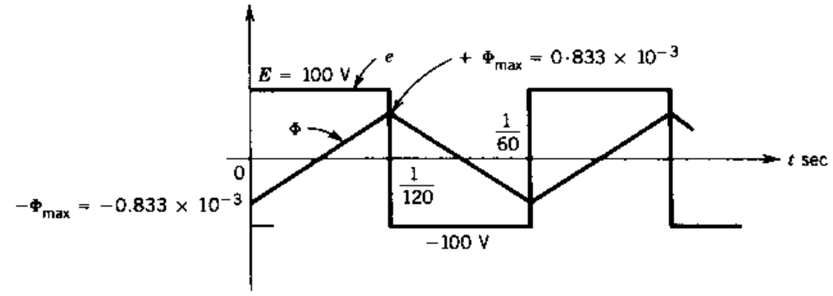

FIGURE E1.7

$$\Phi_{\max} = \frac{100}{1000 \times 120}\,\text{Wb}$$
$$= 0.833 \times 10^{-3}\,\text{Wb}$$

The waveforms of voltage and flux are shown in Fig. E1.7.

**(b)**

$$B_{\max} = 1.2\,\text{T}$$
$$\Phi_{\max} = B_{\max} \times A = 1.2 \times 0.001 = 1.2 \times 10^{-3}\,\text{Wb}$$
$$N(2\Phi_{\max}) = E \times \frac{1}{120}$$
$$E = 120 \times 500 \times 2 \times 1.2 \times 10^{-3}$$
$$= 144\,\text{V} \quad ■$$

## 1.3.1 EXCITING CURRENT

If the coil of Fig. 1.17*a* is connected to a sinusoidal voltage source, a current flows in the coil to establish a sinusoidal flux in the core. This current is called the *exciting current*, $i_\Phi$. If the $B$–$H$ characteristic of the ferromagnetic core is nonlinear, the exciting current will be nonsinusoidal.

### No Hysteresis

Let us first consider a $B$–$H$ characteristic with no hysteresis loop. The $B$–$H$ curve can be rescaled ($\Phi = BA$, $i = Hl/N$) to obtain the $\Phi$–$i$ curve for the core, as shown in Fig. 1.18*a*. From the sinusoidal flux wave and the $\Phi$–$i$ curve, the exciting current waveform is obtained, as shown in Fig. 1.18*a*. Note that the exciting current $i_\phi$ is nonsinusoidal, but it is in phase with the flux wave and is symmetrical with respect to voltage $e$. The fundamental component $i_{\phi 1}$ of the exciting current lags the voltage $e$ by 90°. Therefore no power loss is involved. This was expected, because the hysteresis loop, which

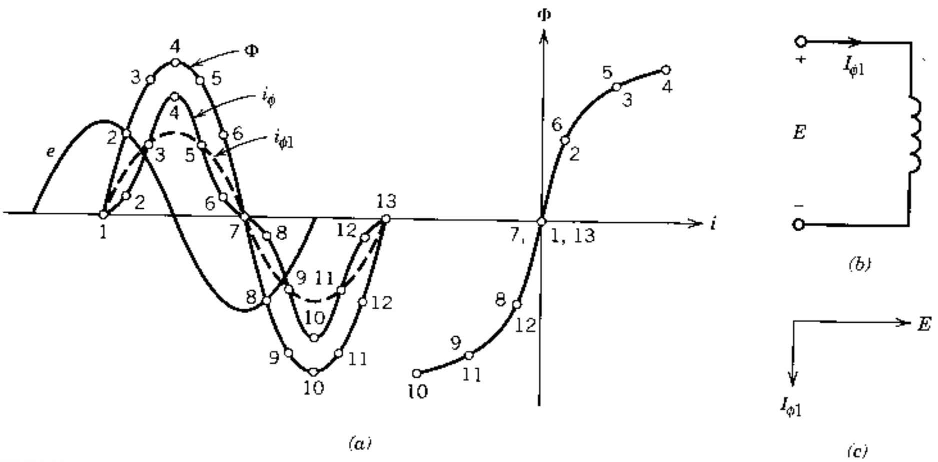

**FIGURE 1.18** Exciting current for no hysteresis. (a) Φ–$i$ characteristic and exciting current. (b) Equivalent circuit. (c) Phasor diagram.

represents power loss, was neglected. The excitation current is therefore a purely lagging current and the exciting winding can be represented by a pure inductance, as shown in Fig. 1.18*b*. The phasor diagram for fundamental current and applied voltage is shown in Fig. 1.18*c*.

### With Hysteresis

We shall now consider the hysteresis loop of the core, as shown in Fig. 1.19*a*. The waveform of the exciting current $i_\phi$ is obtained from the sinusoidal flux waveform and the multivalued Φ–$i$ characteristic of the core. The exciting current is nonsinusoidal as well as nonsymmetrical with respect to the voltage waveform. The exciting current can be split into two components, one ($i_c$) in phase with voltage $e$ accounting for the core loss and the other ($i_m$) in phase with Φ and symmetrical with respect to $e$, accounting for the magnetization of the core. This magnetizing component $i_m$ is the same as the exciting current if the hysteresis loop is neglected. The phasor diagram is shown in Fig. 1.19*b*. The exciting coil can therefore be represented by a resistance $R_c$, to represent core loss, and a magnetizing inductance $L_m$, to represent the magnetization of the core, as shown in Fig. 1.19*c*. In the phasor diagram only the fundamental component of the magnetizing current is considered.

## 1.4 PERMANENT MAGNET

A permanent magnet is capable of maintaining a magnetic field without any excitation mmf provided to it. Permanent magnets are normally alloys of

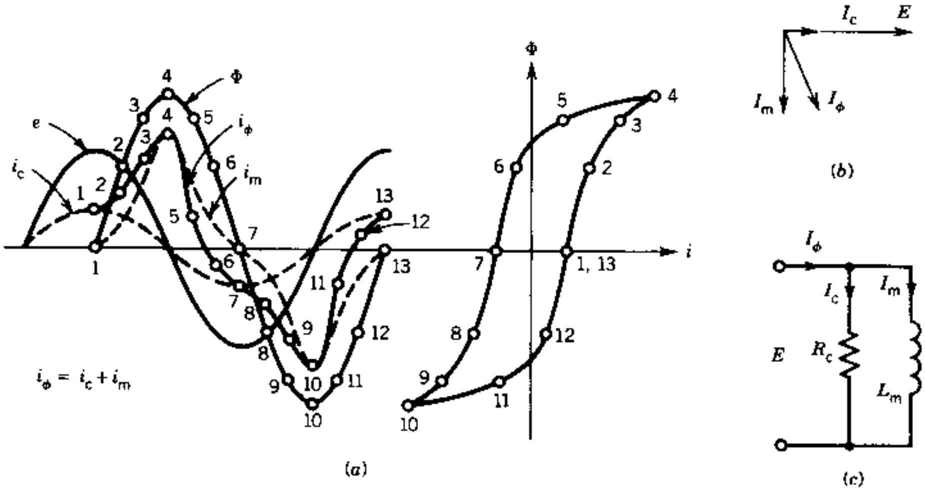

**FIGURE 1.19** Exciting current with hysteresis loop. (a) Φ–$i$ loop and exciting current. (b) Phasor diagram. (c) Equivalent circuit.

iron, nickel, and cobalt. They are characterized by a large $B$–$H$ loop, high retentivity (high value of $B_r$), and high coercive force (high value of $H_c$). These alloys are subjected to heat treatment, resulting in mechanical hardness of the material. Permanent magnets are often referred to as *hard iron* and other magnetic materials as *soft iron*.

## 1.4.1 MAGNETIZATION OF PERMANENT MAGNETS

Consider the magnetic circuit shown in Fig. 1.20*a*. Assume that the magnet material is initially unmagnetized. A large mmf is applied, and on its removal the flux density will remain at the residual value $B_r$ on the magnetization curve, point $a$ in Fig. 1.20*b*. If a reversed magnetic field intensity of magnitude $H_1$ is now applied to the hard iron, the operating point moves to point $b$. If $H_1$ is removed and reapplied, the $B$–$H$ locus follows a minor loop as shown in Fig. 1.20*b*. The minor loop is narrow and for all practical purposes can be represented by the straight line $bc$, known as the *recoil line*. This line is almost parallel to the tangent $xay$ to the demagnetizing curve at point $a$. The slope of the recoil line is called the *recoil permeability* $\mu_{\text{rec}}$. For alnico magnets it is in the range of 3–5$\mu_0$, whereas for ferrite magnets it may be as low as $1.2\mu_0$.

As long as the reversed magnetic field intensity does not exceed $H_1$, the magnet may be considered reasonably permanent. If a negative magnetic field intensity greater than $H_1$ is applied, such as $H_2$, the flux density of the permanent magnet will decrease to the value $B_2$. If $H_2$ is removed, the operation will move along a new recoil line $de$.