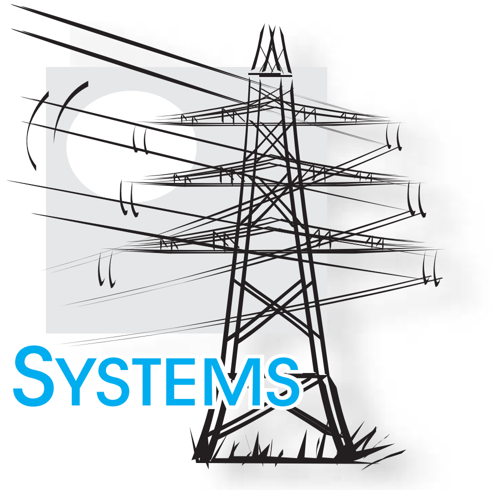
3.3 Rate in Electrical Systems



Objectives

- Define electrical current as a rate.
- Describe what is measured by ammeters and voltmeters. Explain how to connect an ammeter and a voltmeter in an electrical circuit.
- Explain why electrons travel at speeds much lower than the speed of light in a conductor.
- Define frequency and period. Explain the relationship between frequency and period.

In mechanical systems, the important rates are speed (rate of change of position) and acceleration (rate of change of velocity). In fluid systems, the important rates are volume flow rate (rate of change of volume) and mass flow rate (rate of change of mass). In electrical systems, or circuits, the most important rate is current. In Section 2.3 you learned that current is rate of electrical charge flow.

INTERNET connection

To find out more about rate in electrical systems, follow the links at **www.learningincontext.com.**

Electric Current

When a conductor joins two objects of different electric potential, charge flows from the higher potential to the lower potential. The potential difference, or voltage difference, is the prime mover that causes charge to move. In a solid conductor, such as a copper wire, it is the electrons that move in the circuit.

Current is a measure of the net charge Δq that passes through a cross-sectional area in a time interval Δt. The electric current I is defined by the following ratio:

$$\text{Electric current} = \frac{\text{charge moved}}{\text{time interval}}$$

$$I = \frac{\Delta q}{\Delta t}$$

Charge is measured in coulombs (C). Current is measured in *amperes* (A). If one coulomb of charge flows through a conductor in a time interval of one second, the electric current is one **ampere**. 1 A = 1 C/s.

Example 3.11 Charge Flow in a Motor Circuit

A DC electric motor operates an airplane's landing gear. The current in the motor circuit during operation is 6.8 amperes. It takes 10 seconds to raise the landing gear. How much charge flows through any cross section of the circuit while the landing gear is being raised? How many electrons flow through a cross section of the circuit?

Solution: A current of 6.8 amperes is equal to a flow rate of 6.8 coulombs per second.

$$I = 6.8\ \text{A} = 6.8\ \text{C/s}$$

Use the equation for electric current and solve for the charge moved:

$$I = \frac{\Delta q}{\Delta t}$$

$$\Delta q = I\Delta t$$

$$= \left(6.8\ \frac{\text{C}}{\text{s}}\right)(10\ \text{s})$$

$$= 68\ \text{C}$$

The charge on one electron is 1.602×10^{-19} C:

$$\text{Number of electrons} = \frac{68\ \text{C}}{1.602 \times 10^{-19}\ \dfrac{\text{C}}{\text{electron}}} = 4.24 \times 10^{20}\ \text{electrons}$$

In 10 seconds of operation, 68 coulombs of charge or 4.24×10^{20} electrons flow through a cross section of the motor circuit.

Measuring Current and Voltage

You can measure current in electrical circuits with an **ammeter** and potential difference with a **voltmeter**. Each instrument has two terminals, one labeled positive (+) and one labeled negative (–). But the instruments are not connected in the same way.

An ammeter measures *current through* a circuit element. The ammeter is placed in the conducting path, so the current through the circuit element is the same as the current through the ammeter. This type of connection is called a **series connection**. Figure 3.16 shows a simple DC circuit, where a battery provides a potential difference to a light bulb (the load) and an ammeter is connected in series. A schematic diagram of the circuit is shown in Figure 3.17. Notice that the ammeter is in line with, or in series with the load.

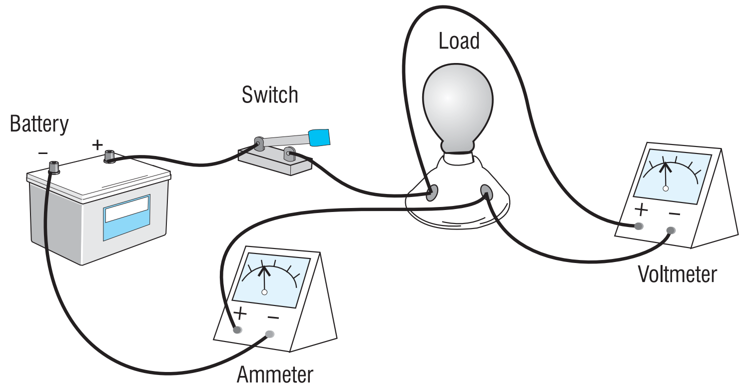


Figure 3.16
A simple DC circuit

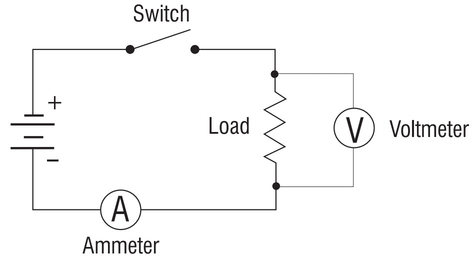


Figure 3.17
A schematic circuit diagram of the DC circuit

A voltmeter measures the potential difference, or *voltage across* a circuit element. The type of connection for measuring voltage, as shown in Figures 3.16 and 3.17, is called a **parallel connection**. The load and the voltmeter appear to be parallel to each other in the circuit diagram. The voltage across the voltmeter is the same as that across the load.

The Speed of Charge Flow

When you close the switch in an electric circuit that contains a battery, a current is generated throughout the circuit almost instantaneously. For example, the light bulb in the circuit in Figure 3.16 appears to glow at the same instant the switch is closed. But in fact there is a slight time delay. The "signal" or electric field from the battery that applies a force on the electrons in the light bulb travels at almost the speed of light through the conductor. But it is *not* the electrons in the conductor that travel at almost the speed of light. It is the electric field. The average speed of the electrons is much less than the speed of light.

A metal conductor has a large number of electrons that move freely about the conductor. These electrons have gained enough energy at room temperature to break their bonds with the metal atoms in the conductor. Since the conductor has a neutral charge, every free electron leaves behind a positive ion. As the free electrons move through the conductor, their paths are constantly being changed by the coulomb forces resulting from interactions between the free electrons and interactions between free electrons and positive ions. A possible random path of a free electron moving through a conductor is shown in Figure 3.18. Between collisions, the average speed of the electron is about 10^6 m/s, or less than one-hundredth the speed of light.

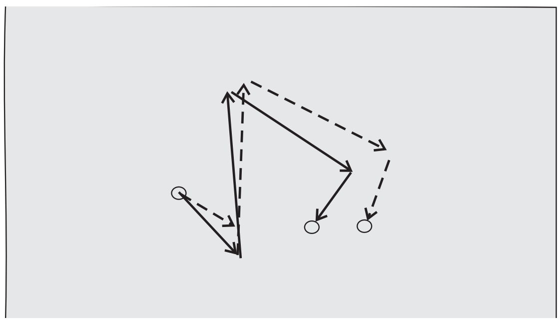


Figure 3.18
A possible path of a free electron in a conductor. The solid lines show a random path. The dashed lines show how the random path could be altered by an electric field.

When an electric field, or voltage, is applied to the conductor, a force is exerted on the free electrons (in Figure 3.18, the force is to the right). The force accelerates the electrons between collisions, resulting in a net movement or *drift* in the direction of the force. This drift is the net displacement of the electron along the conductor. Because collisions interrupt the paths of free electrons, the actual **drift velocity** in the conductor is very slow—less than one centimeter per second.

AC Circuits, Frequency, and Period

In AC circuits, current and voltage vary continuously in a certain pattern. Commercial power companies in the United States and Canada generate *60-cycle* alternating current. This means the pattern of variation of current and voltage repeats itself 60 times each second. **Frequency** is a measure of how often a pattern repeats itself. If there are n repetitions, or cycles, of the pattern in a time interval Δt, the frequency f of the pattern is the following ratio:

$$\text{Frequency} = \frac{\text{number of cycles}}{\text{time interval}}$$

$$f = \frac{n}{\Delta t}$$

If f is measured in Hz, then the units of frequency are cycles/second, or **hertz** (Hz).

$$1\text{ Hz} = 1\text{ cycle/s.}$$

In calculations, the unit "cycle" is dropped, so you will also use

$$1\text{ Hz} = 1\text{ s}^{-1}.$$

The exponent "–1" is shorthand for "reciprocal." You can also write the equation above as

$$1\text{ Hz} = \frac{1}{1\text{ s}}.$$

The **period** of a repeating pattern is the time it takes for one complete cycle. The period and frequency are reciprocals. We use T to represent period.

$$T = \frac{1}{f} \quad \text{and} \quad f = \frac{1}{T}$$

If f is measured in Hz, the units of period are seconds.

Figure 3.19 shows current as a function of time for a typical AC circuit. You can measure period from this graph by measuring the time for a complete cycle. Notice that it doesn't matter where in the pattern you start the measurement. You can start where the graph crosses the time axis, at a crest, or at a trough. But you must measure the time interval for a *complete* cycle. For this graph, $T = 4$ ms. The reciprocal is the frequency:

$$f = \frac{1}{T} = \frac{1}{4 \times 10^{-3}\text{ s}} = 250\text{ s}^{-1} \text{ or } 250\text{ Hz}$$

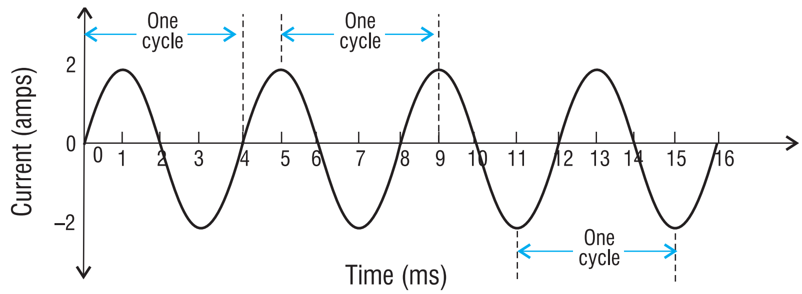
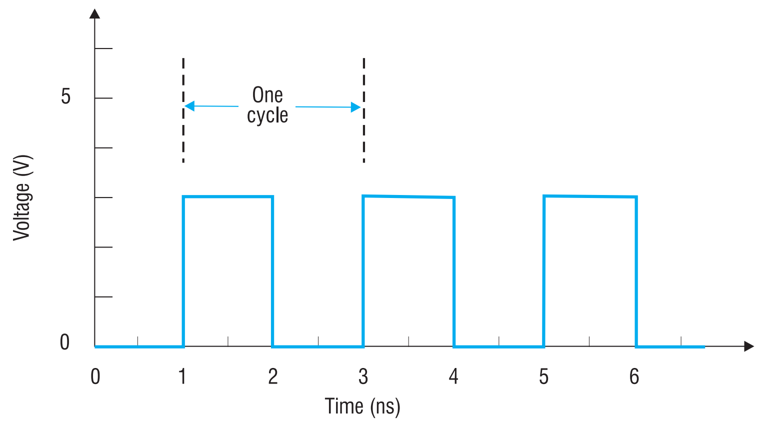


Figure 3.19
Current versus time for a typical AC circuit.
The period is 4 ms and the frequency is 250 Hz.

Voltage and current can also change with a regular pattern that is not smooth like Figure 3.19. In these circuits, voltage is either "on" or "off" and changes abruptly between the two. These patterns are used in microprocessors.

Example 3.12 Period and Frequency in a Microprocessor Circuit

A microprocessor uses a circuit with voltage and current cycles. The current flows in only one direction but alternates in magnitude. The pattern is called a **square wave**. The voltage in the circuit alternates from zero to +3 V, as shown here. The frequency of the square wave is 500 MHz. What is the period?



Voltage pattern in a microprocessor circuit

Solution: The period is the reciprocal of the frequency f, where $f = 500$ MHz or $500 \times 10^6\ s^{-1}$:

$$T = \frac{1}{f} = \frac{1}{500 \times 10^6\ s^{-1}} = 2 \times 10^{-9}\ \text{s or 2 ns}$$

The period of the square wave is 2 nanoseconds.

Summary

- Electrical current is a measure of the amount of charge that flows through a cross section of a conductor per unit time. Current is measured in amperes.
- Ammeters measure current. Voltmeters measure voltage. Ammeters are connected in circuits in series. Voltmeters are connected in parallel.
- An electric field applies forces to electrons in a circuit. A change in the electric field travels at nearly the speed of light along a conductor. Electrons travel at speeds much lower than the speed of light.
- Frequency is the rate at which a pattern repeats. Frequency is measured in hertz.
- Period is the time it takes for a pattern to repeat. The period is the reciprocal of the frequency.

Exercises

1. Rate in DC electrical circuits is associated with how fast _____________ moves in the circuit.
2. Rate in AC electrical circuits can be associated with both how fast _____________ moves in the circuit, and how fast the _____________ of charge flow changes.
3. The rate of charge flow in both DC and AC circuits is expressed in units of _____________.
4. To measure the current through a load in a circuit, you connect an ammeter in _____________ (series or parallel). To measure the voltage across the load, you connect a voltmeter in _____________ (series or parallel).
5. The rate at which the direction of current flow changes in an AC circuit is expressed in units of _____________ and is called the _____________ of the AC current.
6. A charge of 0.020 coulomb flows from a battery in 0.001 second. What is the current flow during this time period?
7. The gate of a transistor acts like a capacitor and collects charge. If an electron current of 2.6 nanoamperes flows into the gate for 12 microseconds, how much does the charge on the gate change?

8. A transistor gate is positively charged with 45 picocoulombs. The gate is discharged in 3.7 nanoseconds. What is the average current during the time the gate is discharged?

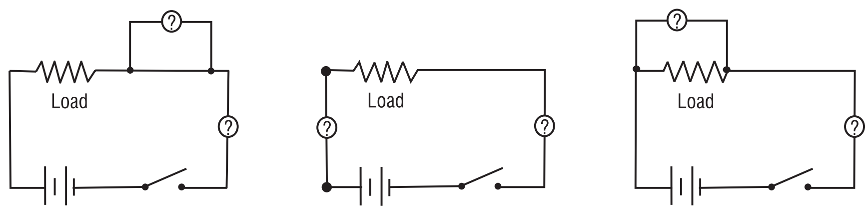
9. An ammeter measures a steady current of 2.5 A flowing through a DC circuit. How long will it take for 2 C of charge to flow past a point in the circuit?

10. Suppose an electric field is applied from the top to the bottom of a conductor.

    (a) What is the direction of the drift velocity of the free electrons in the conductor?

    (b) Explain why the magnitude of the drift velocity is much lower than the actual speed of the free electrons.

11. An ammeter and a voltmeter are used to measure the current through a load and the voltage across the load in a circuit. One of the schematic circuit diagrams below shows the correct way to connect the instruments.Copy the correct diagram and label the ammeter A and the voltmeter V.



12. The graph of voltage vs time for an AC circuit is shown at the right. The scale for the horizontal axis is 5 microseconds per major division.

    (a) What is the period of the voltage?

    (b) What is the frequency of the voltage?