Fundamentals of Electricity

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ATOMIC STRUCTURE

The basic structure of all materials that are seen or used every day conforms with a set pattern known as the atomic structure of matter. When a building is under construction, there are definite steps that are followed by the builders from its beginning to its completion. The materials used in the construction (steel girders, bricks, cement, etc.), when placed in their proper order and number, form a building. This concept of definite parts in a proper order can be related to the basic structure of all matter.

MATTER

Matter is anything that has mass and occupies space. Matter may take many forms. It may be a liquid, such as water; a gas, such as oxygen; or a solid, such as stone. Matter, as we know it, normally has weight because anything that has mass and is on or near the earth is influenced (pulled) by the force of the earth's gravity. Matter may be made up of a single element, or it may be a combination of two or more elements.

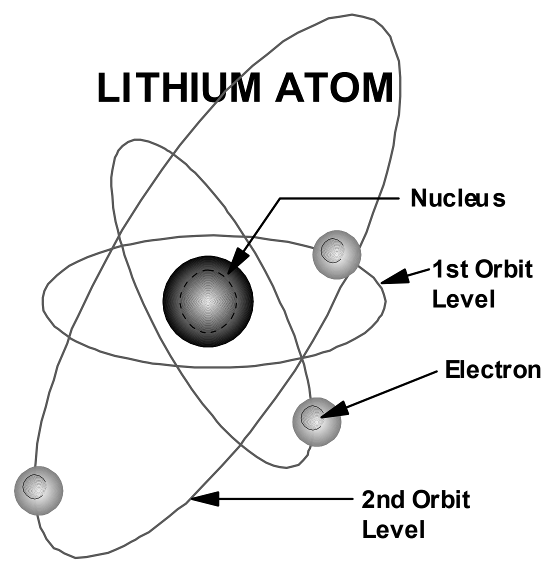
ELEMENT

An element is a substance that cannot be changed by chemical means.

ATOM

The smallest particle to which an element can be reduced and still retain its original characteristics is the atom.

One typical atom is lithium which is shown below. Composed very much like our solar system, the atom consists of a relatively large central body with small bodies revolving in orbits about it.



The simplest atom is hydrogen which is shown on the next page. This atom consists of a central body with one small body revolving around the center in an orbit. The central body is called the nucleus, and the revolving or planetary body is called an electron. The nucleus contains a positive unit particle known as a proton. The electron is a negative unit particle and the proton is a positive unit particle. We can replace the term "unit particle" with "charge". The word "charge" implies a potential force. For instance, a gun is said to be charged if it is ready to fire.

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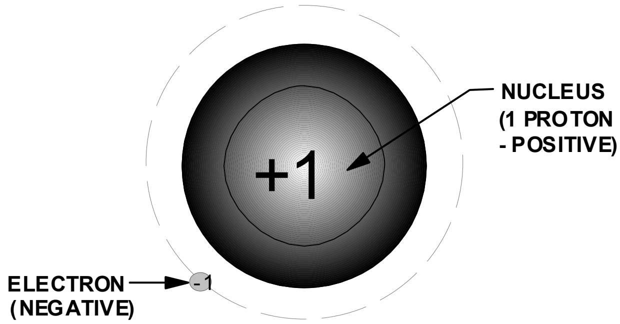
HYDROGEN ATOM



When a particular atom such as copper is neutral, or balanced, the negative charges balance the positive charges, and the net charge on the atom is zero.

Electron Charge +	Proton Charge =	Atom Charge
(-28)	(+29)	+0

If, through some outside force, an electron is broken away from the outer orbit, the atom is no longer neutral. Assume that one electron is removed from a copper atom. When this action takes place, the copper atom becomes a positive body with a net charge to +1 due to the absence of one electron which would make it neutral.

Electron Charge +	Proton Charge =	Atom Charge
(-28)	(+29)	+1

Conversely, if through some outside force, an additional electron is forced into the outer orbit of a copper atom, the atom becomes a negative body with a charge of -1.

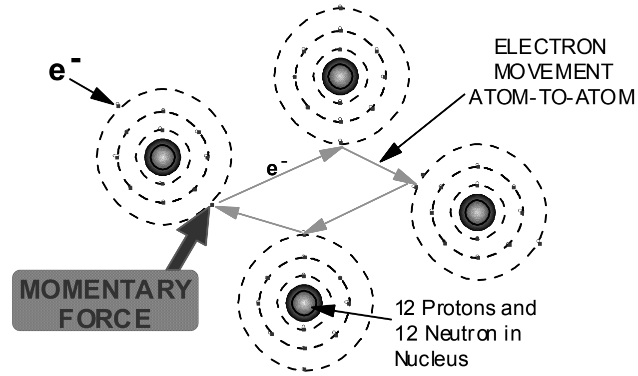
Electron Charge +	Proton Charge =	Atom Charge
(-30)	(+29)	-1

In making the copper atom a positive body, the question arises: What happened to the electron? Whenever an electron is removed from its orbit through the action of some outside force, it becomes a free electron. Free electrons are electrons which have been removed from their orbits and are free to move about among the atoms of the material. The external force which causes the electron to be released gives the free electron motion and, thus velocity.

The movement of free electrons is shown below, where a momentary outside force removes one electron from Atom A, causing the atom to be a positively-charged body.

The electron from Atom A, having velocity, strikes an electron in the outer ring of Atom B. In the collision, the electron from Atom A sticks in Atom B's outer orbit but, knocks out one electron from this orbit.

ELECTRON MOVEMENT IN METAL CONDUCTORS



Because of the equal exchange of the electron in its outer orbit, Atom B still maintains its state of balance. The same process of travel and collision of the free electron occurs with Atoms C and D. The velocity of the free electron leaving Atom D is now quite low because of the three collisions. Upon entering the outer orbit of Atom A, this free electron returns the state of balance to the ring.

The above figure and the related discussion bring to light a very important principle: When the application of a force to a material causes the electrons of that material to move from one atom to another, the result is flow of negative electric charges; or, stated in different words, an electric current is the flow or movement of electrons from one atom to another.

Conductor

Some atoms form free electrons and some do not. Consequently, some substances conduct an electric current readily and are know as conductors, while others do not conduct electric current and are know as insulators. A good conductor of electric current is

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a material that has a large number of electrons that easily become free when acted upon by some external force.

Insulator

An insulator is a material that has few electrons available to become free electrons.

Laws of Electrostatic Charges

There are only two laws which we must concern ourselves with:

- Like charges repel.
- Unlike charges attract.

BASIC ELECTRICITY

Current

An electric current is a flow of electrons, through some material, from a point of negative potential to a point of positive potential. The rate of flow of electrons is expressed in terms of the ampere. A current flow of one ampere is said to flow at a point when one Coulomb (6.24 billion billion electrons = 6.24×10^{18} electrons) passes through a given point in one second. Expressed in a formula:

$$I = Q/T$$

where:

I = Current in amperes

Q = Quantity of electrical charge in Coulombs

T = Time in seconds

ElectroMotive Force (EMF)

Electromotive force is the force that pushes the electrons along a conductor that causes current flow. The strength of this electromotive force is measured with a voltmeter.

Resistance

Resistance to electric current flow is a fundamental characteristic of any material. The resistance of any conductor is directly proportional to the conductor's length and is inversely proportional to its cross-sectional area.

Practical Units

Thus far we have learned that an electromotive force (EMF) is capable of setting up a flow of current in a conductor. The next important step is to learn how much EMF is needed to set up a certain amount of current in a conductor of a given resistance. To do this, we should have definite units of measurements for electric current, EMF and resistance.

Units of Electric Current - Ampere

Electricity makes itself known by its effects. One of its effects is chemical, and this effect is used to establish the basic unit of electric current, which is the ampere.

The ampere is the unvarying electric current which, when passed through a solution of silver nitrate in water, will deposit silver at the rate of 0.001118 grain per second. The weight of the silver deposit is found by a very accurate measurement of the element before and after the run.

In practice, it is neither convenient or practical to measure electric current by this electrochemical technique. An instrument known as an ammeter is used for this purpose. The operation of the ammeter is based on the magnetic effect of electric current, but its readings are based on the result of the fundamental electrochemical action.

Unit of Electromotive Force - Volt

The electromotive force or difference of potential needed to establish a flow of current in a conductor is measured in volts. The ordinary dry cell, when new, has an electromotive force of 1.5 (one and one-half) volts. The unit of electromotive force is responsible for the term voltage being used to express electromotive force and difference of

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potential. The instrument generally used to measure electromotive force, or voltage, is the voltmeter.

Unit of Resistance - Ohm

Any substance, the atoms of which have a number of free electrons, is a conductor of electricity. Copper is a good conductor. Iron, aluminum, silver, gold, and many other metals, are all conductors of electricity. Wire made of these metals, of the same diameter and length as the copper wire, will conduct electricity, but the amount of current measured with an ammeter will be different for every metal used, other conditions, such as the voltage of the battery and the dimensions of the wire, remaining the same. That quality of a conductor which limits or opposes the flow of electrons, or current, is called resistance. Resistance is expressed in ohms.

The resistance of a conductor is 1 ohm when an EMF of 1 volt causes a current flow of 1 ampere to occur. In practice, the resistance of a conductor or of a circuit may be calculated when the values of the applied voltage and the resultant current are known. It may also be measured with an instrument know as an ohmmeter.

Ohms Law

There is a definite relation between the voltage, the current, and the resistance of a circuit. This relation is given by Ohms Law which may be expressed in the form of rules or equations. The rules are as follows:

Rule 1: The current, in amperes, is equal to the applied voltage, in volts, divided by the resistance, in ohms.

Amperes = Volts / Ohms

$I = V/R$

Rule 2: The resistance, in ohms, is equal to the voltage, in volts, divided by the current, in amperes.

Ohms = Volts / Amperes

$R = V/I$

Rule 3: The voltage, in volts, is equal to the current, in amperes, multiplied by the resistance, in ohms.

Volts = Amperes x Ohms

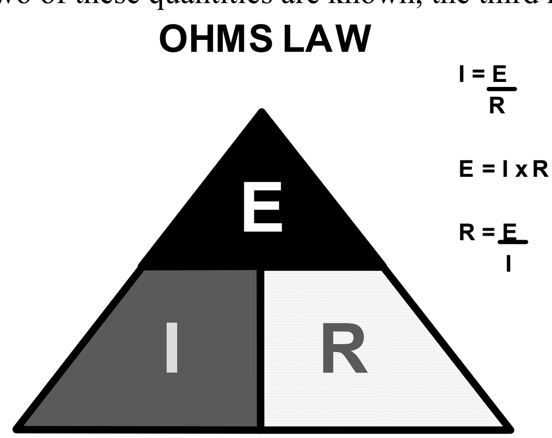
$V = I \times R$

Ohms law is often expressed in the forms above, but with the generally adopted symbols: I for current, or amperes; E for voltage, or volts; and R for resistance, or ohms. When expressed in this manner, Ohms Law becomes:

$I = E/R$ or $R = E/I$ or $E = IxR$

An easy way to remember Ohms Law is with a triangle relation. By covering the parameter you are looking for, the remaining characters tell you what to do. Thus, if you want to know the voltage, place your thumb over the E and that leaves you with I x R. Another example would be current. Cover the I with your thumb and that leaves you E/R.

The foregoing rules and equations show that in a direct current circuit three different quantities are involved, namely, volts, amperes, and ohms. When any two of these quantities are known, the third may



be determined by Ohms Law.

THE TWO GENERAL TYPES OF ELECTRICITY

There are two general types of electric current flow which will be involved with corrosion and corrosion control work. These are alternating current (AC) and direct current (DC).

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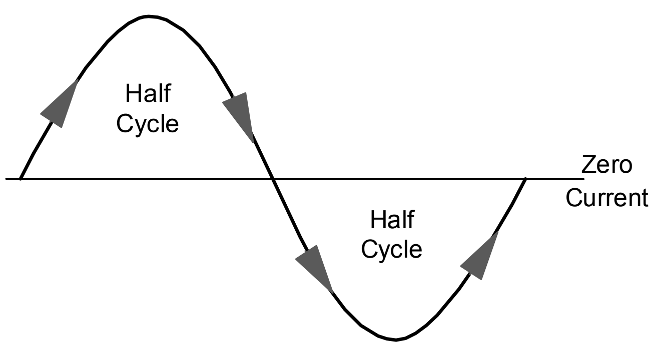
<u>What is Alternating Current?</u>

Alternating current (AC) electricity is that which flows first in one direction and then in the opposite direction in accord with an established pattern. As an example, the usual alternating current power sources used in the United States have a frequency of 60 cycles per second. This is referred to as 60 Hertz (or 60 Hz).

As can be seen from the next illustration, the current flow at the beginning of the cycle (left side of the illustration) is zero. The current builds up to a peak in the forward direction and then drops back to zero at the end of the first half cycle. It then reverses its direction of flow and builds up to a maximum in the reverse direction. Following this, it again drops back to zero at the end of the second half cycle (which is the end of one full cycle). At this point, it again reverses direction to start the next cycle.



ALTERNATING CURRENT (AC)

From this, it can be seen that there are, in effect, two net current reversals for one full cycle. This means that for a normal 60 Hz alternating current power source, the current flow changes direction 120 times per second.

The shape of the normal current flow plot from the usual alternating current commercial power source is known as a sine wave.

<u>Significance of Alternating Current</u>

Alternating current electricity is a relatively insignificant factor as a cause of corrosion except in very special cases.

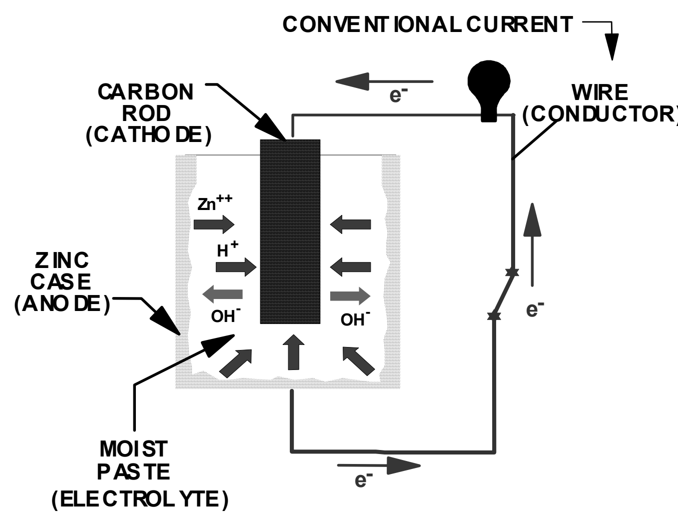
In the control of corrosion, however, commercial AC power sources are used as an energy source to power corrosion control equipment such as rectifiers (which convert AC power to DC power) are widely used in impressed current cathodic protection systems.

<u>What is Direct Current?</u>

Direct current (DC) electricity is that which normally flows in one direction only rather than changing direction in accord with an established pattern as was discussed for alternating current.

An example of direct current is that from a battery powering a common flashlight.

DRY CELL BATTERY



<u>Significance of Direct Current</u>

DC electricity is of prime importance in the consideration of the corrosion process. It is directly involved in various types of corrosion cells. It is also directly involved in corrosion control by the use of various types of cathodic protection.

<u>SERIES CIRCUITS</u>

When all the parts of a circuit are electrically connected end to end, they are said to be in series.

The current flows from the battery E through the resistor R1, then through the resistor R2, and returns to the battery E.

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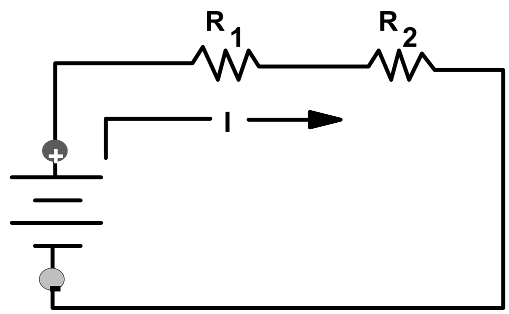
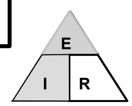
SIMPLE SERIES CIRCUIT





The total resistance of a series circuit is equal to the sum of the individual resistances. If R1 and R2 are the series resistors, then their total resistance is: RT = R1 + R2. Thus, if R1 is 5 ohms and R2 is 10 ohms then:

RT = 10 + 5 = 15 ohms

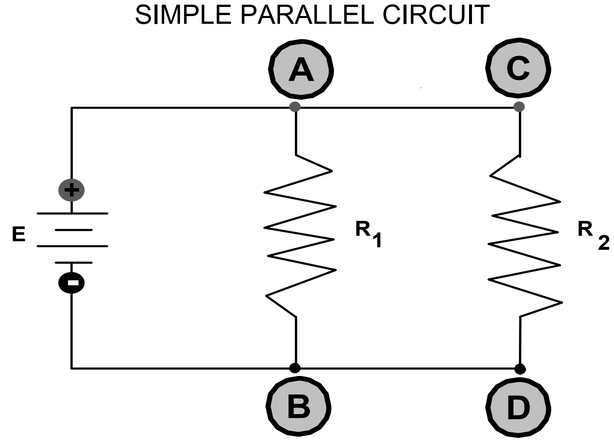
There are three fundamental laws that apply to any series circuit. These laws are:

- In a series circuit, the same current flows through each component in the circuit.
- In a series circuit, the total resistance is the sum of the individual resistance's making up the circuit.
- In a series circuit, the applied voltage is equal to the sum of the individual voltage drops.

PARALLEL CIRCUITS

When two or more electrical devices are connected so that each one offers a separate path for the flow of the current between two points, the devices are said to be in parallel. In the figure below, the two resistors R, and R2 are shown connected in parallel.

SIMPLE PARALLEL CIRCUIT



The total current set up by the battery divides at point A, a part going through the resistor R_1 while the other part flows through the resistor R_2. At the junction point of B, the two currents unite and return to the battery. The resistor R_2 is in parallel with resistor R_1. Similarly, the resistor R_1 is in parallel with resistor R_2.

The two branch circuits consisting of the resistors R_1 and R_2 form two separate paths in parallel. An open circuit in either branch will not stop the flow of current through the other branch, because each branch forms a separate and complete path from point A to point B. An open circuit in the main conductors, between point A or B and the battery, would interrupt the current in the entire circuit.

The total current in a parallel circuit is the sum of the currents in each branch. Since each branch is connected directly to the battery, the current in it is calculated according to Ohms Law. If the battery voltage E is 30 V and R_1 is 5 ohms, then the current in R_1 is E / R_1 or 30 / 5 = 6 amps. If R_2 is 10 ohms, the current in it is 30 / 10 = 3 amps. The total current is the summation of the branch currents, or $I_1 + 1_2 = I_T$. Thus 6 + 3 = 9.

Since the combined current in the two parallel resistors is 9 amps and the voltage is 30, according to Ohms Law the two resistors in parallel must have a resistance R_T = E / I = 30 / 9 = 3 1/3 ohms, which is less than the resistance of either resistor.

Laws for Parallel Circuits

The facts pointed out concerning parallel circuits may be summarized in the form of three fundamental laws which will apply to any parallel circuit. These laws are:

- In a parallel circuit, the same voltage is applied to each individual branch.
- In a parallel circuit, the total current is equal to the sum of the currents in the individual branches.
- In a parallel circuit, the effective resistance is equal to the applied voltage divided by the

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total current, and this value is always less than the smallest resistance contained in the circuit.

Unit of Resistivity

From what has been discussed regarding series circuits, it would be a reasonable conclusion to say that the resistance of a conductor increases as its length increases. By the same token, from what has been said regarding parallel circuits, the resistance of a conductor must decrease as its cross-sectional area increases.

Experiments have proven this true, and it is found that the resistance is proportional to the length and that the resistance is inversely proportional to the cross-sectional area.

To mathematically relate these for any conductor, we must introduce proportionality constant, called resistivity whose symbol is the Greek letter ρ (rho). Combining all of these factors, we can express the resistance of any conductor by, $R=\rho L/A$ or $\rho=RA/L$

Since R is in ohms, and if A is in square centimeters (cm2), and L is in centimeters (cm), then:

ρ=ohms x cm2/cm=ohm-cm

Thus ρ, that is, resistivity has the dimension ohm-centimeter. Resistivity then is equal to the resistance of a conductor which is 1 centimeter long with a constant cross-sectional area of 1 square centimeter.

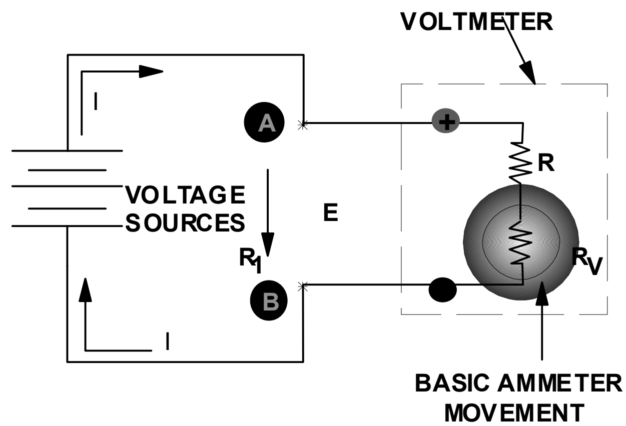
ELECTRICAL INSTRUMENTS

Meter Movement Sensitivity and Accuracy

The sensitivity of a meter movement depends upon the amount of current necessary to operate the moving element of the meter. The meter movement requiring the least amount of current for full scale deflection is considered to be the most sensitive. The amount of current necessary for full scale deflection depends upon the number of turns of wire on the moving coil. When more turns are added, a stronger magnetic field is created; thus, less current is necessary for full scale deflection.

Ammeters

The ammeter is the instrument used to indicate the quantity of current in an electrical circuit. In order to measure the amount of current in a circuit, the ammeter must be placed in series with the circuit. The figure below shows a DC ammeter connected into an electrical circuit.



SERIES EFFECT OF METER RESISTANCE ON CURRENT FLOW IN AN AMMETER CIRCUIT

The two resistors, R and RV, represent the resistance of the ammeter and the over-all circuit, respectively. When the ammeter is manufactured, the resistance RA is kept as small as possible so that the value current indicated by the movement will be close to the actual circuit current when the ammeter is removed. Note that the ammeter has polarized terminals to indicate proper circuit connection of the ammeter.

The ammeter shown in the figure above has the disadvantage of being able to indicate only one range of current. To measure higher values of direct current, the meter may incorporate a suitable resistor called a meter shunt connected in parallel with the meter movement as shown in the below figure.

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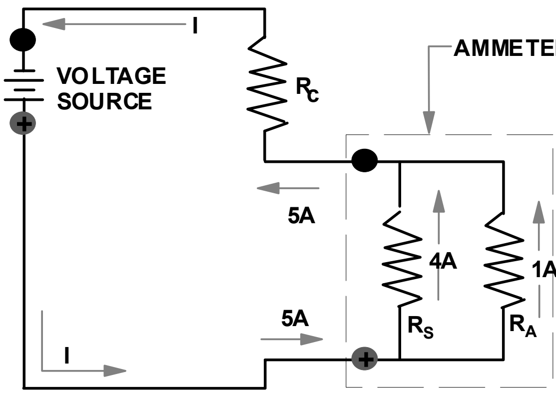
CURRENT DIVISION IN AMMETER WITH SHUNT RESISTOR, RS



For full scale deflection of the meter pointer, the meter shunt provides a path for the portion of the current in excess of that required by the sensitivity of the meter movement. Assume that the movement sensitivity of the meter in the above figure is one ampere. With the addition of the proper shunt resistance, the ammeter circuit allows a total of 5 amperes to pass before the pointer indicates full-scale deflection -- 4 amperes through the shunt and 1 ampere through the movement; therefore, the maximum current reading ability of the ammeter has been increased by the addition of the shunt resistor.

Determination of the correct value of shunt resistances for different meter movements and current ranges can be accomplished by using Ohms Law as applied to parallel circuits. The following illustrates a typical problem in the calculation of a meter shunt. The meter movement shown below has a full-scale deflection sensitivity of one milliampere. It is desired to connect a shunt resistor to increase the current indicating capability of the movement to ten milliamperes. Since the movement can safely handle only one milliampere, nine milliamperes must flow through the shunt.

Expressing the current through the shunt resistance in terms of commonly used symbols provides the following relationship:

$$I_s = I_t - I_m$$

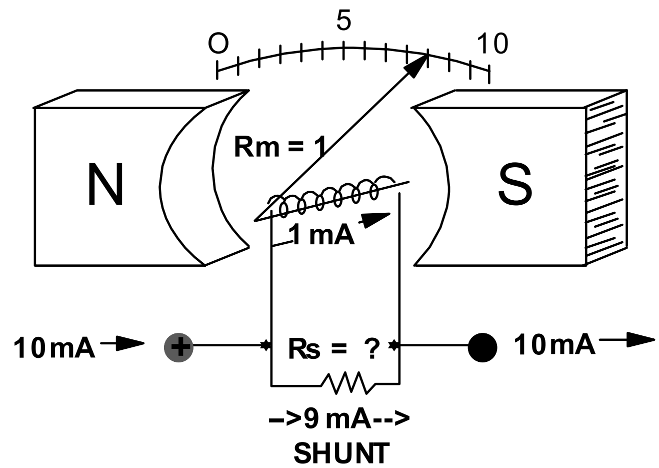
where:

I_s = current through the shunt

I_t = total current to be measured

I_m = current through the meter

ANALOG METER MOVEMENT



Since the internal resistance of the meter is shown to be 45 ohms, the shunt must have one-ninth of this resistance or a resistance of 5 ohms to carry the required current.

To prove the above statement, the following should be considered. Knowing that the current through the meter movement is one milli-ampere (I_m) and its resistance is 45 ohms (R_m), the voltage drop across the meter can be calculated by Ohms Law.

$$E_m = I_m \times R_m$$

$$E_m = 0.001 \times 45$$

$$E_m = 0.045 \text{ volt}$$

Since the voltage across the network (meter movement and shunt) is known, further application of Ohms Law will provide the resistance requirement of the shunt.

$$R_S = E_S/I_S$$

$$R_S = 0.045/0.009$$

$$R_S = 5 \text{ ohms}$$

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Through mathematical substitution, a standard formula can be established for determining the required resistance of any meter shunt, providing the current through the shunt is known. The standard formula is:

$$R = (I_m \times R_m)/I_s$$

Effect of Ammeter Resistance on Circuit Resistance

When an ammeter is inserted in an electrical circuit, it increases the effective circuit resistance. This will reduce the current flow in the circuit in accordance with Ohm's Law.

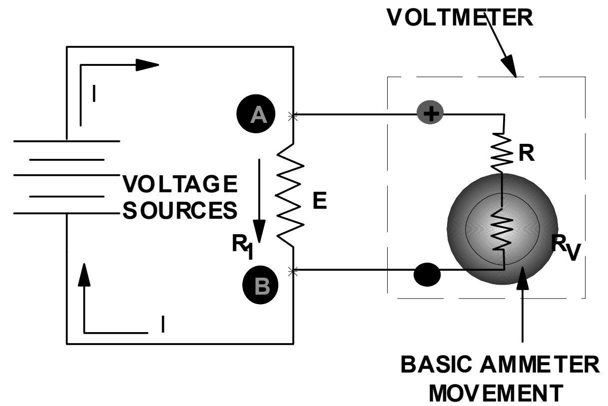
The practical effect may or may not be a consideration depending upon the relative values of the original circuit resistance and the inserted ammeter resistance. The ammeter should, in general, never have a resistance that is greater that 1% of the circuit resistance into which it is being inserted.

Voltmeters

The voltmeter is the instrument used to indicate the quantity of voltage present in an electrical circuit. In order to correctly measure the voltage of a circuit or circuit component, the voltmeter must be placed in parallel with the circuit. A DC voltmeter is capable of measuring only DC voltages, since the current must pass through the meter movement in a specified direction.

The following figure shows the internal components of a voltmeter (enclosed in dotted lines), which is connected as a unit to a circuit for the measurement of voltage. Note that the voltmeter circuit is composed of an ammeter in series with a resistor (Rm). The resistance, Rm, is a high-value resistance placed in series with the meter movement resistance to reduce the amount of current flowing through the movement.

As illustrated, when the voltmeter is placed across the circuit component, R1, the current flowing through the voltmeter causes a deflection of the meter needle. The resistance, Rm, is called the multiplier resistance because, if its ohmic value is increased, the same current would still be required to cause full-scale deflection of the meter movement, but more voltage would be required to cause this current to flow.



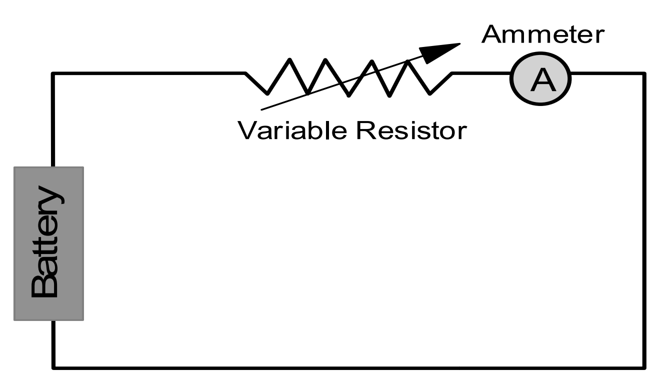
PARALLEL EFFECT OF METER RESISTANCE ON CURRENT FLOW IN A VOLTMETER CIRCUIT

If we experimentally set up the circuit as shown in the figure below we can determine the resistance of the coil assuming that the required current is 1 milli-ampere for full scale deflection.

By adjusting the variable resistor until the meter reads full scale (.001 ampere), we know that the total circuit resistance (meter plus resistor value) must be 1000 ohms. Assume that the variable resistor was measured and found to be 950 ohms, then the meter coil itself must be only 50 ohms. Thus, the basic instrument has a 50 milli-volt drop movement.

$$E=IR=0.001 \times 50= .050 \text{ volts}$$

USING VARIABLE RESISTOR TO DETERMINE VOLTMETER RESISTANCE



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From this we have seen that in order to use this basic instrument as a voltmeter, we had to add series resistance. In this case the total circuit resistance is 1000 ohms. Thus, by definition, this instrument, when used as a voltmeter, would have a sensitivity of 1000 ohms per volt.

R = E/I = 1/0.001 = 1000 ohms

Normally, sensitivity is expressed in the fashion -- ohms per volt. Thus, when you read on the face of a meter its sensitivity, you can, of course, determine the current required for full scale deflection, but you do not know the basic movement resistance.

From the case illustrated, it is obvious that in order to use any meter as a voltmeter, it is necessary that the internal resistance be known. We can then produce a voltmeter to read any voltage utilizing a basic formula.

$$\mathbf{E = I_m \times R_m + I_m \times R_s}$$

where:

$\mathbf{I_m}$ = meter current

$\mathbf{R_m}$ = meter resistance

$\mathbf{R_s}$ = series resistance

E = desired voltage range:

$$\mathbf{R_s = E_m/I_m - R_m}$$

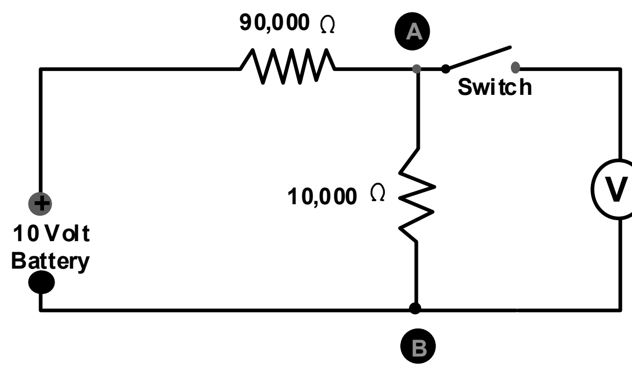
Then to produce a 100 volt full range instrument with the basic movement that has 50 ohms resistance and 0.001 ampere sensitivity, the necessary series resistor is:

R_s = 100/0.001 **-** 50 = 99,950 ohms

The series resistors required for the voltmeter ranges are known as multiplier resistors.

Suppose that it is desired to know the voltage appearing across the load in the figure below.

VOLTAGE DROP MEASURED ACROSS A RESISTOR



Now we know from the circuit values given that a current of .001 ampere must be flowing in the circuit. The voltage drop appearing across the 10K ohm load resistor must be 10 volts. Now, if a 1000 ohm per volt meter with a full scale of 10 volts (that is a total resistance of 10K) were placed in parallel with load, parallel resistance of the load and meter must be 5K.

The circuit resistance then is 95K, and the total current per Ohms Law (100 volts / 95,000 ohms) must be .001053 ampere. The voltage as read by the meter then must be:

E = .001053 x 5000 = 5.263 volts

From the circuit conditions set up, we know it should have read 10 volts. Therefore, the voltmeter itself has introduced a large magnitude of error, and in terms of percent this is:

% error = [1 – (observed voltage/true voltage)] x 100%

% error = [(1 – (5.26/10)] x 100% = 47.4%

We can draw two conclusions from the explanation above.

- Any voltmeter, since it is a current-operated device, will introduce an error.
- To minimize error, the sensitivity of the meter must be high. That is, the smaller the current, the more accurate the reading will be.

<u>THE DIGITAL DIRECT CURRENT INSTRUMENT</u>

Digital instruments are a relatively recent innovation as compared to the moving needle

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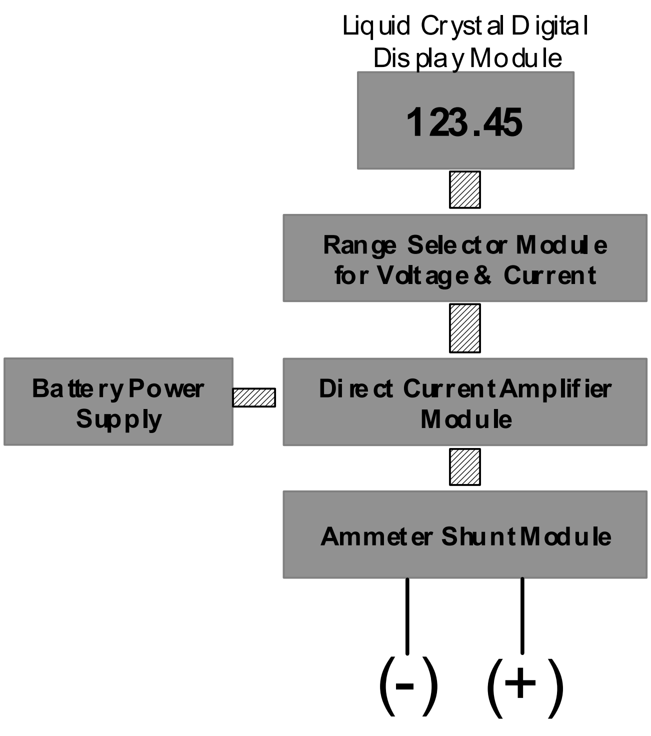
analog instruments. They have many advantages making them particularly useful to the corrosion control worker on underground structures. There are also some disadvantages. The development and improvement of such instruments is a continuing thing with new advances in electronic technology. The corrosion worker will do well to keep abreast of such developments to assure himself that he is equipped with the best available equipment for his purposes.

Operating Principles

The figure below is a representation of a digital instrument for the purpose of illustrating some of the pertinent points concerning such devices. No attempt is made to diagram the electronic circuitry the details of which can be quite complex and which can vary with the instrument manufacturer.

SCHEMATIC REPRESENTATION OF A DIGITAL D-C INSTRUMENT



Whereas the analog instruments described earlier have mechanically moving parts, a digital readout instrument is entirely electronic with no moving parts. Although the figures in the digital readout module may appear to move as the indicated reading changes, this is simply the changing formation of the digital characters as the applied electrical signal changes. There is no actual physical movement.

There are two types of digital readout modules. One of these utilizes LED (light emitting diode) elements to form the characters in the readout. As the name implies, when such a diode is energized by an electrical signal, it shows up as bars of light.

The other type of readout utilizes LCD (liquid crystal diode) elements. Such a diode is normally a neutral light color because it reflects light, but when energized by an electrical signal, it appears as a dark bar (absorbs light) which contrasts with the light background color. Of the two types, the liquefied crystal readouts are normally used in corrosion test instruments for field use since they take less energy from the instrument batteries and can be easily read in bright sunlight. The discussion herein assumes that liquefied crystal readout displays will be used.

One of the more important differences between the analog instruments described earlier and a digital instrument is the fact that all the energy needed to operate a moving coil analog instrument has to come from the external circuit in which measurements are being made. The digital instrument, on the other hand, takes very little energy from the external circuit. The energy needed to operate its circuitry comes from internal long-life batteries in these electronic instruments.

When the digital instrument is used as a voltmeter, the unknown input voltage at the instrument terminals bypasses the ammeter shunt module and is applied to the DC amplifier module. Here the applied voltage encounters a high input resistance -- typically ten million ohms or higher. This will be a fixed value which will be the same regardless of the voltage readout range selected. This very high input resistance means that the current taken from the external circuit will be very small and thus the reading will be more accurate. Although, as indicated, the input resistance normally remains constant for all voltage ranges, there are some digital instruments for corrosion work which have a

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provision for changing the input resistance (by pressing a button or rotating a selector switch) in order to see if the reading remains essentially the same with both values of input resistance. If they are the same, this indicates that external circuit resistance is not a problem. If there is a difference between the two readings, interpretive techniques may be used to arrive at the true potential.

The direct current amplifier, as its name implies, amplifies the input signal to a value that will actuate the readout module after adjustment using the range selector module.

In addition to the numerical figures (or digits) in the readout module, the decimal point will appear in its correct location for the range that has been selected. If the voltage being measured has been incorrectly connected to the instrument (+) to (-) and (-) to (+) instead of (+) to (+) and (-) to (-) as it should be, or if the polarity of the input voltage changes, a (-) sign will normally appear on the readout panel. Depending on the manufacturer, other information may appear as well, such as a low battery indicator when instrument batteries need replacement. There may also be an indication to show if an applied voltage or current is beyond the range selected.

When the instrument is used in the ammeter mode, shunt resistors are used for various current ranges as has been described earlier for analog instruments. The voltage drop across the shunts is then applied to the electronic circuitry as described for the voltmeter mode with the measured value appearing on the readout module. An important difference from the analog ammeter described earlier is that less energy is taken from the external circuit since most of the instrument operating energy comes from its internal batteries. Since shunts are used for the ammeter mode, the discussion relating to the effect of the shunt resistances on the external circuit is generally similar to that discussed under analog instruments.

Accuracy

Digital instruments, being non-mechanical, can be made with greater accuracy than analog instruments in the same price bracket. Normally, the accuracy of a digital instrument is expressed differently from that of an analog instrument as discussed earlier. This may be expressed, for example, as ± (plus or minus) a percentage of the actual reading, ± a percentage of the full scale reading, ± one digit in the last place (right hand figure) of the indicated readout. The net percentage accuracy figures can be quite high (depending on manufacturer and quality) as compared with analog instruments.

Advantages

Some of the advantages of digital instruments compared with analog instruments are as follows.

- High input resistance to electronic circuit with very little energy taken from the external circuit in which measurements are being taken.
- High accuracy.
- Decimal point shown in correct location, thus reducing possibility of human error.
- No interpretation of needle position necessary between divisions (as often required with analog instruments) thus further reducing the possibility of human error.
- No polarity problem -- instrument reads correctly regardless of polarity as long as the reversed polarity indicator (negative sign) is observed.
- Relatively rugged for field use.

Disadvantages

Nothing is perfect. There are some disadvantages with respect to digital instruments although certain of these are subject to improvement. Typical disadvantages are as follows:

- Taking readings under dim light conditions where liquid crystal readouts may be relatively difficult to see.
- Certain components of the electronic circuitry may have a narrower operable temperature range than analog instruments.

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- Liquid crystal read-out panels tend to be sluggish at low temperatures and tend to blank out if the temperature is too high. In extreme cases, the readout panel can be permanently damaged by excessive temperature.
- Reading continuously varying values. In some types of corrosion control work, voltages and currents being measured may be subject to continuous variation rather than being a steady value. Stray current situations are an example. In such situations, the digital readout panel can be a confusing display of continuously changing digits making it difficult to determine or estimate, maximum, minimum and average figures. Although still difficult, this can be more readily done with an analog instrument.
- In order to get the advantages of electronic circuitry and still permit an analog readout, hybrid instruments are available which use the electronic circuitry to operate an analog readout. Such instruments retain the advantage of minimal operating energy taken from the external circuit since the energy needed to operate the analog readout is provided by the instrument internal batteries.

COMBINATION INSTRUMENTS

For use in corrosion control work, combination instruments have been developed which, typically, have two indicating instruments with interconnecting circuitry and selector switches. These are so arranged that various testing requirements may be set up by proper switch settings. This reduces the wiring as compared to that needed for separate instruments. Time needed to set up for a particular test is reduced and possibilities of wiring errors are reduced.

Additionally, single-instrument multi-testers are available (both analog and digital) which measure both DC voltage and current as has been discussed. but in addition can measure AC voltage and (in some instances) AC current and can measure resistance. Such instruments are a great convenience to the underground corrosion control worker.

CLAMP-ON INSTRUMENTS

A specialized type of instrument is available which is useful for measuring currents in conductors where it is desired to do so without interrupting the circuit. These are called clamp-on instruments. These typically incorporate a split or hinged ring of magnetic core material which is clamped around the conductor in which current is to be measured.

Clamp-on instruments are available to measure both AC current and DC current. The sensing device may differ between the two types. Instruments designed for AC current measurement can measure an induced voltage in a coil surrounding the ring at one point with the induced voltage being proportional to the amount of current flow through the conductor. The instrument designed for DC current measurement electronically senses the distortion in the magnetic field in the clamp-on ring caused by the continuous mono-directional current flow.

Both types of instruments are available to cover a wide range of full scale current.

At least one maker of DC clamp-on instruments can supply clamp-on rings in various diameters from smaller sizes for wires or cables to large rings that can surround pipes.

COMPUTER-COMPATIBLE INSTRUMENTS

With the continuing development of computer usage, the appearance of computer-compatible field-testing instruments was inevitable. Typically, this is an adjunct to electronic testing instruments that permits the corrosion worker to store recorded data on command in some form of internal storage device (RAM, ROM, tape, disc, etc.) incorporated in the instrument. Numerical measurements can be supplemented with coded information as to location and type of test plus supplementary information appropriate to the test being made. This data can also normally be recorded and then downloaded into a PC computer for more detailed analysis while in the field

Storing information in the above fashion reduces field time in data taking. The stored information can

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also be later transferred to a desktop computer that can be used to record, analyze and process the data in accord with record keeping programs that have been developed for the operating company's purpose

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