Consideration of Complementary Error During Design of the Alternating Current Coaxial Shunts

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***Abstract*—In the paper, some factors produced instrumental error of the coaxial shunts conversion ratio have been studied. Complementary error influence on the corrected shunt dynamic characteristics with increasing current magnitude has been estimated. The optimal physical properties for material of a resistive pipe coaxial shunt have been determined.**

Keywords—coaxial shunts, bypass resistor, dynamic characteristics, physical properties, manganin.

I. INTRODUCTION

The current sensors in the shape of shunts, alongside with current transformers and Rogovskoy' coils are wide-spread in big current measurement in the wide frequency band [1]. A coaxial structure of shunts is preferable for measurement of such currents, as it contains conductors with forward and backward current direction [2, 3].

A basic parameter determining the practical use of AC current shunts is its amplitude-frequency response. Such responses are improved via different amplitude corrector circuit which enables to fully correct a dynamic component of shunts error in a predetermined frequency band [4].

Nevertheless, a complementary error could contribute to instrumental error of the corrected bypass resistor conversion factor significantly. The complementary error is caused by the change of shunts geometrical dimensions due to changes of the measured current value comparatively to its nominal value, which is set on the stage of corrector circuit design.

The purpose of the paper is to determine the influence of the complementary error on the instrumental error of the corrected coaxial shunt. Determination and improvement of the shunt dynamic properties with regard to the influence of a complementary error on the instrumental error of current measurement will allow to improve its competitive capacities as of the cheapest measuring means among all of the measuring tools.

II. SUBJECT OF RESEARCH

The research of the influence of the conversion factor complementary error have been carried out by the example of a coaxial bypass resistor (Fig. 1) with the following parameters: a resistive pipe thickness is 1 mm, length is 90 mm, inner radius is 9 mm, DC current resistance is $748 \cdot 10^{-6}$ Ohm [4].

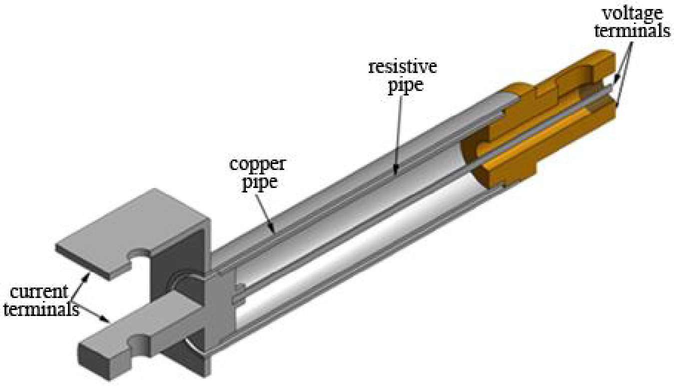

Fig.1. Design of the coaxial shunt

The geometrical dimensions calculation and their following construction designs have been performed by the method described in [5, 6]. It should be noted that this method does not consider change of physical properties of the used materials.

The authors of the previous investigation [1] have determined that connection of potential fans to the inner surface of resistive cylinder (Fig. 2) guarantees the best frequency-response characteristic of the shunt.

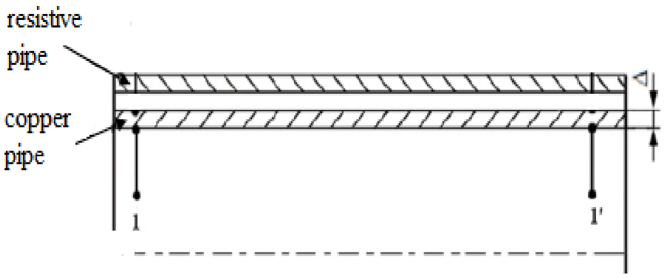

Fig.2. Potential connection terminals

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Thus, for this potential fans connection, the conversion factor of input current to the output voltage (shunt complex resistance) is equal to [4]:

$$\dot{Z}_{\text{sh}} = \frac{\dot{U}}{\dot{I}} = \frac{R(1+j)m\Delta}{\text{sh}[(1+j)m\Delta]} \; , \tag{1}$$

where R is the active resistance of bypass resistor on DC current, Ohm;

$m = \sqrt{\omega\mu / 2\rho}$ is a value reciprocal to the wave penetration equivalent depth, m^{-1};

μ is vacuum permeability, Henry per meter;

ω is circular frequency, radian per second;

ρ is electrical resistance of the resistive pipe material, Ohm•m;

Δ is resistive pipe thickness, m.

Determination of amplitude frequency response (AFR) by formula (1) implies shunt amplitude linearity due to permanence of physical characteristics of the used materials and its geometrical dimensions, i.e. their independence on current and heating temperature.

Nevertheless, a different temperature is set for different values of measured current in a shunt even in stationary conditions, and this temperature varies a range of parameters making a part of the formula (1) and changing its dynamic characteristics. Hence the shunt can be referred to parametric transit-time elements having electrical and heat response time, and its AFR mode depends not only on frequency F, but also on the values of the measured current I, i.e. $\dot{Z}_{\text{sh}} = f(F, I)$.

The last sentence means that theoretically, a shunt will have a separate AFR for each current value, and a separate pass band at the set level of the instrumental error, and its amplitude characteristic will be non-linear.

III. ANALYTICAL RESEARCH OF THE TRANSFORMATION ERROR

An uncorrected shunt has an instrumental error component which can be showed as an integration of the following error components:

$$\Delta_{\text{Ш}} = \Delta_{\text{b}} * \Delta_{\text{dyn}} * \Delta_{\text{comp}} * \Delta_{\text{ext}} \; , \tag{2}$$

where * is a symbol of an error components integration;

Δ_{b} is the basic error of the measuring system which is used in standard environment. Frequency band of the measuring system covers zero frequency. A basic error for the system is generally determined under the constant input signal. This error component in the main case is determined as an error of the R shunt conversion factor on DC current;

Δ_{dyn} is a dynamic error conditioned with the measuring system response to the alternating frequency of the input harmonic current and depending on the characteristics of the measuring system itself as well as on the measured current values;

Δ_{comp} is complementary error which makes the measuring system errors and appearing additionally to the basic error due to deviation of one of the influencing quantities from its normal value. This error derives from deviation from a current nominal value, which results in changing of the resistive element heating temperature;

Δ_{ext} is an error conditioned with the interaction of the measuring system with other metering circuit objects (current supply, voltage multi-meter and oscilloscope). This error depends on the characteristics and parameters of an input and output circuits of the measuring system and it may be not considered owing to its parameters.

According to the analysis of the shunt instrumental error components at relatively small values of the measured harmonic currents which almost do not change the bypass resistor temperature, the dynamic error is characterized by frequency-response ripple mostly contributes to it, i.e. $\Delta_{\text{sh}} \approx \Delta_{\text{dyn}}$.

Single out of the measuring system dynamic error as a separate component of an instrumental error is possible only under the condition that the measuring system is a linear dynamic element [6]. Only when this condition is fulfilled, a shunt bandwidth widening with the set error is carried out via the use of linear amplitude correctors (AC), which represent a proportional differentiating element of the first order [7].

Simply, the key point of a multiplicative correction can be showed by means of the following formulas:

$$Z_{\text{sh.corr.}} = Z_{\text{sh}} \cdot Z_{\text{corr}} \; ,$$

$$\delta_{\text{sh.corr.}} = |k_{\text{sh}} \cdot \delta_{\text{sh}}| + |k_{\text{corr}} \cdot \delta_{\text{corr}}|, \tag{3}$$

where $Z_{\text{sh.corr}}$, Z_{sh}, Z_{corr} are correspondingly transfers of the corrected shunt, the shunt and correction circuit;

$\delta_{\text{sh.corr}}$, δ_{sh}, δ_{corr} are relative errors corresponding to them;

k_{sh}, k_{corr} are coefficient of influence.

It is follows from formula (3) that resultant error reduction will take place in the case if a shunt error in the operational frequencies range is compensated with a corrector error. Relative error of the AC δ_{corr} transfer will have the components similar to formula (2). It is only a dynamic component of the AC error that is of interest at correction. It is known that lessening of other AC components impact on the resultant error of the corrected bypass resistor is possible only if the elements sensitivity of the AC circuit to different destabilizing factors is considered. The example of such analysis is provided in [7]. It gives the recommendations on the choice of elements of passive and active AC circuits for the coaxial shunt of the given type. The analysis shows that the elements making part of the AC must show a more stable response to different destabilizing factors than the correction object parameters, i.e. than the shunt. Under this approach in the limit, only a complementary component of the shunt error remains uncompensated. In adaptive AFR correction has been carried out without considering change of its frequency characteristics in a dynamic range of the measured current.

Fig. 3 illustrates the example of the diagrams of the coefficients standardized in relation to the *R* factors of uncorrected bypass resistor transformation (1) and of the shunt corrected with the simple passive corrector circuit (2–5).

Fig. 3 shows that the enhancement level of dynamic characteristics of the shunt as broadening of its band pass at the set AFR unevenness in the 0.1 % zone is determined by the chosen transfer coefficient values on the DC current $K(0)$ of the AC circuit, and by the $A = \tau_{sh}/\tau$ coefficients which are characterize the correlation of the bypass resistor response time and the AC [1].

Now let's assess the impact of a shunt complementary error depending on increasing of its resistive element heating temperature at increasing of the measured current.

A cooper-nickel alloy of the MHMc3-12 (manganin) has been chosen [8] as a material of the inner resistive pipe. The use of manganin is conditioned by non-significant deviations of its physical characteristics from the impact of different destabilizing factors.

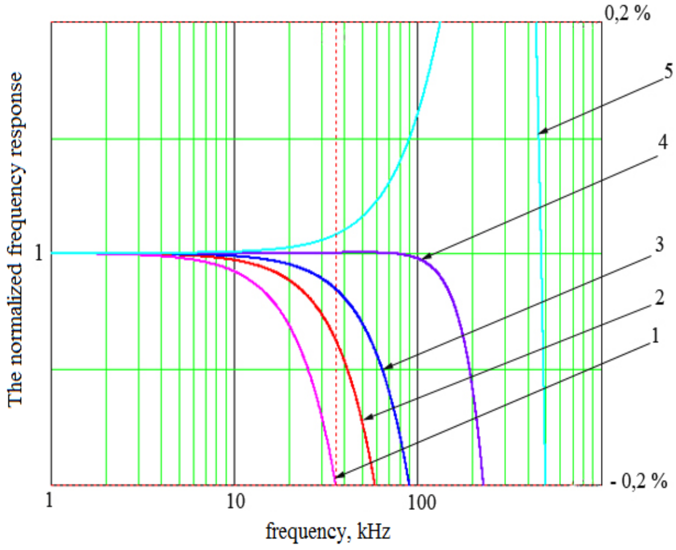

Fig. 3. AFR: 1- of the shunt (upper frequencies $F_{up} = 27$ kHz); 2 – of the shunt and the AC ($A = 1.5$; $K(0) = 0.6$; $F_{up} = 40$ kHz); 3 – of the shunt and the AC ($A = 2$; $K(0) = 0.4$; $F_{up} = 63$ kHz); 4 – of the shunt and the AC ($A = 3$; $K(0) = 0.3$; $F_{up} = 199$ kHz); 5 – of the shunt and the AC ($A = 5$; $K(0) = 0.15$; with the AFR recorrection)

Nevertheless, according to the standard [10], the temperature properties of the manganin of MNMc3-12 are the following: electrical resistivity is $\rho = (0.47 \pm 0.05)$ mkOhm·m at the temperature of 20°C, the temperature coefficient of electrical resistivity α may varying in the range from $1 \cdot 10^{-5}$/°C to $2.5 \cdot 10^{-5}$/°C for the temperature zone from 10°C to 40°C, the temperature coefficient of the linear expansion $\beta = 1.8 \cdot 10^{-5}$/°C. Thus, for the set temperature zone there are different values of electrical resistivity temperature coefficient.

However, for different makes of manganin bands in the range from 0°C to 100°C, the temperature coefficient may reach the value equal to $5 \cdot 10^{-5}$/°C [9]. Thus, when producing a shunt with a broad dynamic current range, one needs to know the initial parameters of the used materials and their response to temperature change.

It's quite difficult to determine the resistive element heat temperature experimentally at the current change due to geometric particularities of the coaxial shunt (the distance between the pipes is about 1 mm). It is advisable to use the software packages for such purposes allowing to carry out simulation and to determine of the physical processes in the research subject [10]. One of these software packages for such studies is ANSYS.

When simulating the shunt temperature profile on DC current, the ρ electrical resistivity change of the materials with the T temperature growth of the shunt details heat. According to the results of the performed simulation, the maximum temperature is observed on the inner and external shunt pipes. Quantitatively, the temperature gradient along the resistive pipe of the shunt is feeble marked [11]. It has been defined that a maximum overheat temperature of 40°C is reached at the DC current range equal to 150 A.

Nevertheless, according to the formula (1), not only changes the *R* bypass resistor active resistance with the change of resistive element heat temperature, but also other parameters such as m, μ, Δ, which influence on its frequency characteristics. When simulating of the corrected shunt AFR, the change of manganin physical characteristics with growth of the research subject heat temperature up to 60°C has been considered. Fig. 4 illustrates the corrected bypass resistor AFR with the following correction parameters: $A = 3$; $K(0) = 0.3$ with due regard for range of the electrical resistance temperature coefficient change and of the fixed value of the temperature coefficient of linear expansion.

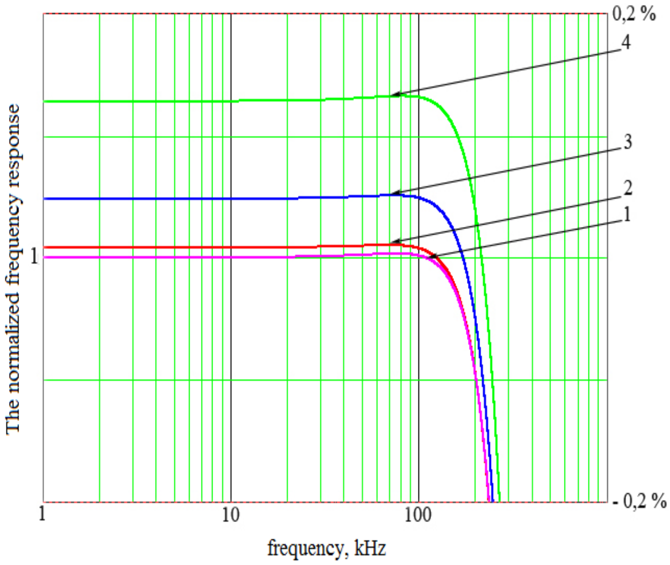

Fig.4. Corrected shunt AFR: 1 – at $\alpha=0$, $\beta=0$; 2 – at $\alpha=2 \cdot 10^{-5}$/°C, $\beta=1.8 \cdot 10^{-5}$/°C; 3 – at $\alpha=3 \cdot 10^{-5}$/°C, $\beta=1.8 \cdot 10^{-5}$/°C; 4 – at $\alpha=5 \cdot 10^{-5}$/°C, $\beta=1.8 \cdot 10^{-5}$/°C.

Fig. 4 shows that the frequency characteristics of the corrected shunt depend on manganin physical properties, which is the material the inner resistive pipe is made of. At the electric resistance temperature coefficient is $\alpha=2\cdot10^{-5}/°C$, coefficient deviation of the shunt conversion on DC current is equal almost to zero. It is resulting from the temperature coefficient of electric resistance is compensated by the temperature coefficient of linear expansion. At the temperature coefficient of electric resistance equal to $\alpha=5\cdot10^{-5}/°C$, coefficient error of the shunt conversion constitutes 0.13 %.

IV. CONCLUSION

Thus, the investigations show that a complementary error at the set value of instrumental error can lead to the change of the shunt dynamic characteristics and can lessen the conversion coefficient accuracy at DC current.

At construction of coaxial shunt which is used at measuring of grand AC currents, one should consider the electrical resistance temperature coefficient of the material a resistive pipe is made of. The analytical researches of the corrected shunt show that for the maintenance of the passband at attenuation at the level 0.1 % one needs to choose manganin with the electrical resistance temperature coefficient which does not exceed the value equal to $\alpha=3\cdot10^{-5}/°C$.

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