ANMESYS
ANALOG MEASUREMENT SYSTEMS

New generation current sources

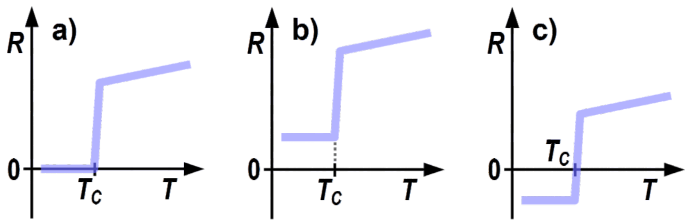
for unconditionally reliable very-low resistance measurements

Measurements of very-low resistances at cryogenic conditions are extremely demanding and frequently accompanied by common-mode errors manifesting themselves by the following symptoms.

Measurements of the same sample give different results

- if performed in ***different apparatuses***, or
- if ***different instrument types and models*** are used for the resistance measurement *at the same sample installation* (i.e. the same cryostat and wiring), or
- if ***different instruments of the same model*** are used for the resistance measurement *at the same sample installation.*

Common-mode voltage signals can easily cause artificial experimental results. For instance, the temperature dependence of the resistance of a superconductor is not measured as expected, but exhibits a non-zero resistance in the superconducting state, either positive or negative.



Temperature dependence of the resistance of a superconductor in the vicinity of T_c: result of correct measurement (a), and results affected by common-mode errors (b, c).

New patented technology : "Current source with active common mode rejection"

- **shifts reliability limits of very-low resistance measurements to the edge of physical limitations**
- **enables the exact solution of common-mode issues in resistance measurements**

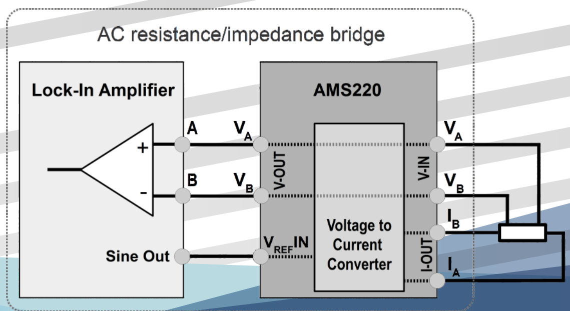
AMS220 Voltage Controlled Current Source

with Active Common Mode Rejection

is the only instrument on the market possessing the patented technology (U.S. #9,285,809, March 2016).

ANMESYS s.r.o. is the only company authorized to utilize and disseminate the patented technology.

The **AMS220** is optimized to operate as an external module of a Lock-In Amplifier to extend its functionality to that of an ac-resistance/impedance bridge.



Very-low resistance measurements: How to ensure reliable results?

Measurements of low-level signals are frequently affected by common-mode errors

The four-wire (Kelvin) method is used to measure low resistances because *it helps to eliminate errors due to lead and contact resistances*. However, its use does not guarantee the correct result of very-low resistance measurements. In a typical four-wire resistance measurement as illustrated in Fig. 1, the test current (I_T) is forced through the resistance (R_T) being measured, and the voltage across the test resistance (V_D) is sensed. The measured resistance is

$$R_T = V_D / I_T ,$$

but in a real measurement the resistance is determined as

$$R_T = V_M / I_T ,$$

where V_M is the value provided by the voltmeter sensing the voltage V_D. If the input impedance of the voltmeter is sufficiently high, the effect of the sense current (I_S) can be neglected. But still, especially at very-low resistance measurements, V_M often differs from V_D due to *common-mode error*, even if high-precision instruments *capable to measure very small voltage differences* (e.g. lock-in amplifiers) are used.

The value V_M is based on a processing of an output voltage signal (V_O) of a differential amplifier (operating with a differential gain G_D) at the input of the voltmeter. The output voltage of an *ideal differential amplifier would be* $V_O^{ideal} = G_D V_D$. However, if the voltage difference that appears across two inputs of the differential amplifier, $V_+ - V_- = V_D$, is much less then the common-mode voltage $V_{CM} = (V_+ + V_-)/2$ (i.e. $V_D << V_{CM}$), then V_O can significantly differ from V_O^{ideal}. In this case, contribution coming from the common-mode voltage has to be considered, and the output voltage can be expressed by the equation

$$V_O = G_D(V_+ - V_-) + G_{CM}(V_+ + V_-)/2 = G_D V_D + G_{CM} V_{CM} ,$$

where G_{CM} is the common-mode gain.

The ratio $G_D / |G_{CM}|$ (so-called common-mode rejection ratio, CMRR) characterizes the extent to which the common-mode voltage is rejected by the differential amplifier. The CMRR can be expressed also in decibels, being then referred to as common-mode rejection (CMR); CMR = $20\log_{10}$ CMRR.

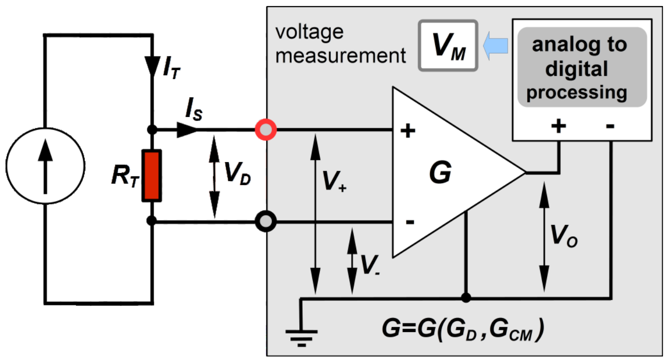


Fig. 1 Depiction of a typical four-wire resistance measurement with a block diagram of the signal processing by the voltmeter.

The CMR of an instrument/device is its key specification indicating how much of the common-mode signal will appear in the measurement. In fact, limiting capability of instruments to reject common-mode signals represents serious limitations for very-low resistance measurements (including those performed by means of Kelvin method), such as resistances in the current path can cause common-mode voltage, which can be even several orders of magnitude greater than the sensed voltage (V_D). Nowadays technology limit is approximately 140 dB (CMRR = 10^7, i.e. amplification of the differential voltage across the amplifier inputs is 10 million times greater than the amplification of the common mode signal). Typically, the CMR varies between 80 dB (CMRR = 10^4) and 120 dB (CMRR = 10^6).

Common-mode errors in "standard" four-wire resistance measurements

Let us imagine measuring the resistance of a 100 µΩ test resistor as illustrated in Fig. 2. If current of 10 mA (AC or DC) is forced through this resistor, the voltage across the resistor is V_D = 1 µV (100 µΩ x 10 mA = 1 µV). Let us consider use of a current source with one of the outputs connected to the signal ground (single-ended current source). If the resistance of the current path connected to the grounded output is $R_{IB} \approx 20\ \Omega$, the common-mode voltage $V_{CM} \approx 20\ \Omega \times 10$ mA = 200 mV will be created in such experimental setup. Note that this value is much greater than V_D. At using an industry standard lock-in amplifier with CMR ≈ 100 dB (i.e. CMRR ≈ 10^5) to sense the voltage, the corresponding common-mode error is ≈ 200 mV /10^5 = 2 µV, thus the value provided by the lock-in amplifier, being a sum of V_D (1 µV) and the common-mode error (2 µV), is **3 µV instead of 1 µV**. Correspondingly, the resistance gained from the experiment is **300 µΩ instead of 100 µΩ**.

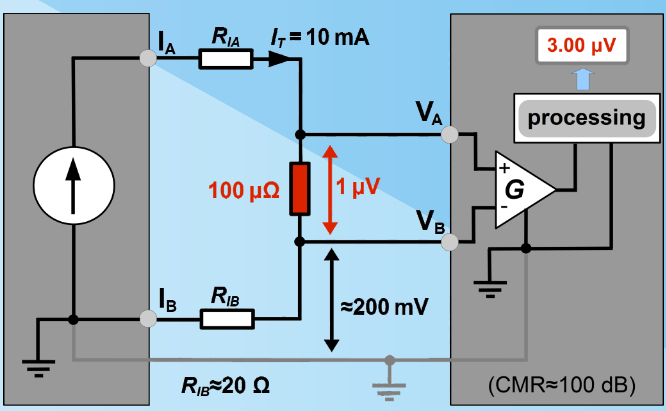


Fig. 2 Four-wire resistance measurement setup with a current source with one of the current outputs connected to the signal ground. The indicated measured value (affected by common-mode error) is illustrative with regard to the discussed example.

How to identify common-mode errors in resistance measurements

A simple test to identify common-mode errors in four-wire resistance measurement can be done by modification of an original four-wire resistance measurement setup as shown in Fig. 3a to one from Fig. 3b. Because in this case both voltage inputs (V_A, V_B) sense the same electrical signal, the sensed voltage difference is zero, so the correct resistance measurement must **unconditionally give a value of 0 Ω**.

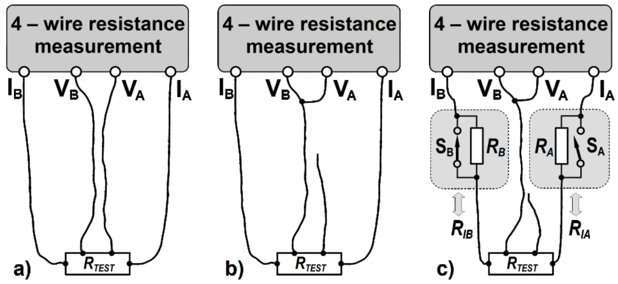


Fig. 3 Tests to identify common-mode errors. Schematic depiction of the standard four-wire resistance measurement setup (a), its modification for the simplified test (b), and connection for the thorough test (c). When the purpose of the thorough test is to check a measuring instrument, without testing a complex wiring, the resistance under test can be replaced by a shortcut.

However, this simplified test yields information relevant only to the particular experimental conditions (particular load, specific temperature, etc.), but it does not necessarily reveal possible system weaknesses in all cases where the setup can be used. For example, it can be insufficient for systems where the resistance of current paths (i.e. resistance of current leads or contact resistances) vary significantly due to temperature changes. This simple test can also be *conditionally* ineffective when using so-called differential current sources. Differential current sources drive the load "symmetrically", i.e. voltage on their outputs I_A and I_B is of the same absolute value but of the opposite polarity. Thus, if both current branches have equal resistances, the common-mode voltage is zero, and so the common-mode error is also zero in this *specific* case. However, when this balance is broken, e.g. by different contact resistances, potentials of voltage signals sensed on the test resistance move towards the potential of the output connected with the branch of lower resistance, which results in a creation of common-mode voltage. This causes corresponding common-mode error that increases with imbalance increase.

A thorough test can be performed using the connection shown in Fig. 3c., containing resistors that can be used to change the resistance of the electric current path by means of the switches S_A and S_B. Resistances (R_A and R_B) of these resistors should be comparable to resistances of current paths in a real experiment, and should not be less than the estimated maximum resistance change of the current path that may occur in (different) experiments. Detailed inspection shall be performed by measuring all combinations possible to be created by the switches S_A and S_B. **A properly measuring system must unconditionally provide a value of 0 Ω** for any of these combinations. Fig. 4 shows examples how the results of the test can look like if $R_A = R_B = 10\ \Omega$, and the CMR of the voltage sensing unit is 100 dB.

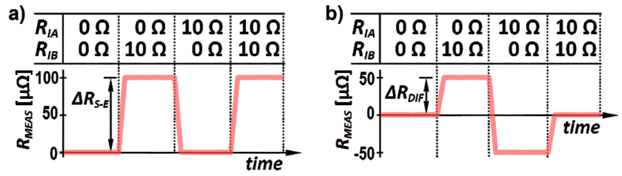


Fig. 4 Possible common-mode errors for a single-ended (a) and a differential (b) current source. A settling time of an instrument is represented by intervals between steady readings.

Results of the test as shown in Fig. 4 can be estimated for different CMR of an instrument*) using the table below if $R_A = R_B = 10\ \Omega$. Note that the higher the resistance values R_A and R_B, the higher the common-mode errors.

CMR [dB]	80	90	100	110	120	130	140
R_{S-E} [μΩ]	1000	316	100	31.6	10	3.16	1
R_{DIF} [μΩ]	500	158	50	15.8	5	1.58	0.5

*) The CMR depends on frequency and instrument settings. For instance, the CMR of a lock-in amplifier is less for AC coupling than for DC one. Manufacturers usually specify the CMR for DC coupling.

Overcoming the common-mode errors in four-wire resistance measurements

Let us imagine measuring the resistance of a 100 μΩ test resistor with the use of the current source with active common-mode rejection as illustrated in Fig. 5. The circuit of active common-mode rejection (ACTIVE CMR) monitors the voltage sensed by the inputs (V_A, V_B) of the voltage sensing device and using a feedback loop regulates the voltage at current outputs in order to achieve that common-mode voltage of the monitored signals is zero ($V_{CM} \rightarrow 0$ V). Thanks to the patented technology the component of V_{CM} originating in the lead and contact resistances in the current path can be suppressed to less than few microvolts. It can be estimated that with the use of measuring device with CMR ≈ 100 dB, or greater, **the common-mode error can be eliminated to the level of tens of picovolts, or less!** The AMS220 is the only instrument on the market possessing the patented technology of active common-mode rejection.

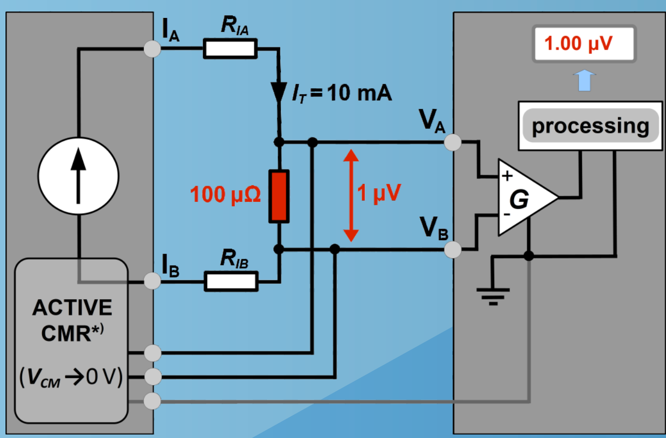
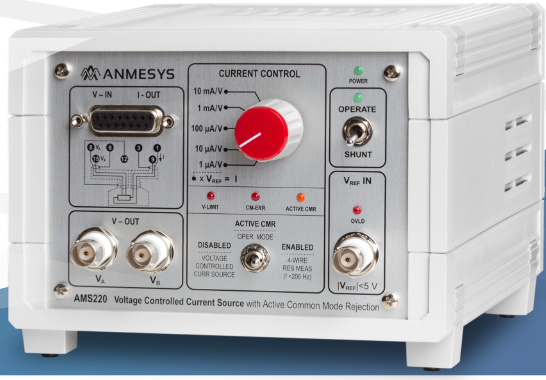


Fig. 5 Four-wire resistance measurement setup utilizing current source with active common-mode rejection (*) U.S. Patent #9,285,809)

AMS220

Voltage Controlled Current Source

with Active Common Mode Rejection



... for lock-in amplifier users performing very-low resistance measurements in the most demanding conditions

FEATURES

- Patented common-mode rejection technology
- Output current to ±50 mA
- Voltage-to-current conversion ranges from 1 µA/V to 10 mA/V
- ±5 V control voltage input range
- Low-noise, all analog design
- Optimized for use with lock-in amplifiers

TARGETED APPLICATIONS

- "Open architecture" AC resistance/impedance bridge when used with lock-in amplifier*)
  - Very-low resistance measurements down to mK temperatures, e.g.
    - Superconductivity research
    - Hall resistance measurements
  - Simultaneous resistance and Hall resistance measurements (with two lock-in amplifiers)
  - Higher harmonic detection (e.g. 2ω, 3ω) in resistance/impedance measurements
  - Thermometry/calorimetry
  - Mutual inductance measurements
- AC and DC electrical measurements with DAQ devices*)
- Replaces floating current sources in resistance measurements

*) The use of the preamplifier AMS560 (Gain=1000) is recommended for measurements in micro- and nanovolt signal levels.

Basic specifications

Ranges of voltage-to-current conversion:	0.001, 0.01, 0.1, 1, 10 [mA /V]
Control voltage input range:	3.6 V_{RMS} / ±5 V_{DC}
Maximum AC/DC output current:	36 mA_{RMS} / ±50 mA_{DC}
Targeted frequency range:	DC - 200 Hz @ 'ACTIVE CMR' operation mode ENABLED DC - 20 kHz (2 kHz for 1µA/V range) @ 'ACTIVE CMR' operation mode DISABLED
Power:	12 V (AC, 50-60 Hz) / 0.6 A

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