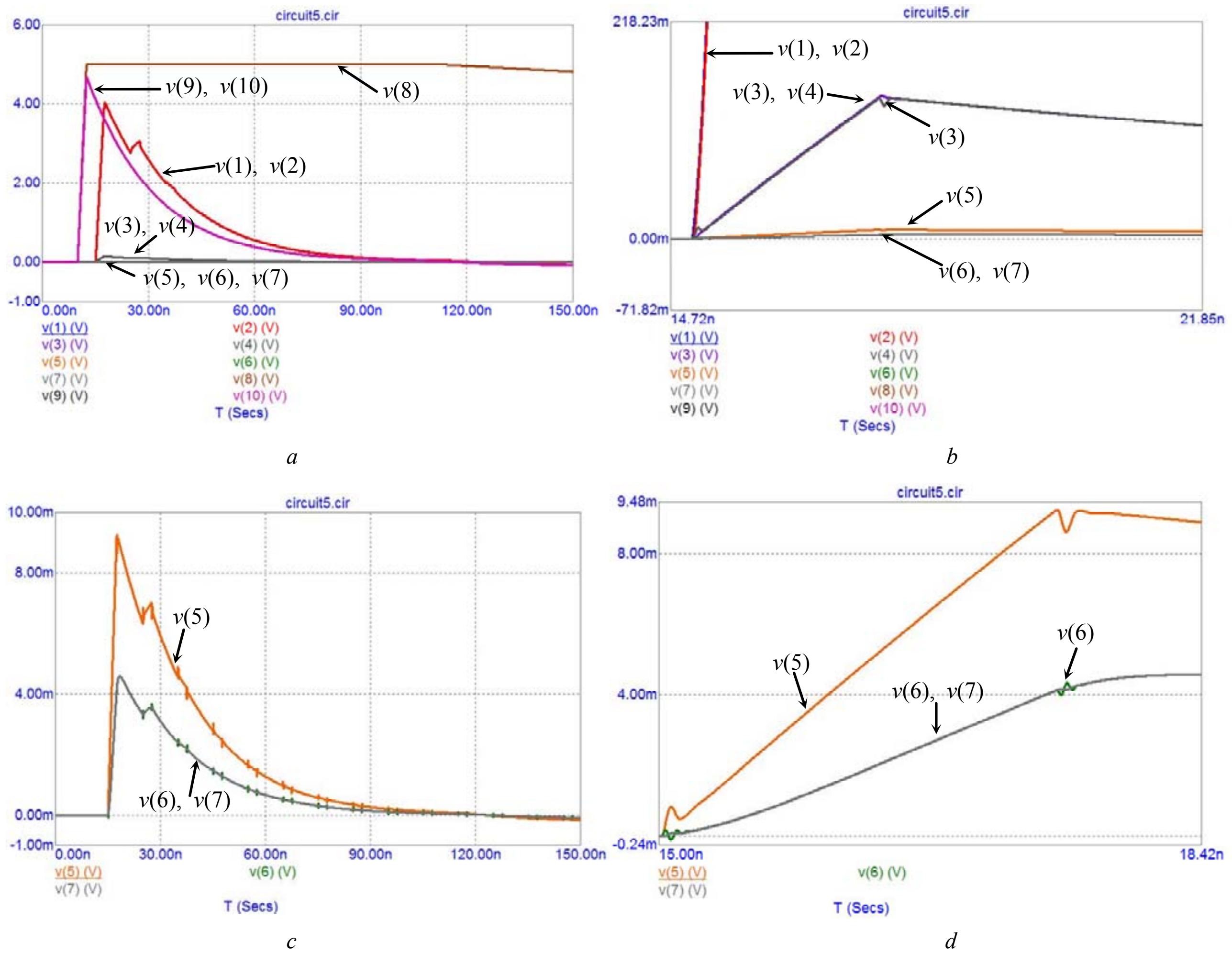


Fig. 13. The results of the simulation of the transient according to the circuit in Fig. 9 at a pulse front duration 2.5 ns from the generator

Modeling at extremely short rise times of the front from the pulse generator, causing the appearance on the front of the oscillograms from the output of the divider of high-frequency oscillations (see Fig. 8,*d*), turned out to be the most difficult at modelling the operation of the divider.

The task is complicated by the fact that the duration of the pulse front from the generator in experiments in the sharpening mode is unknown. It was only clear that the shorter the front from the generator, the greater the amplitude of oscillation on the oscillograms from the output of the divider.

Experiments have shown that the amplitude of these oscillations reaches twice the value compared with the amplitude of the voltage from the output of the divider in the mode without sharpening the front. The selection of the parasitic inductances and divider capacitances in the simulation of oscillations on the front part in the mode of sharpening the front of pulses made it possible to achieve good agreement between the simulation results and the experimental results (see Fig. 8,*d*). The circuit, which allowed to model the oscillations on the front of a sharpened pulse, is shown in Fig. 14, and the simulation results are presented in Fig. 15. The front part of the simulated pulse, close to that in the experiment using the sharpening mode, was obtained with a front duration of 0.1 ns of the original pulse from the generator in the simulation circuit. Hence, in the sharpening mode, the duration of the front from the generator in the experiment was also ≈ 0.1 ns.

The simulation does not take into account the processes in the divider as in a long line, which lead to the emergence of higher types of electromagnetic waves when a long line is excited by pulses with steep fronts whose duration is comparable or less than the electric line length (in our case, of the voltage divider). With a pulse front duration of 0.1 ns, the corresponding path length of an electromagnetic wave in air is 3 cm, and the divider length is 18 cm. Therefore, the appearance of higher-type waves in it is real. This can explain the somewhat higher intensity of oscillations at the front of a sharpened pulse at the output of the divider in the experiment (as compared with the results of computer simulation).

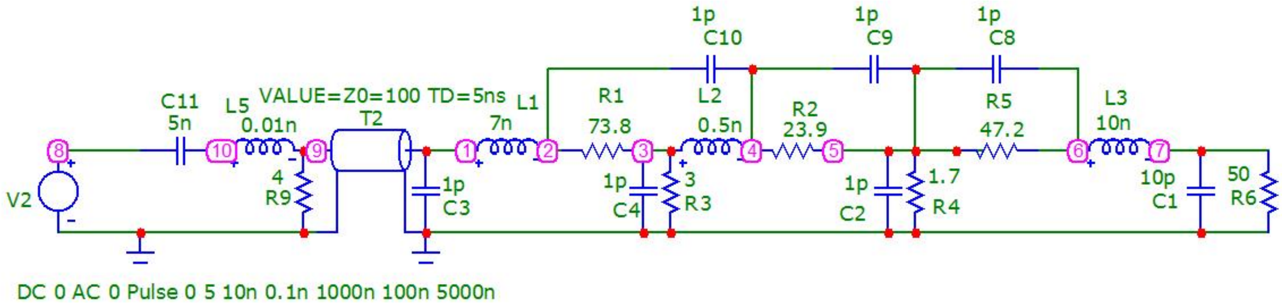
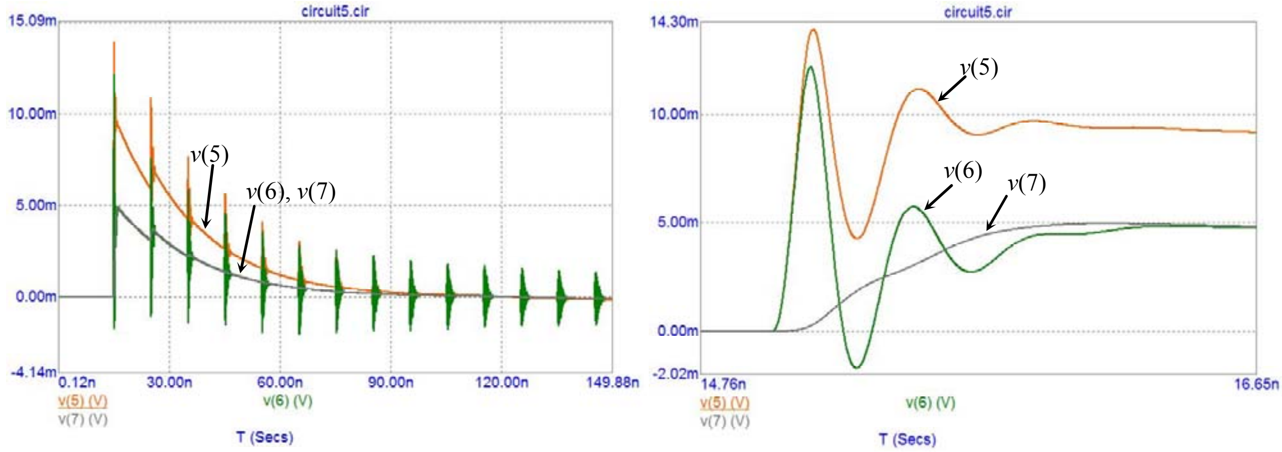


Fig. 14. Circuit with parasitic inductances and divider capacitances, which provided the simulation results of the pulse front at the divider output, closest to the experimental ones

Thus, computer simulation has allowed to clarify the duration of the pulse front from the high-voltage generator used in the experiment in the sharpening mode and to estimate quantitatively the values of the parasitic inductances and capacitances in the considered divider. In particular, the value of the simulated parasitic inductance at the input of the divider was $L1$ = 7 nH, and at the output the divider $L3$ = 10 nH. The rise time of the front of the voltage pulse $v(7)$ at the RC-input of the oscilloscope ($R6$ = 50 Ω, $C1$ = 10 pF in Fig. 14 at point 7) was approximately 0.7 ns (see Fig. 15,*b*), while the rise time of the voltage pulse front $v(7)$ from the generator at point 8 is 0.1 ns. From here it follows that the rise time the transitional characteristics of the divider is ≈ 0.7 ns.



a *b*

Fig. 15. The results of the simulation of the transient at the output of the divider, close to the experimental results;
a – pulse as a whole, *b* – front part of pulse

Simulation has shown that the influence of parasitic capacitances and inductances in the investigated divider at subnanosecond and even shorter rise times of pulses at the input of the divider should be taken into account.

Conclusions.

1. Theoretically (using computer simulation) it is reasonable and experimentally it is confirmed that the developed voltage divider with the rise time of the transient response ≈ 0.7 ns allows to measure high-voltage pulses with a steep front (up to 1 ns as the lower limit) and provides the division factor K_{75low}≈ 861 when using a 75-Ω divider input and with an oscilloscope input resistance of 50 Ω (K_{50low}≈548 when using 50-Ω divider input and at the input resistance of the oscilloscope, equal to 75 Ω).

2. A computer model of VD is created, with the help of which it was possible to explain the presence in the experiment of oscillations with amplitude twice as large as the amplitude of the pulses according to the division factor of the divider at the front of the pulses from the output of the divider. These oscillations (arising when pulses with a very steep front ≈ 0.1 s are applied to the divider input) are caused by the presence in the divider of a parasitic longitudinal capacitance ≈ 0.3 pF and parasitic inductances, the total value of which is ≈ 17.5 nH).

3. This divider can be recommended for measuring the characteristics of high-voltage pulses with steep (nanosecond) fronts.

REFERENCES

1. Mesiats G.A. *Impul'snaia energetika i elektronika* [Pulsed power and electronics]. Moscow, Nauka Publ., 2004. 704 p. (Rus).

2. Shvab A. *Izmereniia na vysokom napriazhenii. Izmeritel'nye pribory i sposoby izmereniia* [Measurements at high voltage. Measuring instruments and methods of measurement]. Moscow, Energoatomizdat Publ., 1983. 264 p. (Rus).

3. Kuffel E., Zaengl W.S., Kuffel J. *High Voltage Engineering (Fundamentals). Second edition*. Oxford, Butterworth-Heinemann Publ., 2000. 539 p.
4. Parks H. High-Voltage Divider Calibration with the Reference Step Method. *NCSLI Measure*, 2016, vol.11, no.1, pp. 34-36. **doi: 10.1080/19315775.2016.1149008.**
5. Early M.D., Sira M., Andersson B.-O., Christian L.A., Gunnarsson O., Rydler K.-E., Streit J. A Simple Build-Up Method for the DC Voltage Scale of a Source. *IEEE Transactions on Instrumentation and Measurement*, 2013, vol.62, no.6, pp. 1600-1607. **doi: 10.1109/TIM.2012.2230734.**
6. Boyko N.I., Safronov I.A., Tondii L.D. ASHEMIT: A device for wideband electromagnetic pulse therapy. *Instruments and Experimental Techniques*, 2000, vol.43, no.5, pp. 675-682. **doi: 10.1007/bf02759082**.
7. Demirchian K.S., Neiman L.R., Korovkin N.V., Chechurin V.L. *Teoreticheskie osnovy elektrotekhniki: V 3-kh t. Uchebnik dlia vuzov. Tom 2* [Theoretical bases of electrical engineering. In 3 vols. Vol.2.]. St. Petersburg, Piter Publ, 2004. 576 p. (Rus).

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