Communication—On Zero-Resistance Ammeter and Zero-Voltage Ammeter

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Zero-resistance ammeters (ZRAs) are often used to measure coupling currents. The ZRAs may have a resistance of 50 kohm when they are used to measure currents near 1 nA, so calling them ZRA is only an appropriate when the measured current is high, but not appropriate when the current is low. The term often causes a wrong perception that ZRAs have zero resistance. In fact, the only criterion to determine whether an ammeter can be effectively used to measure the coupling currents is how its voltage is close to zero. Therefore, such ammeters have been called zero-voltage ammeters (ZVAs).

Ammeters are required for the measurements of the current that flows amongst two or more galvanically coupled electrodes. For the evaluation of galvanic corrosion, ASTM G71 recommends the use of a zero-resistance ammeter (ZRA) for measuring the coupling current between the two metals that are externally coupled. In electrochemical current noise (ECN) studies, ASTM G199 also recommends the use of the ZRA for the measurements of the ECN that flows between two apparently identical electrodes. The ZRAs are also widely used to measure the coupling currents in coupled multielectrode arrays. Ammeters consisted of shunt resistors (called shunt-resistor ammeter in this article) and imposes a negligibly low voltage are also used to measure the coupling currents in coupled multielectrode array sensors (CMAS). In these ammeters, the shunt resistor is inserted into the measurement circuit and a voltmeter is used to measure the voltage across the shunt resistor to derive the current by applying Ohm’s Law. Typical values of the shunt resistors used in a CMAS were from 10 to 100000 ohms. This type of meter has been called zero-voltage ammeters (ZVAs).

Descriptions of ZRAs

There are mainly two types of ZRAs commonly used as ammeters for coupling current measurements. They are discussed in the following sections.

**ZRA formed with inverting operational amplifiers.**—The ammeters that commonly referred to as ZRAs are built with an operational amplifier (Op-Amp) as shown in Figure 1. If the Op-Amp is ideal, the potential at the inverting terminal ($V_n$) is equal to the potential at the non-inverting terminal ($V_p$). Hence, the input resistance which is the ratio of the voltage drop ($V_p-V_n$) to the measured current ($I$) is also zero.

In reality, however, Op-Amps are not ideal and do have input voltage. For example, every Op-Amp has an offset voltage ($V_{os}$) which is defined as the small differential voltage that must be applied to the input of an Op-Amp ($V_p-V_n$) to produce zero output ($V_{out}$). As a matter of fact, the offset voltage is one of the most important parameters that are reported in manufacturers’ product sheets. Figure 2 shows the production distribution of offset voltage of a typical model of high-performance Op-Amps by Texas Instruments. The offset voltage of this type of Op-Amps varies between $-2$ mV and $+2$ mV. In addition, the offset voltage may drift with time and temperature. When they are used to build the ZRA, the input voltage may be as high as 2 mV when the measured current is zero. Special Op-Amps with extremely low offset voltage are available, but the lowest offset voltage is still 5 µV. Because there are other integrated components in an assembled ZRA and the offset voltage also varies with time and temperature, it is difficult to achieve 5 µV for a ZRA. Based on an internet search conducted in February, 2016 for the input voltage specified by the ZRA manufacturers, the lowest values are 50 µV.

**ZRA formed with a potentiostat.**—Potentiostats were often used as ZRAs in galvanic corrosion measurements and ECN studies. In these measurements, the potentiostat’s counter electrode terminal is joined to the reference electrode terminal and both are connected to one of the specimen electrodes in the galvanic couple, and the working electrode terminal is connected to the other specimen electrode. Theoretically, by setting the working electrode potential to zero and measure the current, the potentiostat acts as a ZRA.

The authors conducted an internet search in February, 2016 for the accuracy of the potentiostat’s working electrode potentials. Most of the specified values are between ±1 mV and ±2 mV, but no manufacturers claimed for better than ±1 mV accuracy. Therefore, even the commercial potentiostats with the best ability to control potential may still impose a voltage between −1 mV and +1 mV when used as ZRAs.

**Discussion**

**Resistance of ZRA.**—The resistance of an active electronic component is characterized by static resistance which is defined as the ratio of voltage ($V$) to current ($I$) and dynamic resistance which is $dV/dI$. For the ZRA, the dynamic resistance is close to zero, but the static resistance with an input voltage of 0.05 mV to 1 mV as mentioned above is 50 kohm to 10000 kohm when the current is 1 nA.
which is a typical value for a CMAS probe with 0.78 mm² electrode surface area (corresponding corrosion rate is 1.4 μm/yr for carbon steel). For a large electrode with a surface area of 4 cm² as in the case for ECN studies, the static resistance is still 400 ohm when the input voltage is 1 mV and the measured current is 2.5 μA (corresponding corrosion rate is 7.5 μm/yr for carbon steel). Therefore, the ZRAs may be called “zero-dynamic-resistance ammeters”, but they should not be called “zero-resistance ammeter” because they have stunningly high static resistance when used for low current measurements. Because static resistance is also resistance and, like the resistance of a passive resistor, the static resistance directly relates the current to the voltage which affects the measurements of coupling currents (see below), this paper does not differentiate static resistance from resistance. It should be stated that ZRA is a valid term when it is used for high current measurements. For example, the static resistance is less than 0.2 ohm when the imposed voltage is 2 mV and the current is 10 mA and the dynamic resistance is usually near zero regardless of the current. The term is not appropriate when the current is low (10 μA or lower) which is often the case for small electrodes.

Definitions of ZVA and ZRA by ASTM standards.—In the newly published ASTM standard for CMAS probes (G0217), a ZVA is defined as a device that imposes a negligibly low voltage drop when inserted into a circuit for measurement of current. In the ASTM standard for ECN measurements (G199), a ZRA is defined as an electronic device used to measure current without imposing a significant IR drop by maintaining close to O-V potential difference between the inputs. According to the above definitions, a ZRA is also a ZVA, and the term ZVA includes both the ZRA built with Op-Amps and the shunt-resistor ammeter that produces a negligibly low voltage. The shunt-resistor ammeter cannot be called ZRA because the shunt resistance is not zero (usually between 10 ohm and 100 kohm). As most of the ammeters built with the Op-Amps exhibit astonishingly high resistance (400 to 1,000,000 ohm) when used for low level current measurements, calling them as ZRA may be confusing and often leads to the common belief that they have zero resistance. As a matter of fact, resistance is not mentioned in the definition of the ZRA and the value of the resistance is irrelevant for determining whether an ammeter can be used as a ZRA. The only criterion is whether the voltage it imposes to the measurement circuit is close to zero. Unlike the ZRA term, the ZVA term also includes the low-cost shunt-resistor ammeters which are as effective as the high-cost ZRAs for the measurement of low level coupling current (see below). The price of ZRAs is usually more than $2000 a piece and the price of the shunt-resistor ammeters is usually less than $200 if built with thermocouple-grade voltmeters. The use of the term ZVA in the corrosion community would mean a huge saving because corrosion professionals can then use any type of ammeters, including the low-cost shunt-resistor ammeters, for measuring coupling currents as long as they do not impose a significant voltage.

Effect of the voltage drop imposed by ZVAs.—Even though, real-world ZVAs may have a resistance up to 1000 kohms for the case of the commonly called ZRA and 100 kohms for the shunt-resistor ammeters, they have been effect tools for measuring coupling currents. Simulation analyses on the effect of the voltage imposed by ammeters on corrosion current measurements were performed using the Butler–Volmer Equation. The analyses concluded that the effect of 0.5-mV voltage was less than 5% for the worst case if the electrode potential after coupling is 20 mV higher than its open-circuit potential (before coupling), which is often the case for the small (~0.0078 cm²) anodic electrode of a CMAS probe. A large range of the Tafel slopes from the literature (βa = 30 to 120 mV/Dec; βc = 50 mV/Dec to infinity) were used in the different cases of simulations. Therefore, most of the ZVAs, including the shunt-resistor ammeters and the ammeters commonly referred to as ZRAs, are effective for non-uniform corrosion measurements with CMAS probes.

On the other hand, the analyses showed that the effect of even 0.2-mV voltage on the coupling current measurement can be 3.8% even for the best case (largest βc and smallest βa) if the electrode potential after coupling is only 5 mV higher than its open-circuit potential. The 5 mV increase by coupling is often the bounding case for a large anodic steel electrode (~4 cm²) used in ECN studies in simulated seawater. Clearly, the ZRA formed with a potentiostat does not meet this requirement because such ZRAs may impose a 1-mV voltage in the circuit.

When the shunt-resistor ammeter is used, multiple resistors should be used and they should be auto selected to handle different range of currents without producing a significant voltage in the measurement circuit.

Summary

The zero-resistance ammeter (ZRA) is a valid term when the ZRA is used for measurement of high currents. However, no ZRAs can be guaranteed to be true ZRAs when the current is low. The best commercially available ZRA may have a resistance near 50 kohm when the measured current is 1 mA. ZRAs formed with a high-cost potentiostat may have a resistance close to 1000 kohm when the coupling current is 1 mA and 400 ohm when the coupling current is 2.5 μA. Therefore, calling them ZRA is misleading when they are used to measure low current. In fact, the resistance of these ZRAs is irrelevant and the only criterion to determine whether an ammeter can be used to measure the coupling current is how the imposed voltage is close to zero. Therefore, zero-voltage ammeter (ZVA) has been used as another term for the ZRA when they are used to measure low current. Unlike the ZRA term, the ZVA term can be applied to not only the ammeters commonly referred to as ZRAs but also the low-cost ammeters formed with shunt resistors.

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