Transformers

The electrical devices you use every day all have different electrical energy requirements. An electric stove requires a lot of electrical energy, while an LED requires very little. Some devices require different currents and voltages. For example, a computer may require only 12 V to operate, so the voltage in your home needs to be lowered from 120 V to 12 V. Devices that are capable of raising or lowering AC voltage are called **transformers**. Transformers are used in many electronic devices to lower or raise the AC voltage to the value that the device is designed for **(Figure 1)**. Adapters, such as cellphone chargers, have transformers as part of their circuitry. Adapters also contain a circuit that converts AC voltage to DC voltage.

transformer an electromagnetic device that can raise or lower voltage

Figure 1 A transformer

How Transformers Work

To understand how a transformer works, recall Faraday's ring from Section 13.1. The ring has a primary circuit and a secondary circuit. These circuits are not in physical contact, but a current in the primary circuit induces a current in the secondary circuit. According to the law of electromagnetic induction, a changing magnetic field is required to induce a current. A changing magnetic field can be produced by using alternating current. An alternating current in the primary coil is the most critical part to producing an alternating current in the secondary coil of a Faraday's ring.

Suppose that we change the number of windings in the coils on either the primary or the secondary circuit of a Faraday's ring. Would the same AC voltage be measured across both the primary circuit and the secondary circuit?

Transformers have different numbers of windings on the primary circuit compared to the secondary circuit (**Figure 2**). If the secondary circuit has fewer windings than the primary circuit, the voltage on the secondary side is less than the voltage on the primary side. Transformers that have fewer windings on the secondary circuit than the primary circuit are called **step-down transformers**. They are called step-down transformers because they lower the AC voltage by a specific amount.

step-down transformer a transformer with fewer secondary windings than primary windings

If the situation is reversed and the secondary circuit has more windings, then the voltage is higher on the secondary side. Transformers that have more windings on the secondary circuit than on the primary circuit are called **step-up transformers**. They are called step-up transformers because they increase the AC voltage by a specific amount. So we can lower or raise the voltage in the secondary circuit just by changing the number of windings.

step-up transformer a transformer with more secondary windings than primary windings

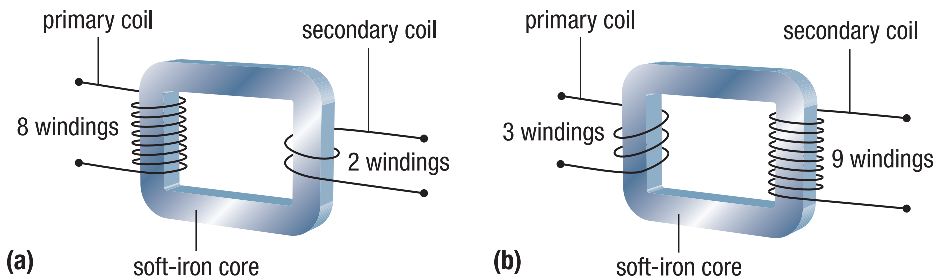

Figure 2 (a) A step-down transformer has fewer windings on the secondary coil than on the primary coil. (b) A step-up transformer has more windings on the secondary coil than on the primary coil.

Mini Investigation

Observing Transformers at Work

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A1.2, A2.1, A3

In this investigation, you will observe how a transformer works with direct current and alternating current.

Equipment and Materials: variable AC/DC power supply; 2 AC/DC multimeters with probes; transformer with different number of windings on primary and secondary coils; 2 alligator clip leads

1. Set up a circuit with the variable DC power supply connected to the transformer using the leads as shown in **Figure 3**. Make sure that the power supply is off.

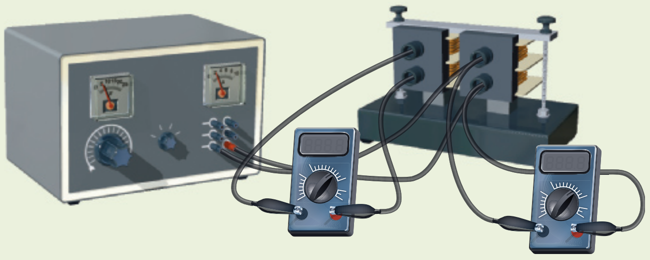

Figure 3

2. With the power supply off, set to the voltage specified by your teacher.
3. Set the multimeters to measure DC voltage, and connect one multimeter to the primary coil and the other multimeter to the secondary coil.
4. While watching the display on the multimeters, turn on the DC power supply. Only turn on the power supply when instructed to do so by your teacher. Record your observations. Turn off the power supply and record your observations.
5. Disconnect the transformer from the DC power supply and connect the alligator clip leads to the AC connection. Set your multimeters to measure AC voltages and repeat Step 4.

A. How effectively did the transformer work with DC? T/I C

B. How did the AC voltage on the primary coil compare to the AC voltage on the secondary coil? T/I

C. Is your transformer a step-up or a step-down transformer? T/I

Conservation of Energy in Transformers

Transformers must obey the law of conservation of energy. Therefore, the energy going into the primary coil must equal the energy coming out of the secondary coil if there are no energy losses. Recall from Section 5.5 that the change in energy is expressed as $\Delta E = P\Delta t$. Power in an electrical circuit is expressed as the product of voltage and current, or $P = VI$. Using the energy and power equations, we can express the law of conservation of energy as shown below. (The subscript "p" represents primary and the subscript "s" represents secondary.)

$$\Delta E_p = \Delta E_s$$

$$P_p t = P_s t$$

$$P_p = P_s$$

substitute $P = VI$

$$V_p I_p = V_s I_s$$

In the above expression, you can see that both sides of the equation have the same terms. Whatever amount of energy goes into the primary coil must come out of the secondary coil. If the number of windings is the same on both sides, the voltages and currents are the same.

In a step-down transformer, the voltage on the secondary coil, V_s, is lower than the voltage on the primary coil, V_p. So, from the equation above and the law of conservation of energy, we can deduce that the current on the secondary side, I_s, must be greater than the current on the primary side, I_p. In a step-up transformer, the voltage on the secondary coil, V_s, is higher than the voltage on the primary coil, V_p. To comply with the law of conservation of energy, the current in the secondary side, I_s, must be less than the current on the primary side, I_p. Therefore, the voltage and current are inversely proportional. For example, if voltage is doubled, current is halved, and vice versa.

Transformer Equations

From the law of conservation of energy we derived the following equation:

$$V_pI_p = V_sI_s$$

Grouping *I* and *V* together gives

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} \text{ (equation 1)}$$

The voltage in the coil is directly proportional to the number of windings, so

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \text{ (equation 2)}$$

where N_p is the number of windings on the primary coil and N_s is the number of windings on the secondary coil. We can also express current in a transformer with respect to the number of windings by combining equations 1 and 2.

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} \quad \text{and} \quad \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Thus,

$$\frac{I_s}{I_p} = \frac{N_p}{N_s}$$

So the current is inversely proportional to the number of windings. We will use these equations in the following Tutorials.

LEARNING TIP

Transformer Equations

You can remember one equation:

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$$

LEARNING TIP

Significant Digits and Windings

The number of windings is an exact number and does not limit the number of significant digits in a calculation.

Tutorial 1 Voltage in a Transformer

We will use the equation $\frac{V_p}{V_s} = \frac{N_p}{N_s}$ to solve a problem involving voltage in a step-down transformer.

Sample Problem 1

A step-down transformer used in an adapter for a laptop has a primary voltage of 120 V. There are 250 windings in the primary coil and 25 windings in the secondary coil. Calculate the voltage in the secondary coil.

Given: $V_p = 120$ V; $N_p = 250$; $N_s = 25$

Required: V_s

Analysis: $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

Rearrange the equation as follows, allowing for easier subsequent rearranging:

$$V_pN_s = V_sN_p$$

Solve for V_s:

$$V_s = \frac{V_pN_s}{N_p}$$

Solution:
$$V_s = \frac{V_pN_s}{N_p}$$
$$= \frac{(120 \text{ V})(25)}{250}$$
$$V_s = 12 \text{ V}$$

Statement: The voltage in the secondary coil is 12 V.

Practice

1. A step-down transformer has a primary voltage of 240 V. The number of windings in the primary coil is 550 and the number of windings in the secondary coil is 110. Determine the voltage of the secondary coil. T/I [ans: 48 V]
2. A step-up transformer has a primary voltage of 31.0 V. The number of windings in the primary coil is 211 and the number of windings in the secondary coil is 844. Determine the voltage of the secondary coil. T/I [ans: 124 V]

Tutorial 2 Current in a Transformer

We will use the equation $\frac{I_s}{I_p} = \frac{V_p}{V_s}$ to solve a problem involving current in a step-down transformer.

Sample Problem 1

A step-down transformer used in the adapter for a cellphone charger has a primary voltage of 120 V and a secondary voltage of 5.0 V. The current in the primary coil is 0.10 A. Calculate the current in the secondary coil.

Given: $V_p = 120$ V; $V_s = 5.0$ V; $I_p = 0.10$ A

Required: I_s

Analysis: $\frac{I_s}{I_p} = \frac{V_p}{V_s}$

Solve for I_s:

$$I_s = \frac{V_p I_p}{V_s}$$

Solution:
$$I_s = \frac{V_p I_p}{V_s} = \frac{(120\ \text{V})(0.10\ \text{A})}{5.0\ \text{V}}$$
$$I_s = 2.4\ \text{A}$$

Statement: The current in the secondary coil is 2.4 A.

Practice

1. A step-down transformer has a primary voltage of 240 V and a secondary voltage of 12 V. The primary current is 0.15 A. Determine the current in the secondary coil. T/I [ans: 3.0 A]
2. A step-up transformer has a primary voltage of 620 V and a secondary voltage of 12 000 V. The current in the secondary coil is 1.3 A. Determine the current in the primary coil. T/I [ans: 25 A]

Transformer Efficiency

The law of conservation of energy states that no energy is lost, but in practice some energy is converted into unusable energy. In a transformer, some of the energy is transformed into unusable thermal energy in the coils, as well as sound energy. Some transformers make a noticeable hum because the transformer core is vibrating. Typically, transformers are better than 90 % efficient. To maximize efficiency, the coils are made from conductors with low resistance, such as copper, and the core is rectangular to ensure that the magnetic field lines go through both coils effectively.

13.5 Summary

- A transformer raises or lowers AC voltage. It consists of a primary coil, a secondary coil, and a soft-iron core.
- Step-down transformers have fewer secondary windings than primary windings and decrease the voltage in the secondary coil.
- Step-up transformers have more secondary windings than primary windings and increase the voltage in the secondary coil.
- The voltage is directly proportional to the number of windings.
- The current is inversely proportional to the number of windings.
- The equations related to transformers are

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}, \quad \frac{I_s}{I_p} = \frac{N_p}{N_s}, \quad \text{and} \quad \frac{I_s}{I_p} = \frac{V_p}{V_s}.$$

13.5 Questions

1. Why do transformers need an alternating current to operate continuously? K/U
2. How can you tell the difference between a step-up and a step-down transformer? K/U
3. A student is discussing transformers and states that the voltage and the current both increase in a step-up transformer. Explain why this is not possible. K/U
4. Suppose that you increase the number of windings on the secondary coil compared to the primary coil. What would you expect the effect on voltage and current to be? K/U
5. Would a device that has the same number of windings on both the primary coil and the secondary coil be classified as a transformer? Explain. K/U
6. Are transformers 100 % efficient? Explain. K/U
7. The number of windings on the primary coil of a transformer is 1.5 times greater than on the secondary coil. The primary coil has a current of 3.0 A and a voltage of 12.0 V. Determine the voltage and current on the secondary coil. T/I
8. Copy **Table 1** into your notebook and find the missing values. T/I

Table 1

Transformer	V_p	V_s	N_p	N_s	I_p	I_s	Step-up or step-down?
1	12 V	120 V	100		1.2 A		
2		110 V	600	100	150 mA		
3	30 V		120		0.28 A	1.68 A	

9. An AC adapter for a laptop has a transformer inside it. It will take a 120 V AC and step it down to 15.0 V AC. Determine the ratio of primary windings to secondary windings in the transformer. T/I