Applied Physics For Engineers

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# Efficiency

Any device, circuit, system, or machine that utilizes electricity to perform some useful function does so by converting work or energy to some other form. The energy or work that must be supplied to achieve a desired outcome is called the *input*, and the modified form of work or energy that represents that outcome is the *output*. Following are some familiar examples:

1. An electric motor
   Input: Electrical energy.
   Output: Work, in the form of a force rotating a mechanical load.
2. An electric generator
   Input: Work, in the form of a force rotating an armature.
   Output: Electrical energy.
3. An electronic amplifier
   Input: Electrical energy, obtained from a dc power supply.
   Output: Electrical energy in the form of ac voltages and currents.
4. A dc power supply
   Input: Electrical energy in the form of ac voltage and current.
   Output: Electrical energy in the form of dc voltage and current.
5. An electric heater
   Input: Electrical energy.
   Output: Heat energy.
6. A public address (PA) system
   Input: Electrical energy.
   Output: Sound energy.
7. An incandescent lamp
   Input: Electrical energy.
   Output: Light energy.

In the process of converting work or energy from one form to a different form, it is inevitably the case that some energy is *lost*, in the sense that it is converted to a form different from that which constitutes useful output. For example, in an electric motor, some of the electrical energy supplied as input is converted to heat, because the motor has resistance. That energy is not converted to useful ouput (work), and it is therefore called a *loss*. On the other hand, in an electric heater the desired output is heat energy, and the loss is light energy, manifesting itself in the glow of the heater element. The desired output of an incandescent lamp is light energy, and the heat it produces is a loss. We can see that the form of energy we call a "loss" depends entirely on how output is defined.

When output and input are both expressed in the same units of work or energy, *efficiency* is defined to be the ratio of the two:

$$\eta = \frac{W_o}{W_i} \tag{3.9}$$

where $\eta$ is efficiency (often expressed as a percent by multiplying 3.9 by 100%), $W_o$ is output work or energy, and $W_i$ is input work or energy. Since losses are inevitable, $W_o$ is always less than $W_i$, and we conclude that *$\eta$ is always less than 1*. In other words, every system is less than 100% efficient. In spite of a long history of claims by amateur inventors to have developed machines capable of producing more energy than they consume ($W_o > W_i$), it is ***never*** possible for $\eta$ to be greater than 1. The total energy supplied to a system equals the sum of the output energy and the losses:

$$W_i = W_o + W_L \tag{3.10}$$

where $W_L$ is sum of all energy losses. Using (3.10), we can rewrite (3.9) in the equivalent forms:

$$\eta = \frac{W_o}{W_o + W_L} = \frac{W_i - W_L}{W_i} = 1 - \frac{W_L}{W_i} \tag{3.11}$$

If we divide input work or energy by the time $t$ during which it is furnished to a system, we obtain the rate at which that work or energy is furnished, that is, the ***input power*** $P_i$:

$$P_i = \frac{W_i}{t} \quad \text{watts} \tag{3.12}$$

Similarly, output power, $P_o$, is

$$P_o = \frac{W_o}{t} \quad \text{watts} \tag{3.13}$$

Dividing numerator and denominator of equation (3.9) by $t$, we obtain

$$\eta = \frac{W_o/t}{W_i/t} = \frac{P_o}{P_i} \tag{3.14}$$

Thus, efficiency can be computed as the ratio of output power to input power. Also, regarding $W_L/t$ as power loss $P_L$ (the rate at which energy is lost), we can write equation (3.11) as

$$\eta = \frac{P_o}{P_o + P_L} = \frac{P_i - P_L}{P_i} = 1 - \frac{P_L}{P_i} \tag{3.15}$$

## Example 3.9

Mechanical energy is supplied to a dc generator at the rate of 4200 J/s. The generator delivers 32.2 A at 120 V.

(a) What is the percent efficiency of the generator?
(b) How much energy is lost per minute of operation?

**SOLUTION**

(a) $P_i = 4200\ \text{J/s} = 4200\ \text{W}$

$P_o = EI = (120\ \text{V})(32.2\ \text{A}) = 3864\ \text{W}$

$$\eta = \frac{P_o}{P_i} = \frac{3864\ \text{W}}{4200\ \text{W}} = 0.92, \text{ or } 92\%$$

(b) $P_L = P_i - P_o = 4200\ \text{W} - 3864\ \text{W} = 336\ \text{W}$

$W_L = P_L t = (336\ \text{J/s})(60\ \text{s}) = 20{,}160\ \text{J}$

**Drill Exercise 3.9**

If the generator in Example 3.9 were 98% efficient, how much current would it supply at 120 V?

**ANSWER:** 34.3 A.

## Horsepower

Although not in the SI system, the units of horsepower (hp) are widely used to specify the output power of electric motors. The relationship between horsepower and watts is

$$1 \text{ hp} = 746 \text{ W} \tag{3.16}$$

When one speaks of a motor as having a certain horsepower, it is understood that the horsepower specification refers to *output* power. When using equation (3.14) to compute the efficiency of a motor, both $P_i$ and $P_o$ must be expressed in watts, or both must be expressed in hp.

**Example 3.10**

What is the efficiency of a $\frac{1}{2}$-hp motor that draws 3.5 A from a 120-V source?

**SOLUTION**

$$P_o = (0.5 \text{ hp})\left(\frac{746 \text{ W}}{1 \text{ hp}}\right) = 373 \text{ W}$$

$$P_i = EI = (120 \text{ V})(3.5 \text{ A}) = 420 \text{ W}$$

$$\eta = \frac{P_o}{P_i} = \frac{373 \text{ W}}{420 \text{ W}} = 0.888 \quad \text{or} \quad 88.8\%$$

**Drill Exercise 3.10**

How much energy is lost in the motor of Example 3.10 when it is operated for 1h?

**ANSWER:** $16.92 \times 10^4$ J.

When the output of one device or system is the input to another, the two are said to be in *cascade*. The overall efficiency of several such cascaded components is the *product* of their individual efficiencies.

**Example 3.11**

Figure 3.11 shows an electric motor driving an electric generator. The 2-hp motor draws 14.6 A from a 120-V source and the generator supplies 56 A at 24 V.

(a) Find the motor efficiency and the generator efficiency.
(b) Find the overall efficiency.

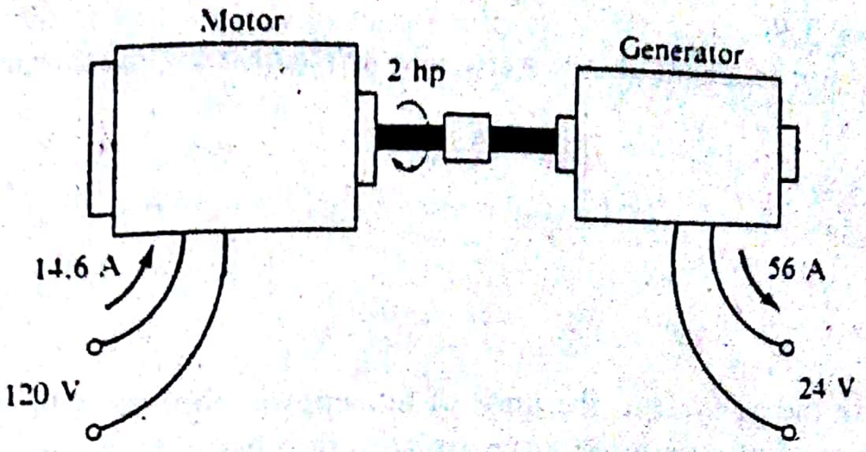


**FIGURE 3.11** (Example 3.11)

**SOLUTION**

(a)
$$P_i(\text{motor}) = (120\ \text{V})(14.6\ \text{A}) = 1752\ \text{W}$$
$$P_o(\text{motor}) = (2\ \text{hp})(746\ \text{W/hp}) = 1492\ \text{W}$$
$$\eta(\text{motor}) = \frac{1492\ \text{W}}{1752\ \text{W}} = 0.8516$$
$$P_i(\text{generator}) = 2\ \text{hp} = 1492\ \text{W}$$
$$P_o(\text{generator}) = (24\ \text{V})(56\ \text{A}) = 1344\ \text{W}$$
$$\eta(\text{generator}) = \frac{1344\ \text{W}}{1492\ \text{W}} = 0.90$$

(b)
$$\eta(\text{overall}) = \frac{P_o(\text{generator})}{P_i(\text{motor})} = \frac{1344\ \text{W}}{1752\ \text{W}} = 0.767$$

Note that $\eta$(overall) is the product of the efficiencies of the individual machines:

$$\eta(\text{overall}) = (0.8516)(0.90) = 0.767$$

### Drill Exercise 3.11

If the overall efficiency of the motor and generator in Example 3.11 were 48.02% and if the generator were twice as efficient as the motor, what would be the efficiency of each?

**ANSWER:** $\eta(\text{motor}) = 49\%$; $\eta(\text{generator}) = 98\%$. □

## Real and Ideal Sources

An *ideal* voltage source is one that maintains a constant terminal voltage no matter how much current is drawn from it. For example, an ideal 12-V source would theoretically maintain 12 V across its terminals when a 1-MΩ resistor is connected (so $I = 12\ \text{V}/1\ \text{M}\Omega = 12\ \mu\text{A}$), as well as when a 1-kΩ resistor is connected

($I$ = 12 mA), or when a 1-Ω resistor is connected ($I$ = 12 A), and even when a 0.01-Ω resistor is connected ($I$ = 1200 A). It is not possible to construct an ideal voltage source, because all *real* voltage sources have *internal resistance* that causes the terminal voltage to drop if the current is made sufficiently large (i.e., if a small enough resistance is connected across the terminals). Nevertheless, it is convenient when analyzing electric circuits to assume that a real voltage source behaves like an ideal one. That assumption is justified by the fact that in circuit analysis we are not usually concerned with changing current over a wide range of values (if, in fact, we are concerned with any current change at all).

## Voltage Regulation

In applications where the current drawn from a voltage source may vary over a wide enough range to cause the terminal voltage to change, we must have some knowledge of how great that change is liable to be. One measure of how well a voltage source maintains a constant output voltage is the percent change in voltage that occurs as a result of some specified variation in current. This measure is called percent *voltage regulation*. The percent change in voltage is that which occurs due to a change in current from zero amperes, called the *no-load* condition, to the maximum rated current of the source, called the *full-load* condition (see Figure 3.12). Percent voltage regulation (% VR) is thus computed as

$$\% \text{ VR} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% \tag{3.17}$$

where $V_{NL}$ is the no-load voltage and $V_{FL}$ is the full-load voltage. It is clear that an ideal source has *zero* percent voltage regulation.

mcq

### Example 3.12

A certain power supply is specified to have a voltage regulation of 1.2%. If its no-load voltage is 15 V, what is its full-load voltage?

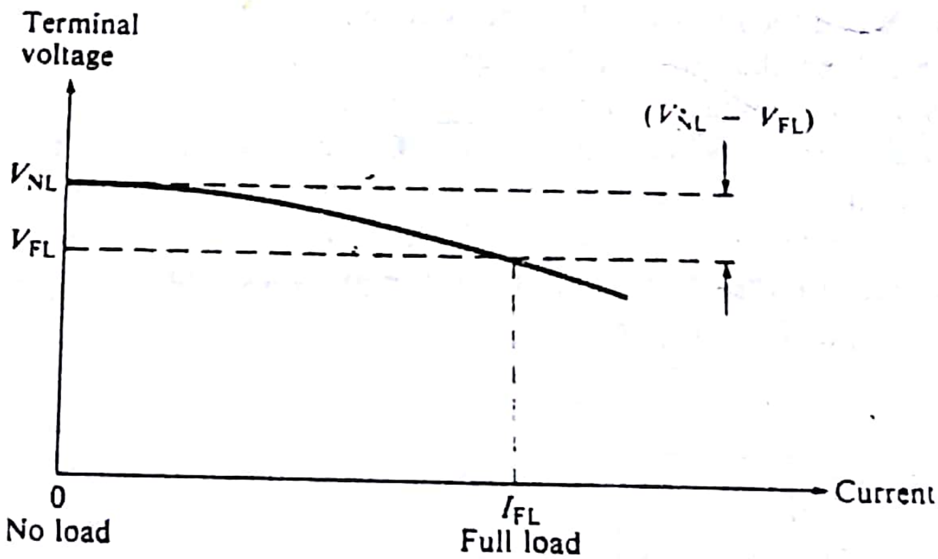


**FIGURE 3.12** Typical plot of the variation in output voltage of a real voltage source as the current varies from no load to full load.

**SOLUTION** Using the decimal form of equation (3.17), we have

$$0.012 = \frac{15 - V_{FL}}{V_{FL}}$$

Solving for $V_{FL}$ gives

$$V_{FL} = \frac{15}{1.012} = 14.822 \text{ V}$$

### Drill Exercise 3.12

What is the no-load voltage of a power supply if its voltage regulation is 1% and its full-load voltage is 25 V?

**ANSWER:** 25.25 V. □

## Current Sources

An *ideal current source*, also called a constant-current source, will supply the same current to any resistance connected across its terminals. Figure 3.13 shows the symbol used to represent an ideal current source. The arrow shows the direction of the (conventional) current produced by the source.

Since an ideal current source supplies the same current to any resistance, it is clear that the voltage across the terminals of the source must change if the resistance is changed. For example, if a 2-A current source has 10 Ω across its terminals, the voltage is $E = (2\text{ A})(10\ \Omega) = 20$ V. If the resistance is changed to 100 Ω, the voltage becomes $E = (2\text{ A})(100\ \Omega) = 200$ V. An ideal current source cannot be constructed because a real current source always has some internal resistance that causes the current to drop if the voltage developed across the terminals becomes sufficiently large (i.e., if the resistance connected across the terminals is made too large). However, in practical circuit analysis it is convenient to assume that current sources are ideal, unless a wide range of resistance values must be considered.

Unlike a voltage source, which we can imagine as two oppositely charged electrodes (Figure 2.3), it is difficult to visualize the structure of a current source. However, as we will learn in a later chapter, a real current source can always be replaced by (i.e., is *equivalent* to) a real voltage source having certain characteristics. In other words, we can regard a current source as a convenient fiction that aids in solving circuit problems, yet feel secure in the knowledge that the current source could always be replaced by an equivalent voltage source, if so desired. Voltage and current sources are called *active* components, because they furnish electrical energy to a circuit. In contrast, a resistor is an example of a *passive* component.

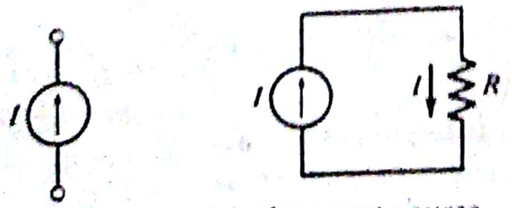


**FIGURE 3.13** Ideal current source.

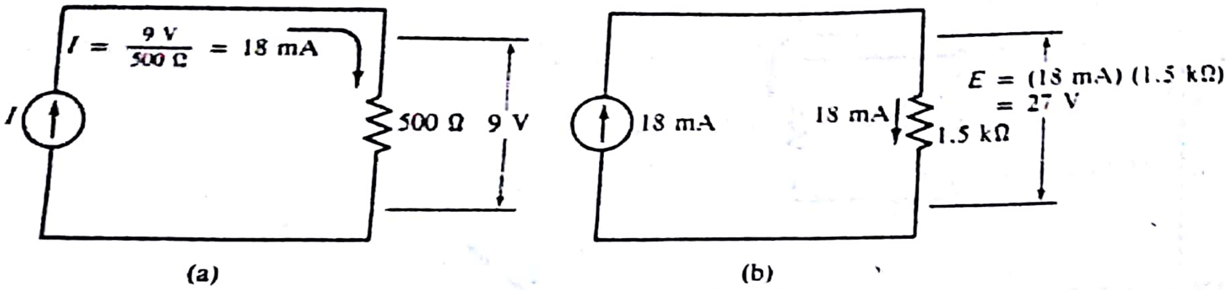


**FIGURE 3.14** (Example 3.13)

## Example 3.13

A constant-current source develops a terminal voltage of 9 V when a 500-Ω resistor is connected across its terminals. What is its terminal voltage when the 500-Ω resistor is replaced by a 1.5-kΩ resistor?

**SOLUTION** As shown in Figure 3.14(a), we use Ohm's law to find the value of the current when the 500-Ω resistor is connected:

$$I = \frac{E}{R} = \frac{9\ \text{V}}{500\ \Omega} = 18\ \text{mA}$$

Since the current remains constant at 18 mA when the 1.5-kΩ resistor is connected, as shown in Figure 3.14(b), the terminal voltage becomes

$$E = IR = (18\ \text{mA})(1.5\ \text{k}\Omega) = 27\ \text{V}$$

## Drill Exercise 3.13

What is the maximum voltage that could be expected across a 120-Ω 5% resistor when it is connected across a 400-mA constant-current source?

**ANSWER:** 50.4 V.