UDC 536.532:681.5.015 DOI: 10.24027/2306-7039.2.2021.236102

Voltage spectral structure of the thermocouple with temperature dependent wires

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Abstract

The article presents a study of the origin of extra harmonics in the frequency spectrum of thermocouple output signal when being heated by sinusoidal waveform current. It is natural to have the first harmonic, which arises according to Ohm's law, as a product of current and the total resistance of thermocouple and junction conductors, as well as the Peltier, Thomson effects, and the presence of the second harmonic, which is caused by a heating of junction and thermocouple conductors. The fact that third and higher harmonics arise when the resistance of conductors and junction is thermally dependent was identified.

The analytical dependence of the resulting voltage across the thermocouple terminals as a function of the total resistance of conductors and junction, and the voltages due to the effects of Joule, Seebeck, Peltier and Thomson, is established. Based on the analysis of the obtained function and experimentally obtained voltage spectra across the terminal of the thermocouple, an assumption was made about the nature of the voltage spectrum that heats thermally dependent wires of the thermocouple. Recommendations are given to reduce the influence of the first, third and higher harmonics, which are uninformative, and to separate the voltage of the second informative harmonic, which is used to get frequency response of the thermocouple.

Keywords: frequency response; thermocouple; EMF; spectrum; thermally dependent resistance; voltage.

Received: 05.05.2021 Edited: 07.06.2021 Approved for publication: 11.06.2021

1. Introduction

One of the most common devices for technical temperature measurement is the thermocouple. The thermocouple covers wide range of temperature measurements in static mode and has significant variation of its thermal inertia parameters. Most often thermocouple technical documentation includes only nominal static characteristic, and does not include dynamic characteristics of the thermocouple. Therefore, it is necessary to determine and indicate the dynamic characteristics of the thermocouples to perform dynamic temperature measurements.

Among dynamic characteristics such as transient response, pulse response and frequency response, the frequency response is more advanced due to usage of stationary process of sinusoidal waveform temperature changing. Sinusoidal waveform change of temperature is easier and more accurate to implement in contrast to temperature impulse.

The use of current for internal heating of a thermocouple with the intention to determine its dynamic characteristics is not commonly reported in the literature. In study [1] thermocouple is heated by current, and after the current is turned off the transient cooling process is registered. This technique involves recalculation of the resulting transient process taking into account the absence of a source of heat supply and changes in heat transfer conditions.

In study [2] the thermocouple was heated by current in order to obtain its static and dynamic characteristics. Since the EMF of the thermocouple was also registered only after the current was turned off and the direction of its passage was changed the frequency spectrum of the output signal contained only EMF.

The authors proposed a method [3] for determining the dynamic characteristics of thermocouples and created a device [4] to implement the proposed method. The method is based on obtaining a step response of a thermocouple by internal heating by means of a radiopulse of sinusoidal waveform current with a period less than the smallest time constant of the thermocouple to create a step change in temperature.

These methods have disadvantages in determining the time constants and their number, as the first two methods take into account only one time constant, as well as the presence of random errors in EMF measurement, which are associated with the presence of non-stationary processes in EMF measurement, which leads to errors in determination of time constants.

In study [5] the authors proposed a new method for determining the frequency response of a thermocouple to define its time constants. The essence of the method is as follows. A sinusoidal waveform current is passed through the thermocouple. The amplitude response of the thermocouple will be obtained as the ratio of the amplitudes of the electromotive force of

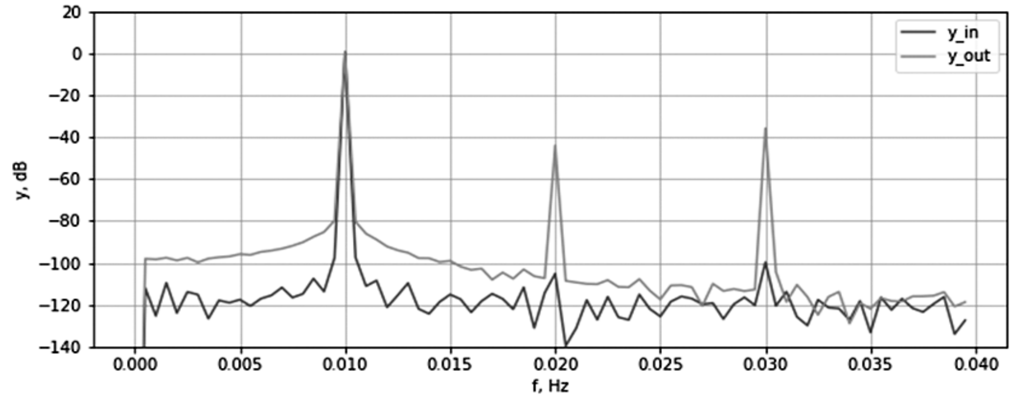

Fig. 1. Heating signal (y_in) and thermocouple EMF (y_out) spectra

the thermocouple and the second harmonic of the input signal obtained by raising the amplitude of the heating signal to the square. The phase response of the thermocouple was also defined as the difference between the EMF phase of the thermocouple and the phase of the variable component of the squared input signal. Based on the obtained frequency response the parameters of the dynamic characteristic were determined in the form of several time constants of the first-order aperiodic units connected in series.

It is necessary to further investigate the spectral composition of the voltage at the thermocouple terminals, because the total voltage consists of component voltages that can be caused by other physical processes.

2. Spectral composition of the voltage that heats the thermocouple

When determining the dynamic characteristics of the thermocouple in the form of frequency response [5] it was found that in addition to the expected first and second harmonics frequency spectrum of the voltage at the terminals of the thermocouple, there was also a significant third harmonic (Fig. 1). The ratio of harmonics was as follows $u_{f_1} : u_{f_2} : u_{f_3} = 1.5 : 0.008 : 0.01$.

The first harmonic is obvious and arises according to Ohm's law as the product of the current and the total resistance of the wires of the thermocouple and the resistance of the junction, as well as the Peltier and Thomson effects. The presence of the second harmonic is due to the heating of the junction and wires. The junction temperature according to the Joule effect is proportional to the power released at the junction, which is proportional to the square of the current flowing through the thermocouple. If the current has a sinusoidal waveform then its squared value is proportional to the sum of the constant component and the cosine component at the frequency of the second harmonic (1).

$$I_m^2 \sin^2(\omega t) = 0.5 I_m^2 \left(1 - \cos(2\omega t)\right). \quad (1)$$

The third and other harmonics arise when the resistance of the conductors and junction is thermally dependent.

To explain the causes of the third and other harmonics, we present an equivalent thermocouple circuit in the form of series-connected thermocouple resistances, junction resistance and Seebeck EMF source (Fig. 2),

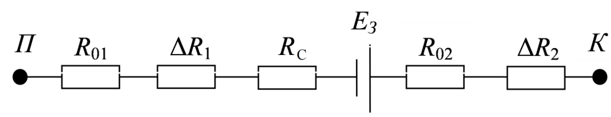

Fig. 2. Equivalent thermocouple scheme

where R_{01}, R_{02} are initial resistances of thermocouple conductors; ΔR_1, ΔR_2 are increases in the resistance of the conductors from their heating; R_C is a junction resistance; E_3 is a Seebeck's electromotive force; *П*, *К* are beginning and end shown in Fig. 2.

Thermal dependent resistance is usually expressed as (2).

$$R(\theta) = R_0\left(1 + \alpha\theta + \beta\theta^2 + \gamma\theta^3 + \ldots\right), \quad (2)$$

where θ is a temperature, α, β, γ are the polynomial coefficients; R_0 is an initial resistance at 0°C.

A simplified model of the resistance of conductors is used and takes into account only the linear part (3).

$$R(\theta) = R_0\left(1 + \alpha\theta\right). \quad (3)$$

If we accept such a simplified model then voltage at the terminals will be as in (4).

$$U_{ПК} = I_m \sin(\omega t)\Big[R_{01}\Big[1 + k_1\alpha_1\left(I_m \sin(\omega t)\right)^2\Big] + R_{02}\Big[1 + k_2\alpha_2\left(I_m \sin(\omega t)\right)^2\Big] + R_C\Big] \pm k_3\left(I_m \sin(\omega t)\right)^2 \quad (4)$$

where $k_1\alpha_1$, $k_2\alpha_2$ are the temperature coefficients of resistance of the first and second wires; k_3 is a Seebeck coefficient of thermocouple.

After transforming out the equation (4) we get equation (5) of the spectral composition of the voltage at the thermocouple terminals in (Fig. 2).

$$U_{ПК} = I_m \sin(\omega t)\left[R_{01} + R_{02} + R_C + 0.75 I_m^2\left(R_{01}k_1\alpha_1 + R_{02}k_2\alpha_2\right)\right] \pm k_3 I_m^2 \sin(2\omega t) - 0.25 I_m^3\left(R_{01}k_1\alpha_1 + R_{02}k_2\alpha_2\right)\sin(3\omega t). \quad (5)$$

Equation (5) shows that the voltage at the thermocouple terminals is represented by the three harmonic components at frequencies ω, 2ω, 3ω.

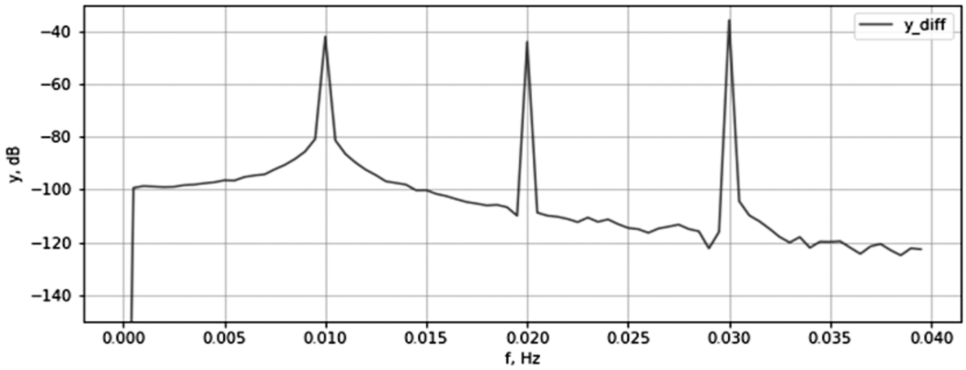

Fig. 3. The spectrum of the output signal with the suppressed first harmonic

The largest component of the voltage occurs at the frequency of the first harmonic. The second harmonic formed by the Seebeck effect with the coefficient k_3 is much smaller.

Moreover, the Seebeck coefficient k_3 depends on the materials of thermocouples and has the lowest value for high-temperature thermocouples, such as Tungsten-Rhenium, and the highest value for semiconductor thermocouples.

The third harmonic represents the component caused by the temperature dependence of the resistance of the thermocouple and junction wires.

The application of the spectral analysis procedure allows to separate the voltage of the second harmonic used to construct frequency response which will be obtained as the ratio of the amplitudes of the electromotive force of the thermocouple and the second harmonic of the input signal obtained by raising the amplitude to the square.

To minimize the influence of the third and other harmonics, the resolution of the spectrum analyzer is increased by increasing the analysis time and synchronization of the beginning and end of the analysis with the moments of transition through zero of the signal as it increases with a given number of periods chosen at least 20–100.

As noted and experimentally confirmed [5] the amplitude of the first harmonic is 100–200 times greater than the amplitude of the second harmonic. Therefore, specifically to improve the dynamic range of the analysis, a scheme was created to suppress the first harmonic (Fig. 3).

Such a setting of the experimental system allows to use the maximum number of bits (about 20) of twenty-four bit ADC to measure the instantaneous voltage values.

To create the maximum sine signal in the digital-to-analog converter, the maximum possible number of its bits were used (in NI PXI-4461 there are 24 of them).

With a stepwise approximation of a sinusoid, the higher harmonics have numbers $N=pn\pm1$ where p is a natural number and n is the number of sampling points per period. If $p=1$ and $n=1000$ then the nearest harmonics will have numbers 999 and 1001.

Nonlinear distortions occur not only due to the stepwise approximation of the sine wave but also due to further amplification. As a result the second, the third harmonics etc. may appear.

Therefore for experimental research an amplifier is created with deep feedback $k\beta>>1000$ two-stroke output stages operating in mode “A” with pre-setting to decrease the constant component of the output signal, in the absence of input signal, to a level less than $|\pm5$ mV$|$, with the ability to provide the amplitude of the output voltage of ±10 V.

The measured nonlinear distortions of the output voltage ±10 V at a current load of ±0.2 A and operation at non-thermal resistance did not exceed -100 dB.

3. Conclusion

When determining the frequency response of a thermocouple by internal heating with a sinusoidal current, harmonics with numbers above the second may be present in the voltage spectrum at the terminals of the thermocouple, which are due to the thermal dependence of conductors and junction. Increasing the resolution of the spectrum analyzer by increasing the analysis time and synchronization of the beginning and the end of the analysis with the moments of transition through zero of the studied signal as it increases, at a given number of periods, will minimize the influence of the third and other harmonics.

Спектральний склад напруги термоперетворювача із термозалежними дротами

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Анотація

Визначення динамічних характеристик термопар необхідно для вимірювання температури швидкозмінних високотемпературних теплових процесів. Серед динамічних характеристик перехідної, імпульсної та амплітудо-фазочастотної характеристик, амплітудо-частотна характеристика має переваги, оскільки для її отримання використовують стаціонарний процес зміни температури шляхом розігріву термопари струмом синусної форми. Зміну температури за гармонічним законом простіше та точніше реалізувати у порівнянні зі стрибком та імпульсом температури.

У статті розглянуто та досліджено виникнення додаткових гармонік у спектрі вихідного сигналу термопари при розігріві її струмом синусної форми. Природною є наявність першої гармоніки, яка виникає згідно із законом Ома як добуток струму та сумарного опору провідників термопари й опору спаю, а також ефектами Пельт'є та Томсона, та другої гармоніки, яка зумовлена розігрівом спаю та провідників. Встановлено, що третя та інші гармоніки можуть виникати, коли опори провідників та спаю є термозалежними.

Отримано аналітичну залежність результуючої напруги на затискачах термопари як функцію опорів провідників та спаю, а також напруг, які зумовлені ефектами Джоуля та Зеєбека. На основі аналізу отриманої залежності та отриманих експериментальним шляхом спектрів напруги на затискачах термопари зроблено припущення щодо природи спектрального складу напруги, яка розігріває термопару із термозалежних дротів. Наведено рекомендації щодо зменшення впливу першої, третьої та вищих гармонік, які є неінформативними, та виокремлення напруги другої інформативної гармоніки, яка використовується для побудови амплітудо-фазочастотної характеристики термопари.

Ключові слова: амплітудо-фазочастотна характеристика; термопара; ЕРС; спектральний склад; термозалежний опір; напруга.

Спектральный состав напряжения термопреобразователя с термозависимыми проводами

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Аннотация

В статье рассмотрены и исследованы возникновения дополнительных гармоник в спектре выходного сигнала термопары при разогреве ее гармоничным током. Естественным является наличие первой гармоники, которая возникает по закону Ома как произведение тока на суммарное сопротивление проводников термопары и спая, а также эффектами Пельтье, Томсона, и наличие второй гармоники, обусловленной разогревом спая и проводников термопары. Установлено, что третья и высшие гармоники могут возникать, когда сопротивления проводников и спая являются термозависимыми.

Получена аналитическая зависимость результирующего напряжения на зажимах термопары как функции суммарного сопротивления проводников и спая, а также напряжений, обусловленных эффектами Джоуля, Зеебека, Пельтье и Томсона. На основе анализа полученной зависимости и полученных экспериментальным путем спектров напряжения на зажимах термопары сделано предположение о природе спектрального состава напряжения, которое разогревает термопару из термозависимых проводов. Даны рекомендации по уменьшению влияния первой, третьей и высших гармоник, которые являются неинформативными, и выделению напряжения второй информативной гармоники, которая используется для построения амплитудо-фазочастотной характеристики термопары.

Ключевые слова: амплитудо-фазочастотная характеристика; термопара; ЕДС; спектральный состав; термозависимое сопротивление; напряжение.

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