Common mode errors in very-low resistance measurements

The four-wire (Kelvin) method is usually used to measure low resistances *to eliminate errors due to lead and contact resistances*. However, this does not guarantee correct results of very-low resistance measurements, because measurements of low-level signals are frequently affected by *common mode errors.* 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 V_D across the test resistance is sensed. The measured resistance is $R_T = V_D / I_T$, however, in a real measurement it is determined as $R_T = V_M / I_T$, where V_M is the value provided by the voltmeter sensing the voltage V_D. Especially at very-low resistance measurements, the V_M often differs from V_D due to *common mode error*, even with the use of high-precision instruments *dedicated to measure very small voltage differences* (e.g. lock-in amplifiers).

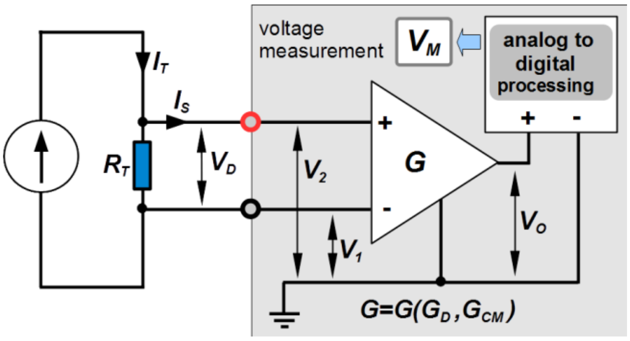

Fig. 1 Depiction of a typical four-wire resistance measurement with a block diagram of the signal processing by the voltmeter.

If a digital voltmeter processes the output voltage signal V_O of the differential amplifier at its input, as depicted in Fig. 1, the result of this processing is V_M. The output voltage of *the ideal differential amplifier* operating with a differential gain G_D *would be* $V_O^{ideal} = G_D V_D$. However, if the voltage difference across the inputs of the differential amplifier $V_2 - V_1 = V_D$ is much less than the common mode voltage $V_{CM} = (V_2 + V_1) / 2$ (i.e. $V_D << V_{CM}$), V_O can significantly differ from V_O^{ideal}. In such case, **the common mode voltage will affect the output voltage** V_O. For a "real" differential amplifier, V_O can be expressed as

$$V_O = G_D(V_2 - V_1) + G_{CM}(V_2 + V_1)/2 = G_D V_D + G_{CM} V_{CM}, \quad (1)$$

where G_{CM} is the common mode gain. The ratio $G_D / |G_{CM}|$ = CMRR (so-called common mode rejection ratio) 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.

Typical situations where common mode errors occur to a significant extent are measurements of small electrical resistances if the resistance of the electric current path is much higher than the measured resistance itself. As the result, a much higher voltage drop occurs on the supply current leads than on the measured resistance.

Let us imagine measuring the test resistor of 100 µΩ. If current I_T = 10 mA is forced through this resistor, the corresponding voltage across the test resistor will be V_D = 1 µV (100 µΩ x 10 mA = 1 µV). Let the resistances of branches of the current path (R_{IA}, R_{IB} in Fig. 2) are 20 Ω.

When using a "classical" current source with one of the outputs connected to the signal ground (single-ended current source), as illustrated in Fig. 2, the common-mode voltage of the value V_{CM} ≈ 20 Ω × 10 mA = 200 mV appears at the input of the voltage sensing instrument. (Note that this value is much greater than V_D = 1 µV). 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 will be at level of 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), will be **3 µV instead of 1 µV**. Correspondingly, the resistance gained from the experiment is **300 µΩ instead of 100 µΩ! To ensure the correct result** at the output of the voltage sensing instrument, **the common mode voltage signals on its inputs need to be eliminated.**

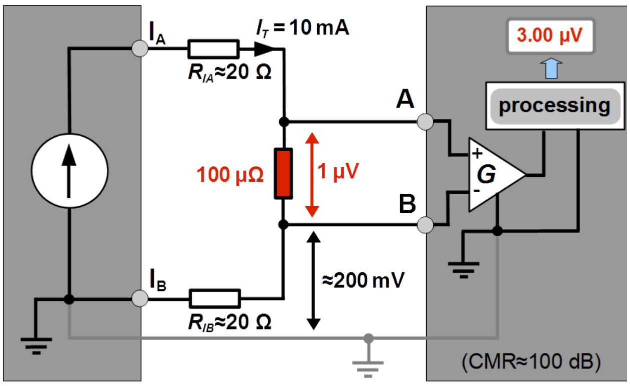

Fig. 2 Four-wire resistance measurement setup at the use of a current source with one of the current outputs connected to the signal ground. The indicated measured value (affected by common mode error) is illustrative, with respect to the discussed example.

*) CMR is a key specification of an instrument/device. It indicates 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), because resistances in the current path may 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).

Elimination of common mode errors by use of the AMS220

Common mode errors in low resistance measurements can be avoided by use of the AMS220 voltage controlled current source with active common mode rejection.

When using the AMS220 to measure the test resistor, as illustrated in Fig. 3, the patented circuit of active common mode rejection (ACTIVE CMR) monitors the voltage sensed by the inputs (**A**, **B**) of the voltage sensing device and using a feedback loop **"shifts" the voltage potentials of the current outputs in order to assure zero common mode voltage of the monitored signal** (**V_{CM}** → 0 V). Thanks to the patented technology, the component **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 at use of the measuring device with CMR ≈ 100 dB or greater **the common mode error can be eliminated to the level of tens of picovolts or less!** Thus, the measured voltage for the taken example will be **1 µV**, as expected for the test resistance of 100 µΩ.

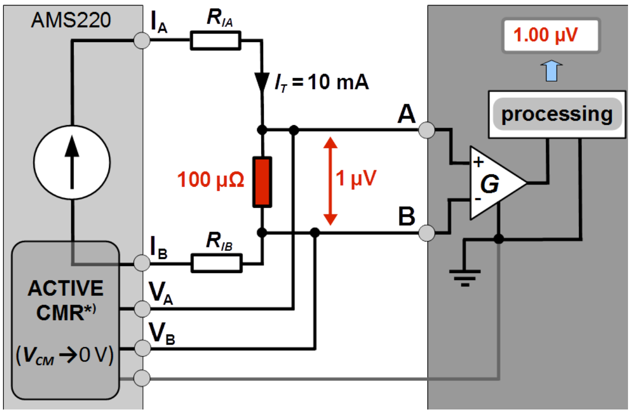

Fig. 3 Example of four-wire resistance measurement setup utilizing the AMS220 voltage controlled current source with active common mode rejection (*) U.S. Patent #9,285,809)

Using the AMS220 in combination with a lock-in amplifier to replace an AC resistance/impedance bridge

The AMS220 in combination with an industry standard lock-in amplifier represents an advantageous solution to perform routine and reliable resistance measurements by the four-wire method. The functionality of an AC resistance bridge is obtained simply by interconnecting the reference voltage output (Sine Out) and the voltage sensing inputs of the lock-in amplifier with the corresponding input and outputs of the AMS220, while the measured resistor/sample is connected to the AMS220, as schematically shown in Fig. 4. The excitation current provided by the AMS220 is proportional to the reference voltage provided by the lock-in amplifier and the select-ed voltage-to-current conversion factor of the AMS220.

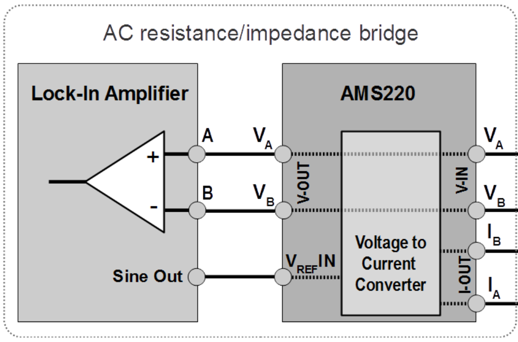

Fig. 4 Block diagram of the connection of the AMS220 with the lock-in amplifier that replaces the AC-resistance/impedance bridge.

If the AMS220 in active common mode rejection regime (ACTIVE CMR - ENABLED) is used to excite the measured resistor/sample, the voltage potentials at the voltage sensing terminals of the measured resistor/sample are monitored by the AMS220. Simultaneously, the AMS220 adjusts the voltage potentials of the current outputs so that the common-mode voltage of the sensed signals is kept at the potential of the signal ground. As the result, voltage potentials ***V(A)*** and ***V(B)*** applied to the corresponding inputs **A** and **B** of the lock-in amplifier are practically symmetrical with respect to the signal ground (as depicted in Fig. 5 by solid lines), what indicates practically zero common mode voltage, and assures reliable lock-in detection not affected by common mode signal at the measuring (lock-in) frequency. Just the combination of the active common mode rejection ability of the AMS220 and the lock-in technique (which enables very-low voltage measurements also in the background of significant disturbance signals, if however, the common mode signal *at measuring frequency* is sufficiently low) eminently shifts reliability limits of very-low resistance measurements. Note that the greatest improvements due to the use of the AMS220 can be expected in experiments where the sum of the resistances distributed in the current path is very much greater than the measured resistance.

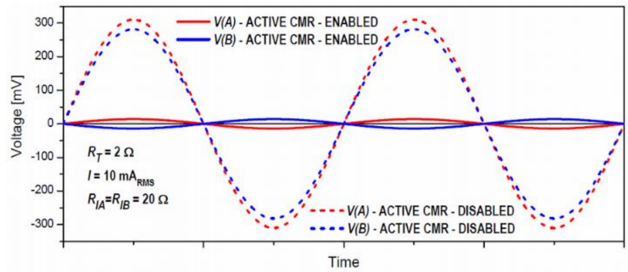

Fig. 5 Time dependence of the voltage potentials ***V(A)*** and ***V(B)*** sensed by the inputs of the lock-in amplifier in resistance measurements using the AMS220 with active common mode rejection enabled (solid lines). For comparison, analogous situation is depicted for case when the active common mode rejection circuit of the AMS220 is disabled (dashed lines), thus the AMS220 operates analogously as a "classical" current source. Note that in the later case a huge common mode voltage signal ***[V(A)+V(B)]/2*** *exactly* at the driving/measuring frequency and of *the same phase* as the measured AC signal is present.

Tests to identify the occurrence of errors due to common mode voltage in electrical resistance measurements

Realization of the following tests should help to identify existing or potential problems in resistance measurement setups and eventually indicate a requirement to use the AMS220 voltage controlled current source with active common mode rejection.

The simplified test

A simple test to identify common mode errors in four-wire resistance measurement can be done by the simple modification of an original four-wire resistance measurement setup as shown in Fig. 6a to one from Fig. 6b, where both voltage inputs **(V_A, V_B)** sense the same electrical signal, so the sensed voltage difference is zero. After such modification, **the correct resistance measurement must give the value of 0 Ω.**

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 path (i.e. resistance of current leads and/or contact resistances) varies significantly due to temperature changes. This simple test can also be conditionally ineffective at use of so-called differential current sources, which 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. 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, the potentials of voltage signals sensed on the test resistance move towards the potential of the output connected with the branch of lower resistance, and the common mode voltage becomes non-zero. This causes the common mode error that increases with increasing resistance imbalance in current branches.

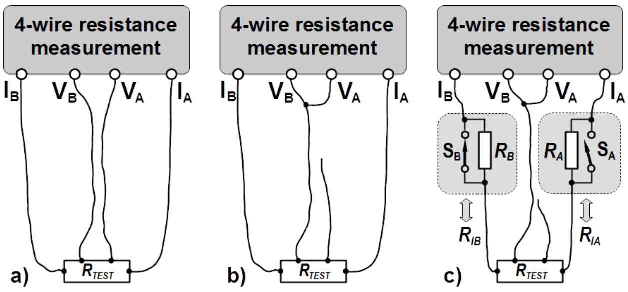

Fig. 6 Tests to identify common mode errors. Schematic depiction of the standard four-wire resistance measurement setup (a), its modification for the simplified test (b), and the connection for the thorough test (c). When the purpose of the thorough test is to check a measuring instrument, without testing a complex wiring, the resistance under test can be replaced by a shortcut.

The detailed test

A thorough test can be performed using the connection shown in Fig. 6c that contains resistors allowing to change the resistances of the current branches 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 experiments 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 possible combinations of the resistances of current branches (***R_{IA}***, ***R_{IB}***) created by the switches **S_A** and **S_B**. **A properly measuring system must provide a value of 0 Ω** for any of these combinations. Fig. 7 shows examples (for two different types of utilized current sources) how the results of the test can look like if ***R_A* = *R_B*** = 10 Ω, and the CMR of the voltage sensing unit is 100 dB.

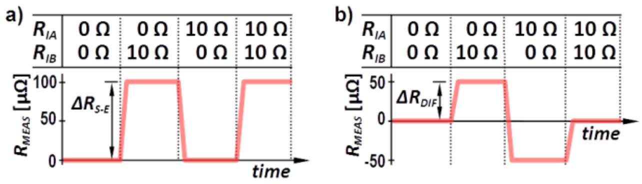

Fig. 7 Possible common mode errors in resistance measurements utilizing a single-ended (a) or differential (b) current source. A settling time of an instrument/setup is represented by intervals between steady readings.

Results of the test as shown in Fig. 7 can be estimated for different CMR of an instrument**) using the table below. 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**
$\Delta R_{S\text{-}E}$ [µΩ]	1000	316	100	31.6	10	3.16	1
ΔR_{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.