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Note: Development of 9 A current source for precise resistance measurement method

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In this Note, design of voltage controlled current source intended to be used in precise resistance measurement system in the range from 0.1 mΩ to 10 Ω is presented. The design specifications of current source include gross-tuning of current in the range from 0.1 mA to 9 A, low noise, low temperature coefficient, and short term stability better than 50 ppm. The realized current source has achieved better short term stability than comparable commercial devices. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4759022]

Today, standard resistors are compared to each other using various methods, and many of these methods use stabilized current source. In this Note, design of precision dc source intended to be used in precise resistance comparison method is described. Current source with a maximum current of 1 A has already been realized,[1] and the experience gained has been used in designing current source with higher maximum current of 9 A. Several different current source circuits were contemplated and tested as proposed in Ref. 2, and finally one of the current source circuits has been chosen and carefully modified to obtain larger currents. The most important modification was to choose suitable power MOSFETs, however all other components were carefully selected in order to achieve required levels of low noise, precision, and stability.

Before building the circuit, National Instruments Multisim software was used for schematic capture and simulation in order to test different design possibilities and circuit behavior. Figure 1 shows simplified model of the current source in its development phase, where one of the main differences is that the final design has eight MOSFETs, rather than two in the model. The larger number of MOSFETs allows achieving higher currents with lower heating of each MOSFET, thus maintaining the longer stability of the source. The designed current source is a low-drift current regulator that provides constant current sink using N-channel silicon MOSFETs to drive the load (Fig. 2.). It is running off a single supply of +12 V. The operational amplifier buffers the precision voltage reference (Linear Technology 1027) output and the resistive divider from the gate of the MOSFETs. This provides better stability with higher current levels. The voltage reference output is picked off from the potentiometer and used as a reference level for the operational amplifier non-inverting input. This voltage is thus transferred across the current-setting resistor (chosen between R_1 to R_6) and converted to a constant current I_o.

The operational amplifier OP27 is a precision, high speed and low noise. It also combines the low offset of 25 mV and maximum drift of only 0.6 μV/°C which is sufficient for precision current source application. Several precision, wire wound power resistors from Tyco Electronics (from 0.47 Ω to 400 k Ω; 50 W) with a temperature coefficient of 50 ppm/°C are used to define the MOSFETs source current. The temperature coefficient of power resistor basically determines the temperature coefficient of current source, as all other key components have considerably lower temperature coefficients. The MOSFET chosen is Sanyo 2SK1420, with low on-state resistance of less than 0.045 Ω. It comes in standard TO-220 power transistor package, so it can be easily mounted on a heat sink. All eight MOSFETs are connected on the same large fined heat sink.

The cooling was improved with 12 cm ventilator to reduce heating in the power resistor and MOSFET vicinity. Higher currents are obtained simply by paralleling several power MOSFETs. Initially, the MOSFET with the highest transconductance draws the most drain current, and as a result will have the highest power dissipation. However, the resulting increase of temperature will also increase its on-resistance R_{ds} which has a positive temperature coefficient that helps limit the drain current. As a result, the total drain current will automatically balance through all of the other MOSFETs in the circuit. A separate gate resistor of 1 kΩ is used between the operational amplifier output and the gate of each MOSFET.

The following equipment was used for testing purposes:

- C-series module NI-USB-9239 for analog to digital conversion—it has four simultaneous 24 bit channels; range of ±10 V and 50 kS/(s ch).
- Agilent 3458A digital multimeter—for the determination of current source output impedance.
- Fluke 5220A transconductance amplifier to compare the current source with commercial device.
- Four terminal current shunts (2 mΩ and 5 mΩ)—to measure voltage and current noise levels and test the current source for designed application.
- Test software written in LabVIEW™ graphical programming language.

The self-developed software for testing was made to characterise the current source on its noise level and time stability. The testing was performed by measuring the voltage drop on two precision current shunts connected in series ($R_{L1} = 2$ mΩ and $R_{L2} = 5$ mΩ), excited from current source, and analyzed with self written software in order to test the

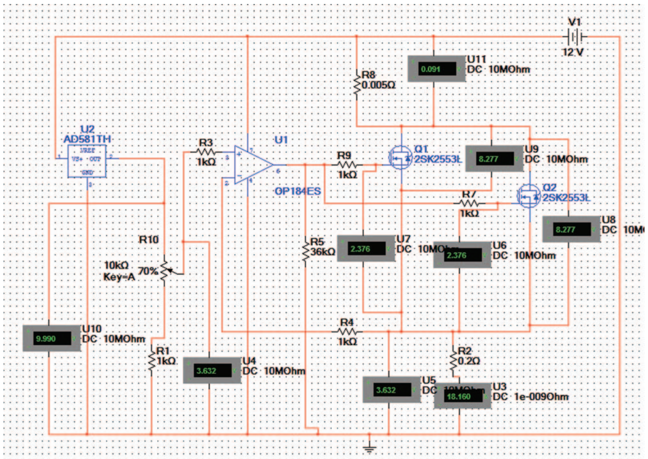

FIG. 1. Model of current source tested in NI Multisim.

current source as closely as possible to the final application. The data acquisition (DAQ) card NI 9239 has four distinct channels, and the channels 2 and 3 of the DAQ were used for current source testing, as they performed best during DAQ card tests.[3] In analog to digital conversion the noise floor depends on the sampling rate and number of points in the spectrum bandwidth. That means that the noise level at each frequency line reads as if it were measured through an Δf Hz filter centered at that frequency line. Therefore, for a given sampling rate, doubling the number of points acquired reduces the noise power that appears in each bin by 3 dB.[4] Because of noise-level scaling with Δf, spectrum for noise measurement is often displayed in a normalized format called power or amplitude spectral density (PSD) which is calculated as

$$\mathrm{PSD} = \frac{\text{power spectrum in } \mathrm{V}^2_{\mathrm{rms}}}{\Delta \mathrm{f} \times \text{noise power bandwith of window}}. \tag{1}$$

For uniform window, noise power bandwidth is equal to 1, and the units are then expressed as V^2/Hz. The power spectrum density and FFT of the voltage fluctuations across current shunts are shown in Fig. 3.

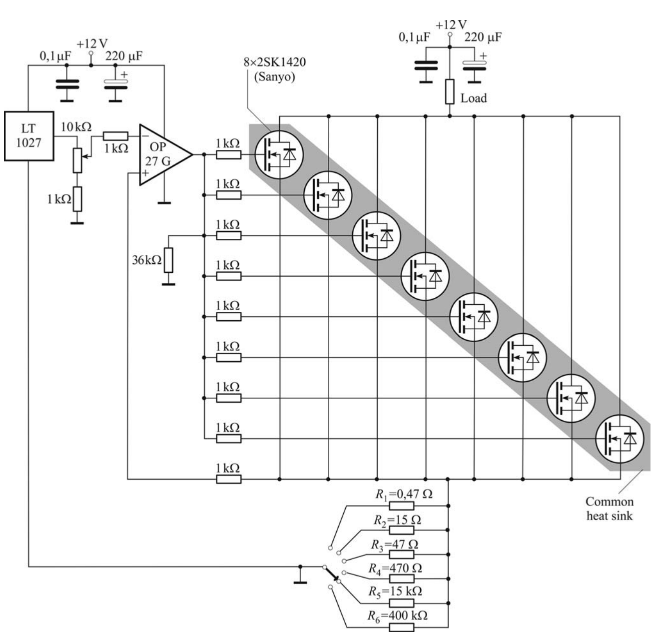

FIG. 2. Current source circuit.

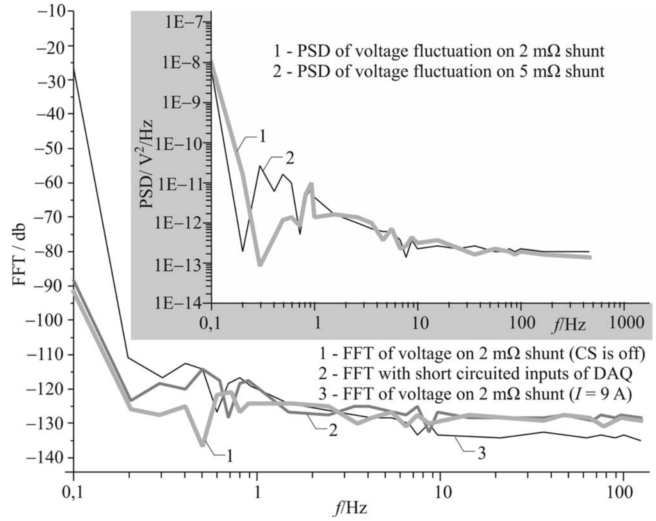

FIG. 3. Power spectral density (PSD) and FFT of voltage noise measurements (averaged for higher frequencies).

The voltage noise floor measurements have been performed by short circuiting the high and low inputs of DAQ with short wire, then by measuring the voltage on current shunts to determine the thermal noise of current shunt with current source off, and finally with current source providing 9 A to current shunts. The noise floor measured with these experiments yielded noise level of more than 120 dB below full scale and PSD below the level of 10^{-12} V^2/Hz. It appears then that the noise measurement depends on the applied A/D conversion hardware, while the noise level of the current source is below these levels, confirming that the current source can be used in resistance measurement application. The power spectrum of the current fluctuations through the load decreases with increasing of the current setting resistance R_{L} squared.[5,6] Several current ranges have been added for the purpose of determination of current noise floor (Fig. 2). A measurement of voltage drop on 1 kΩ load with current of 0.8 mA yielded current noise floor at the level of 10^{-19} A^2/Hz.

In order to test the stability of current source, a measurement of voltage drop on current shunts with maximum current of 9 A has been started as soon as the current source has been turned on with the temperature measurement at two MOSFETs and current setting resistor using the Epcos S863 type NTC thermistors. Figure 4 shows that the settling time is approximately 4 min from the start of current source operation, largely depending on the heating of current setting resistor which heats to more than 220 °C, while two MOSFETs heat up to around 60 °C. The standard deviation of voltage ratio in two channels after stabilization time was around 1 ppm, even though the voltage levels were 20 mV, a small portion of 10 V voltage range. The standard deviation of voltage ratio is actually type A uncertainty of resistance measurement method and this result is satisfactory for the required 10 ppm of total uncertainty for low value resistance standards.

The current source was also compared with Fluke 5220A transconductance current amplifier, which states that for

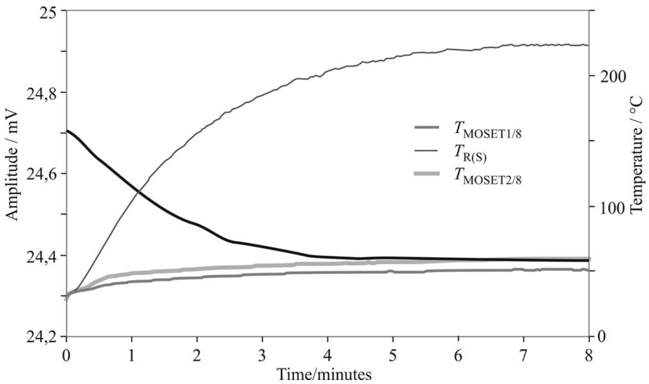

FIG. 4. Settling time and temperature measurement (black bold line represents the voltage measurement).

currents of 20 A the output changes less than ±0.005% of output current ±200 μA in 10 min with constant line, load, and temperature. The Fluke 5220A was driven by the LT 1027 voltage reference from the current source, the output connected to the same type of current shunts. The voltage drops on shunts were sampled simultaneously on two channels of NI 9239 for 10 min after thermal equilibrium was achieved. It was determined that the voltage ratio has standard deviation of 1.3 ppm, this time confirming that current source has comparable, or slightly better time stability than Fluke 5220A.

Finally, the output impedance of the current source was determined by adding the 5 Ω resistor in series with the current source and measuring the difference of voltage drop on measured shunt with the Agilent 3458A digital multimeter with long integration time (NPLC set to 100), whose own input resistances have been already determined to be in the range of TΩ.[7] In this way it was determined that current source has output impedance higher than 250 MΩ. At such high value, the influence of current source output impedance in measurement of low value resistance standards can largely be neglected.[8]

In conclusion, it can be said that the design, realization, and testing of the low noise current source have been described in this Note. The careful design and the accurate selection of active and passive components have made it possible to obtain noise levels similar to those which were previously possible only by means of low noise batteries. The current source will be used in developing the precision resistance comparison method for low resistance values. The future research will utilize programmable gain amplifier as DAQ front end to better use the DAQ card capabilities and complete testing of the current source in resistance measurement system as well as the automatization of current source with the use of LabVIEW programming language and suitable hardware.

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