Thermal noise thermometer for conducive media

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Abstract. Temperature is an important parameter in different technological and production processes. Measuring temperature of bulk, liquid and plastic environments is necessary in ecological monitoring, agriculture, chemical and energy industry, etc. Contactless measurement methods in this case are hard to use due to relatively low heat emission that causes significant errors. Present research is devoted to design of such device based on thermal noise method Use of classical contact methods and sensors in such cases may be difficult due to numerous reasons so it necessary to use the equipment that will provide required measurement accuracy and allow to remove disadvantages of existing instrumentation. It includes the block diagram and mathematical model of measuring device that will allow to measure averaged temperature of different conductive environments with high accuracy that is necessary when performing monitoring tasks. Designed instrument can also be implemented in forestry, medical research and chemical industry due to its constructive features.

1. Introduction

Temperature measurements are widely used not only in industry. Temperature monitoring allows to obtain information about other parameters, such as, for example, soil moisture level that is widely used in ecological monitoring [1-3], agriculture [4] and air temperature monitoring in meteorology [5]. Most of modern researches are devoted to contactless thermometry for different industrial implementations [6-12]. Devices and methods for such measurements are widely used and well-known. But sometimes it is necessary to know the average temperature of some media.

Such necessity occurs when assessing the thermal state of a number of bulk, liquid and plastic media (soil condition under environmental control, grain in elevators, petroleum products in storage, coal in warehouses, etc.). Placing local temperature sensors in a controlled volume and connecting wires in some cases is complicated and expensive. It is difficult to verify and calibrate the array of temperature sensors in such conditions. So it is necessary to create measuring equipment that will remove these disadvantages.

2. Problem statement

One of the ways to deal with above-mentioned disadvantages is use of thermal-noise based measurement method. Existing thermometric equipment (Ukrainian patent No 62713), is the step, made to solve the task. However, the presence of feedback in the device through a selective amplifier at the switching frequency leads to the appearance of an additional DC voltage component at the output of the multiplier, which distorts the readings of the output voltmeter. In addition, the bandwidth of the differential amplifiers included at the inputs of the multiplier, low-frequency noise such as flicker-noise, which also distorts the result of measuring the conversion of thermal noise into output DC voltage. in which the introduction of new elements and connections would ensure the release of thermal noise in a given frequency band and its conversion into a constant voltage proportional to temperature, without distortion from parasitic noise and interference, which will increase the accuracy of temperature measurement and expand its measurement range.

3. Results

The problem is solved by adding two needle electrodes, a resonant circuit of a capacitor and an inductor connected in series, a common bus and a DC-DC converter, the input of which is connected to the output of the low-pass filter, and its different polarity outputs connected to needle electrodes, between which a resonant circuit is connected, the midpoint of which is connected to a common bus, high-potential inputs of amplifiers are connected via distribution capacitors with needle electrodes, low-potential inputs of amplifiers are connected to a common bus, and digital voltmeter between the different polarity outputs of the DC voltage-to-current converter.

Block diagram of proposed device is shown in Figure 1.

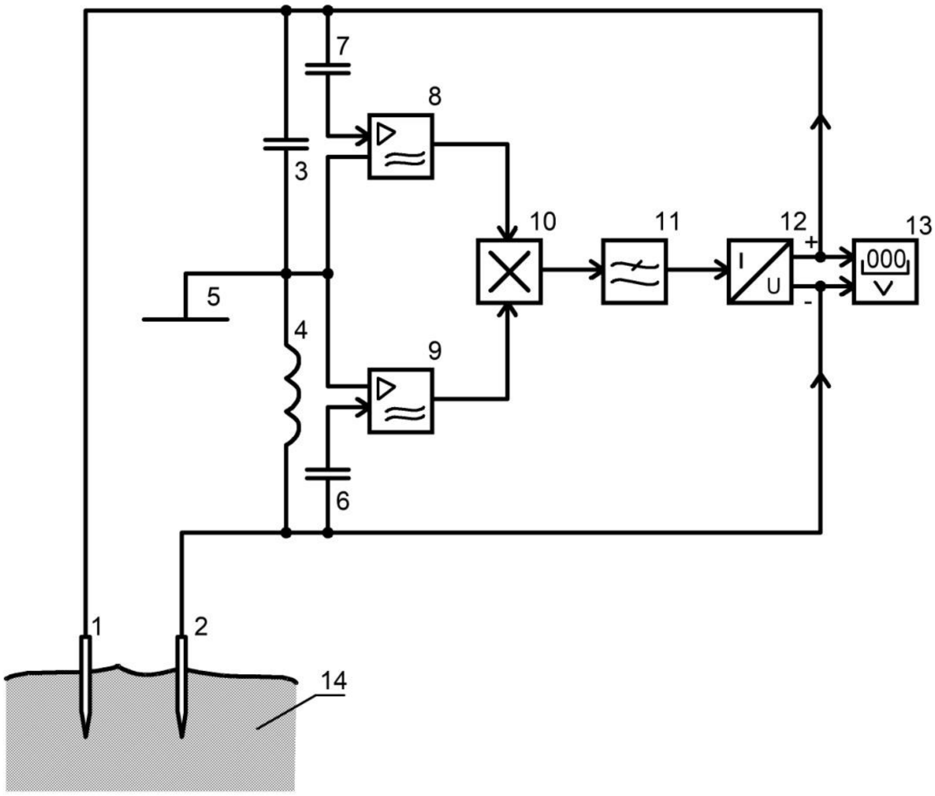

Figure 1. Block diagram of noise thermometer.

The circuit of the device includes needle electrodes 1 and 2, between which is included a resonant circuit of series-connected capacitor 3 and inductor 4, the middle point of which is connected to a common bus 5. Distribution capacitors 6 and 7 are included between needle electrodes 1 and 2 and high-potential inputs of amplifiers 8 and 9, low-potential inputs of which are connected to a common bus 5. The multiplier 10 with its inputs is connected to the outputs of amplifiers 8 and 9, and its output through the low-pass filter 11 is connected to a DC-DC converter 12. Multipolar outputs of the DC-DC converter 12 are connected to the needle electrodes 1 and 2 and the inputs of the digital voltmeter 13.

Position 14 denotes a controlled medium in which the needle electrodes 1 and 2 are placed.

The device for measuring the temperature of the conductive media works as follows.

Before the measurements, the needle electrodes 1 and 2 are placed in a controlled environment 14 in which thermal noise is present due to thermal fluctuations of the current carriers (electrons or ions). In addition, there are other types of noise (flicker noise, contact noise, etc.). In the conductive medium, parasitic currents from the mains and guidance are also inevitable. The selection of thermal noise from the spectrum of random signals and interference is carried out using a resonant circuit of the capacitor 3 and the inductor 4, tuned to the resonant frequency

$$f_0 = \frac{1}{2\pi\sqrt{LC}}, \tag{1}$$

where C is electrical capacity of capacitor 3;

L is inductance of coil 4.

The resonance frequency f_0 is chosen in the range of 200 - 500 kHz, in which there is no low-frequency noise and the effect of distributed capacities is still weak. The bandwidth of the spectral components of thermal noise by the resonant circuit is determined by the expression

$$\Delta f = \frac{f_0}{Q}, \tag{2}$$

where Q is the quality factor of the resonant circuit.

At the resonant frequency f_0 the condition of equality of reactive resistances of the circuit is fulfilled:

$$2\pi f_0 L = \frac{1}{2\pi f_0 C}. \tag{3}$$

Equality of resistances (3) means that the noise current at this frequency is practically determined by the resistance of the controlled medium between electrodes 1 and 2. According to the Nyquist formula, the RMS value of this current

$$I_n = \sqrt{\frac{4kT_x\Delta f}{R}}, \tag{4}$$

where k is Bolzmann`s constant;

T_x is thermodynamic temperature of the controlled medium;

R is the resistance of the medium between the electrodes 1 and 2;

Δf is the frequency band of thermal noise selected by the resonant circuit 3, 4.

Noise current (4) creates a voltage drops across the capacitor 3 and the inductor 4, the RMS values of which:

$$U_1 = \frac{I_n}{2\pi f_0 C}, \tag{5}$$

$$U_2 = 2\pi f_0 L I_n. \tag{6}$$

Noise voltages (5) and (6) are amplified by amplifiers 8 and 9, and then multiplied by the multiplier 10. Along with the noise voltages (5) and (6) are multiplied by the natural noise of amplifiers 8 and 9, which are proportional to the information thermal noise, especially when measuring low temperatures.

The resulting voltage at the output of the multiplier 10 is averaged by the low-pass filter 11. It should be noted that the noise of the two independent amplifiers 8 and 9 are uncorrelated, and information noise (5) and (6) are correlated because generated by one source (controlled environment 14). Therefore, the average product of noise voltages can be represented as:

$$\overline{U}_3 = \overline{k_1 U_1 k_2 U_2}, \tag{7}$$

where k_1 and k_2 are amplification factors of amplifiers 8 and 9;

" — " is time averaging symbol.

Substituting in expression (7) the values of voltages (5) and (6), we obtain

$$\overline{U}_4 = \overline{S_1 k_1 k_2 \frac{L}{C} I_n^2}, \tag{8}$$

where S_1 is the steepness of the conversion of the multiplier 10.

The square of the noise current determines the DC voltage component, which is released at the output of the low-pass filter 11. Substituting in the expression (8) the value of the noise current from (4), we obtain the value of the DC voltage

$$U_5 = 4S_1 k k_1 k_2 \frac{L}{C} \frac{\Delta f}{R} T_x. \tag{9}$$

The voltage (9) allocated by the low-pass filter 11 is converted into direct current by means of a voltage-to-current converter 12:

$$I = 4S_1 S_2 k k_1 k_2 \frac{L}{C} \frac{\Delta f}{R} T_x, \tag{10}$$

where S_2 is steepness of the voltage-to-current conversion.

The DC-to-current converter 12 is loaded through the needle electrodes 1 and 2 to the external resistance R of the controlled medium 14 through which the current flows (10). The voltage drop across the external load is measured by a voltmeter 13

$$U_6 = IR = 4S_1 S_2 k k_1 k_2 \frac{L}{C} \Delta f T_x, \tag{11}$$

where the product $4S_1 S_2 k k_1 k_2 \frac{L}{C} \Delta f$ can be considered as the resulting steepness of the conversion of temperature into voltage:

$$S_p = \frac{U_6}{T_x} = 4S_1 S_2 k k_1 k_2 \frac{L}{C} \Delta f. \tag{12}$$

Since the function of measuring the conversion of temperature into voltage (11) is linear, the resulting steepness of the transformation (12) can be determined experimentally by the calibration temperature:

$$S_p = \frac{U_c}{T_c}, \tag{13}$$

where U_c is measured voltage at calibration temperature T_c.

When measuring the current temperature of the controlled medium, it is sufficient to measure the voltage drop between the needle electrodes 1 and 2 with a voltmeter 13, and the temperature T_x is determined by the formula

$$T_x = \frac{U_x}{S_p}, \tag{14}$$

where U_x is reading of voltmeter 13.

4. Discussion

Thus, the use of a resonant circuit at the input of the proposed device eliminates the influence of non-thermal noise on the result of temperature measurement and stabilizes the bandwidth of the used thermal noise, which largely determines the resulting steepness of the transformation (13). At the same time, the resonant frequency of the circuit (1) is not included in the resulting steepness, which reduces the requirements for the stability of the elements of this circuit. The presence of feedback from the output of the device to the object of control through the needle electrodes 1 and 2 eliminates the appearance of additional bias of the output voltage in the multiplier 10 due to distribution capacitors 6 and 7. Connection of the midpoint of the resonant circuit 3, 4 and low-potential amplifier inputs 8 and 9 to the common bus 5 stabilizes the operation of the entire device and increases its noise immunity. The introduced DC-DC voltage converter allows to solve the input and output of the device according to the informative parameter and to eliminate parasitic connections on noise and interference, which helps to increase the accuracy of temperature measurement.

The inclusion of needle electrodes in the circuit expands the scope, as it makes it possible to remove thermal noise not only from bulk and plastic media, but also a number of solid materials, such as boards, logs, building materials. Promising use of the device in medicine for measuring the temperature of acupuncture points and individual areas of biological tissues. By immersing the electrodes at different depths in a controlled environment, you can determine the gradient of the temperature field and assess the non-uniformity of the thermal field.

Eliminating the influence of the resistance R of the controlled medium according to (11) on the accuracy of measuring the temperature of this medium allows you to place the electrodes 1 and 2 at any distance from each other. The changes in the interelectrode resistance that occur in this case are compensated by the corresponding changes in the output current of the converter 12, which makes it possible to scan the controlled medium by moving one electrode relative to the stationary reference electrode. In this case, any changes in the physicochemical properties of the controlled environment will not affect the results of temperature control. The invariance of temperature measurements by the proposed device in relation to the object of control provides the possibility of its use in aggressive environments, as well as in cases where the calibration of the temperature sensor is difficult.

Since the proposed device has no temperature sensor as such, the service life is long and is limited only by the corrosion resistance of the needle electrodes.

Conclusions

Proposed design of noise thermometer allows to increase the measurement accuracy of averaged temperature of conductive environments. Use of needle electrodes makes it applicable for measuring temperatures of loose, liquid and solid conductive materials. It can also be used in hazardous environments or in cases where calibration of thermocouples or other sensors may be difficult. Exploitation time of such measuring device is limited only by corrosion resistance of needle electrodes.

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