Digitally Controlled Thermoelectric Ammeter

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Abstract. The main objective of this project was the development of fully functional microprocessor controlled thermoelectric ammeter for laboratory and didactic purposes. Device is based on analog thermoammeter transducer, Kamduino platform and thermocouple transducer with cold junction temperature compensation. The main advantage of this unit is direct measurement of the effective value of the electrical current (True RMS), regardless of the shape and frequency of the signal, combined with modern signal processing and data output capabilities.

Keywords: Thermoelectric effect · Ammeter · RMS

1 Introduction

Current measurements in electronic circuits are one of the most important issues in electronic technology. Greater accuracy usually results in a limited measurement range, so other meters are used for measuring small currents (galvanometers and electrometers in the case of millionths of ampere), and completely different for much larger currents. Generally, however, the ammeter designs rely on the measurement of the voltage drop on a reference resistance, from which Ohm's law can be used to determine the current value. Few devices make such measurements directly.

High frequency current measurements are problematic, because as the frequency increases, the system behaves differently, and the meters fail to follow the changes, generating significant errors in the measured values. Usually, processing circuits are used to compensate the frequency dependence, but it is no longer a direct measurement, and these circuits have their limitations. A commonly used solution is to connect a shunt resistance, to which an oscilloscope is connected. With this solution you can measure AC currents up to a few hundred kilohertz, however, in the case of higher frequencies even this solution is ineffective [1].

Previously, to calibrate various kinds of ammeters, thermoelectric ammeters were used owing to their unique properties. They always indicate the effective value of the current (RMS), regardless of the shape or frequency of the signal. It was possible to achieve a very wide frequency range for which the desired metrological parameters of the measurement were maintained.

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In this work, the analogue thermoelectric ammeter has been transformed into digital form, thus increasing the accuracy and comfort of reading. Moreover, the microprocessor system used enables easy calibration, storage and transmission of data. The principle of operation has been thoroughly investigated, the characteristics for different frequencies and various signal shapes have been measured. The source of the errors was identified as well, comparing the indications with the precision laboratory ammeters.

2 Operation Principle

Thermoelectric meters are based on the working principle of thermocouples. Historically, they were built of a thermoelectric transducer and a magnetoelectric millivoltmeter calibrated in units of measured current [2]. Thermoelectric transducers are made of a heater and a thermocouple in the form of two wires connected at one end, made of different metals. When the current flows through the heater, it is heated, and a voltage appears in the cell, as in an ordinary thermocouple, and is read by the millivolt meter. The transducer can be placed inside or outside the magnetoelectric meter - the latter option is most commonly used for remote measurements and for high frequency current measurements.

Thermoelectric transducers are divided into indirect and direct heating transducers. In the latter case, the heater has direct ohmic contact to the hot junction of the thermocouple. In the case of indirect heating, the heater is heated by means of an insulating tube or glass ball. Commonly, a thin layer of tantalum oxide is used, which increases the cell's durability while lowering the thermal inertia compared to previous solutions [3, 4] (Fig. 1).

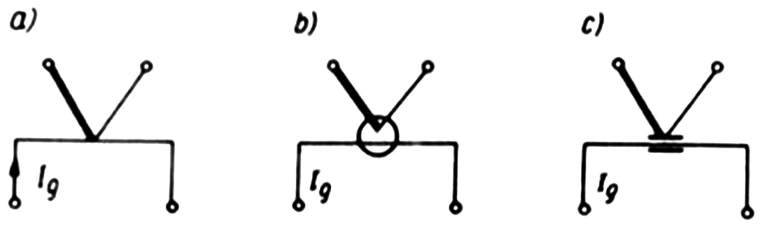


Fig. 1. Heating transducers: (a) direct, (b) indirectly through the glass ball, (c) indirectly via the insulating tube [3].

3 Thermoelectric Transducer

The main element of the project is a thermoelectric ammeter type T 5-1. Originally, the device was equipped with an analogue indicator. The device was stripped of the analogue meter and connected to a digital microcontroller circuit. The transducer itself is shown in Fig. 2.

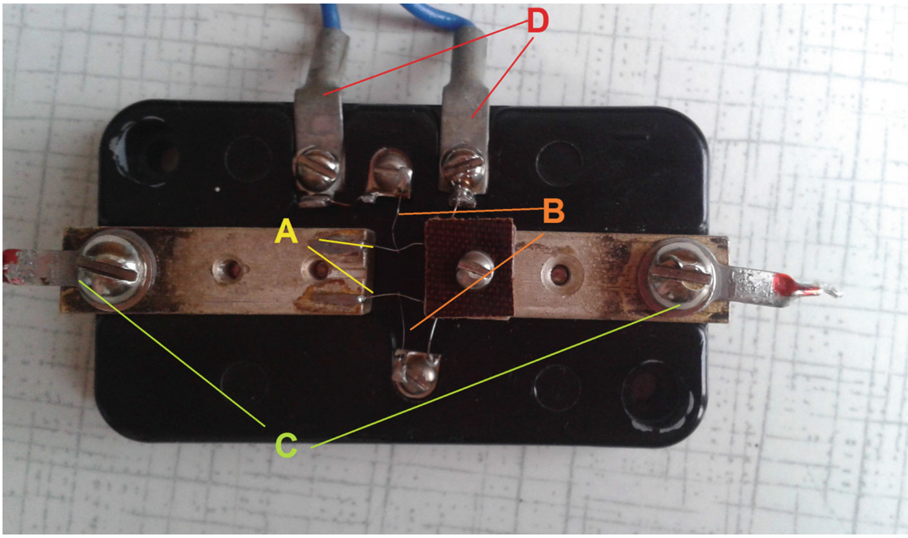


Fig. 2. Photo of the transducer without protective shielding.

The ammeter is connected to the investigated circuit in series, by means of the terminals C. The current flows through the connectors to which two thin wires (A) are soldered, which act as a heater. To each of them, another wire (B) is welded, which is made from dissimilar metals, as in a thermocouple. These connections form a thermoelectric cell. The current flowing through the heater causes the temperature to rise at the hot junction, from which voltage is measured on terminals D. The transducer is enclosed in a casing to protect the delicate construction.

The meter works for currents from 0 A to 3 A, but declared 5% accuracy is for range from 1 A to 3 A. Limitations are due to the construction of the device and the type of thermocouple used. Less than 1 A of current decreases the accuracy of the measurement, while passing through the heater more than 3 A can melt the material (the connector exceeds 1000 °C). There are also versions ranging from 1 A to 10 A available.

The frequency range for which the manufacturer declares the correct operation of the device is from 30 Hz to 7.5 MHz. The lower range is due to the fast reaction time of the system – the pulses of the signal will immediately translate into pulsations of the display. The upper range is limited mainly by the parasitic capacities of the system.

4 Signal Processing

In order to construct a complete digitally controlled circuit, in addition to the thermocouple, it was necessary to select a suitable amplifier to convert a (0–50) mV signal to (0–5) V, an A/D converter that converts an analogue signal from a thermocouple to a digital signal, microcontroller and display. In the later phase of the project, it was decided to replace the amplifier and A/D converter with a ready-to-use IC for thermocouples, with cold junction compensation, which perfectly fulfilled the role of the replaced components [5]. Because of its ease of use, component compatibility, ready-to-communicate libraries, and the simplicity of connecting components, the Kamduino platform was used as a microcontroller.

The IC used is MAX6675 with cold junction compensation. The 12-bit output from the transmitter is compatible with SPI communications [6], matching the Kamduino input. The resolution of the transmitter is 0.25 °C and can be measured from zero to over 1000 °C. Transmitter inputs reduce the effect of noise from thermocouple wires. The transducer corrects the cold end of the transducer's ambient temperature and the reference temperature (0 °C) before changing the signal in volts to the temperature display. For the K-type thermocouple this correction is 41 µV/°C, giving a linear characteristic:

$$V_{out} = (41\mu\mathrm{V}/^{\circ}\mathrm{C}) \cdot (T_{cold} - T_a)$$

where:
V_{out} - voltage at the thermocouple output,
T_{cold} - cold end temperature,
T_a - ambient temperature

Before starting to build the system, it was necessary to investigate the metrological properties of the thermoelectric transducer, so the current-voltage characteristic was determined. To obtain this characteristic a measurement system was made, following the block diagram given in Fig. 3.

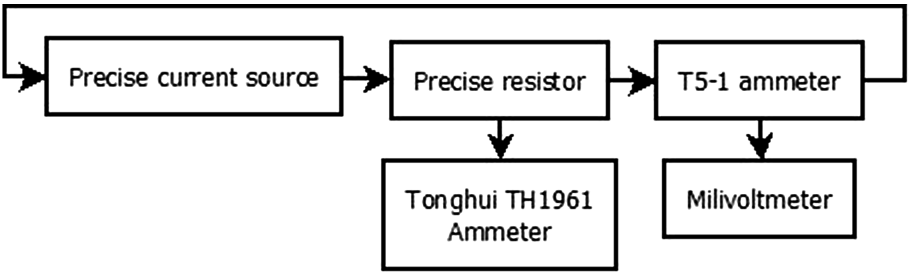


Fig. 3. Block diagram of a measurement stand for thermoelectric transducer investigation.

A precise resistor and T5-1 thermoelectric transducer are included in the current loop of the current power supply. The reference results are given by the Tonghui TH1961 multimeter, while the measured thermoelectric voltage values were taken from a millivoltmeter connected to the T5-1.

5 Thermoelectric Ammeter Construction

The block diagram in Fig. 4 shows the developed ammeter. The current flows to the system via a 3.15 A fuse, which protects the thermocouple from melting if the current is too high. The thermocouple voltage is applied to the thermocouple transducer, which compensates for the temperature of the cold end of the thermocouple. Additionally, the signal from the transducer has a separate analogue direct output from the device. The signal from the transducer is passed on to the microcontroller via the SPI interface. The microcontroller collects the data, converts the temperature display to the current one according to the implemented characteristic, averages 10 results for better indication stability and displays this value on the front panel LCD.

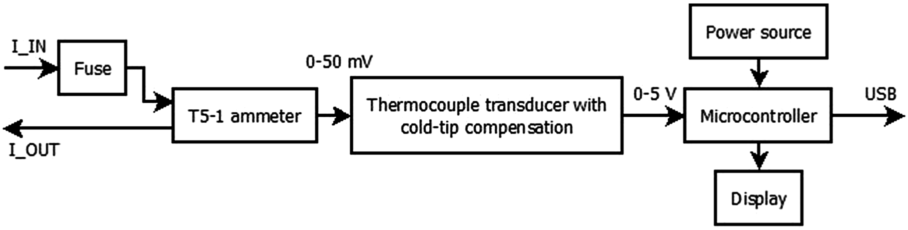


Fig. 4. Block diagram of the developed ammeter

6 Measurement Results

The data obtained from measurement of the characteristic of the transducer was fit to the formula:

$$y = a(x + b)^c + d$$

The function and its fitting is presented in Fig. 5.

The coefficients obtained from fitting data with the custom function are:

- $a = 0.1515$
- $b = -17.29$
- $c = 0.4608$
- $d = -0.3868$

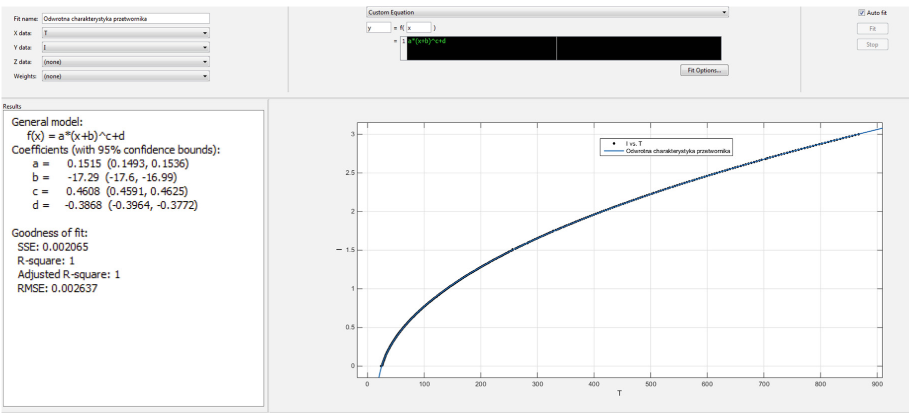


Fig. 5. Obtained characteristic of the transducer.

Applying the obtained formula in the microprocessor software allowed for automatic calculation of the ammeter measurement indication in amperes.

The RMS validation experiment was to study the effect of the signal shape on the reading of the device, for currents of 1 A and 2 A. The oscilloscope was connected and the waveforms shown in the Table 1 were used. For comparison, the results of the APPA62 m, which does not have the function of measuring True RMS current, are included. The results of the measurements are summarized in the Tables 1 and 2.

Table 1. Measurement results for 1 A of current.

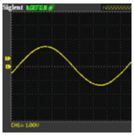
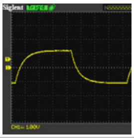
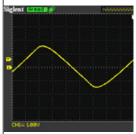
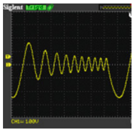
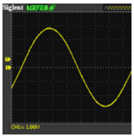
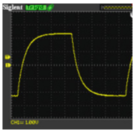
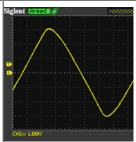
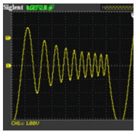
Shape		Sinusoidal 1 A	Square 1 A	Triangle 1 A	Chirp 1 A
Waveform					
Thermoelectric	Min	0.983 A	0.975 A	0.973 A	0.951 A
	Max	1.049 A	1.045 A	1.049 A	0.998 A
APPA62		1.002 A	1.064 A	0.976 A	**0.861 A**

Table 2. Measurement results for 2 A of current.

Shape		Sinusoidal 2 A	Square 2 A	Triangle 2 A	Chirp 1.8 A (Current source limitation)
Waveform					
Thermoelectric	Min	1.96 A	1.962 A	1.964 A	1.742 A
	Max	2.041 A	2.037 A	2.045 A	1.792 A
APPA62		1.99 A	2.12 A	1.958 A	**1.533 A**

7 Conclusions

The greatest advantage of thermoelectric ammeters is the ability to directly measure the True RMS current regardless of the shape of the signal, or its frequency. Especially the frequency range is orders of magnitude better than for most commercial multimeters. Additionally, microprocessor control and modern IC allowed for greater accuracy and resolution of the developed ammeter than the transducer's producer originally intended. Specifically, the resolution was changed from 0.1 A to 0.001 A, the accuracy from 5% to 1%, and the measurement range from (1–3) A to (0.1–3) A. Moreover, linking to a computer program improves the reading of results and allows for automatic data acquisition. However, the device has its limits. The measured ammeter exhibited worse metrological parameters than other TRMS meters available on the market in case of too low frequency values of the test signal, or its amplitude. Unfortunately, it was not possible to compare the results of such measurements for sufficiently high frequencies, mainly because the declared bandwidth is greater than those of other available devices. Measurement error, as well as uncertainty of measurement, decreases as the signal frequency increases. Below the 30 Hz, the error is unacceptably high. The DC and AC-current measurement capability is one of main advantages of such devices. The microcontroller can be programmed to adjust the measurement to the current type (DC or AC), either manually or automatically. The disadvantage of the tested ammeter is the inaccuracy of the design, which unfortunately has translated into erroneous indications in the case of the reverse than assumed direction of DC current flow, and thus needs to be calibrated with alternating current.

The main source of error in this type of meter is the influence of outside temperature. In the laboratory where all the tests in this work were carried out, there was an approximately constant temperature of 23 °C. However, in order to obtain constant time indication, it was necessary to wait 15 to 30 min after turning on the measuring system. During this time both the thermo-ammeters and the current generators have warmed up, which translated into more stable operation of the devices.

The remaining errors include the voltage measurement error on the transmitter, the gain and conversion error of the analog to digital signal by the thermocouple transducer, the compensation error, especially when the sensor temperature is at a different temperature than the thermocouple, as well as hysteresis and drift. Compensation can also be provided by adding a temperature sensor and galvanic isolation.

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