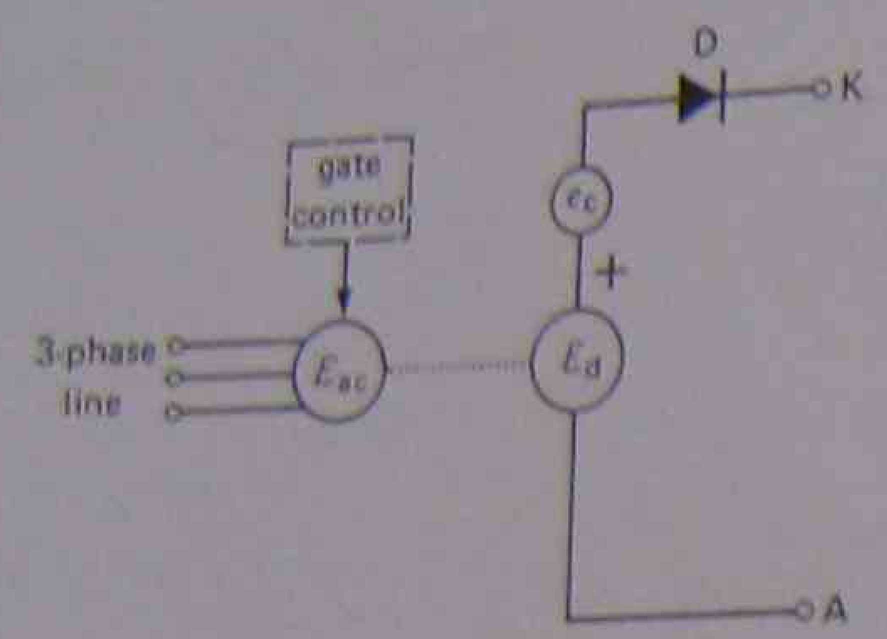

Figure 21-55
Equivalent circuit of a converter.

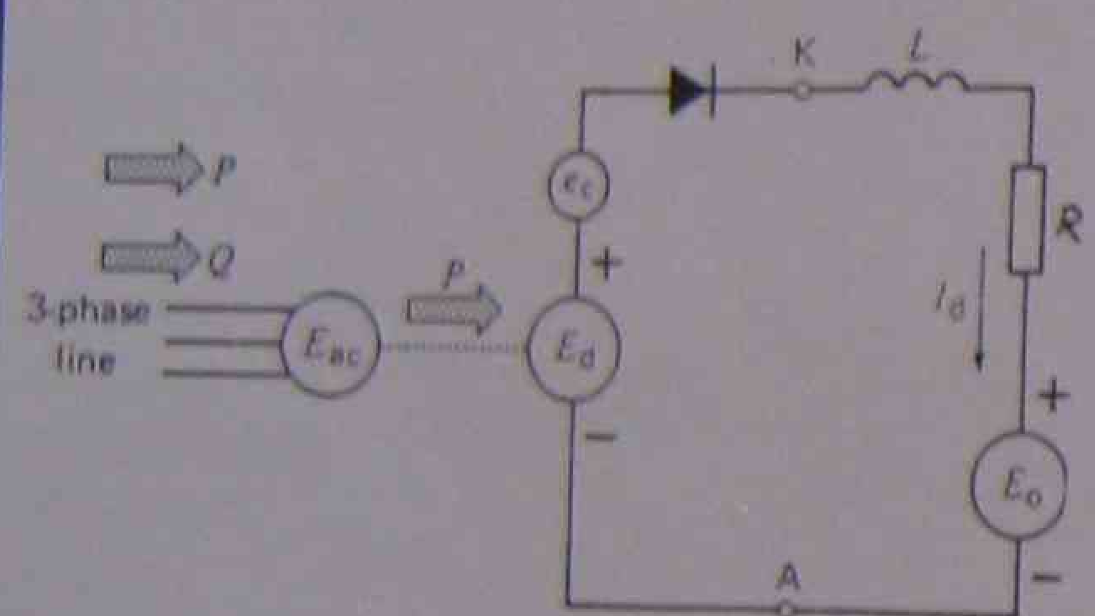

Figure 21-56
Equivalent circuit of a 3-phase converter in the rectifier mode.

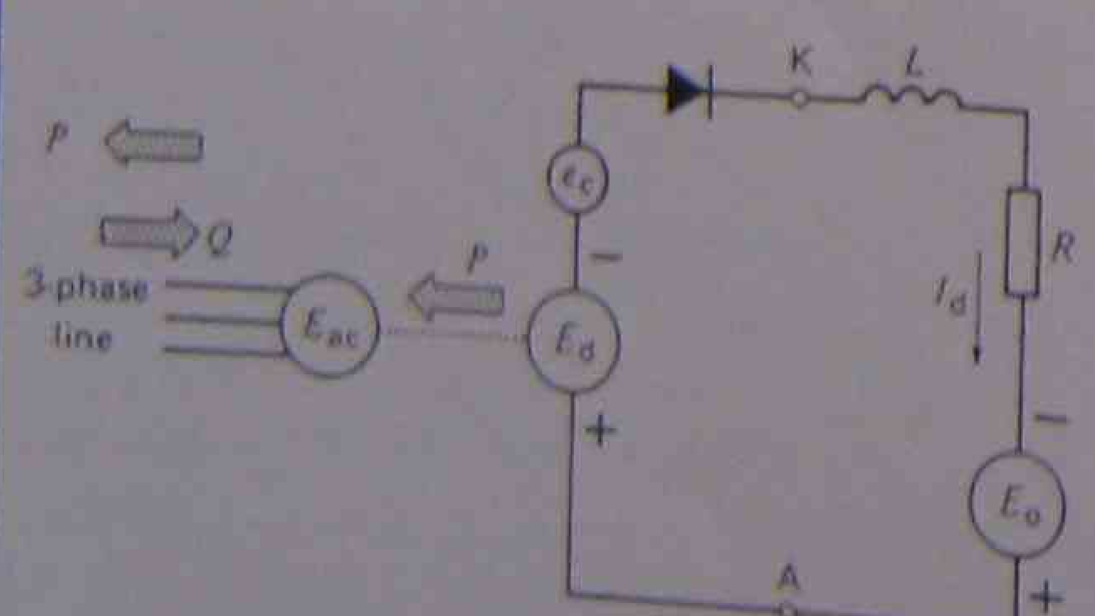

Figure 21-57
Equivalent circuit of a 3-phase converter in the inverter mode.

21.31 Equivalent circuit of a converter

We may think of a converter as being a s[...] ac/dc motor-generator set whose dc output vol[tage] E_d changes both in magnitude and pola[rity] depending upon the gate pulse delay. Ho[w]ever, the dc "generator" has some spe[cial] properties:

1. it can carry current in only one direction
2. it generates an increasingly large ac rip[ple] voltage as the dc voltage decreases.

The analogy may be represented by the c[ir]cuit of Fig. 21-55, in which:

- E_{ac} represents the 3-phase line voltage
- E_d is the dc voltage generated by the co[n]verter
- e_c is the ac voltage generated by the co[n]verter (mainly 6th and 12th harmonics)
- D is a diode to remind us that current c[an] flow in only one direction
- The dotted line between E_{ac} and E_d indicat[es] that active power can flow between the a[c] and dc systems.
- Unlike a motor/generator set, the dc and a[c] systems are not electrically isolated fro[m] each other.

When the converter is operating as a re[cti]fier, the equivalent circuit is shown [in] Fig. 21-56. When operating as in inverter [the] circuit is given by Fig. 21-57. The ac vol[tage] generated by the converter appears acr[oss] inductor L. Its inductance is sufficiently la[rge to] ensure an almost ripple-free dc current.

$$Q = P \tan \alpha \qquad (21\text{-}1[\ldots])$$

where

Q = reactive power absorbed by the converter [var]

P = dc power of the converter (positive for a rectifier, negative for an inverter) [W]

α = triggering angle [°]

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21.32 Currents in a 3-phase, 6-pulse converter

Figure 21-58 shows the voltage and current waveshapes when the converter functions as a rectifier at a firing angle of 45°. The current i_1, i_2, i_3, i_4, i_5, i_6 in each thyristor flows for 120° and its peak value is equal to the dc current I_d. This holds true for any firing angle between zero and 180°. Consequently, the currents in a thyristor converter are identical to those in a plain 3-phase diode rectifier (Fig. 21-20). The only difference is that they flow later in the cycle.

The waveshapes of the corresponding ac line currents are easily found because they are equal to the difference between the respective thyristor currents. Thus, referring to Fig. 21-52, line current $I_a = i_1 - i_4$. These line currents also have a peak value I_d, but they flow in positive and negative pulses of 120°.

21.33 Power factor

When the currents are in phase with the voltages, the so-called *displacement power factor* is 100%. As a result, the rectifier draws no reactive power from the line. The same remarks apply to a 3-phase, 6-pulse rectifier (Fig. 21-20)

Referring now to Fig. 21-58, where triggering has been delayed by 45°, we note that the thyristor currents have all been shifted ("displaced") by 45°, to the right. Consequently, the line currents lag the respective voltages by 45°; the displacement power factor is no longer unity but only 0.707 (cos 45° = 0.707). This means that a converter absorbs reactive power from the ac system to which it is connected. This is true whether the converter operates as a rectifier or inverter. The reactive power is given by:

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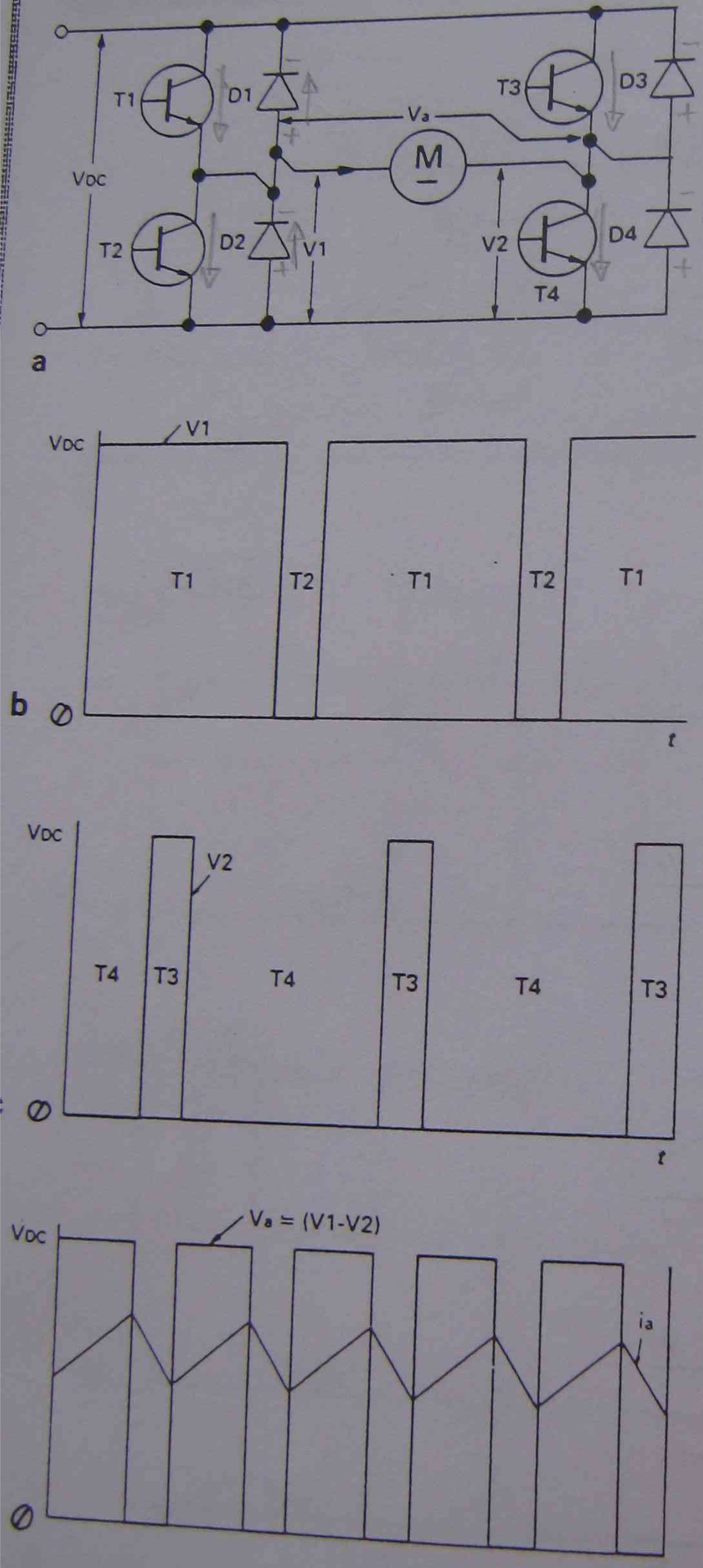
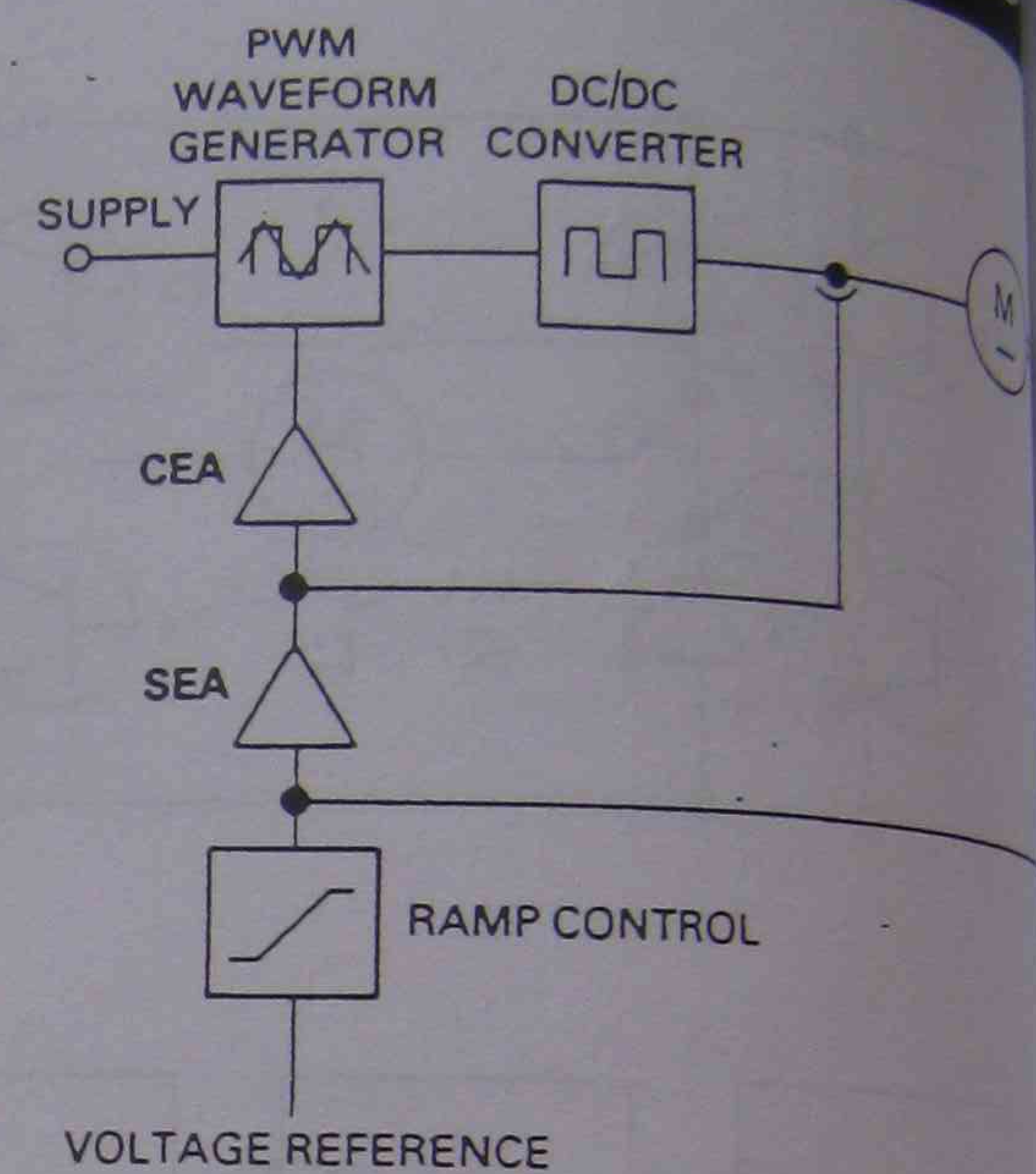
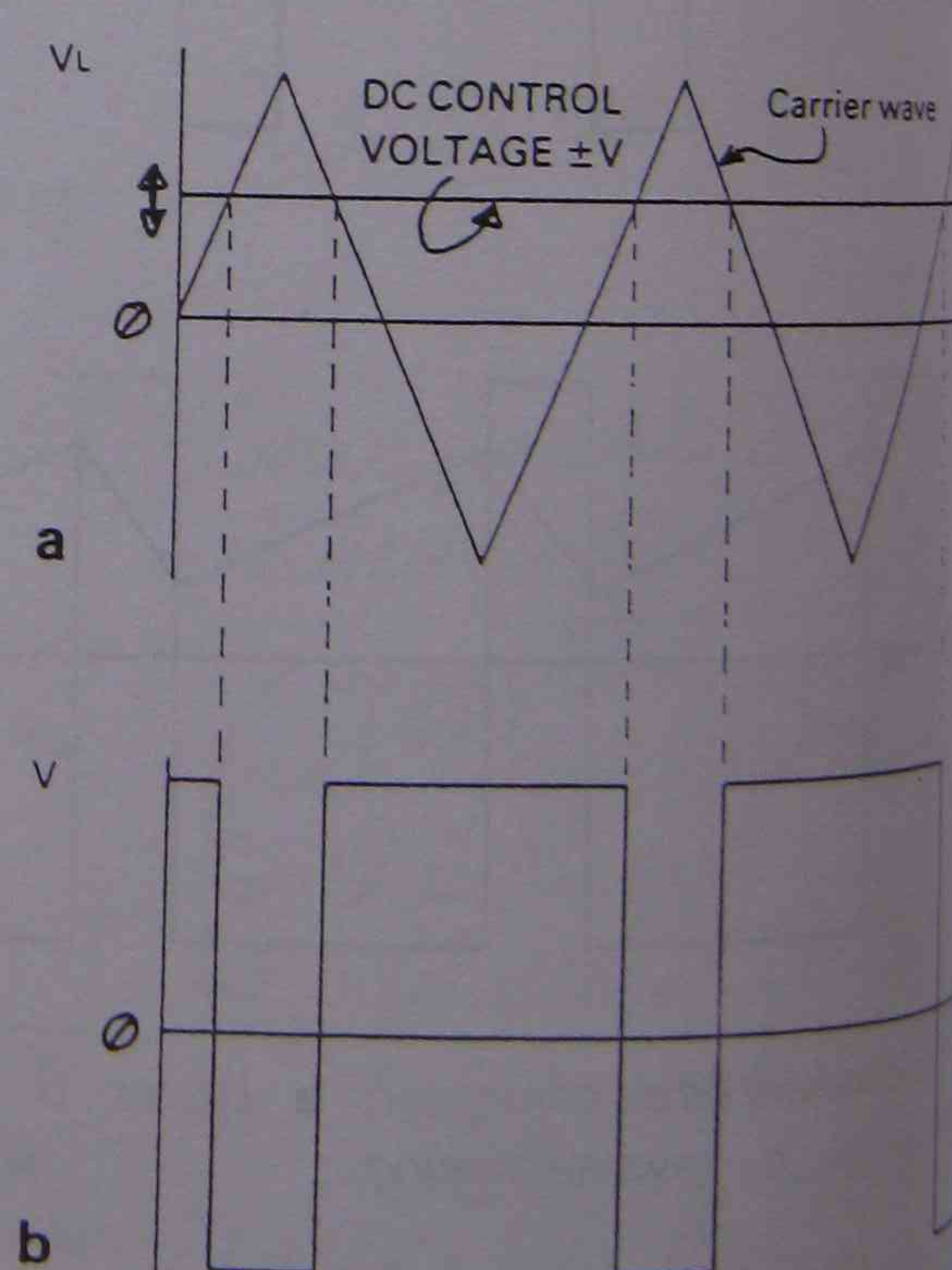


Double-edged modulation; **a** circuit; **b** conduction periods of T1 and T2; **c** conduction periods of T3 and T4; **d** resultant output.



6 *Typical transistor dc drive, control loops.*



7 *PWM waveform generation;* **a** *carrier wave, control voltage;* **b** *converter transistor control waveform.*

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The step-down chopper in Fig. 9-1a only allows power to flow from the supply to the load, and is referred to as class A chopper. Depending on the directions of current and voltage flows, choppers can be classified into five types:

Class A chopper
Class B chopper
Class C chopper
Class D chopper
Class E chopper

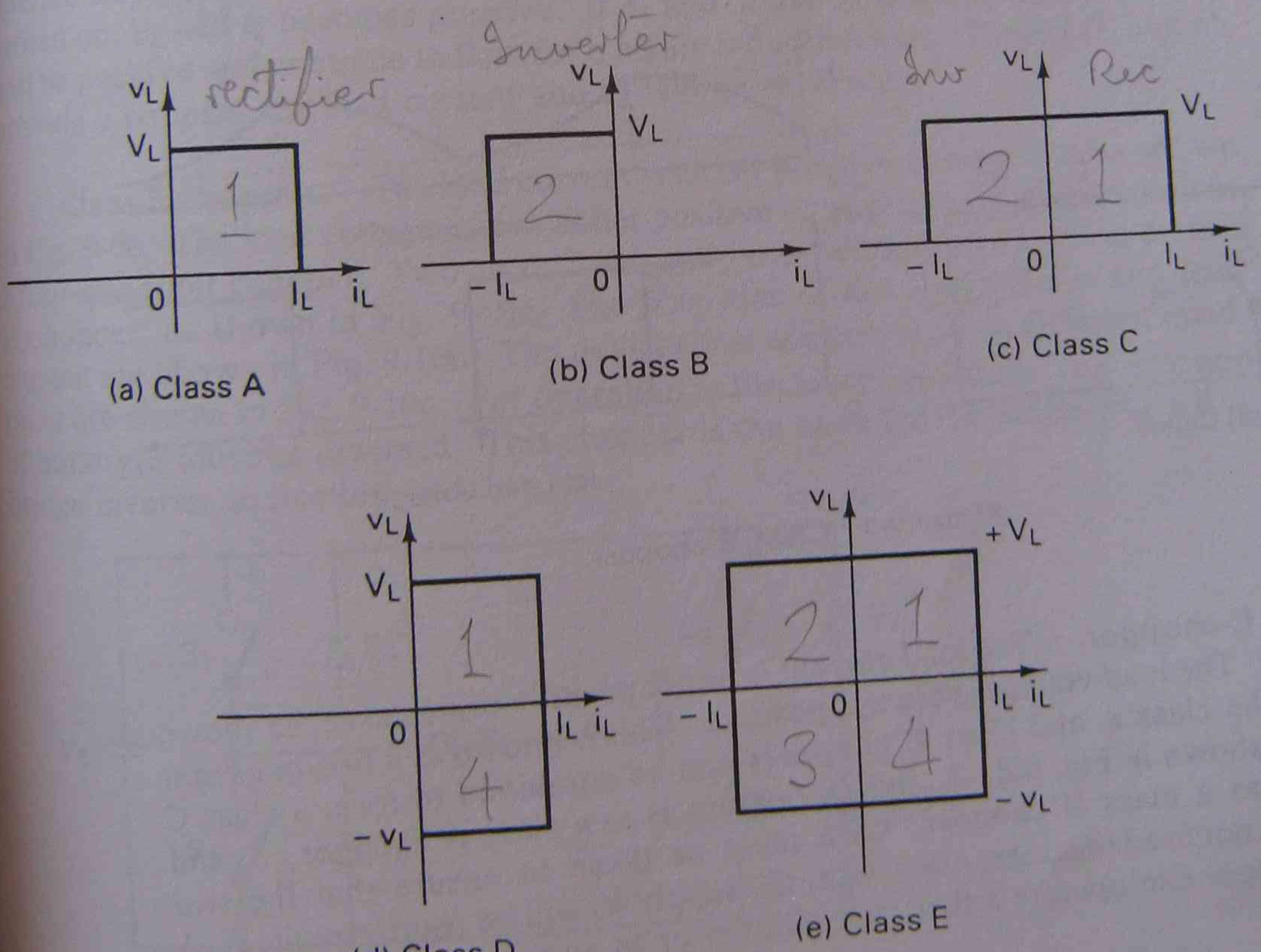

Figure 9-6 Chopper classification.

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Class A chopper. The load current flows into the load. Both the load voltage and the load current are positive, as shown in Fig. 9-6a. This is a single-quadrant chopper and is said to be operated as a rectifier.

Class B chopper. The load current flows out of the load. The load voltage is positive, but the load current is negative, as shown in Fig. 9-6b. This is also a single-quadrant chopper, but operates in the second quadrant and is said to be operated as an inverter. A class B chopper is shown in Fig. 9-7a, where the battery E is a part of the load and may be the back emf of a dc motor.

When switch S_1 is turned on, the voltage E drives current through inductor L and load voltage v_L becomes zero. The instantaneous load voltage v_L and load voltage E combine to forward bias D_1 and supply power back to the supply.

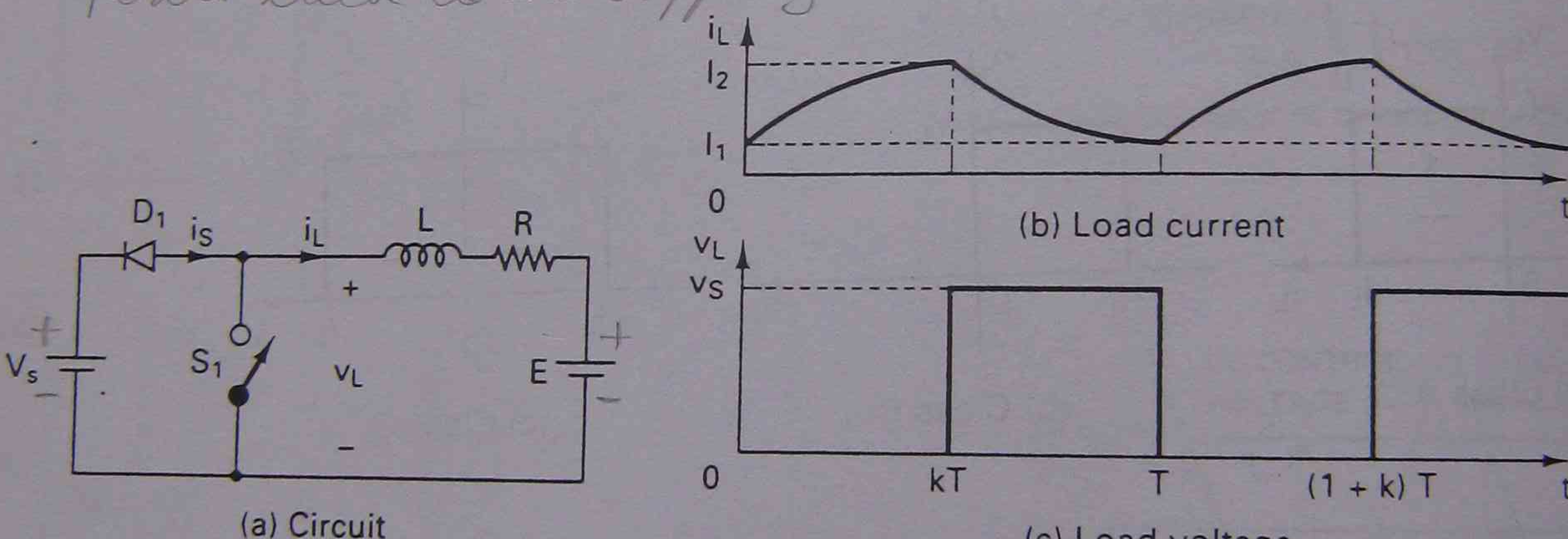
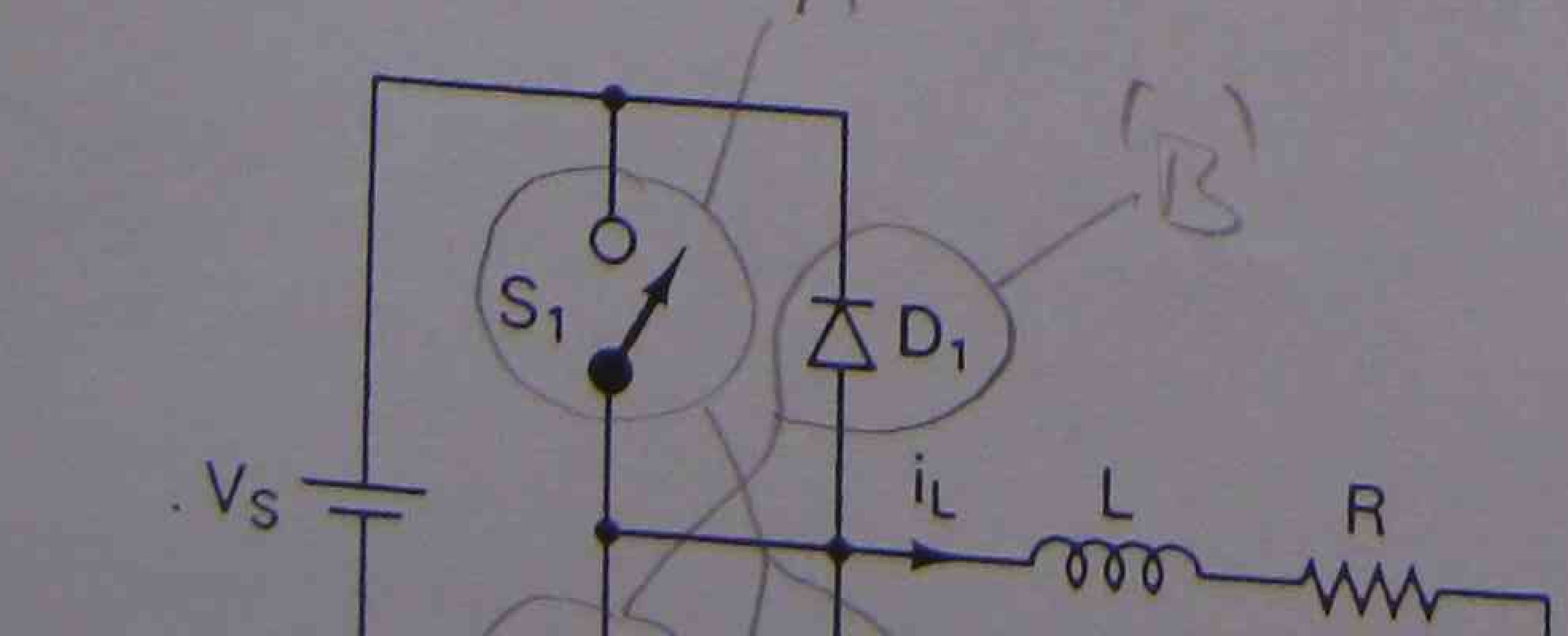


Figure 9-7 Class B chopper.

Class C chopper. The load current is either positive or negative, as shown in Fig. 9-6c. The load voltage is always positive. This is known as a *two-quadrant chopper*. The class A and class B choppers can be combined to form a class C chopper as shown in Fig. 9-8. S_1 and D_2 operate as as a class A chopper. S_2 and D_1 operate as a class B chopper. Care must be taken to ensure that the two switches are not fired together; otherwise, the supply V_s will be short-circuited. A class C chopper can operate either as a rectifier or as an inverter.



Class A chopper. The load current flows into the load. Both the load voltage and the load current are positive, as shown in Fig. 9-6a. This is a single-quadrant chopper and is said to be operated as a rectifier.

Class B chopper. The load current flows out of the load. The load voltage is positive, but the load current is negative, as shown in Fig. 9-6b. This is also a single-quadrant chopper, but operates in the second quadrant and is said to be operated as an inverter. A class B chopper is shown in Fig. 9-7a, where the battery E is a part of the load and may be the back emf of a dc motor.

When switch S_1 is turned on, the voltage E drives current through inductor L and load voltage v_L becomes zero. The instantaneous load voltage v_L and load

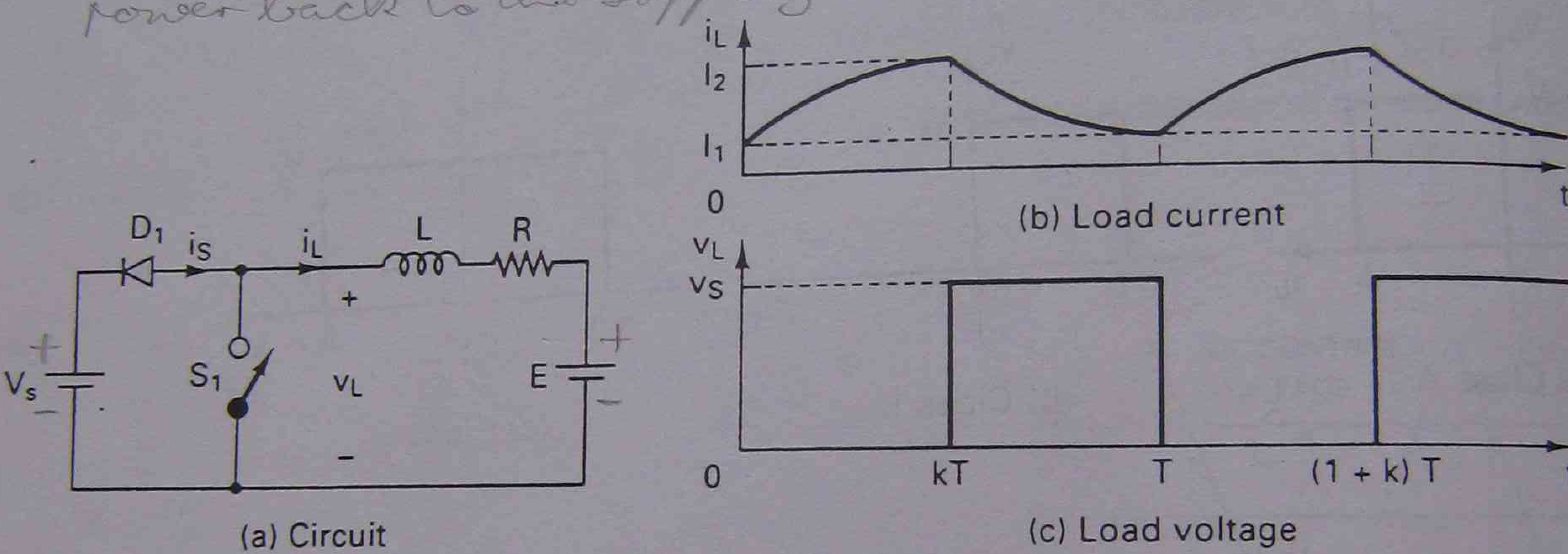
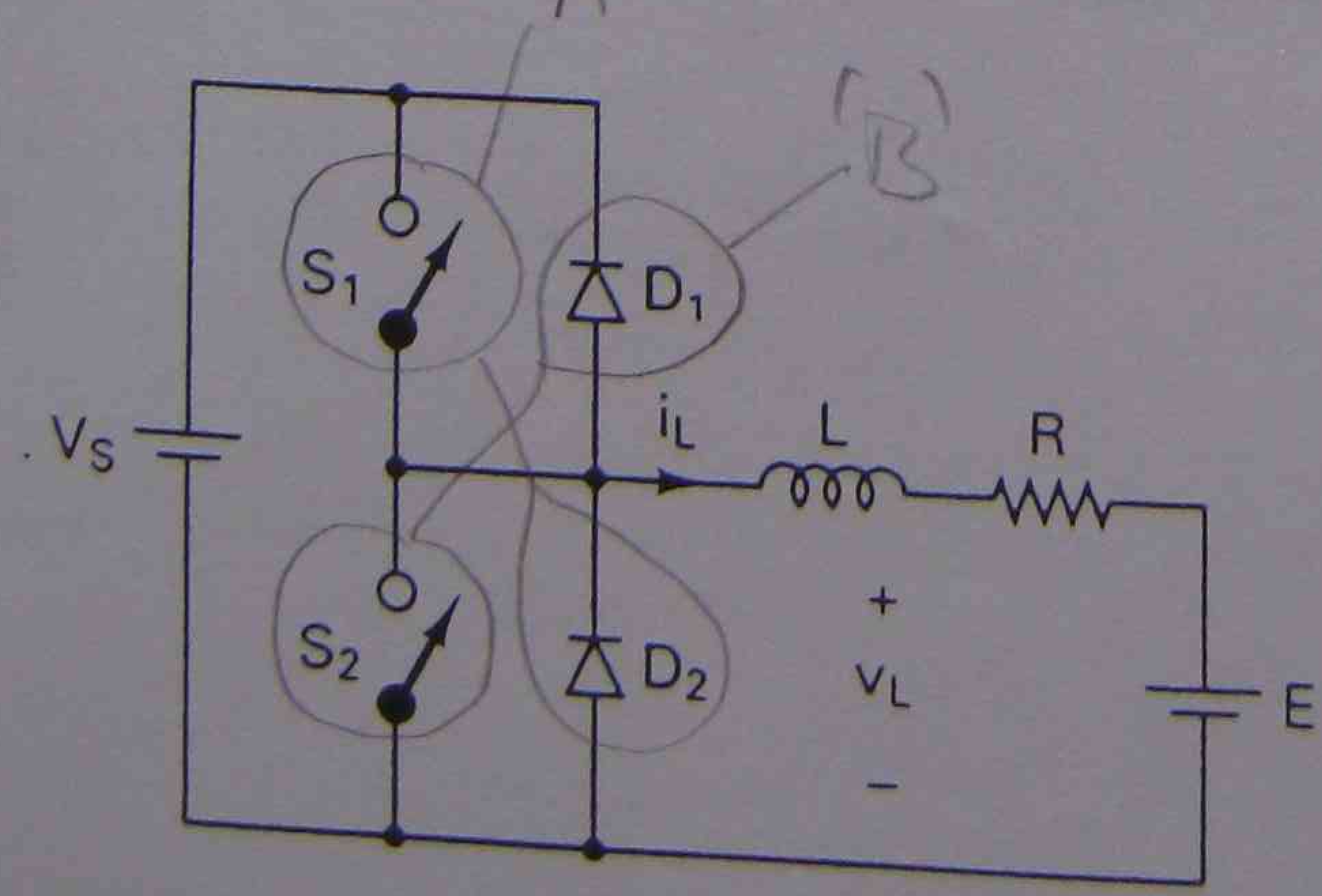


Figure 9-7 Class B chopper.

Class C chopper. The load current is either positive or negative, as shown in Fig. 9-6c. The load voltage is always positive. This is known as a *two-quadrant chopper*. The class A and class B choppers can be combined to form a class C chopper as shown in Fig. 9-8. S_1 and D_2 operate as as a class A chopper. S_2 and D_1 operate as a class B chopper. Care must be taken to ensure that the two switches are not fired together; otherwise, the supply V_s will be short-circuited. A class C chopper can operate either as a rectifier or as an inverter.



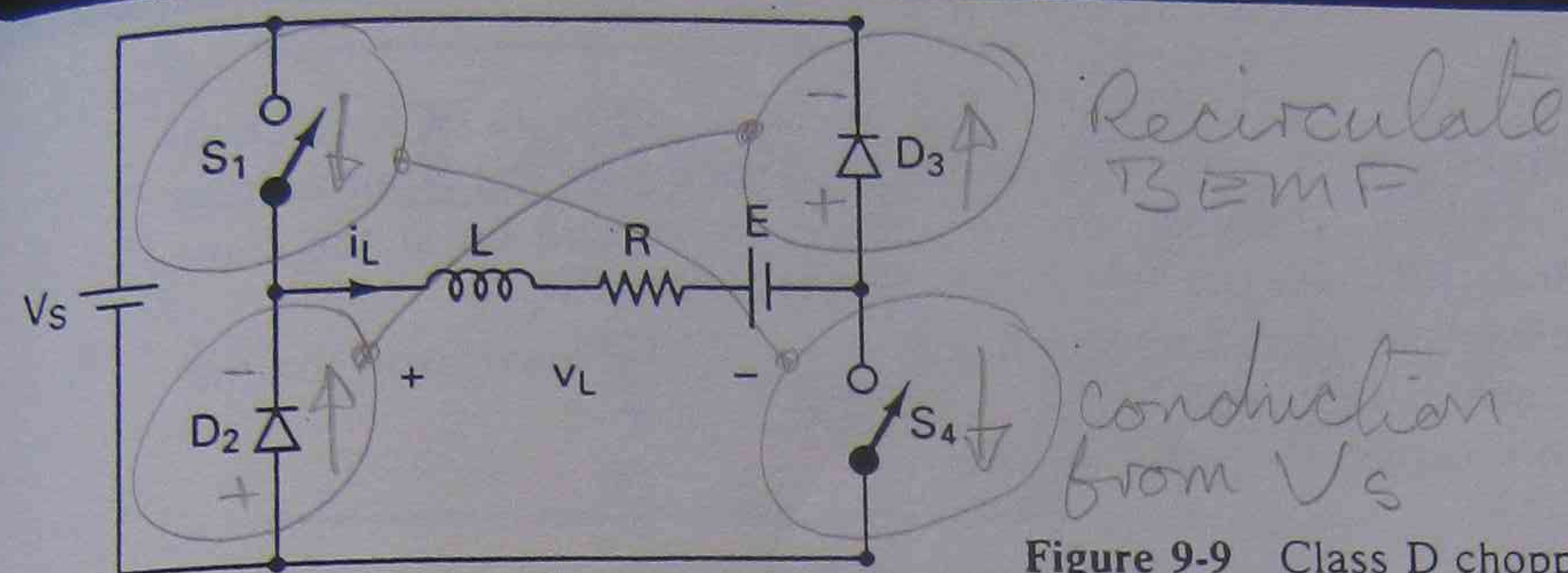
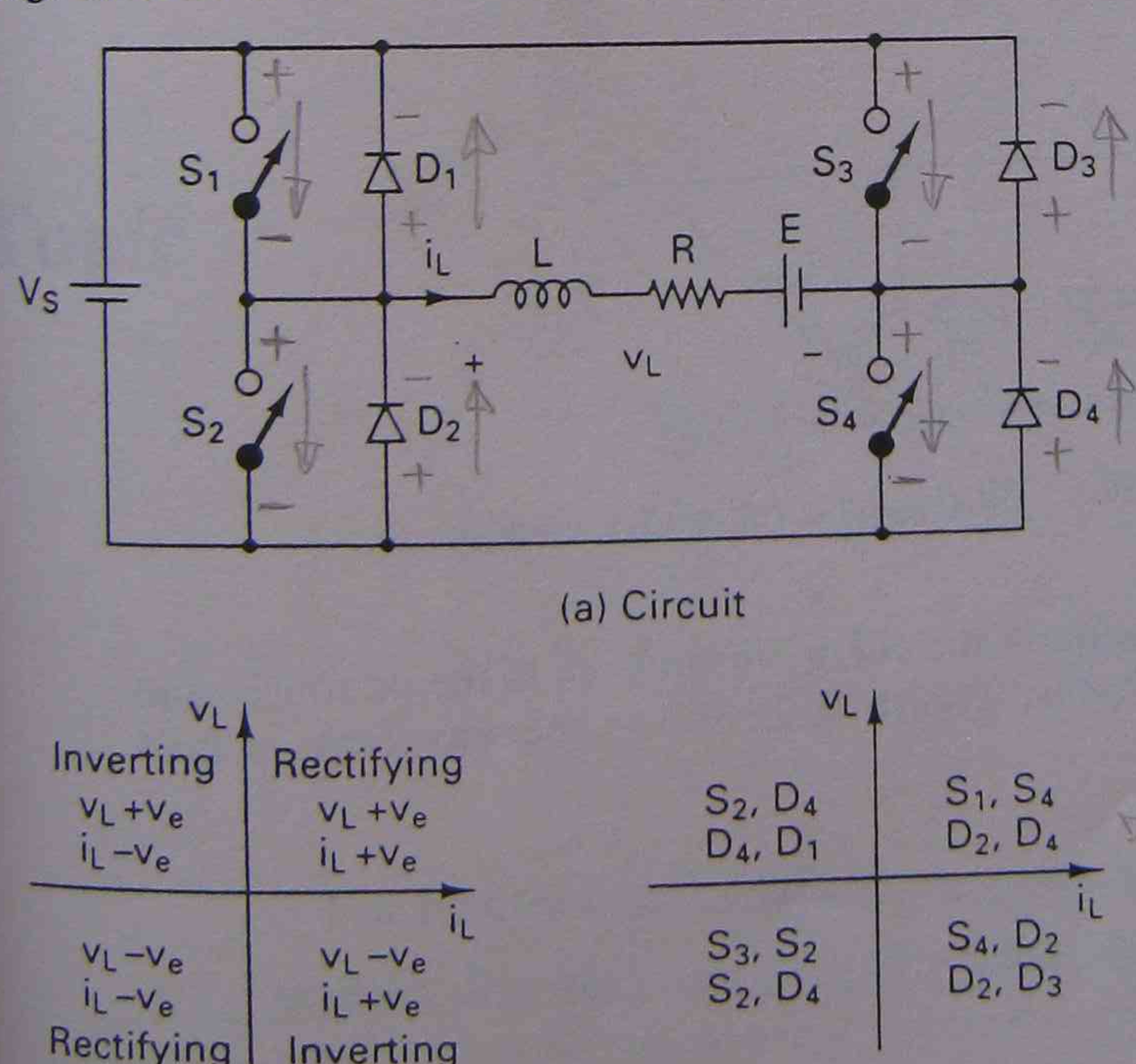


Figure 9-9 Class D chopper.

Class D chopper. The load current is always positive. The load voltage is either positive or negative, as shown in Fig. 9-6d. A class D chopper can also operate either as a rectifier or as an inverter, as shown in Fig. 9-9. If S_1 and S_4 are turned on, v_L and i_L becomes positive. If S_1 and S_4 are turned off, load current i_L will be positive and continue to flow for a highly inductive load. Diodes D_2 and D_3 provide a path for the load current and v_L will be reversed.

Class E chopper. The load current is either positive or negative, as shown in Fig. 9-6e. The load voltage is also either positive or negative. This is known as a *four-quadrant chopper*. Two class C choppers can be combined to form a class E chopper, as shown in Fig. 9-10a. The polarities of the load voltage and load current are shown in Fig. 9-10b. The devices that are operative in different quadrants are shown in Fig. 9-10c. For operation in the fourth quadrant, the direction of battery E must be reversed. This chopper is the basis for the single-phase full-bridge inverter in Section 10-4.



(a) Circuit

(b) Polarities

(c) Conducting devices

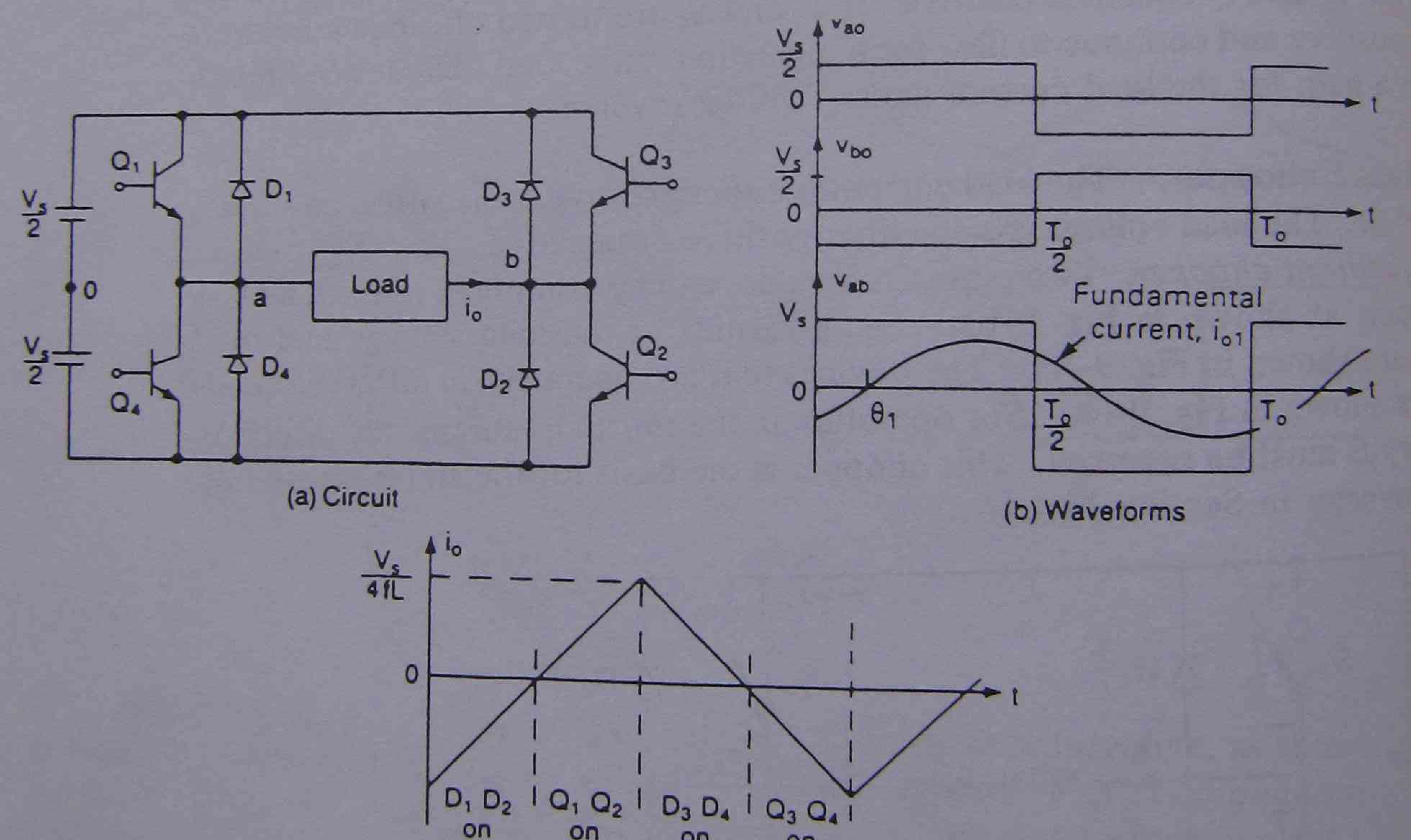
Figure 9-10 Class E chopper.

A single-phase bridge inverter is shown in Fig. 10-2a. It consists of four choppers. When transistors Q_1 and Q_2 are turned on simultaneously, the input voltage V_s appears across the load. If transistors Q_3 and Q_4 are turned on at the same time, WITH TRANSISTORS Q1 AND Q2 TURNED OFF, the voltage across the load is reversed and is $-V_s$. The waveform for the output voltage is shown in Fig. 10-2b.

The rms output voltage can be found from

$$V_1 = \frac{4V_s}{\sqrt{2}\,\pi} = 0.90V_s$$

gives the rms value of fundamental component



(a) Circuit

(b) Waveforms

(c) Load current with highly inductive load

Figure 10-2 Single-phase full-bridge inverter.

When diodes D_1 and D_2 conduct, the energy is fed back to the dc source and they are known as *feedback diodes*. Figure 10-2c shows the waveform of load current for an inductive load.

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Module **NE76**

A.C. Motor Control

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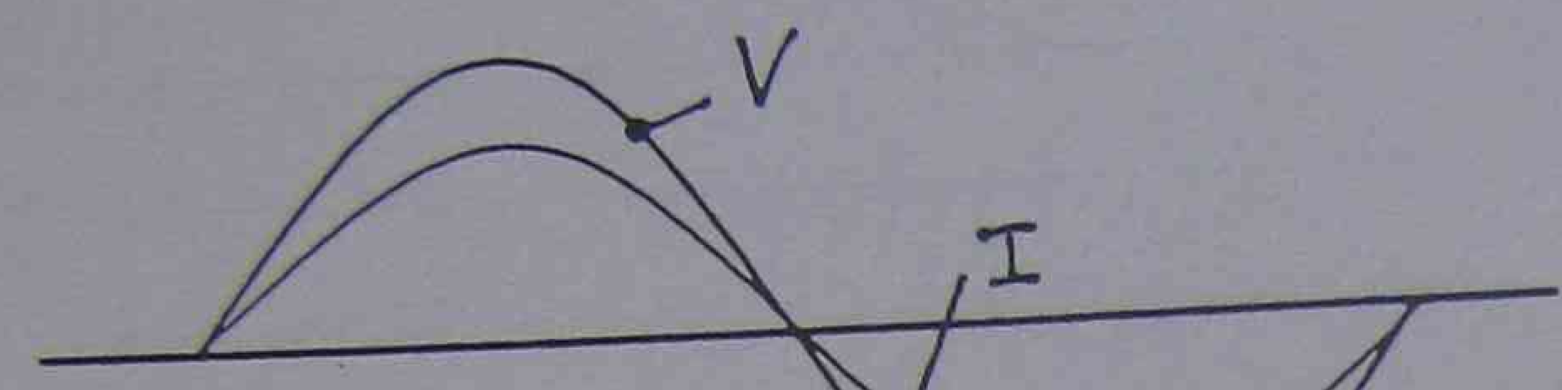
A.C. Motor Control.

Topic -

Power Factor

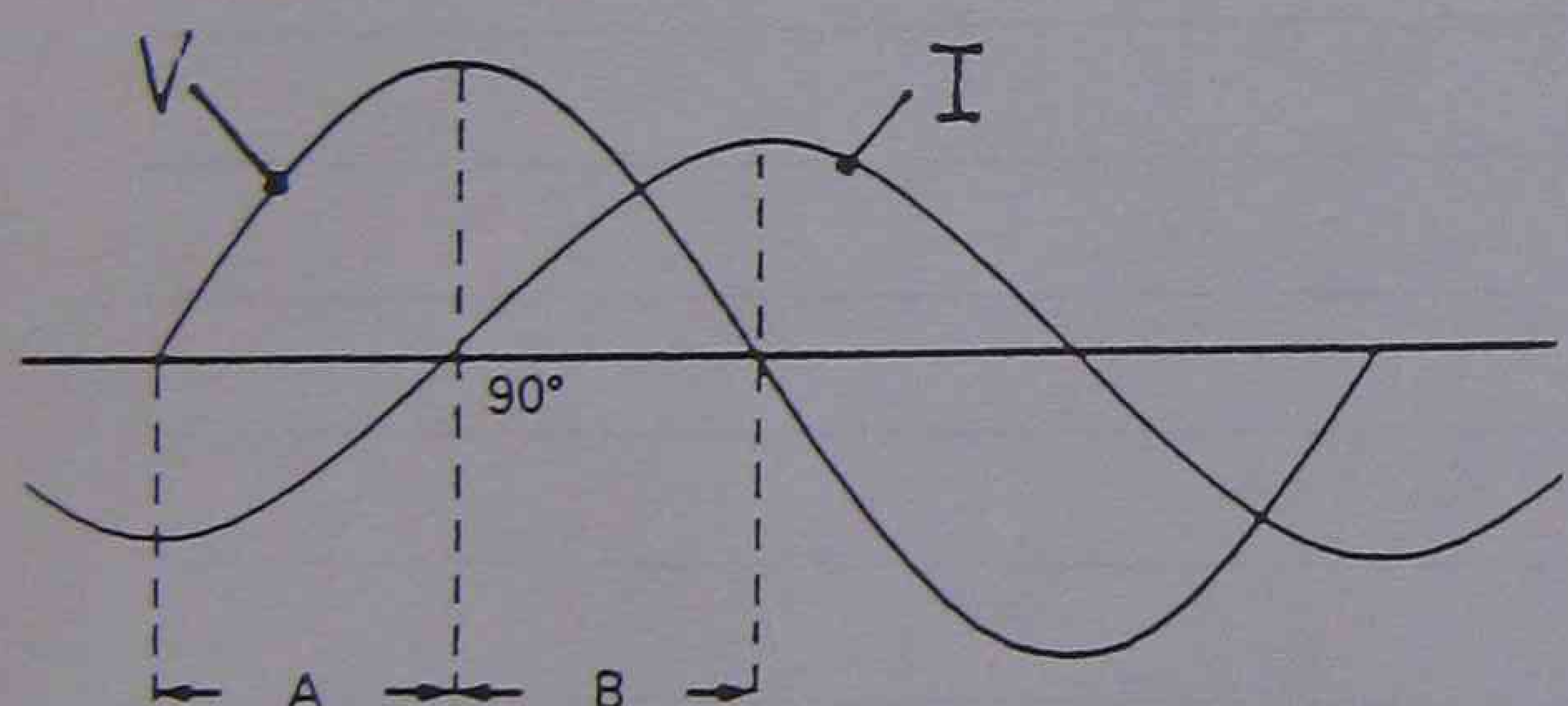
Typical voltage and current waveforms for a resistive load connected to an ac supply are shown in Fig.10. The two waveforms are in phase, or to express the relationship in another way, the voltage and current have the same polarity at any instant (thus the zero crossing points coincide).



— VOLTAGE
— CURRENT

10 *Voltage and current waveforms – purely resistive load*

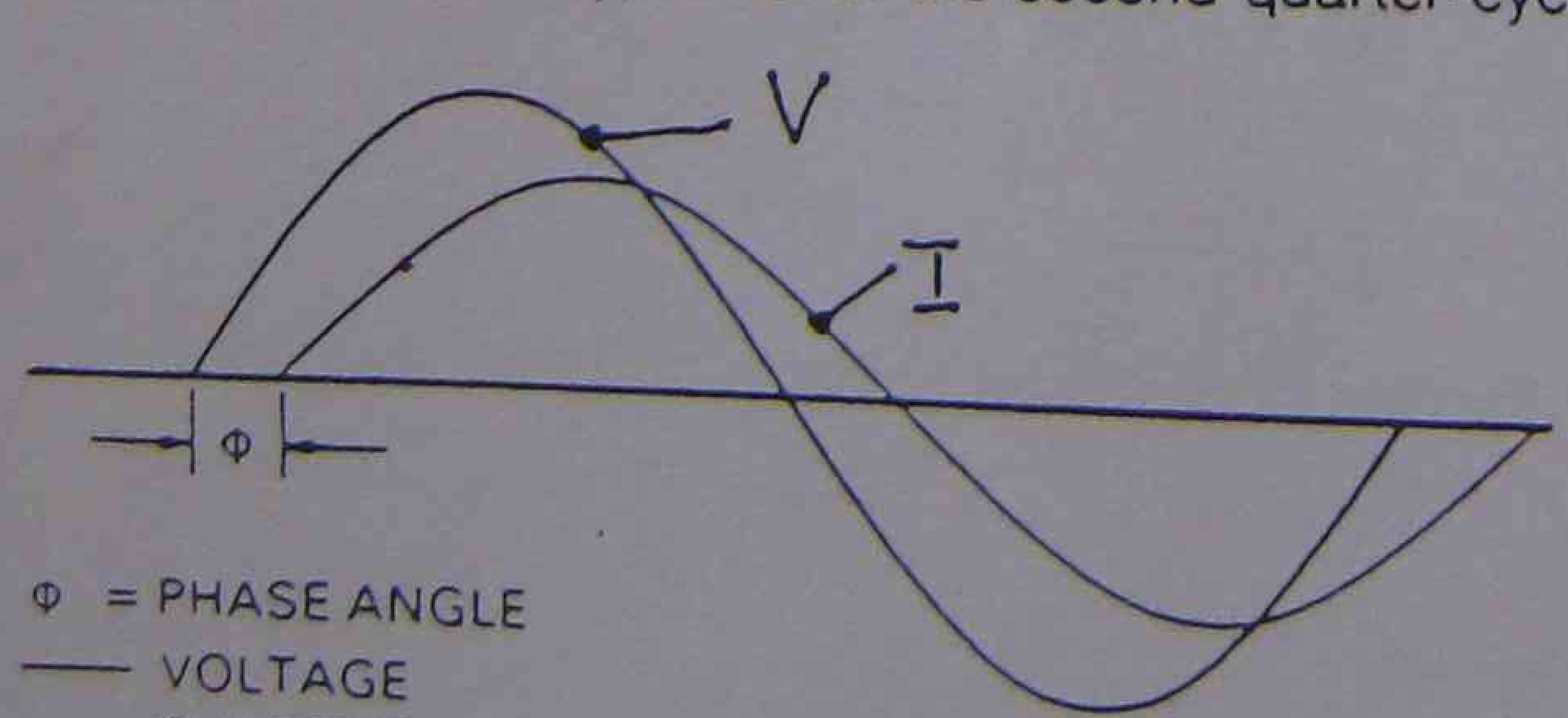
Since power is the product of voltage and current, it can be seen that during each half cycle the result is always positive, and therefore all the resultant power is available to be used.



— VOLTAGE
— CURRENT

11 *Voltage and current waveforms – purely inductive load*

In contrast, consider the waveforms shown in Fig.11, the load in this case being a pure inductance. The current waveform lags behind the voltage waveform by 90° due to the effect of the load inductance, and it can be seen that during the first quarter-cycle (A) the voltage and the current are of opposite polarity, whilst in the second quarter-cycle



Φ = PHASE ANGLE
— VOLTAGE
— CURRENT

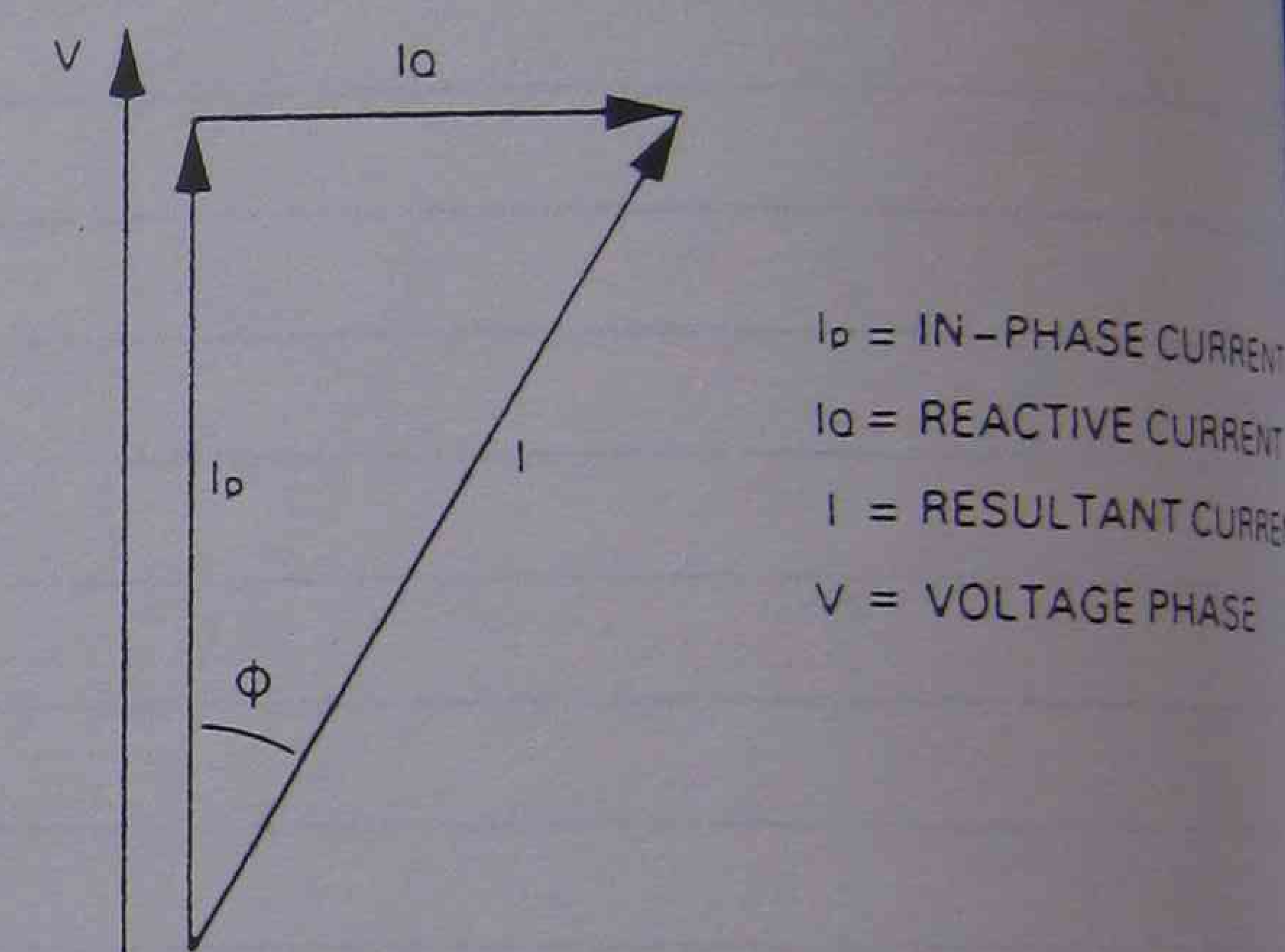
12 *Voltage and current waveforms for a load having both resistance and inductance*

(B) they are of the same polarity. Therefore the resultant power for the half-cycle being the product of voltage and current, is zero. In this case, no useful power is produced, and the product of rms voltage and ...

In Fig.12, a load having both resistance and inductance connected to the supply and, as expected, the current waveform lags behind the voltage waveform, the degree of displacement, φ, being referred to as the phase angle. In this case, the current waveform has a component which is in phase with the voltage waveform (due to the resistive property of the load) and a component which lags the voltage waveform by 90° (due to the inductive property of the load). The resulting phase angle is therefore between 0° and 90°, and lagging, as shown in Fig.13. Clearly, the ratio of in-phase current to total current is given by the cosine of the phase angle, therefore:

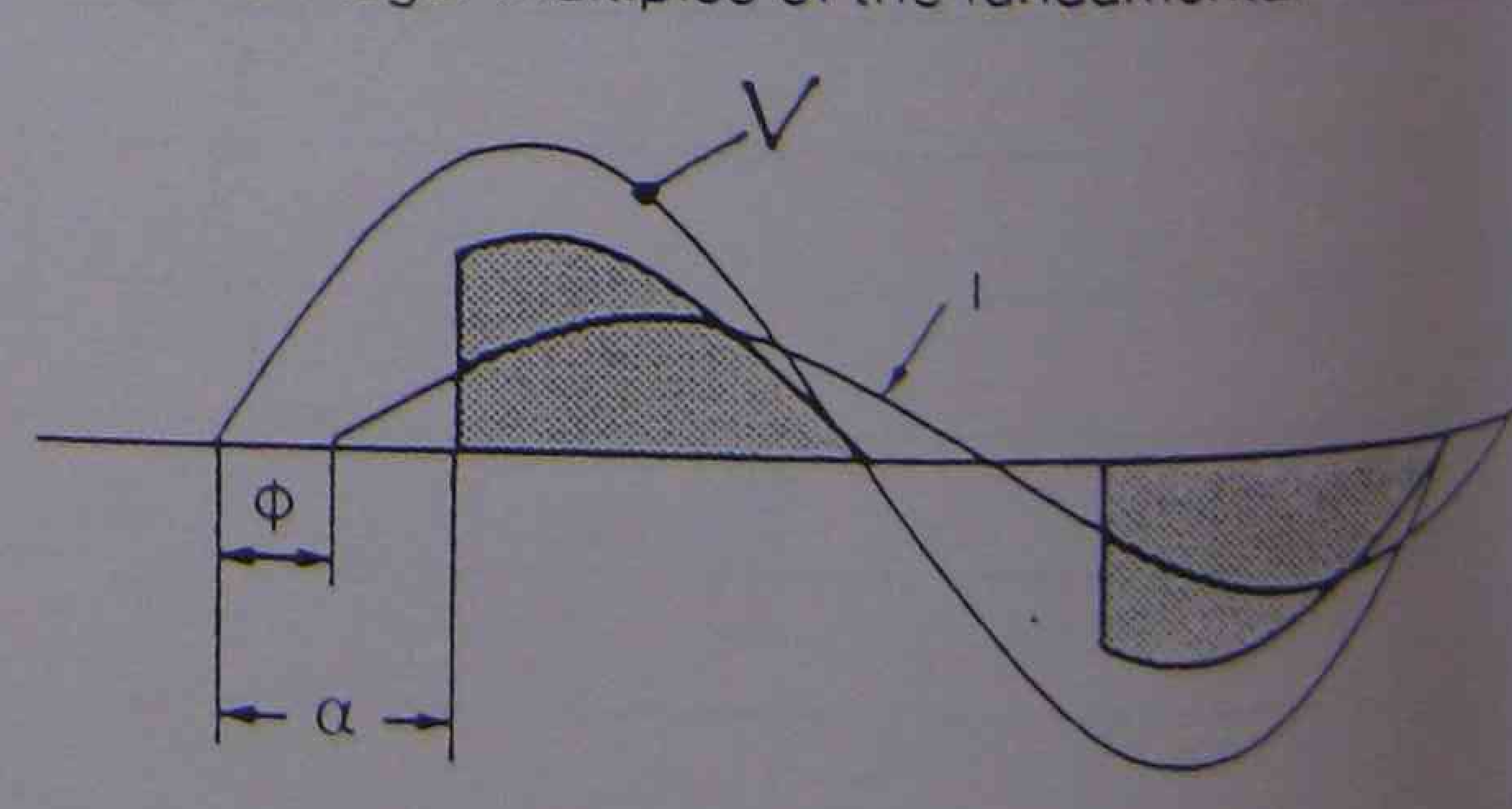
$$\cos \varphi = \frac{WATTS}{VA}.$$

Cos φ is known as the Power Factor (pf).



13 *Phasor diagram for a load having both resistance and inductance*

Voltage and current waveforms for a thyristor drive are shown in Fig.14. The shaded areas indicate the periods during which the thyristors are in conduction, having a firing angle α. The current waveform is therefore non-sinusoidal but can be resolved by Fourier analysis into a number of sinusoidal waves of different frequencies and amplitudes which, when combined, yield the actual waveform. This process results in a fundamental frequency, and harmonics which are integer multiples of the fundamental



— VOLTAGE WAVEFORM
CONDUCTION REGION
— FUNDAMENTAL OF CURRENT WAVEFORM
Φ PHASE ANGLE OF FUNDAMENTAL
α FIRING ANGLE

The fundamental I_L is shown in Fig.14, and it can be seen that a phase angle φ_1 exists between it and the voltage waveform, resulting in a lagging power factor analogous to that obtained with an inductive load.

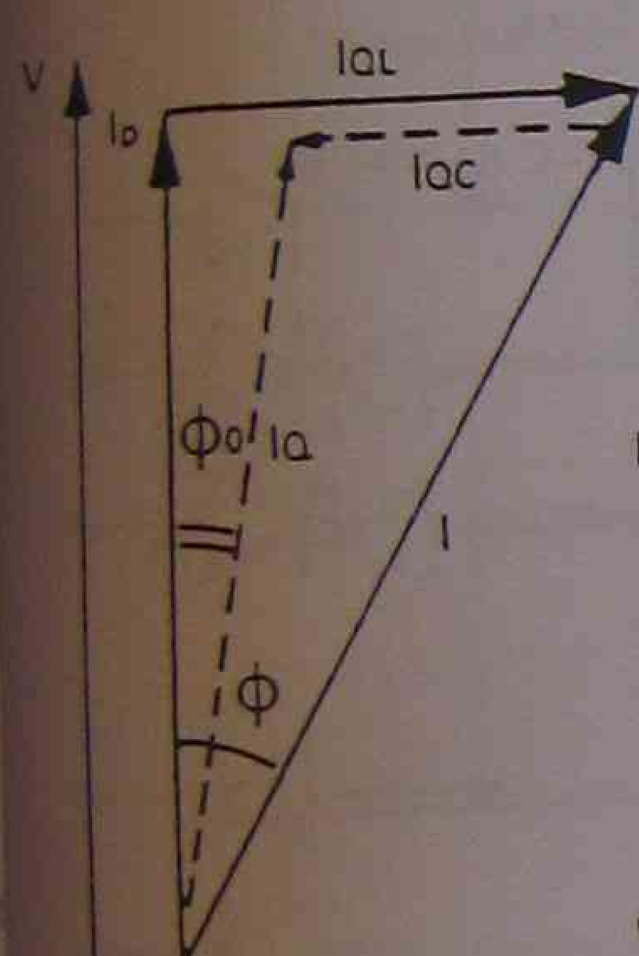
A practical way of calculating the power factor is to consider the ac in-phase component (power) to be equal to the dc output power; then the expression for power factor becomes,

$$pf = \frac{W}{VA} = \frac{V_{DC} \times I_{DC}}{\sqrt{3} \times V_{LINE} \times I_{LINE}}$$

Line current is often calculated as 0.833 x dc current, in which case

$$pf = \frac{V_{DC} \times I_{DC}}{\sqrt{3} \times V_{LINE} \times 0.833 \times I_{DC}} = \frac{0.7\, V_{DC}}{V_{LINE}}$$

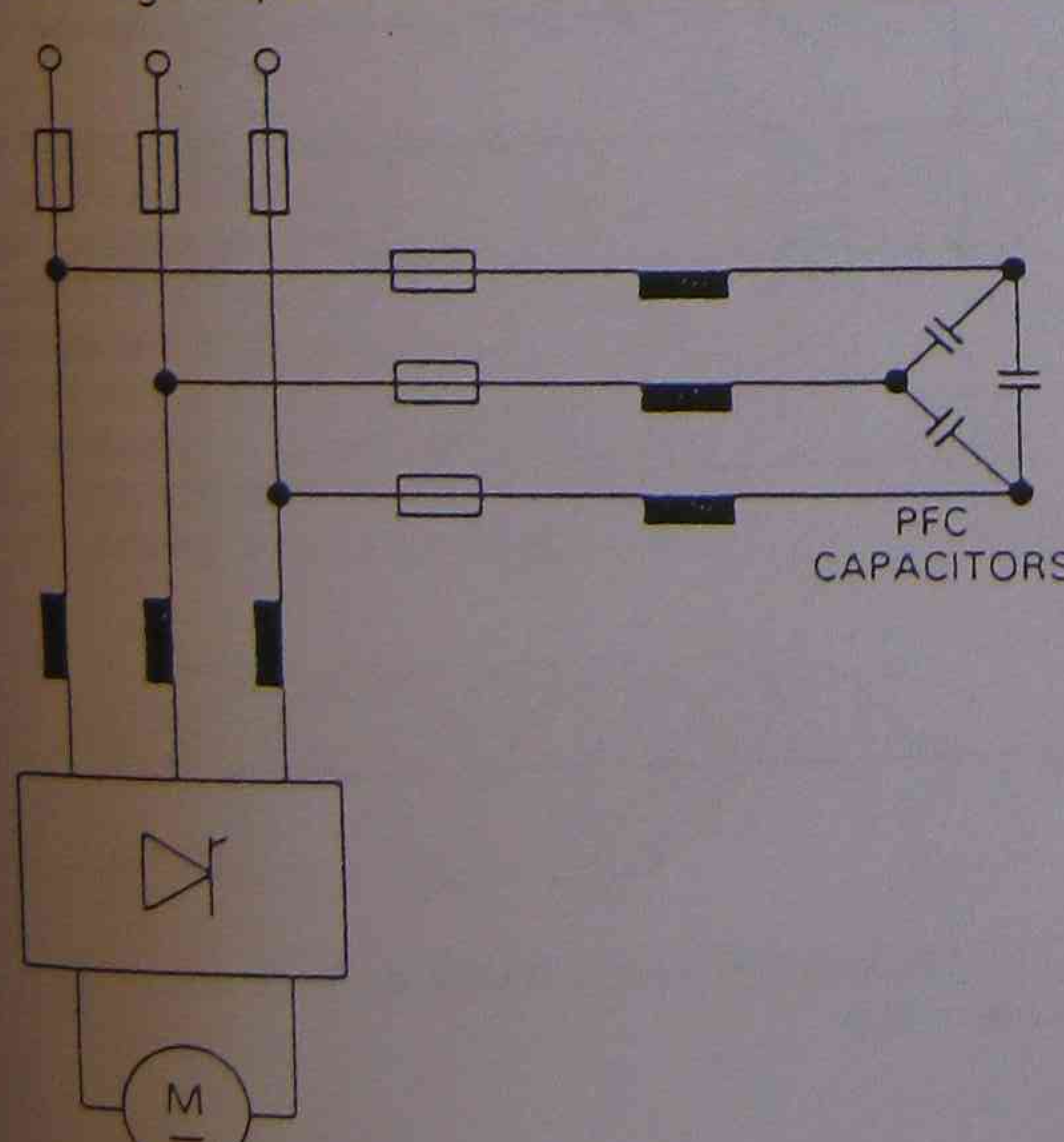
This expression shows that the power factor of a thyristor drive is dependent on output voltage and, therefore, on speed. At maximum speed, the power factor of a thyristor drive is roughly comparable with that of an ac induction motor connected direct-on-line.



15 *Power factor correction*

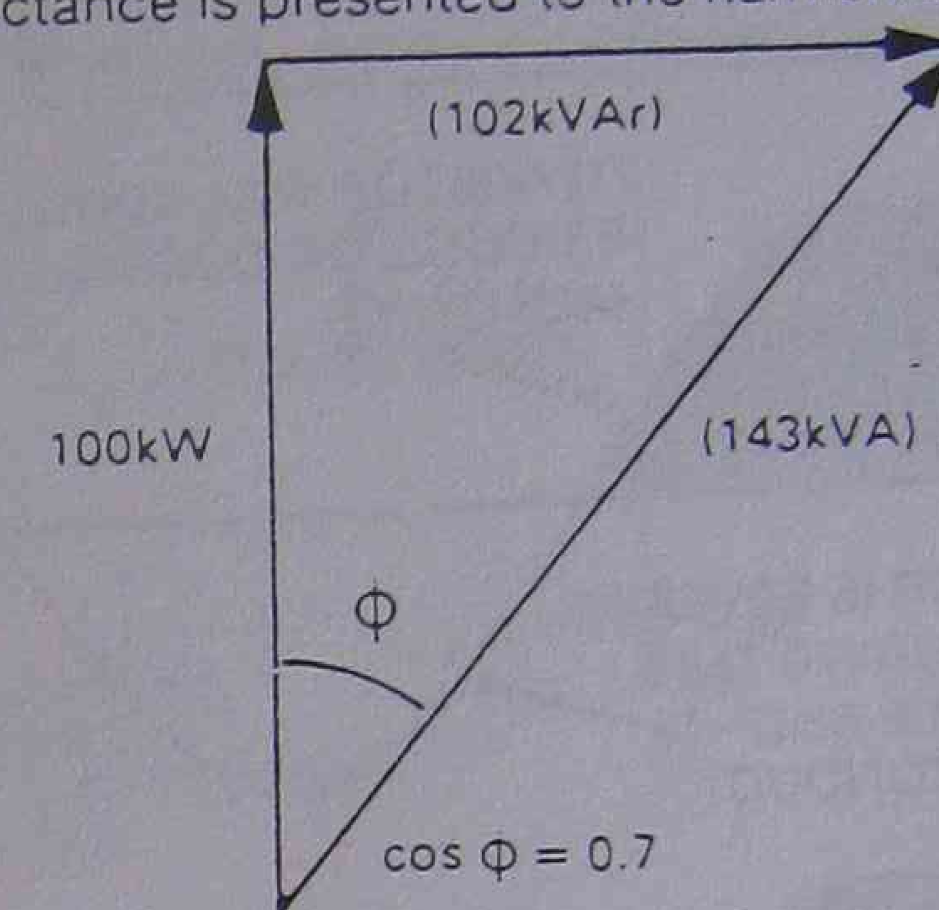
With larger drives it is often desirable to employ power factor correction (PFC) in order to improve the power factor of the total load connected to the supply.

This is done by means of capacitors connected between the supply lines, and chosen to give the required correction at a particular speed, typically correcting to a pf of 0.9 at full speed, although capacitors can be switched to accommodate other speeds should the application demand it. Fig.15 illustrates the principle, which is based on the fact that a capacitive load results in a leading phase angle, which can be used to offset the lagging phase angle of the thyristor drive.



16 *Typical circuit for power factor correction*

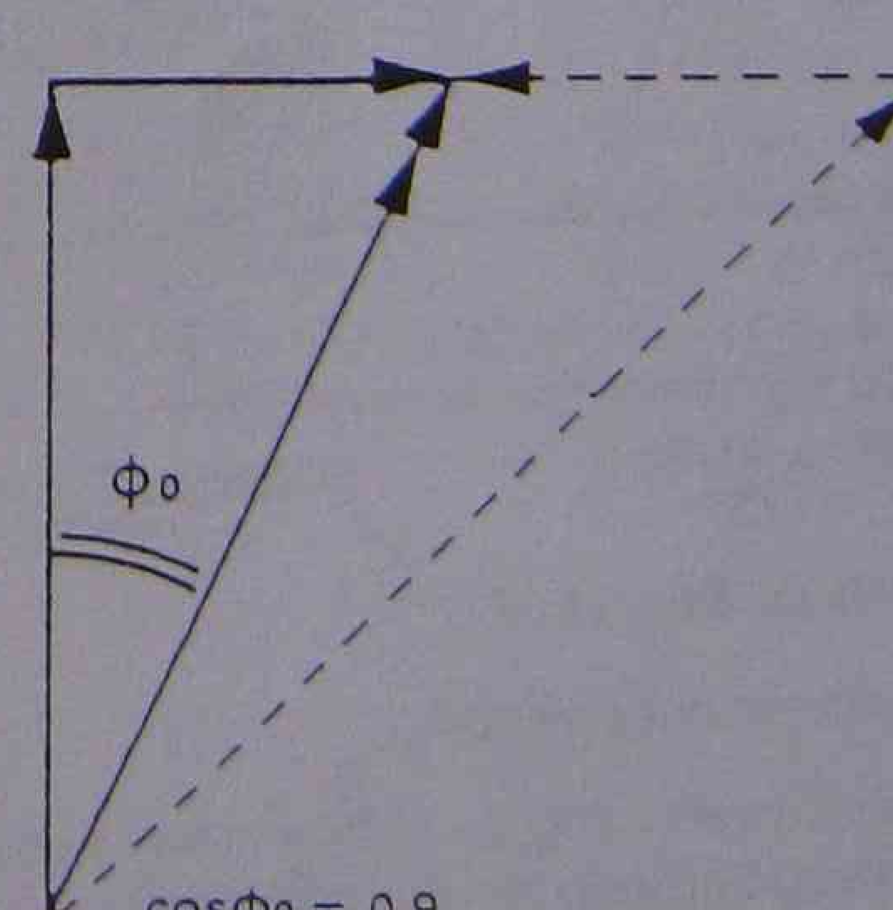
Because the capacitors present a low impedance to the high-frequency harmonics it is necessary to insert chokes between the lines and the capacitors, Fig.16, to limit harmonic currents. The resulting combination of capacitance and inductance is tuned so that a capacitive reactance is presented to the fundamental (supply) frequency, whilst an inductive reactance is presented to the harmonics.



17 *Phasor diagram for 100kW drive at pf = 0.7*

Example To calculate the PFC capacitors required to correct a 100kW drive from a pf of 0.7 to 0.9. Fig.17 shows the phase diagram of the uncorrected arrangement.

Knowing power and pf (cos φ), the kVA can be calculated:



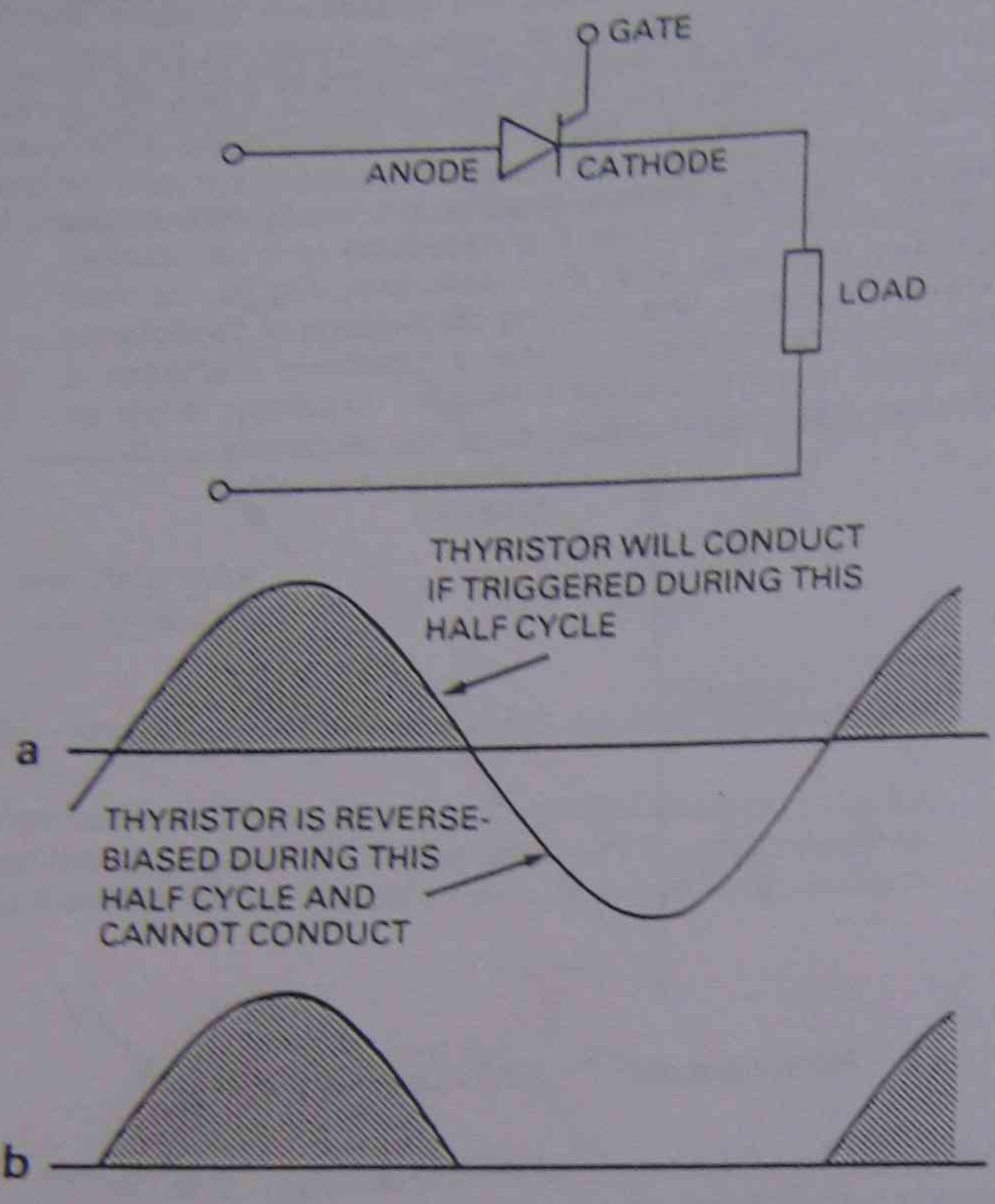
18 *Phasor diagram for 100kW drive with PF corrected to 0.9*

The capacitance required is the difference between the actual and the required reactive components:

102 – 48 = 54kVAr capacitative, required for correction, illustrated in Fig.18.

A.C. Motor Control.

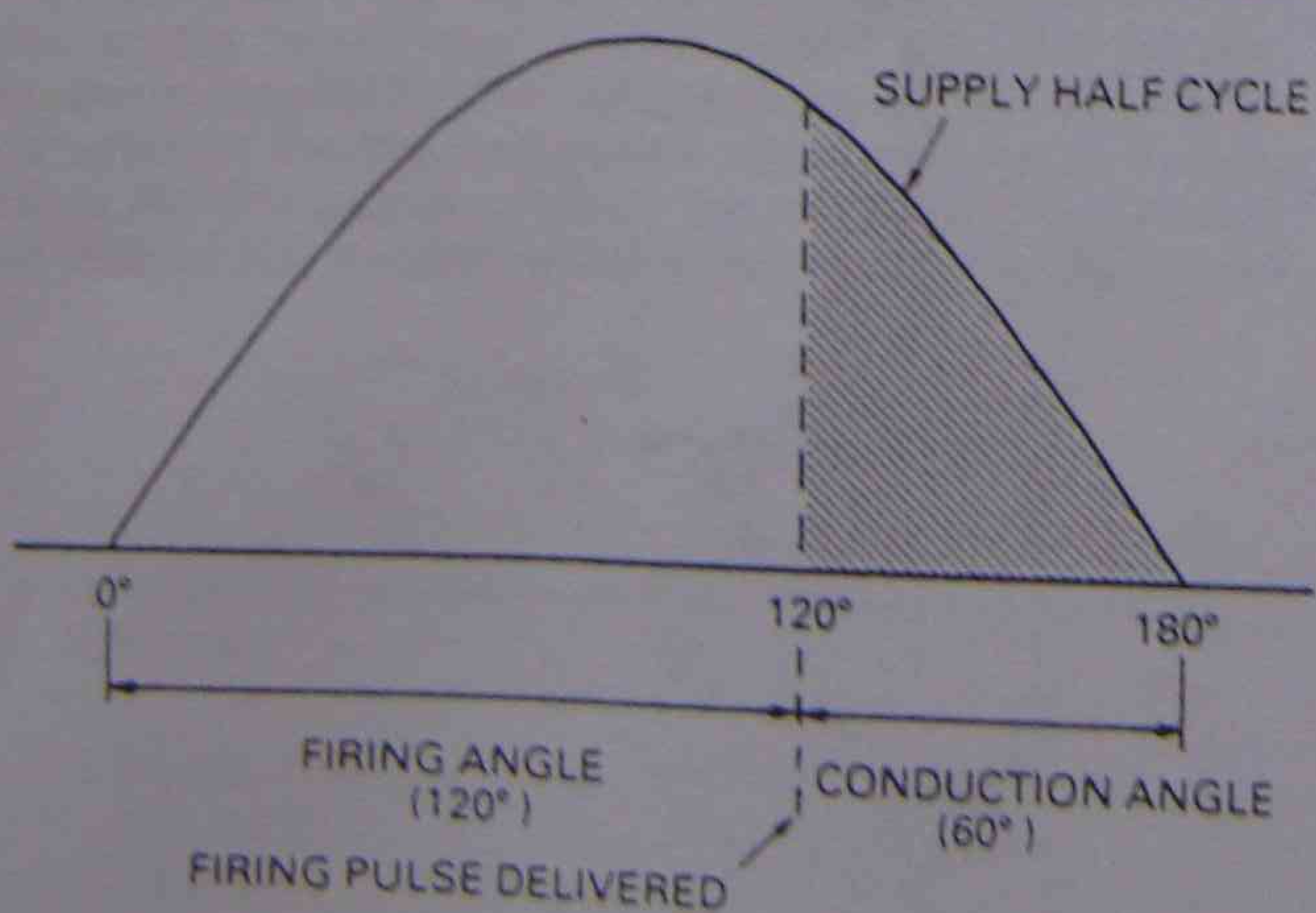
Topic -



1 *Thyristor full wave conduction* **a** *Supply* **b** *Output*

which the thyristor is fired is known as the firing angle, or phase angle, and the portion of the half-cycle during which the device is conducting is called the conduction angle, Fig.2.

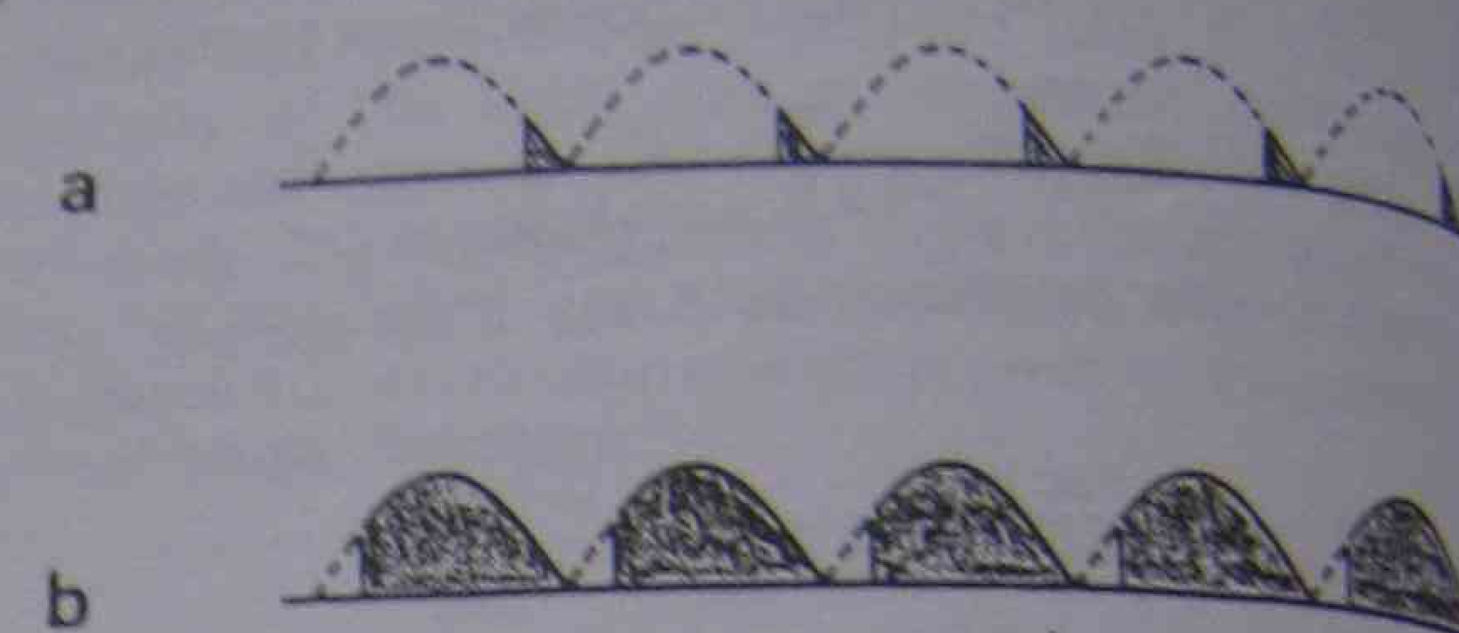
It can be seen that by 'phasing forward' or advancing the firing angle from 180° to zero, to use the conventional expression, the output through the thyristor is increased



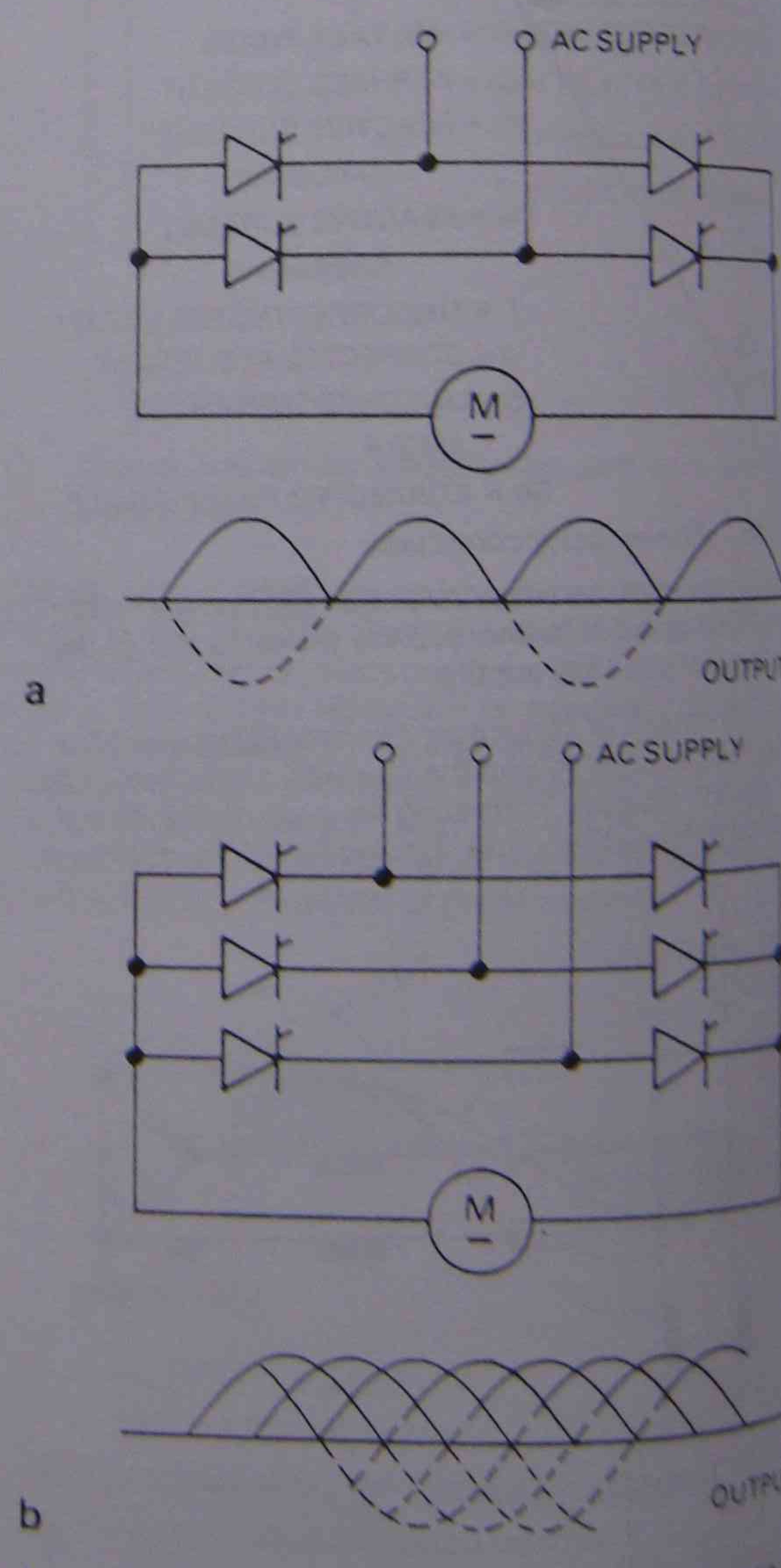
2 *Triggered thyristor conduction*

from zero to maximum, Fig.3, since this progressively increases the corresponding conduction angle from zero to 180°.

By arranging thyristors in a bridge configuration, a full-wave rectified output is obtained, which is smoother than the half-wave output of a single device, Fig.4a, and if the supply is 3-phase, the output (at 180° firing angle) is smoother still, Fig.4b.



3 *Typical output of a single-phase thyristor bridge for large and small firing angles:* **a** *Output waveform with small conduction angle (firing pulses retarded or " phased back")* **b** *Output waveform with large conduction angle (firing pulses advanced or " phased forward").*



4 **a** *Single phase, Full wave bridge* **b** *Three phase*

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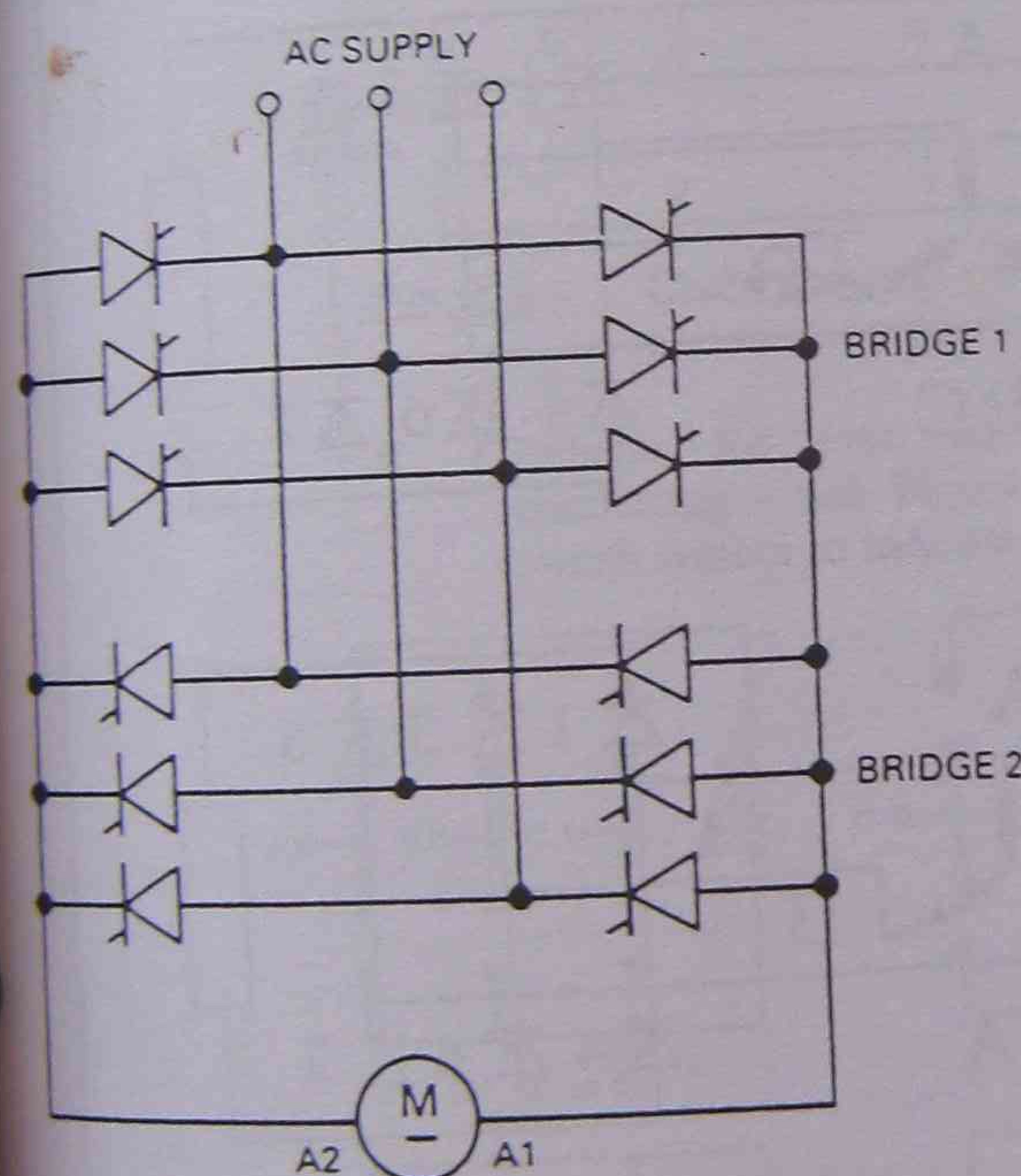
Topic -

Four Quadrant Operation

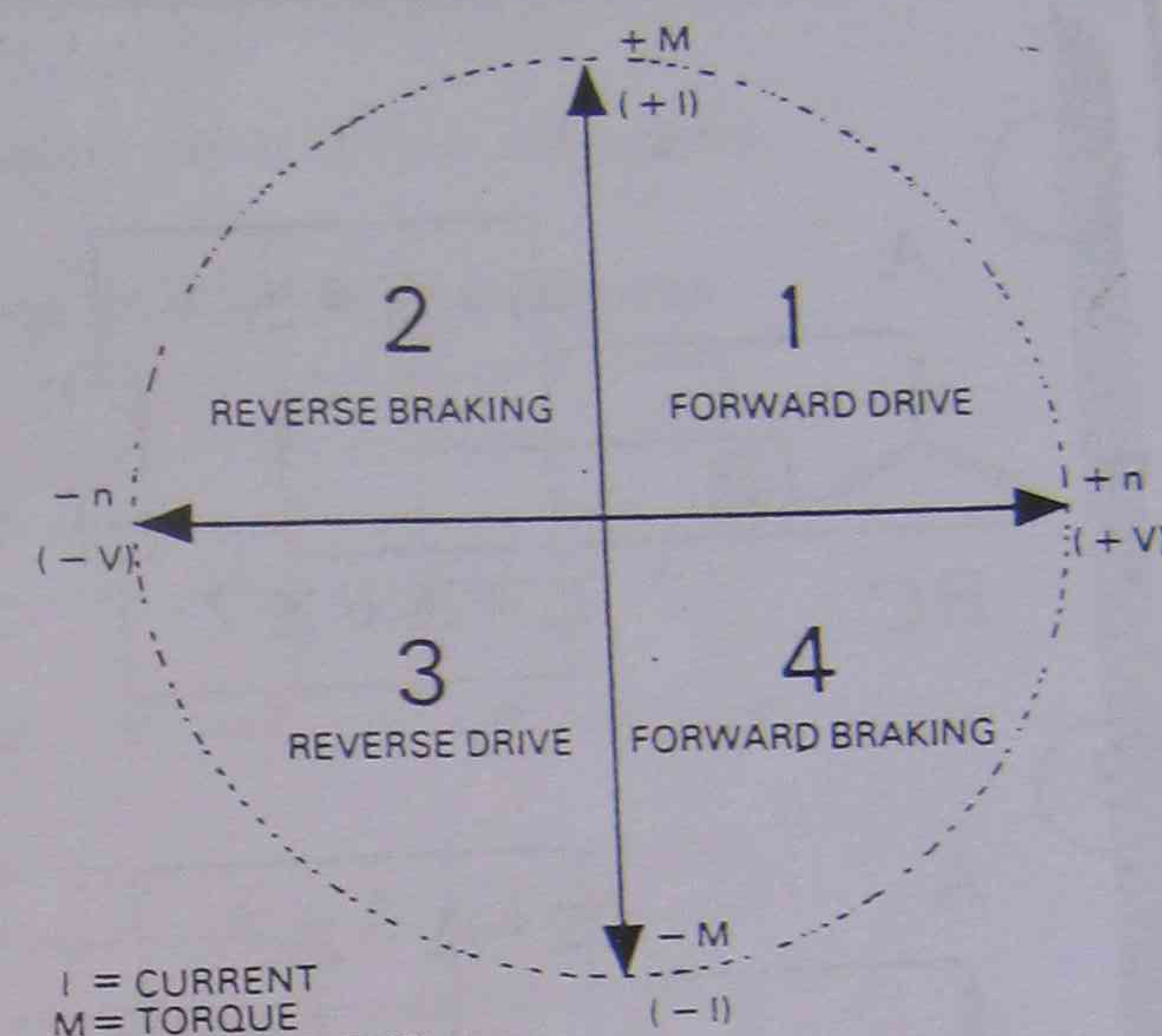
By definition, the output current of a rectifier is unidirectional, therefore the torque produced by the motor will also be in one direction or sense of rotation. In applications where only one direction of rotation is required, and the load can be allowed to coast to rest, this is adequate. However, there are many applications in which reversal of rotation is necessary, or where large load inertias must be decelerated.

In such cases, two thyristor bridges are connected in inverse-parallel as shown in Fig.5. When Bridge 1 is conducting, current flow in the motor is from A1 to A2. Current flow is reversed when Bridge 2 conducts, and therefore the motor torque reverses. This effect can be used to reverse the direction of rotation of the motor, and to provide braking torque.



5 *Power circuit of a four quadrant thyristor drive.*

The arrangement described above is known as a Four-Quadrant (4Q) drive, since it is capable of operation in any of the four quadrants of the torque-speed diagram (Fig.6). In Quadrant 1, both voltage and current, and therefore speed and torque are in the positive, or forward, direction. This is consistent with a motor driving a load, taking power from the mains. Similarly, in Quadrant 3, both speed and torque are negative; this corresponds to a motor turning in the reverse direction, driving a load and again taking power from the mains.



I = CURRENT
M = TORQUE
V = VOLTAGE (EMF)
n = SPEED

6 *The four quadrants of the dc torque speed diagram*

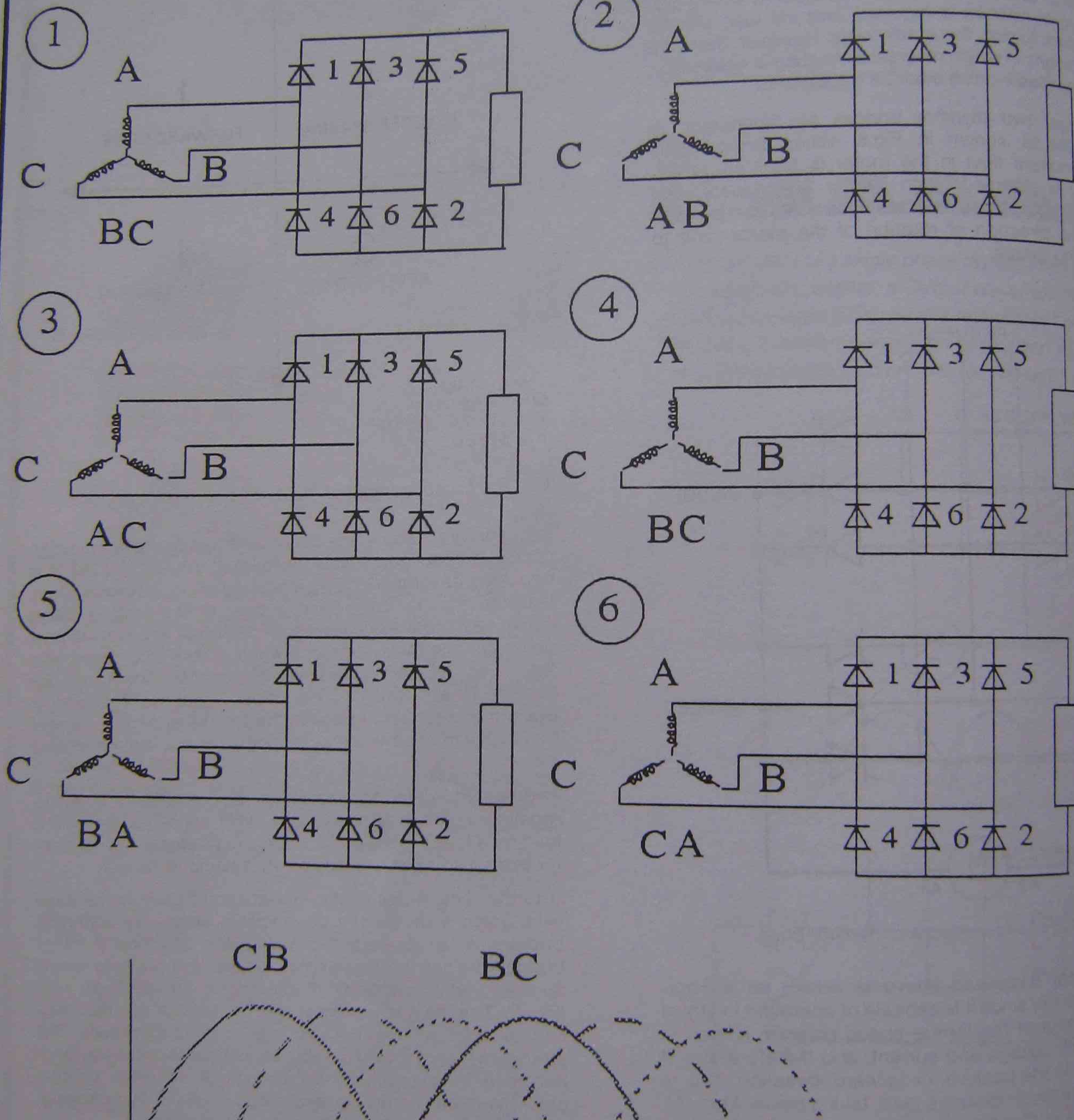
In quadrants 2 and 4, the speed and torque are in mutually-opposed directions, that is to say the torque of the motor is opposing its rotation, giving a braking effect. It follows, then, that the mechanical kinetic energy of the load is being converted into electrical energy; the motor is behaving as a generator and the system as a whole is delivering power into the mains. This behaviour is known as regeneration, and has two main applications. The most usual is regenerative braking of a rotating mass (eg the spindle of a machine tool or a coil of material in a process line) to give a fast, controlled stop.

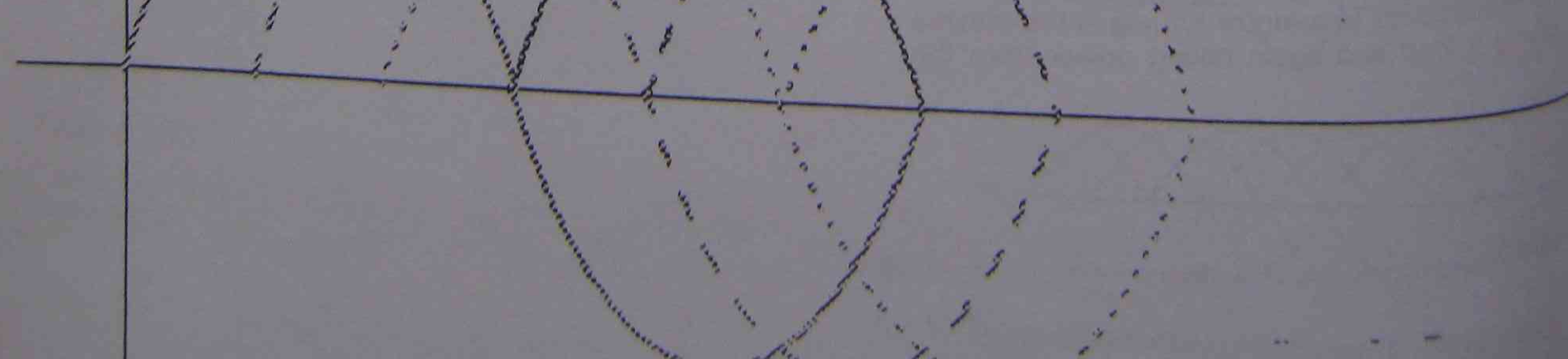
Another important application of regeneration is in dynamometers, where a regenerative drive is used to provide a load for a mechanical power source (eg a diesel engine) both for testing it under load and for measuring its output.

A further advantage of the four-quadrant drive is the ease with which a motor can be reversed, simply by changing bridges. A 'single-ended' drive (having only one thyristor bridge) can only be reversed by means of contactors which reverse the connections to the motor armature or field (Fig.7). The contactors must be interlocked so that they cannot operate together and cause a short-circuit. The arrangement obviously introduces an operational delay and the need for external control circuits. A 4Q drive, on the other hand, can be quickly and simply reversed by switching from the firing circuit of one bridge to the other.

A.C. Motor Control.

Topic - ____________________





(c) Operation of Three Phase Full Wave Rectifier

- List inside each rectangle, the highest positive voltage and negative voltage for the periods indicated.
- List which diode would be conducting (ON) for each period indicated

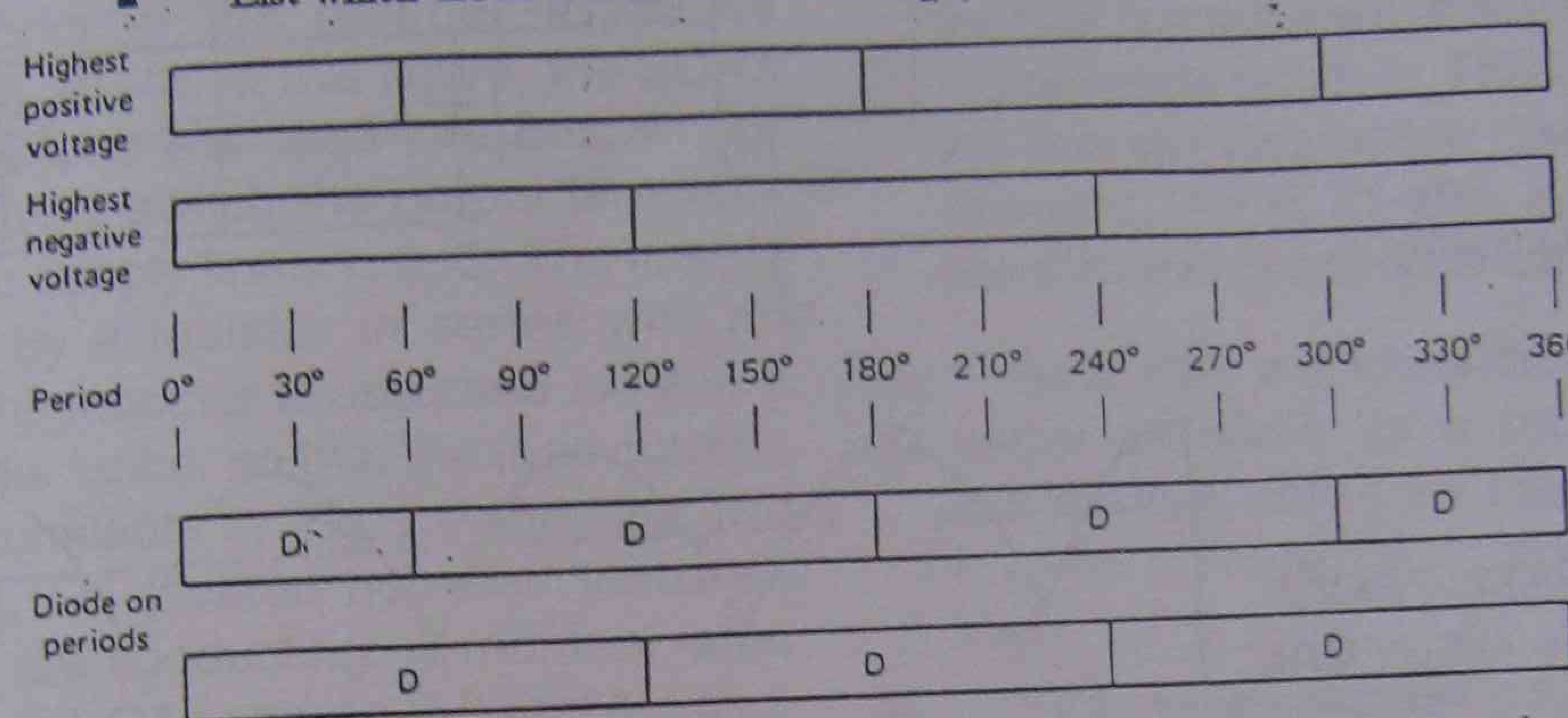


Figure 8 - Chart showing periods of highest positive and negative voltages and their respective ON diodes.

- Indicate for each 60° period which two (2) diodes would be conducting - use Figure 8 results above and use the standard close switch symbol to indicate the ON diode.

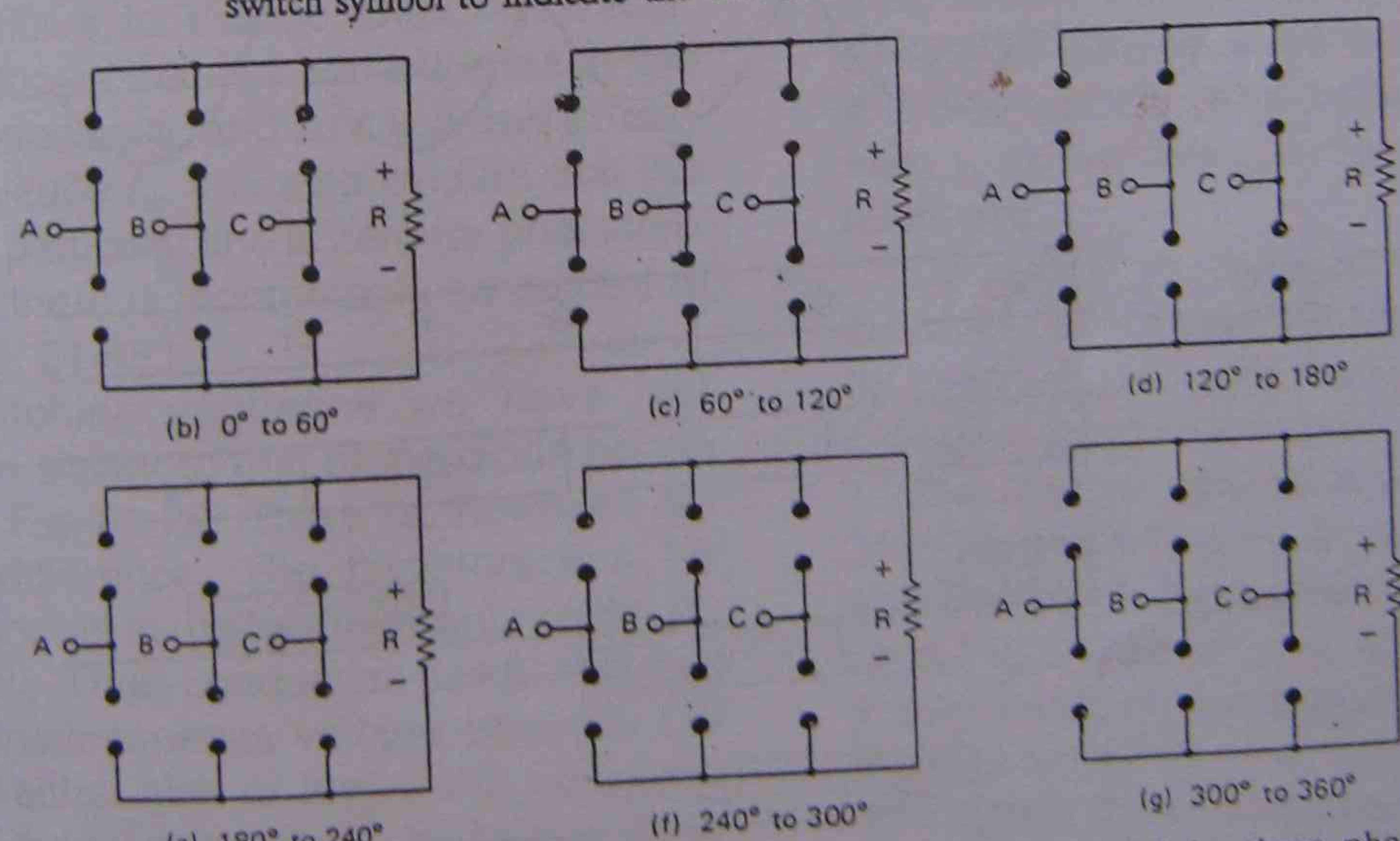


Figure 9 - ON diode chart and switch equivalent circuits of the three phase full wave rectifier.

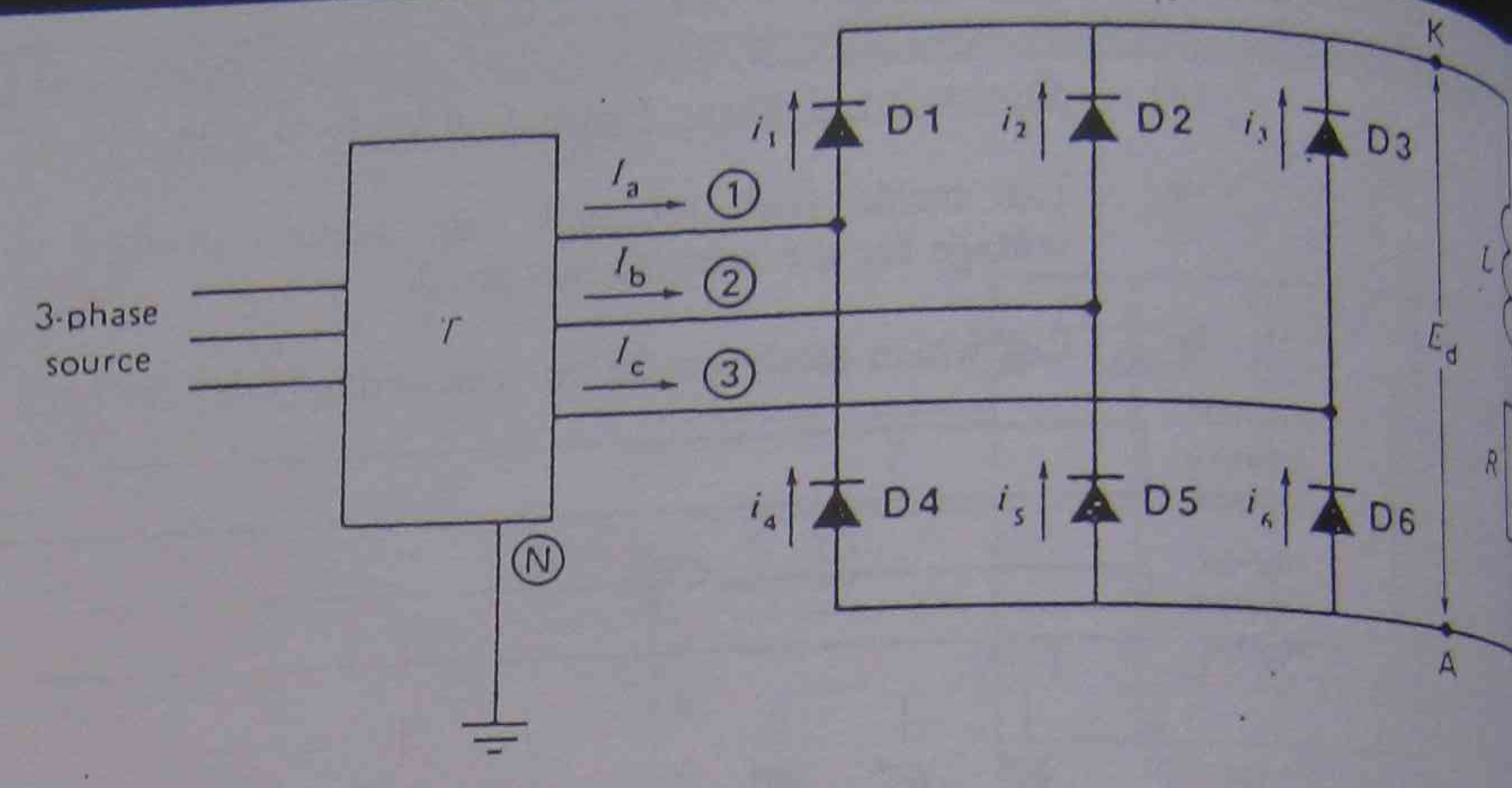


Figure 21-19
Three-phase, 6-pulse rectifier
with inductive filter.

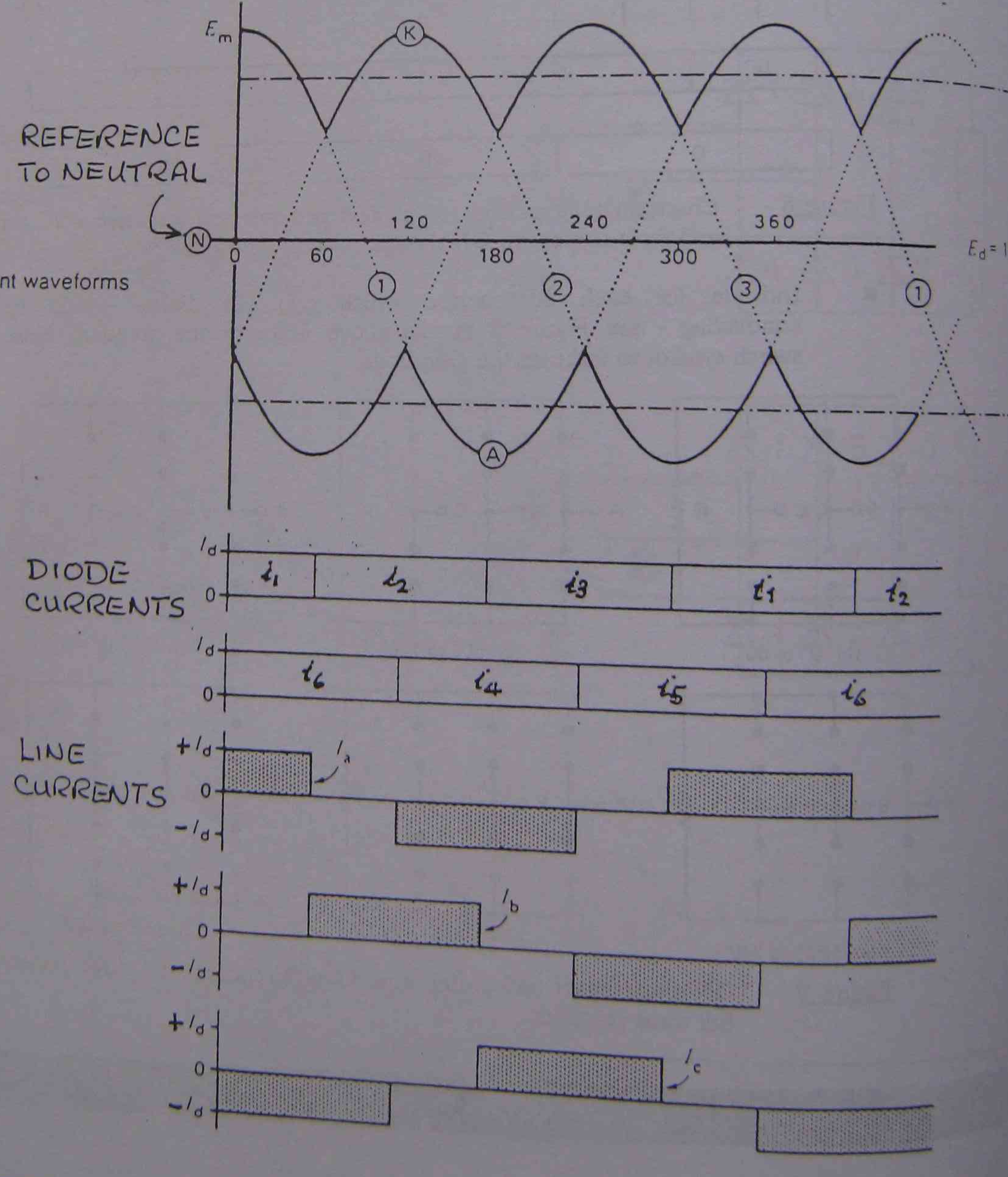


Figure 21-20
Voltage and current waveforms
in Fig. 21-19.

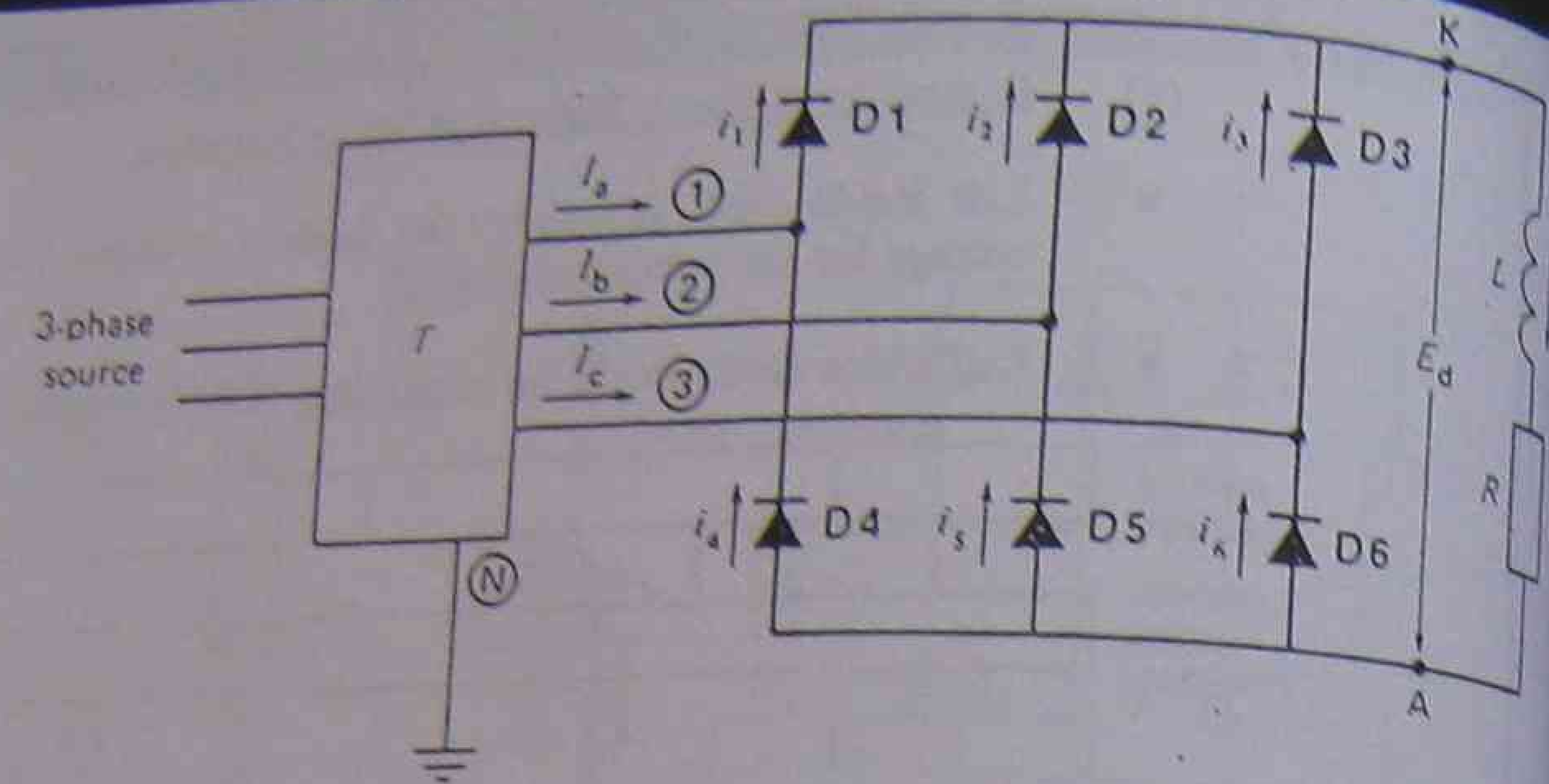


Figure 21-19
Three-phase, 6-pulse rectifier with inductive filter

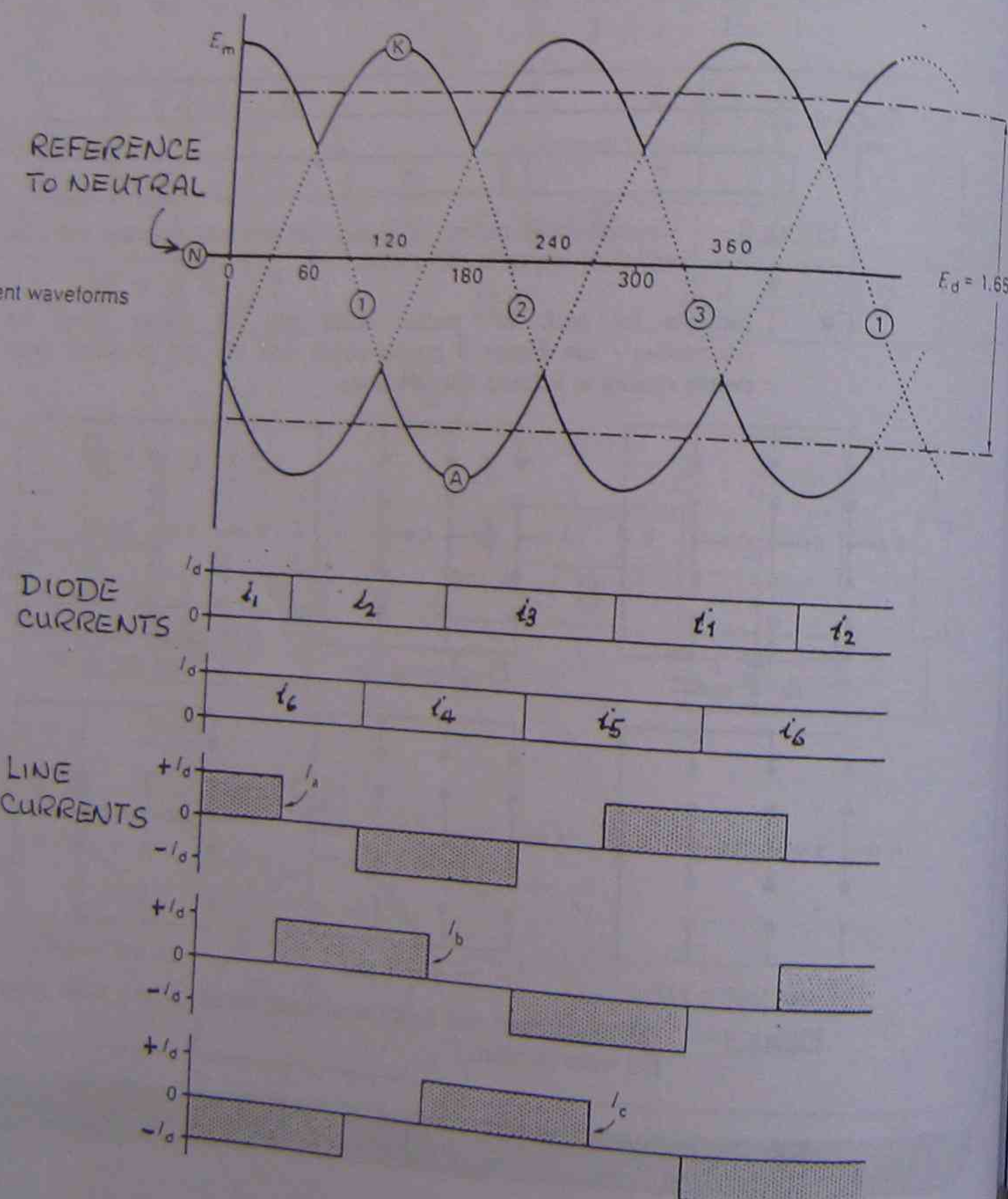


Figure 21-20
Voltage and current waveforms in Fig. 21-19.

21.26 Basic principle of operation

We can gain a basic understanding of how the converter works in the rectifier mode by referring to Fig. 21-48. In this figure, the SCRs are assumed to be enclosed in a box, where they successively switch the output terminals K, A to the ac supply lines 1, 2, 3. The load is represented by a resistor in series with an inductor L. The inductor is assumed to have a very large inductance, so that the load current I_d remains constant. In Fig. 21-48a, the two thyristors Q1, Q5 located between terminals K-1 and A-2 are conducting. A moment later, the thyristors Q2, Q4 between K-2 and A-1 conduct (Fig. 21-48b). The other thyristors are similarly switched, in sequence. When these steps have been completed, the entire switching cycle repeats. The reader will note that the dc current I_d flows in the ac lines. However, Fig. 21-48 shows that the current in each line reverses periodically, and so it is a true ac current of amplitude I_d. It is also evident that the current in a particular line is zero for brief intervals. Thus, there is momentarily no current in line 3 of Fig. 21-48.

The switching sequence we have just described is similar to that of the diode bridge rectifier of Fig. 21-22. There is, however, an important difference. The thyristors can be made to conduct at precise moments on the ac voltage cycle. Thus, conduction can be initiated when the instantaneous voltage between the ac lines is either high or low. If the voltage is low, the dc output voltage will also be low. Conversely, if the thyristors conduct when the ac line voltage is momentarily near its peak, the dc output voltage will be high. In effect, the output voltage E_{KA} is composed of short 60-degree segments of the ac line voltage. The average value of E_{KA} is the dc output voltage E_d.

In examining Fig. 21-48, it can be seen that the line current always flows out of a line that is momentarily positive. This must be so because the line delivers active power to the load. For example, in Fig. 21-48a, e_{12} is positive when I_d flows in the direction shown.

Now that we know how the thyristor converter behaves as a rectifier, the question arises; how can it be made to operate as an inverter? Three basic conditions have to be met.

- First, we must have a source of dc current I_d. Such a current source can be provided if a voltage source E_0 is connected in series with a large inductance (Fig. 21-49a).
- Second, the converter must be connected to a 3-phase line that can maintain an undistorted sinusoidal voltage, even when the line current is nonsinusoidal. The voltage may be taken from a power utility, or generated by a local alternator.
- Third, the thyristors must be switched so that current I_d flows into an ac line that is momentarily positive. The gate firing must therefore be precisely synchronized with the line frequency.

The inverter operation can best be understood by referring to Fig. 21-49. The SCRs enclosed in the box are arranged the same way as in Fig. 21-48. In other words, the converters in the two figures are absolutely identical. Looking first at the dc side, the dc current I_d must flow in the same direction as before because SCRs cannot conduct in reverse. On the other hand, because we want the dc source E_0 to deliver power, I_d must flow out of the positive terminal, as shown. In other words, the positive side of E_0 must be connected to terminal A.

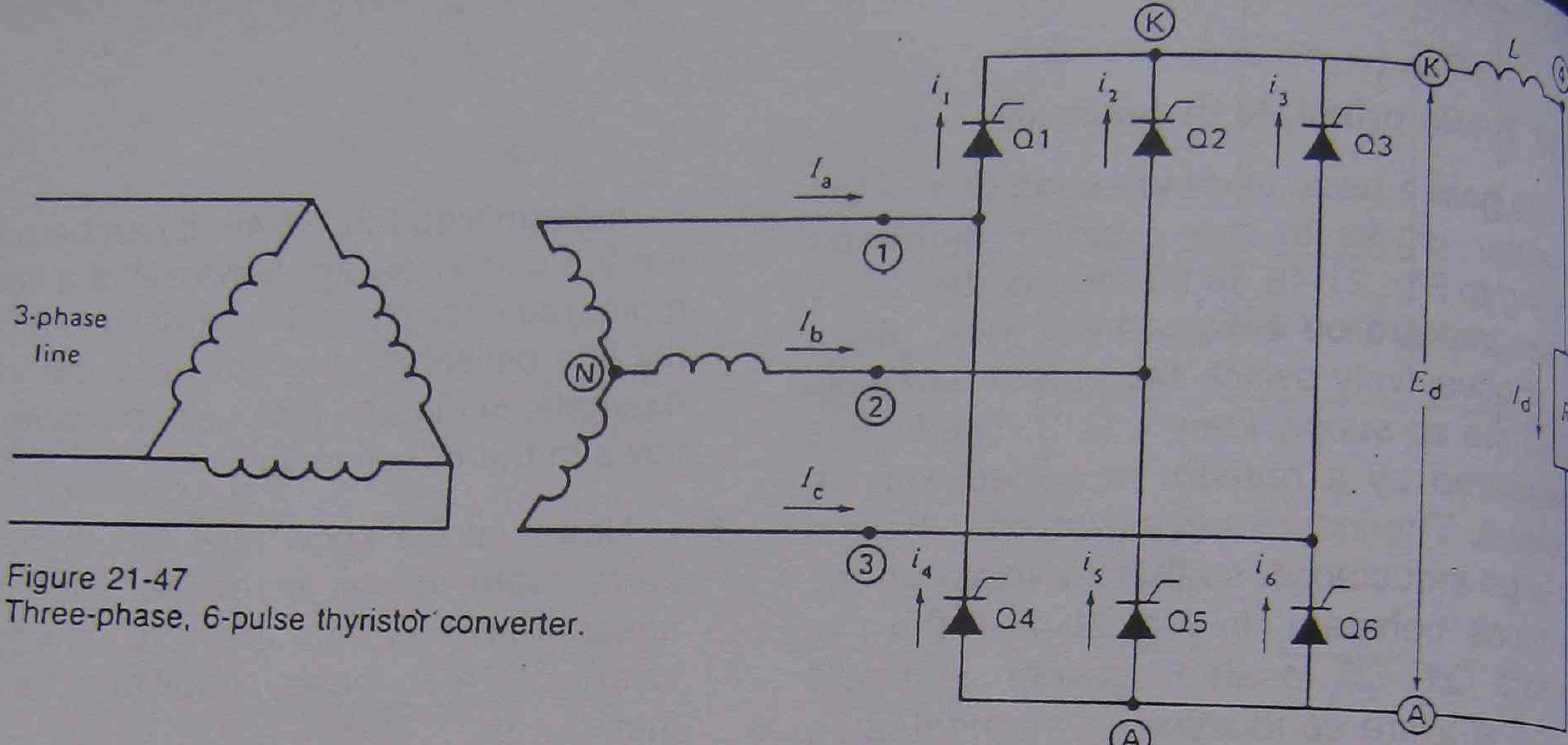


Figure 21-47
Three-phase, 6-pulse thyristor converter.

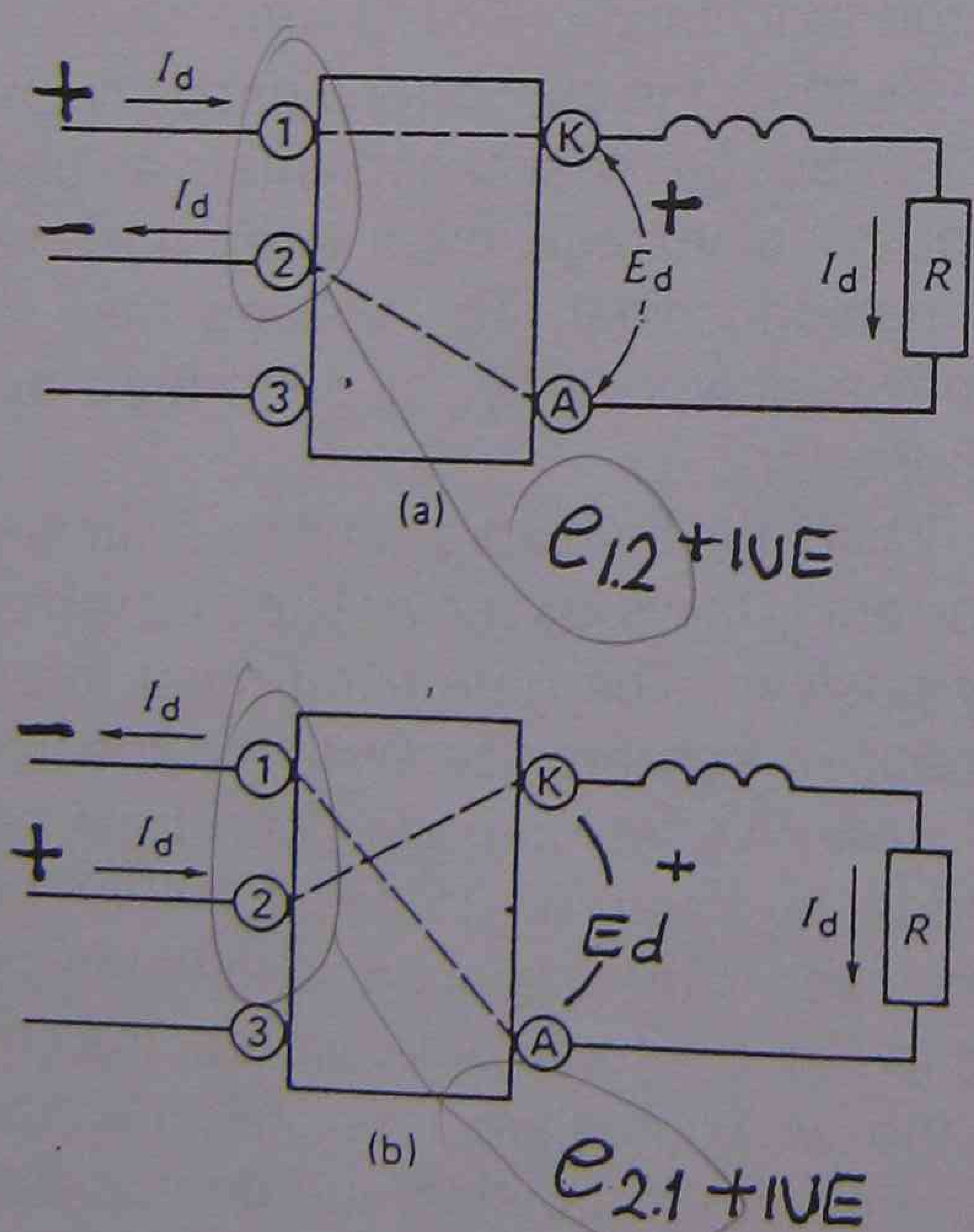


Figure 21-48
Rectifier mode (see Fig. 21-47)
a. Q1 and Q5 conducting.
b. Q2 and Q4 conducting.

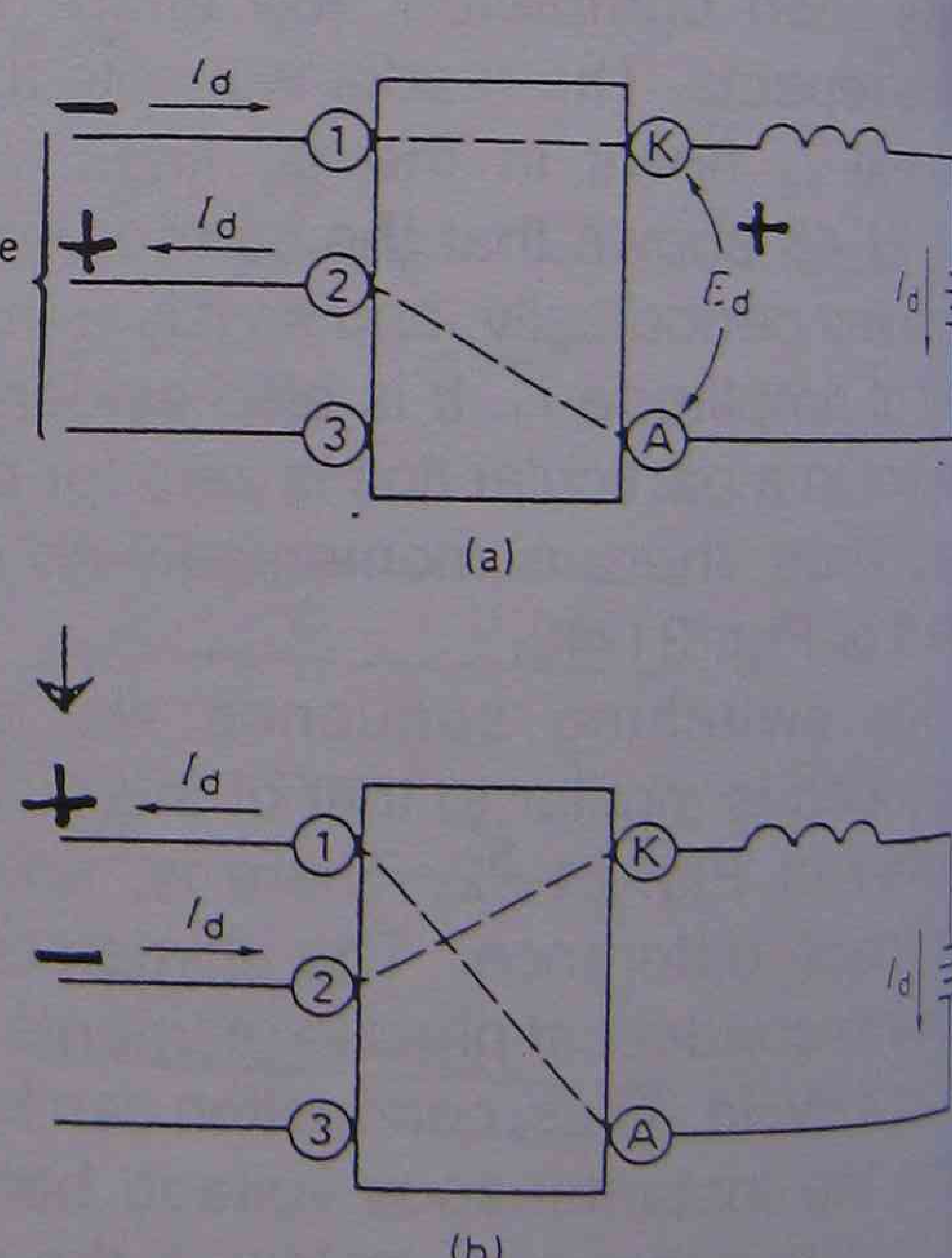


Figure 21-49
Inverter mode (see Fig. 21-47)
a. Q1 and Q5 conducting.
b. Q2 and Q4 conducting.

Because we can initiate conduction whenever we please, the thyristors enable us to vary the dc output voltage when the converter operates in the rectifier mode. The converter can also function as an inverter, provided that a dc source is used in place of the load

Figure 21-19
Three-phase, 6-pu
with inductive filte

Figure 21-20
Voltage and curre
in Fig. 21-19.

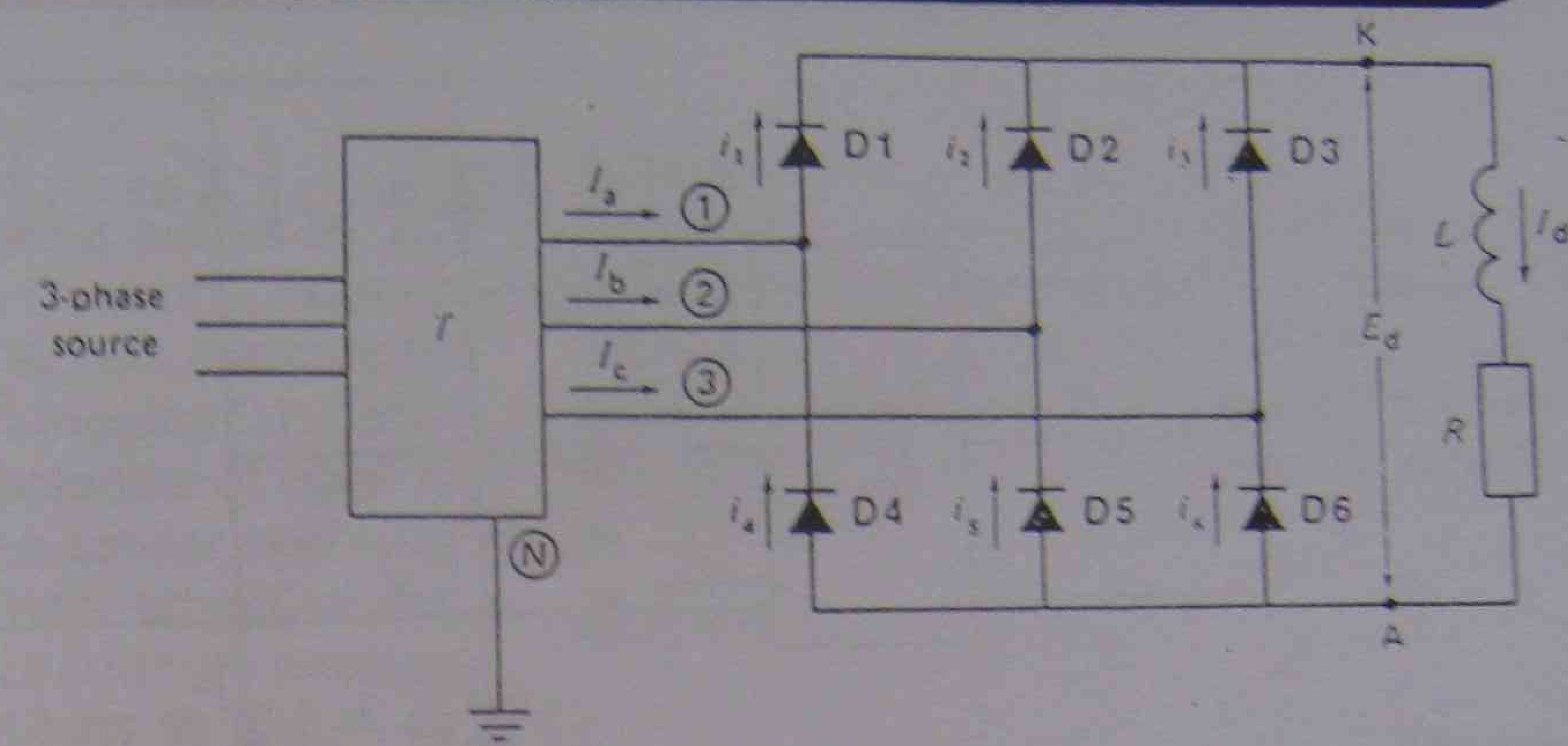


Figure 21-19
Three-phase, 6-pulse rectifier with inductive filter.

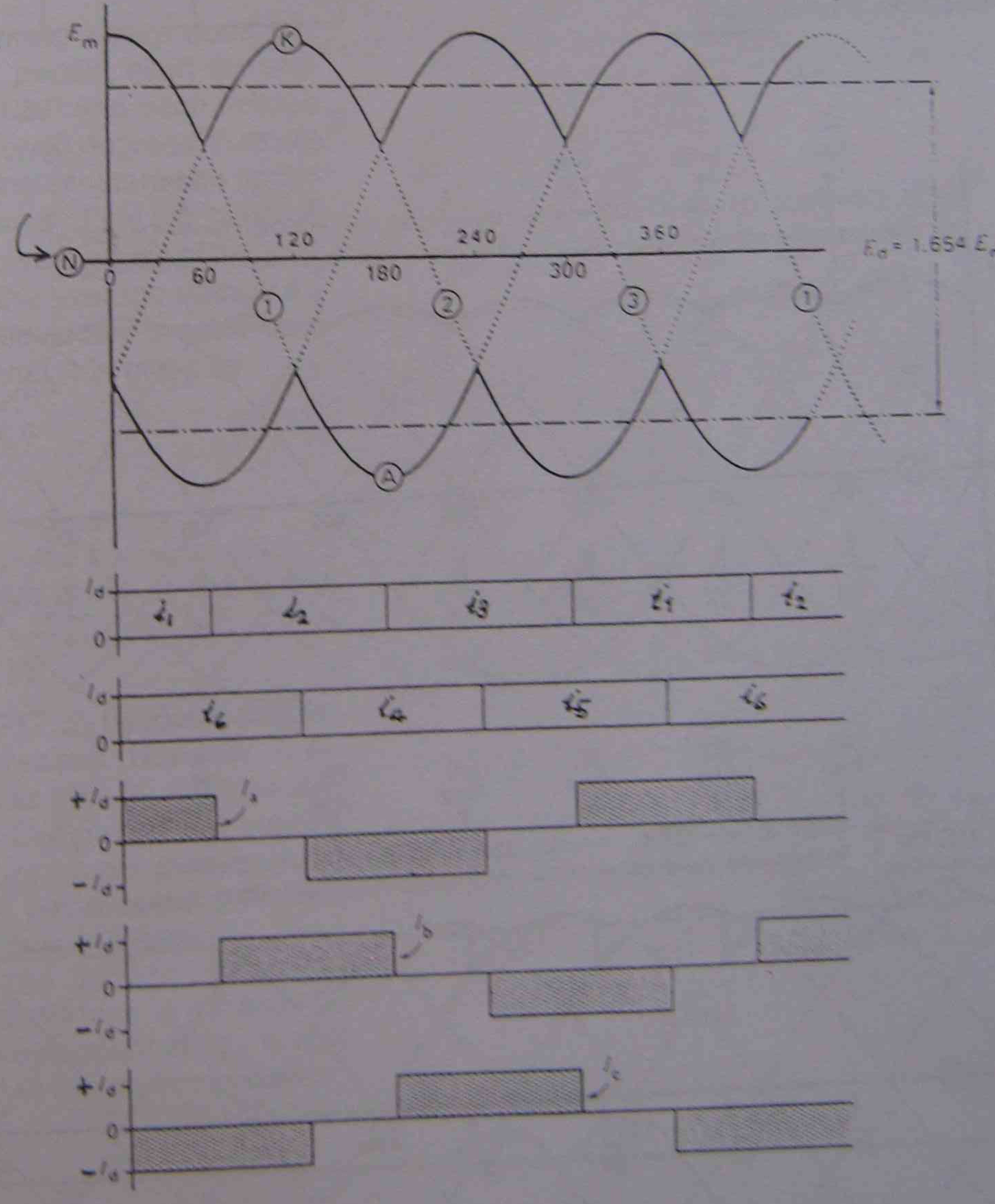


Figure 21-20
Voltage and current waveforms in Fig. 21-19.

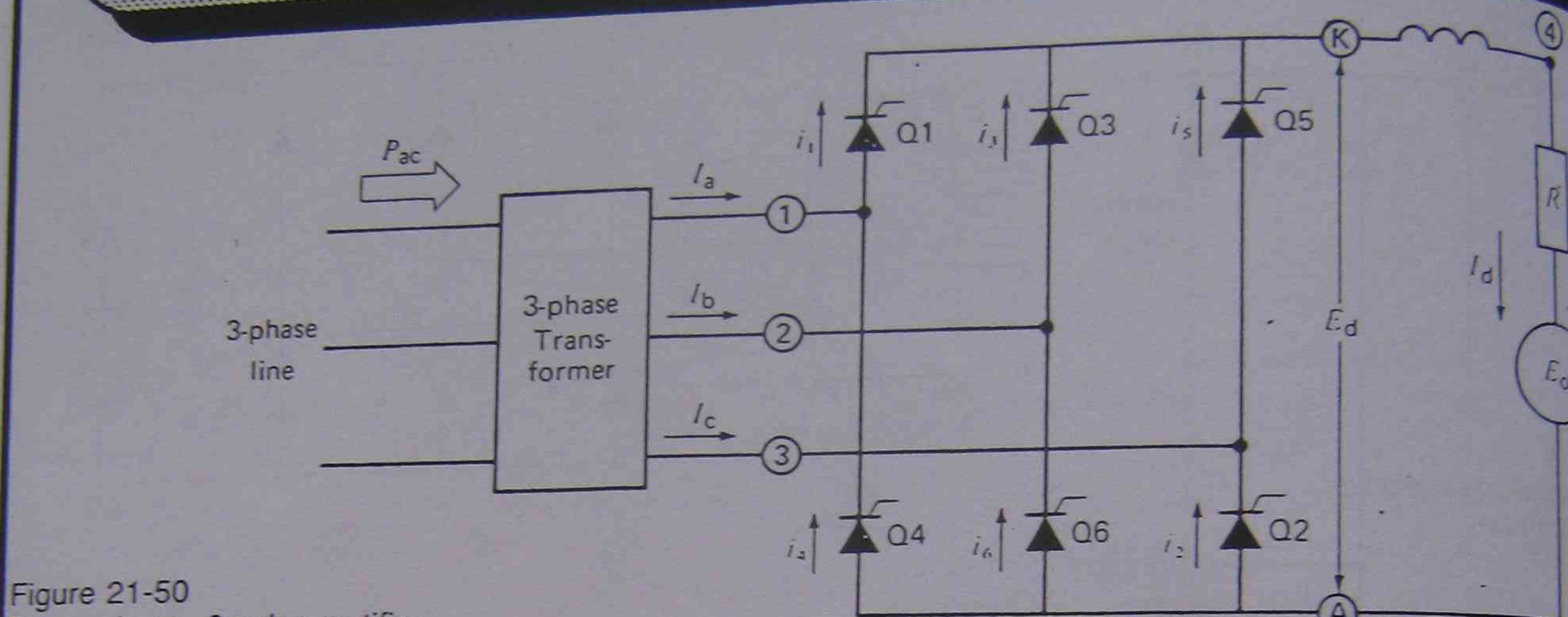


Figure 21-50
Three-phase, 6-pulse rectifier.

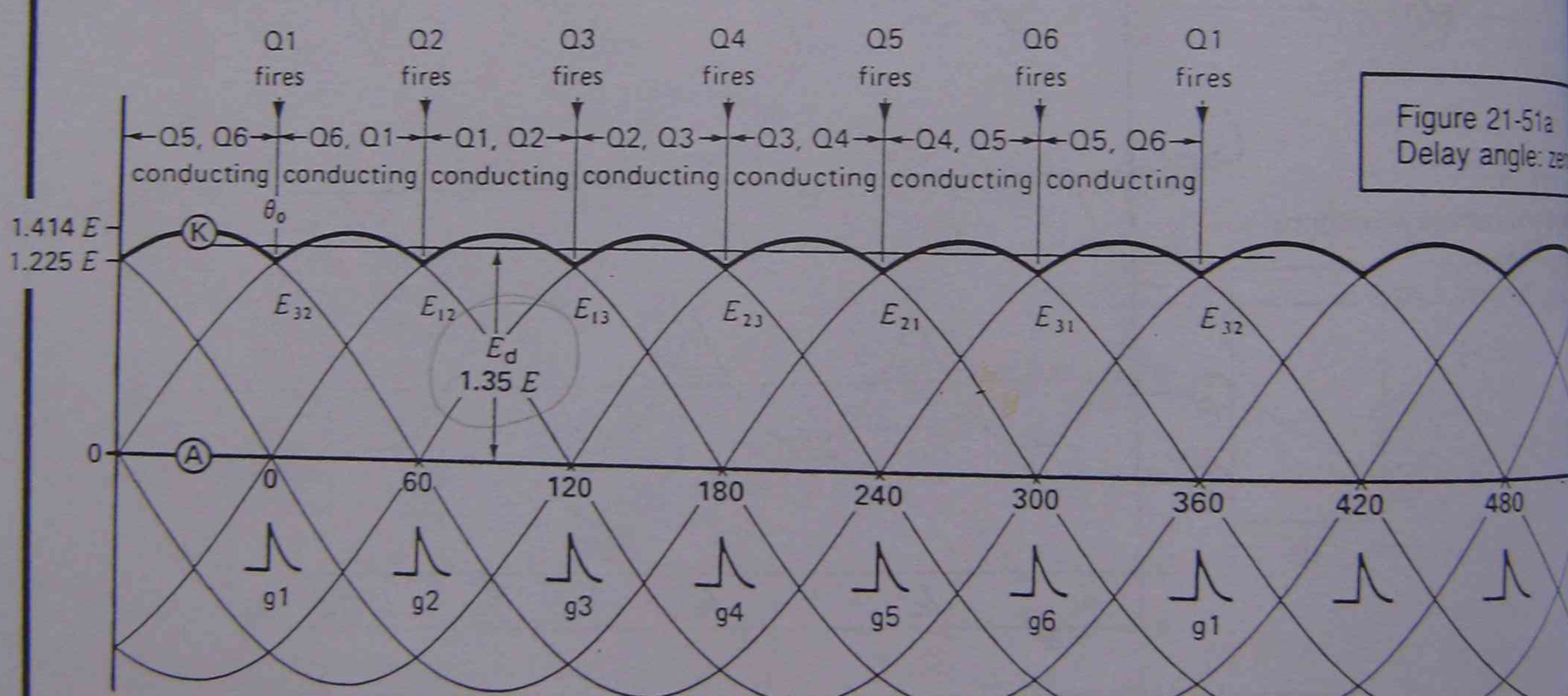


Figure 21-51a
Delay angle: zero

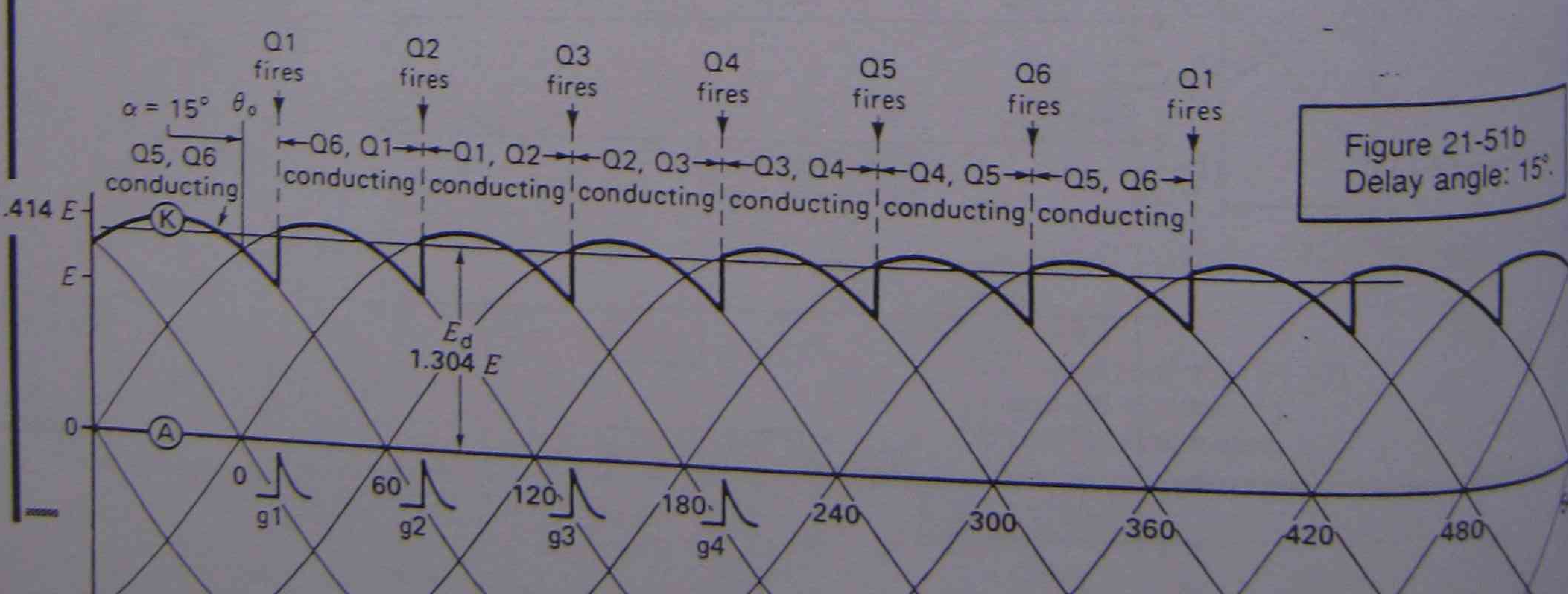


Figure 21-51b
Delay angle: 15°.

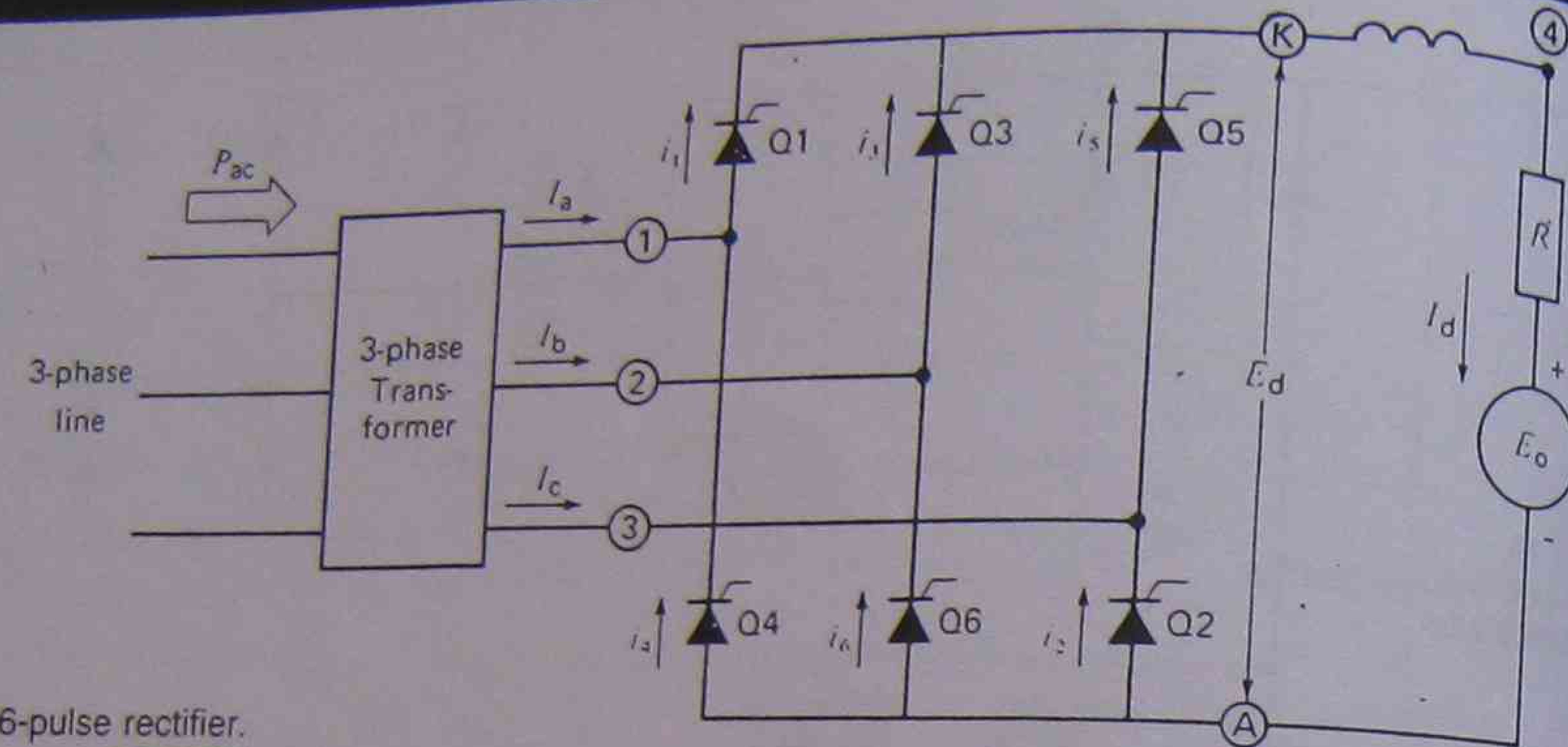


Figure 21-50
Three-phase, 6-pulse rectifier.

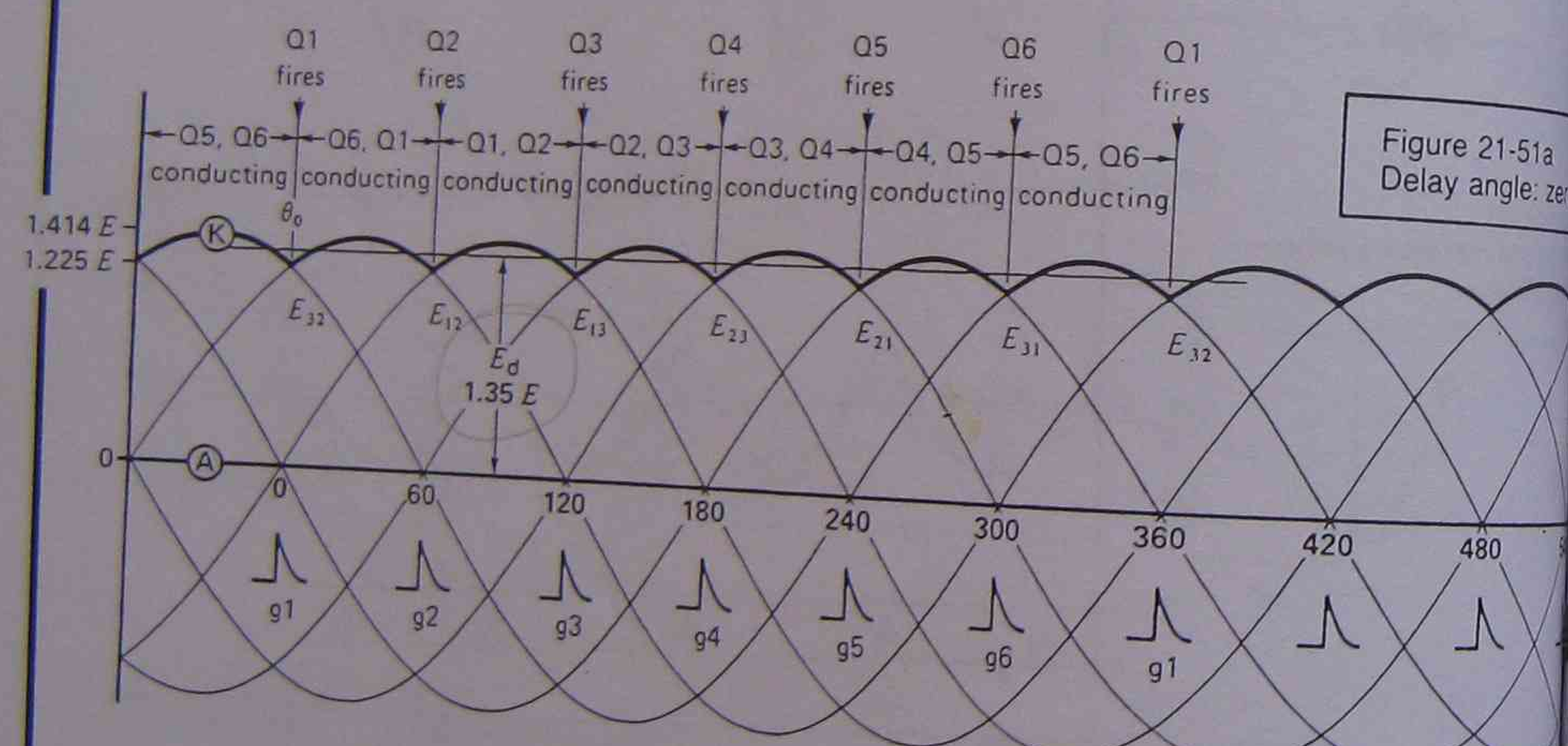


Figure 21-51a
Delay angle: zero

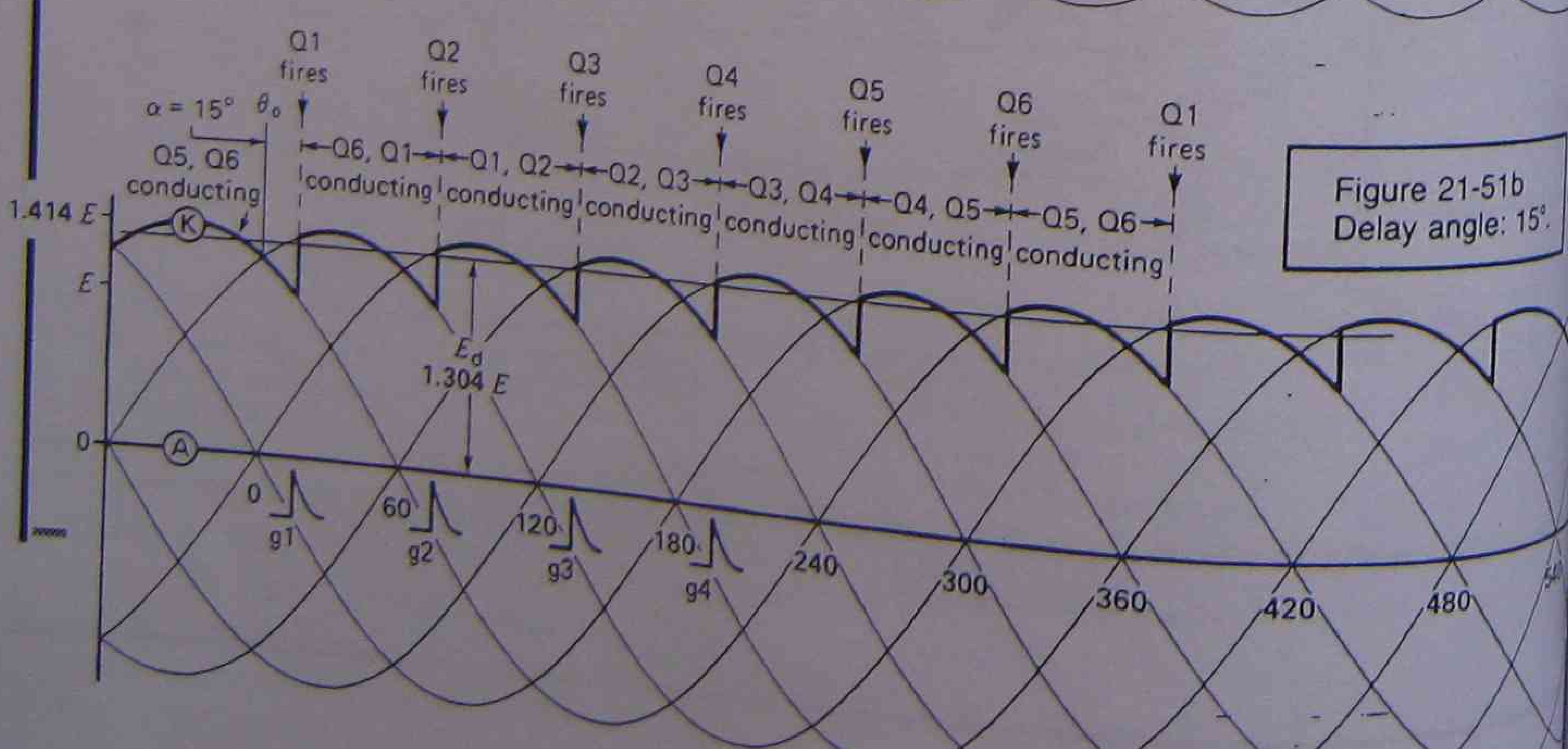


Figure 21-51b
Delay angle: 15°.

21.28 Delayed triggering – rectifier mode

Let us now delay all triggering pulses by an angle α of 15° (Fig. 21-51b). Current I_d, instead of switching over to Q1 at θ_o, will continue to flow in Q5 until gate pulse g1 triggers Q1. Commutation occurs, and the potential of point K jumps from line 3 to line 1. A similar switching action takes place (but at later times) for the other thyristors. The resulting choppy waveshape between terminals K and A is shown in Fig. 21-51b.

Note that the triggering delay does not shorten the conduction period; each thyristor still conducts for a full 120° and each voltage segment has a duration of 60 degrees. Furthermore, the current remains constant and ripple-free, owing to the presence of the big inductor. The level of point K follows the tops of the individual sine waves, but the average voltage E_d, between K and A, is obviously smaller than before. We can prove that it is given by:

$$E_d = 1.35E\cos\alpha \qquad (21\text{-}17)$$

where

E_d = dc voltage produced by the 3-phase, 6-pulse converter [V]

E = effective value of the ac line-to-line voltage [V] — Vrms

α = firing angle [°]

According to Eq. 21-17, E_d becomes smaller and smaller as α increases. However, if E_d becomes equal to or less than E_0, the load current ceases to flow. Ordinarily, the current would reverse when E_d is smaller than E_0. However, this is impossible, because the SCRs can only conduct in the forward direction.

Figures 21-51c and 21-51d show the waveform between K and A for α = 45° and 75°, respectively. The ac component in E_{KA} is now very large, compared to the dc component.

Example 21-9.

The 3-phase converter of Fig. 21-50 is connected to a 3-phase 480 V, 60 Hz source. The load consists of a 500 V dc source having an internal resistance of 2 Ω. Calculate the power supplied to the load for triggering delays of a. 15°, b. 75°.

Solution:

(3) Active Power $P_1 = S_1 \cos\phi$ KW
$P_1 = 1.35 V_{rms} I_D \cos\phi$ KW

(2) Apparent Power $S_1 = \sqrt{3} V_{rms} I_1$ KVA
$= \sqrt{3} V_{rms}\, 0.78 I_D$ KVA
$= 1.35 V_{rms} I_D$

(4) Reactive Power $Q = S_1 \sin\phi$ kVAr

(1) $I_{1\,rms} = \sqrt{3}\,\frac{\sqrt{2}}{\pi} I_D = 0.78 I_D$ amps
I_D = DC current.

Delay angle	converter behaviour
α = 0°	Resistive load
0° < α < 90°	Resistive/Inductive load
α = 90°	Pure Inductive load
α > 90°	Source from Ind load

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Module **NE76**

A.C. Motor Control

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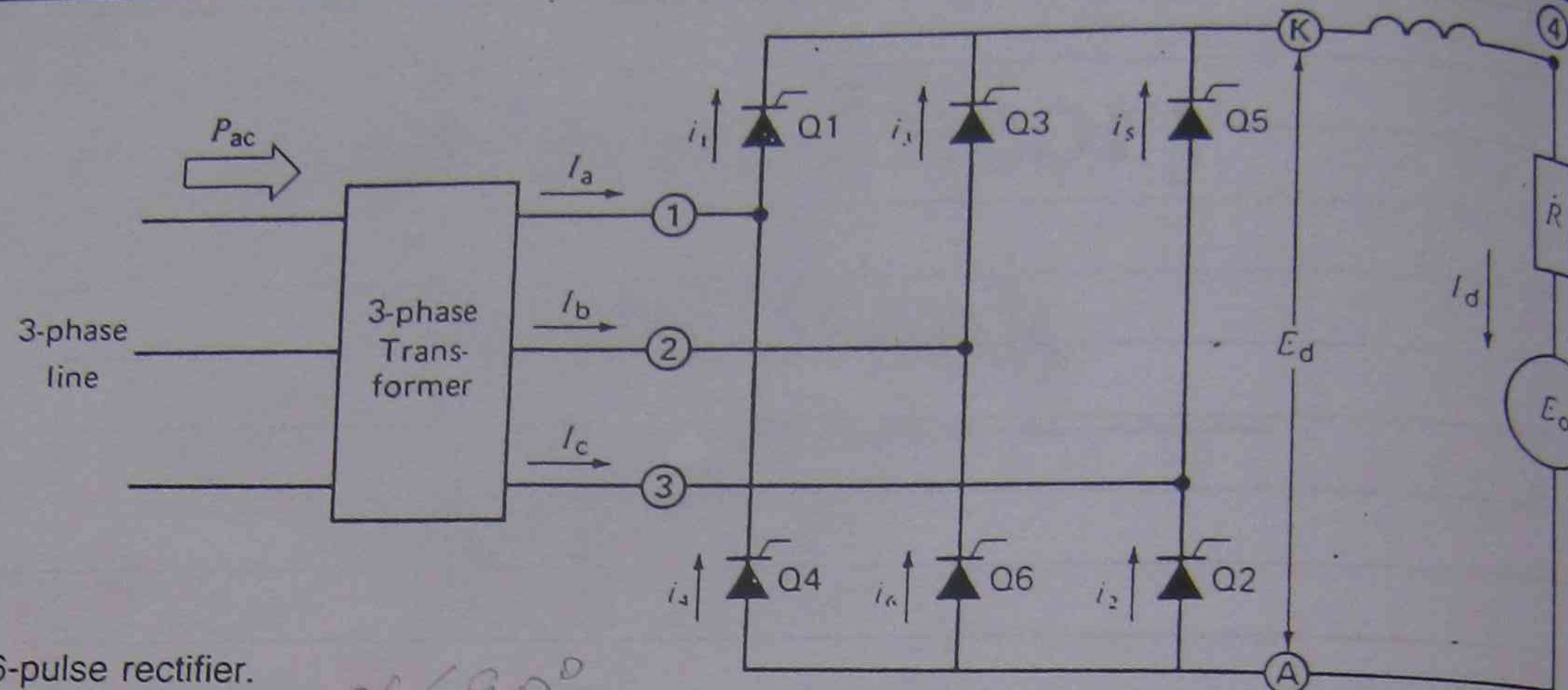

Figure 21-50
Three-phase, 6-pulse rectifier.

α<90°

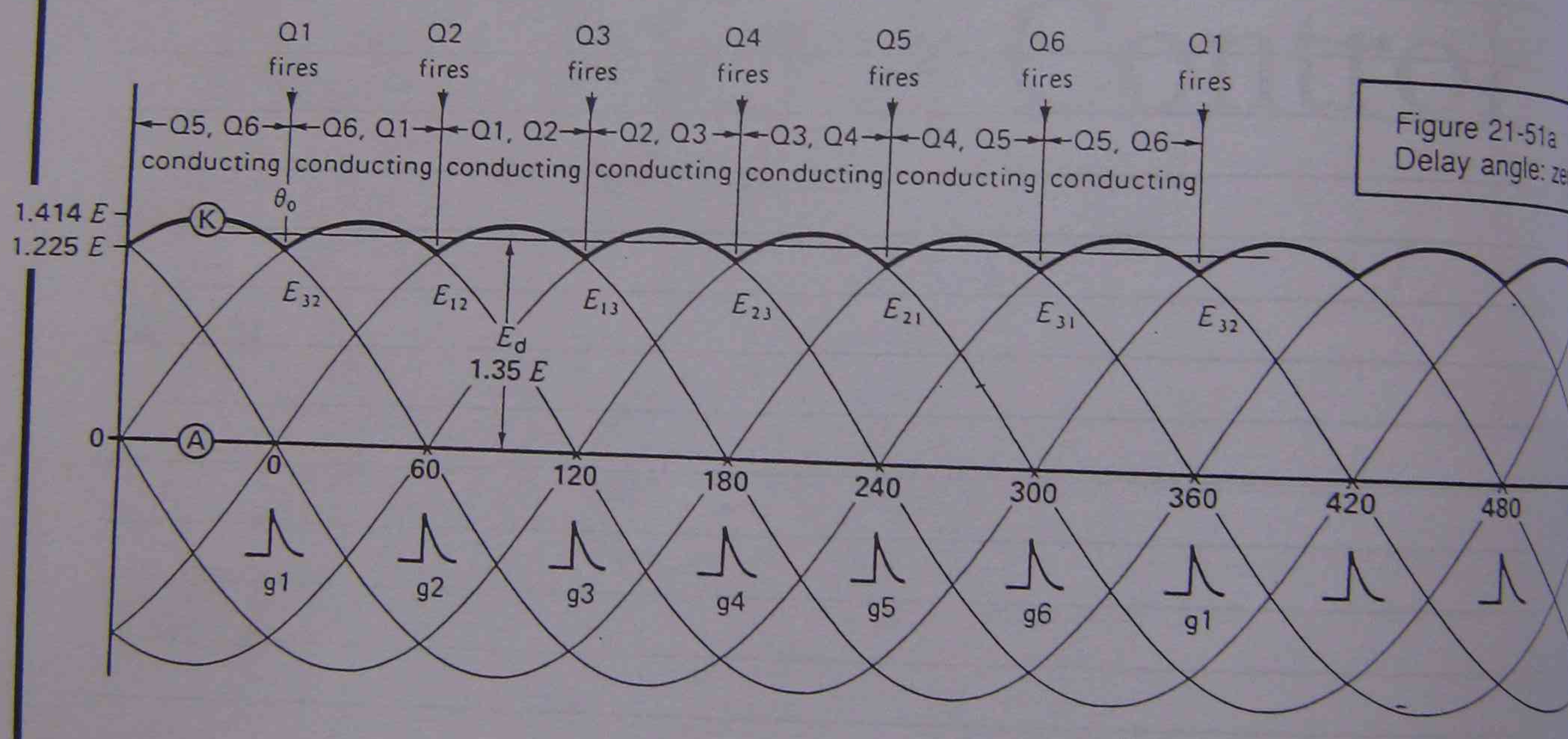

Figure 21-51a
Delay angle: zero

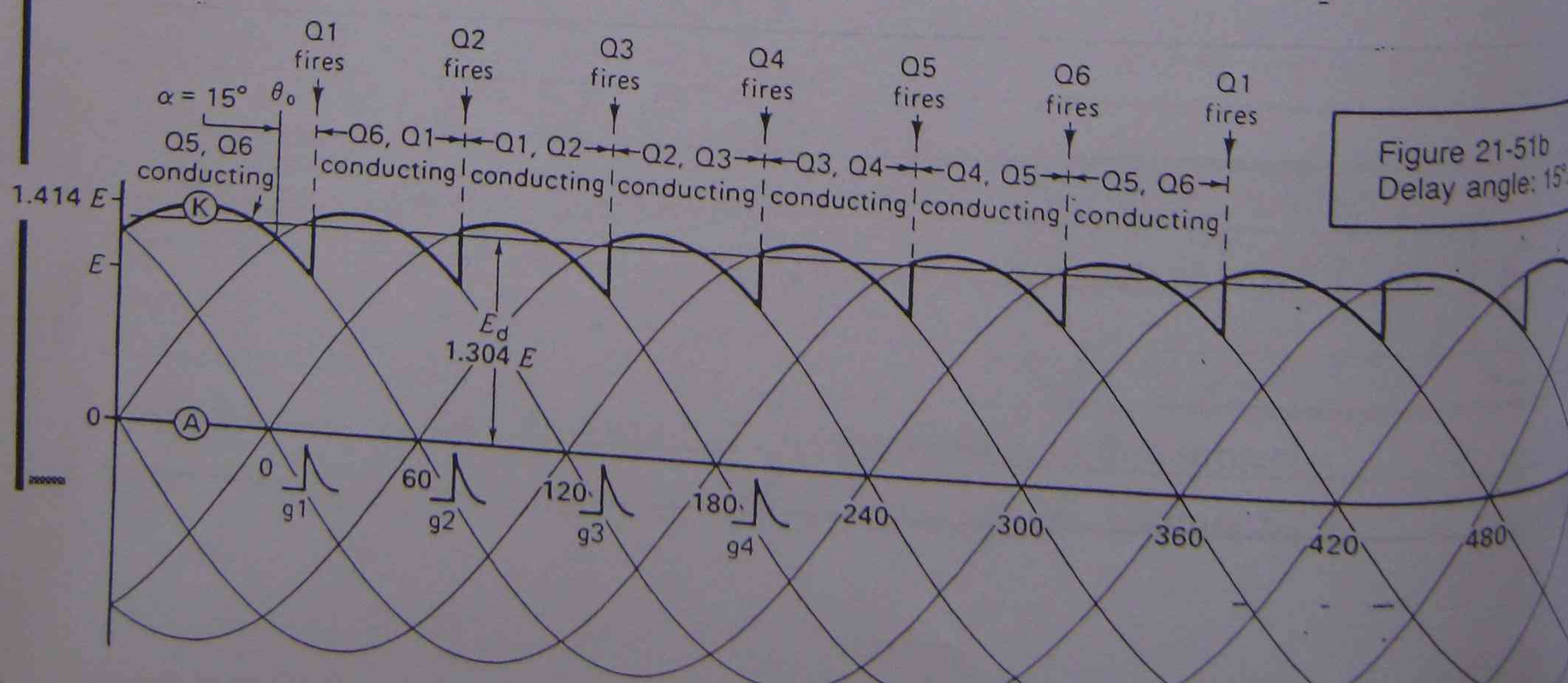

Figure 21-51b
Delay angle: 15°

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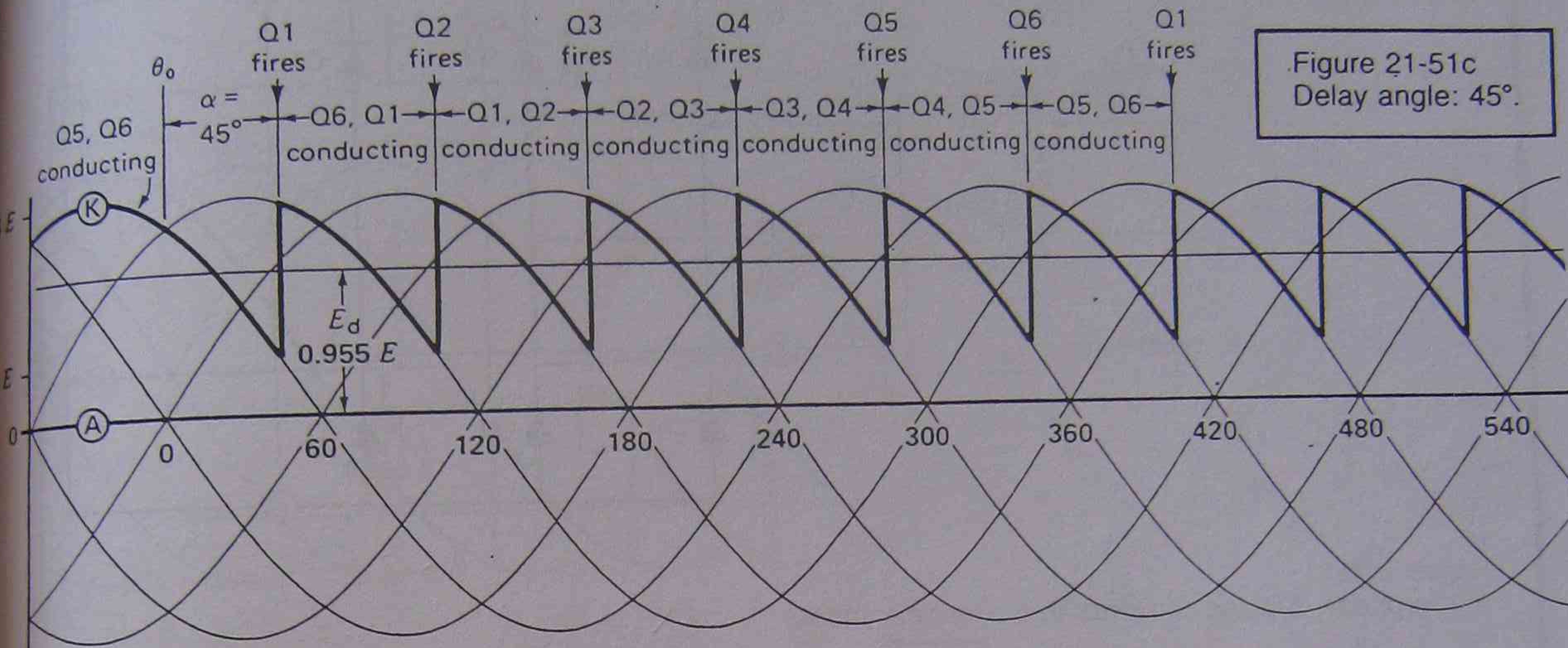

Figure 21-51c
Delay angle: 45°.

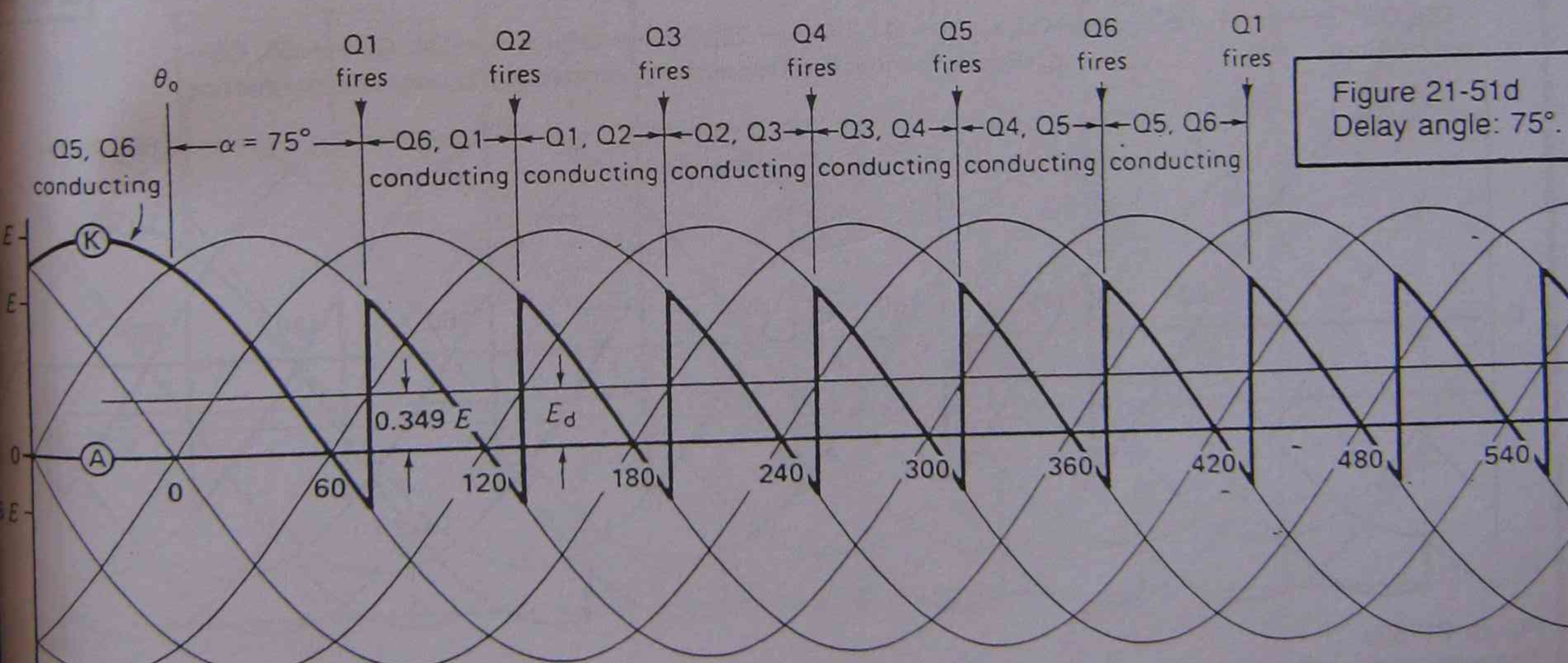

Figure 21-51d
Delay angle: 75°.

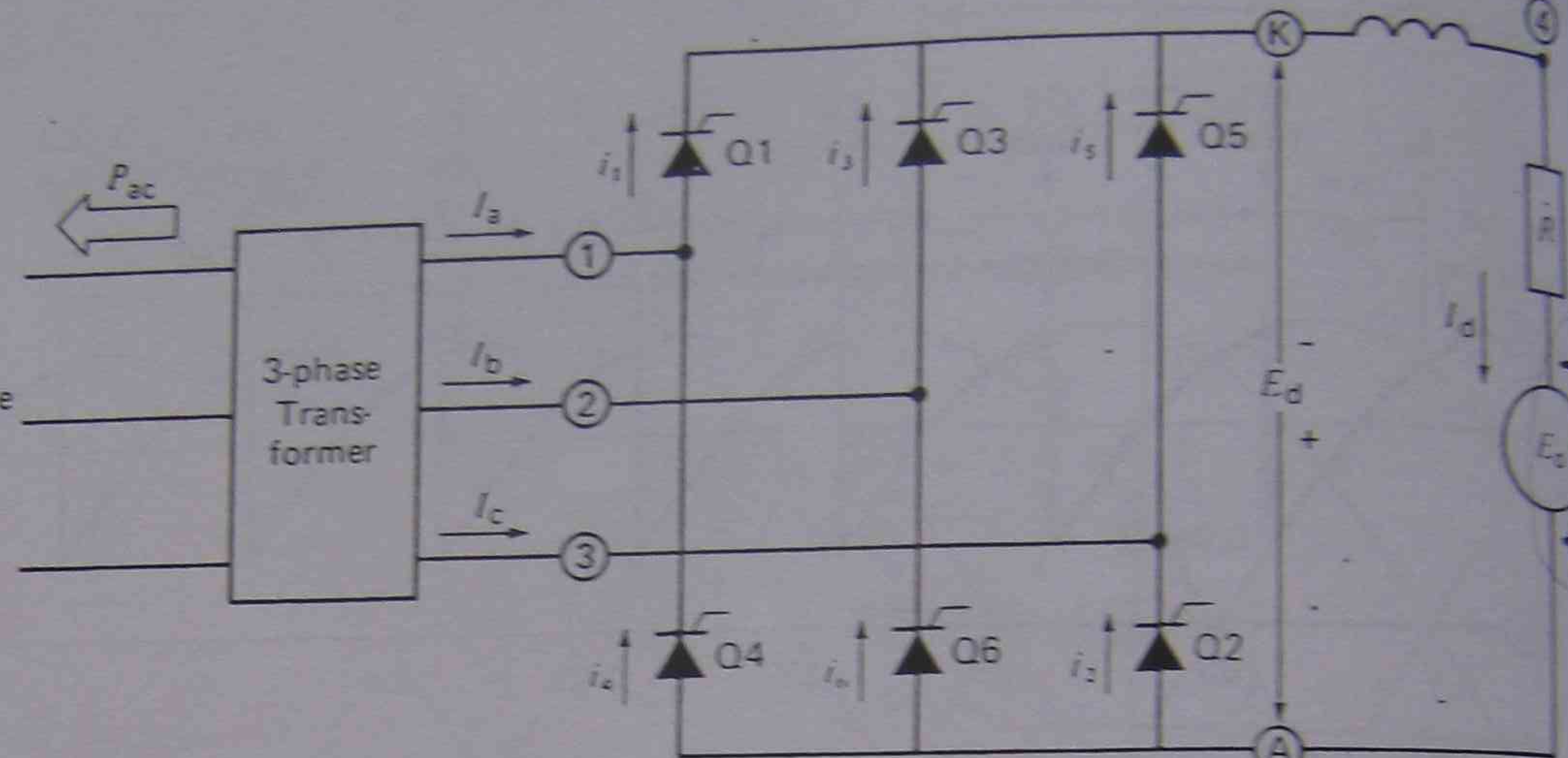

Figure 21-52
Three-phase, 6-pulse converter in the inverter mode.

α > 90°   note E_o polarity i.e. BEMF

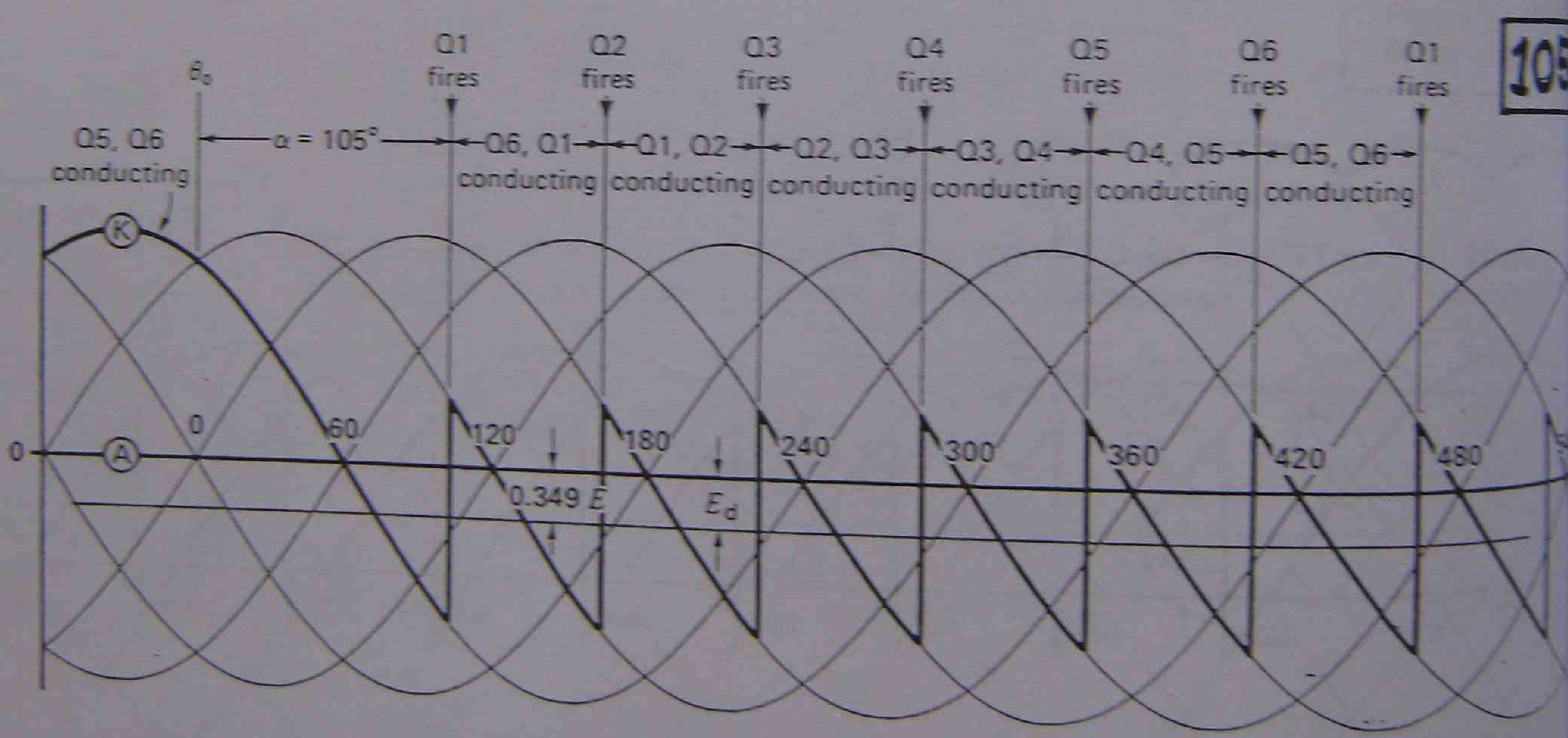

Figure 21-53a
Triggering sequence and waveforms with a delay angle of 105°

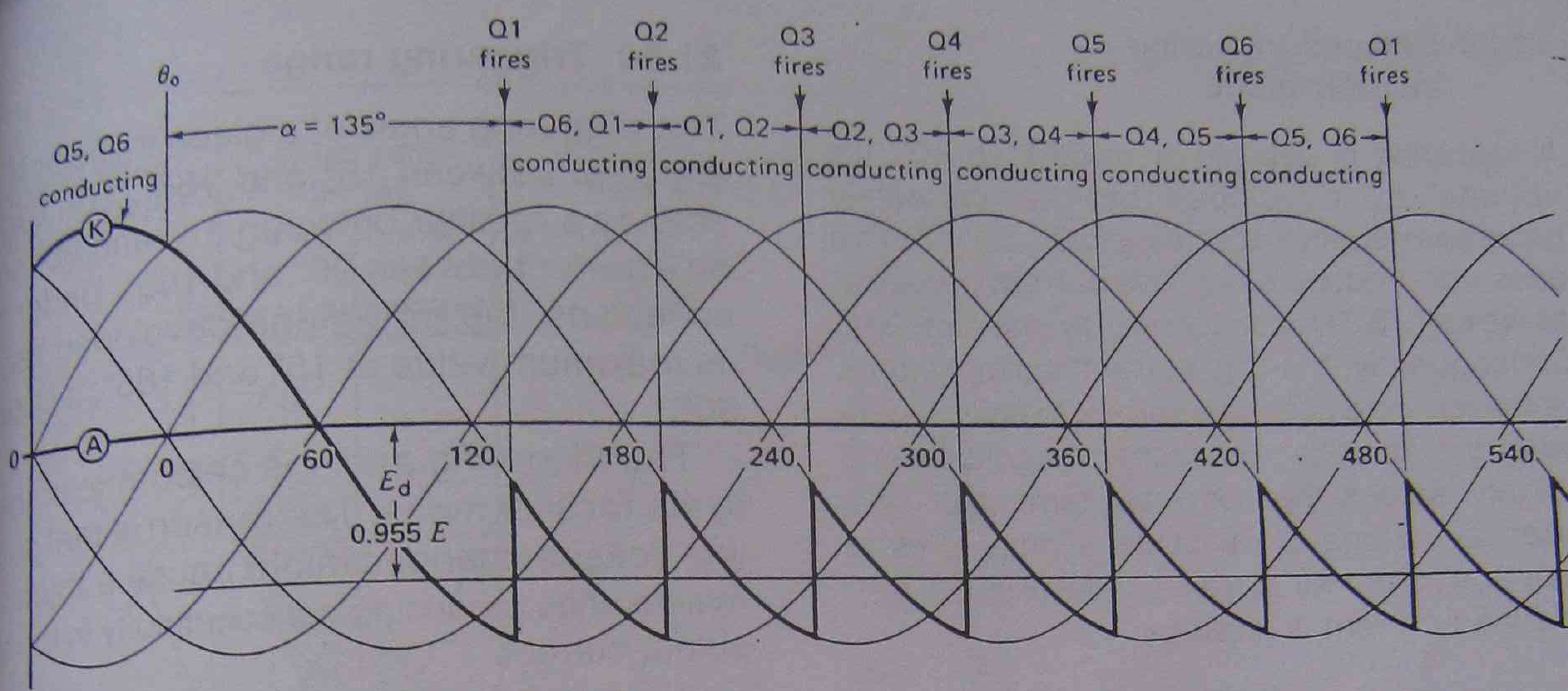

Figure 21-53b
Triggering sequence and waveforms with a delay angle of 135°

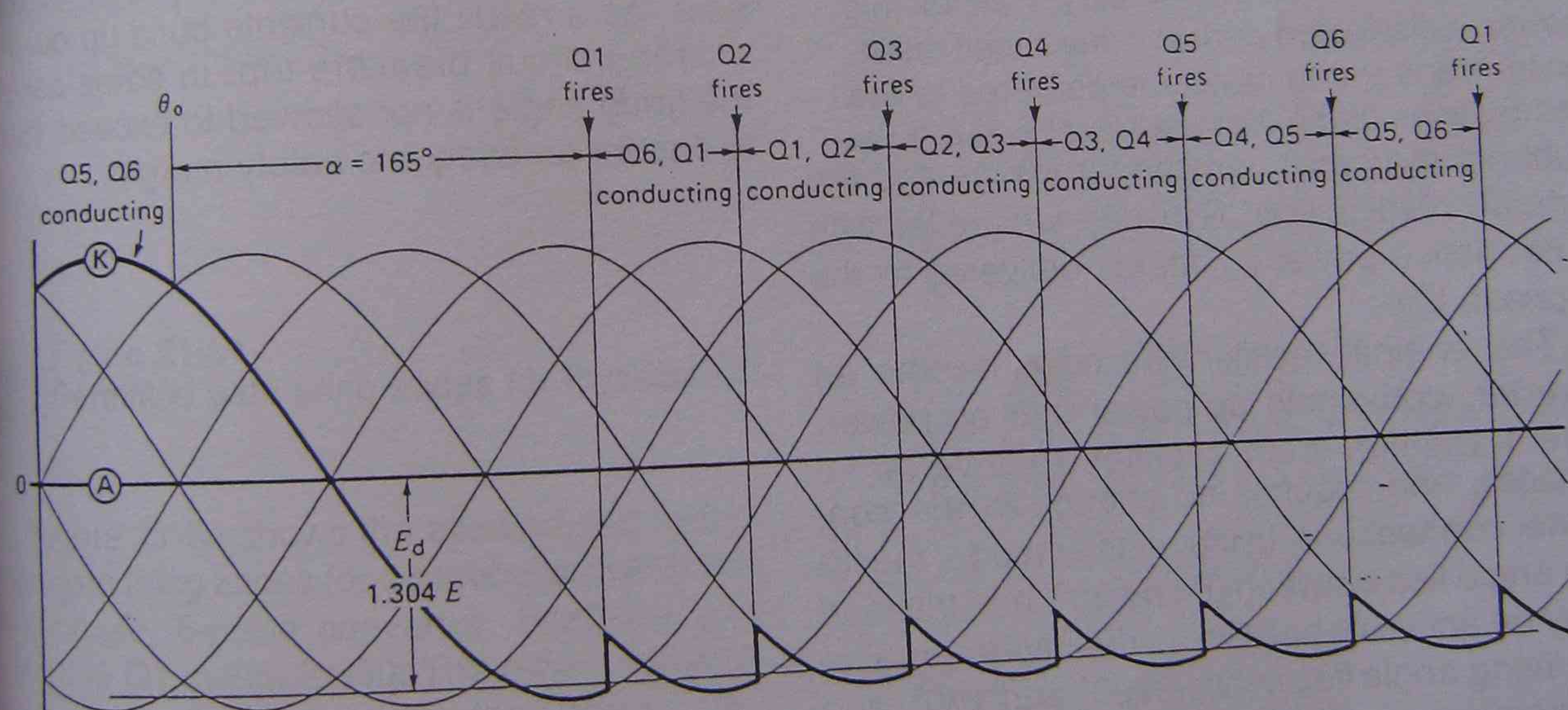

Figure 21-53c
Triggering sequence and waveforms with a delay angle of 165°.

21.29 Delayed triggering – inverter mode

If triggering is delayed by more than 90°, the voltage E_d developed by the converter becomes negative according to Eq. 21-17. This does not produce a negative current because, as we said, SCRs conduct in only one direction. Consequently, the load current is simply zero. However, we can *force* a current to flow by connecting a dc voltage of proper magnitude and polarity across the converter terminals. This external voltage E_0 must be slightly greater than E_d in order for current to flow (Fig. 21-52). The load current is given by:

$$I = (E_0 - E_d)/R$$

Because current flows out of the positive terminal of E_0, the "load" is actually a source, delivering a power output $P = E_0 I_d$. Part of this power is dissipated as heat in the circuit resistance R and the remainder is delivered to the secondaries of the 3-phase transformer. If we subtract the small transformer losses and the virtually negligible SCR losses, we are left with a net active power P_{ac} that is delivered to the 3-phase line.

The original rectifier has now become an *inverter*, converting dc power into ac power. The transition from rectifier to inverter is smooth, and requires no change in the converter connections. In the rectifier mode, the firing angle lies between 0° and 90°, and the load may be active or passive. In the inverter mode, the firing angle lies between 90° and 180°, and a dc source of proper polarity *must* be provided.

Figure 21-53 shows the waveshapes at firing angles of 105°, 135° and 165°. The dc voltage E_d generated by the inverter is still given by Eq. 21-17. It reaches a maximum value of $E_d = -1.35E$ at a firing angle of 180°.

21.30 Triggering range

The triggering angle of a given thyristor is u ally kept between 15° and 165°. The thyris acts as a rectifier between 15° and 90° and an inverter between 90° and 165°. Under th conditions, the dc voltage developed reac its maximum value at 15° and 165°; it is zero 90°.

The triggering angle is seldom less than in the rectifier mode. The reason is that sudd line voltage changes might cause a thyristor misfire, thus producing a discontinuity in the dc output current.

In the inverter mode, we never permit the firing angle to exceed 165°. If we go beyond this point, the inverter begins to lose its ability to switch reliably from one thyristor to the next. As a result the currents build up quickly until the circuit breakers trip. In some cases the firing angle is not allowed to exceed 150° to ensure an adequate safety margin.

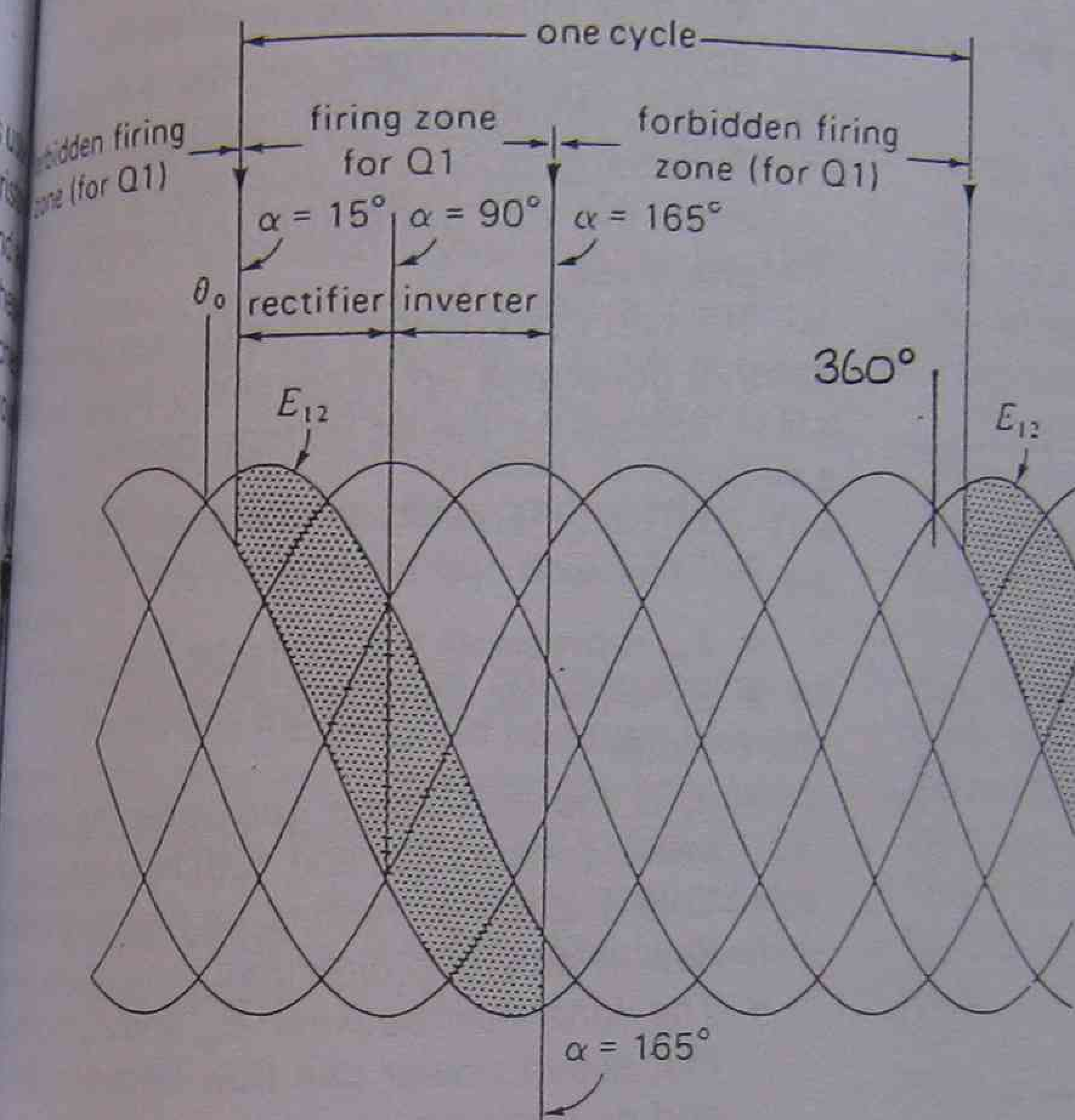

Figure 21-54
Permitted gate firing zones for thyristor Q1.

Figure 21-54 shows the allowed and forbidden gate firing zones for a particular thyristor in a 3-phase, 6-pulse converter. Specifically, it refers to Q1 in Fig. 21-50. The other thyristors have similar firing zones, but they occur at different times.

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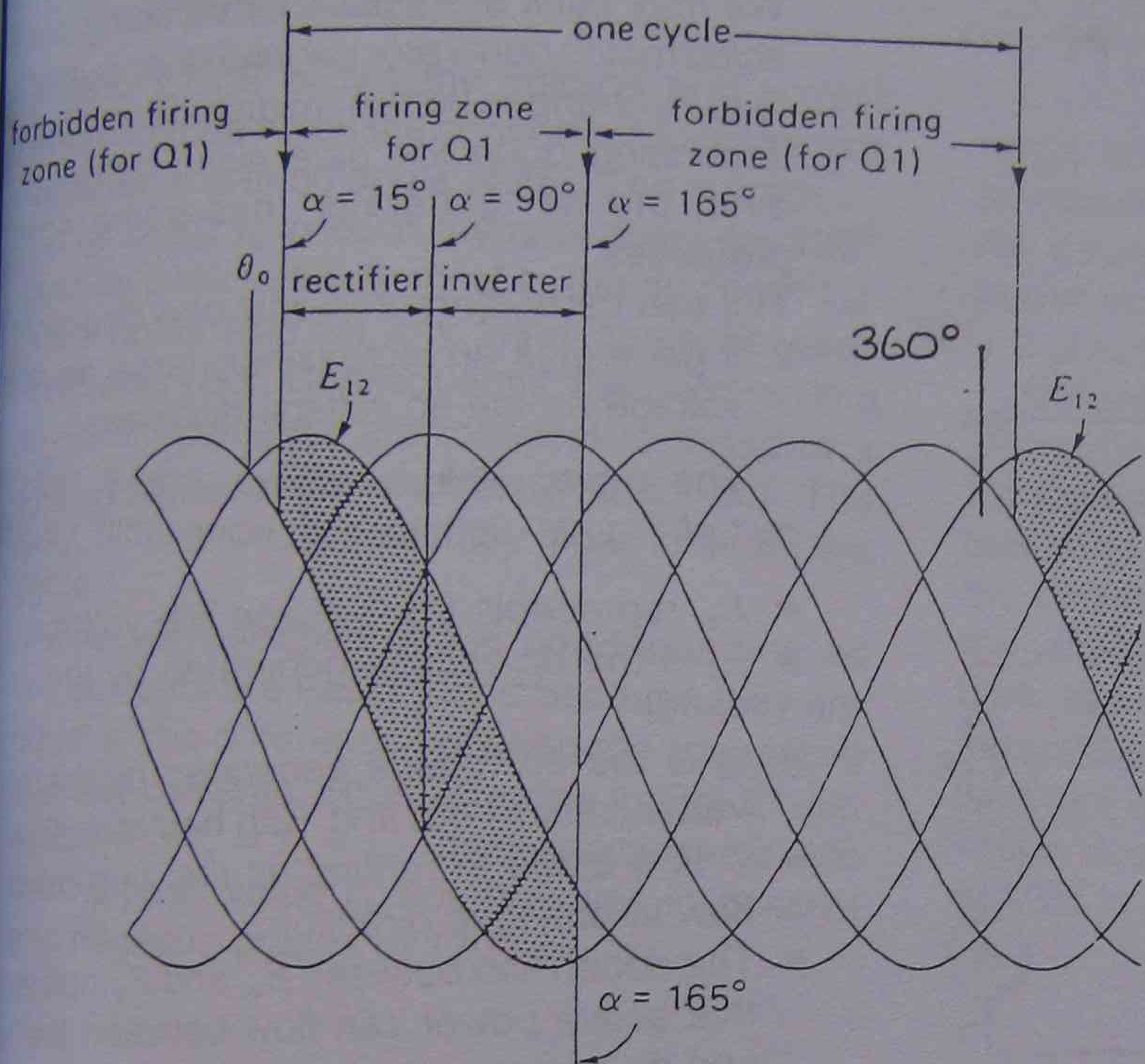

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