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# Temperature Influence Analysis on the Selected Current Sources Stability in the Static and Dynamic Operating States

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***Abstract*—The present work contains the stability test results of the current sources located in an environment of variable temperature. Two types of tests were conducted for four circuits stabilizing the current of the value close to 50 mA. One test consisted in changing the temperature in which the current sources loaded with variable resistance were placed. The other test related to the analysis of the transient state during switching on and off the load for two values of temperature. The article presents the obtained results of experiments and discusses the reasons of the measurement errors.**

***Index Terms*—Current source; temperature test; Grubbs test; Shapiro-Wilk test.**

## I. INTRODUCTION

The practice of electronic construction exploits a range of current sources to supply circuits. The usage of proper current sources of the LED diodes supply or sensors for temperature measurement (e.g. Pt100) can serve as an example [1]. Current sources may also supply circuits used for electric and non-electric quantities measurement [2]. The use of the 4 mA÷20 mA electrical loop in industrial measurement systems, used to measure e.g. temperature, pressure, deflection etc., is one of the best-known examples. In such devices, a transducer system excites the current flow in the loop circuit depending on the input parameters change of the measurement sensor. The Anderson's loop [3]–[6] is another example of using current sources in measurement. It is a series circuit of sensors connected with a current source and a reference resistor ($R_r$). Measuring the sensors resistance increase consists in subtracting the potentials with the use of functional blocks with operational measurement amplifiers. On the basis of the measured current drops on certain resistance sensors, the deflection decrease of the strain gauges or the temperature increase can be estimated with the use of a Pt100 sensor.

The authors have worked out other usages of current sources in a measurement circuit, which is a signal conditioner for resistance sensors, and a circuit called 2J4K2R (2 – current sources, 4 – switching keys, 2 – reference resistors) [7]. In this circuit, which is visually similar to the Wheatstone's bridge, the resistance elements are connected into a 4-armed bridge. Two of those elements have constant resistance $R_1 = R_2$, and other elements work as resistance sensors $R_3$, $R_4$. Two supplying current sources of identical parameters $J_1$, $J_2$ are connected to the opposite nodes of the conditioner, whereas two additional reference resistors $R_{r1} = R_{r2}$ are attached to the other tips. Such circuit works on the basis of the potential difference analysis through appropriate reading of the voltage decreases on the opposite nodes of the bridge system. It should be mentioned that the described circuit contains appropriate electronic keys that enable switching the circuit quickly and changing it into 4 circuits of the Anderson's loop. This solution has a significant advantage – the possibility of estimating two quantities in one measurement cycle and conducting a simple reconfiguration into the Anderson's loop circuits.

The described measurement system, despite its advantages, has also a drawback. The measurement precision depends on the temperature stability of the current sources. The authors of works [8]–[11] present new constructing solutions of the current sources, whose main feature is a small dependence of the temperature influence on their stability. Obviously, achieving the stability of a current source in laboratory conditions is rather easy, but it can be quite problematic in various thermal conditions, e.g. connected with the weather changes, when the circuit is placed out of the laboratory.

Apart from the electronic keys switching time, the duration of the transient state in the moment of switching on the current source and its disconnecting from the conditioner system is an additional factor related to the measurement uncertainty, which determines the frequency of switching particular arms of the 2J4K2R conditioning circuit. Therefore, the authors of this paper have suggested a procedure of testing the current sources that considers their temperature stability in the steady state (the static working mode) or in the transient state (the dynamic working mode).

It is worth stressing that the worked out conditioning circuit required current of 50 mA. For this reason, a prototype testing system consisting of 4 various constructing solutions of current sources of 50 mA placed on one PCB

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was built.

## II. CURRENT SOURCES USED FOR TESTS

In order to conduct the tests, it was decided to implement commonly used solutions, based on a well-known LM317 circuit, of a dedicated LT3092 2-Terminal Programmable Current Source, and 2 solutions based on measurement amplifiers which steer the MOSFET-N and MOSFET-P transistors. The circuits applied currently used embedded or external measurement instrumentation amplifiers. They steer the transistors, through which the set current flows, through the process of equalizing the voltage values.

LM317 is the first analysed circuit [12]. It is a commonly known and cheap integrated, regulated stabilizer of the positive voltage. Its role is to keep the $V_{ref}$ voltage on the level of 1.25 V on an R40 resistor (Fig. 1). The system, then, steers the output voltage in such a way that the flowing current causes the previously mentioned voltage decrease at the known resistance of R40. In this way, the constant output voltage value is obtained.

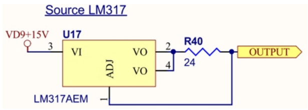
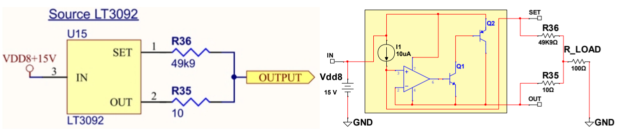



Fig. 1. Electrical circuit diagram of the LM317 circuit working as a current source.

LT3092 is another source which could be analysed in relation to the upper (positive) R_LOAD node, because at this point the voltage is identical for the steering (SET) and the working (OUT) brunches (Fig. 2) [13]. For the purpose of simplifying the analysis, the potential of 0 V can be assumed here. In this case, the current from the I1 source causes cumulating the voltage of about 0.5 V at the R36 resistance. The operational amplifier begins steering the output in order to set the input voltage at the 0.5 V as well. The voltage drop induced on the resistor R35 = 10 Ω causes imposing the current of 50 mA. Connecting two transistors in this circuit aims at maximum limiting the output current of the amplifier. The R_LOAD change does not vary the current value because both branches (SET and OUT) join before the load resistance of the source. Assuming that the Ohm's law must be fulfilled, a certain part of voltage stores on the resistor R35 and the R_LOAD (depending on the R_LOAD value), and the remaining part of the 15 V voltage – on the transistor Q2.

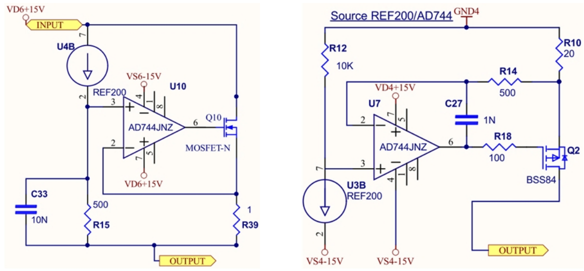



(a) (b)

Fig. 2. Electrical circuit diagram of the LT3092 current source connections and an adequate simulation model with the use of the Multisim circuit simulation software by National Instruments.

A floating current source based on an N-type MOSFET transistor may work as a current sinking and current source mode (Fig. 3) [12]. Similarly as in the first circuit with the LT3092, the current causes the voltage drop of 50 mV at the R15 resistance. The operational amplifier increases the output voltage until the voltages on (U10, 3 +) and (U10, 2 -) reach the equal value. Then, the MOSFET transistor begins conducting the current of about 50 mA.

The last tested source is based on an operational amplifier and a P-type MOSFET transistor (Fig. 3). This circuit works similarly as the current source in the previously discussed circuit [12]. The difference in the operating mode is that this circuit works on the negative voltage values – the current I imposes the voltage drop on the R12 resistance, hence, the voltage value at the (U7, 3 +) of the operational amplifier should be about -1 V. The R18 resistor protects the operational amplifier against the gate breakdown short circuit and decreases the equivalent gate capacitance charge current.




(a) (b)

Fig. 3. Electrical circuit diagram of the connections in the circuits working as current sources with MOSFET N and MOSFET P transistors.

As it can be observed, all the presented circuits are dependent on the temperature influence on their work because of the applied components. In the MOS transistors, for example, the following components depend on temperature: the threshold voltage and the media mobility in the transistor channel. Both components are the decreasing functions of temperature, but the resistors used to construct the circuits have a positive temperature coefficient of resistance, which may lead to disturbances in the current stabilization.

## III. THE LABORATORY STAND

The presented circuits of various current sources are all composed in a form of one PCB (Fig. 4). In this way, identical conditions of the supply voltage and temperature stability were provided for all electronic components. Additionally, before conducting the laboratory tests, the heat distributions caused by heating up the components of the test board were checked (Fig. 5).The figure below presents the temperature field distribution recorded by an infrared camera.

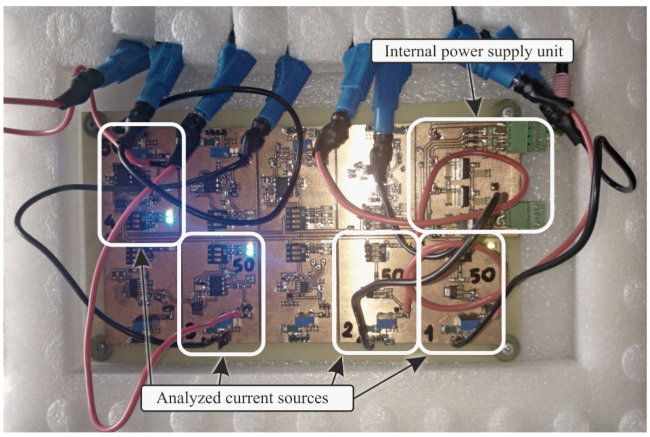



Fig. 4. General view of the tested circuit containing current sources of various types.

As it can be easily observed, the test board heated up mainly in the points of adjusting the LED diodes which signalized switching on and out the current sources. The local heating up of the PCB did not cover the components of the current sources, which allows the assumption that in further analysis this effect will be neglected.

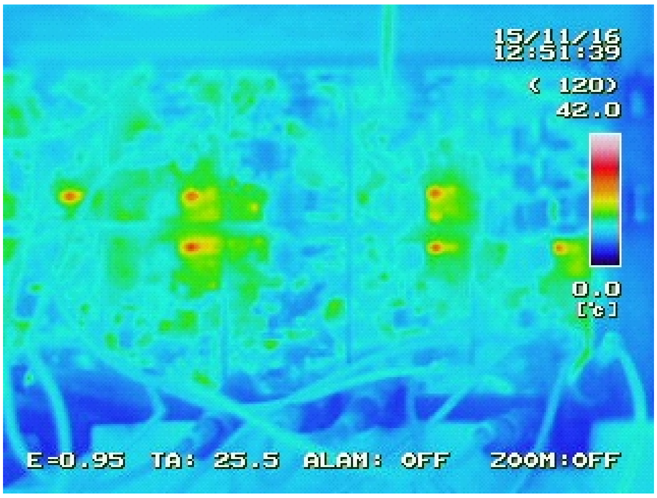



Fig. 5. Thermal field distribution on the PCB measured in a climatic chamber at 5 °C.

In order to test the current sources, a laboratory stand consisting of a set of devices steered by a LabVIEW environment, was built (Fig. 6). This was aimed at automating the research procedure, which consists of a number of factors that can be measured, such as temperature, current value, and voltage on the current source output, load resistance value and the transient state during switching on the load. The temperature measurement of the tested object was conducted in the steady state with the use of the data sent through a serial interface from the climatic chamber.

A KBK-1150W (WAMED) chamber of 1600 $dm^3$ was used. It was especially adjusted by the manufacturer for testing electronic devices. The chamber enables testing electronic circuits within the temperature range of -5 °C to +70 °C with the precision of 0.1 °C and long-term stability of ±0.3 °C. Additionally, it is possible to set the relative air humidity in the chamber within the range of 10 % to 95 % with the precision of ±0.1 %. The chamber is equipped with the RS232 interface, which enables cooperation with a PC and the LabVIEW software. RIGOL 3068 digital multimeters of 6½ digits readings resolution, a USB interface and a remote control with SCPI commands were used to measure current and voltage of the sources. The authors also applied the ARRAY 3723A DC electronic load of Constant Resistance Mode: low range 0.0666÷6.66 Ω with resolution of 0.1 mΩ, middle range 6.66÷666 Ω with resolution of 2.6 µS and high range 66.6÷6660 Ω with resolution of 0.29 µS. The load steering was done with the use of Standard Commands for Programmable Instruments (SCPI). For transient state analysis of current sources the Mixed Signal Oscilloscope Tektronix MSO2012B with parameters such as: 100 MHz bandwidth, 1 GS/s sample rate and a standard instrument programming interface for common applications written e.g. in LabVIEW, was used.

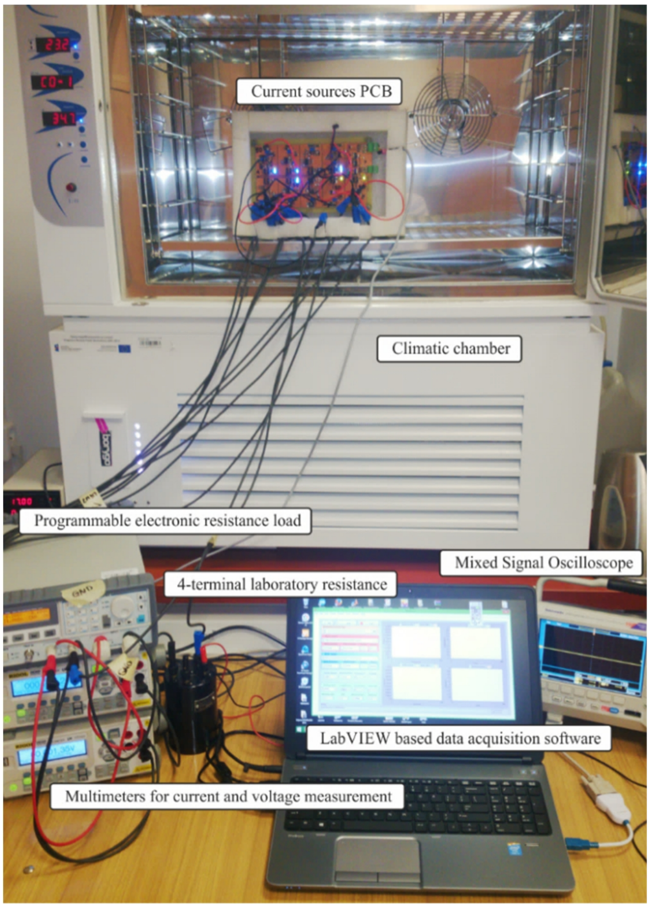



Fig. 6. General view of the current source test bench.

The devices were connected with a PC through a USB interface with a LabVIEW environment. It is worth mentioning that the software enabled the steering, recording the process of the current sources testing, storing the measurement results and their visualization. Additionally, a procedure of conducting the measurements with calculating Type A, Type B and combined standard uncertainty for the current and the voltage on the current source was implemented in the software.

The software created in LabVIEW is based on architecture employing a state machine. The use of such a program construction is implicated by the fact that the complex measurement process has to be cohesive and tightly-coupled. The State Machine approach in LabVIEW uses a Case structure inside a While loop to handle the different states in the program, and the transitions between them. The Shift Register is used to save data from and between the different states. In order to steer the state machine, names presented symbolically in the form of String data are usually used.

In order to create a state machine conducting the measurement data recording, a diagram showing the completed tasks and the transitions between the states was worked out (Fig. 7.).

Firstly, the procedures of operating the multimeters, the climatic chamber and the electronic load are initiated. Then, when the virtual communication ports function, the stage of parameters setting begins. At this stage, devices such as ammeter or voltmeter are set. In the following step, the processes of operating the climatic chamber, the measurement equipment and the electronic load are initiated as separate threads.

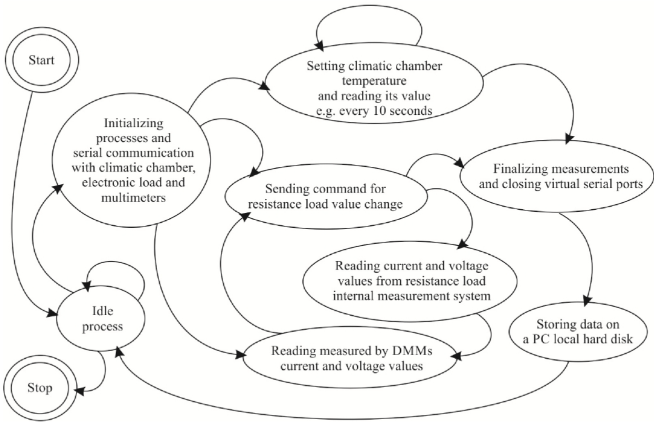



Fig. 7. Simplified visualization of a state machine used for working out software in LabVIEW.

Next, the measurement process is run according to the determined algorithm, presented in *Test 1*. The process consists of setting proper values steering the range of the set resistance, temperature in the climatic chamber or the interval of data reading from the meter. After the measurement procedure has been completed, the program records the data on the local hard disc and takes on the idle state while waiting for the beginning of a new test series initiated by the user. Figure 8 below presents the view of the user's panel applied in the research.

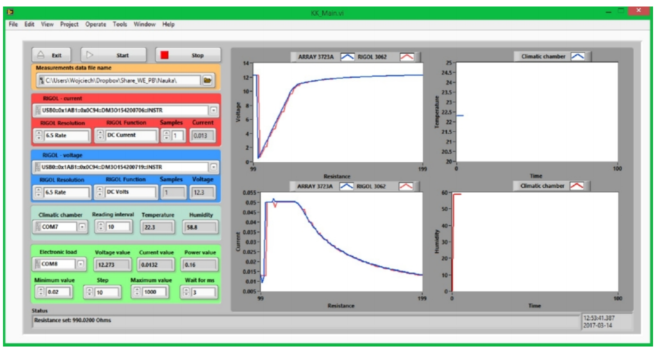


Fig. 8. The view of the dialogue window of the virtual measurement system for testing current sources.

## IV. The Research Procedure

The research concerning the influence of temperature on the current sources performance can be divided into two issues. One of them is testing the current sources at the variable load $R_{load}$ for various temperature values $T_{temp}$ and steady voltage value of the source circuit. Another important issue is checking the time duration of the transient state at switching on and off the current source.

### *A. Test 1. Steady State – Resistance Load Changing*

In order to test the influence temperature on the current sources performance, the following procedure was applied:

1. The temperature measurement parameters in the climatic chamber were set as: the step - every 5 °C, from -5 °C to 70 °C.
2. After the temperature had been stabilized, the resistance load was changed.
3. Five measurements of the voltage on the load and the current values of the source were conducted sequentially for the set load.
4. Uncertainties of the A, B and C types were determined on the basis of the measurements.
5. The load value was increased of 5 Ω, up to the maximum value, e.g. 400 Ω, proceeding 3÷5 steps of the algorithm.
6. After the measurements and the uncertainties calculations had been completed, the temperature was changed, so the procedure was started from step 1 of the algorithm.

As a result, a set of temperature characteristics for four current source circuits was obtained. The range of the Current axis (mA) was changed from the value of 0 mA to 0.03 mA, so the characteristics visualizations were clearer.

As it is easily observable, in all the discussed cases the circuits were stable in terms of temperature within the range of the stabilized current work. The greatest differences of the stabilized current values occurred for the circuit with the MOSFET P transistor and equaled 0.14 μA. The value was calculated by subtracting the value of the stabilized current obtained for the current source at the temperature $T_{temp}$ of 70 °C from the current value obtained at the temperature $T_{ref}$ of 0 °C. We can see that the temperature stability of the tested sources is very high and the revealed differences (Fig. 9, Fig. 11, Fig. 13, Fig. 15) can be assumed as insignificant. The greatest differences (Fig. 10, Fig. 12, Fig. 14, Fig. 16) occurred in all analysed cases in the non-stabilized parts of the characteristics, which, from the user's point of view, are not important in practical applications.

It is also worth mentioning that unexpected disturbances in the characteristics flows occurred in all analysed cases. It is observable especially in the characteristics showing the $T_{temp}/T_{ref}$ difference (in relation to the temperature of 0 °C) vs. resistance load $R_{load}$ characteristic (Fig. 10, Fig. 12, Fig. 14, Fig. 16). The disturbances, observed as peak values, were caused by dynamic switching of the electronic load ranges at 6.66 Ω and 66.6 Ω.

Another slight incorrectness worth mentioning is the fact that all tested current sources begin working correctly from the load value of about 5 Ω. The device behaves correctly when it works in the constant current mode, which was proved experimentally in a separate test by the short circuit of sources outputs. The incorrect work, mentioned above, is probably caused by the specifics of the electric load working mode. A device of this type simulates the resistance load by an executive element based on a MOSFET transistor which is not properly steered in the applied electronic load.

### *B. Test 2. Transient State – Switching ON and OFF the Current Source*

Testing the transient state duration time at switching on and off the current source into an electrical circuit with a resistance load was connected with the following research procedure:

1. The test was done for two edge temperature values: -5 °C and 70 °C;
2. The set temperature was estimated in the climatic chamber;
3. After the temperature had been stabilized, the resistance load value was set as 100 Ω;

4. The electronic resistance load was switched on and off 10 times in order to test the transient state duration;
5. After conducting the experiments, the analysis of the measurement results (outlier detection etc.) was done with the use of external software created in the Matlab environment.

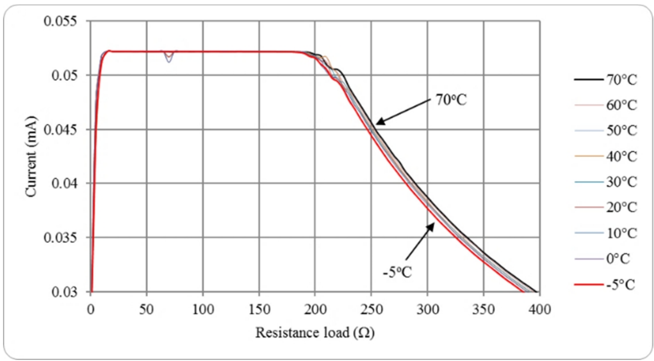



Fig. 9. The current - resistance load $R_{load}$ characteristic of a LM317 source based circuit.

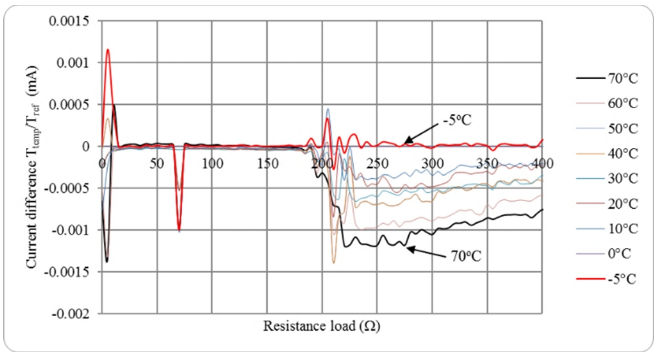



Fig. 10. The current difference $T_{temp}/T_{ref}$ (in relation to the temperature of 0 °C) vs. resistance load $R_{load}$ characteristic of a LM317 current source based circuit.

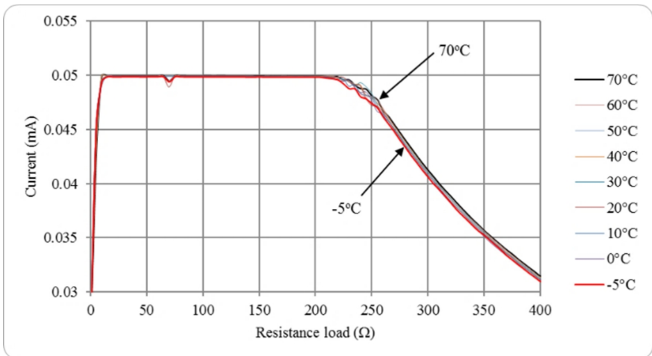



Fig. 11. The current – resistance load $R_{load}$ characteristic of a LT3092 source based circuit.

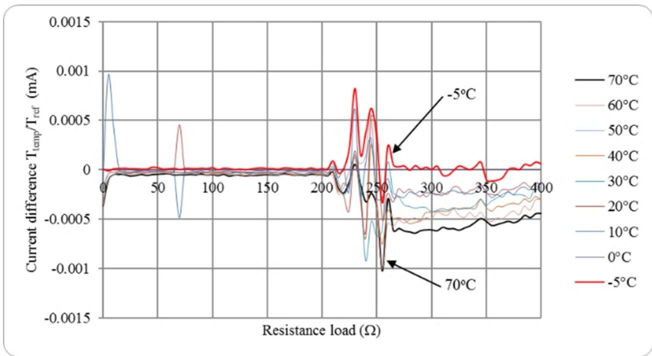



Fig. 12. The current difference $T_{temp}/T_{ref}$ (in relation to the temperature of 0 °C) vs. resistance load $R_{load}$ characteristic of a LT3092 current source based circuit.

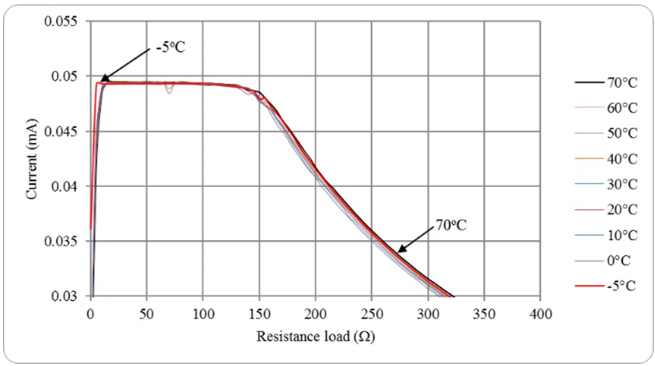



Fig. 13. The current – resistance load $R_{load}$ characteristic of a MOSFET N source based circuit.

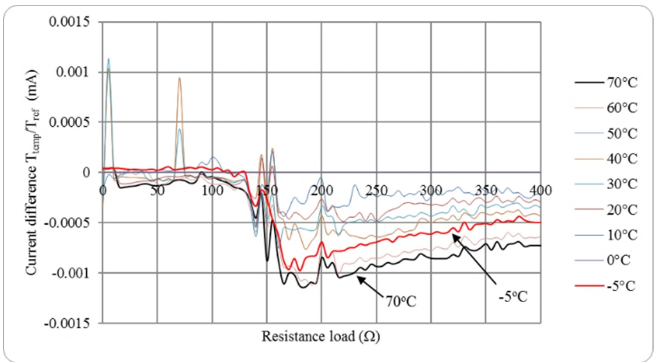



Fig. 14. The current difference $T_{temp}/T_{ref}$ (in relation to the temperature of 0 °C) vs. resistance load $R_{load}$ characteristic of a MOSFET N current source based circuit.

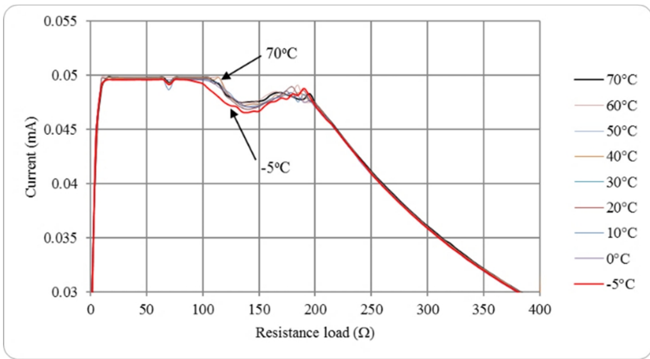



Fig. 15. The current – resistance load $R_{load}$ characteristic of a MOSFET P source based circuit.

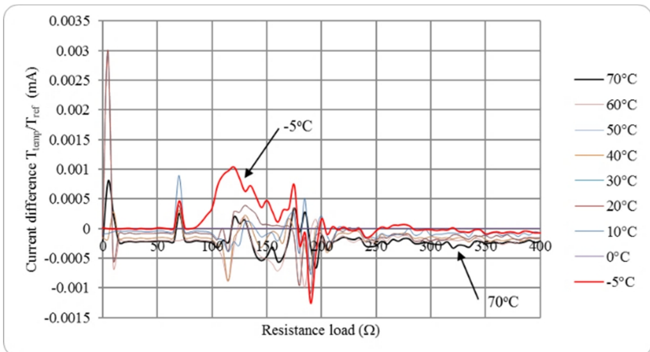



Fig. 16. The current difference $T_{temp}/T_{ref}$ (in relation to the temperature of 0 °C) vs. resistance load $R_{load}$ characteristic of a MOSFET P current source based circuit.

It appeared (Tab. 1) during the test that the dedicated LT3092 current source had the shortest transient state after switching on and off the resistance load. Additionally, it can be observed that, when the current source is switched on, the transient state durations at the temperature of -5 °C and

70 °C are nearly identical. The transient state was the longest when the current source was switched off for all tested cases. The circuit with the MOSFET N transistor appeared to be the most stable current source. Nevertheless, the transient state at the switched on current source lasted for about 1 s.

TABLE I. AVERAGE VALUES OF THE TIMES OF SWITCHING ON AND SWITCHING OFF THE LOAD OF 100 Ω TO PARTICULAR CURRENT SOURCES.

| | -5 °C Rise time (µs) | -5 °C Fall time (µs) | 70 °C Rise time (µs) | 70 °C Fall time (µs) |
|---|---|---|---|---|
| **LM317** | 53.12 | 197.26 | 70.47 | 213.71 |
| **LT3092** | 23.31 | 112.85 | 23.81 | 159.93 |
| **MOSFET N** | 1014.30 | 564.96 | 1000.17 | 584.02 |
| **MOSFET P** | 82.67 | 559.06 | 80.63 | 606.17 |

## V. SOURCES OF MEASUREMENT ERRORS

In the conducted tests, several factors influencing the obtained measurement results can be distinguished. The procedure of conducting the measurements is the most important one. Errors resulting from the incorrectly set process of measurement, e.g. conducting a test of a given current source without prior heating the source up, hence without achieving the temperature transient state, can lead to obtaining unpredicted characteristics. Additionally, conducting the measurements only once at particular points may result in obtaining significant deflections towards the average value within the range of characteristics in which the current is stabilized.

Factors related to the research equipment are another source of the measurement uncertainty. An unstable supply source or conducting the experiment in a climatic chamber of unstable parameters may be examples. Both cases would make the appropriate evaluation of the current source performance impossible. Moreover, using an electronic resistance load, which is unstable in terms of temperature, or distorts the measurement process at the change of the work range (Fig. 17.) may be another source of errors.

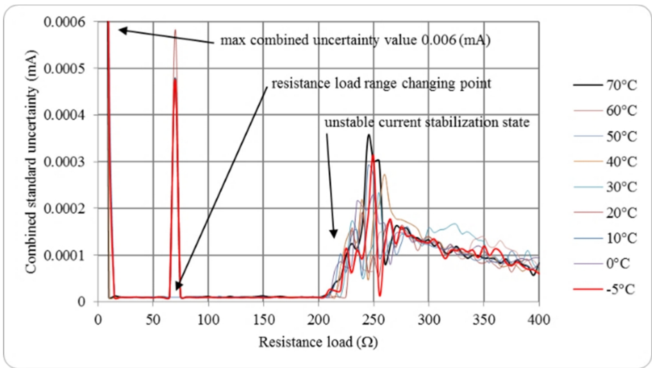



Fig. 17. Combined standard uncertainty chart calculated during experiments for the LT3092 source. One of possible sources of measurement errors generated by electronic resistance load is presented in the middle part of the chart.

The measurement results analysis is the last factor influencing the errors. In each case in which the measurements are conducted several times, the analysis of the results uncertainty should be completed. Additionally, except for the standard approach using the Law of Propagation of Uncertainty (LPU), presented by Guide ISO GUM [14], other, alternative methods of the measurement data correctness verification should be applied [15]–[17]. The Shapiro-Wilk test was used to check whether the obtained results come from a normally distributed propagation [18]. Next, on the basis of a proved hypothesis that the distribution is normal, outliers may be sought [19]. Testing the outliers is aimed at finding the diverging measurement results which mainly result from the errors committed during the experiments (Fig. 18).

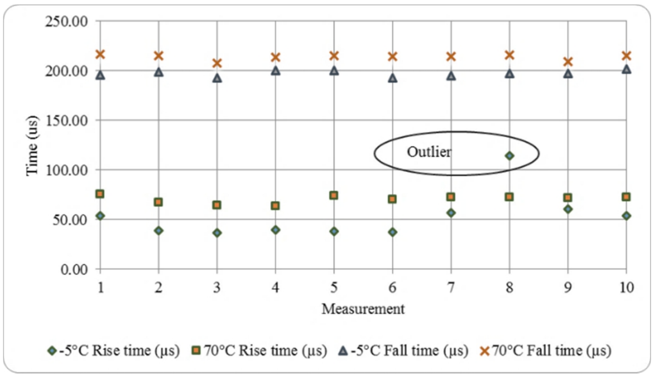



Fig. 18. The outlier example achieved during dynamic tests of the LM317 integrated circuit based current source.

The Grubbs' test may be applied in such analysis [20], [21]. It assumes a zero hypothesis which states that the data does not have an outlier, and an alternative hypothesis stating that there is only one outlier. The testing statistics has the following form

$$G = \frac{\max\left|x_i - \bar{x}\right|}{s}, \tag{1}$$

where $x_i$ – subsequent measurement value, $\bar{x}$ – average measurement value, s – standard deviation.

The Grubbs' test is a two-tiled test, but it may be used as a one-tiled test, as well. If we expect that there is an outlier in the form of the maximum value in the measurement data, the following formula is applied

$$G = \frac{x_{\max} - \bar{x}}{s}. \tag{2}$$

If the outlier in the measurement data can have the minimum value, the following test should be applied

$$G = \frac{\bar{x} - x_{\min}}{s}. \tag{3}$$

The described procedure allows to evaluate whether the data obtained during the experiment is correct. On this basis it can be confirmed that the obtained results have normal propagation without the diverging data, or that a detailed analysis of its value should be done. If outliers occur in the data, an attempt to eliminate them can be made, or the measurement experiment should be repeated.

The present research considers the reasons of measurement errors mentioned above, which were tried to be eliminated. The greatest possibility of correcting the errors occurred at the stage of the data analysis through eliminating an unwanted outlier. In the conducted experiments they were replaced by other, excessive data.

## VI. CONCLUSIONS

The article presents the results of the temperature analysis of four current sources circuits. The tests were conducted with due diligence with the use of an automated laboratory stand based on software created in the LabVIEW environment. The tests were conducted in two stages.

During the first one, the current sources stability at the transient state was analysed. This resulted in obtaining the characteristics of the stabilized current dependences in the temperature function (Fig. 9, Fig. 11, Fig. 13, Fig. 15). The analysis of the results showed the following conclusions:

– The current sources based on the LM317 circuit and the integrated LT3092 source appeared to be the optimal solutions. This was caused by a small number of external components used for constructing the circuits.

– In the sources based on the MOSFET transistors the temperature stability was weaker. This might be caused by an increased sensitivity of the operational amplifier and the external transistor to the set outer temperature value in the climatic chamber.

Another experiment consisted in testing the influence of temperature on the transient state duration at switching on and off the electronic load. This resulted in obtaining data which proved that:

– The sources based on the MOSFET transistors were more stable in terms of temperature.

– The transient states duration at the temperature of -5 °C and 70 °C differed slightly, which may be treated as an advantage when using the circuits in practical implementations. They proved to be very stable in terms of temperature.

– Unfortunately, the time of switching on e.g. the source with a MOSFET N type transistor reached the value of 1 s, which eliminates this solution in the 2J4K2R circuit, mentioned in the introduction to this paper.

– On the basis of the obtained results, it can be assumed that the issue of choosing current sources for measurement circuits is vital. Unfortunately, the choice is between current sources stable in terms of temperature at variable load, but slower, and sources which can be dynamically switched on at a measurement circuit, but with a variable sensibility to the temperature change.

In further experiments, the authors intend to conduct tests concerning the dynamic effects analysis of the discussed current sources adjusted to measurement circuits based on the 2J4K2R bridge.

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