Elimination of common mode errors in low-level resistance measurements

Application Note

Low-resistance measurements are, as a rule, made using the four-wire method with the aim to eliminate the effect of wire- and contact- resistances on the measurement. Typically, the test current (**I**) provided by a current source (AC or DC) is forced through the current leads and the measured test resistor (**R_T**), and the potential drop across the measurement terminals is determined by means of a suitable (AC or DC) voltmeter (let's say, as shown in Fig. 1).

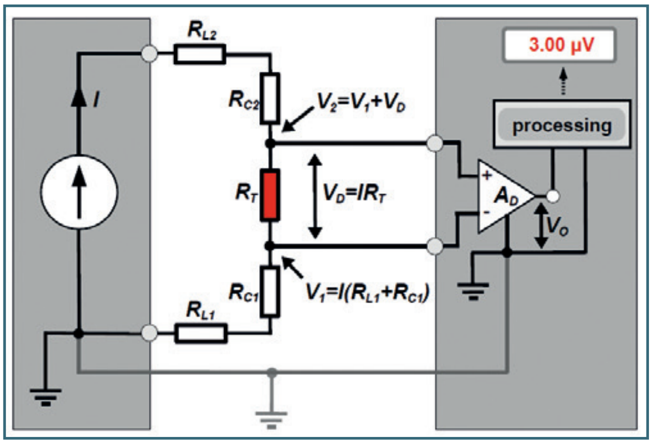

Fig. 1 Schematic depiction of four-wire resistance measurement, where one of current leads is connected to ground. The indicated measured value (affected by common-mode error) is illustrative with regard to the discussed example.

Although such a measurement should provide a result with the value equal to $\mathbf{V_D = V_2 - V_1 = R_{TI}}$, where $\mathbf{V_1}$ and $\mathbf{V_2}$ are sensed voltage potentials on the test resistor referenced against the signal ground, in the case of low resistance measurements the result of the measurement can significantly differ from the expected value ($\mathbf{V_D}$). Typically, such errors arise in situations when the common mode voltage, $\mathbf{V_{CM} = (V_2 + V_1)/2}$, becomes much higher than the measured voltage potential drop, $\mathbf{V_D}$. It is caused by the fact that the output signal ($\mathbf{V_O}$) of the real differential amplifier which is used to amplify the differential signal $\mathbf{V_D}$ does not comprise only the amplified input differential signal $\mathbf{A_DV_D}$ (where $\mathbf{A_D}$ represents the amplification of the differential signal $\mathbf{V_D}$), but also the $\mathbf{A_{CM}V_{CM}}$ component, where $\mathbf{A_{CM}}$ represents the amplification of the common mode voltage, $\mathbf{V_{CM}}$.
Subsequently, the amplified signal on the output of the real differential amplifier is

$$\mathbf{V_O = A_DV_D + A_{CM}V_{CM} = A_D(V_2 - V_1) + A_{CM}(V_2 + V_1)/2.} \quad (1)$$

The ratio $\mathbf{A_D/|A_{CM}|}$ (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=20log(CMRR). The CMR of an differential amplifier (or an instrument) is its key specification and determines how many times more the differential amplifier amplifies the differential voltage $\mathbf{V_D}$ than it amplifies the common mode voltage $\mathbf{V_{CM}}$.

For example, CMR=100 dB means that $\mathbf{V_D}$ is amplified 105 times more than $\mathbf{V_{CM}}$. If, for the sake of illustration, we consider voltages $\mathbf{V_2}$ = 1.1 V and $\mathbf{V_1}$ = 0.9 V applied to the differential amplifier inputs with the amplification $\mathbf{A_D}$ = 10 and CMR=100 dB, then, in addition to the expected amplified differential signal of 10×(1.1 V – 0.9 V) = 2 V, also the error (defined as common mode error) resulting from the common mode voltage 10^{-4}×(1.1 V + 0.9 V)/2 = 10 µV occurs on its output. (Here we considered ACM= AD/10^5 = 10^{-4}).

In such a case, the common mode error 10 µV compared to the 2 V useful signal is relatively small, and it can be neglected in many practical applications. However, in a situation, where signals $\mathbf{V_2}$ = 1.00001 V and $\mathbf{V_1}$ = 0.99999 V are applied to the differential amplifier inputs with the amplification $\mathbf{A_D}$ = 10^3 and CMR=100 dB, then in addition to the amplified differential signal of 10^3×(1.00001 V-0.99999 V) = 20 mV, also the common mode error 10^{-2}×(1.00001 V + 0.99999 V)/2 = 10 mV occurs on its output. However, this represents almost 50% undesired increase compared to the expected real value, i.e., a very significant error in the processing of the input differential signal $\mathbf{V_D}$ **=20 µV**. As it can be easily deduced from this example, the common mode error at the output (resulting from the common mode voltage at the inputs of the differential amplifier) increases with the increase of the $\mathbf{V_{CM}/V_D}$ signal ratio.

A typical situation, when this error occurs to a significant extent, is the measurement of small electrical resistances in the arrangement, where the electrical resistance of the electric current path is much higher than the measured resistance itself, which results in a much higher voltage drop on the supply current leads than the voltage drop on the measured resistance. This frequent experimental case is analyzed in more detail in the following example.

Common mode errors in very-low resistance measurements

Let's consider the situation shown in Fig. 1 where the current source providing current to the test resistor (**R_T**) has one output connected to the experiment ground. Measuring of resistance **R_T** = 0.1 mΩ by means of the 10 mA test current will cause voltage across the measurement terminals **V_D** = 1 µV. Supposing that the resistance of the current lead **R_{L1}** (connected to the grounded output) together with the contact resistance **R_{C1}** between the lead and the test resistance is **$R_{L1} + R_{C1}$** = 20 Ω, then the voltage potential **V_1** will be **V_1 = 20** Ω **×** 10 mA = 200 mV, thus the corresponding common mode voltage is **$V_{CM} = (V_1 + V_2)/2$** = 200.0005 mV.

If we consider AC-voltage measurement by means of an industry standard lock-in amplifier with the CMR of ≈100 dB (i.e. CMRR ≈ 10^5), then the voltage measurement will be affected by a common mode error that is approximately 200 mV/10^5 = 2 µV. Because, as follows from Eq. 1 above, the result provided by the lock-in amplifier is a sum of the voltage difference applied to its voltage-sense inputs (**V_D** = 1 µV) and common mode error (2 µV), the result provided by the lock-in amplifier can reach the level of 3 µV! Of course, this is an artificial result, which, in this example, is as much as 3-times higher than the real value!

If the the test resistor is excited by a "classic" current source which has one of the current outputs connected to ground, analogously as it is shown in Fig. 1, and we consider excitation of this test resistor by AC current at the condition that **$R_T << R_{L1} + R_{C1}$**, then time dependence of voltage potentials **V_1** and **V_2** at the test resistor will be characterised by high common mode voltage (e.g. as depicted in Fig.2), so the measurement will be burdened with a significant error due to the common mode voltage because of the same reasons as given in the example above. However, if the test resistor is exccited with the AMS220 Voltage Controlled Current Source in the mode with enabled active common mode rejection circuit (ACTIVE CMR / ENABLED), the active common mode rejection circuit will monitor voltage potentials at voltage sensing terminals of the test resistor (see Fig. 3), and will adjust voltage potentials of current outputs so that common mode voltage of the test resistor is kept close to zero with respect to signal ground (see Fig. 2). In typical applications where the AMS220 is used to excite the test resistance with enabled active common mode rejection circuit, the AC component of the common mode voltage is typically suppressed to the level of few microvolts, or less. Thus, if we again consider AC-voltage measurement by means of an industry standard lock-in amplifier with the CMR≈100 dB, it can be estimated that common mode errors will not exceed tens of picovolts. Taking into account sensitivity limitations of industry standard lock-in amplifiers, it can be concluded that resistance measurements utilizing AMS220 in combination with industry standard lock-in amplifiers are not affected by common mode errors.

As follows from the explanation above, the AMS220 in combination with an industry standard lock-in amplifier (or a suitable DAQ unit) represents an advantageous solution to perform routine and reliable resistance measurements by the four-wire method.

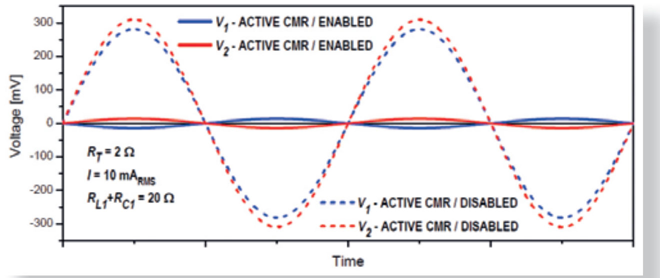

Fig. 2: Time dependence of voltage potentials V1 and V2 at the test resistor for resistance measurements using the AMS220 with the enabled active common mode rejection circuit (solid lines) and with the disabled active common mode rejection circuit (dashed lines), when the AMS220 operates as a "classic" current source.

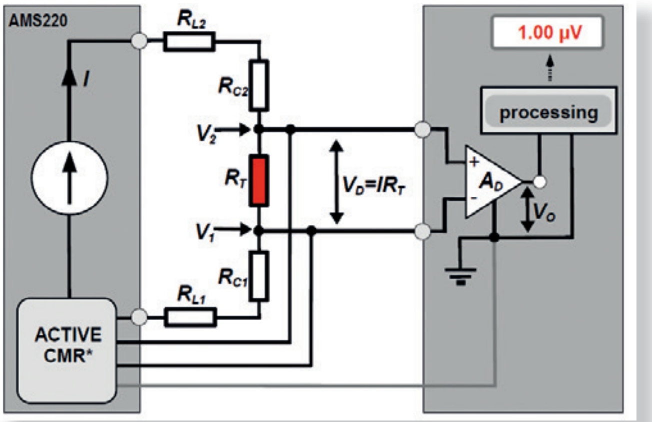

Fig. 3: Schematic depiction of four-wire resistance measurement using the AMS220 with the enabled active common mode rejection circuit (*U.S. Patent #9,285,809).

Connection of the AMS220 in the configuration replacing the AC-resistance/impedance bridge is schematically shown in the figure below. In fact, the AMS220 operating in the mode with the activated circuit of active common mode rejection enables the realization of low resistance measurements even in the most demanding conditions (e.g. at very low temperatures), where measurements using classical current sources are not usually reliable, or are even impossible, and frequently yield artificial results.

The section below describes a simple procedure for detecting the presence of errors caused by common mode voltage for any four-wire resistance measurement setup. The realization of the proposed tests should help researchers to identify existing or potential problems in their resistance measurement setups, and eventually indicate a requirement to use the AMS220 in their applications.

Tests of the electrical resistance measurement system to identify the occurrence of errors due to common mode voltage

The tests below enable simple identification of the occurrence of common mode errors for any electrical resistance measurement by using the four-wire method.

The simplified test

If a particular connection for the measurement of the electrical resistance is considered, as schematically depicted in Fig. 5 (a), then the occurrence of a common mode voltage error **for this particular connection** can be detected using the following procedure.

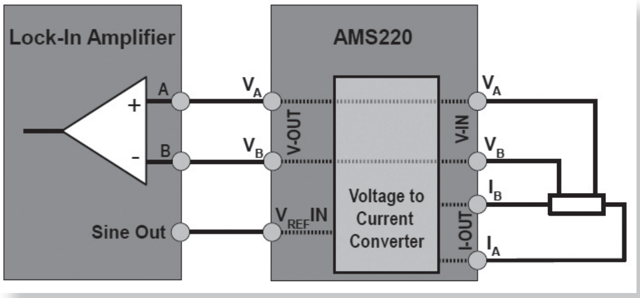

Fig. 4: Block diagram of connection of the AMS220 with the lock-in amplifier which replaces the AC-resistance/impedance bridge.

- In the first step, the measurement of tested resistor is made using relevant settings of the measurement system.
- In the second step, disconnect (let's say) the first voltage lead (V^+) from the first voltage terminal on the testing resistor and connect it to the second voltage terminal on the testing resistor, as shown in Fig. 5 (b).
- Repeat the measurement. As now both voltage signal wires sense the same electric potential on the test resistor, the differential voltage equals exactly to zero ($V_D = 0$ V); subsequently, the result of the measurement of the properly functioning system must **unconditionally have the value 0** Ω.
- Mutually exchange the current leads, and repeat the measurement. Also in this case, the result of the precise measurement must have the value 0 Ω.

If the measurement result pursuant to the test above is different from the value 0 Ω, and, moreover, if different values of the measured resistance are observed for the configurations with the mutually changed current leads, in all probability this error results from the common mode voltage.

However, the above described simplified test yields information relevant only to the measurement in the given arrangement with the particular load, and does not necessarily have to reveal drawbacks of the used measurement system in all cases when it is used (different supply lead resistances, different contact resistances, different types of the examined resistive load). It means that the measurement system can, under certain circumstances, provide correct results, while in other instances it provides artifacts.

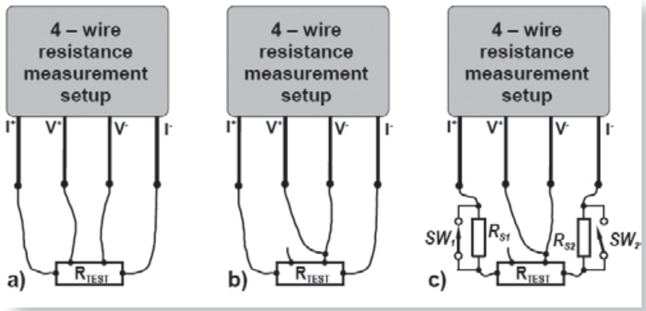

Fig. 5: Schematic depiction of the four-wire resistance measurement of the tested measurement system in the used connection (a), modification of the used connection to carry out the simplified test pursuant to the above description (b), extended modification of the used connection to carry out the below described detailed test (c).

A situation when resistances of the current paths (i.e., supply lead resistances or contact resistances in the current path) change significantly due to, for example, changes in temperature, can be given as an example. Another example is a measurement which uses the so-called differential current source, which excites the load using a method when voltage potentials of its current outputs are symmetric to the signal ground. (It means, if the voltage of one current output against the ground is e.g. 2 V, then the voltage on the terminal of the other output is -2 V.) Therefore, if the above described simplified test is carried out in the situation when both current branches have identical resistances, then the potentials of the voltage signals sensed on the load will be correspondingly in the vicinity of the signal ground with a correspondingly small component of the common mode voltage, and therefore error due to the common mode voltage does not occur in this specific case. However, when the symmetry of the resistance distribution in the current branches is broken, potentials of voltage signals sensed on the load move towards the potential of the differential current source output, to which the branch with a lower resistance of the current path is connected. This results in the rise of common mode voltage, which increases with the increasing "imbalance" of the current branches.

The detailed test

A thorough check of the experimental arrangement to detect the occurrence of common mode voltage errors can be carried out using the connection according to Fig. 5 (c). In contrast with the connection in Fig. 5 (b), this connection contains the $\mathbf{R_{S1}}$ and $\mathbf{R_{S2}}$ resistors, which can be included in or excluded from the electric current path by means of the $\mathbf{SW_1}$ and $\mathbf{SW_2}$ switches. The $\mathbf{R_{S1}}$ and $\mathbf{R_{S2}}$ resistors should have values approximately corresponding to the maximum expected changes of the current path resistances resulting from the changing measurement conditions, including also the changes related to various characteristics of the different tested loads. The detailed inspection of the experimental system shall be carried out by a series of measurements pursuant to the above described simplified test, namely for all combinations created by the inclusion/exclusion of the $\mathbf{R_{S1}}$ and $\mathbf{R_{S2}}$ resistances. We would like to note that a properly measuring system must unconditionally provide value 0 Ω for any combination created that way.

Obtaining a different result indicates that the measurement system does not have sufficient capability to eliminate effects of common mode voltages, and its usage in measurements within the range of the tested values of current path resistances may easily cause (or even systematically result in) experimental artifacts.

Using the current source AMS220 in the operation mode with the enabled active common mode voltage rejection circuit for the current excitation of the load enables the exact solution of this issue.