Development of a high-voltage divider for kilovoltmeters used in testing and training of electrovacuum devices

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Abstract. The paper discusses the main approaches to the design of high-voltage dividers intended for use in devices that provide voltage control during testing and training of electrovacuum devices. The main circuits of such dividers, namely resistive, capacitive and compensated, are modeled. As a result of research, the optimal parameters of the compensated divider that is most suitable for use in such devices were found, and the design of this device was developed.

One of the tasks when testing electrovacuum devices [1–3] is to measure high voltages: constant and especially pulsed. In particular, at the stage of factory testing of high-power X-ray tubes, it is necessary to control the anode voltage with an error of at least ±1 kV. Exceeding the voltage above the set value can lead to dangerous overheating, breakdowns, and the appearance of harder X-ray radiation for the controlled tubes. Insufficient voltage is also unacceptable, because it does not allow detecting dangerous defects in manufactured devices, which are then manifested during the operation of X-ray tubes. In connection with the expansion of the range of pulsed X-ray devices, the question of measuring the parameters of pulsed anode voltage with duration of 1…0.1 ms or even less is acute. It is important not only to measure the amplitude of the voltage pulse, but also the depth of pulsations, as well as the pulse duration. It is obvious that pulse measurements cannot be performed using "classical" means that use electrostatic kilovoltmeters.

The most modern, simple and cost-effective technical solution is one that uses a high-voltage divider and an electronic device that represents the result of measurements of pulsed or constant voltages in digital form and allows data to be transmitted to a computer.

Measuring voltages up to 250 kV with an error of at least ±1 kV using a semiconductor measuring device requires a voltage divider with a division coefficient of the order of 50 000. Such a high value of the division coefficient is due to the fact that the maximum input voltage of semiconductor measuring devices usually does not exceed 5 V. Converting a low-power analog signal with an amplitude of about 5 V to the corresponding digital code with an error of at least ±0.5 % does not pose any problems for modern electronic circuits.

A number of requirements are imposed on a high-voltage divider: to have a stable division coefficient that does not depend on the operating mode; to ensure accurate reproduction of the shape of the measured voltage; not to affect the operating mode of the circuit under study.

The divider, which is a chain of series-connected active or reactive resistances, is a kind of transfer link in the measurement chain and must have a certain effect on the measurement accuracy. Therefore,
a fairly strict basic requirement is imposed on voltage dividers: the voltage on the low-voltage arm of the divider must repeat the measured voltage in shape.

In all dividers, it is common to place working elements in a cylinder made of high-quality insulation material of a relatively small diameter. Filling the cylinder with oil provides insulation between the elements, heat removal and eliminates discharges [4] on the surface of the elements that occur on the high potential side at high field strength.

The choice of the divider type and its parameters, first of all, the high-voltage arm, should be made taking into account its possible influence on the voltage source and on the distortion of the measured voltage itself. The compensated divider provides minimal distortion of signals at high and low frequencies, but it has a significant impact on the measured circuit.

The equivalent scheme of the measuring circuit, according to which the calculation was made, is shown in figure 1. It also shows the values of the elements that make up the scheme.

![Figure 1. Equivalent circuit diagram of the measuring circuit for calculation.](image)

In order to see how different types of voltage dividers behave, it was decided to model their amplitude-frequency characteristics.

The frequency response of the voltage dividers was modeled using the OrCAD automatic design package. In the course of modeling, the frequency response of the following voltage dividers was studied:

1) perfect ohmic voltage divider;
2) ohmic voltage divider with parasitic capacity to the ground;
3) capacitive voltage divider;
4) compensated voltage divider;
5) compensated voltage divider with parasitic capacity to the ground.

As seen in figure 2(a) the schematic diagram of an ideal ohmic voltage divider does not have parasitic elements, so its frequency response at all frequencies is a straight line (figure 3(a)), i.e. the division coefficient of such a voltage divider is constant at all input frequencies, and such a voltage divider would ideally repeat the shape of the input effect, without introducing any distortion.

In figure 2(b) a schematic diagram of an ohmic voltage divider with a parasitic capacitance to the ground is presented. It is obvious that in this case we obtain a low-pass filter of the first order.

In figure 3(b) the frequency response of such a divider is presented, it has a typical form of the frequency response for the low-pass filter. The cutoff frequency of the resulting low-pass filter is about 17 Hz. Thus, this voltage divider is not suitable for measuring pulse signals, since the division
The coefficient of such a voltage divider increases rapidly with increasing frequency and tends to infinity at frequencies above 10 kHz.

Let's now consider a purely capacitive voltage divider, which has good characteristics at high frequencies. The schematic diagram of such a divider is shown in Figure 2(c), and its frequency response is shown in Figure 3(c).

The frequency response of a capacitive voltage divider is similar to a high-pass filter. Such a voltage divider works well at relatively high frequencies and is not suitable for measuring constant voltages.

To obtain the required frequency response, it is necessary to combine the ohmic divider with the capacitive one. In this case, the action of the low-pass filter will be compensated by the action of the high-pass filter. The schematic diagram of such a compensated high-voltage divider is shown in Figure 2(d). We do not consider the presence of a parasitic capacity relative to the ground yet.

**Figure 2.** Schematic diagrams of voltage dividers: (a) – perfect ohmic voltage divider; (b) – ohmic voltage divider with parasitic capacity to the ground; (c) – capacitive voltage divider; (d) – compensated voltage divider; (e) – compensated voltage divider with parasitic capacity to the ground.
Figure 3. Frequency responses of voltage dividers: (a) – perfect ohmic voltage divider; (b) – ohmic voltage divider with parasitic capacity to the ground; (c) – capacitive voltage divider; (d) – compensated voltage divider; (e) – compensated voltage divider with parasitic capacity to the ground.

In figure 3(d) the frequency response of the compensated voltage divider is shown. It is similar in appearance to the frequency response of an ideal ohmic voltage divider, with the only difference that it has a slight rise near the 1 Hz point. This rise is caused by not quite accurate fulfillment of the equality of division coefficient in resistances and capacitances, which is always the case in real conditions due to the action of destabilizing factors (temperature, parasitic interaction, humidity) and the spread of the values of resistance and capacitance of real resistors and capacitors.

We now introduce a concentrated capacitance relative to the ground into the model, as was done in the case of the ohmic divider. The schematic diagram of a compensated divider with a parasitic capacitance is shown in figure 2(e).

The resistive branch of the compensated voltage divider operates at a constant voltage and at low frequencies. With an increase in the frequency of the input signal, the frequency response begins to fall, i.e. the effect of the low-pass filter affects. But with increasing frequency, the capacitive branch of the compensated voltage divider is switched on, so that the frequency response begins to equalize and at frequencies above 100 Hz, the division coefficient again takes a constant value, independent of the frequency.

Thus, the frequency response of the compensated voltage divider has a small dip in the frequency range of the order of units of hertz. The decrease in division coefficient at the extreme of the frequency response curve (figure 3(e)) does not exceed 3.5 %.

It is obvious that at very large values of the capacitance of the high-voltage arm of the voltage divider, i.e. at $C_1/C_g \rightarrow \infty$, the dip in the frequency response decreases to zero, and the frequency response is exactly the same as in the case of an ideal ohmic voltage divider.

Now let’s create conditions for undercompensation of voltage divider by reducing the capacity of $C_1$ by 50 % of the calculated value, and overcompensation by increasing the same capacity also by 50 %. In the first case, the capacity of $C_1$ will be about 39 pf, in the second – about 118 pf. The simulation results are shown in figure 4.

The figure shows that insufficient compensation and overcompensation of the voltage divider leads to a strong change in the division coefficient depending on the frequency.
**Figure 4.** Frequency response of the compensated voltage divider with sufficient compensation (a), undercompensation (b) and overcompensation (c).

**Figure 5.** Sketch of the compensated voltage divider (in section): 1 – expanding oil tank plug; 2 – high-voltage input; 3 – high-voltage arm resistors; 4, 5 – high-voltage arm capacitors; 6 – divider housing; 7 – low-voltage arm resistor; 8 – low-voltage arm capacitor; 9 – base; 10 – connector; 11 – buffer board.
The compensated voltage divider introduces small distortions when converting a high input voltage to a low output voltage. At higher frequencies, distortion is reduced. At lower levels, it remains at approximately the same level.

Modeling has shown that the compensated voltage divider allows getting a low level of distortion when converting pulse voltages, in contrast to purely ohmic and purely capacitive dividers. A sketch of one of the possible compensated voltage divider designs that was developed after the modeling is shown in figure 5.

A plastic pipe with a diameter of 150 mm is fixed on a dielectric platform with legs. Inside the plastic tube is placed a small plastic tube with a high-voltage arm of a voltage divider placed inside it, formed by resistors $R_1$ and capacitors $C_1$. Soldering is used to connect individual elements of the high-voltage arm of the compensated voltage divider. Both pipes are connected and filled with transformer oil.

In the upper part of the divider there is a metal ball that serves as a reservoir for the transformer oil that expands when heated and simultaneously acts as a high-voltage input.

A large pipe at both ends is plugged with dielectric inserts. In the lower insert, there is a hole in which a plug is inserted with a low-voltage compensated voltage divider arm – resistor $R_2$ and capacitor $C_2$, as well as a buffer. A connector for connecting a 10 m long measuring cable is mounted to the same plug. A protective varistor with a classification voltage of about 18 V can also be connected to the contacts of the low-voltage divider arm, which protects the low-voltage part of the device from overvoltage.

References

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