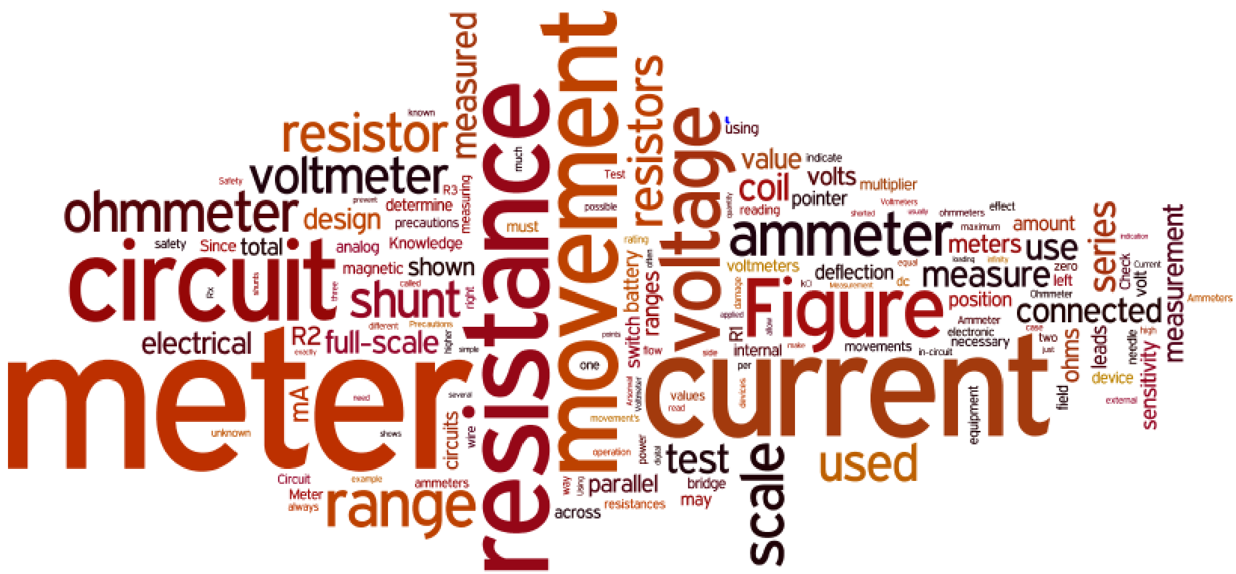
8 Circuit Measurement



Contents

Introduction to Circuit Measurement

In a previous module, the use of the digital multimeter and the analog volt-ohm-meter was covered. Rather than be concerned with how to use meters, this module will acquaint you with the basics of circuit measurement including the design of devices used to measure current, voltage, and resistance. As you progress through your training, you will work with other quantities, such as capacitance, inductance, impedance, true power, and effective power. It is possible to measure any circuit quantity once you are able to select and use the proper circuit measuring device. For this module, however, the focus is on circuit measurement as related to current, voltage, and resistance in dc circuits.

In the discussion and explanation of electrical and electronic circuits, the quantities in the circuit (voltage, current, and resistance) are important. If you can measure the electrical quantities in a circuit, it is easier to understand what is happening in that circuit. This is especially true when you are troubleshooting defective circuits. By measuring the voltage, current, capacitance, inductance, impedance, or resistance in a circuit, you can determine why the circuit is not doing what it is supposed to do. For instance, you can determine why a radio is not receiving or transmitting, why your automobile will not start, or why an electric oven is not working. Measurement will also assist you in determining why an electrical component is not doing its job. The measurement of the electrical parameters quantities in a circuit is an essential part of working on electrical and electronic equipment.

Circuit measurement is used to monitor the operation of an electrical or electronic device, or to determine the reason a device is not operating properly. Since electricity is invisible, you must use some sort of device to determine what is happening in an electrical circuit. Various devices called test equipment are used to measure electrical quantities. The most common types of test equipment use some kind of metering device.

What is a meter?

A **meter** is any device built to accurately detect and display an electrical quantity in a form readable by a human being. Usually this readable form is visual, such as the motion of a pointer on a scale, a series of lights, or a numerical display. In the analysis and testing of circuits, there are meters designed to accurately measure the basic quantities of voltage, current, and resistance. There are many other types of meters as well, but this module primarily covers the design and operation of the basic three.

In-Circuit Meters

Some electrical and electronic devices have meters built into them. These meters are known as **in-circuit meters**. An in-circuit meter is used to monitor the operation of the device in which it is installed. Some examples of in-circuit meters are the generator or alternator meter on some automobiles; the voltage, current, and frequency meters on control panels at electrical power plants; and the electrical power meter that records the amount of electricity used in a building.

It is not practical to install an in-circuit meter in every circuit. However, it is possible to install an in-circuit meter in each critical or representative circuit to monitor the operation of a piece of electrical equipment. A mere glance at or scan of the in-circuit meters on a control board is often sufficient to tell if the equipment is working properly.

While an in-circuit meter will indicate that an electrical device is not functioning properly, the cause of the malfunction is determined by troubleshooting. Troubleshooting is the process of locating and repairing faults in equipment after they have occurred. Since troubleshooting is covered elsewhere in this course, it will be mentioned here only as it applies to circuit measurement.

Out-of-Circuit Meters

In troubleshooting, it is usually necessary to use a meter that can be connected to the electrical or electronic equipment at various testing points and may be moved from one piece of equipment to another. These meters are generally portable and self-contained, and are known as **out-of-circuit meters**.

Out-of-circuit meters are more versatile than in-circuit meters in that the out-of-circuit meter can be used wherever you wish to connect it. Therefore, the out-of-circuit meter is more valuable in locating the cause of a malfunction in a device.

Knowledge Check

1. What are two ways that circuit measurement is used?
2. Why are in-circuit meters used?
3. What is one advantage of an out-of-circuit meter when it is compared with an in-circuit meter?

Basic Meter Movements

The display mechanism of a meter is often referred to as a **movement**, borrowing from its mechanical nature to move a pointer along a scale so that a measured value may be read. Though modern digital meters have no moving parts, the term "movement" may be applied to the same basic device performing the display function. A meter movement converts electrical energy into mechanical energy.

The first meter movements built were known as **galvanometers**, and were usually designed with maximum sensitivity in mind. A very simple galvanometer may be made from a magnetized needle (such as the needle from a magnetic compass) suspended from a string, and positioned within a coil of wire. Current through the wire coil will produce a magnetic field which will deflect the needle from pointing in the direction of earth's magnetic field. Such instruments were useful in their time, but have little place in the modern world except as proof-of-concept and elementary experimental devices. They are highly susceptible to motion of any kind, and to any disturbances in the natural magnetic field of the earth. Now, the term "galvanometer" usually refers to any design of electromagnetic meter movement built for exceptional sensitivity.

Most modern meters are digital in design, meaning that their readable display is in the form of numerical digits. Older designs of meters are mechanical in nature, using some kind of pointer device to show quantity of measurement. These types of meters are often referred to as analog meters. In either case, the principles applied in adapting a display unit to the measurement of voltage, current, or resistance is the same. It is important to realize that digital doesn't necessarily mean better. There are cases where an analog meter is the better choice.

The design of digital movements is beyond the scope of this module, but mechanical, or analog, meter movement designs are very understandable. Most mechanical movements are based on the principle of electromagnetism, which states that electric current through a conductor produces a magnetic field perpendicular to the axis of electron flow. The greater the electric current, the stronger the magnetic field produced. If the magnetic field formed by the conductor is allowed to interact with another magnetic field, a physical force will be generated between the two sources of fields. If one of these sources is free to move with respect to the other, it will do so as current is conducted through the wire, the motion (usually against the resistance of a spring) being proportional to strength of current. The first meter movement we will be looking at operates in this manner.

Permanent-Magnet Moving-Coil Movement

A permanent-magnet moving-coil movement is based upon a fixed permanent magnet and a coil of wire which is able to move, as in Figure 1. When the switch is closed, causing current through the coil, the coil will have a magnetic field which will react to the magnetic field of the permanent magnet. The bottom portion of the coil in Figure 1 will be the north pole of this electromagnet. Since opposite poles attract, the coil will move to the position shown in Figure 2.

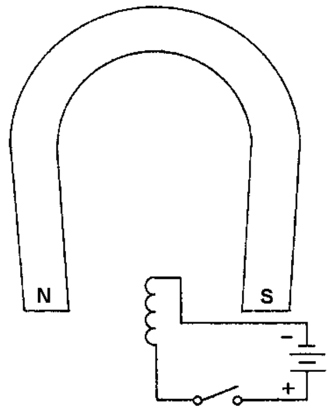


Figure 1: A movable coil in a magnetic field (no current)

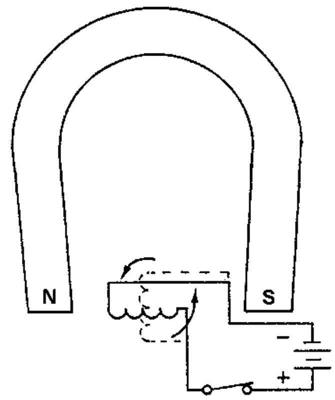


Figure 2: A movable coil in a magnetic field (current).

The coil of wire is wound on an aluminum frame, or bobbin, and the bobbin is supported by jeweled bearings which allow it to move freely. This is shown in Figure 3.

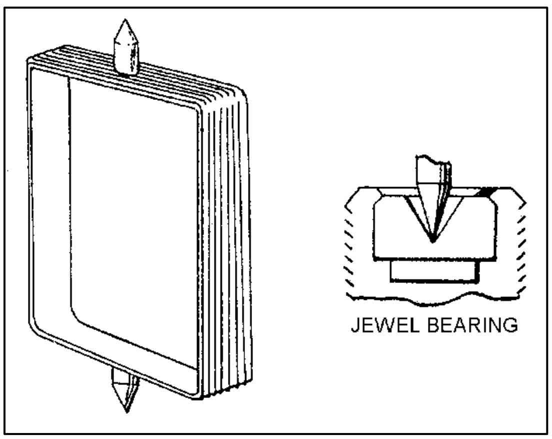


Figure 3: A basic coil arrangement.

To use this permanent-magnet moving-coil device as a meter, two problems must be solved. First, a way must be found to return the coil to its original position when there is no current through the coil. Second, a method is needed to indicate the amount of coil movement.

The first problem is solved by the use of hairsprings attached to each end of the coil as shown in Figure 4. These hairsprings can also be used to make the electrical connections to the coil. With the use of hairsprings, the coil will return to its initial position when there is no current. The springs will also tend to resist the movement of the coil when there is current through the coil. When the attraction between the magnetic fields (from the permanent magnet and the coil) is exactly equal to the force of the hairsprings, the coil will stop moving toward the magnet.

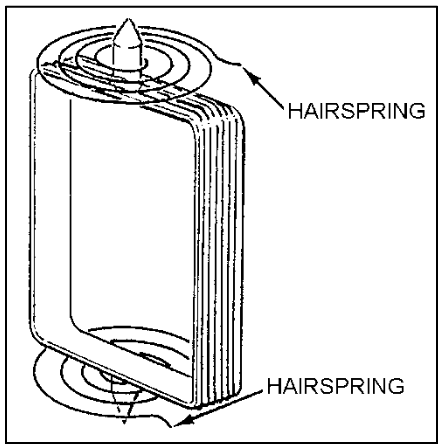


Figure 4: Coil and hairsprings.

As the current through the coil increases, the magnetic field generated around the coil increases. The stronger the magnetic field around the coil, the farther the coil will move. This is a good basis for a meter.

But, how will you know how far the coil moves? If a pointer is attached to the coil and extended out to a scale, the pointer will move as the coil moves, and the scale can be marked to indicate the amount of current through the coil. This is shown in Figure 5.

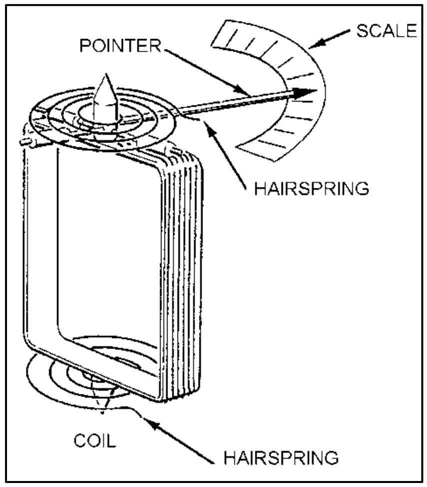


Figure 5: A complete coil.

Two other features are used to increase the accuracy and efficiency of this meter movement. First, an iron core is placed inside the coil to concentrate the magnetic fields. Second, curved pole pieces are attached to the magnet to ensure that the turning force on the coil increases steadily as the current increases.

The meter movement as it appears when fully assembled is shown in Figure 6.

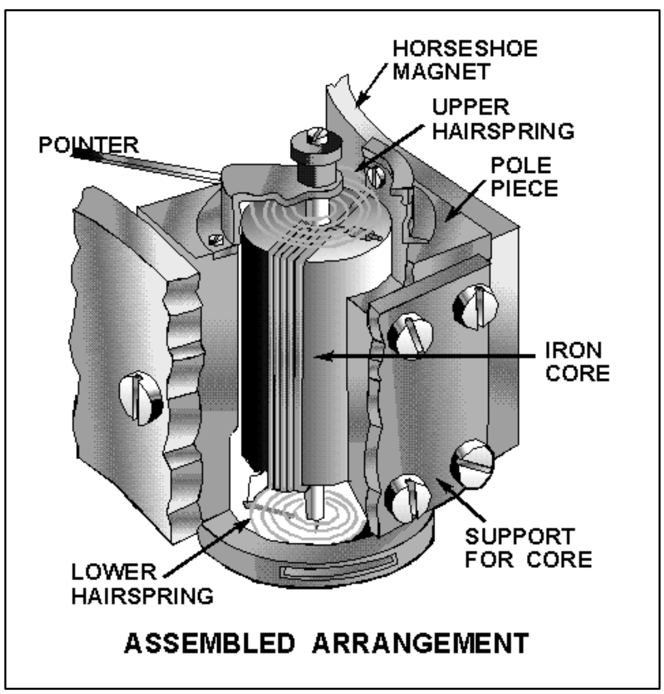


Figure 6: Assembled meter movement.

This permanent-magnet moving-coil meter movement is the basic movement in most measuring instruments. It is commonly called the d'Arsonval movement because it was first employed by Jacques-Arsène d'Arsonval (1851 – 1940) in making electrical measurements. Figure 7 is a view of the d'Arsonval Meter movement used in a meter.

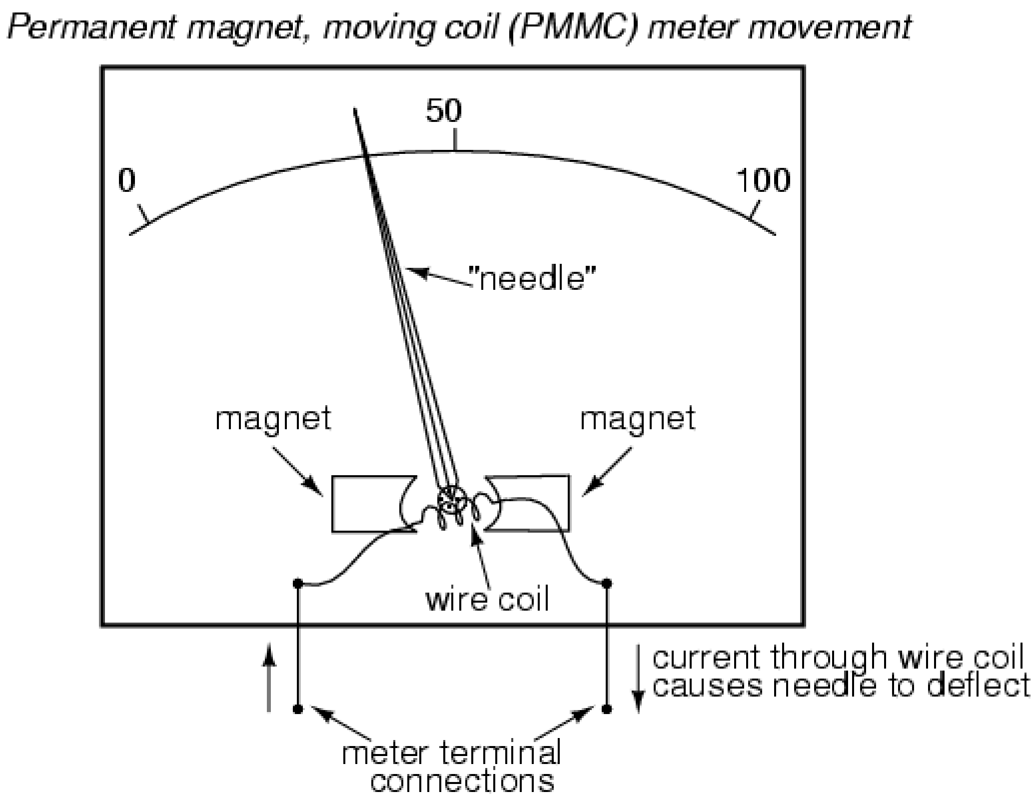


Figure 7: A meter using a d'Arsonval movement.

In Figure 7, the meter movement needle is shown pointing somewhere around 35 percent of full-scale, zero being full to the left of the arc and full-scale being completely to the right of the arc. An increase in measured current will drive the needle to point further to the right and a decrease will cause the needle to drop back down toward its resting point on the left. The arc on the meter display is labeled with numbers to indicate the value of the quantity being measured, whatever that quantity is. In other words, if it takes 50 uA (microamps) of current to drive the needle fully to the right, the scale would have 0 µA written at the very left end and 50 µA at the very right, 25 µA being marked in the middle of the scale. The scale would then be divided into much smaller graduating marks, probably every 5 or 1 µA, to allow for more precise readings from the needle's position.

The meter movement will have a pair of metal connection terminals on the back for current to enter and exit. Most meter movements are polarity-sensitive, one direction of current driving the needle to the right and the other driving it to the left. Some meter movements have a needle that is spring-centered in the middle of the scale sweep instead of to the left, thus enabling measurements of either polarity as shown in Figure 8.

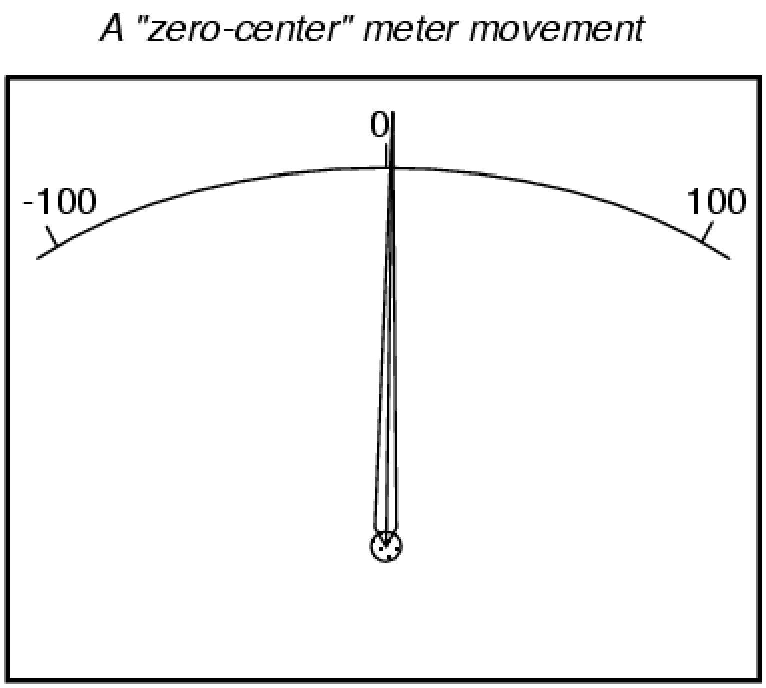


Figure 8: Zero-centered meter movement.

Common polarity-sensitive movements include the D'Arsonval and Weston designs, both PMMC-type instruments. Current in one direction through the wire will produce a clockwise torque on the needle mechanism; while current the other direction will produce a counter-clockwise torque.

Knowledge Check

1. What type of meter movement is the d'Arsonval meter movement?
2. What is the effect of current flow through the coil in a d' Arsonval meter movement?
3. What are three functions of the hairsprings in a d' Arsonval meter movement?

Ammeters

An ammeter is a device that measures current. Since all meter movements have resistance, a resistor will be used to represent a meter in the following explanations. Direct current circuits will be used for simplicity of explanation.

Why Ammeters are Connected in Series

In Figure 9(A), R_1 and R_2 are in series. The total circuit resistance is $R_2 + R_2$ and total circuit current flows through both resistors. However, in Figure 9(B), R_1 and R_2 are in parallel. The total circuit resistance is:

$$\frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

and total circuit current does not flow through either resistor.

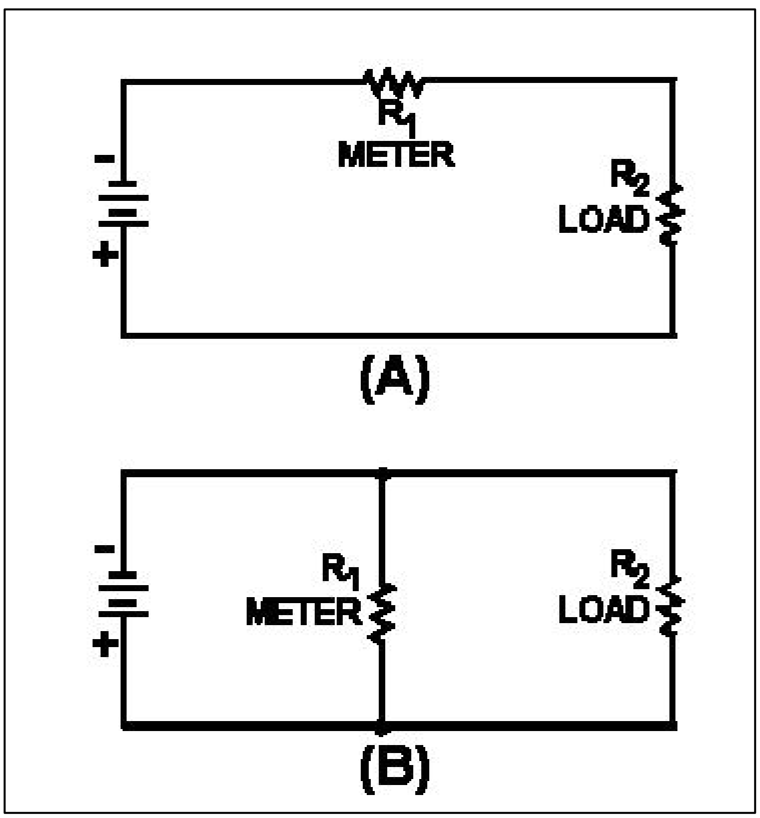


Figure 9: A series and a parallel circuit.

If R_1 represents an ammeter, the only way in which total circuit current will flow through the meter (and thus be measured) is to have the meter (R_1) in series with the circuit load (R_2), as shown in Figure 9(A). In complex electrical circuits, you are not always concerned with total circuit current. You may be interested in the current through a particular component or group of components. In any case, an ammeter is always connected in series with the circuit you wish to test.

Figure 10 shows various circuit arrangements with the ammeter(s) properly connected for measuring current in various portions of the circuit. Connecting an ammeter in parallel would give you not only an incorrect measurement; it would also damage the ammeter, because too much current would pass through the meter.

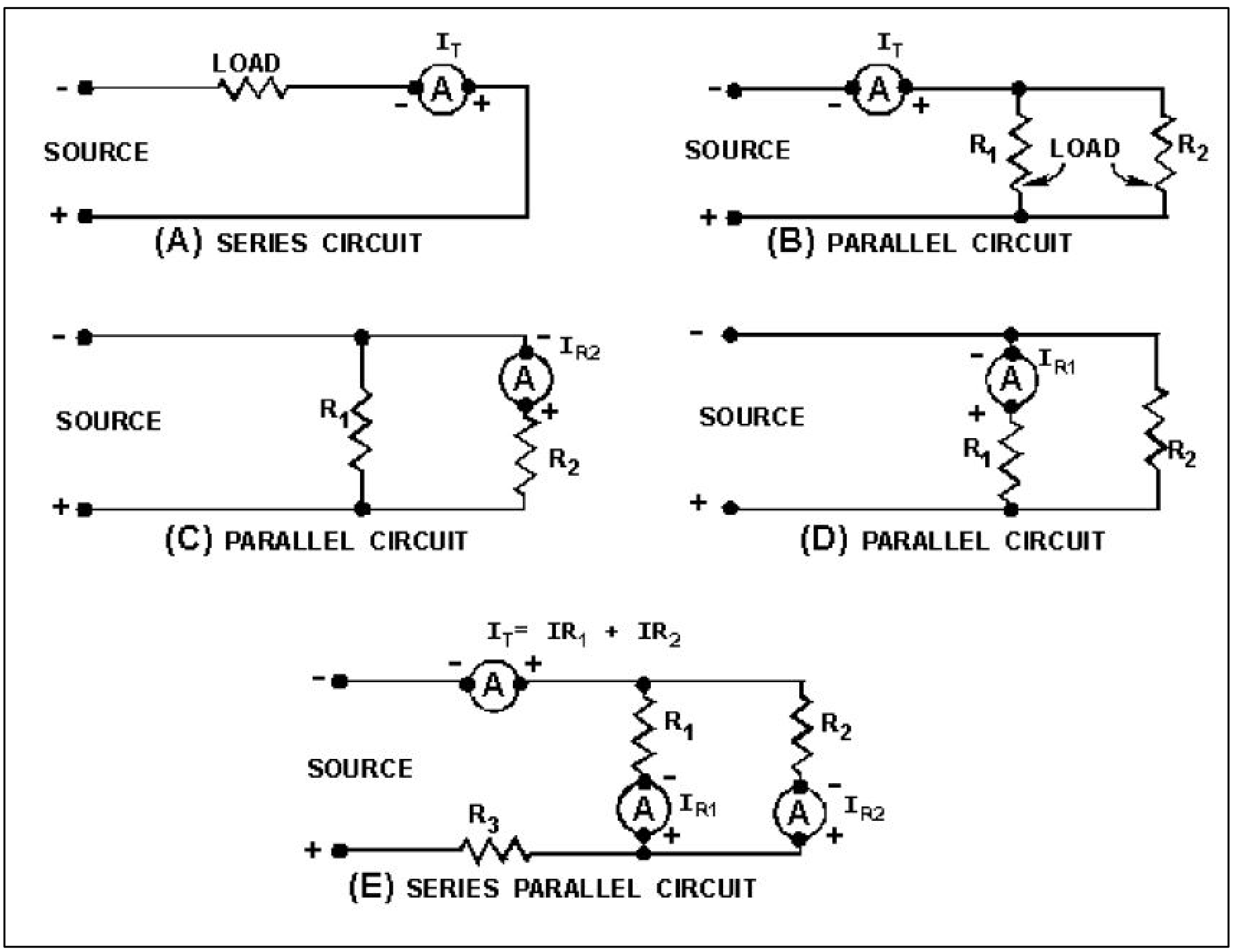


Figure 10: Proper ammeter connections

Ammeter Sensitivity

Ammeter sensitivity is the amount of current necessary to cause full scale deflection (maximum reading) of the ammeter. The smaller the amount of current, the more "sensitive" the ammeter. For example, an ammeter with a maximum current reading of 1 mA would have a sensitivity of 1 mA, and be more sensitive than an ammeter with a maximum reading of 1 ampere and a sensitivity of 1 ampere. Sensitivity can be given for a meter movement, but the term "ammeter sensitivity" usually refers to the entire ammeter and not just the meter movement. An ammeter consists of more than just the meter movement.

Ammeter Ranges

If you have a meter movement with a sensitivity of 1 mA, you can connect it in series with a circuit and measure currents up to 1 mA. But what do you do to measure currents over 1 mA?

To answer this question, look at Figure 11. In Figure 11(A), 10 volts are applied to two resistors in parallel.

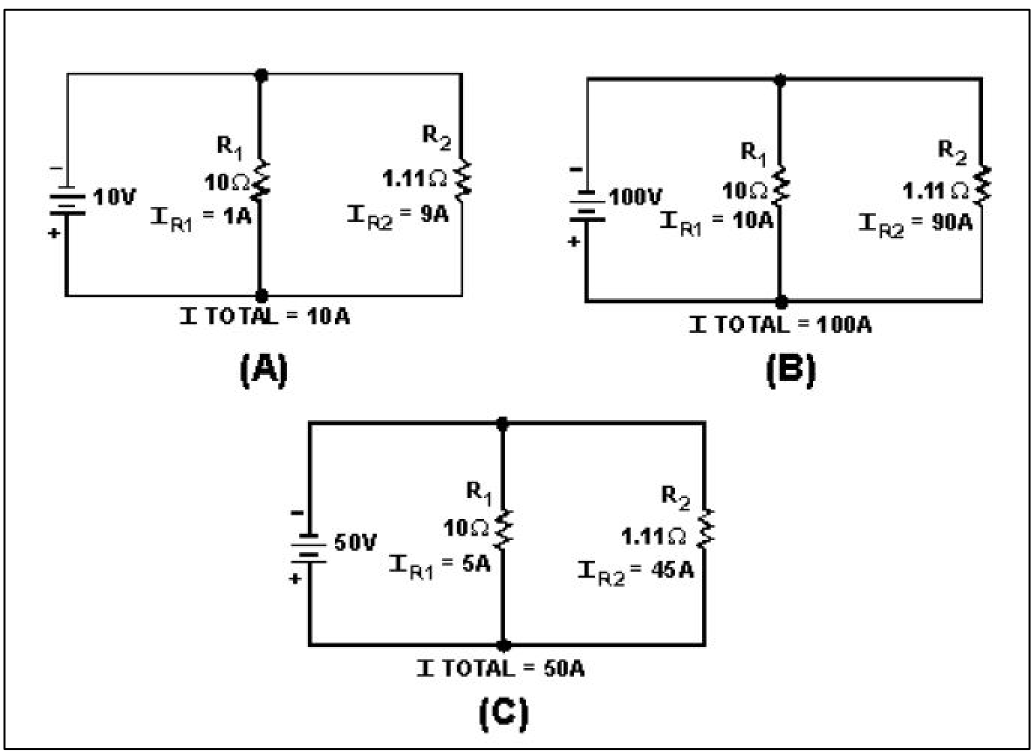


Figure 11: Current in a parallel circuit

In Figure 11(B), the voltage is increased to 100 volts. Now, IR1 equals 10 A and IR2 equals 90 A. In Figure 11(C), the voltage is reduced from 100 volts to 50 volts. In this case, I_{R1} equals 5 A and IR2 equals 45 A. Notice that the relationship (ratio) of I_{R1} and I_{R2} remains the same. I_{R2} is nine times greater than I_{R1} and I_{R1} has one-tenth of the total current.

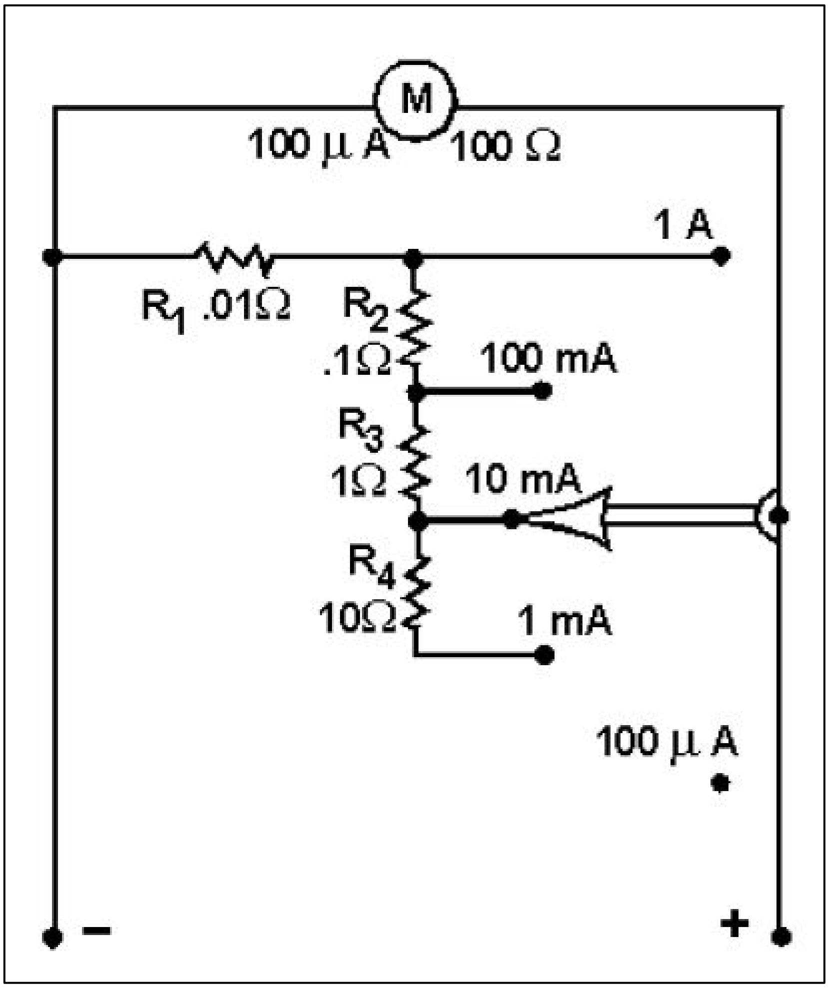


Figure 12: An ammeter with internal shunt resistors.

If R_1 is replaced by a meter movement that has 10 ohms of resistance and a sensitivity of 10 amperes, the reading of the meter will represent one-tenth of the current in the circuit and R_2 will carry nine-tenths of the current. R_2 is a SHUNT resistor because it diverts, or shunts, a portion of the current from the meter movement (R_1). By this method, a 10-ampere meter movement will measure current up to 100 amperes. By adding a second scale to the face of the meter, the current can be read directly.

By adding several shunt resistors in the meter case, with a switch to select the desired resistor, the ammeter will be capable of measuring several different maximum current readings or ranges. It should be noted that digital ammeters have options for auto-ranging or for selecting specific ranges. Analog ammeters, however, require careful attention to sensitivity and ranging to prevent damage to the meter.

Most analog meter movements in use today have sensitivities of from 5 microamperes to 1 milliampere. Figure 12 shows the circuit of an ammeter that uses a meter movement with a sensitivity of 100 microamperes and shunt resistors.

This ammeter has five ranges (100 microamperes; 1, 10, and 100 mA; 1 ampere) selected by a switch. With the switch in the 100 microampere position, all the current being measured will go through the meter movement. None of the current will go through any of the shunt resistors. If the ammeter is switched to the 1 mA position, the current being measured will have parallel paths of the meter movement and all the shunt resistors (R_1 , R_2, R_3, and R_4). Now, only a portion of the current will go through the meter movement and the rest of the current will go through the shunt resistors. When the meter is switched to the 10-milliampere position (as shown in Figure 12), only resistors R_1, R_2, and R_3 shunt the meter. Since the resistance of the shunting resistance is less than with R_4 in the circuit (as was the case in the 1-milliampere position), more current will go through the shunt resistors and less current will go through the meter movement. As the resistance decreases and more current goes through the shunt resistors. As long as the current to be measured does not exceed the range selected, the meter movement will never have more than 100 microamperes of current through it.

Shunt resistors are made with close tolerances. That means if a shunt resistor is selected with a resistance of .01 ohms (as R_1 in Figure 12), the actual resistance of that shunt resistor will not vary from that value by more than 1 percent. Since a shunt resistor is used to protect a meter movement and to allow accurate measurement, it is important that the resistance of the shunt resistor is known very accurately.

Figure 12 represents an analog ammeter with internal shunts. The shunt resistors are inside the meter case and selected by a switch. For limited current ranges (below 50 amperes), internal shunts are most often employed.

For higher current ranges (above 50 amperes) ammeters that use external shunts are used. The external shunt resistor serves the same purpose as the internal shunt resistor. The external shunt is connected in series with the circuit to be measured and in parallel with the ammeter.

This shunts (bypasses) the ammeter so only a portion of the current goes through the meter. Each external shunt will

be marked with the maximum current value that the ammeter will measure when that shunt is used. Figure 12 shows an ammeter that is designed to use external shunts and a d'Arsonval meter movement. Figure 13(A) shows the internal construction of the meter and the way in which the external shunt is connected to the meter and to the circuit being measured. Figure 13(C) shows some typical external shunts.

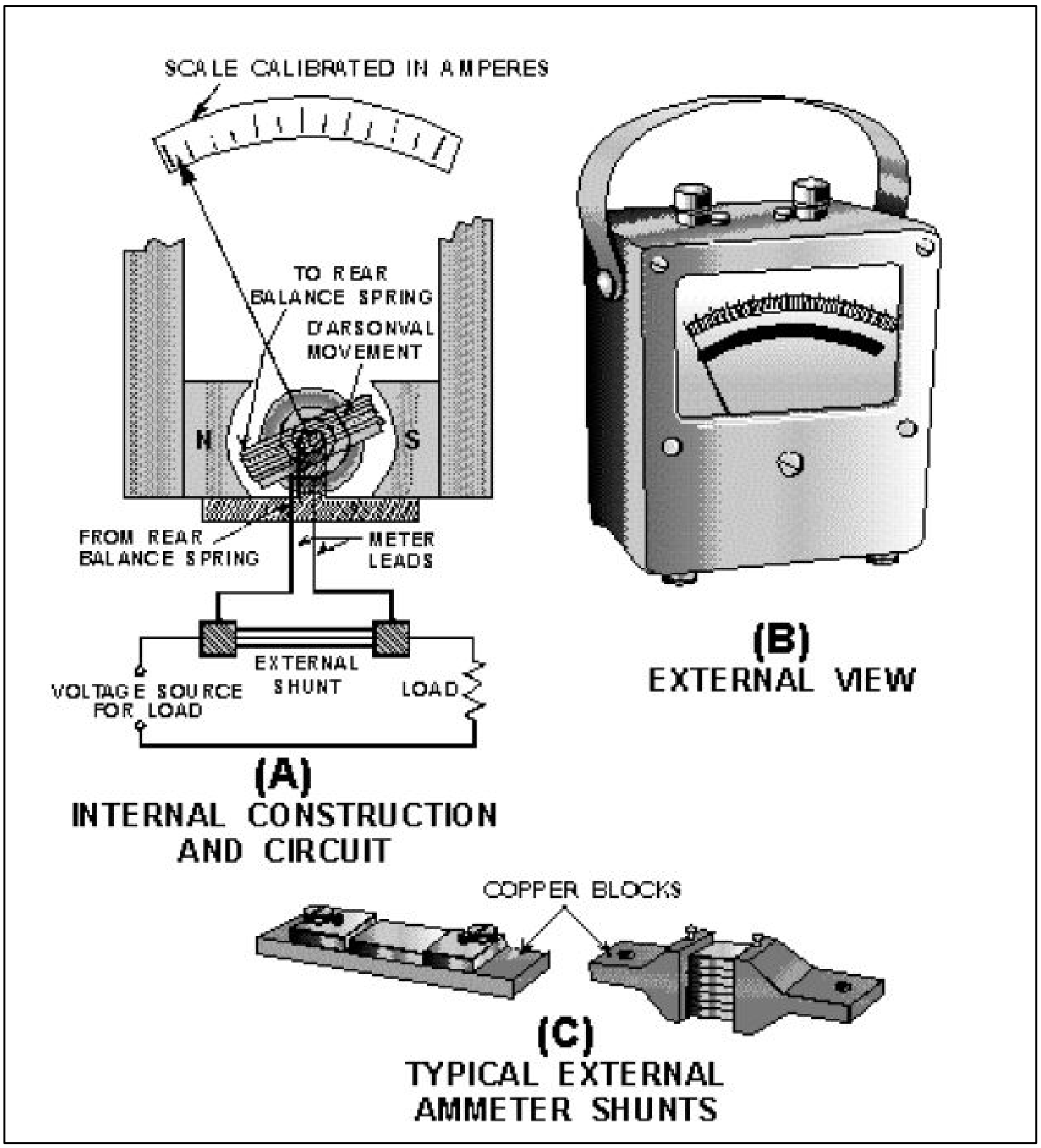


Figure 13: An ammeter employing the d'Arsonval principle and external shunts.

A shunt resistor is nothing more than a resistor in parallel with the meter movement. To measure high currents, very small resistance shunts are used so the majority of the current will go through the shunt. Since the total resistance of a parallel circuit (the meter movement and shunt resistor) is always less than the resistance of the smallest resistor, as an ammeter's range is increased, its resistance decreases.

This is important because the load resistance of high-current circuits is smaller than the load resistance of low-current circuits. To obtain accurate measurements, it is necessary that the ammeter resistance be much less than the load resistance, since the ammeter is connected in series with the load.

Knowledge Check

1. What electrical property does an ammeter measure?
2. How is an ammeter connected to the circuit under test?
3. How does an ammeter affect the circuit being measured?
4. How is the ammeter's effect on the circuit being measured kept to a minimum?
5. What is ammeter sensitivity?
6. What is used to allow an ammeter to measure different ranges?

Other Ammeters

When using standard ammeters that connect in series with the circuit being measured, it might not be practical or possible to redesign the meter for a lower input (lead-to-lead) resistance. However, if we were selecting a value of shunt resistor to place in the circuit for a current measurement based on voltage drop, and we had our choice of a wide range of resistances, it would be best to choose the lowest practical resistance for the application. Any more resistance than necessary and the shunt may impact the circuit adversely by adding excessive resistance in the current path.

One ingenious way to reduce the impact that a current-measuring device has on a circuit is to use the circuit wire as part of the ammeter movement itself. All current-carrying wires produce a magnetic field, the strength of which is in direct proportion to the strength of the current. By building an instrument that measures the strength of that magnetic field, a no-contact ammeter can be produced. Such a meter is able to measure the current through a conductor without even having to make physical contact with the circuit, much less break continuity or insert additional resistance.

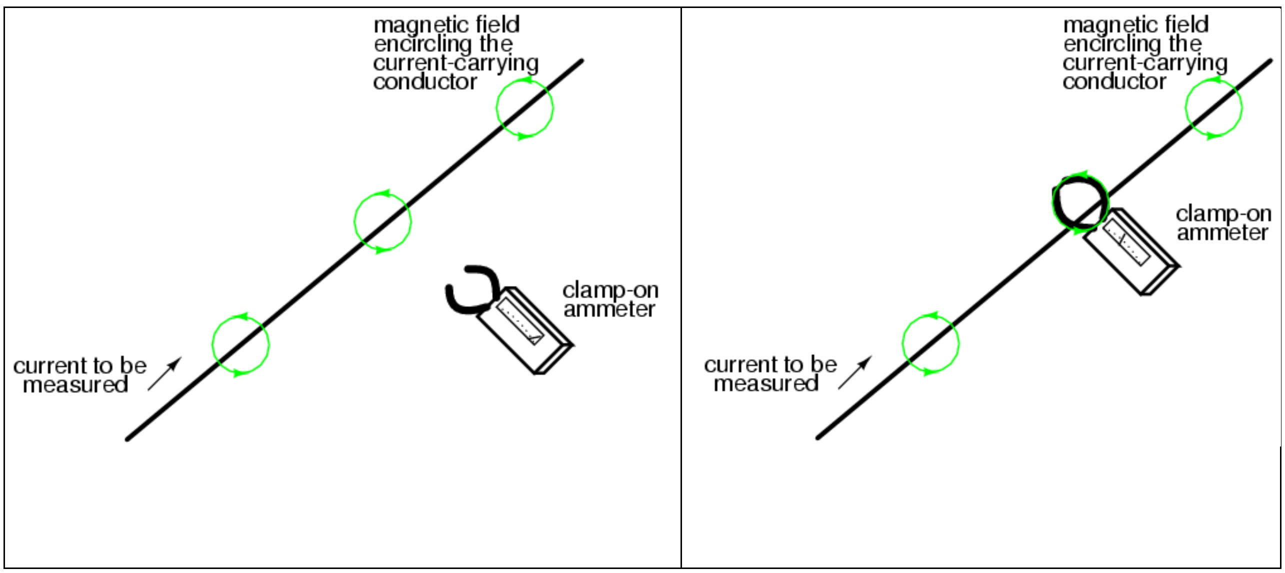


Figure 14: Clamp-on ammeter.

Ammeters of this design are made, and are called "*clamp-on*" meters because they have "jaws" which can be opened and then secured around a circuit wire. Clamp-on ammeters make for quick and safe current measurements, especially on high-power industrial circuits. Because the circuit under test has had no additional resistance inserted into it by a clamp-on meter, there is no error induced in taking a current measurement.

The actual movement mechanism of a clamp-on ammeter is much the same as for an iron-vane instrument, except that there is no internal wire coil to generate the magnetic field. More modern designs of clamp-on ammeters utilize a small magnetic field detector device called a *Hall-effect sensor* to accurately determine field strength. Some clamp-on meters contain electronic amplifier circuitry to generate a small voltage proportional to the current in the wire between the jaws, that small voltage connected to a voltmeter for convenient readout by a technician. Thus, a clamp-on unit can be an accessory device to a voltmeter, for current measurement.

Ammeter Safety Precautions

Even though safety precautions for the various meters have been covered previously, it is easy to become complacent. Reviewing safety precautions will help alert you to any bad habits that may have been acquired over time. When you use an ammeter, certain precautions must be observed to prevent injury to yourself or others and to prevent damage to the ammeter or the equipment on which you are working. The following list contains the minimum precautions to observe when using an ammeter.

- Ammeters must always be connected in series with the circuit under test.
- Always start with the highest range of an ammeter.
- Deenergize and discharge the circuit completely before you connect or disconnect the ammeter.
- In dc ammeters, observe the proper circuit polarity to prevent the meter from being damaged.
- Never use a dc ammeter to measure ac.
- Observe the general safety precautions of electrical and electronic devices.

Knowledge Check

1. Why should you use the highest range of an ammeter for the initial measurement?
2. What range of an ammeter is selected for the final measurement?
3. List the six safety precautions for the use of ammeters.
4. Why will an ammeter be damaged if connected in parallel with the circuit to be measured?

Ammeter design

In ammeter designs, external resistors added to extend the usable range of the movement are connected in parallel with the movement rather than in series as is the case for voltmeters. This is because we want to divide the measured current, not the measured voltage, going to the movement, and because current divider circuits are always formed by parallel resistances.

After extending a meter movement's current-measuring ability, we would have to correspondingly re-label the movement's scale so that it read differently for an extended current range. For example, if we wanted to design an ammeter to have a full-scale range of 5 amps using the same meter movement as before (having an intrinsic full-scale range of only 1 mA), we would have to re-label the movement's scale to read 0 A on the far left and 5 A on the far right, rather than 0 mA to 1 mA as before. Whatever extended range provided by the parallel-connected resistors, we would have to represent graphically on the meter movement face.

Example

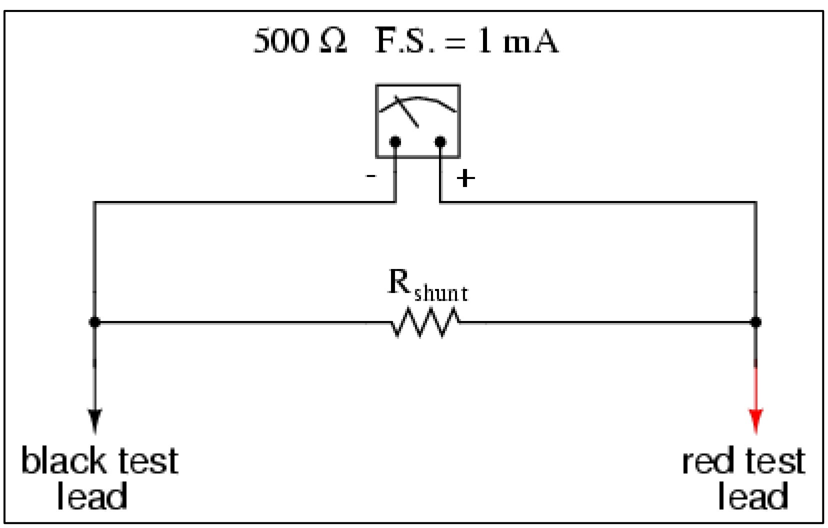


Figure 15: Simple Ammeter Design

Using 5 amps as an extended range for the design shown in Figure 15, determine the amount of parallel resistance necessary to "shunt," or bypass, the majority of current so that only 1 mA will go through the movement with a total current of 5 A.

Solution

Start by noting the given values.

	Movement	R_{shunt}	Total	
E				Volts
I	1m		5	Amps
R	500			Ohms

From our given values of movement current, movement resistance, and total circuit (measured) current, we can determine the voltage across the meter movement:

	Movement	R_{shunt}	Total	
E	**0.5**			Volts
I	1m		5	Amps
R	500			Ohms

Knowing that the circuit formed by the movement and the shunt is of a parallel configuration, we know that the voltage across the movement, shunt, and test leads (total) must be the same:

	Movement	R_{shunt}	Total	
E	0.5	**0.5**	**0.5**	Volts
I	1m		5	Amps
R	500			Ohms

We also know that the current through the shunt must be the difference between the total current (5 amps) and the current through the movement (1 mA), because branch currents add in a parallel configuration:

	Movement	R_{shunt}	Total	
E	0.5	0.5	0.5	Volts
I	1m	**4.999**	5	Amps
R	500			Ohms

Then, using Ohm's Law in the right column, we can determine the necessary shunt resistance:

	Movement	R_{shunt}	Total	
E	0.5	0.5	0.5	Volts
I	1m	4.999	5	Amps
R	500	**100.02m**		Ohms

In real life, the shunt resistor of an ammeter will usually be encased within the protective metal housing of the meter unit, hidden from sight. Note the construction of the ammeter in Figure 16.

Figure 16: Ammeter

This particular ammeter is an automotive unit manufactured by Stewart-Warner. Although the d'Arsonval meter movement itself probably has a full scale rating in the range of milliamps, the meter as a whole has a range of +/- 60 amps. The shunt resistor providing this high current range is enclosed within the metal housing of the meter. Note also with this particular meter that the needle centers at zero amps and can indicate either a "positive" current or a "negative" current. Connected to the battery charging circuit of an automobile, this meter is able to indicate a charging condition (electrons flowing from generator to battery) or a discharging condition (electrons flowing from battery to the rest of the car's loads).

Multiple Range Ammeters

As is the case with multiple-range voltmeters, ammeters can be given more than one usable range by incorporating several shunt resistors switched with a multi-pole switch (Figure 17).

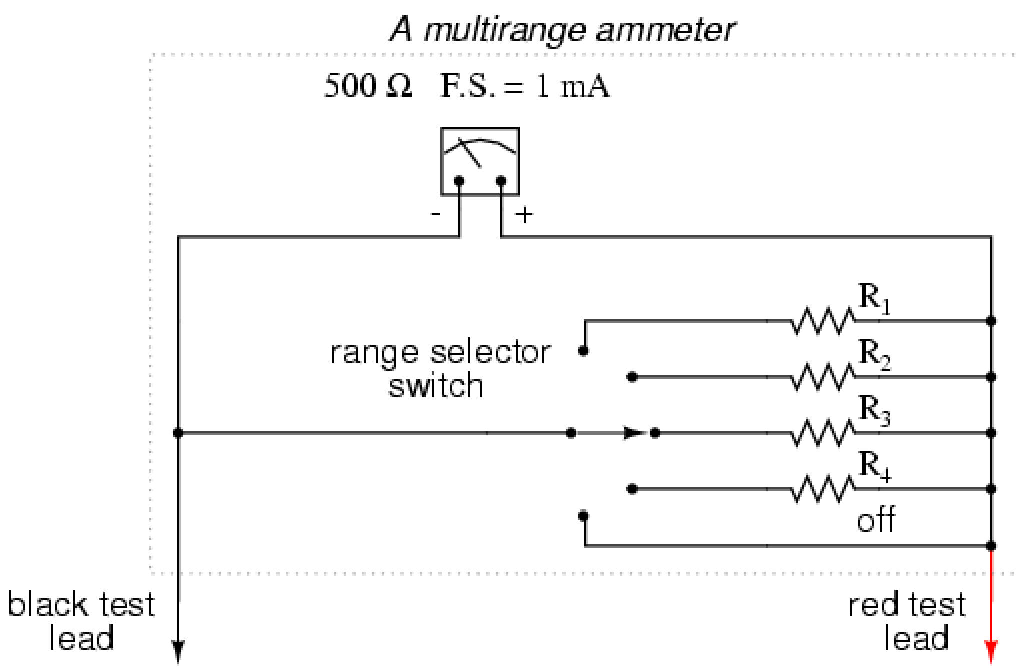


Figure 17: Multi-range ammeter.

Notice that the range resistors are connected through the switch so as to be in parallel with the meter movement, rather than in series as it was in the voltmeter design. The five-position switch makes contact with only one resistor at a time, of course. Each resistor is sized accordingly for a different full-scale range, based on the particular rating of the meter movement (1 mA, 500 Ω).

With such a meter design, each resistor value is determined by the same technique, using a known total current, movement full-scale deflection rating, and movement resistance. For an ammeter with ranges of 100 mA, 1 A, 10 A, and 100 A, the shunt resistances would be as shown in Figure 18:

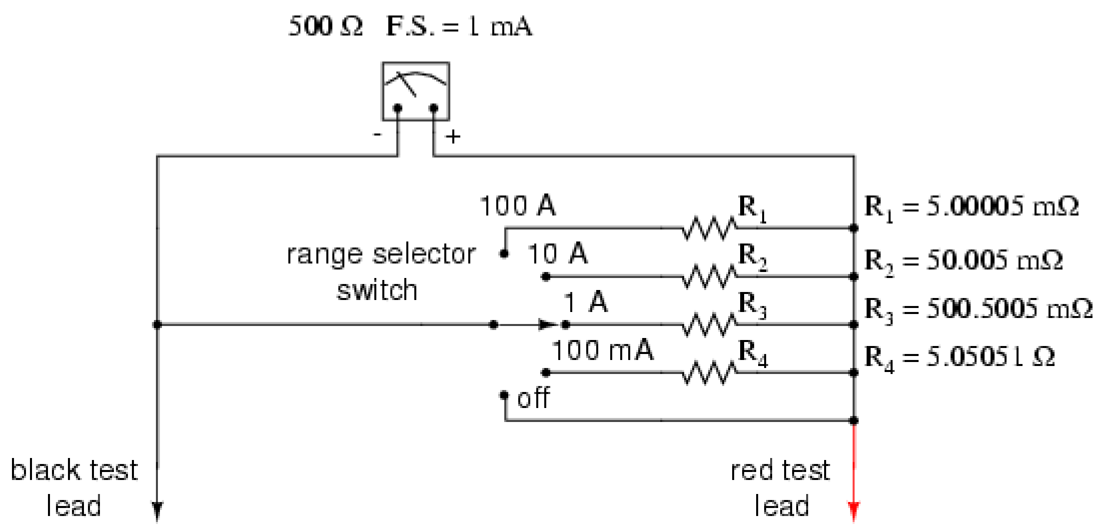


Figure 18: Multi-range ammeter with shunt resistance values.

Notice that these shunt resistor values are very low! 5.00005 mΩ is 5.00005 milli-ohms, or 0.00500005 ohms! To achieve these low resistances, ammeter shunt resistors often have to be custom-made from relatively large-diameter wire or solid pieces of metal.

One thing to be aware of when sizing ammeter shunt resistors is the factor of power dissipation. Unlike the voltmeter, an ammeter's range resistors have to carry large amounts of current. If those shunt resistors are not sized accordingly, they may overheat and suffer damage, or at the very least lose accuracy due to overheating. For the example meter above, the power dissipations at full-scale indication are (the double-squiggly lines represent "approximately equal to" in mathematics):

$$P_{R1} = \frac{E^2}{R_1} = \frac{(0.5\ V)^2}{5.00005\ m\Omega} \approx 50\ W$$

$$P_{R2} = \frac{E^2}{R_2} = \frac{(0.5\ V)^2}{50.005\ m\Omega} \approx 5\ W$$

$$P_{R3} = \frac{E^2}{R_3} = \frac{(0.5\ V)^2}{500.5\ m\Omega} \approx 0.5\ W$$

$$P_{R4} = \frac{E^2}{R_4} = \frac{(0.5\ V)^2}{5.05\ \Omega} \approx 49.5\ mW$$

An 1/8 watt resistor would work just fine for R_4, a 1/2 watt resistor would suffice for R_3 and a 5 watt for R_2 (although resistors tend to maintain their long-term accuracy better if not operated near their rated power dissipation, so you might want to over-rate resistors R_2 and R_3), but precision 50 watt resistors are rare and expensive components indeed. A custom resistor made from metal stock or thick wire may have to be constructed for R_1 to meet both the requirements of low resistance and high power rating.

Other Methods of Measuring Current

Sometimes, shunt resistors are used in conjunction with voltmeters of high input resistance to measure current. In these cases, the current through the voltmeter movement is small enough to be considered negligible, and the shunt resistance can be sized according to how many volts or millivolts of drop will be produced per amp of current.

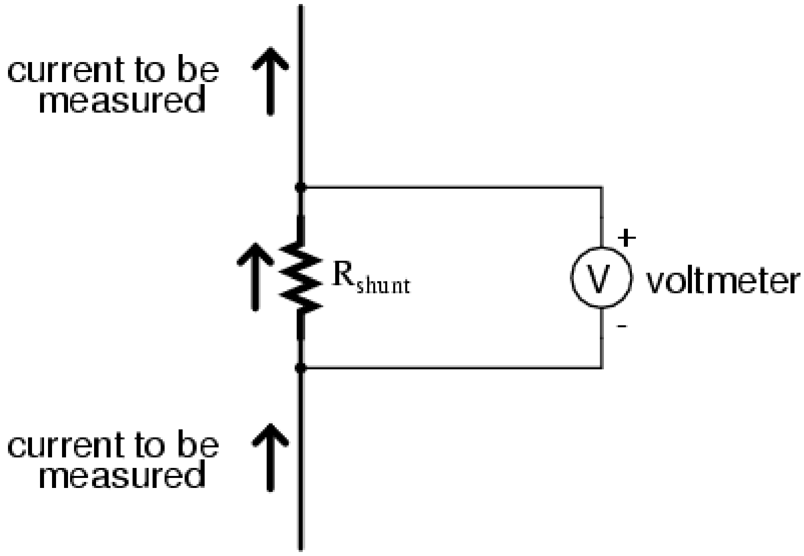


Figure 19: Shunt resistance

If, for example, the shunt resistor Figure 19 were sized at precisely 1 Ω, there would be 1 volt dropped across it for every amp of current through it. The voltmeter indication could then be taken as a direct indication of current through the shunt. For measuring very small currents, higher values of shunt resistance could be used to generate more voltage drop per given unit of current, thus extending the usable range of the (volt)meter down into lower amounts of current. The use of voltmeters in conjunction with low-value shunt resistances for the measurement of current is something commonly seen in industrial applications.

The use of a shunt resistor along with a voltmeter to measure current can be a useful trick for simplifying the task of frequent current measurements in a circuit. Normally, to measure current through a circuit with an ammeter, the circuit would have to be broken (interrupted) and the ammeter inserted between the separated wire ends, as shown below.

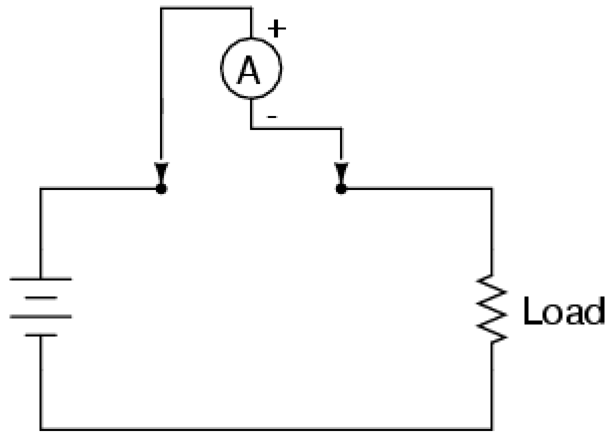


Figure 20: Normal use of an ammeter to measure current.

If we have a circuit where current needs to be measured often, or we would just like to make the process of current measurement more convenient, a shunt resistor could be placed between those points and left there permanently, current readings taken with a voltmeter as needed without interrupting continuity in the circuit (Figure 21).

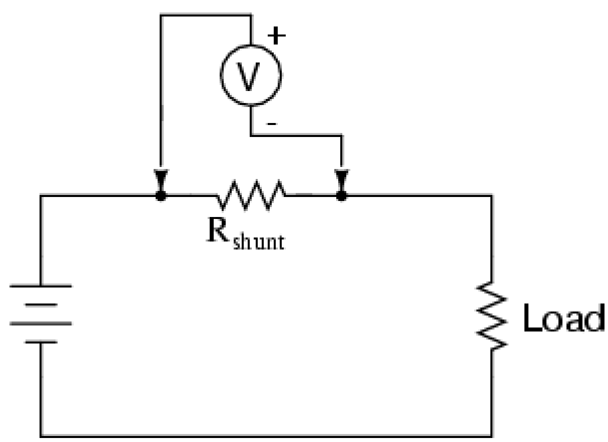


Figure 21: Using a shunt resistor and voltmeter to measure current.

Of course, care must be taken in sizing the shunt resistor low enough so that it doesn't adversely affect the circuit's normal operation, but this is generally not difficult to do.

Voltmeters

All the meter movements discussed so far react to current, and you have been shown how ammeters are constructed from those meter movements. It is often necessary to measure circuit properties other than current. Voltage measurement, for example, is accomplished with a **voltmeter.**

Why voltmeters are connected in parallel

While ammeters are always connected in series, voltmeters are always connected in parallel. Figure 22 (and the following figures) use resistors to represent the voltmeter movement. Since a meter movement can be considered as a resistor, the concepts illustrated are true for voltmeters as well as resistors. For simplicity, dc circuits are shown, but the principles apply to both ac and dc voltmeters.

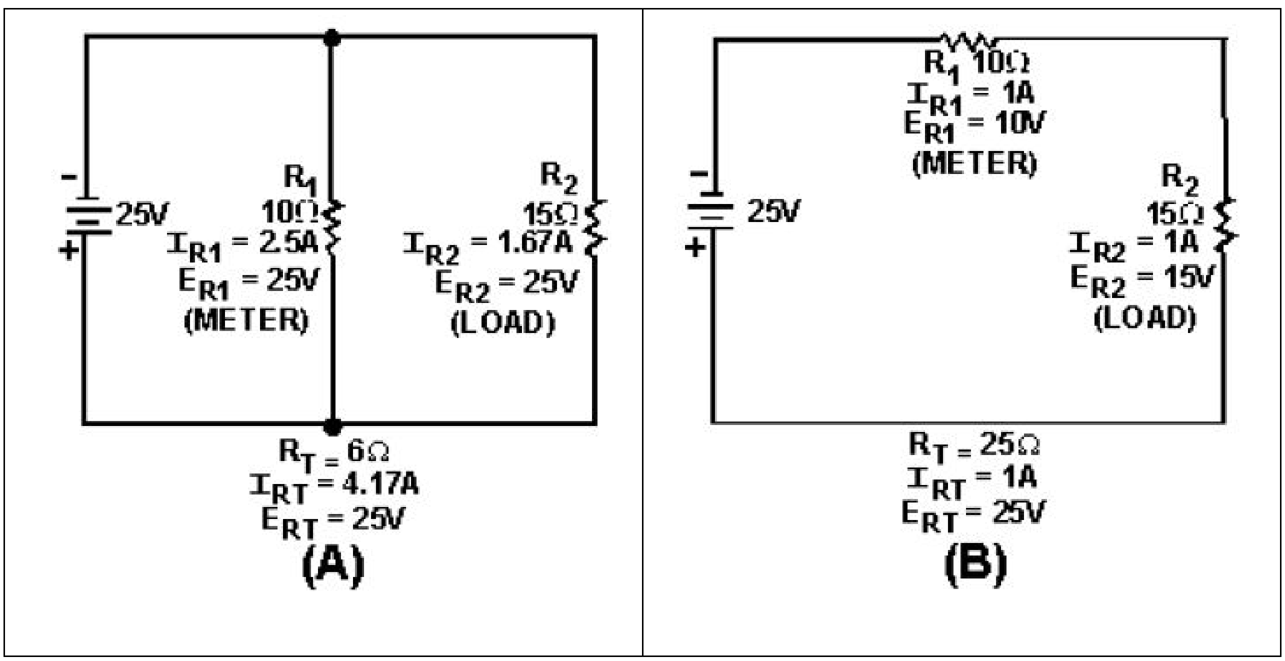


Figure 22: Current and voltage in series and parallel circuits.

Figure 22(A) shows two resistors connected in parallel. Notice that the voltage across both resistors is equal. In Figure 22(B) the same resistors are connected in series. In this case, the voltage across the resistors is not equal. If R_1 represents a voltmeter, the only way in which it can be connected to measure the voltage of R_2 is in parallel with R_2, as in Figure 22(A).

Loading Effect

Every meter impacts the circuit it is measuring to some extent, just as any tire-pressure gauge changes the measured tire pressure slightly as some air is let out to operate the gauge. While some impact is inevitable, it can be minimized through good meter design. Since voltmeters are always connected in parallel with the component or components under test, any current through the voltmeter will contribute to the overall current in the tested circuit, potentially affecting the voltage being measured. A perfect voltmeter has infinite resistance, so that it draws no current from the circuit under test. However, perfect voltmeters only exist in the pages of textbooks, not in real life! This effect on the circuit being measured is called **loading** the circuit. Figure 23 illustrates the loading effect and the way in which the loading effect is kept to a minimum.

In Figure 23(A), a series circuit is shown with R_1 equaling 15 ohms and R_2 equaling 10 ohms. The voltage across R_2 (E_{R2}) equals 10 volts. If a meter (represented by R_3) with a resistance of 10 ohms is connected in parallel with R_2, as in Figure 23(B), the combined resistance of R_2 and R_3 (R_n) is equal to 5 ohms. The voltage across R_2 and R_3 is now 6.25 volts, and that is what the meter will indicate. Notice that the voltage across R_1 and the circuit current have both increased. The addition of the meter (R_3) has loaded the circuit.

In Figure 23(C), the low-resistance meter (R_3) is replaced by a higher resistance meter (R_4) with a resistance of 10 kΩ. The combined resistance of R_2 and R_4 (R_n) is equal to 9.99 ohms. The voltage across R_2 and R_4 is now 9.99 volts, the value that will be indicated on the meter. This is much closer to the voltage across R_2, with no meter (R_3 or R_4) in the circuit. Notice that the voltage across R, and the circuit current in Figure 23(C) are much closer to the values in Figure 23(A). The current (I_{R4}) through the meter (R_4) in Figure 23(C) is also very small compared to the current (I_{R2}) through R_2. In Figure 23(C) the meter (R_4) has much less effect on the circuit and does not load the circuit as much. Therefore, <u>a voltmeter should have a high resistance compared to the circuit being measured, to minimize the loading effect.</u>

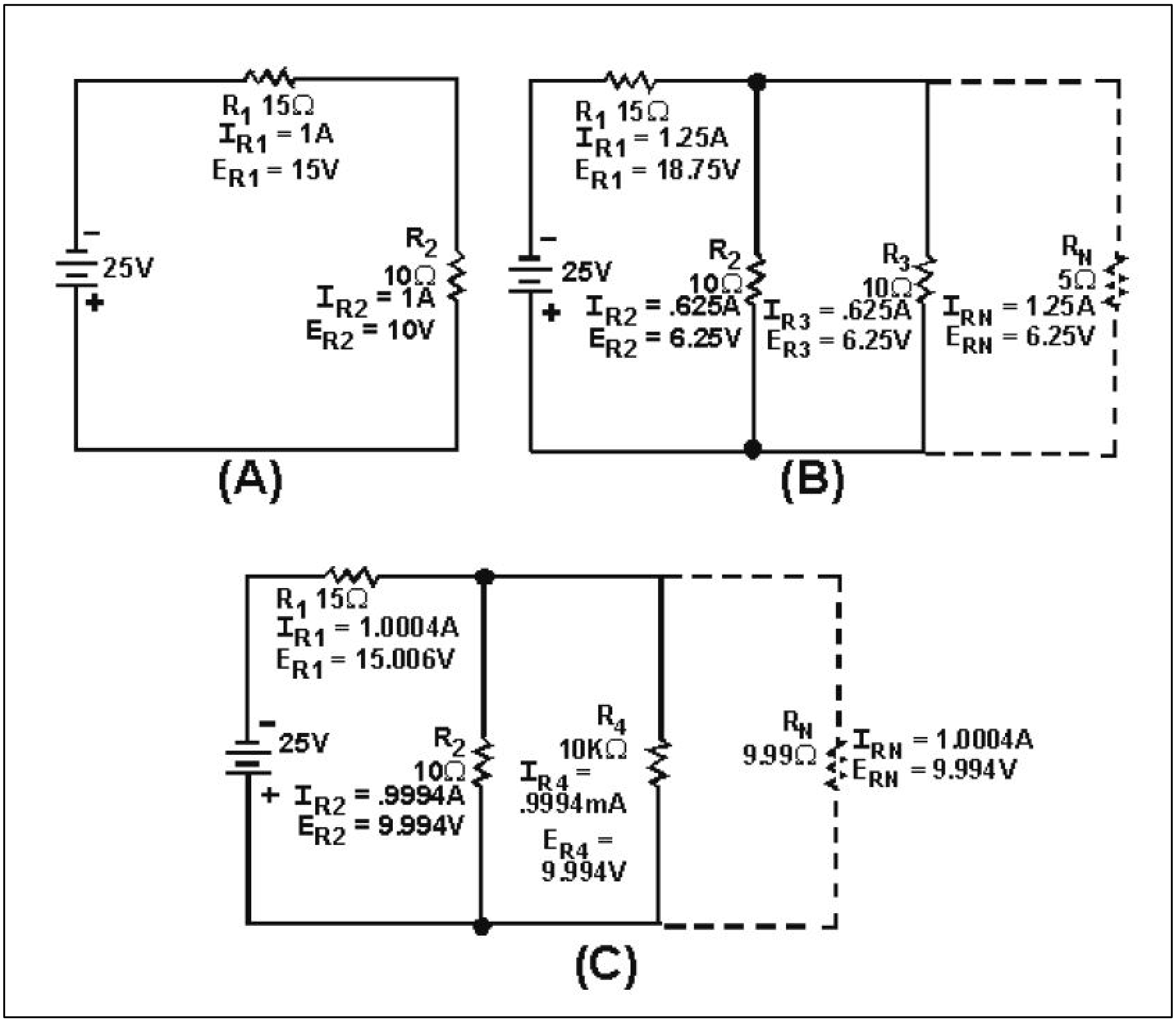


Figure 23: The loading effect.

Knowledge Check

1. Q30. What electrical quantity is measured by a voltmeter?
2. Q31. How is a voltmeter connected to the circuit to be measured?
3. Q32. What is the loading effect of a voltmeter?
4. Q33. How is the loading effect of a voltmeter kept to a minimum?

Sensitivity of Voltmeters

Voltmeter sensitivity is expressed in ohms per volt (Ω/V). It is the resistance of the voltmeter at the full-scale reading in volts. Since the voltmeter's resistance does not change with the position of the pointer, the total resistance of the meter is the sensitivity multiplied by the full-scale voltage reading. The higher the sensitivity of a voltmeter, the higher the voltmeter's resistance. Since high resistance voltmeters have less loading effect on circuits, a high-sensitivity meter will provide a more accurate voltage measurement.

Voltmeters with electromechanical movements are typically given ratings in "ohms per volt" of range to designate the amount of circuit impact created by the current draw of the movement. Because such meters rely on different values of multiplier resistors to give different measurement ranges, their lead-to-lead resistances will change depending on what range they're set to. Digital voltmeters, on the other hand, often exhibit a constant resistance across their test leads regardless of range setting, and as such are usually rated simply in ohms of input resistance, rather than "ohms per volt" sensitivity.

Ohms-per-volt refers to the amount of lead-to-lead resistance for every volt of range setting on the selector switch.

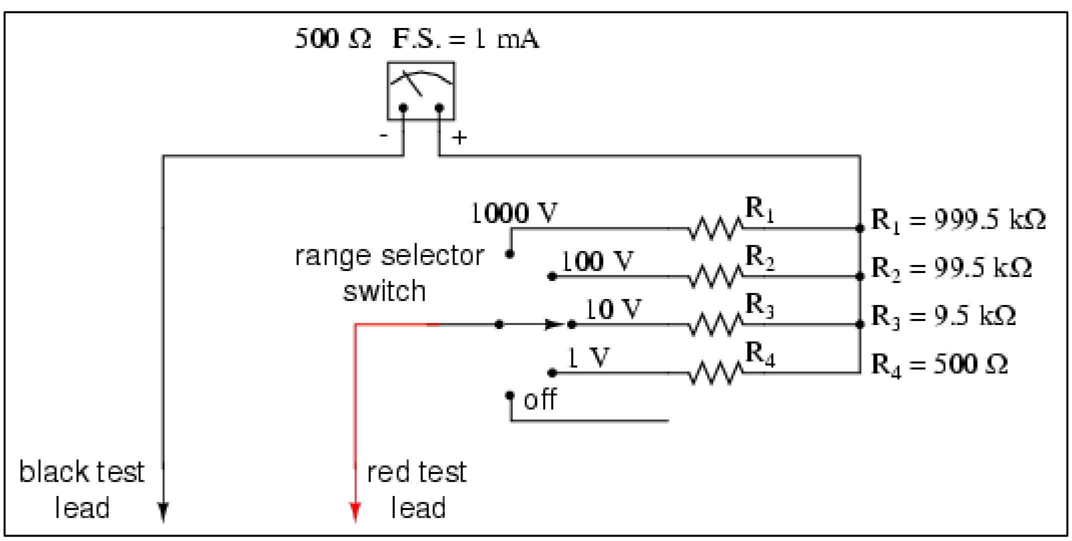


Figure 24: Typical multi-range analog volt meter.

On the 1000 volt scale, the total resistance is 1 MΩ (999.5 kΩ + 500Ω), giving 1,000,000 Ω per 1000 volts of range, or 1000 ohms per volt (1 kΩ/V). This ohms-per-volt "sensitivity" rating remains constant for any range of this meter:

$$\textit{100 volt range} \quad \frac{100\ \text{k}\Omega}{100\ \text{V}} = 1000\ \Omega/\text{V sensitivity}$$

$$\textit{10 volt range} \quad \frac{10\ \text{k}\Omega}{10\ \text{V}} = 1000\ \Omega/\text{V sensitivity}$$

$$\textit{1 volt range} \quad \frac{1\ \text{k}\Omega}{1\ \text{V}} = 1000\ \Omega/\text{V sensitivity}$$

The astute observer will notice that the ohms-per-volt rating of any meter is determined by a single factor: the full-scale current of the movement, in this case 1 mA. "Ohms per volt" is the mathematical reciprocal of "volts per ohm," which is defined by Ohm's Law as current (I=E/R). Consequently, the full-scale *current* of the movement dictates the Ω/volt sensitivity of the meter, regardless of what ranges the designer equips it with through multiplier resistors. In this case, the meter movement's full-scale current rating of 1 mA gives it a voltmeter sensitivity of 1000 Ω/V regardless of how we range it with multiplier resistors.

To minimize the loading of a voltmeter on any circuit, the designer must seek to minimize the current draw of its movement. This can be accomplished by re-designing the movement itself for maximum sensitivity (less current required for full-scale deflection), but the tradeoff here is typically ruggedness: a more sensitive movement tends to be more fragile.

Ranges

Current to deflect full-scale	Resistance	Sensitivity	Voltage full-scale
1mA	100 Ω	1 kΩ/VOLT	0.1 V
50 uA	960 Ω	20 kΩ/VOLT	0.048V V
5 uA	5750 Ω	200 kΩ/VOLT	0.029 V

Table 1: Meter Movement Characteristics

Table 1 shows the figures for most meter movements in use today. Notice that the meter movements shown in Table 1 will indicate 0.029 volts to 0.1 volt at full scale, and the sensitivity ranges from 1000 ohms per volt to 200,000 ohms per volt. The higher sensitivity meters indicate smaller amounts of voltage. Since most voltage measurements involve voltage larger than 0.1 volt, a method must be used to extend the voltage reading.

Figure 25 illustrates the method of increasing the voltage range of a voltmeter.

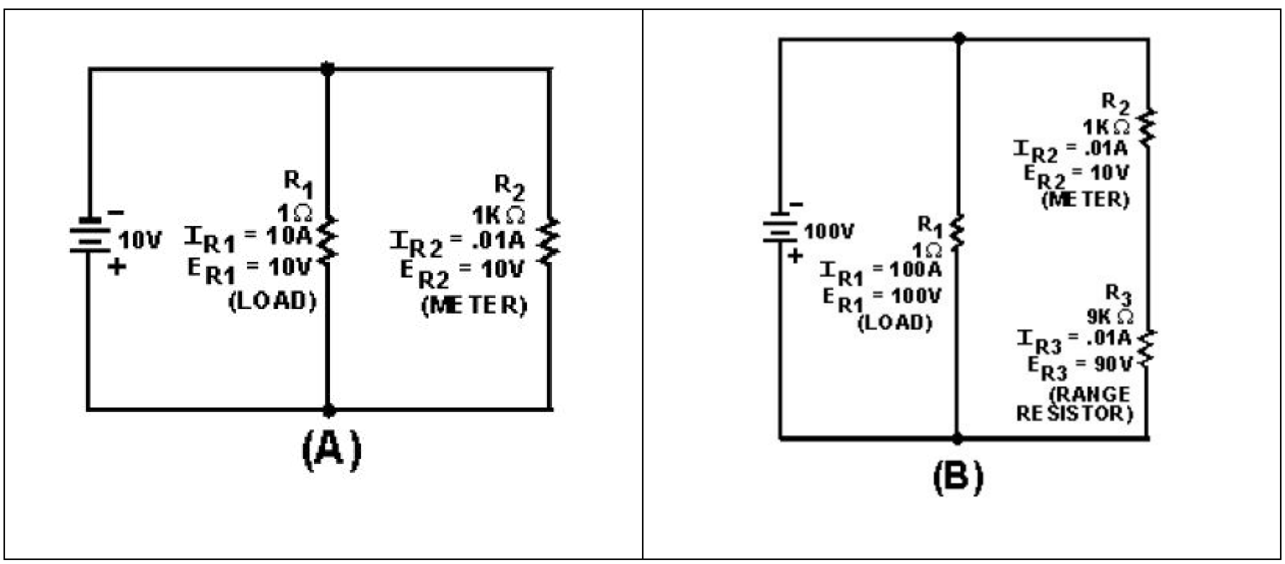


Figure 25: A voltmeter and a range resistor.

In Figure 25(A), a voltmeter with a range of 10 volts and a resistance of 1 kΩ (R_2) is connected in parallel to resistor R_1. The meter has 0.01 ampere of current (full-scale deflection) and indicates 10 volts. In Figure 25(B), the voltage has been increased to 100 volts. This is more than the meter can measure. A 9 kΩ resistor (R_3) is connected in series with the meter (R_2). The meter (R_2) now has 0.01 ampere of current (full-scale deflection). But since R_3 has increased the voltage capability of the meter, the meter indicates 100 volts. R_3 has changed the range of the meter.

Voltmeters can be constructed with several ranges by the use of a switch and internal resistors. Figure 26 shows a voltmeter with a meter movement of 100 ohms and 1 mA full-scale deflection with 5 ranges of voltage through the use of a switch. In this way a voltmeter can be used to measure several different ranges of voltage.

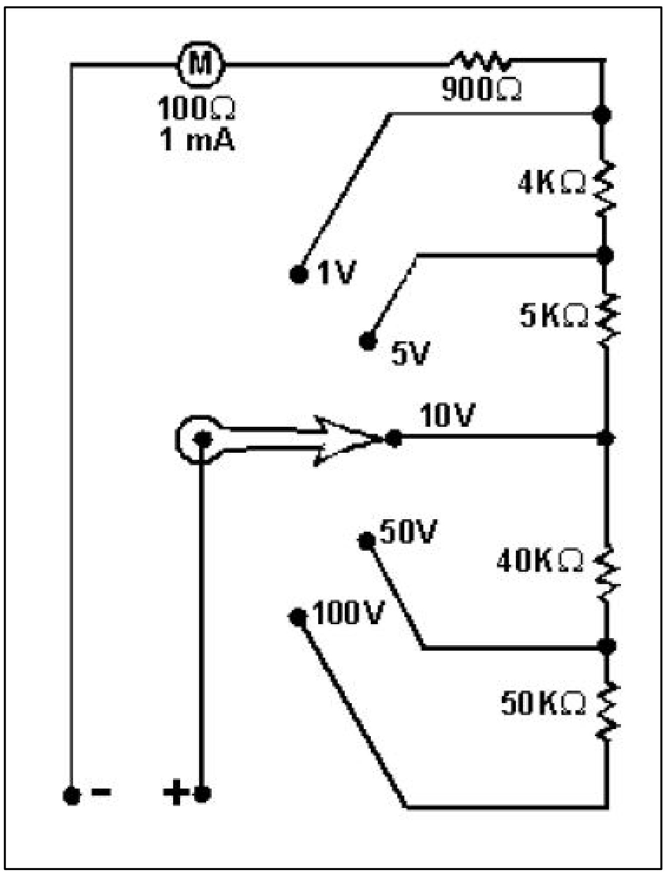


Figure 26: A voltmeter with internal range resistors.

The current through the meter movement is determined by the voltage being measured. If the voltage measured is higher than the range of the voltmeter, excess current will flow through the meter movement and the meter will be damaged. Therefore, you should always start with the highest range of a voltmeter and switch the ranges until a reading is obtained near the center of the scale. Figure 27 illustrates these points.

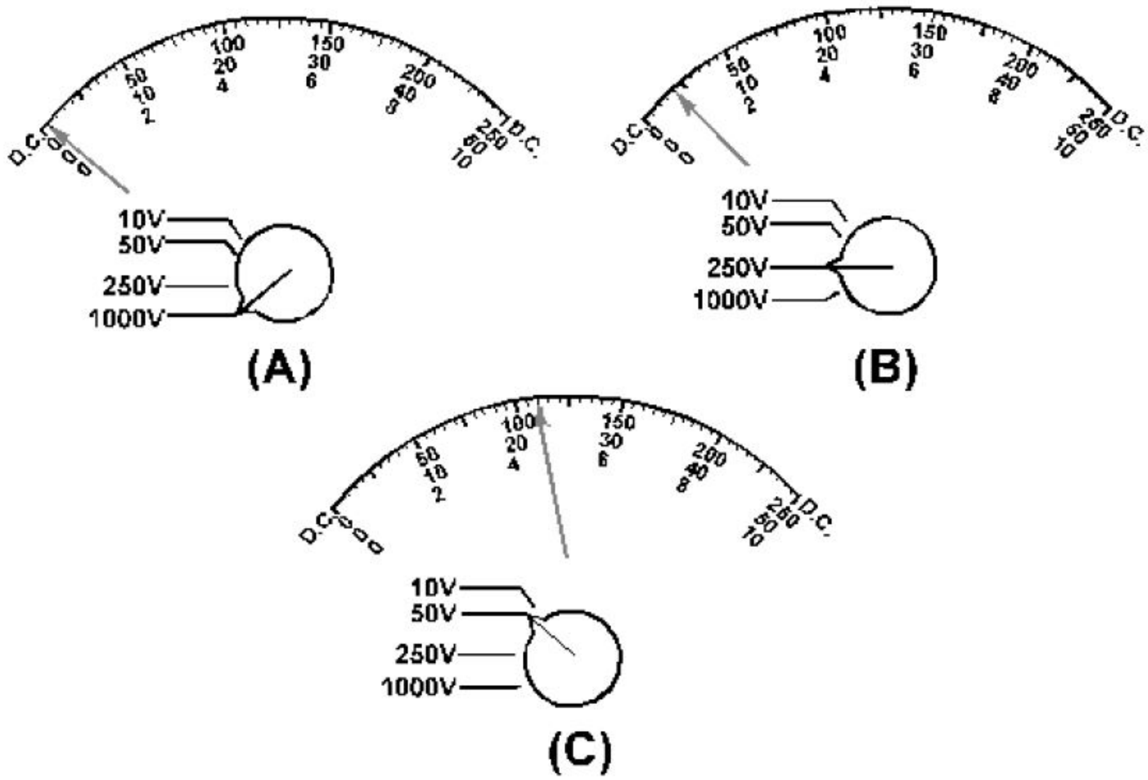


Figure 27: Reading a voltmeter at various ranges.

In Figure 27(A) the meter is in the 1000-volt range. The pointer is barely above the 0 position. It is not possible to accurately read this voltage. In Figure 27(B) the meter is switched to the 250 volt range. From the pointer position it is possible to approximate the voltage as 20 volts. Since this is well below the next range, the meter is switched, as in Figure 27(C). With the meter in the 50-volt range, it is possible to read the voltage as 22 volts. Since this is more than the next range of the meter (10 volts), the meter would not be switched to the next (lower) scale.

Knowledge Check

1. How is it possible to use a current sensitive meter movement to measure voltage?
2. What is voltmeter sensitivity?
3. What method is used to allow a voltmeter to have several ranges?
4. Why should you always use the highest range when connecting a voltmeter to a circuit?

Voltmeter Safety Precautions

Just as with ammeters, voltmeters require safety precautions to prevent injury to personnel and damage to the voltmeter or equipment. The following is a list of the **minimum** safety precautions for using a voltmeter.

- Always connect voltmeters in parallel.
- Always start with the highest range of a voltmeter.
- Deenergize and discharge the circuit completely before connecting or disconnecting the voltmeter.
- In dc voltmeters, observe the proper circuit polarity to prevent damage to the meter.
- Never use a dc voltmeter to measure ac voltage.
- Observe the general safety precautions of electrical and electronic devices.

Knowledge Check

1. List the six safety precautions for the use of voltmeters.

Other Voltmeters

Electrostatic Meter Movements

The final meter movement covered in this chapter is the electrostatic meter movement. The other meter movements you have studied all react to current, the electrostatic meter movement reacts to voltage.

The mechanism is based on the repulsion of like charges on the plates of a capacitor. The electrostatic meter movement is actually a large variable capacitor in which one set of plates is allowed to move. The movement of the plates is opposed by a spring attached to the plates. A pointer that indicates the value of the voltage is attached to these movable plates. As the voltage increases, the plates develop more torque. To develop sufficient torque, the plates must be large and closely spaced. A very high voltage is necessary to provide movement; therefore, electrostatic voltmeters are used only for high voltage measurement.

Voltmeter design

As was stated earlier, most meter movements are sensitive devices. Some d'Arsonval movements have full-scale deflection current ratings as little as 50 µA, with an (internal) wire resistance of less than 1000 Ω. This makes for a voltmeter with a full-scale rating of only 50 millivolts (50 µA X 1000 Ω)! In order to build voltmeters with practical (higher voltage) scales from such sensitive movements, we need to find some way to reduce the measured quantity of voltage down to a level the movement can handle.

Let's start our example problem with a d'Arsonval meter movement having a full-scale deflection rating of 1 mA and a coil resistance of 500 Ω (Figure 28).

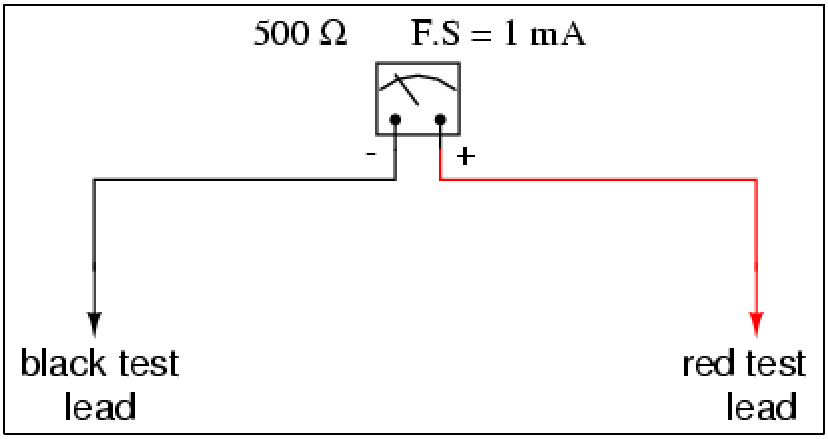


Figure 28: Basic analog voltmeter.

Using Ohm's Law (E=IR), we can determine how much voltage will drive this meter movement directly to full scale:

$E = I R$

$E = (1\ mA)(500\ \Omega)$

$E = 0.5$ volts

If all we wanted was a meter that could measure 1/2 of a volt, the bare meter movement we have here would suffice. But to measure greater levels of voltage, something more is needed. To get an effective voltmeter meter range in excess of 1/2 volt, we'll need to design a circuit allowing only a precise proportion of measured voltage to drop across the meter movement. This will extend the meter movement's range to higher voltages. Correspondingly, we will need to re-label the scale on the meter face to indicate its new measurement range with this proportioning circuit connected.

But how do we create the necessary proportioning circuit? Well, if our intention is to allow this meter movement to measure a greater voltage than it does now, what we need is a voltage divider circuit to proportion the total measured voltage into a lesser fraction across the meter movement's connection points. Knowing that voltage divider circuits are built from series resistances, we can connect a resistor in series with the meter movement (using the movement's own internal resistance as the second resistance in the divider) as shown in Figure 29

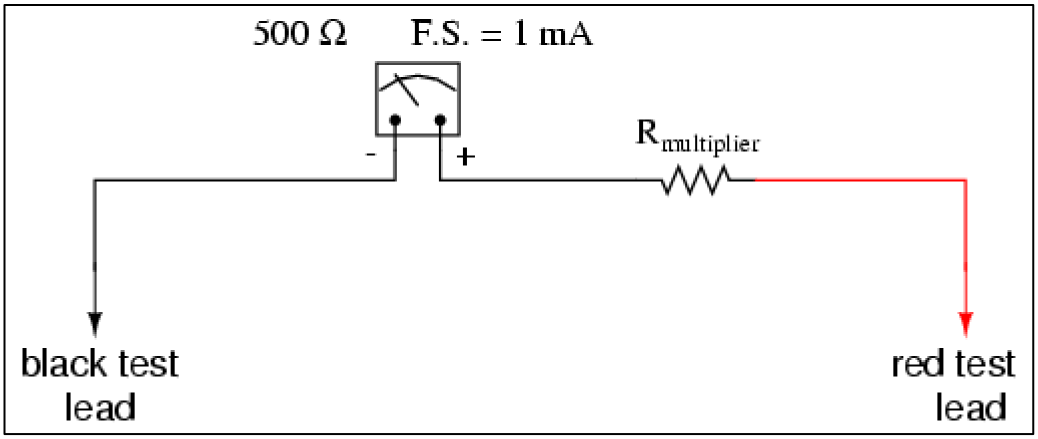


Figure 29: Analog voltmeter with multiplier.

The series resistor is called a "multiplier" resistor because it *multiplies* the working range of the meter movement as it proportionately divides the measured voltage across it. Determining the required multiplier resistance value is an easy task if you're familiar with series circuit analysis.

For example, let's determine the necessary multiplier value to make this 1 mA, 500 Ω movement read exactly full-scale at an applied voltage of 10 volts. To do this, we first need to set up an E/I/R table for the two series components:

	Movement	$R_{multiplier}$	Total	
E				Volts
I				Amps
R				Ohms

Knowing that the movement will be at full-scale with 1 mA of current going through it, and that we want this to happen at an applied (total series circuit) voltage of 10 volts, we can fill in the table as such:

	Movement	$R_{multiplier}$	Total	
E			10	Volts
I	1m	1m	1m	Amps
R	500			Ohms

There are a couple of ways to determine the resistance value of the multiplier. One way is to determine total circuit resistance using Ohm's Law in the "total" column (R=E/I), then subtract the 500 Ω of the movement to arrive at the value for the multiplier:

	Movement	$R_{multiplier}$	Total	
E			10	Volts
I	1m	1m	1m	Amps
R	500	**9.5k**	**10k**	Ohms

Another way to figure the same value of resistance would be to determine voltage drop across the movement at full-scale deflection (E=IR), then subtract that voltage drop from the total to arrive at the voltage across the multiplier resistor. Finally, Ohm's Law could be used again to determine resistance (R=E/I) for the multiplier:

	Movement	$R_{multiplier}$	Total	
E	**0.5**	**9.5**	10	Volts
I	1m	1m	1m	Amps
R	500	9.5k	10k	Ohms

Either way provides the same answer (9.5 kΩ), and one method could be used as verification for the other, to check accuracy of work.

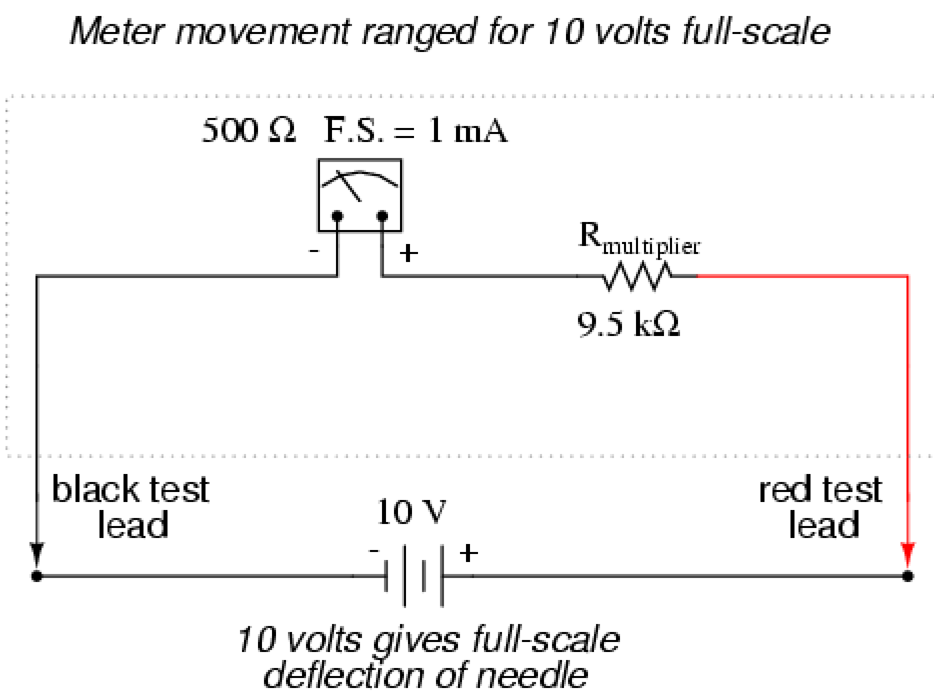


Figure 30: 10 V meter movement range.

With exactly 10 volts applied between the meter test leads (from some battery or precision power supply), there will be exactly 1 mA of current through the meter movement, as restricted by the "multiplier" resistor and the movement's own internal resistance. Exactly 1/2 volt will be dropped across the resistance of the movement's wire coil, and the needle will be pointing precisely at full-scale. Having re-labeled the scale to read from 0 to 10 V (instead of 0 to 1 mA), anyone viewing the scale will interpret its indication as ten volts. Please take note that the meter user does not have to be aware at all that the movement itself is actually measuring just a fraction of that ten volts from the external source. All that matters to the user is that the circuit as a whole functions to accurately display the total, applied voltage.

This is how practical electrical meters are designed and used: a sensitive meter movement is built to operate with as little voltage and current as possible for maximum sensitivity, then it is "fooled" by some sort of divider circuit built of precision resistors so that it indicates full-scale when a much larger voltage or current is impressed on the circuit as a whole. We have examined the design of a simple voltmeter here. Ammeters follow the same general rule, except that parallel-connected "shunt" resistors are used to create a *current divider* circuit as opposed to the series-connected voltage divider "multiplier" resistors used for voltmeter designs.

Generally, it is useful to have multiple ranges established for an electromechanical meter such as this, allowing it to read a broad range of voltages with a single movement mechanism. This is accomplished through the use of a multi-pole switch and several multiplier resistors, each one sized for a particular voltage range (Figure 30).

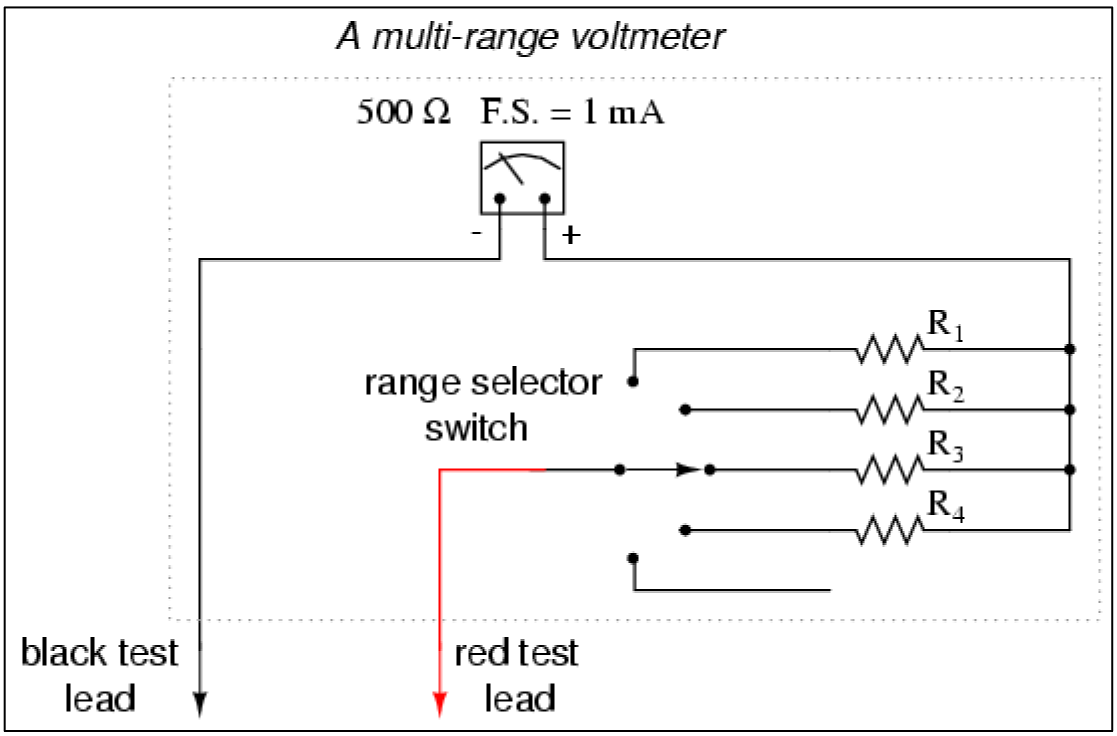


Figure 31: Multi-ranged voltmeter.

The five-position switch makes contact with only one resistor at a time. In the bottom (full clockwise) position, it makes contact with no resistor at all, providing an "off" setting. Each resistor is sized to provide a particular full-scale range for the voltmeter, all based on the particular rating of the meter movement (1 mA, 500 Ω). The end result is a voltmeter with four different full-scale ranges of measurement. Of course, in order to make this work sensibly, the meter movement's scale must be equipped with labels appropriate for each range.

With such a meter design, each resistor value is determined by the same technique, using a known total voltage, movement full-scale deflection rating, and movement resistance. For a voltmeter with ranges of 1 volt, 10 volts, 100 volts, and 1000 volts, the multiplier resistances are shown in Figure 32 below.

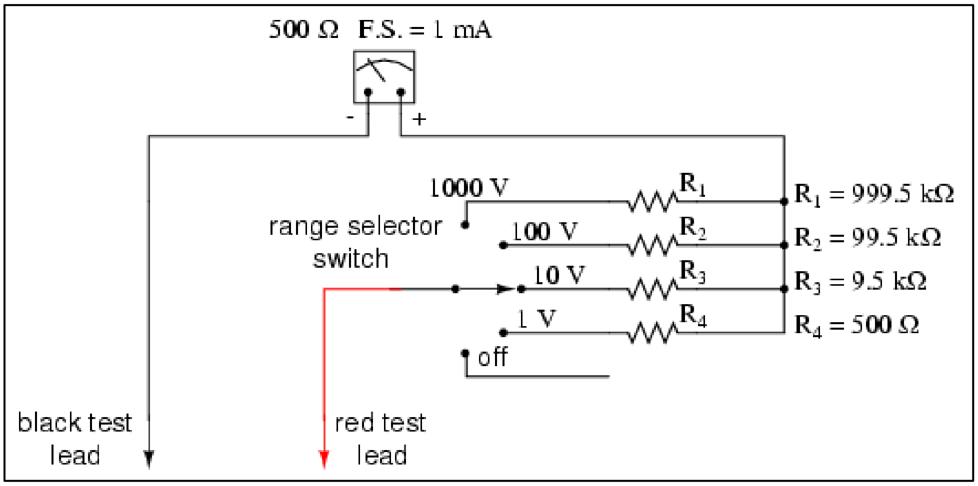


Figure 32: Multi-ranged voltmeter with resistors.

Note the multiplier resistor values used for these ranges, and how odd they are. It is highly unlikely that a 999.5 kΩ precision resistor will ever be found in a parts bin, so voltmeter designers often opt for a variation of the above design which uses more common resistor values as shown in Figure 33.

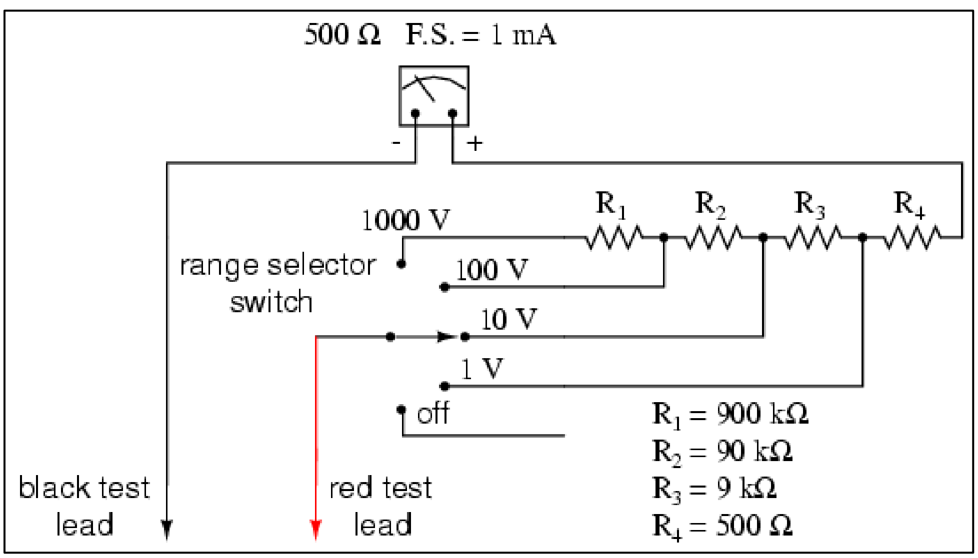


Figure 33: Multi-ranged voltmeter with standard resistors.

With each successively higher voltage range, more multiplier resistors are pressed into service by the selector switch, making their series resistances add for the necessary total. For example, with the range selector switch set to the 1000 volt position, we need a total multiplier resistance value of 999.5 kΩ. With this meter design, that's exactly what we'll get:

$R_{Total} = R_4 + R_3 + R_2 + R_1$

$R_{Total} = 900\ k\Omega + 90\ k\Omega + 9\ k\Omega + 500\ \Omega$

$R_{Total} = 999.5\ k\Omega$

The advantage, of course, is that the individual multiplier resistor values are more common (900k, 90k, 9k) than some of the odd values in the first design (999.5k, 99.5k, 9.5k). From the perspective of the meter user, however, there will be no discernible difference in function.

Ohmmeters

The two instruments most commonly used to check if a circuit is complete (continuity), or to measure the resistance of a circuit or circuit element, are the **ohmmeter** and the **megger** (megohm meter). The ohmmeter is widely used to measure resistance and check the continuity of electrical circuits and devices. Its range usually extends to only a few megohms. The megger is widely used for measuring insulation resistance, such as between a wire and the outer surface of the insulation, and insulation resistance of cables and insulators. The range of a megger may extend to more than 1,000 megohms (1k MΩ), or 1 gigohms (1 GΩ).

The ohmmeter consists of a dc ammeter, with a few added features. The added features are:

- A dc source of potential (usually a 3-volt battery)
- One or more resistors (one of which is variable)

A simple ohmmeter circuit is shown in Figure 34.

The ohmmeter's pointer deflection is controlled by the amount of battery current passing through the meter's moving coil. Before measuring the resistance of an unknown resistor or electrical circuit, the test leads of the ohmmeter are first shorted together, as shown in Figure

34. With the leads shorted, the meter is calibrated for proper operation on the selected range. While the leads are shorted, meter current is maximum and the pointer deflects a maximum amount, somewhere near the zero position on the ohms scale. Because of this current through the meter with the leads shorted, it is necessary to remove the test leads when you are finished using the ohmmeter. If the leads were left connected, they could come in contact with each other and discharge the ohmmeter battery. When the variable resistor (rheostat) is adjusted properly, with the leads shorted, the pointer of the meter will come to rest exactly on the zero position. This is often referred to as "zeroing the meter." This indicates **zero resistance** between the test leads, which, in fact, are shorted together. The zero reading of a series-type ohmmeter is on the right-hand side of the scale, whereas the zero reading for an ammeter or a voltmeter is generally to the left-hand side of the scale. The differences will be discussed later in this module. When the test leads of an ohmmeter are separated, the pointer of the meter will return to the left side of the scale. The interruption of current and the spring tension act on the movable coil assembly, moving the pointer to the left side (infinity or ∞) of the scale.

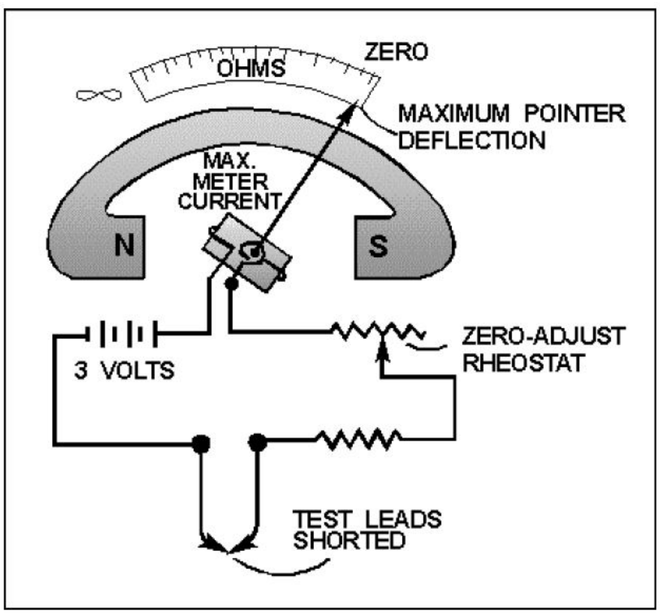


Figure 34: A simple ohmmeter circuit.

Using the Ohmmeter

After the ohmmeter is zeroed, it is ready to be connected in a circuit to measure resistance. A typical circuit and ohmmeter arrangement is shown in Figure 35.

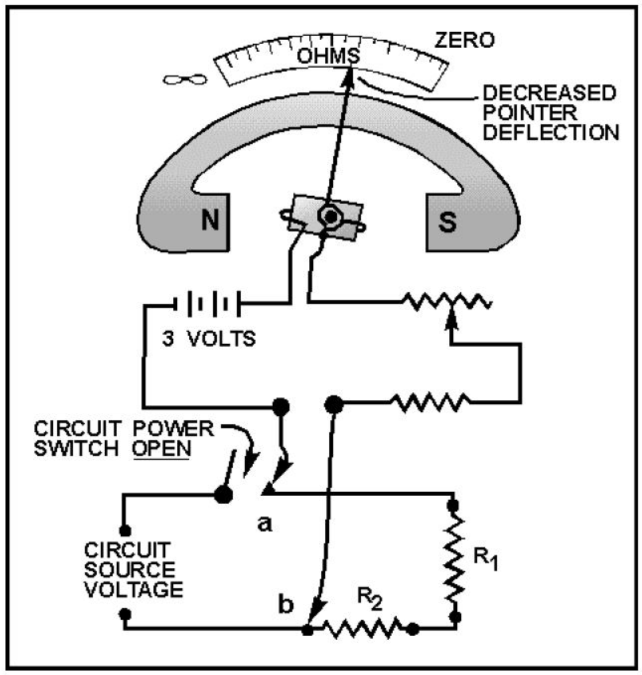


Figure 35: Measuring circuit resistance with an ohmmeter.

The power switch of the circuit to be measured should always be in the **OFF** position. This prevents the source voltage of the circuit from being applied across the meter, which could cause damage to the meter movement.

The test leads of the ohmmeter are connected in series with the circuit to be measured (Figure 35). This causes the current produced by the 3-volt battery of the meter to flow through the circuit being tested. Assume that the meter test leads are connected at points a and b of Figure 35. The amount of current that flows through the meter coil will depend on the total resistance of resistors R_1 and R_2, and the resistance of the meter. Since the meter has been preadjusted (zeroed), the amount of coil movement now depends solely on the resistance of $R_1$and R_2. The inclusion of R_1 and R_2 raises the total series resistance, decreasing the current, and thus decreasing the pointer deflection. The pointer will now come to rest at a scale figure indicating the combined resistance of R_1 and R_2. If R_1 or R_2, or both, were replaced with a resistor(s) having a larger value, the current flow in the moving coil of the meter would be decreased further. The deflection would also be further decreased, and the scale indication would read a still higher circuit resistance. Movement of the moving coil is proportional to the amount of current flow.

Ohmmeter Ranges

The amount of circuit resistance to be measured may vary over a wide range. In some cases it may be only a few ohms, and in others it may be as great as 1,000,000 ohms (1 MΩ). To enable the meter to indicate any value being measured, with the least error, scale multiplication features are used in most analog ohmmeters. As with digital ammeters, digital ohmmeters may have auto-ranging. However, be aware that most hand-held digital multimeters (voltmeter, ammeter, and ohmmeter) may have both auto-ranging and range selection. For example, a typical meter will have four test lead jacks:

- **COMMON**
- R × 1
- R × 10
- R × 100

The jack marked **COMMON** is connected internally through the battery to one side of the moving coil of the ohmmeter. The jacks marked R × 1, R × 10, and R × 100 are connected to three different size resistors located within the ohmmeter. This is shown in Figure 36.

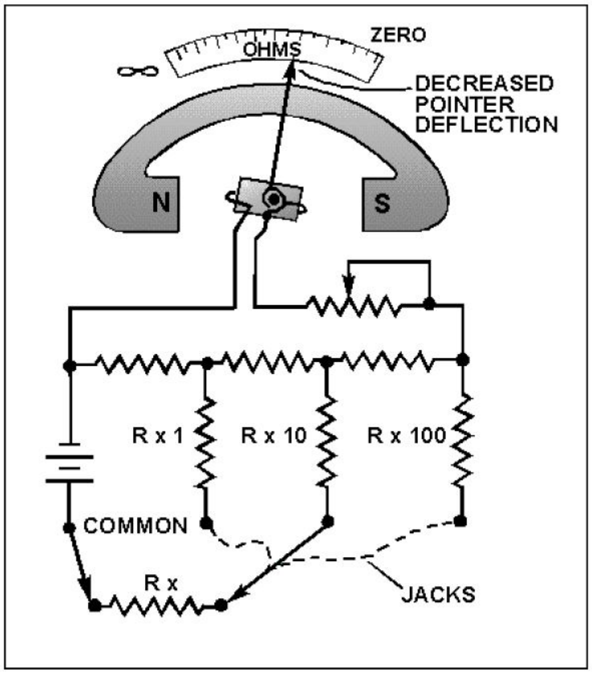


Figure 36: An ohmmeter with multiplication jacks.

Some ohmmeters are equipped with a selector switch for selecting the multiplication scale desired, so only two test lead jacks are necessary. Other meters have a separate jack for each range, as shown in Figure 36. The range to be used in measuring any particular unknown resistance (R_x in Figure 36) depends on the approximate value of the unknown resistance. For instance, assume the ohmmeter in Figure 36 is calibrated in divisions from 0 to 1,000. If R_x is greater than 1,000 ohms, and the R × 1 range is being used, the ohmmeter cannot measure it. This occurs because the combined series resistance of resistor R × 1 and R_x is too great to allow sufficient battery current to flow to deflect the pointer away from infinity (∞). (The concept of infinity as it relates to ohmmeters is discussed in more detail under the section of ohmmeter design.) The test lead would have to be plugged into the next range, R × 10. With this done, assume the pointer deflects to indicate 375 ohms. This would indicate that R_x has 375 ohms × 10, or 3,750 ohms resistance. The change of range caused the deflection because resistor R × 10 has about 1/10 the resistance of resistor R × 1. Thus, selecting the smaller series resistance permitted a battery current of sufficient amount to cause a useful pointer deflection. If the R × 100 range were used to measure the same 3,750-ohm resistor, the pointer would deflect still further, to the 37.5-ohm position. This increased deflection would occur because resistor R × 100 has about 1/10 the resistance of resistor R × 10.

The foregoing circuit arrangement allows the same amount of current to flow through the meter’s moving coil whether the meter measures 10,000 ohms on the R × 10 scale, or 100,000 ohms on the R × 100 scale.

It always takes the same amount of current to deflect the pointer to a certain position on the scale (midscale position for example), regardless of the multiplication factor being used. Since the multiplier resistors are of different values, it is necessary to **always** "zero" adjust the meter for each multiplication fact or selected.

You should select the multiplication factor (range) that will result in the pointer coming to rest as near as possible to the midpoint of the scale. This enables you to read the resistance more accurately, because the scale readings are more easily interpreted at or near midpoint.

Knowledge Check

1. What electrical quantity is measured by an ohmmeter?
2. What other measurement can an ohmmeter make?
3. How is a series-type ohmmeter connected to the circuit being measured?
4. What is used to provide the ohmmeter with several ranges?
5. What area of an ohmmeter scale should be used when measuring circuits?

Shunt Ohmmeter

The ohmmeter described to this point is known as a series ohmmeter, because the resistance to be measured is in series with the internal resistors and the meter movement of the ohmmeter. Another type of ohmmeter is the **SHUNT OHMMETER**. In the shunt ohmmeter, the resistance to be measured shunts, or is in parallel with, the meter movement of the ohmmeter. The most obvious way to tell the difference between the series and shunt ohmmeters is by the scale of the meter. Figure 37 shows the scale of a series ohmmeter and the scale of a shunt ohmmeter.

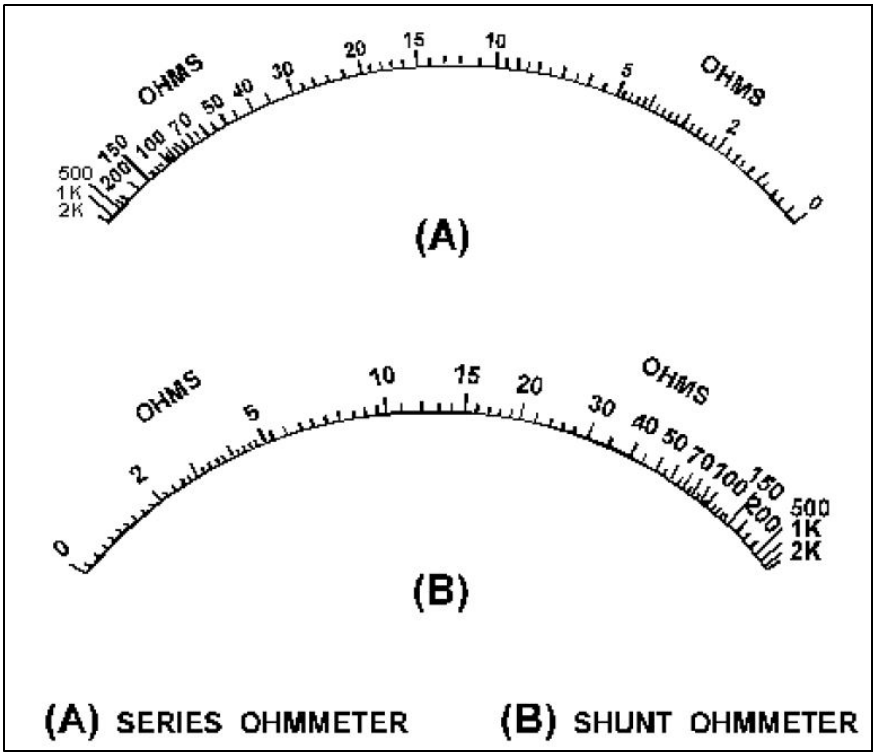


Figure 37: Series and shunt ohmmeter scales.

Figure 37(A) is the scale of a series ohmmeter. Notice "0" is on the right and "∞" is on the left. Figure 37(B) is the scale of a shunt ohmmeter. In the shunt ohmmeter "∞" is on the right and "0" is on the left. A shunt ohmmeter circuit is shown in Figure 37.

In Figure 38, R_1 is a rheostat used to adjust the ∞ reading of the meter (full-scale deflection). R_2, R_3, and R_4 are used to provide the R × 1, R × 10, and R × 100 ranges. Points A and B represent the meter leads. With no resistance connected between points A and B the meter has full-scale current and indicates ∞. If a resistance is connected between points A and B, it shunts some of the current from the meter movement and the meter movement reacts to this lower current. Since the scale of the meter is marked in ohms, the resistance of the shunting resistor (between points A and B) is indicated. Notice that the switch has an **OFF** position, as well as positions for R

× 1, R × 10, and R × 100. This is provided to stop current flow and prevent the battery from being discharged while the meter is not being used.

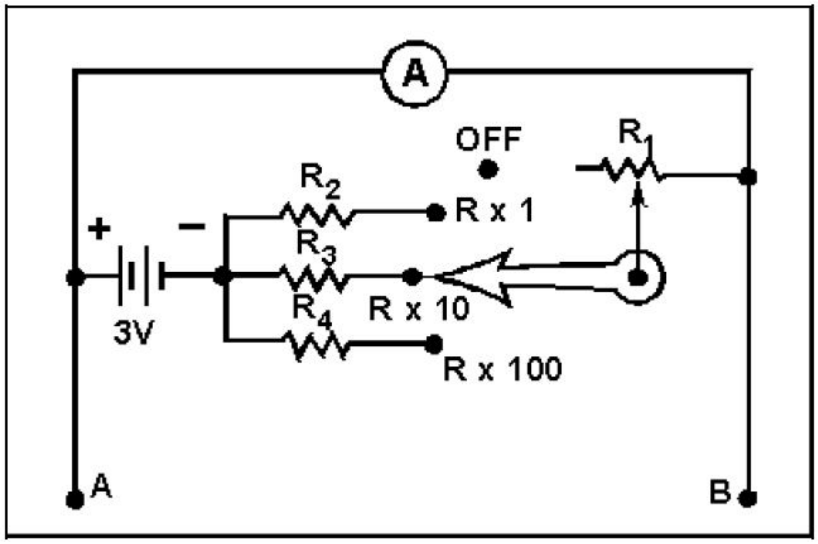


Figure 38: A shunt ohmmeter with internal range resistors.

The shunt ohmmeter is connected to the circuit to be measured in the same way the series ohmmeter is connected. The only difference is that on the shunt ohmmeter the ∞ reading is adjusted, while on the series ohmmeter the 0 reading is adjusted. Shunt ohmmeters are not commonly used because they are limited generally to measuring resistances from 5 ohms to 400 ohms. If you use a shunt ohmmeter, be certain to switch it to the **OFF** position when you are finished using it.

1. Q46. What are the two types of ohmmeters?
2. Q47. What is the most obvious difference between the two types of ohmmeters?
3. Q48. List the four safety precautions observed when using ohmmeters.

Ohmmeter Safety Precautions

The following safety precautions and operating procedures for ohmmeters are the **minimum** necessary to prevent injury and damage.

- Be certain the circuit is deenergized and discharged before connecting an ohmmeter.
- Do not apply power to a circuit while measuring resistance.
- When you are finished using an ohmmeter, switch it to the OFF position if one is provided and remove the leads from the meter.
- Always adjust the ohmmeter for 0 (or ∞ in shunt ohmmeter) after you change ranges before making the resistance measurement.

Knowledge Check

1. List four safety precautions for the use of ohmmeters.

Megohmmeter

An ordinary ohmmeter cannot be used for measuring resistance of multimillions of ohms, such as in conductor insulation. To adequately test for insulation break-down, it is necessary to use a much higher potential than is furnished by the battery of an ohmmeter. This potential is placed between the conductor and the outside surface of the insulation.

An instrument called a **megohmmeter (megger)** is used for these tests. The analog megger is a portable instrument consisting of two primary elements: (1) a hand-driven dc generator which supplies the high voltage for making the measurement, and (2) the instrument portion, which indicates the value of the resistance being measured. A digital megger operates on the same principle, but has an internal power source rather than a hand-driven dc generator.

When a megger is used, the generator voltage is present on the test leads. This voltage could be hazardous to you or to the equipment you are checking. Therefore, **NEVER TOUCH THE TEST LEADS WHILE THE MEGGER IS BEING USED** and isolate the item you are checking from the equipment before using the megger. It is important to follow proper safety procedures when using a megger as improper use can lead to serious injury to yourself or others as well as damage to the equipment.

Ohmmeter design

Though mechanical (or analog) ohmmeter designs are rarely used today their operation is nonetheless intriguing and worthy of study.

The purpose of an ohmmeter is to measure the resistance placed between its leads. This resistance reading is indicated through a mechanical meter movement which operates on electric current. Therefore, the ohmmeter must have an internal source of voltage to create the necessary current to operate the movement. In addition, it must also have appropriate ranging resistors to allow just the right amount of current through the movement at any given resistance.

Figure 39 shows a simple ohmmeter consisting of a meter movement and a battery.

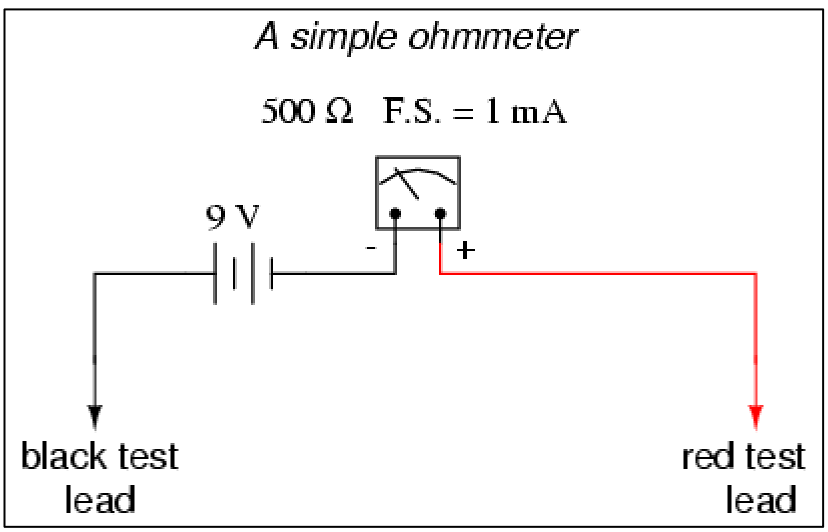


Figure 39: Simple ohmmeter circuit.

When there is infinite resistance (no continuity between test leads), there is zero current through the meter movement, and the needle points toward the far left of the scale. In this regard, the ohmmeter indication is "backwards" because maximum indication (infinity) is on the left of the scale, while voltage and current meters have zero at the left of their scales.

If the test leads of this ohmmeter are directly shorted together, as shown in Figure 40, the meter movement will have a maximum amount of current through it, limited only by the battery voltage and the movement's internal resistance:

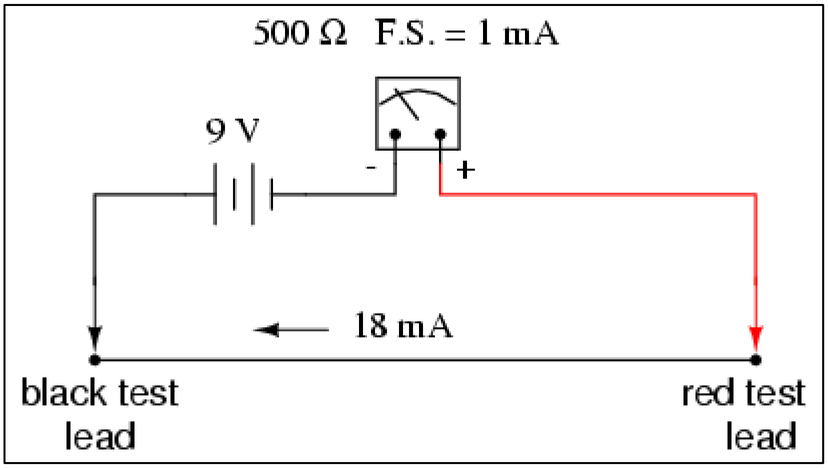


Figure 40: Test leads shorted together.

With 9 volts of battery potential and only 500 Ω of internal movement resistance, our circuit current will be 18 mA, which is far beyond the full-scale rating of the movement. Such an excess of current will likely damage the meter.

Not only that, but having such a condition limits the usefulness of the device. If full left-of-scale on the meter face represents an infinite amount of resistance, then full right-of-scale should represent zero. Currently, our design "pegs" the meter movement hard to the right when zero resistance is attached between the leads. We need a way to make it so that the movement just registers full-scale when the test leads are shorted together. This is accomplished by adding a series resistance to the meter's circuit, as shown in Figure 41.

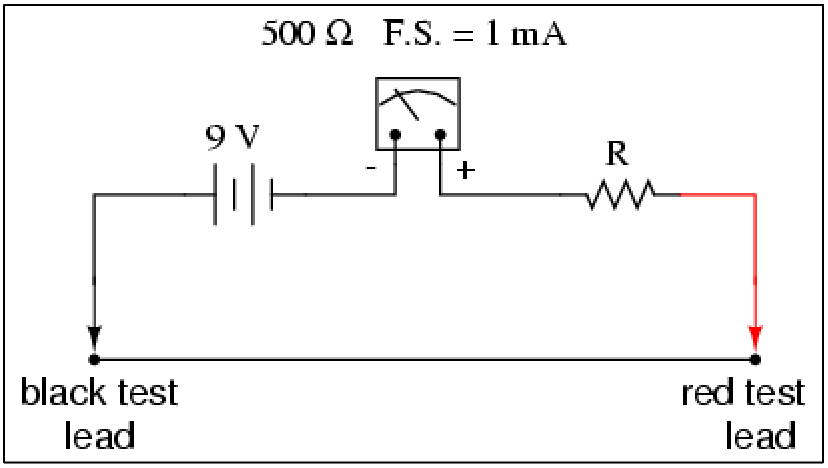


Figure 41: A series resistance added to ohmmeter.

To determine the proper value for R, we calculate the total circuit resistance needed to limit current to 1 mA (full-scale deflection on the movement) with 9 volts of potential from the battery, then subtract the movement's internal resistance from that figure:

$$R_{total} = \frac{E}{1} = \frac{9\text{ V}}{1\text{ mA}}$$

$$R_{total} = 9\text{ k}\Omega$$

$$R = R_{total} - 500\ \Omega = 8.5\text{ k}\Omega$$

Now that the right value for R has been calculated, we're still left with a problem of meter range. On the left side of the scale we have "infinity" and on the right side we have zero. Besides being "backwards" from the scales of voltmeters and ammeters, this scale is strange because it goes from nothing to everything, rather than from nothing to a finite value (such as 10 volts, 1 amp, etc.). One might pause to wonder what middle-of-scale does represent and what figure lies exactly between zero and infinity? Infinity is more than just a *very big* amount: it is an incalculable quantity, larger than any definite number ever could be. If half-scale indication on any other type of meter represents 1/2 of the full-scale range value, then what is half of infinity on an ohmmeter scale?

The answer to this paradox is a **nonlinear scale.** Simply put, the scale of an ohmmeter does not smoothly progress from zero to infinity as the needle sweeps from right to left as it would if it were linear. Rather, the scale starts out expanded at the right-hand side, with the successive resistance values growing closer and closer to each other toward the left side of the scale.

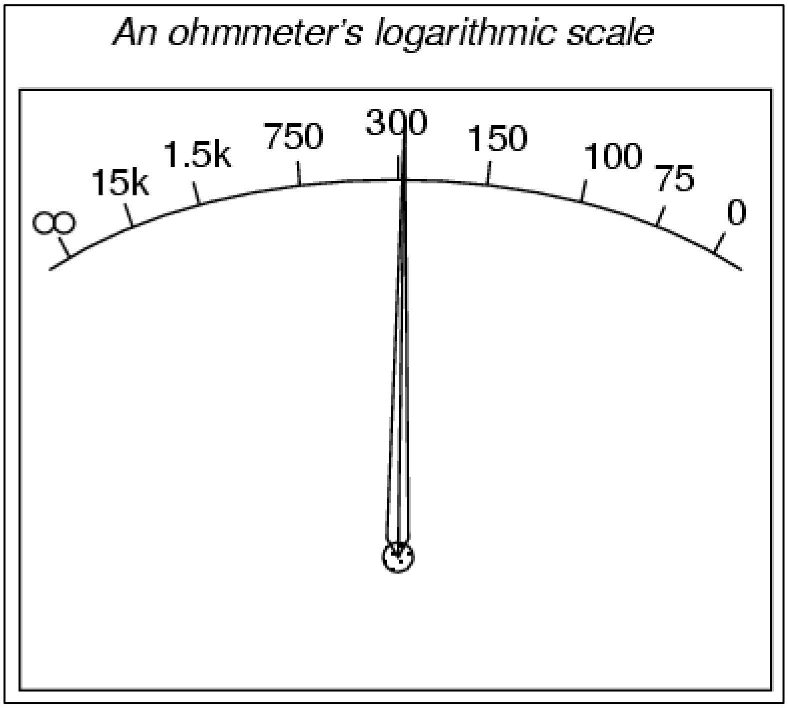


Figure 42: Logarithmic scale of an ohmmeter.

Infinity cannot be approached in a linear fashion, because the scale would *never* get there. With a nonlinear scale, the amount of resistance spanned for any given distance on the scale increases as the scale progresses toward infinity, making infinity an attainable goal.

We still have a question of range for our ohmmeter, though. What value of resistance between the test leads will cause exactly 1/2 scale deflection of the needle? If we know that the movement has a full-scale rating of 1 mA, then 0.5 mA (500 µA) must be the value needed for half-scale deflection. Following our design with the 9 volt battery as a source we get:

$$R_{total} = \frac{E}{1} = \frac{9\ V}{500\ \mu A}$$

$$R_{total} = 18\ k\Omega$$

With an internal movement resistance of 500 Ω and a series range resistor of 8.5 kΩ, this leaves 9 kΩ for an external (lead-to-lead) test resistance at 1/2 scale. In other words, the test resistance giving 1/2 scale deflection in an ohmmeter is equal in value to the (internal) series total resistance of the meter circuit.

Using Ohm's Law a few more times, we can determine the test resistance value for 1/4 and 3/4 scale deflection as well:

1/4 scale deflection (0.25 mA of meter current):

$$R_{total} = \frac{E}{I} = \frac{9\ V}{250\ \mu A}$$

$$R_{total} = 36\ k\Omega$$

$$R_{test} = R_{total} - R_{internal}$$

$$R_{test} = 36\ k\Omega - 9\ k\Omega$$

$$R_{test} = 27\ k\Omega$$

3/4 scale deflection (0.75 mA of meter current):

$$R_{total} = \frac{E}{I} = \frac{9\ V}{750\ \mu A}$$

$$R_{total} = 12\ k\Omega$$

$$R_{test} = R_{total} - R_{internal}$$

$$R_{test} = 12\ k\Omega - 9\ k\Omega$$

$$R_{test} = 3\ k\Omega$$

So, the scale for this ohmmeter looks similar to Figure 43.

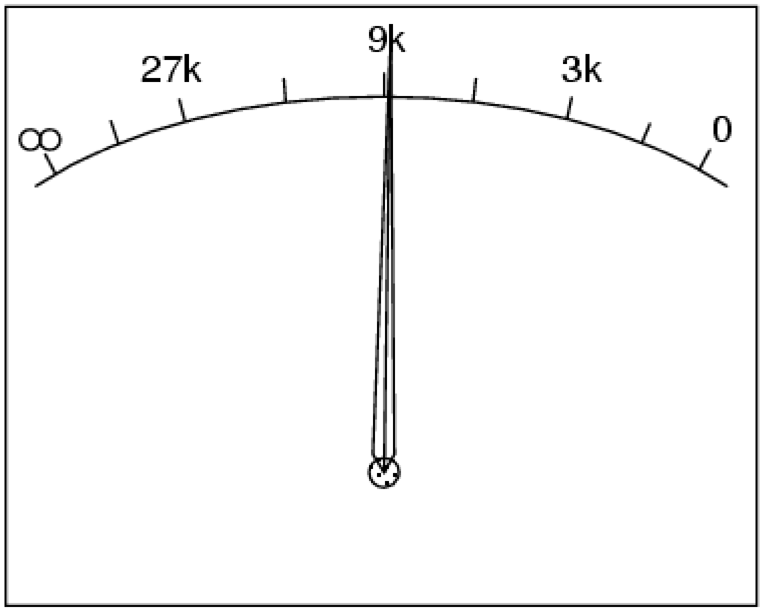


Figure 43: Scale for an ohmmeter.

One major problem with this design is its reliance upon a stable battery voltage for accurate resistance reading. As the battery voltage decreases over time, the ohmmeter scale will lose accuracy. With the series range resistor at a constant value of 8.5 kΩ and the battery voltage decreasing, the meter will no longer deflect full-scale to the right when the test leads are shorted together (0 Ω). Likewise, a test resistance of 9 kΩ will fail to deflect the needle to exactly 1/2 scale with a lesser battery voltage.

There are design techniques used to compensate for varying battery voltage, but they do not completely take care of the problem and are to be considered approximations at best. For this reason, and for the fact of the nonlinear scale, this type of ohmmeter is never considered to be a precision instrument.

Bridge circuits

No text on electrical metering could be called complete without a section on bridge circuits. These ingenious circuits make use of a null-balance meter to compare two voltages, just like the laboratory balance scale compares two weights and indicates when they're equal. Unlike the "potentiometer" circuit used to simply measure an unknown voltage, bridge circuits can be used to measure all kinds of electrical values, not the least of which being resistance.

The standard bridge circuit, often called a *Wheatstone bridge*, looks something like this:

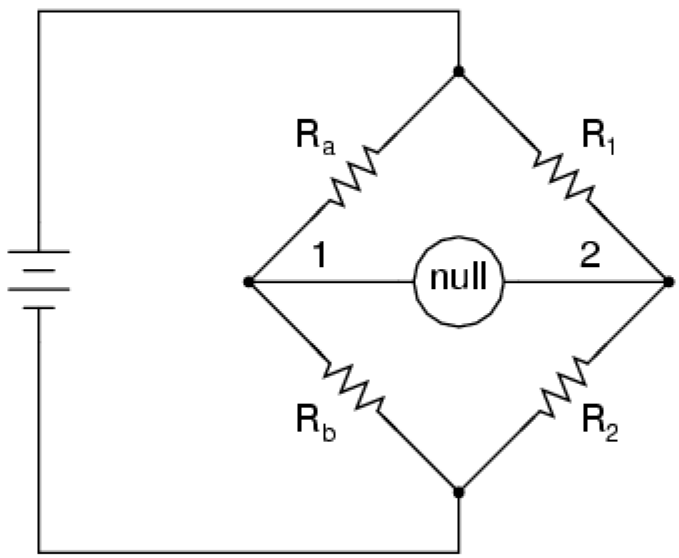


Figure 44: Wheatstone bridge circuit.

When the voltage between point 1 and the negative side of the battery is equal to the voltage between point 2 and the negative side of the battery, the null detector will indicate zero and the bridge is said to be "balanced." The bridge's state of balance is solely dependent on the ratios of R_a/R_b and R_1/R_2, and is quite independent of the supply voltage (battery). To measure resistance with a Wheatstone bridge, an unknown resistance is connected in the place of R_a or R_b, while the other three resistors are precision devices of known value. Either of the other three resistors can be replaced or adjusted until the bridge is balanced, and when balance has been reached the unknown resistor value can be determined from the ratios of the known resistances.

A requirement for this to be a measurement system is to have a set of variable resistors available whose resistances are precisely known, to serve as reference standards. For example, if we connect a bridge circuit to measure an unknown resistance R_x, we will have to know the *exact* values of the other three resistors at balance to determine the value of R_x:

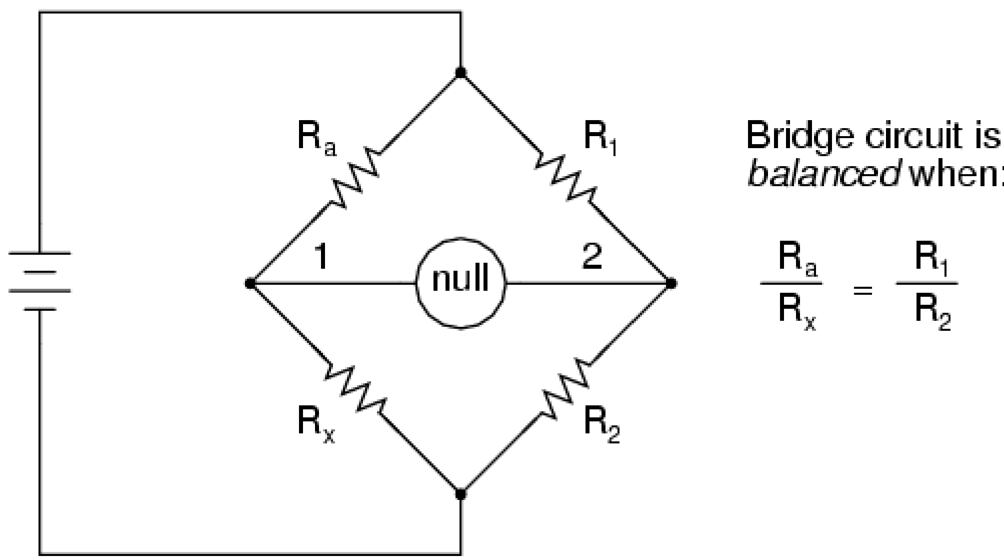


Figure 45: A balanced Wheatstone bridge.

Each of the four resistances in a bridge circuit are referred to as *arms*. The resistor in series with the unknown resistance R_x (this would be R_a in the above schematic) is commonly called the *rheostat* of the bridge, while the other two resistors are called the *ratio* arms of the bridge.

Wheatstone bridges are considered a superior means of resistance measurement to the series battery-movement-resistor meter circuit discussed in the last section. Unlike that circuit, with all its nonlinearities (nonlinear scale) and associated inaccuracies, the bridge circuit is linear (the mathematics describing its operation are based on simple ratios and proportions) and quite accurate.

Given standard resistances of sufficient precision and a null detector device of sufficient sensitivity, resistance measurement accuracies of at least +/- 0.05% are attainable with a

Wheatstone bridge. It is the preferred method of resistance measurement in calibration laboratories due to its high accuracy.

There are many variations of the basic Wheatstone bridge circuit. Most DC bridges are used to measure resistance, while bridges powered by alternating current (AC) may be used to measure different electrical quantities like inductance, capacitance, and frequency.

A *Wheatstone bridge* can be used to measure resistance by comparing the unknown resistor against precision resistors of known value; much like a laboratory scale measures an unknown weight by comparing it against known standard weights.

Example

Problem: The circuit diagram for a Wheatstone bridge is shown in Figure 46, resistors Ra, R1, and R2 are precision, variable resistors. The value of R_x is an unknown value of resistance that must be determined. After the bridge has been properly balanced the unknown resistance may be determined by means of a simple formula.

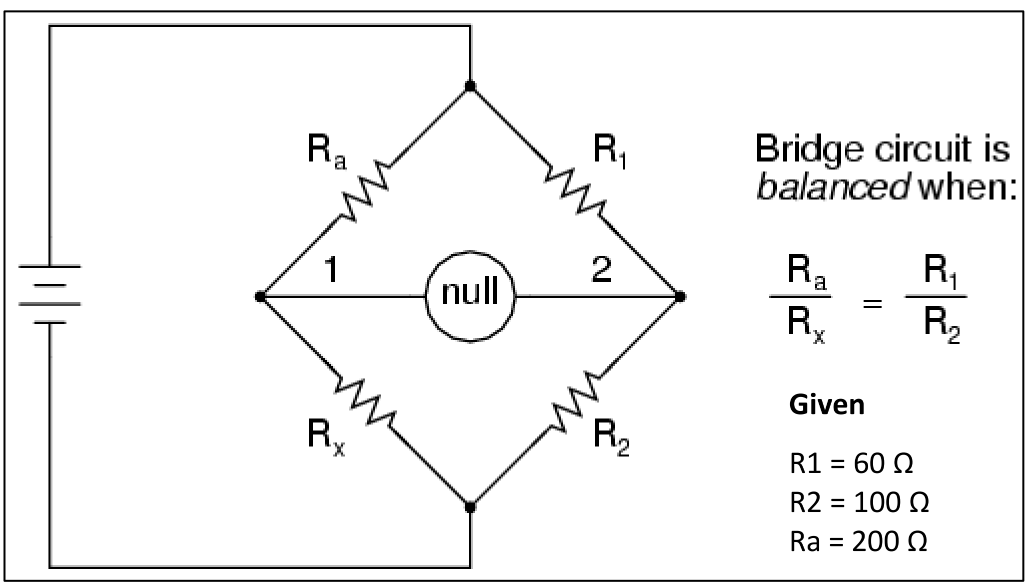


Figure 46: Example problem with Wheatstone bridge.

Solution: First, create a formula based on the principles of Ohm's law.

We know that the E1 and Ea are equal because R1 and Ra are in parallel. The same holds true for E2 and Ex. Using Ohm's law we can rewrite the formulas as shown below:

$$E_1 = E_a$$
$$I_1R_1 = 1_2R_a$$
$$E_2 = E_X$$
$$I_1R_2 = 1_2R_X$$

With this information, we can figure the value of the unknown resistor R_X. Divide the voltage drops across R1 and R3 by their respective voltage drops across R2 and R_x as follows:

$$\frac{I_1R_1}{I_1R_2} = \frac{I_2R_a}{I_2R_X}$$

We can simplify this equation by reducing like amounts from nominator and denominator:

$$\left[\frac{\cancel{I_1}R_1}{\cancel{I_1}R_2} = \frac{\cancel{I_2}R_a}{\cancel{I_2}R_X}\right] \; becomes \; \left[\frac{R_1}{R_2} = \frac{R_a}{R_X}\right]$$

Then we algebraically separate Rx through the following steps by multiplying both sides by R_x:

$$\left[\left(\frac{R_x}{1}\right)\left(\frac{R_1}{R_2}\right)\right] = \left[\left(\frac{R_a}{\cancel{R_x}}\right)\left(\frac{\cancel{R_x}}{1}\right)\right] = \left[\frac{R_xR_1}{R_2} = R_a\right]$$

Now, isolate Rx by dividing both sides by $\frac{R_1}{R_2}$. Recall that when dividing fractions, you multiply using the inverse (or reverse).

$$\left(\frac{R_2}{R_1}\right)\left(\frac{R_xR_1}{R_2}\right) = R_a\left(\frac{R_2}{R_1}\right) \; becomes \; R_x = R_a\left(\frac{R_2}{R_1}\right), then\ solve$$

$$R_x = 200\left(\frac{60}{100}\right) = 333.3\Omega$$

Labs for Circuit Measurement

Overview

Students will build an analog voltmeter and an analog current meter using specifications given. Test circuits will allow students to analyze their designs.

Requirements

To meet all requirements for this lab, you must complete all activities, questions, critical thinking activities and questions, and observations and conclusions.

Course Objectives

- Understand the loading effect of various types of test equipment.
- Understand the limitations of the various test equipment.
- Demonstrate acceptable techniques to construct circuits from schematic drawings on solderless and/or solder type breadboards.
- Demonstrate proper decoupling methods for work on breadboard proto-type circuits.
- Demonstrate ability to document a breadboard circuit, schematic, or pictorial layout.
- Demonstrate ability to predict circuit operation
- Demonstrate ability to test circuit operation

Module Objectives

- Calculate the required shunt resistances for an analog voltmeter.
- Construct and analyze an analog voltmeter
- Calculate the required shunt resistances for an analog current meter.
- Construct and analyze an analog current meter.
- Explain the purpose of the fuse in the analog current meter.

Activities & Assessments

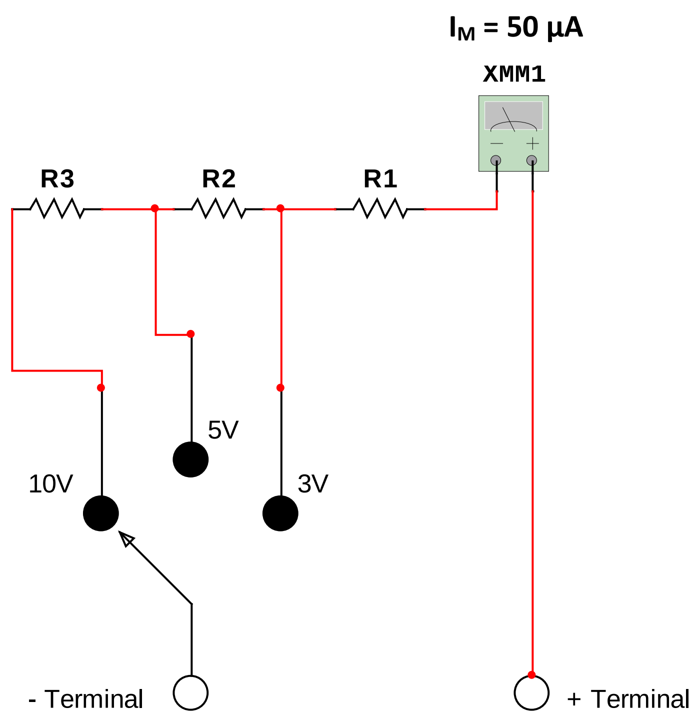
1. Analog Voltmeter
2. Analog Current Meter

1: Analog Voltmeter

Components

- **50µA meter movement**
- **3-position rotary switch**
- **½ Watt Standard ±5% Resistors (TBD)**

Circuit Diagram



Procedure

Step 1: **Design the Meter:** Using the specifications shown in the schematic, design an analog voltmeter. Support your design with calculations

Step 2: **Build the Meter:** Using **only** Standard ±5 % Resistors, build the design on a breadboard. Select resistors that are as close to your calculated values as possible. Remember, you may use only ONE resistor for each range.

Rotary Switch: There are 4 pins on a 3-position rotary switch. You will need to use a continuity checker to determine which pin is common. That pin will be connected to the negative terminal of your analog meter.

Step 3: **Test the Meter:** You will need to perform three (3) sets of tests on your voltmeter. Follow the directions for each test. The results to be included in your report are the actual voltage in number form and a simple drawing (or photograph) of the meter face indicating the voltage.

Performing the tests: Use a dc power supply set at the required voltage for each test. Set the meter **before** attaching the meter.

Test 1 – Test Voltage: **2.5 V** (test at each of the three ranges)

Test 2 – Test Voltage: **4.0 V** (test at ONLY the 5 V and the 10 V ranges)

Test 3 – Test Voltage: **8.0 V** (test at ONLY the 10V range)

FAILURE TO FOLLOW DIRECTIONS may result in the meter being irreparably damaged.

Observations & Conclusions

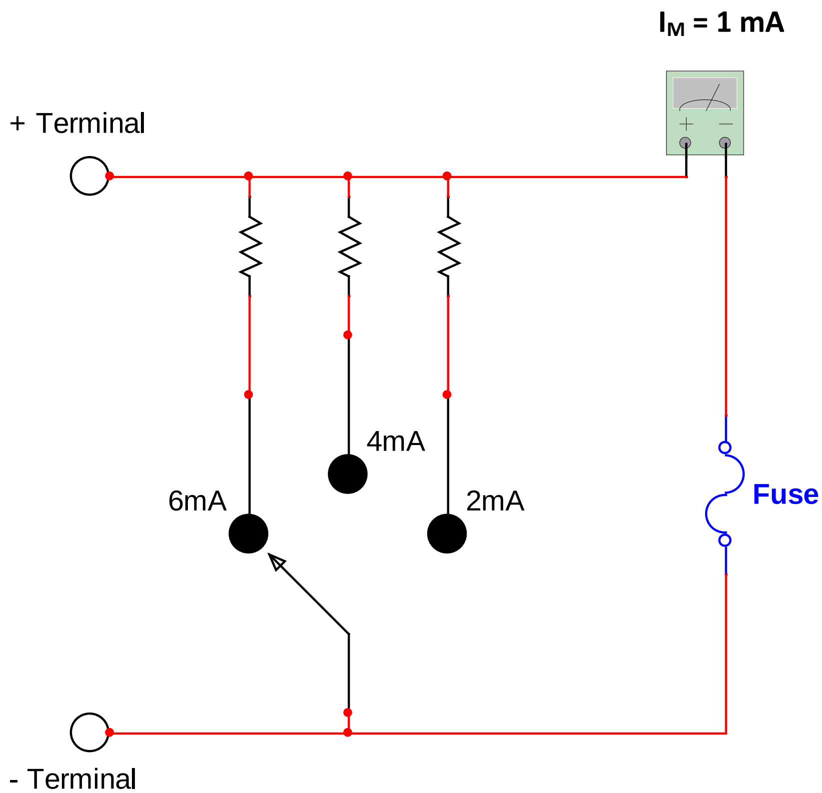
In your lab report, include your results from each voltage test as well as any observations or conclusions you may have made during the design and testing process.

2: Analog Current Meter

Components

- **1mA meter movement**
- **3-position rotary switch**
- **½ Watt Standard ±5% Resistors (TBD)**
- **Fuse assembly (1/10th amp fuse)**

Circuit diagram



Procedure

Step 1: **<u>Design the Meter:</u>** Using the specifications shown in the schematic, design an analog current meter. Support your design with calculations

Step 2: **<u>Build the Meter:</u>** Using only Standard ±5 % Resistors, build the design on a breadboard. Select resistors that are as close to your calculated values as possible**.** Remember, you may use only ONE resistor for each range. **The fuse assembly has been provided*. Be sure it is installed <u>before</u> you test your meter.***

Step 3: **<u>Test the Meter:</u>** You will need to perform three (3) sets of tests on your current meter. Follow the directions for each test. The results to be included in your report are the actual voltage in number form and a simple drawing (or photograph) of the meter face indicating the current.

<u>Test Circuit:</u> Build a simple circuit using a variable dc power source and a 2 kΩ resistor to obtain the test voltages below. Ohm's law will help you determine the amount of voltage that needs to be applied to obtain the test currents.

Test 1 –**I = 1.5 mA** <u>test at each of the three ranges</u>.

Test 2 –**I = 3.5 mA** <u>test at ONLY the 5 V and the 10 V ranges</u>.

Test 3 –**I = 5.5 mA** <u>test at ONLY the 10V range</u>.

Observations & Conclusions

In your lab report, include your results from each voltage test as well as any observations or conclusions you may have made during the design and testing process.

Answers to Knowledge Checks

Introduction to Circuit Measurement

1. What are two ways that circuit measurement is used?

   A. *Circuit measurement is used to (1) monitor the operation of a piece of electrical or electronic equipment and (2) determine the reason a piece of electrical or electronic equipment is not functioning properly.*

2. Why are in-circuit meters used?

   A. *In-circuit meters are used to monitor the operation of electrical or electronic devices.*

3. What is one advantage of an out-of-circuit meter when it is compared with an in-circuit meter?

   A. *Out-of-circuit meters can be used on more than one electrical or electronic device.*

Basic Meter Movements

1. What type of meter movement is the d'Arsonval meter movement?

   A. *A permanent-magnet moving-coil meter movement used in most electrical and electronic meters.*

2. What is the effect of current flow through the coil in a d' Arsonval meter movement?

   A. *A magnetic field is generated around the coil and the attraction of this field with the permanent magnet causes the coil to move.*

3. What are three functions of the hairsprings in a d' Arsonval meter movement?

   A. *To return the pointer to its rest position when there is no current flow; to oppose the coil movement when there is current flow; to provide electrical connections for the coil.*

Ammeters

1. What electrical property does an ammeter measure?

    A. *Current.*

2. How is an ammeter connected to the circuit under test?

    A. *In series.*

3. How does an ammeter affect the circuit being measured?

    A. *Since the ammeter is a resistor in series with the load, it increases the resistance of the circuit and lowers circuit current.*

4. How is the ammeter's effect on the circuit being measured kept to a minimum?

    A. *The resistance of the ammeter must be much smaller than the circuit load.*

5. What is ammeter sensitivity?

    A. *The amount of current that will cause full-scale deflection.*

6. What is used to allow an ammeter to measure different ranges?

    A. *Shunt resistors (internal or external).*

Ammeter Safety Precautions

1. Why should you use the highest range of an ammeter for the initial measurement?

    A. *To prevent damage to the meter movement from excessive current.*

2. What range of an ammeter is selected for the final measurement?

    A. *A range that allows a meter reading near the center of the scale.*

3. List the six safety precautions for the use of ammeters.

    A. Always connect an ammeter in series.

    B. Always start with the highest range.

    C. In dc ammeters, observe the proper polarity.

    D. Deenergize and discharge the circuit before connecting or disconnecting the ammeter.

E. Never use a dc ammeter to measure ac current.

F. Observe the general safety precautions of electric and electronic devices.

4. Why will an ammeter be damaged if connected in parallel with the circuit to be measured?

   A. *Since the ammeter has a small resistance compared to the load, it will have very high current if it is connected in parallel. This high current will damage the meter.*

Voltmeters

1. How is it possible to use a current sensitive meter movement to measure voltage?

   A. *Since the resistance of a meter movement remains the same as the pointer is deflected, the amount of current through the movement is proportional to the voltage applied. Therefore, only the scale of the movement must be changed.*

2. What is voltmeter sensitivity?

   A. *It is an indication of the resistance of the meter expressed in ohms per volt. The total resistance of the meter is the sensitivity multiplied by the full-scale voltage.*

3. What method is used to allow a voltmeter to have several ranges?

   A. *The use of resistors in series with the meter movement.*

4. Why should you always use the highest range when connecting a voltmeter to a circuit?

   A. *To prevent excess current through the meter movement.*

Voltmeter Safety Precautions

1. List the six safety precautions for the use of voltmeters.

   A. Always connect a voltmeter in parallel.

   B. Always start with the highest range.

   C. Deenergize and discharge the circuit before connecting or disconnecting the voltmeter.

   D. In a dc voltmeter, observe the proper polarity.

E. Never use a dc voltmeter to measure ac voltage.

F. Observe the general safety precautions of electric and electronic devices.

Ohmmeters

1. What electrical quantity is measured by an ohmmeter?

   A. *Resistance*

2. What other measurement can an ohmmeter make?

   A. *Circuit continuity.*

3. How is a series-type ohmmeter connected to the circuit being measured?

   A. *The ohmmeter is connected in series with the resistance to be measured.*

4. What is used to provide the ohmmeter with several ranges?

   A. *An ohmmeter has several internal range resistors and a switch or a series of jacks to select the proper range.*

5. What area of an ohmmeter scale should be used when measuring circuits?

   A. *The middle of the scale.*

Ohmmeter Safety Precautions

2. List four safety precautions for the use of ohmmeters.

   A. *Deenergize and discharge the circuit before connecting an ohmmeter.*

   B. *Do not apply power to a circuit while measuring resistance.*

   C. *Switch ohmmeters to the OFF position, if provided, or to highest range and remove meter leads from the meter when finished measuring resistance.*

   D. *Adjust the ohmmeter after changing resistance range and before measuring reading indicates the resistance.*

Additional Resources

Physics Resources

Georgia State University – HyperPhysics

http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

Video Resources

Khan Academy – Electricity and magnetisim

https://www.khanacademy.org/science/physics/electricity-and-magnetism

FedFlix – Review of Series and Parallel Resistive Circuits (Starting at 22:25)

https://archive.org/details/gov.dod.dimoc.41464

References

Kuphaldt, T. (n.d.). *Ammeter Design*. Retrieved April 18, 2014, from All About Circuits: http://www.allaboutcircuits.com/vol_1/chpt_8/4.html

Kuphaldt, T. (n.d.). *Ammeter impact on measured circuit*. Retrieved April 18, 2014, from All About Circuits: http://www.allaboutcircuits.com/vol_1/chpt_8/5.html

Kuphaldt, T. (n.d.). *Bridge Circuits*. Retrieved April 18, 2014, from All About Circuits: http://www.allaboutcircuits.com/vol_1/chpt_8/10.html

Kuphaldt, T. (n.d.). *Ohmmeter Design*. Retrieved April 18, 2014, from All About Circuits: http://www.allaboutcircuits.com/vol_1/chpt_8/6.html

Kuphaldt, T. (n.d.). *Voltmeter Design*. Retrieved April 18, 2014, from All About Circuits: http://www.allaboutcircuits.com/vol_1/chpt_8/2.html

Kuphaldt, T. (n.d.). *Voltmeter impact on measured circuit*. Retrieved April 18, 2014, from All About Circuits: http://www.allaboutcircuits.com/vol_1/chpt_8/3.html

Kuphaldt, T. (n.d.). *What is a meter?* Retrieved April 18, 2014, from All About Circuits: http://www.allaboutcircuits.com/vol_1/chpt_8/1.html

United States Navy. (1998). Module 16 - Test Equipment. In *Navy Electricity and Electronics Training Series (NEETS).* Pensacola, FL: Naval Education and Training Professional Development and Technology Center.

United States Navy. (2003). Module 3 - Circuit Protection, Control, and Measurement. In *Navy Electricity and Electronics Training Series (NEETS).* Pensacola, Florida: Naval Education and Training Professional Development and Technology Center.

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