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Feasibility of using T-shaped feedback in teraohmmeters

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Abstract. The paper investigates the feasibility of using T-shaped feedback in teraohmmeters. Theoretical and experimental dependences of the output voltage of the T-shaped feedback converter on the measured resistance and circuit parameters are obtained. The use of T-shaped feedback is found to decrease the reference resistance rating from 10 GOhm to 100 Ohm that indicates 100-fold reduction (with an error of less than 1%).

1. Introduction

The methods of testing, control and measurement employed to determine the state of insulation for current-carrying parts of electrical equipment depend on physical nature of isolation. Any insulation (dielectric) used in electrical machines and apparatus is a capacitor with a complex medium. The plates are external components of the apparatus (housing and core) and current-carrying components (cables, wires and buses), and the medium is an insulating material with the structure that depends not only on the material used, but also on its state – the presence of defects [1].

Electrical resistance is the main indicator of the insulation material state, and its measurement is obligatory for testing of all types of electrical equipment and electrical circuits. Teraohmmeters are used to measure the resistance of insulating materials [2].

The main problems to challenge during teraohmmeter development are the stability of the device to industrial frequency noise, error, and the settling time for indicating the insulating material resistance if the object possesses electrical capacity, or the measuring device is supplied with filtering circuits [3–5].

Teraohmmeters based on an operational amplifier (op amp) and supplied with a circuit of a resistance-to-voltage converter with inverse scale have been widely used (Figure 1). The teraohmmeters operating on this principle are advantageous since they operate at a zero common-mode signal and have good noise immunity [6].

The main requirement to such teraohmmeters is low input current of the op amp to increase the upper measurement limit. The modern operational amplifiers of this type are AD549 and ADA4530-1 (Analog Devices), LTC6268 (Linear Technology), and OPA128 and LMC6041 (Texas Instruments). The input current of all of the above microchips is less than 100 fA that theoretically enables measurement of the resistance up to 1000 TOhm at a reference voltage of 100 V.

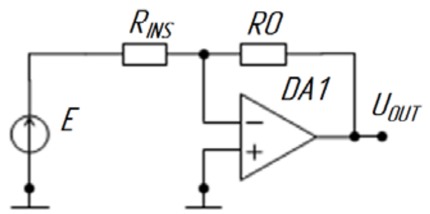

Figure 1. Resistance-to-voltage converter with inverse scale, based on op amp: *DA1* is op amp; *E* is the EMF value of the source; R_{INS} is insulation resistance; $R0$ is reference resistance.

In case of an ideal op amp, the output voltage of the teraohmmeter is [7]

$$U_{OUT(ID)} = -E \cdot \frac{R0}{R_{INS}} \quad (1)$$

2. Problem statement

As seen from equation (1), the larger the resistance $R0$ in the feedback circuit, the greater resistance can be measured. However, typically, the greater the resistance of the resistor, the lower its accuracy. Therefore, to reduce an error in the teraohmmeter, the least possible value for the feedback resistance must be chosen (less than 1 GOhm). For example, high-resistance precision chip resistors Riedon's HVS exhibit an error of 1–2% in the range from 1 GOhm to 100 GOhm. While, in the range from 1 MOhm to 1 GOhm, the error is 0.25–0.5%, which is 4-times less than that in the range 1 GOhm to 100 GOhm. However, the feedback resistance decreases simultaneously with the output voltage amplitude of the resistance-to-voltage converter.

Theoretically, T-shaped feedback can eliminate this contradiction (Figure 2).

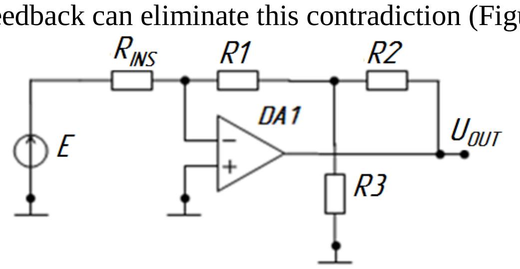

Figure 2. Resistance-to-voltage converter with T-shaped feedback: *R1*, *R2* and *R3* are resistances of T-shaped feedback.

In this case, we need lower value resistances to obtain a stable useful signal. For an ideal op amp, the conversion equation for this circuit can be written as [8]:

$$U_{OUT(ID)} = -E \cdot \frac{R1 + R2 + \frac{R1 \cdot R2}{R3}}{R_{INS}} = -E\,\frac{R_{EQ}}{R_{INS}}, \quad (2)$$

where R_{EQ} is the equivalent resistance of the amplifier feedback and $U_{OUT(ID)}$ is the output voltage of the T-shaped feedback converter for an ideal op amp.

Equation (2) does not take into account many parameters of the op amp (input resistance and current, offset voltage, finite voltage gain, presence of protection from static electricity, etc.), which limit the use of T-shaped feedback to design a teraohmmeter. In order to consider the given parameters of the op-amp, it is advisable to perform the analysis using special programs for electrical circuit simulation.

The study aims to experimentally and theoretically investigate the applicability of T-shaped feedback in teraohmmeters, and to determine the conditions under which the circuit remains operational. All the experiments used a constant voltage source *E*=100V, and an ADA4530-1 op amp, with less than 20 fA input current at temperatures ranging from –40 to +85° C and differential voltage gain of at least 30 million.

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The Altium Designer software was used to determine the theoretical value of the output voltage of the teraohmmeter $U_{OUT(T)}$ to compare it with the experimental results. Equation (2) was used to calculate the theoretical values of the output voltage of the teraohmmeter using an ideal op amp $U_{OUT(ID)}$.

As described in [9], an op amp of the teraohmmeter should have a three-stage structure with an integrator in the first stage to provide protection from noise. Therefore, this circuit diagram was used for the experiments and modeling. Figure 3 illustrates the circuit diagram of the teraohmmeter in the Altium Designer.

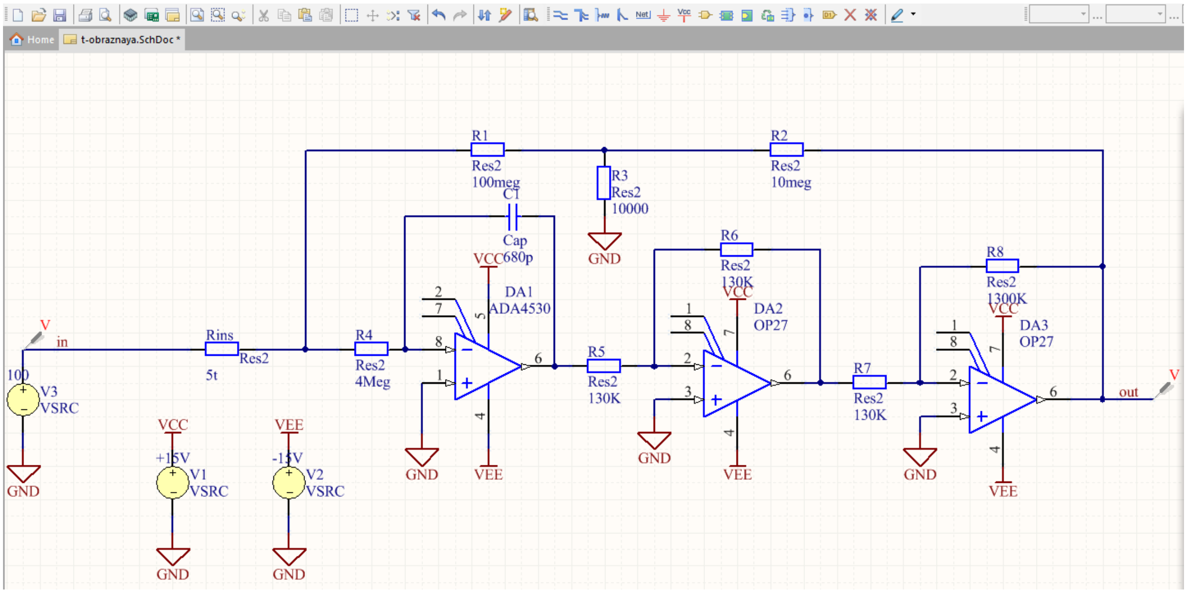

Figure 3. Circuit diagram of the teraohmmeter in the Altium Designer.

3. Investigation of T-shaped feedback

The experimental study revealed that the output voltage of the converter with T-shaped feedback $U_{OUT(EXP)}$ does not depend on the combination of resistances *R2* and *R3*, if they provide the same equivalent resistance R_{EQ}. This can be verified through the analysis of the measurement results at a constant resistance rating *R1* and varying resistances *R2* and *R3* (Table 1).

With this, the changes in resistance rating *R1* affect the output signal. Figures 4 and 5 show the dependences of the output voltage on the insulation resistance at different values of resistance *R1*.

Table 1. Dependences of the output voltage for the T-shaped feedback converter at different combinations of resistances $R2$ and $R3$ ($R_{EQ} = const$).

$R1$, MOhm	$R2$, kOhm	$R3$, Ohm	R_{EQ}, GOhm	R_{INS}, TOhm	$U_{OUT(ID)}$, mV	$U_{OUT(EXP)}$, mV
10	10	101	1	1	100	103
10	100	998	1.012	1	101.2	105
10	1001	10070	1.005	1	100.5	103
100	10	101	10	5	200	205
100	100	998	10.12	5	202	210
100	1001	10070	10.04	5	201	207

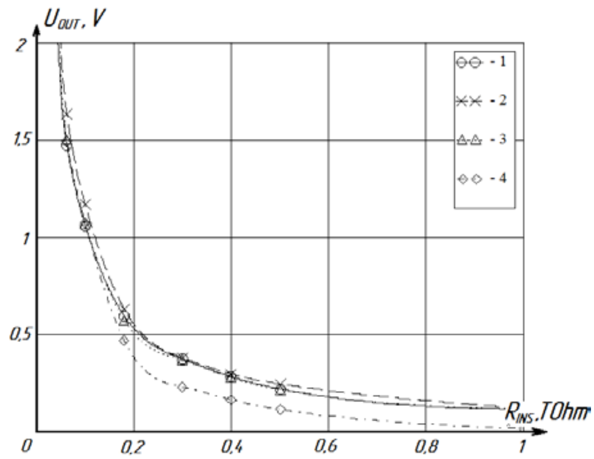

Figure 4. Dependences of the output voltage of the T-shaped feedback converter on the insulation resistance at $R_{EQ} = 1$ GOhm : 1 is dependence for an ideal op amp $U_{OUT(ID)}$ ($R1 = R2 = 1.001$ MOhm, $R3 = 998$ Ohm); 2 is dependence for $U_{OUT(EXP)}$ at $R1 = 100$ MOhm, $R2 = 100$ kOhm, $R3 = 10.07$ kOhm; 3 is dependence for $U_{OUT(EXP)}$ at $R1 = 10$ MOhm, $R2 = 100$ kOhm, $R3 = 998$ Ohm; 4 is dependence for $U_{OUT(EXP)}$ at $R1 = R2 = 1.001$ MOhm, $R3 = 998$ Ohm.

The graph in Figure 4 shows that the experimental dependences are equal to the theoretical ones, when reproducing $R_{EQ} = 1$ GOhm using resistances *R1*=100 MOhm and *R1*=10 MOhm. However, the error is 20% or more at *R1*=1 MOhm and the measured resistances exceeding 200 GOhm. At resistance rating *R1* less than 1 MOhm, the error becomes even greater.

A similar result can be observed in Figure 5, which illustrates the dependences at $R_{EQ} = 10$ GOhm. As can be seen from the graph, the error is more than 20% at $R1 = 10$ MOhm and the measured resistances exceeding 2.5 TOhm.

The experimental data presented above show that T-shaped feedback enables reduction of the reference resistance rating at least by a factor of 100. With a larger ratio, the measurement error increases, and the output signal of the converter tends to zero at the upper measurement limit when the resistance is reduced by a factor of 1000 or more.

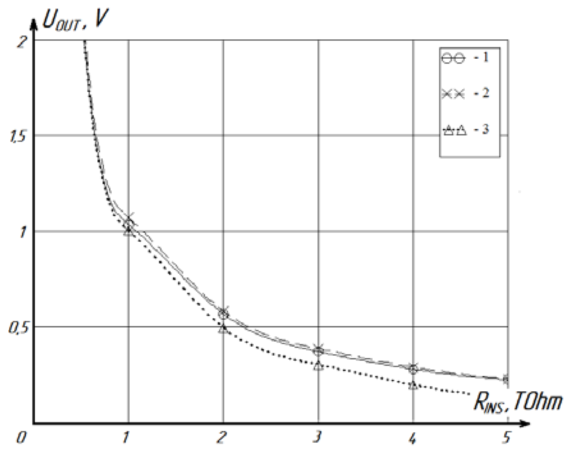

Figure 5. Dependences of the output voltage of the T-shaped feedback converter on the insulation resistance at $R_{EQ} = 10$ GOhm: 1 is dependence for an ideal op amp at $R1 = 10$ MOhm, $R2 = 1.001$ MOhm, $R3 = 998$ Ohm; 2 is dependence for $U_{OUT(EXP)}$ at $R1 = 100$ MOhm, $R2 = 1.001$ MOhm, $R3 = 10.07$ kOhm; 3 is dependence for $U_{OUT(EXP)}$ at $R1 = 10$ MOhm, $R2 = 1.001$ MOhm, $R3 =$ 998 Ohm.

This causes the problem of finding optimal rating for reference resistance *R1* of T-shaped feedback for a certain upper measurement limit.

For this purpose, compare the experimental and theoretical dependences of the output voltage on the changes in reference resistance *R1* of T-shaped feedback at $R_{EQ} = const$ (Figure 6).

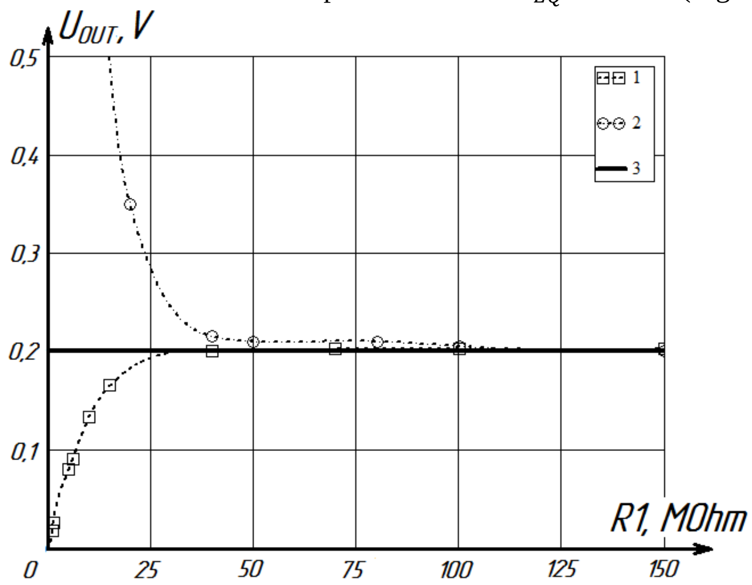

Figure 6. Dependences of the output voltage of the T-shaped feedback converter on reference resistance $R1$ at $R_{EQ} = 10$ GOhm, $R_{INS} = 5$ TOhm: 1 is experimental dependence for $U_{OUT(EXP)}$; 2 is theoretical dependence for $U_{OUT(T)}$; 3 is theoretical dependence for an ideal op amp $U_{OUT(ID)}$.

Based on equation (2), the output voltage of the converter $U_{OUT(ID)}$ should be equal to 0.2 V at $R_{INS} = 5$ TOhm and $R_{EQ} = 10$ GOhm. However, the experimental dependence shows that the use of T-shaped feedback at this measurement limit is possible for *R1* greater than 25 MOhm to make an error less than 10%. Lower values of resistance *R1* cause improper operation of the converter, and make the output voltage tend to zero.

Theoretical dependence is slightly different in nature. At *R1* less than 10 MOhm, the op amp is saturated, and the output voltage of the converter is equal to the supply voltage of the op amp. The converter operates within the range of resistance *R1* from 40 MOhm to 100 MOhm, but there is an additive error of about 10%. In the range from 100 MOhm, the converter output voltage corresponds to the calculated value with an error of less than 1%.

The results of both experimental and theoretical studies show that at resistance *R1* in the range from 100 kOhm to 40 MOhm the op amp of the teraohmmeter cannot provide proper operation of the teraohmmeter based on an ideal op amp.

4. Conclusions

The feasibility of using T-shaped feedback has been studied for teraohmmeters. The ADA4530-1 op amp with the input current of 20 fA was used, which theoretically enabled measurements of the resistance up to 5000 TOhm at a reference voltage of 100 V.

It was experimentally and theoretically proved that the dependence of the output voltage of the T-shaped feedback converter does not depend on the combination of *R2* and *R3* resistances, if they have the same equivalent resistance $R_{eq} = const$, and resistance *R3* ranges from 100 Ohm to 10 kOhm. At the same time, the changes in resistance *R1* significantly affect the output signal. According to the experimental data, the use of T-shaped feedback enables 100-fold reduction of the reference resistance rating. For example, resistor *R1* with a resistance not less than 100 MOhm is required to reproduce equivalent resistance $R_{EQ} = 10$ GOhm with an error of less than 1%.

References

[1] Leonov A P *et al* 2015 *IOP Conf. Ser.: Mater. Sci. Eng.* **81** 012094 doi: 10.1088/1757-899X/81/1/012094
[2] Leonov A *et al* 2014 *IOP Conf. Ser.: Mater. Sci. Eng.* **66** 012004 doi: 10.1088/1757-899X/66/1/012004
[3] Yakimov E *et al* 2016 *MATEC Web of Conferences* **79** 01069 doi: 10.1051/matecconf/20167901069
[4] Goldshtein A E, Fedorov E M 2010 *Russian Journal of Nondestructive Testing* **46** 424–430 doi: 10.1134/S1061830910060069
[5] Yakimov E *et al* 2017 *J. Phys.: Conf. Ser.* **783** 012061 doi: 10.1088/1742-6596/783/1/012061
[6] Fedorov E M, Bortnikov I D 2015 *Technical Physics* **60** 1689–1692 doi: 10.1134/S1063784215110110
[7] Popov V P 2007 *Fundamentals of circuit theory* (Moscow: High School)
[8] Bessonov L A 2014 *Theoretical Foundations of Electrical Engineering. Electrical circuits* (Moscow: Jurajt)
[9] Yakimov E V, Zhukov V K 2003 *Measurement Techniques* 35–39