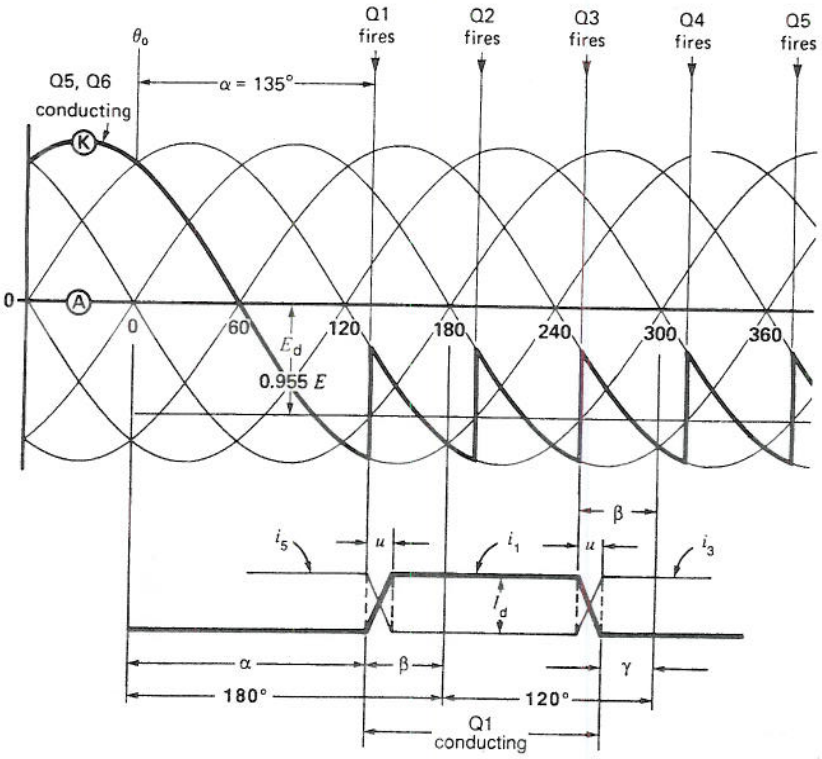

Figure 21.50
Waveshape of i_1 in thyristor Q1 for a delay angle α. The extinction angle γ permits Q1 to establish its blocking ability before the critical angle of 300° is reached. At 300° the anode of Q1 becomes positive with respect to its cathode. The figure also shows the relationship between angles α, β, γ, and u.

In the case of an inverter, we often define the firing instant by the *angle of advance* β, rather than by the angle of delay α. From Fig. 21.50 it can be shown that the following relationships exist between the commutation angle u, the delay angle α, the angle of advance β, and the extinction angle γ:

$$\beta = 180 - \alpha \tag{21.15}$$

$$\beta = u + \gamma \tag{21.16}$$

DC-TO-DC SWITCHING CONVERTERS

21.36 Semiconductor switches

So far we have studied circuits in which the electronic switching is accomplished by thyristors. We saw that one of its shortcomings was that conduction only stopped when the anode current dropped naturally to zero. Although it is possible to force the anode current to zero by special techniques, such as mentioned in Section 21.18, the additional circuit components make this solution cumbersome and expensive. Another problem is that thyristor switching is limited to a maximum of about 2 kHz.

To overcome this problem, special semiconductor switches have been developed whereby conduction can be initiated or blocked by controlling the gate current or gate voltage. These devices are constantly being improved upon, but we will limit our attention to those that are most frequently used. As mentioned in the introduction to this chapter, they are GTOs, bipo-

lar transistors, power MOSFETs, and IGBTs. These controllable on/off switching devices enable us to design dc-to-dc and dc-to-ac converters of extraordinary versatility. The basic principles of these switch-type converters are explained in the ensuing sections.

Thyristor and GTO Basic Characteristics Apart from their important gate turn-off feature, GTOs are very similar to ordinary thyristors. The characteristics of both these devices in the on and off states are illustrated in Fig. 21.51. Thus, in the off state, when the current is zero the thyristor can withstand both forward and reverse blocking voltages E_{AK}, up to the maximum limits bounded by the cross-hatched bands (Fig. 21.51a). During the on state, when the thyristor conducts, the figure shows that the E_{AK} voltage drop is about 2 V, and the upper limit of the anode current I_{AK} is again indicated by the cross-hatched band. These bands merely indicate the broad-brush maximum values that are currently available. Most thyristors are designed to operate far within the limits shown.

Fig. 21.51b shows that GTOs are able to withstand forward voltages but not reverse blocking voltages. Furthermore, the voltage drop is about 3 V compared to 2 V for thyristors. As in the case of a thyristor, conduction in a GTO is initiated by injecting a positive current pulse into the gate. In order to keep conducting, the anode current must not fall below the *holding current* of the GTO. However, the GTO is a device in which the anode current can be blocked by injecting a strong negative current into the base for a few microseconds. To ensure extinction, the amplitude of the gate pulse has to be about one-third the value of the anode current. GTOs are high-power switches, some of which can handle currents of several thousand amperes at voltages of up to 4000 V.

BJT Basic Characteristics The bipolar junction transistor, or BJT, is designated bipolar because conduction is due to the migration of both electrons and holes within the device. The transistor has three terminals named collector C, emitter E, and base B (Fig. 21.52). The collector current I_C that flows from collector to emitter is initiated and maintained by causing a sustained current I_B to flow into the base. When operated as a switch, the base current must be large enough to drive the BJT into *saturation*. Under these conditions, the voltage E_{CE} between the collector and emitter is about 2 to 3 volts, at rated collector current. Conduction ceases as soon as the base current is suppressed. The characteristics

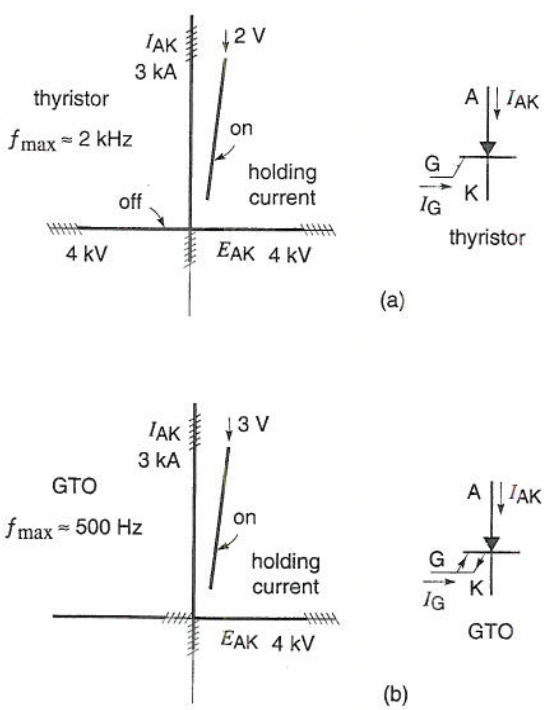

Figure 21.51
Typical properties and approximate limits of GTOs and thyristors in the on and off states.

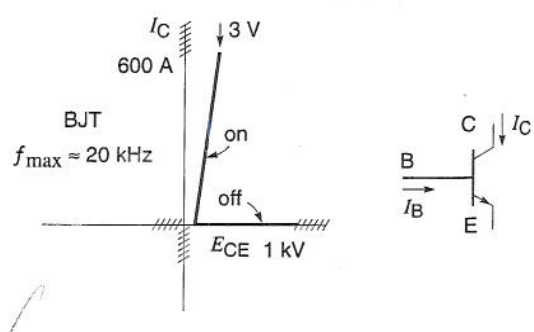

Figure 21.52
Typical properties and approximate limits of BJTs.

of the BJT in the on and off states are shown in Fig. 21.52, together with the approximate limits of the collector-emitter voltage E_{CE} and collector current I_C. Note that the transistor cannot tolerate negative values of E_{CE}. Power transistors can carry currents of several hundred amperes and withstand E_{CE} voltages of about 1 kV. To establish collector currents of 100 A, the corresponding base current is typically about 1 A.

MOSFET Basic Characteristics The power MOSFET is a voltage-controlled three-terminal device having an anode and cathode, respectively called drain D, source S, and gate G (Fig. 21.53). The drain current I_D is initiated by applying and maintaining a voltage E_{GS} of about 12 V between the gate and the source. Conduction stops whenever E_{GS} falls below a threshold limit (about 1 V). The gate currents are extremely small; consequently, very little power is needed to drive this electronic switch. The characteristics in the on and off states are shown in Fig. 21.53, together with typical maximum limits of drain voltage E_{DS} and drain current I_D. The MOSFET cannot tolerate negative values of E_{DS} To meet this requirement, it has incorporated within it a reverse-biased diode, as shown in the symbol for the device. Power MOSFETs can carry drain currents of about a hundred amperes and withstand E_{CE} voltages of about 500 V. At rated current, when driven into saturation, the E_{DS} voltage drop ranges from about 2 V to 5 V.

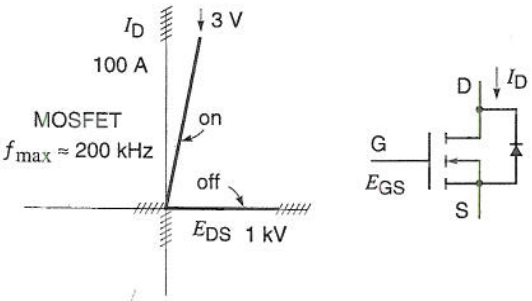

Figure 21.53
Typical properties and approximate limits of MOSFETs.

IGBT Basic Characteristics The IGBT is also a voltage-controlled switch whose terminals are identified the same way as those in a transistor, namely collector, emitter, and base. The characteristics in the on and off states are shown in Fig. 21.54, together with the limiting voltages and current. The collector current in an IGBT is much higher than in a MOSFET. Consequently, the IGBT can handle more power.

Compared to GTOs, an important feature of BJTs, MOSFETs, and IGBTs is their fast turn-on and turn-off times. This enables these switches to be used at much higher frequencies. As a result, the associated transformers, inductors, and capacitors are smaller and cheaper. Typical maximum frequencies are shown in Figs. 21.51 to 21.54. Another advantage of high-speed switching is that the semiconductor switches can generate lower-frequency voltages and currents whose waveshapes and phase can be tailored to meet almost any requirement.

21.37 DC-to-DC switching converter

In some power systems there is a need to transform dc power from one dc voltage level to either a higher or lower dc level. For example, in a public transportation system, a 4000 V dc overhead line may be the source to drive a 300 V dc motor in a bus. In other cases, a 12 V battery may have to power a device rated at 120 V dc. In alternating-current systems the voltage step-up or step-down can easily be done with a transformer. But in dc sys-

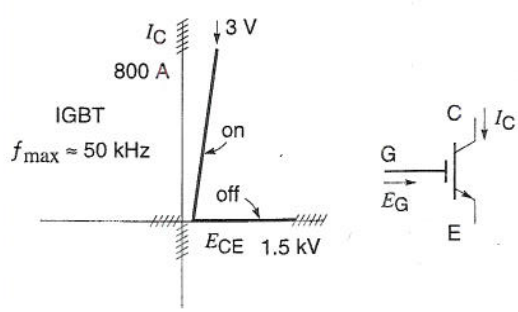

Figure 21.54
Typical properties and approximate limits of IGBTs.

tems, an entirely different approach is required. It involves the use of a dc-to-dc switching converter, sometimes called a *chopper*.

Suppose that power has to be transferred from a high-voltage dc source E_S to a lower-voltage dc load E_0. One solution is to connect an inductor between the source and the load and to open and close the circuit periodically with a switch (Fig. 21.55). In order to follow the transfer of energy, assume the switch closes for a time T_1. During this interval, the voltage across the inductor is $E_S - E_0$, with polarities as shown in Fig. 21.56. The inductor accumulates volt-seconds, and the resulting current i increases at a constant rate given by

$$i = \frac{(E_S - E_0)\,t}{L}$$

After a time T_1 (when i has reached a value I_a, say, and the switch is about to open), the current is

$$I_a = (E_S - E_0)\,T_1/L \qquad (21.17)$$

The corresponding magnetic energy stored in the inductor is

$$W = \frac{1}{2} L I_a^2 \qquad (2.8)$$

When the switch opens (Fig. 21.57) the current collapses and all the stored energy is dissipated in the arc across the switch. At the same time, a high voltage e_L is induced across the inductor because the current is collapsing so quickly. The polarity of this voltage is *opposite* to what it was when the current was increasing (compare Figs. 21.56 and 21.57). The high negative voltage indicates that the inductor is rapidly discharging the volt-seconds it had previously accumulated. As a result, the current decreases very quickly.

Although some energy is transferred from the source E_S to the load E_0 while the switch is closed, there is a great loss of energy every time the switch opens. The efficiency is therefore poor.

We can prevent this energy loss by adding a diode to the circuit as shown in Fig. 21.58. When the switch closes, the current rises to I_a as before. The diode has no effect because its cathode is positive with respect to the anode and so the diode does not conduct. When the switch opens, current i again begins to fall, inducing a voltage e_L. However, e_L cannot jump to the high value it reached before because as soon as it exceeds E_0, the anode of the diode becomes positive

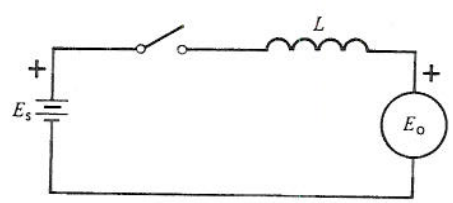

Figure 21.55
Energy transfer using an inductor.

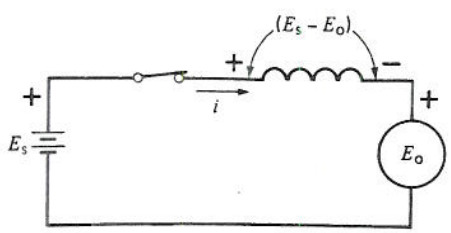

Figure 21.56
Energy is stored in the inductor.

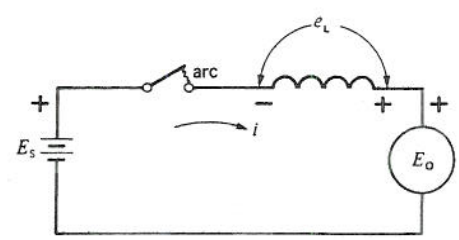

Figure 21.57
Energy is dissipated in the arc. Note the polarity of e_L.

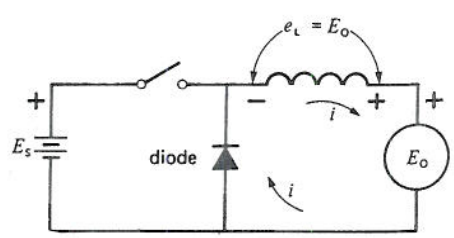

Figure 21.58
Energy transferred without loss.

and so the diode begins to conduct. Assuming the diode voltage drop is negligible, it follows that $e_L = E_0$. Because E_0 is constant, the voltage across the inductor is also constant. Starting from I_a, current i therefore falls at a uniform rate given by

$$i = I_a - \frac{E_0 t}{L} \qquad (2.27)$$

The current eventually becomes zero after a time T_2. We can calculate T_2 because the volt-seconds accumulated during the charging period T_1 must equal the volt-seconds released during the discharge interval T_2. Referring to Fig. 21.59, we have

V·s during charge period = V·s during discharge period

$$A_{(+)} = A_{(-)}$$

$$(E_S - E_0)\, T_1 = E_0 T_2$$

Consequently,

$$T_2 = \frac{(E_S - E_0)\, T_1}{E_0} \qquad (21.18)$$

When the current is zero, the inductor will have delivered all its stored energy to load E_0. Simultaneously, the diode will cease to conduct. We can therefore reclose the switch for another interval T_1 and repeat the cycle indefinitely. Consequently, this circuit enables us to transfer energy from a high-voltage dc source to a lower-voltage dc load without incurring any losses. In effect, the inductor absorbs energy at a relatively high voltage $(E_S - E_0)$ and delivers it at a lower voltage E_0.

The diode is sometimes called a *freewheeling diode* because it automatically starts conducting as soon as the switch opens and stops conducting when the switch closes.

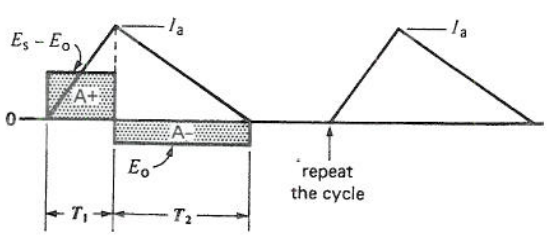

Figure 21.59
E and *I* in the inductor of Fig. 21.58.

The switch is actually a GTO, MOSFET, or IGBT, whose on/off state is controlled by a signal applied to the gate. The combination of the electronic switch, inductor, and diode constitutes what is known as a step-down dc-to-dc converter, or *buck chopper*.

21.38 Rapid switching

Instead of letting the load current swing between zero and I_a, we can close the switch for a short period T_1 (as in Fig. 21.59) until the current reaches the desired value I_a. We then open and close the switch rapidly so that the current increases and decreases by small increments. Referring to Fig. 21.60a, the switch is closed for an interval T_a and open during an interval T_b. When the switch is open, the load current falls from its peak value I_a to a lower value I_b. During this interval, current flows in the inductor, the load, and the freewheeling diode. The current decreases at the same rate as it did in Fig. 21.59.

When the current has fallen to a value I_b, the switch recloses. Because the cathode of the diode is now (+), the current in the diode immediately stops flowing, and the source now supplies current I_b. The current then builds up and when it reaches the value I_a (after a time T_a), the switch reopens. The freewheeling diode again comes into play and the cycle repeats. The current supplied to the load fluctuates therefore between I_a and the slightly lower value I_b (Fig. 21.60b). Its average or dc value I_0 is nearly equal to I_a, but the exact value is given by

$$I_0 = (I_a + I_b)/2 \qquad (21.19)$$

Whereas the current in the load is essentially constant, having only a small ripple (Fig. 21.60b), the current supplied by the source is composed of a series of sharp pulses, as shown in Fig. 21.60c. What is the average value of these pulses? It is found by noting that the average current during each *pulse* (duration T_a) is $(I_a + I_b)/2 = I_0$. Consequently, the average current I_S during one *cycle* (time T) is

$$I_S = I_0\,(T_a/T)$$

that is

$$I_S = I_0\, D \qquad (21.20)$$

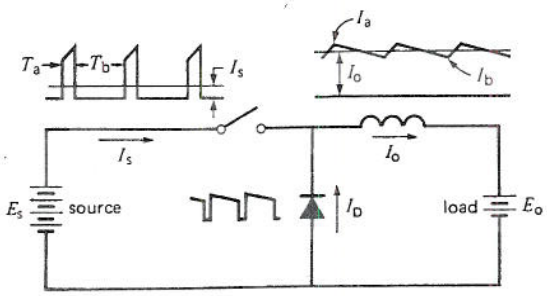

Figure 21.60a
Currents in a chopper circuit.

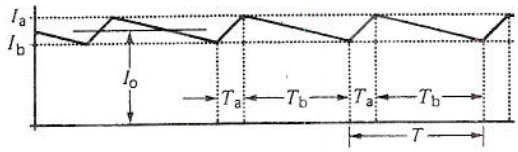

Figure 21.60b
Current in the load.

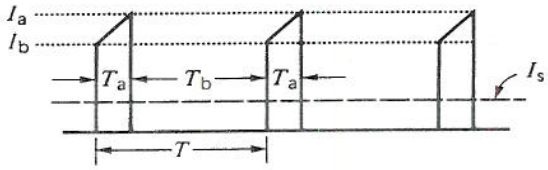

Figure 21.60c
Current pulses provided by the source.

where

I_S = dc current drawn from the source [A]
I_0 = dc current absorbed by the load [A]
T_a = *on* time of the switch [s]
T = period of one cycle [s]
D = duty cycle = T_a/T

The circuit of Fig. 21.60a shows the current waveshapes in the source, the load, and the diode. Although the waveshapes are choppy and discontinuous, they still obey Kirchhoff's current law, instant by instant.

Turning our attention to the power aspects, the dc power drawn from the source must equal the dc power absorbed by the load because, ideally, there is no power loss in the switch, the inductor, or the freewheeling diode. We can, therefore, write

$$E_S I_S = E_0 I_0$$

If we substitute Eq. 21.20 in the above equation, we obtain

$$E_0 = E_S \frac{I_S}{I_0} = E_S \frac{T_a}{T}$$

which gives the important relationship

$$E_0 = DE_S \tag{21.21}$$

where

E_0 = dc output voltage of the converter [V]
E_S = dc voltage of the source [V]
D = duty cycle

Equation 21.21 signifies that the dc output voltage E_0 can be controlled simply by varying the duty cycle D. Thus, the converter behaves like a highly efficient dc transformer in which the "turns ratio" is D. For a given switching frequency, this ratio can be changed as needed by varying the *on* time of the switch.

In practice, the mechanical switch is replaced by an electronic switch, such as an IGBT. It can be turned on and off at a frequency that may be as high as 50 kHz. If more power is required, a GTO is used, wherein the frequency could be of the order of 300 Hz.

Example 21-10 T = 50 mS

The switch in Fig. 21.60a opens and closes at a frequency of 20 Hz and remains closed for 3 ms per cycle. A dc ammeter connected in series with the load E_0 indicates a current of 70 A.

a. If a dc ammeter is connected in series with the source, what current will it indicate?
b. What is the average current per pulse?

Solution

a. Using Eq. 21.20, we have

$$\text{period } T = \frac{1}{20} = 50 \text{ ms}$$

$$\text{duty cycle} = \frac{T_a}{T} = \frac{3}{50} = 0.06$$

$$I_S = I_0 D$$
$$= 70 \times 0.06$$
$$= 4.2 \text{ A}$$

b. The average current during each *pulse* (duration T_a) is 70 A. Considering that the average current is only 4.2 A, the source has to be specially designed to supply such a high 70 A pulse. In most cases a large capacitor is connected across the terminals of the source. It can readily furnish the high current pulses as it discharges.

Example 21-11

We wish to charge a 120 V battery from a 600 V dc source using a dc chopper. The average battery current should be 20 A, with a peak-to-peak ripple of 2 A. If the chopper frequency is 200 Hz, calculate the following:

a. The dc current drawn from the source
b. The dc current in the diode
c. The duty cycle
d. The inductance of the inductor

Solution

The circuit diagram is shown in Fig. 21.61a and the desired battery current is given in Fig. 21.61b. It fluctuates between 19 A and 21 A, thus yielding an average of 20 A with a peak-to-peak ripple of 2 A.

a. The power supplied to the battery is

$$P = 120\text{ V} \times 20\text{ A} = 2400\text{ W}$$

The power supplied by the source is, therefore, 2400 W.

The dc current from the source is

$$I_S = P/E_S = 2400/600 = 4\text{ A}$$

b. To calculate the average current in the diode, we refer to Fig. 21.61a. Current I_0 is 20 A and I_S was found to be 4 A. By applying Kirchhoff's current law to the diode/inductor junction, the average diode current I_D is

$$I_D = I_0 - I_S$$
$$= 20 - 4$$
$$= 16\text{ A}$$

c. The duty cycle is

$$D = E_0/E_S = 120/600 = 0.2$$
$$T = 1/f = 1/200 = 5\text{ ms}$$

Consequently, the *on* time T_a is

$$T_a = DT = 0.2 \times 5\text{ ms} = 1\text{ ms}$$

The waveshapes of I_S and I_D are shown in Figs. 21.61c and 21.61d, respectively. Note the sharp pulses delivered by the source.

d. During interval T_a the average voltage across the inductor is $(600 - 120) = 480$ V.

The volt-seconds accumulated by the inductor during this interval is $A_{(+)} = 480\text{ V} \times 1\text{ ms} = 480\text{ mV·s} = 0.48\text{ V·s}$. The change in current during the interval is 2 A; consequently,

$$\Delta I = A_{(+)}/L \qquad (2.28)$$
$$2 = 0.48/L$$
$$L \geq 0.24\text{ H}$$

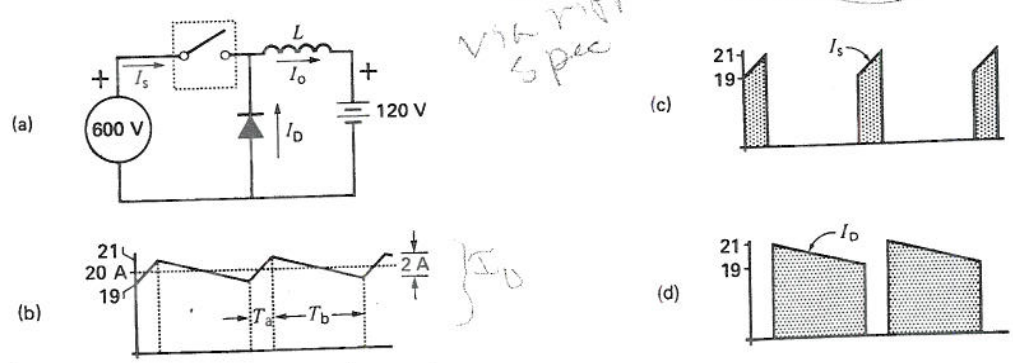

Figure 21.61
a. Circuit of Example 21-11.
b. Current in the load.
c. Current drawn from the source.
d. Current in the freewheeling diode.