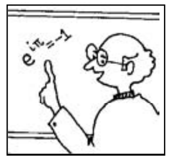
Classroom



In this section of *Resonance*, we invite readers to pose questions likely to be raised in a classroom situation. We may suggest strategies for dealing with them, or invite responses, or both. "Classroom" is equally a forum for raising broader issues and sharing personal experiences and viewpoints on matters related to teaching and learning science.

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The Analogue of Potentiometer for Current Zero Resistance Ammeter (ZRA)

Voltmeter and ammeter were invented to measure potential difference across two points and current in a circuit respectively. But, they suffered from the drawback of altering the values to be measured. The potentiometer was invented to overcome this drawback of the voltmeter. What about an analogous device for current? Well, it is not surprising that somebody has already designed such a device. But, what is surprising is that this device has become so obsolete that it appears neither in detailed textbooks nor in standard search engines. Therefore, it is worthwhile to describe the design of this analogous device, namely the 'Zero Resistance Ammeter' (ZRA).

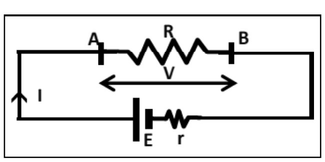
Keywords
Potentiometer, ammeter, voltmeter, current, voltage, corrosion, galvanic current.

1. General Circuit to Measure Current and Potential Difference

Consider a circuit consisting of a battery of emf E and internal resistance r connected to a resistance R (*Figure* 1). Let I be the current in the circuit and V be the potential difference across AB. It can be argued that

$$I = \frac{E}{R+r}\ , \qquad (1)$$

Figure 1 General circuit to measure I and V.



Box 1. Example for Current (Decreased) Measurement by Ammeter

Using typical values* : $R = 100\Omega$, $r = 4\Omega$, $R_a = 1\Omega$ and $E = 10$V, we get $\Delta I = 0.9524\%$, $I = 0.09615$ A and $I' = (1-\Delta I/100) \times I = 0.09524$ A. This is an error in the second significant figure and is not acceptable.

* These are values usually found in a high school/undergraduate laboratory.

$$V = \frac{ER}{R+r} \ . \tag{2}$$

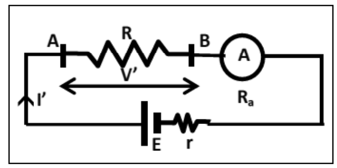


Figure 2. Circuit with ammeter showing measurement of current (decreased).

1.1 *Ammeter Gives Lower Value of I*

A circuit in which an ammeter of resistance R_a is connected in series with the resistance R to measure the current, is shown in *Figure* 2. Let the current in this circuit be I' and the potential difference across R be V'. Let ΔI be the percentage change in current. Then

$$I' = \frac{E}{R+r+R_a} \ , \tag{3}$$

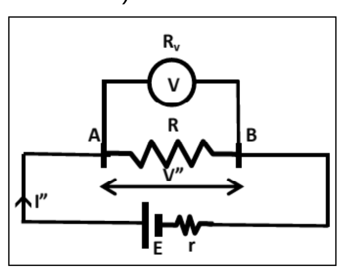
$$\Delta I = \frac{1}{\frac{R+r}{R_a}+1} \ . \tag{4}$$

A typical example is given in *Box* 1.

1.2 *Voltmeter Gives Lower Value of V*

A circuit in which a voltmeter of resistance R_v is connected in parallel with the resistance R to measure the potential difference is shown in *Figure* 3. Let the current in the circuit be I'' and the potential difference across R be V''. Let ΔV be the percentage change in potential difference. Then

Figure 3. Circuit with voltmeter showing measurement of potential difference (decreased).



$$V'' = \frac{E}{\frac{(R+R_v)r}{RR_v}+1} \ , \tag{5}$$

$$\Delta V = \frac{1}{\frac{(R+r)R_v}{rR}+1} \ . \tag{6}$$

Box 2. Example for Voltage (Decreased) Measurement by Voltmeter

Using typical values* : $R = 100\Omega$, $r = 4\Omega$, $R_v = 500\Omega$ and $E = 10$V, we get $\Delta V = 0.7634\%$, $V = 9.6154$V and $V'' = (1-\Delta V/100) \times V = 9.5420$ A. This is an error in the second significant figure and is not acceptable.

* These are values usually found in a high school/undergraduate laboratory.

A typical example is given in *Box* 2.

2. Search for Utopia in Ammeter and Voltmeter

By observing (4) and (6), we see that the ammeter will give an unchanged reading if R_a tends to zero and the voltmeter will give an unchanged reading when R_v tends to infinity.

2.1 *An Ideal Voltmeter is Impossible*

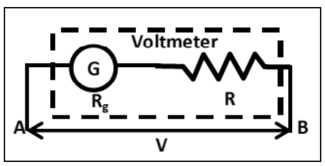


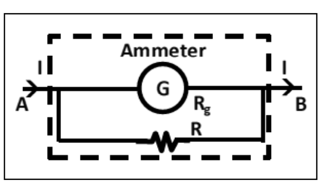
Figure 4. Construction of voltmeter using galvanometer and resistor of high resistance.

A general voltmeter consists of a galvanometer connected in series to a resistor of high resistance (*Figure* 4). Let the galvanometer and the resistor have resistances R_g and R, respectively. Let θ be the deflection in the galvanometer and k the deflection per unit current of the galvanometer. Let V be the potential difference between the two points across which the galvanometer is connected. We can show that

$$\theta = \frac{V}{(R + R_g)/k} \quad . \tag{7}$$

In the case of an ideal voltmeter, $R_v \to \infty$. So, $R \to \infty$ in the ideal case, as $R_v = R + R_g$ and R_g is a constant. From (7), $\theta \to 0$. So, the deflection in the galvanometer is infinitesimal in the ideal case. So, this deflection and thus the potential difference across the two points are almost impossible to measure.

Figure 5. Construction of ammeter using galvanometer and shunt resistor of low resistance.



2.2 *An Ideal Ammeter is Impossible*

A general ammeter consists of a galvanometer connected in parallel with a resistor of very low resistance (*Figure* 5). The symbols R, R_g, θ, k have the same meaning as in the previous section. Let I be the current in the circuit in which the galvanometer is connected. We can show that

$$\theta = \frac{IR}{(R + R_g)/k} \quad . \qquad (8)$$

In the case of an ideal voltmeter, $R_a \to 0$. So, $R \to 0$ in the ideal case, as $R_a = RR_g/(R + R_g)$ and R_g is a constant. From (8), $\theta \to 0$. So the deflection in the galvanometer is infinitesimal in the ideal case. So this deflection and thus the current between the two points are almost impossible to measure.

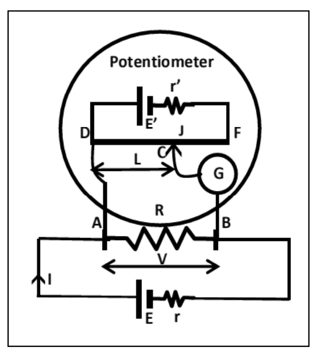
3. Potentiometer – the Ideal Voltmeter

A potentiometer is a device used to measure potential difference across two points without drawing any current. It has infinite resistance. It contains a potentiometer wire, a driver cell, a galvanometer and a jockey and is connected in parallel to the component across which the potential difference is to be measured, as shown in *Figure* 6.

3.1 *Working*

A driver cell with emf E' is used to maintain a potential gradient ϕ across the potentiometer wire. Without loss of generality, let us assume that the potentials at A and D are zero. So, the potential at J (position of the jockey) is ϕl and that at B is V, where l is the distance of the jockey from D. Current flows in the galvanometer when the potential at J is different from that at B. The position of the jockey is varied till the galvanometer gives no deflection. Let this happen at position C and let C be at a distance L from D. If the galvanometer shows no deflection, $V = \phi L$. Thus, we can measure the potential difference across two points A and B without drawing any current from the circuit and thereby keeping the potential difference unchanged.

Figure 6. Circuit with potentiometer showing measurement of potential difference without changing it.



3.2 *Condition for Successful Measurement*

The potential difference across the whole of the potentiometer wire must be more than across AB. Else, $V = \phi l$ will not be true for any l. This condition can be checked by ensuring that the galvanometer gives deflections in opposite directions at D and F. If this condition is not met, the driver cell should be replaced with one of higher emf.

3.3 *Range*

The maximum potential difference which can be measured by the potentiometer is ϕM, where M is the length of the potentiometer wire. Of course, the minimum potential difference which can be measured is 0. So, the range of potential difference that a potentiometer can measure is $0 - \phi M$.

4. Envisioning the Characteristics of the ZRA

Comparing the essential characteristics of a voltmeter and an ammeter *Table* 1 will bring us closer to understanding the characteristics of the ZRA. Let us try to derive the characteristics of the ZRA from that of the potentiometer by writing the latter's characteristics and applying the changes seen in the table to these properties, and then checking to what extent these characteristics match with those of the actual design. This will help us to perceive the analogy between ZRA and the potentiometer. This has been done in *Table* 2.

5. Actual Design of the ZRA

5.1 *Design*

We take a look at the actual design of the ZRA and compare the characteristics we derived with that of the actual design (*Figure* 7). But, this figure satisfies only the characteristics 2, 3 and 4 from the list we derived. The remaining will be shown to be met in the next subsection.

Table 1. Voltmeter vs Ammeter.

No.	Characteristic	Voltmeter	Ammeter	Change
1	Resistance	Very high	Very low	Reciprocal was taken
2	Type of connection to the component whose property is to be measured	Parallel	Series	Parallel $\rightarrow$ series
3	Components of the device	Resistor with high resistance, galvanometer	Shunt resistance*, galvanometer	Reciprocal of the resistor's resistance was taken but the other components were kept unchanged
4	Type of connection of the component resistor to the galvanometer	Series	Parallel	Series $\rightarrow$ parallel
5	Limiting quantity to make it ideal	Current through it must be zero	Potential difference across it must be zero	Current $\rightarrow$ potential difference

* Resistor of very low resistance.

Table 2. Deriving the characteristics of the ZRA.

No.	Characteristic	Potentiometer	Change to be applied	ZRA
1	Resistance	Infinity	Take reciprocal	Zero
2	Type of connection to component whose property is to be measured	Parallel	Parallel $\rightarrow$ series	Series
3	Components of the device	Potentiometer wire with low resistance per unit length, battery, jockey, galvanometer	Reciprocal of the resistor's resistance to be taken but the other components to be kept unchanged	Potentiometer wire with high resistance per unit length, battery, jockey, galvanometer
4	Connection of the component resistor to the galvanometer	Series*	Series $\rightarrow$ parallel	Parallel*
5	Limiting quantity to make it ideal	Current through it must be zero	Current $\rightarrow$ potential difference	Potential difference across it must be zero

* Here, the potentiometer wire along with the battery acts as the component resistor.

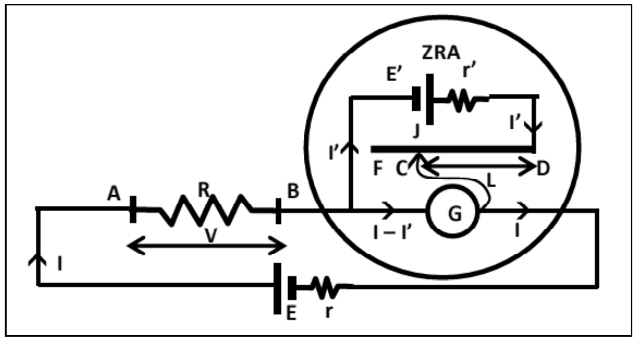


Figure 7. Circuit with potentiometer showing measurement of current without changing it.

5.2 *Working*

A driver cell with emf E' is used to drive current in the galvanometer

$$I' = \frac{E' + IR_{\mathrm{g}}}{r' + \phi l + R_{\mathrm{g}}} \ , \tag{9}$$

in the direction opposite to that in the circuit, where l is the distance of the jockey J from D and ϕ is the resistance per unit length of the potentiometer wire. The potential difference across the galvanometer and thus across the ZRA is

$$(I - I')R_{\mathrm{g}} = \frac{(I(r' + \phi l) - E')\, R_{\mathrm{g}}}{r' + \phi l + R_{\mathrm{g}}} \ . \tag{10}$$

The current flowing in the galvanometer is $I - I'$. The position of the jockey is varied till the galvanometer gives no deflection. Let the position of no deflection be C and let it be at a distance L from D. If the galvanometer shows no deflection, then $I - I'$ is zero. From (10), we find that

$$I = \frac{E'}{r' + \phi L} \ . \tag{11}$$

Since $I - I'$ is zero, $(I - I')R_{\mathrm{g}}$ is zero but this happens to be the potential difference across the ZRA. So, the characteristic 5 is satisfied by the design. By applying Ohm's law, the characteristic 1 can be shown to be met. So, the characteristics we derived fully match those of the actual design.

5.3 *Conditions for Successful Measurement*

The current when none of the potentiometer wire is used must be more than that in the circuit. Else, $I - I'$ will not be zero for any l. Also, the current in the circuit when the whole of the potentiometer is used must be less than that in the circuit.

These conditions can be checked by ensuring that the galvanometer gives deflections in opposite directions at D and F. When the first condition is not met, the driver cell is replaced with one of higher emf and when the second is not met, the driver cell is replaced with one of lower emf.

5.4 *Range*

The maximum current which can be measured by the ZRA is determined by putting $L \to 0$ in (11) to get $I \to \frac{E'}{r'}$. This is analogous to the upper limit on the potential difference which can be measured by a potentiometer.

The minimum current which can be measured by the ZRA is determined by putting $L = N$, where N is the length of the potentiometer wire, to get $I = \frac{E'}{r'+\phi N}$. The analogy between ZRA and potentiometer ends here because the lowest potential difference which a potentiometer can measure is 0.

So, the range of current that a ZRA can measure is $\left(\frac{E'}{r'+\phi N} - \frac{E'}{r'}\right)$. Thus, to decrease the lower limit of the range, we must increase ϕ, the resistance per unit length of the wire.

6. Present Status of the ZRA

A century ago, active components like diodes and transistors were not common. In those days the ZRA was very popular, since it was made up of passive components. With the advent of opamp circuits and transistor circuits to measure current, the ZRA has become

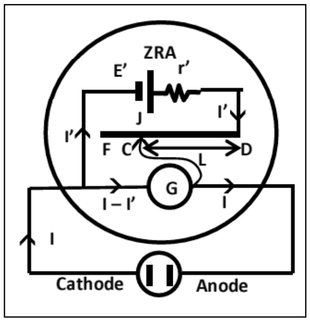


Figure 8. Use of ZRA to measure galvanic currents.

obsolete. This is because these circuits can measure current to an accuracy of 1 part in a million. Moreover, these circuits are smaller than ZRA, being made up of active components which are smaller in size than passive components which make up the ZRA. Yet, ZRAs are very popular among corrosion engineers who use it to measure large galvanic currents (*Figure* 8) which can easily damage the opamp and the transistor circuits. (This is contrary to the saying, 'small is beautiful'!)

7. Conclusions

We have given an account of the ZRA which is basically a device which measures the current in a circuit without altering the actual value of the current. It does this by applying a potential difference equal in magnitude but opposite in direction to the voltage drop across the resistance it introduces.

Suggested Reading

[1] Moving Charges and Magnetism, *PHYSICS Part 1*, Chapter 4, (Textbook for Class XII), NCERT, New Delhi, India, 2006.

[2] R Baboian, Electrochemical Techniques for Predicting Galvanic Corrosion, Galvanic and Pitting Corrosion – Field and Laboratory Studies, *ASTM STP* 576, American Society for Testing and Materials, 1976.

[3] J Wolstenholme, Inexpensive Zero-Resistance Ammeter for Galvanic Studies, *British Corrosion Journal*, Vol.9, No.2, pp.116–117, 1974.