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Measurement of the Current Transfer Function for Power Transducers of Current to Voltage

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Abstract. Transducers of current to voltage, such as current shunts are widely used in control systems for the mechanical engineering. The shunt is required to determine the value of its resistance on DC and AC currents to determine the transfer ratio error in the wide frequency band in process of verification or calibration. Well-known methods for resistance measuring (by Thompson' double bridge; magnetic comparator, compensation technique, etc.) require a commerce resistance and difficult to implement for shunts with resistance less than 0.1 Ohms. The paper describes a procedure for measuring the complex impedance of transfer ratio of current shunts in the frequency band using the lock-in amplifier with the differential input. The experimental results of the proposed procedure for coaxial shunt with nominal resistance at DC 750 uOhm and 160 uOhm are described.

Introduction

The current scale measuring transducers, so called current shunts [1–4] are widely used in control systems in mechanical engineering. The coaxial shunts are frequently used for control of high-quality micro-welding contact of critical destination products, which is characterized by the pulse current in the widely range up to 20 kA and by the pulse duration from a few to hundreds of milliseconds [5–6]. The current shunts to measure DC and AC currents are used in the high power laboratories, such as CESI (Italy), ESEF (France), JSTC (Japan), KEMA (Netherlands), PEHLA (Germany) etc. [7–8].

The main metrological characteristic of the scale measuring transducers is transfer ratio at the specified frequency. In [9–11] the measurement procedure for IDN transfer ratio was described at the specified frequency using the lock-in amplifier with the differential input. This paper presents the procedure for measuring of the complex transfer ratio of current shunts using lock-in amplifier with the differential input.

Procedure for measuring the transfer ratio of shunts

The coaxial current shunts are used for measurement of the AC currents over wide frequency band [12–14]. The shunt is a measurement current transducer, containing current and voltages pins (Fig. 1) and structurally consists of two embedded in one another cylinders on which the current flows in opposite directions.

The inner cylinder is manufactured by the resistive material with high resistivity (e.g. manganin), external cylinder is manufactured by the resistive material with lower resistivity (e.g. copper).

During the verification or calibration of shunt to determine the value of its resistance on DC and AC the determination of the transfer ratio error in the frequency band is required. It is known that the impedance of the coaxial shunt on AC current depends on the thickness of the inner cylinder, the voltage pins connection and has an active-reactive nature.

Methods for measuring of the resistance (by Thompson' double bridge, magnetic comparator compensation technique, etc.) require a standard resistance and difficult to implement for shunts with resistance less than 0.1 Ohm [14–20].

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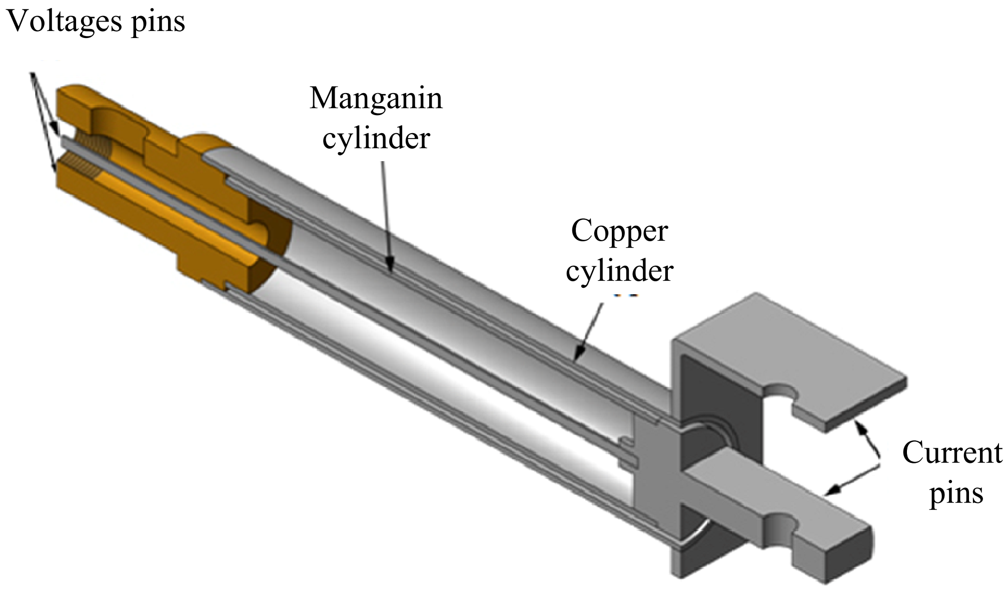

Fig. 1. Construction of the coaxial shunt

We propose the use of highly sensitive comparison instrument, lock-in amplifier (LIA) with the differential input to measure resistance of shunt on AC current. Its structure is shown in Fig. 2.

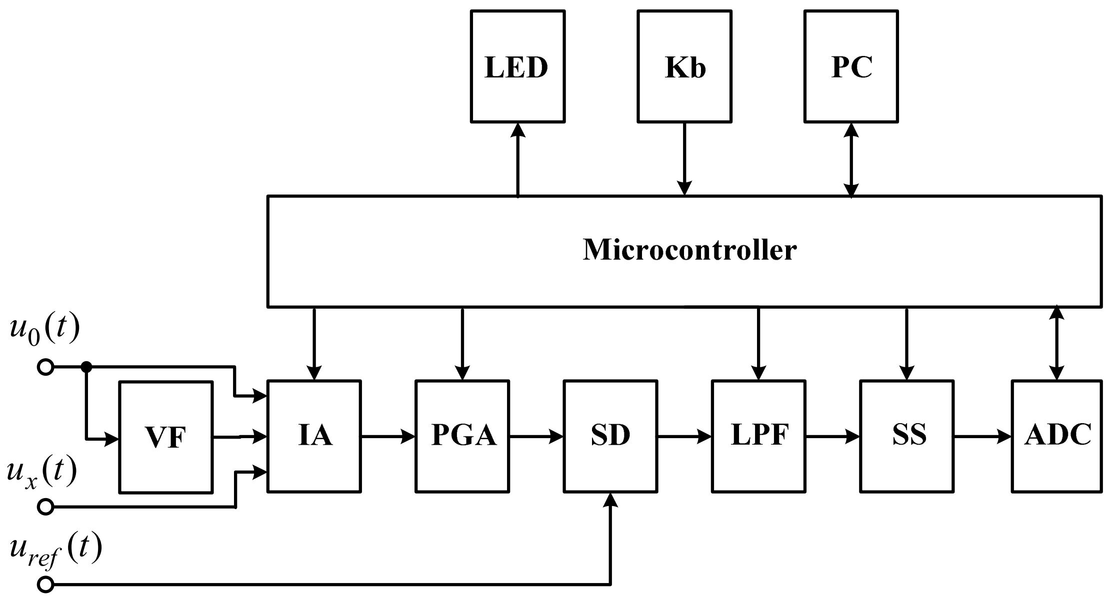

Fig. 2. Structure of lock-in amplifier with the differential input

The structure of the LIA includes: voltage follower (VF), instrumentation amplifier (IA), amplifier with programmable gain (PGA), synchronous detector (SD), low-pass filter (LPF), sample-and-storage (SS), analog-to-digital converter (ADC), microcontroller, seven-segment LED (LED), keyboard (Kb) and personal computer (PC).

This structural scheme allows realizing in LIA with the differential input four modes of operation:

1) calibration mode 1. In this mode, both inputs IA are connected to source u0(t), SS is in the "sample" mode;

2) calibration mode 2. In this mode, the inputs IA are connected to sources u0(t) and ux(t) respectively, SS is in the "sample" mode;

3) "setting zero" mode. Irrespective of used calibration type "setting zero" mode changes SS into the "storage" mode, readings of the indicator are zeroed;

4) measurement mode. Measurement mode occurs when the inputs IA are connected to sources $u_0(t)$ and $u_x(t)$, and the scheme of the SS is in "storage" mode.

Connection scheme for measuring the resistance of the current shunts is shown in Fig. 3.

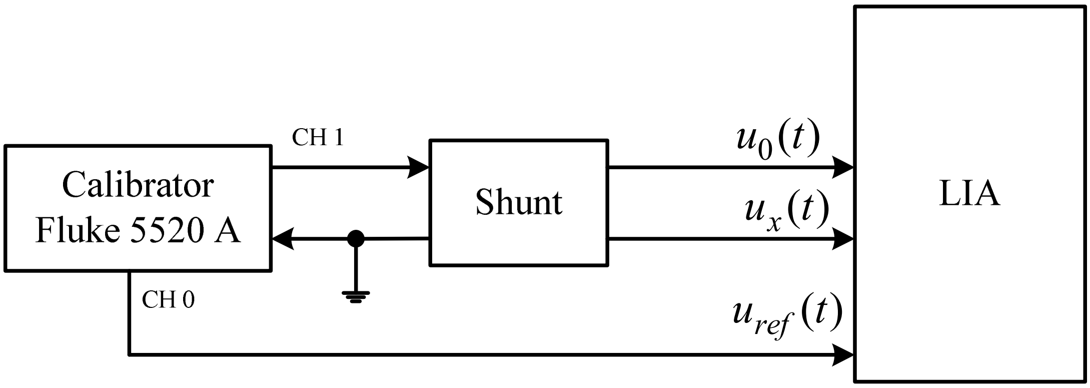

Fig. 3. The scheme for measurement resistance of shunts

Measurement of the active component of the shunt resistance requires the reference AC voltage with the output channel CH0 Fluke 5520A, supplied reference input of LIA and current at the same frequency with the output channel CH1 is supplied to shunt. Difference of voltage ΔUp between pins of shunt is measured by LIA and calculated as the real part of its resistance by (1):

$$R_{f(re)} = \Delta U_p / I_f, \tag{1}$$

where $R_{f(re)}$ is real part of the shunt resistance on AC, Ohm;
ΔU_p is voltage difference appropriate projection on the in-phase vector, V;
I_f is AC value set on the calibrator, A.

Measurement of the module and phase shift for shunt transfer ratio is carried out in two stages. The first stage output channel CH0 calibrator supplied the reference input of LIA AC voltage and current at the same frequency with the output channel CH1 is supplied to shunt with zero phases offset from the reference voltage. Difference ΔU_p between voltage pins of shunt appropriate in-phase projection of vector is measured by LIA. In the second stage shunt is supplied by AC from the output of CH1 calibrator with a phase shift –90° relative to the reference voltage. Difference ΔU_q between potential pins of shunt appropriate to the quadrature projection of vector is measured by LIA.

Resistance modulus R_f and phase shift θ_R of current shunt transfer ratio is calculated according to the formulas (2) and (3) respectively:

$$R_f = \frac{\sqrt{\Delta U_p^2 + \Delta U_q^2}}{I_f}; \tag{2}$$

$$\theta_R = \operatorname{arctg}\left(\frac{\Delta U_q / I_f}{\Delta U_p / I_f}\right). \tag{3}$$

Experimental investigations of the proposed procedure

Verification of the proposed procedure was carried out on coaxial shunts with the parameters given in Table 1. The potential pins were connected to the inner surface of the inner cylinder.

Table 1.Shunts parameters

Parameters	Shunt 1	Shunt 2
The thickness of the inner cylinder, [m]	$1\cdot10^{-3}$	$1.5\cdot10^{-3}$
Length, [m]	$90\cdot10^{-3}$	$125\cdot10^{-3}$
The radius of the inner cylinder, [m]	$10\cdot10^{-3}$	$48\cdot10^{-3}$
The resistivity of the material of the inner cylinder, [Ohm·m]	$0.46\cdot10^{-6}$	$0.46\cdot10^{-6}$
DC resistance, [Ohm]	$750\cdot10^{-6}$	$160\cdot10^{-6}$

The resistance modulus R_f and phase shift θ_R of shunts were theoretically calculated at 1 kHz by the formula (4) for comparison of theoretically values with experimental results:

$$\dot{Z} = \frac{R(1+j)m\Delta}{\mathrm{sh}[(1+j)m\Delta]}, \tag{4}$$

where R is DC resistance of shunt, Ohm;

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

μ is absolute magnetic permeability, H/m;

ω is angular frequency, rad/s;

ρ is resistivity of the material of the inner cylinder, Ohm·m;

Δ is thickness of the inner cylinder, m.

Results of measurements and calculated values of the real component of the shunt resistance at 1 kHz frequency for different values of the output current is shown in Table 2 and Fig. 4.

The measurement relative error of the resistance real component calculated by the formula:

$$\gamma_R = \frac{\left|\left|\dot{Z}\right| - R_{f(re)}\right|}{\left|\dot{Z}\right|}\cdot 100. \tag{5}$$

Table 2. Measurements results of shunts resistance at 1 kHz frequency

Output current, [A]	Theoretical voltage module of shunts, [μV]		Measurement voltage, [μV]		Relative error, [%]	
	Shunt 1	Shunt 2	Shunt 1	Shunt 2	Shunt 1	Shunt 2
0.1	75	16	74,4	16.3	0.8	1.9
0.2	150	32	148	32.5	1.3	1.7
0.3	225	48	222	48.9	1.3	1.9
0.4	300	64	297	65.2	1.0	1.9
0.5	375	80	370	80.9	1.3	1.1
0.6	450	96	444	97.7	1.3	1.8
0.7	525	112	518	113	1.3	0.9
0.8	600	128	590	130	1.7	1.6
0.9	675	144	666	146	1.3	1.4
1	750	160	740	162	1.3	1.2

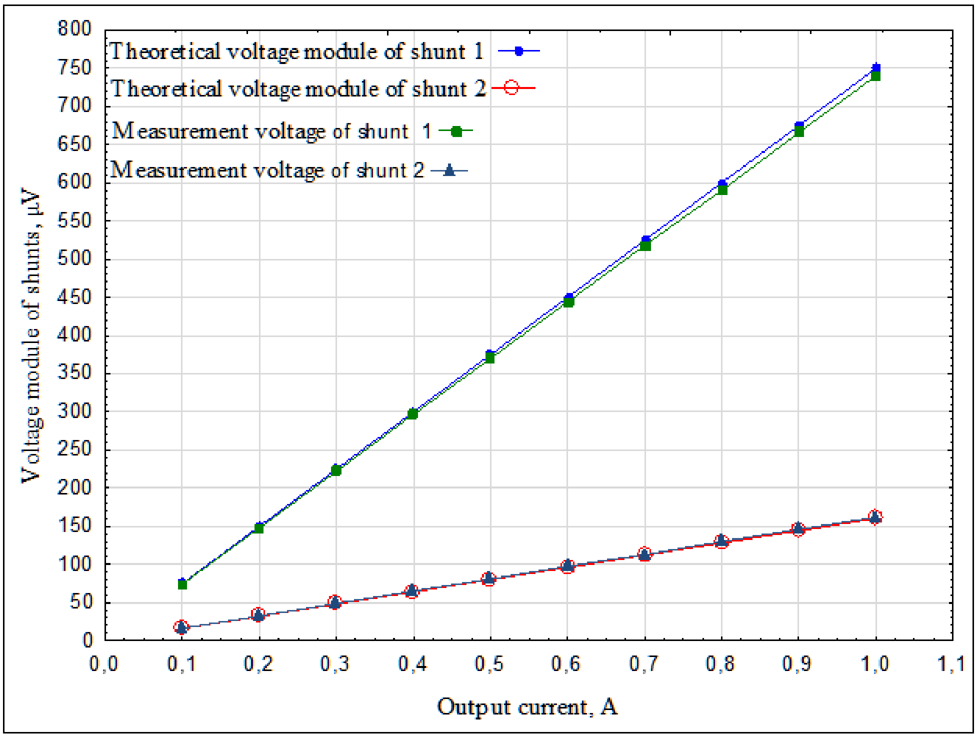

Fig. 4. Dependences of shunts voltage of the calibrator current

It is follows from data in Table 2 that measurement results are independent of calibrator current (shunt has linear transfer ratio), and the relative error of measurement of the real component of the shunt resistance at 1 kHz for different values of the current does not exceed 2 %.

The results of experimentally determined the resistance module and phase shift shunts transfer ratio, as well as their values obtained by calculation on the basis of formula (4) at a current of 0.1 A for the shunt 1 are shown in Table 3.

Table 3. Results of determination resistance module and phase shift of transfer ratio at current 0.1 A

Frequency, [kHz]	Theoretical voltage module of shunt, [μV]	Theoretical phase shift, [deg]	Measurement voltage, [μV]	Measurement phase shift, [deg]	Resistance module error, [%]	Phase shift error, [deg]
1	74.99	-0.175	74.46	0.077	0.71	-0.252
5	74.99	-0.877	74.38	-0.925	0.80	0.048
10	74.98	-1.753	74.32	-1.968	0.87	0.215
15	74.97	-2.630	74.31	-2.975	0.88	0.345
20	74.94	-3.506	74.29	-4.064	0.86	0.558
25	74.91	-4.382	74.26	-5.122	0.86	0.740
30	74.87	-5.257	74.24	-6.068	0.84	0.811

Absolute error in the determination of the phase shift may be calculated by formula:

$$\Delta\theta_R = \mathrm{arctg}\left(\dot{Z}\right) - \theta_R \tag{6}$$

It is follows from Table 3 that the relative error in determining shunt resistance module transfer ratio does not exceed 1 %, and the absolute error in the determination of the phase shift does not exceed ±1°.

Conclusions

Procedure for measuring of the active component of the resistance current shunts is proposed and experimentally checked. The relative error of measurement results at 1 kHz for different values of the current does not exceed 2 %.

Procedure for measuring of the resistance of the module and phase shift transfer ratio of current shunts in the frequency range using a lock-in amplifier with a differential input is proposed and experimentally tested. Relative error of the shunt module transfer ratio does not exceed 1 %. The absolute error in the determination of the transfer ratio phase shift does not exceed ± 1 °.

The proposed procedure with the appropriate software allows in automatic mode to carry out verification and calibration of current shunts in the frequency band.

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