Solar Fundamentals

0 people liked this 0 discussions

READING ASSIGNMENT

Fundamental Electrical Concepts

You need to explore some fundamental concepts from electrical theory to understand how photovoltaic systems work and how to build them. What is electricity? The answer to this question will vary, even among scientists and engineers. The simplest definition is that *electricity* is the movement of electrical charges from one place to another.

When electricity moves through an *electric circuit,* the following three things are always present and are the three fundamental quantities that you need to know:

1. A power source
2. An electric current
3. Resistance in the circuit

Electrical phenomena extend far beyond the three areas previously listed, but these are the three areas where you will focus to learn how solar arrays generate power and supply that power to users.

In a photovoltaic system, the *power sources* in the system are the solar panels and any batteries that are used to store energy. The power sources drive an *electric current* (or simply current) in an electric circuit. As the current moves through the circuit, it encounters *resistance* along the way. Resistance comes from the devices that use the current and from the wires that are used to connect devices in the circuit.

Once you know the voltage and the current that are flowing through a circuit, you can calculate the *power output* from the devices in the circuit. Applying the same idea to a solar array, if you know the total voltage and the total current generated by a solar array, you can calculate the power output by the array. The equation for power output is: $P = V \times I$

In this equation, P is the power output, V is the voltage, and I is the current. This is an important equation and it will be used repeatedly.

Electrical Charges

All matter is composed of electrical charges. If you've ever taken a chemistry class, you know that the fundamental electric charges are electrons and protons. Electrons have a negative charge and protons have a positive charge. All matter is made up of protons, neutrons, and electrons. Electrical phenomena occur because of the natural forces that exist between protons and electrons. Electrons and protons attract each other. Electrons repel other electrons and protons repel other protons. This attraction and repulsion is what gives rise to *voltage*.

Voltage and Current

An electrical power source supplies what's known as voltage. The voltage of a power source is a measure of how much energy it supplies to electrical charges. Batteries, generators, and solar panels are all voltage sources. Voltage is what causes electric charges to move between two points, and this flow of electric charge is called *current*. Voltage is measured in units of volts (V). An electric current is a flow of electric charges between two points. This quantity is a measure of the electric charge per second that flows in a circuit, called units of amperes, or amps (A). One way to think of current is that it tells you the number of electrons moving through a circuit every second.

Resistance and Ohm's Law

Resistance is a property of all materials that limits how much current can flow through a circuit. All materials have resistance to electricity, including the wires that are used to connect elements in a circuit. Electrical resistance is measured in units of ohms (using the Greek letter Ω). The specific mathematical relationship between voltage, current, and resistance is known as *Ohm's Law*. This law is used to determine the current moving through a circuit. The following is the equation for Ohm's Law:

$$I = \frac{V}{R}$$

In this equation, V is the voltage you supply to the circuit, I is the current in the circuit, and R is the total resistance of the circuit.

> You can visit the following website to learn more about electrical concepts.

Electrical resistance converts electrical energy to heat. This explains why electronic devices get warm when they are in operation. If a device heats up to a very high temperature, the wiring in the device could oxidize and break, or the device could catch on fire. This is particularly dangerous for devices that have low resistance. If a device has low resistance, it has high current and high power output, so it can heat up much faster than a device that runs at low current.

Resistors are the simplest elements that are present in electrical circuits. These devices simply convert electrical energy into heat. In a resistor, the power output determines how fast the resistor heats up, and a larger power output will bring a resistor up to a high temperature very quickly. Resistors are rated for a certain power output. A resistor will burn out if the power output is too large. In other words, if the current in a resistor is too high, the resistor can burn up and it will stop conducting electricity.

All of the units previously discussed are metric units, and you can use the metric prefixes in the same way you would with other units that you might be familiar with. The important metric prefixes that are used in electrical measurements are as follows:

- μ (micro): one millionth
- m (milli): one thousandth
- k (kilo): one thousand
- M: (mega): one million

For example, 30 kΩ (pronounced "kilo-ohms") means 30,000 Ω. As another example, 100 μV (or "microvolts") means 100 millionths of a volt, or 0.0001 V. These units will become more important when you learn about multimeters in the next section. When using Ohm's Law to calculate the electrical properties of the circuit, always convert the voltage values into V, the current values into A, and the resistance values into Ω.

Read more about metric prefixes.

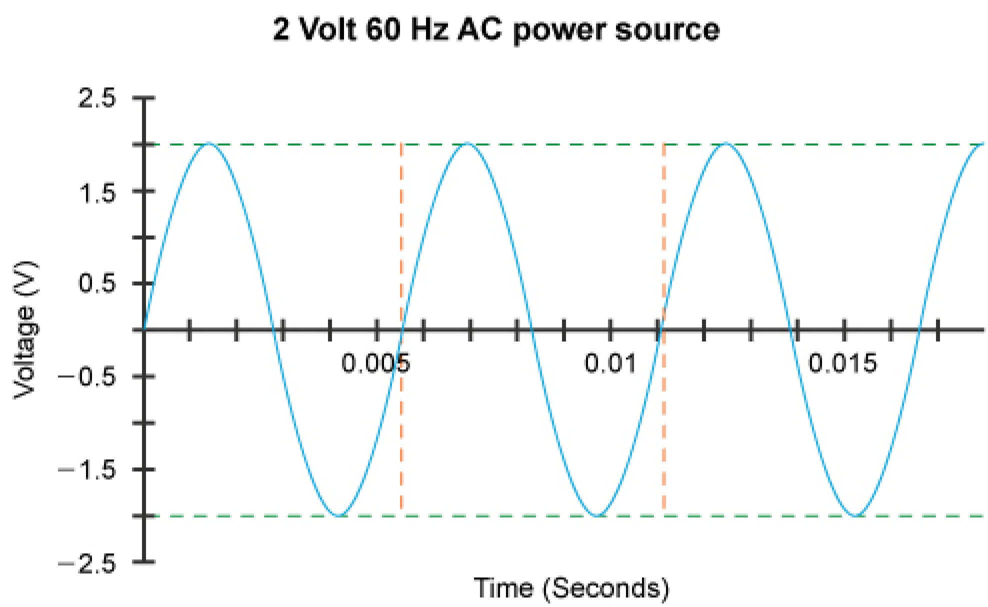
Direct Current and Alternating Current

Current can flow in a circuit in two ways; these two modes are called *direct current* (DC) and *alternating current* (AC). Both of these terms refer to the direction the current moves through a circuit at different times. Both types of current have specific applications and safety precautions that must be taken. DC power can be converted into AC power using a power inverter. AC power can also be converted into DC; however, this topic is beyond the scope of the course.

If you have a simple circuit connected to a power source with DC voltage, the current will be DC. If you have a power source with AC voltage connected to a simple circuit, the current will run in AC.

DC current doesn't change its magnitude or direction over time. This means that the current always flows in the same direction as it moves through the circuit, and you'll always measure the same amount of current.

Many power sources, including solar cells and batteries, produce DC power. Although many of the earliest utility companies intended to sell DC power to the general public, DC power isn't used for transmitting electricity through the power grid. There are two principal reasons for this. The first reason is safety. Because DC power generates a constant current in a circuit, a person exposed to DC current can be electrocuted very easily. The second reason is due to the heat that DC current can generate in a circuit. Because the current doesn't change in magnitude or direction, it constantly generates heat. When DC is transmitted through a long wire, the large current heats up the wire very quickly. If DC current were used in the power grid, it would melt the transmission wires before the electricity was received by the customer. For these reasons, the civilian power grid runs on AC.



Voltage Generated by a 60 Hz AC Power Source

AC current changes its direction over time, meaning the current moves back and forth through the circuit. The current also changes its magnitude over time. Think of the voltage and current generated by an AC power source as a wave. The voltage and current both fluctuate back and forth in the circuit, and if you plot this behavior on a graph you see a repetitive wave pattern. The rate at which the voltage and current fluctuate is called the *frequency* and is measured in units of Hertz (Hz). This image shows a plot of a 2 V 60 Hz AC power source. This voltage source fluctuates back and forth 60 times per second. The fluctuation ranges between +2 V and -2 V. The green dashed lines show the magnitude of the voltage and the orange dashed lines show the amount of time it takes to complete a single cycle (1/60 of a second).

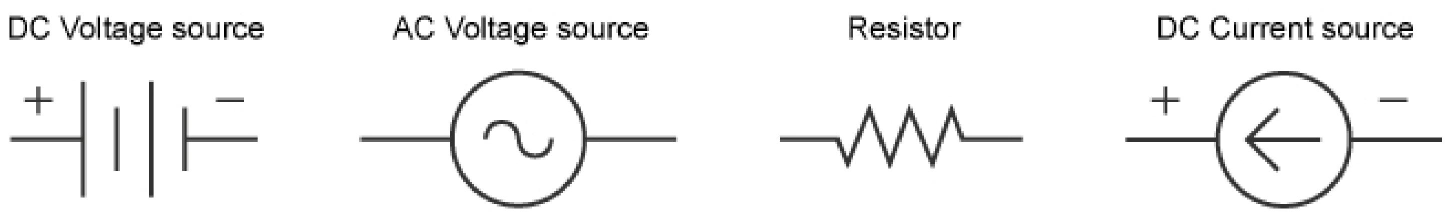
The US power grid runs on 110 V and 60 Hz AC power, and European power grids use 220 V and 50 Hz AC power. AC power can be generated directly by a rotating turbine; this is the standard method that wind turbines, hydroelectric dams, biomass, and fossil fuel plants use to generate electricity. Solar panels are the only alternative energy source that generate DC electricity. AC power systems can run at high voltage with low current, or at low voltage with high current. Because the current and voltage can be controlled in an AC system, AC power can be safer than DC power under certain conditions, and it can be transmitted over long distances.

Electricity Produced by Solar Energy Systems

The electricity produced by a solar panel or an array of solar panels is always DC. Think of a solar panel as a large battery, and the output leads from a panel supply electricity to any circuit you like. In a real photovoltaic system, the DC power generated by a solar array needs to be converted to AC power so that it can be used to power home electronics. You would also like to capture and store some of that DC electricity in a battery so that it can be used later. This is why photovoltaic systems are more than just a group of solar panels, you need the other pieces of electronic equipment to capture the solar energy so that it can be stored and used.

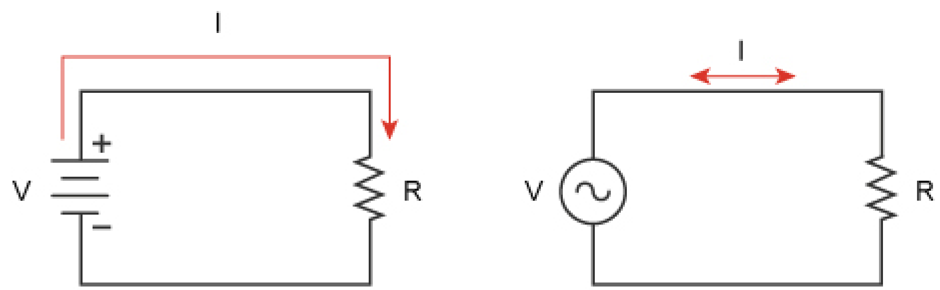
Applying Ohm’s Law to Simple Circuits

The simplest electric circuit consists of a voltage source (for example, a battery) and a resistor; these are also called *trivial circuits*. Circuits are drawn using diagrams with symbols to represent resistors and voltage sources. This figure shows the symbols for voltage sources, current sources, and resistors.



Symbols for Voltage Sources, Current Sources, and Resistors

Diagrams for a trivial circuit with a voltage source are shown in the image. The positive and negative terminals of the voltage source are wired directly to each end of the resistor, and the current in the circuit can be calculated with Ohm’s Law. The red arrow in each diagram shows the direction of the current in the circuit. The double-ended arrows in the circuit with the AC voltage source mean that the current moves back and forth in the circuit.



In this simple circuit, the left diagram uses a DC voltage source, and the right diagram uses an AC voltage source.

Look at what happens in the DC circuit. If the voltage source supplies 2 V of power, and the resistor is 10 Ω, then the current in the circuit is found by putting V = 2 and R = 10 into Ohm's Law. The current in the circuit is:

$$I = \frac{2}{10} = 0.2A$$

The current in this circuit is 0.2 A. Currents can also be quoted in units of milliamps (mA), and you can convert amps to milliamps by multiplying the amps by 1000. This means the current in the circuit is 200 mA. If you use the same numbers in the AC circuit, there will still be 200 mA of current, but the current will move back and forth in the circuit.

You can also use the power equation to calculate the power consumed by the circuit. You found that the current is 0.2 A, and the voltage is 2 V. Plugging these numbers into the power equation gives us the power: $P = 2 \times 0.2 = 0.4$ W

The power in this circuit is 0.4 W. This is the case for both the DC and the AC circuit. Because you only have a resistor in this circuit, this is the power that's converted to heat in the resistor, and you should create this circuit with a resistor that has a power rating higher than 0.4 W.

Low Current and High Current AC Power Systems

Some people mistake high voltage systems as being more dangerous than low voltage systems. While this is true in DC power systems, this is not always the case in AC systems. The important thing to remember when working with electrical systems is that the current, not the voltage, is what causes severe injuries due to electrocution. DC power is more dangerous than AC power; DC voltage doesn't change, and if the voltage is large then the current will always be large. This means that a high voltage DC power source also supplies high DC current, and this creates a high risk of electrocution when working with DC power sources. The table shows the physical effects that can occur from exposure to different amounts of current.

Symptom	DC Current (A)	60 Hz AC Current (A)
Slight sensation	0.001	0.0005
Threshold of pain	0.04	0.001

Painful	0.05	0.01
Involuntary muscle contractions	0.06	0.015
Severe pain, difficulty breathing	0.08	0.02
Possible heart fibrillation	0.5	0.1
Death	1	0.2

Notice that it takes a smaller amount of AC current than DC current to cause the same type of bodily harm. However, the ability to control whether AC power runs at high or low current means that AC power systems can be made safer than DC power systems.

Remember that, in any circuit, the exact amount of current will depend on the resistance of the elements in the circuit. If you're exposed to an electrical current while working with a power system, your body becomes part of the circuit, and the resistance of your body determines the amount of current you experience. You can reduce the amount of current that moves through the body by using protective equipment such as gloves and insulated boots. The gloves and boots have high electrical resistance, and they will reduce the current that you experience.

Low current AC systems are used for transmission of electrical power over long distances. The US power grid runs on low current AC power. Recall that low current AC power has high voltage; the voltage on a power line in a metropolitan area can be tens of thousands of volts. Once the power lines reach a building, the low current is converted to high current. This means that the high voltage is converted down to low voltage. High current and low current can be converted using a device known as a *transformer*; this device only works with AC power and it's the last step in the power grid before AC power is sent to residential buildings. The transformer converts the low current (high voltage) power lines that hang from utility poles to high current (low voltage), and the output lines from the transformer are used to power home electronics.

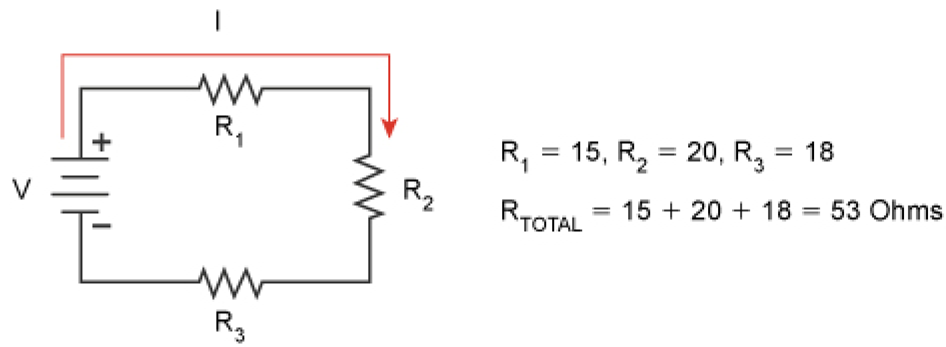
Series and Parallel Connections

There are a number of ways to connect multiple devices in a circuit. The simplest connections that can be made between circuit elements are series and parallel connections. These connections are important because they'll determine the total resistance of a circuit and how current moves through the circuit. The same connections can be made between multiple solar panels, and the connections between solar panels will determine how much current and voltage is generated by a solar array.

First, you'll look at series connections between multiple elements in a circuit. When multiple resistors or devices are combined in series, the total resistance can be calculated easily. The same idea applies to multiple power sources that are connected in series, and you can use the rules to calculate the total voltage and total current supplied by the connected power sources.

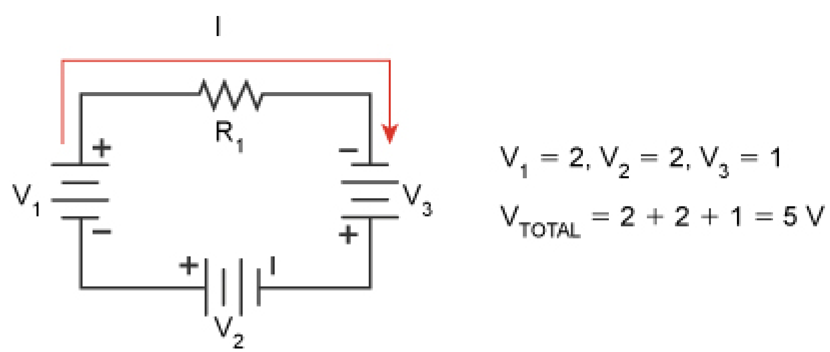
Parallel connections are mathematically more complicated. You can still use the rules for resistors connected in parallel to calculate the total resistance in a circuit. There are also rules for multiple power sources connected in parallel, and you can use them to calculate the total voltage and current supplied by interconnected solar panels. This is important because the power output of a solar array actually depends on the way solar panels are connected and the total resistance of the circuit that's connected to it.

Series Connections



A Circuit with Three Resistors Connected in Series

When multiple resistors are connected in series, the total resistance in the circuit is found by adding up all the values for all the resistors. This example shows a circuit with three resistors in series, with $R_1 = 15\ \Omega$, $R_2 = 20\ \Omega$, and $R_3 = 18\ \Omega$. The calculation for the total resistance is on the right side of the figure, and you see that the total resistance in the circuit is 53 Ω. Once you know the total resistance, you could use Ohm's law to calculate the current in the circuit.



A Circuit with Three DC Voltage Sources Connected in Series

Now let's look at multiple power sources connected in series. When you have multiple voltage sources, the total voltage is found by adding up all the voltages from each of the sources. The example shows a circuit with three voltage sources in series with $V_1 = 2$ V, $V_2 = 2$ V, and $V_3 = 1$ V. This situation is similar to what happens when multiple batteries are connected end to end. The calculation for the total voltage is on the right side of the figure, and you see that the total voltage in the circuit is 5 V. Once you know the total voltage, you could use Ohm's law and the value of the resistor R_1 to calculate the current in the circuit. In this example, you looked at DC voltage sources, but the same rules apply to AC voltage sources.

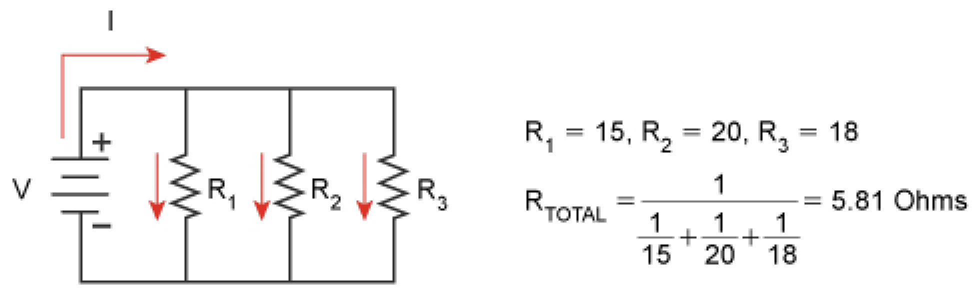
When you connect multiple current sources in series, the rules change. When multiple current sources are connected in series, the total current is just the smallest current among all the current sources. Suppose you connect three different DC current sources with different outputs of 6 A, 4 A, and 3 A. The total current is just the smallest current among these three values, or 3 A.

Parallel Connections

When *N* resistors are connected in parallel, the total resistance in the circuit is found by the following formula:

$$R_{\text{Total}} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_N}}$$

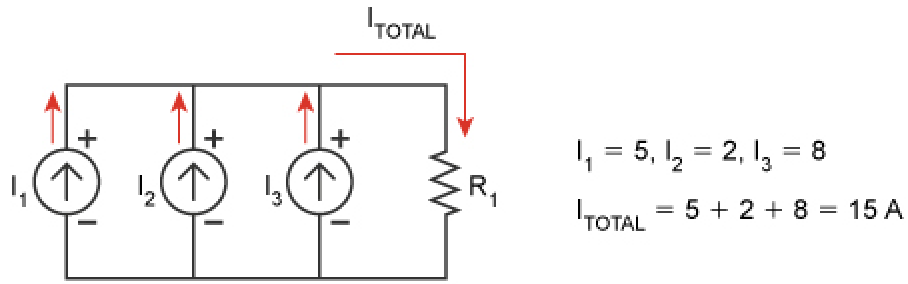
Take the same three resistors in the previous example and connect them in parallel. This circuit is shown in the image with R_1 = 15 Ω, R_2 = 20 Ω, and R_3 = 18 Ω. The calculation for the total resistance is on the right side of the image, and you see that the total resistance in the circuit is 5.81 Ω. When current begins flowing through the circuit, it splits at each junction; this is illustrated using the three red arrows in the figure.



A Circuit with Three Resistors Connected in Parallel

When you connect multiple voltage sources in parallel, the total voltage is just the smallest voltage among all the voltage sources. Suppose you connect four different DC voltage sources with different outputs of 13 V, 10 V, and 12 V, and 9 V. The total voltage is just the smallest voltage among these four values, or 9 V.

Multiple current sources connected in parallel behave similar to multiple voltage sources connected in series. The total current that flows in the circuit is found by adding all the currents from each of the sources. The figure shows a circuit with multiple current sources connected in parallel with I_1 = 5 A, I_2 = 2 A, and I_3 = 8 A. The total current is just the sum of these numbers, or 15 A.



A Circuit with Three DC Current Sources Connected in Parallel

These rules will be important later and will be used to design solar arrays. A solar array will need to have a specific voltage and current output depending on the specifications of the components in the photovoltaic system. Before you read about the construction of solar arrays and installation of solar arrays, you need to read about typical electrical safety standards.

Overview of the National Electric Code

The National Electrical Code (NEC), also known as NFPA 70, is a standard for the safe installation of electrical wiring and electrical equipment in the United States. It's part of the National Fire Codes series and is published by the National Fire Protection Association (NFPA). It's important to note that the NEC is not part of federal law. However, these standards are adopted by states and municipalities, and the standards provide a minimum benchmark for enforcement of electrical safety.

The NEC makes a distinction between high and low voltage systems, and there are specific installation standards and safety considerations required for each type of system. Low voltage systems are defined as systems that run at a peak voltage of 100 V or less. High voltage systems run at greater than 100 V, and there are some important considerations that need to be made for systems that run at greater than 600 V. In some jurisdictions, there's no requirement for licensing, training, or certification of installers for low voltage systems. Inspection of completed work may not be required, for either residential or commercial work.

When dealing with photovoltaic systems, especially in the residential area, you're typically working with low voltage systems. The wiring for low voltage systems can run in the walls and ceilings of commercial buildings, and is typically excluded from the requirements to be installed in protective conduit. Although low voltage cabling doesn't require inspection or training to install in some jurisdictions, it's still important for technicians to be aware of specific electric code and construction safety rules. In particular, installers should know how to correctly penetrate building fire barriers and use firestop putty to patch any holes that are used to install wiring. This is done to prevent a low voltage cable from increasing the risk of fire hazard.

According to the NEC, the current in an electrical circuit should be run at 80% of the device’s current rating in order to minimize the risk of fire or damage to an electrical device. This includes circuit breakers that are used in residential or commercial buildings. This is an important standard that needs to be met when installing the electronics that are used to convert the electrical power generated by a solar array into a usable AC voltage and current. The table shows a comparison of maximum current ratings and device ratings for different amounts of current. The table shows rated and maximum current values based on the NEC 80% standard.

Device Current Rating	Maximum Current

5 amps	4 amps
10 amps	8 amps
15 amps	12 amps
20 amps	16 amps
50 amps	40 amps
100 amps	80 amps
200 amps	160 amps

The NEC is an extensive list of safety standards and it would be impossible to cover everything here. The important parts of the NEC that you need to consider depend on the state and city where the photovoltaic system will be installed. See the NEC link at the end of this section for further information.

Reflect and Respond

If you have three resistors (37 Ω, 23 Ω, and 20 Ω) and 2 voltage sources (36 V and 12 V) connected in series, what's the total resistance, the total voltage, and the current in the circuit?

A sample answer could look like this: The total resistance is found by adding up all the resistors, so the total resistance is 80 Ω. The total voltage is found by adding up the voltages, so the total voltage is 48 V. The current is the total voltage divided by the total resistance, or 0.6 A.