

FIGURE 11-23 Inverter section, Graham CSI controller

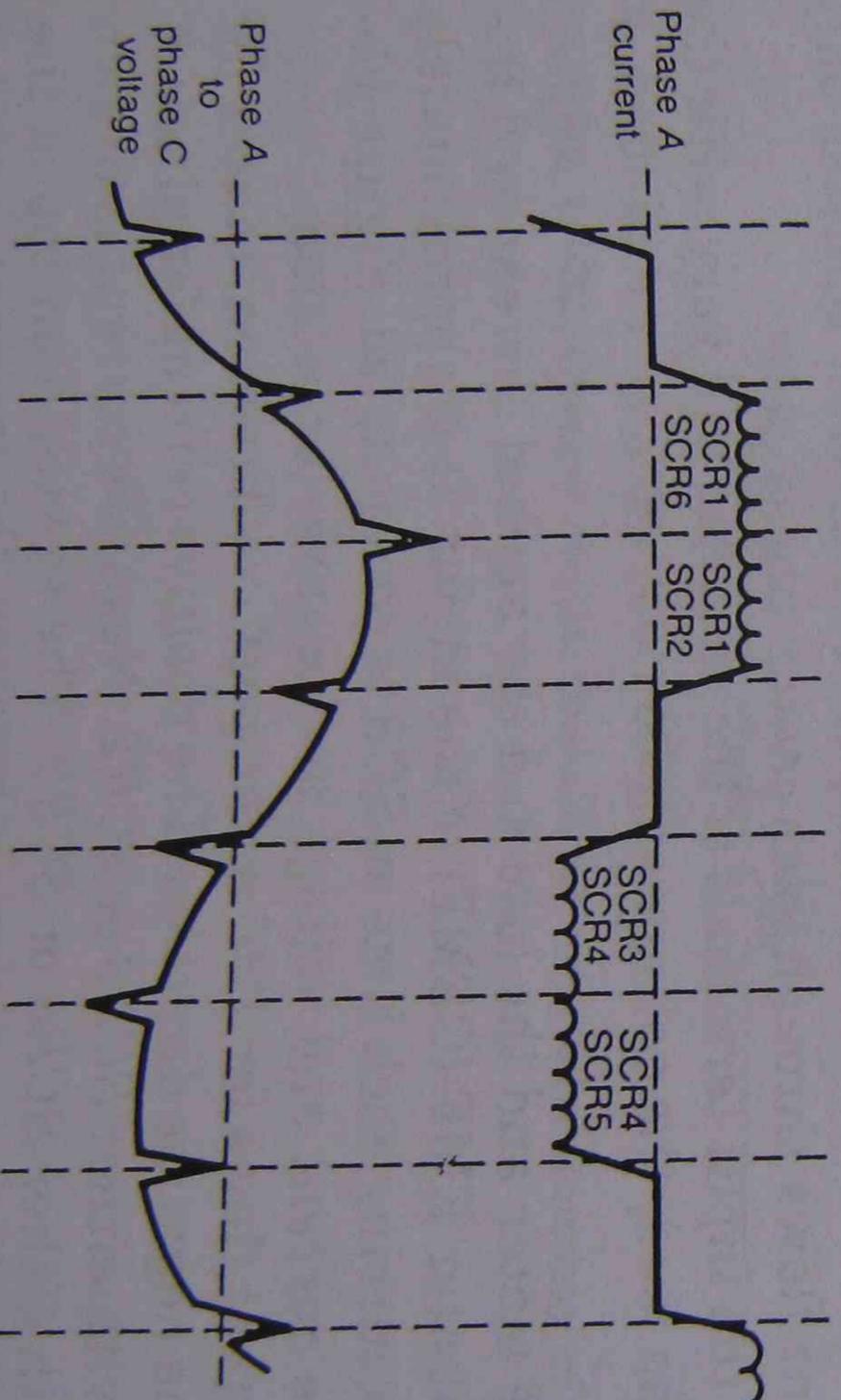


FIGURE 11-24 Synchrogram showing currents and voltages in inverter (courtesy of Graham Co.)

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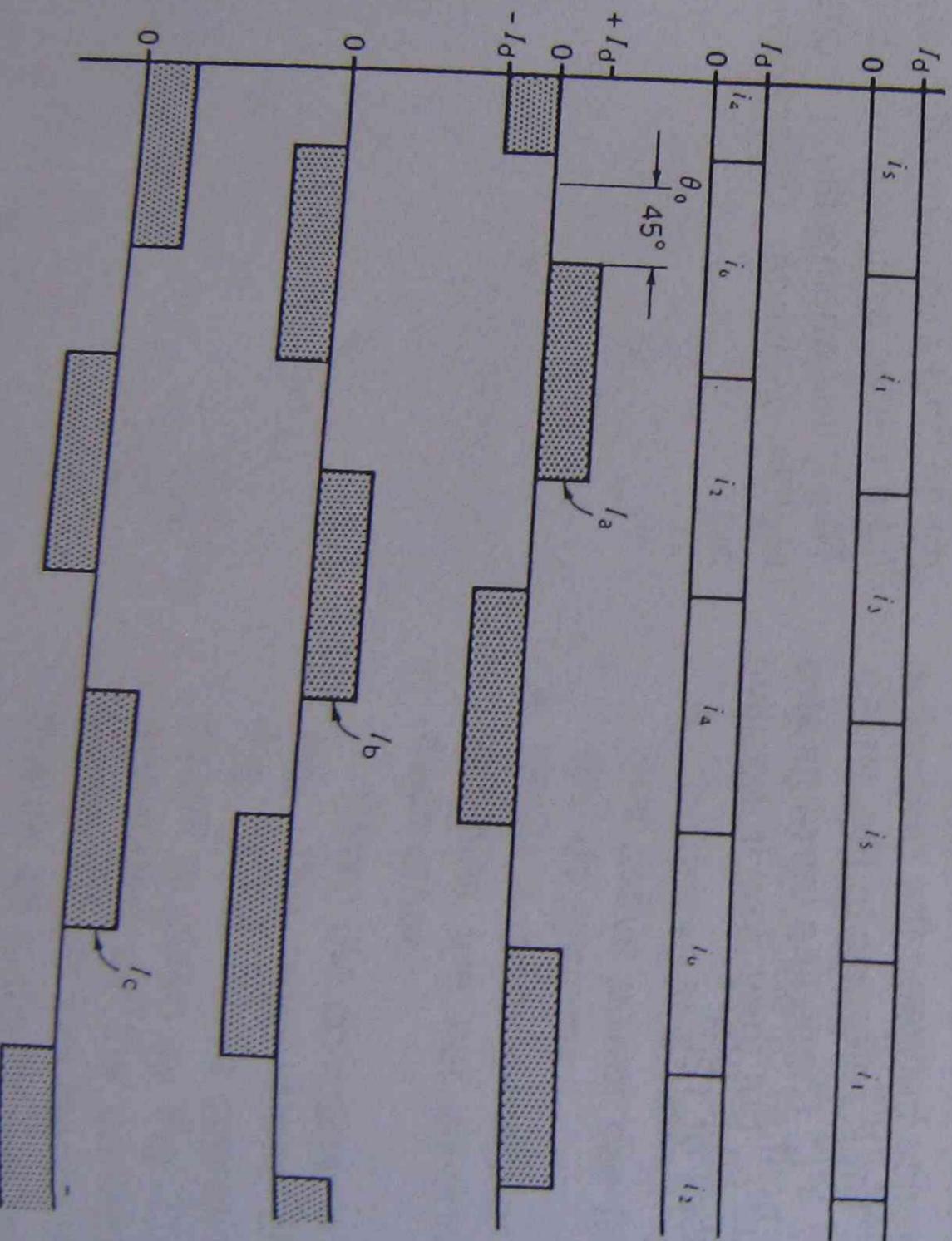
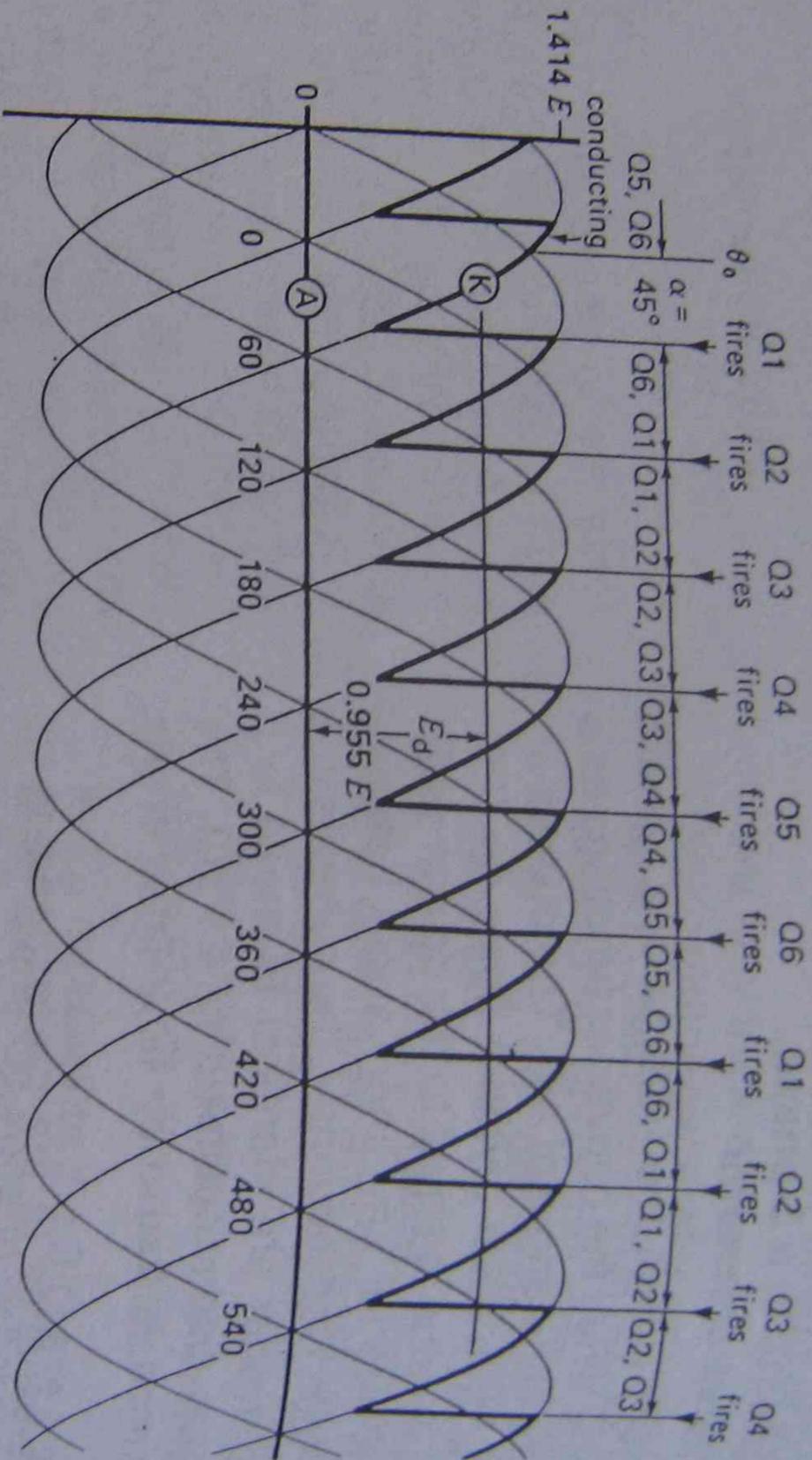


Figure 21-58  
Voltage and current waveforms in the converter of Figure 21-50 with a delay angle of  $45^\circ$ .

Figure 21-  
Instanta  
(see Fig  
Same  
showing

(b)  
 $\alpha = 45^\circ$

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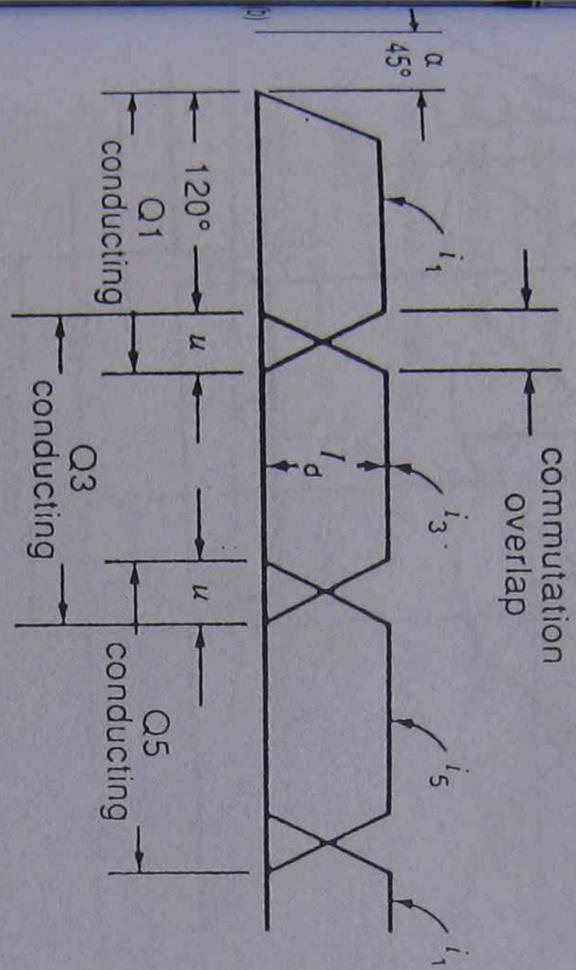
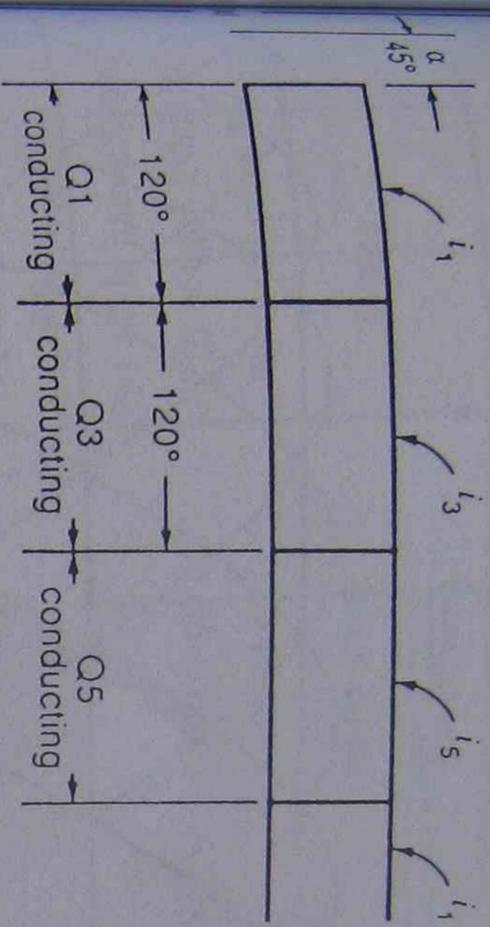


Figure 21-60

Instantaneous commutation in a rectifier when  $\alpha = 45^\circ$  (see Fig. 21-58).

Same conditions with commutation overlap of  $30^\circ$ , showing current waveshapes in Q1, Q3, Q5.

## 21.34 Commutation overlap

We mentioned in Section 21-9, that the current in a three-pulse rectifier cannot switch instantaneously from one diode to the next. The commutation process takes time and this is also true for thyristors. Thus, in a six-pulse converter, the commutation from Q1 to Q3 to Q5 is not instantaneous (as shown in Figure 21-58), but is more like that shown in Figure 21-60b.

The transfer of  $I_d$  from one thyristor to the next is effected during the so-called commutation overlap period, defined by angle  $\mu$ . The amount of overlap varies with the current  $I_d$ . At full load,  $\mu$  lies typically between  $20^\circ$  and  $30^\circ$ . At light load it can be as small as  $5^\circ$ .

On account of commutation overlap, the current in each thyristor flows for a period of  $120 + \mu$  degrees instead of  $120^\circ$ , as we have assumed so far. The commutation overlap modifies the waveshape of  $E_{ak}$ , but we do not have to examine this aspect of converter behavior.

The commutation overlap delays the current buildup by angle  $\mu$ . It also delays the current cutoff by the same angle. Owing to these delays, the effective firing angle is somewhat greater than  $\alpha$ . This reduces the power factor of the converter in both the rectifier and inverter mode. It also reduces the average dc voltage  $E_{dc}$ .



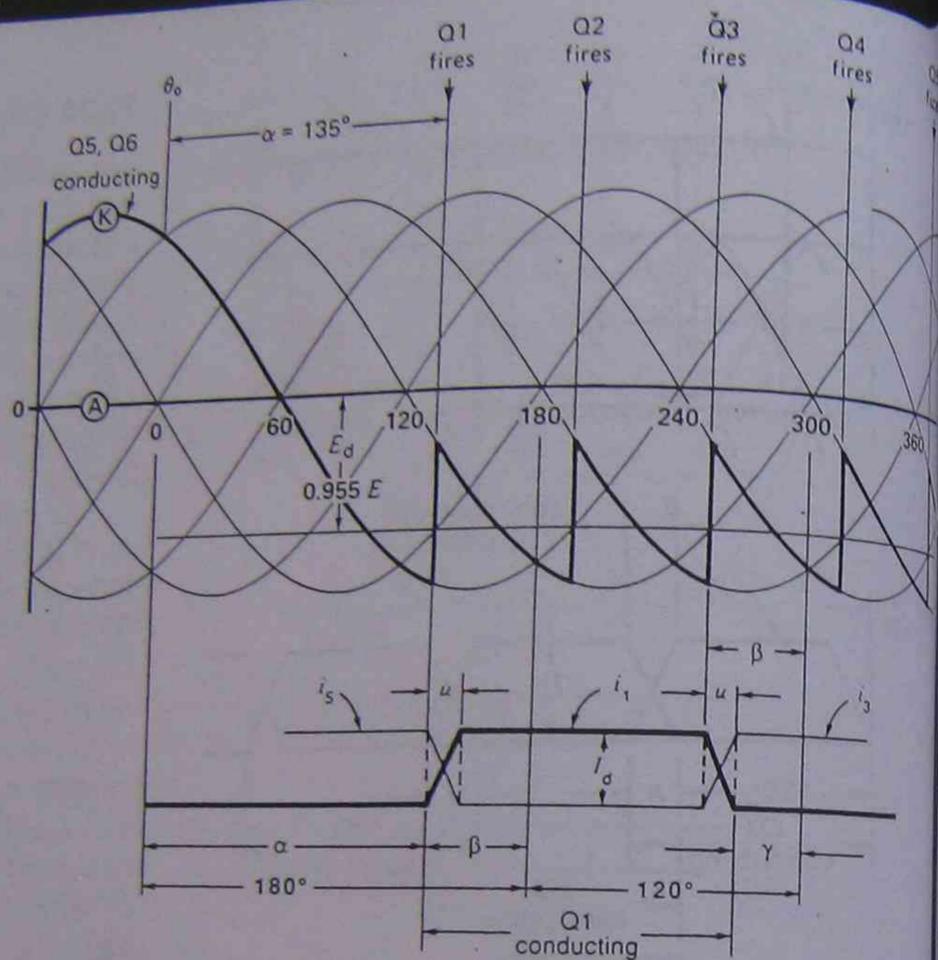


Figure 21-61  
Waveshape of  $i_1$  in thyristor Q1 for a delay angle  $\alpha$ . The extinction angle  $\gamma$  permits Q1 to establish its blocking ability before the critical angle of  $300^\circ$  is reached. At  $300^\circ$  the anode of Q1 becomes positive with respect to its cathode. The figure also shows the relationship between angles  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\mu$ .

### 21.35 Extinction angle

We have seen that when a converter operates in the inverter mode, it is very important that conduction be initiated prior to  $\alpha = 180^\circ$ . Because the current in an ideal inverter flows for  $120^\circ$ , the conduction must also cease before the angle of  $(180 + 120) = 300^\circ$  is reached. The interval between the end of commutation and  $300^\circ$  is called the *extinction angle*  $\gamma$  (Fig. 21-61). The extinction angle permits thyristor Q1 to recover its blocking ability before its anode (1) again becomes positive with respect to the cathode K. The value of  $\gamma$  lies typically between  $15^\circ$  and  $20^\circ$ .

In the case of an inverter, we often delay the firing instant by the *angle of advance* rather than by the angle of delay  $\alpha$ . It is easy to show that the following relationships exist between the commutation angle  $\mu$ , the delay angle  $\alpha$ , the angle of advance  $\beta$  and the extinction angle  $\gamma$ :

$$\beta = 180 - \alpha \quad (21-15)$$

$$\beta = \mu + \gamma \quad (21-20)$$

TABLE 22A PROPERTIES OF SOME RECTIFIER CONVERTERS (RESISTIVE LOAD)

ITEMS	Converter A	Converter B	Converter C
	3ph, 6-pulse	3 ph, 6-pulse + free-wheel diode	half bridge
Firing angle ( $\alpha$ ) limits	0 to $90^\circ$	$60^\circ$ to $120^\circ$	$60^\circ$ to $180^\circ$
dc output voltage ( $E_d$ )	$1.35 E \cos \alpha$	$1.35E (1 - \cos(120 - \alpha))$	$0.675 E (1 + \cos \alpha)$
displacement angle ( $\phi_d$ )	$\alpha$	$30 + \alpha/2$	$\alpha/2$
PF (displacement) = $\cos \phi_d$	$\cos \alpha$	$\cos (30 + \alpha/2)$	$\cos \alpha/2$
effective line current ( $I$ )	$0.816 I_d$	$I_d \sqrt{(120 - \alpha)/90}$	$I_d \sqrt{(180 - \alpha)/180}$
Total apparent power (S)	$EI \sqrt{3}$	$EI \sqrt{3}$	$EI \sqrt{3}$
Total active power (P)	$E_d I_d$	$E_d I_d$	$E_d I_d$
Total reactive power (Q)	$P \tan \phi_d$	$P \tan \phi_d$	$P \tan \phi_d$
PF (total)	PIS	PIS	PIS
PF (distortion)	PIS $\cos \phi_d$	PIS $\cos \phi_d$	PIS $\cos \phi_d$

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Module

# A.C. Motor Control

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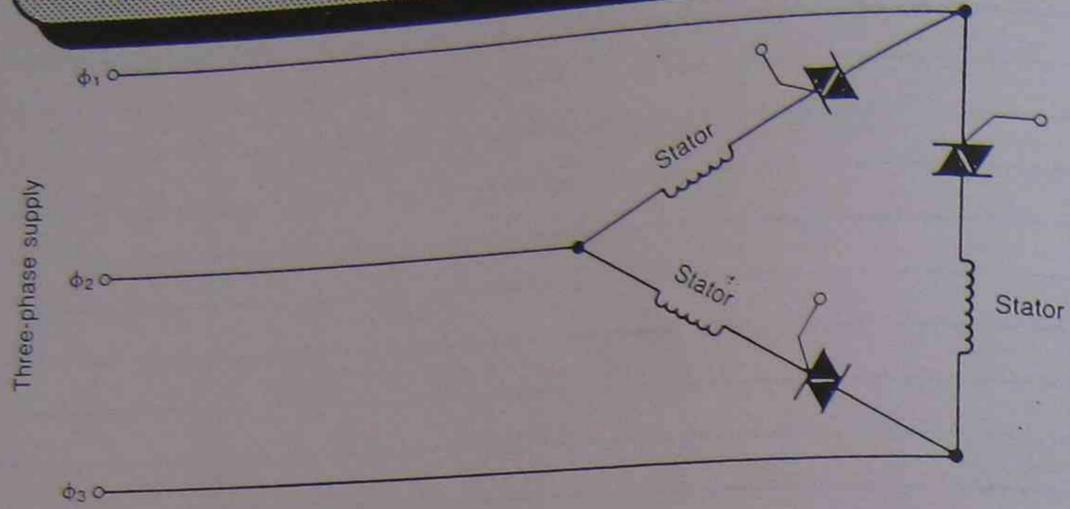
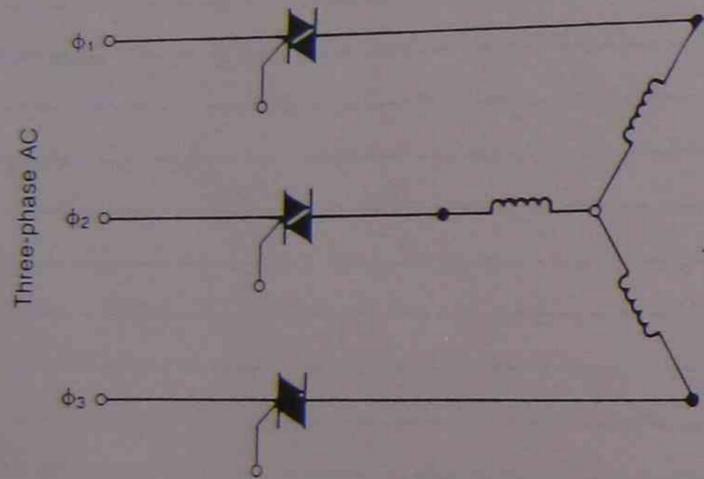
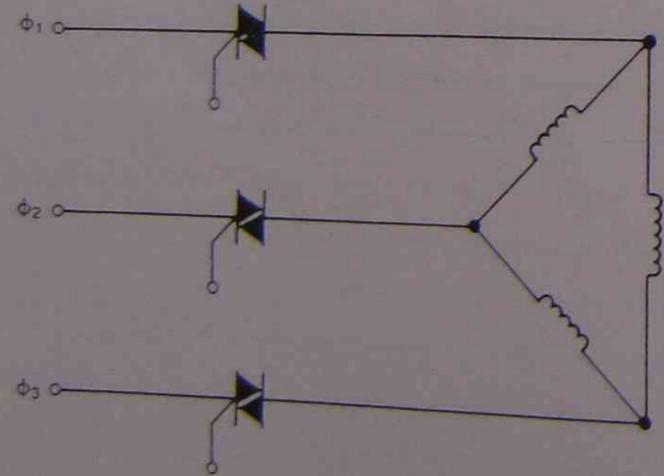


FIGURE 11-4 Triacs controlling three-phase motor



a. Triacs controlling,  $\star$  connected stators



b. Triacs controlling,  $\Delta$  connected stators

FIGURE 11-5 Triacs controlling three-phase motors

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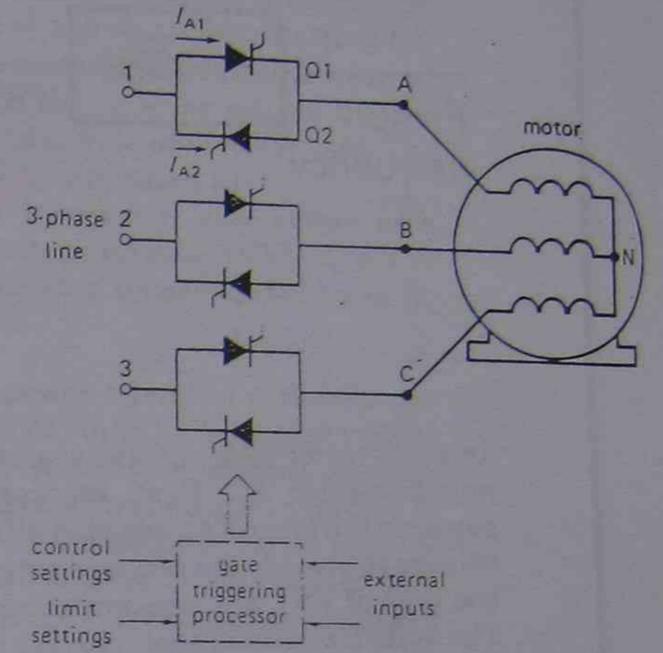
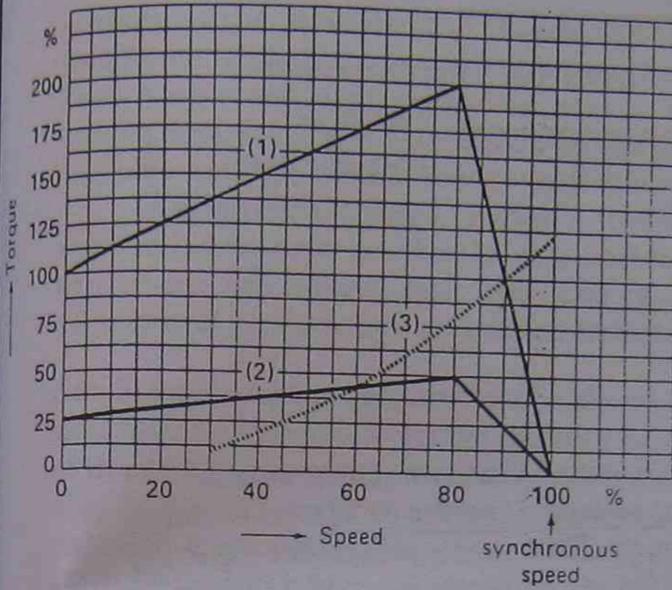


Figure 23-6 Variable-voltage speed control of a squirrel-cage induction motor.

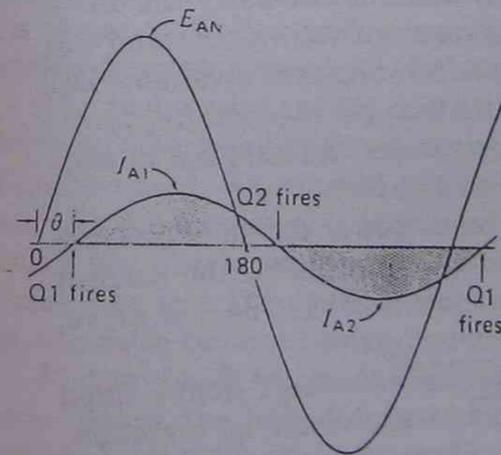


Figure 23-7 Waveshapes at rated voltage.

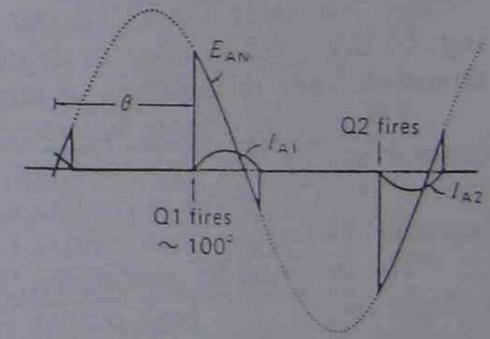


Figure 23-8 Waveshapes (very approximately) at 50% rated voltage

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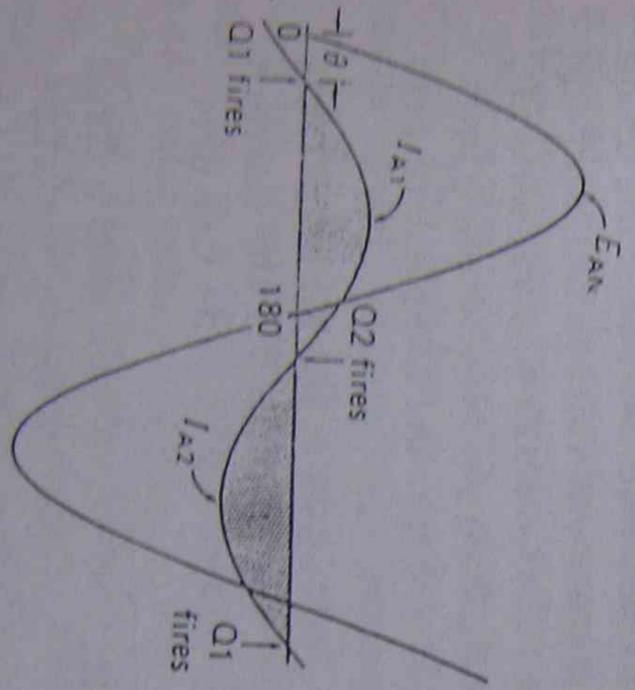
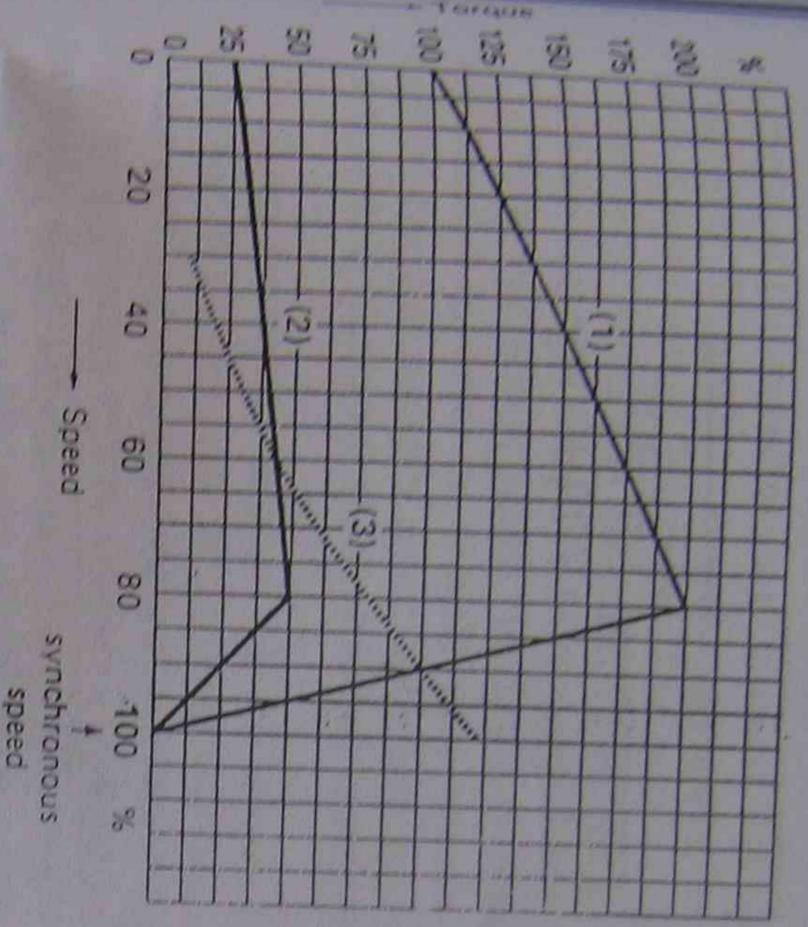


Figure 23-7  
Waveshapes at rated voltage.

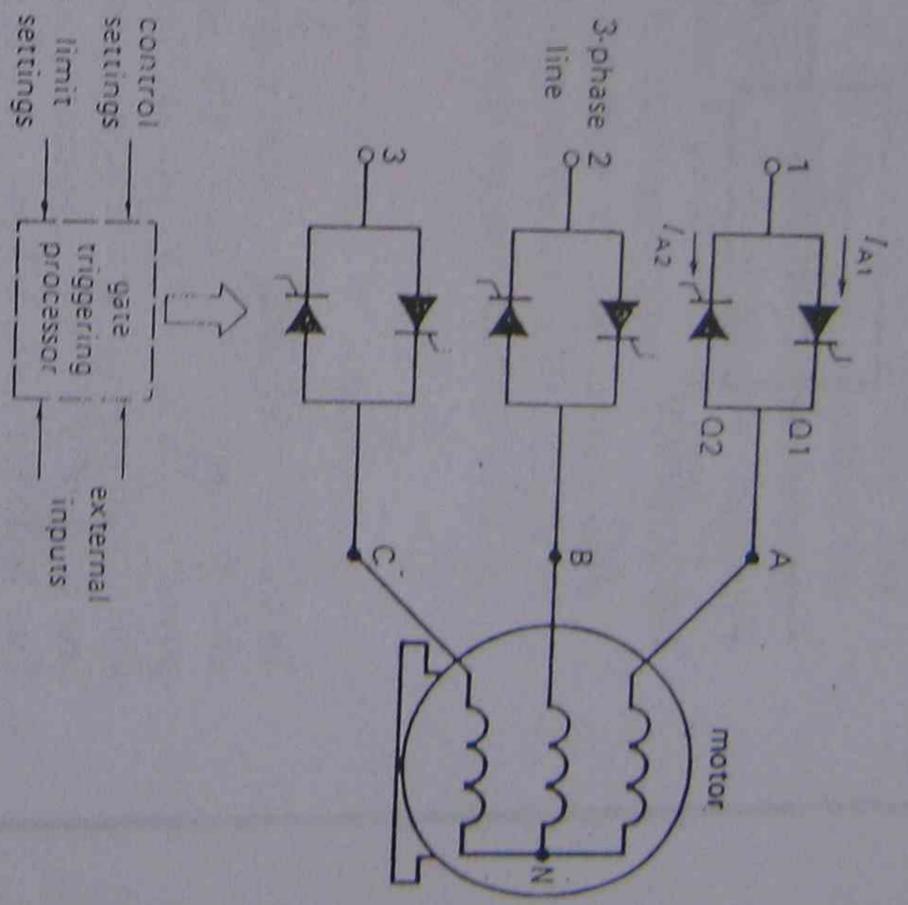


Figure 23-6  
Variable-voltage speed control of a squirrel-cage induction motor.

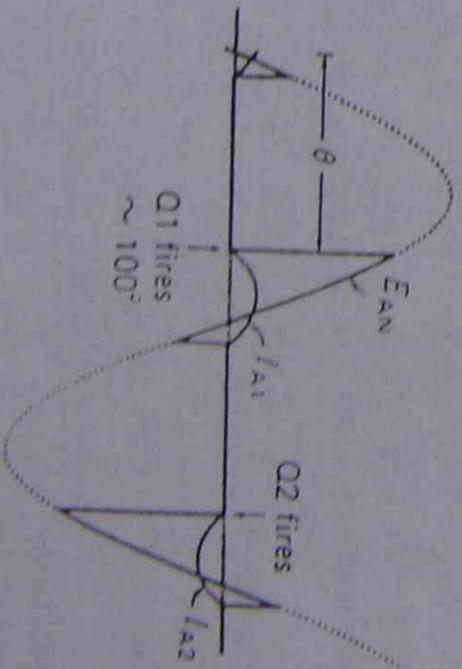
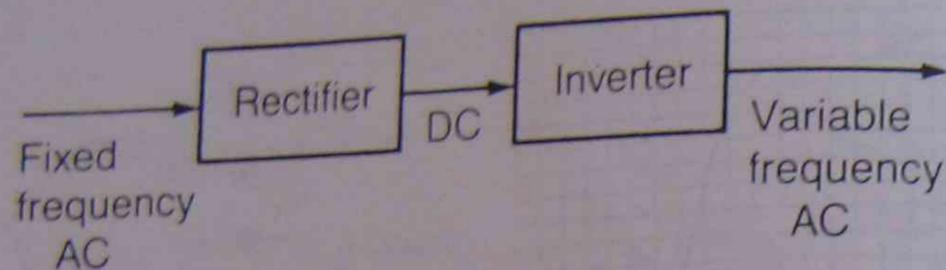


Figure 23-8  
Waveshapes (very approximately) at 50% rated voltage.

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In the inverter section, three approaches are used to convert DC to adjustable-frequency AC. First, the variable-voltage inverter (VVI) takes input power in the form of an adjustable DC source. This source presets the input DC voltage to provide the required output voltage amplitude from the inverter. In one type of VVI, a phase-controlled bridge rectifies the incoming AC voltage. The volts/Hz ratio is kept constant by changing the amplitude of the rectified DC as the frequency is changed. A second type of VVI replaces the phase-controlled rectifier bridge with a diode bridge and a DC regulator or chopper. This system, therefore, has a rectifier that is divided into two parts: the diode bridge, which converts fixed frequency AC to a constant voltage DC, and the regulator or chopper, which changes the constant DC voltage to a variable DC voltage. Normally, the VVI drives lack the ability to apply regenerative braking. Of the types of inverter drives, the VVI drives are the simplest in construction, used in industry for applications up to 400 HP.

The current-source inverter (CSI) takes input power for an adjustable current source, not a voltage source, as in the VVI. Except for the current source, the CSI drive is similar in construction to the VVI. The CSI drive, however, can apply regenerative braking to a motor. \*

The pulse-width modulated (PWM) inverter takes voltage from a fixed voltage source. The peak output voltage applied to the motor is, therefore, constant. The average value of the output voltage wave form is controlled by changing the width of the zero voltage interval in the output wave form.

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### 11-2.3 Variable-Voltage, Variable-Frequency Control

This type of induction motor speed control uses a circuit called an inverter. The purpose of the inverter is to control the speed of the motor by adjusting the frequency. To produce a constant torque for the motor, the inverter drive must keep a constant V/Hz ratio. The way in which the inverter adjusts the frequency and voltage is determined by the particular type of inverter used. The variable-voltage, variable-frequency drive will be discussed first.

The variable-voltage, variable-frequency inverter is also known as a voltage-fed inverter or, simply, as a variable-voltage inverter (VVI). The VVI can be further broken down into two types: six-step (quasi-square wave inverter) and pulse-width modulated inverters.

**Six-Step Inverter** Figure 11-7a shows the power circuit of a three-phase inverter. A three-phase bridge rectifier converts AC to DC. The output voltage of the rectifier section is varied by a DC chopper. A thyristor chopper is preferable to a transistor chopper, which must use several transistors connected in parallel. Regardless of the type of chopper used, the chopper varies the constant DC voltage from the rectifier, which is then applied to the inverter. This type of inverter is called voltage fed because a large filter capacitor provides a stiff voltage supply to the inverter.

The inverter output voltage wave forms are not affected by the nature of the load. Figure 11-7b shows another way to vary the input voltage. In this method, the uncontrolled diode rectifier and the chopper regulator are replaced by a phase-controlled bridge rectifier. The principle of the variable-voltage, variable-frequency speed control method is shown in Figures 11-8 and 11-9.

The motor used in this drive has a low slip characteristic that improves efficiency. The speed of the motor can be changed by simply varying its synchronous speed. Varying the inverter frequency changes the synchronous speed. As the frequency is increased, however, the machine air gap flux falls, causing low developed torque capability. The air gap flux can be maintained constant, as in a DC shunt motor, if the voltage is varied with frequency so that the ratio remains constant.

Figure 11-8 shows the desired voltage-frequency relationship of the motor. Below the base frequency, the air gap flux is kept constant by the constant V/Hz ratio, which keeps the torque constant. At a very low frequency, the stator resistance is greater than the leakage inductance. To counter this effect, additional voltage is applied. At the base frequency, the input voltage regulator establishes full-motor voltage. Beyond this point, as frequency increases, the torque decreases because of loss of air gap flux. From this point on, the machine operates in a constant horsepower mode, as shown in Figure 11-9. In the constant horsepower mode, each torque-speed curve corresponds to a particular voltage and frequency combination at the machine terminal.

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WVI

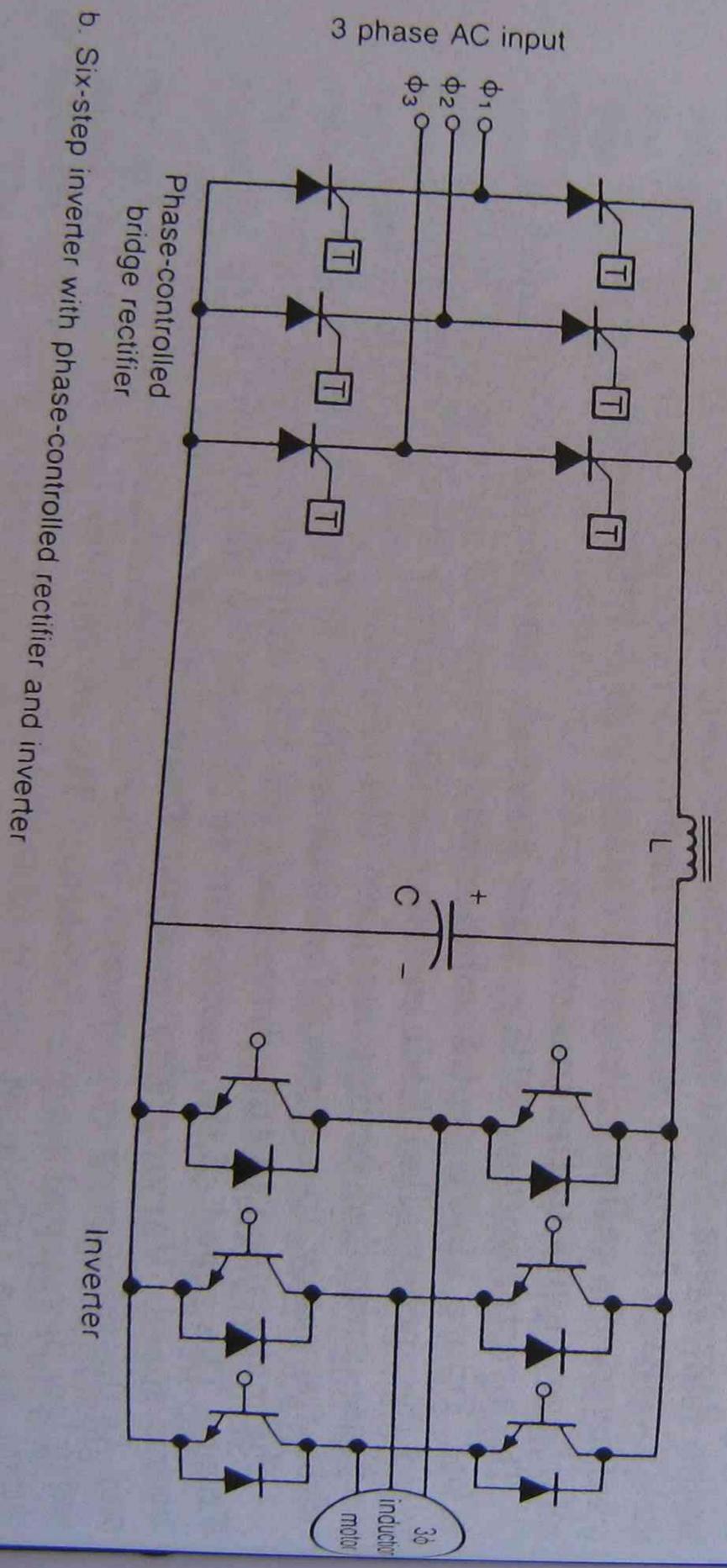
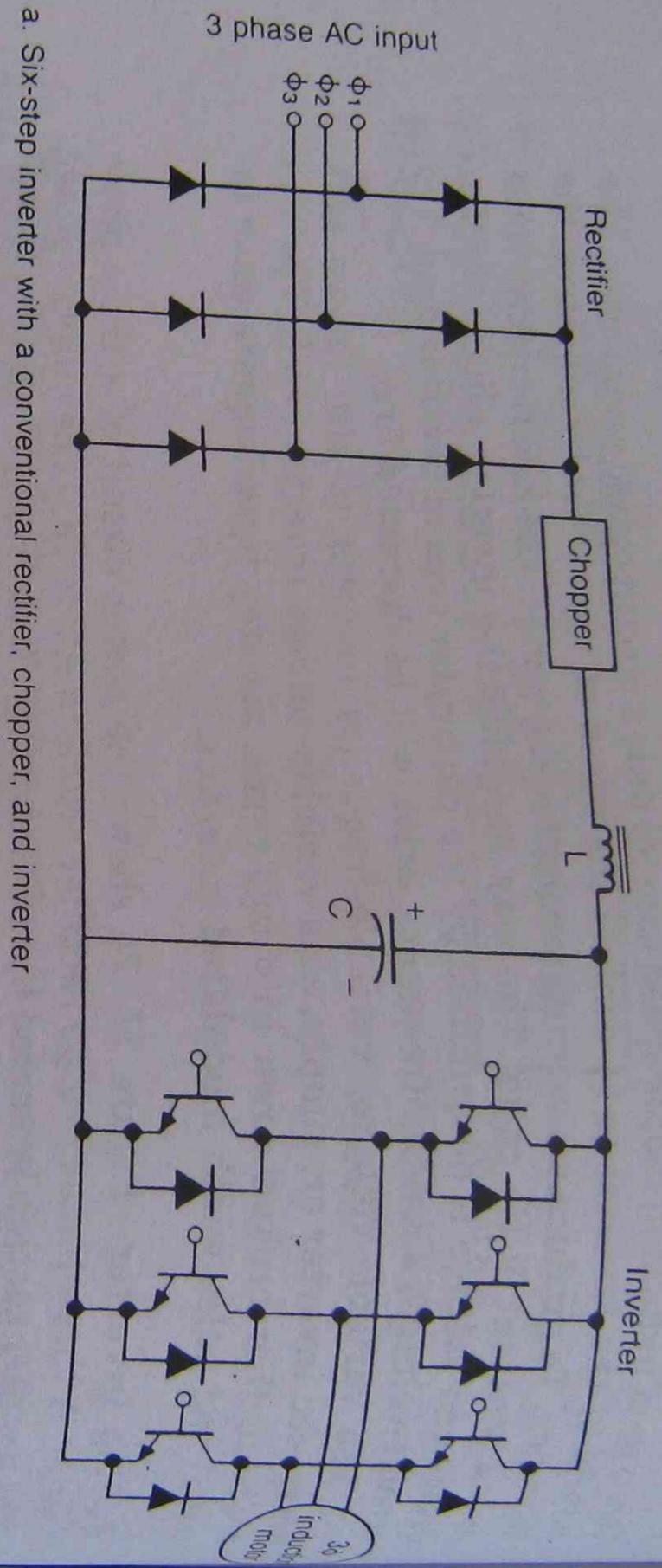


FIGURE 11-7 Three-phase inverter

FIG 11-7

Torque →

F

Voltage

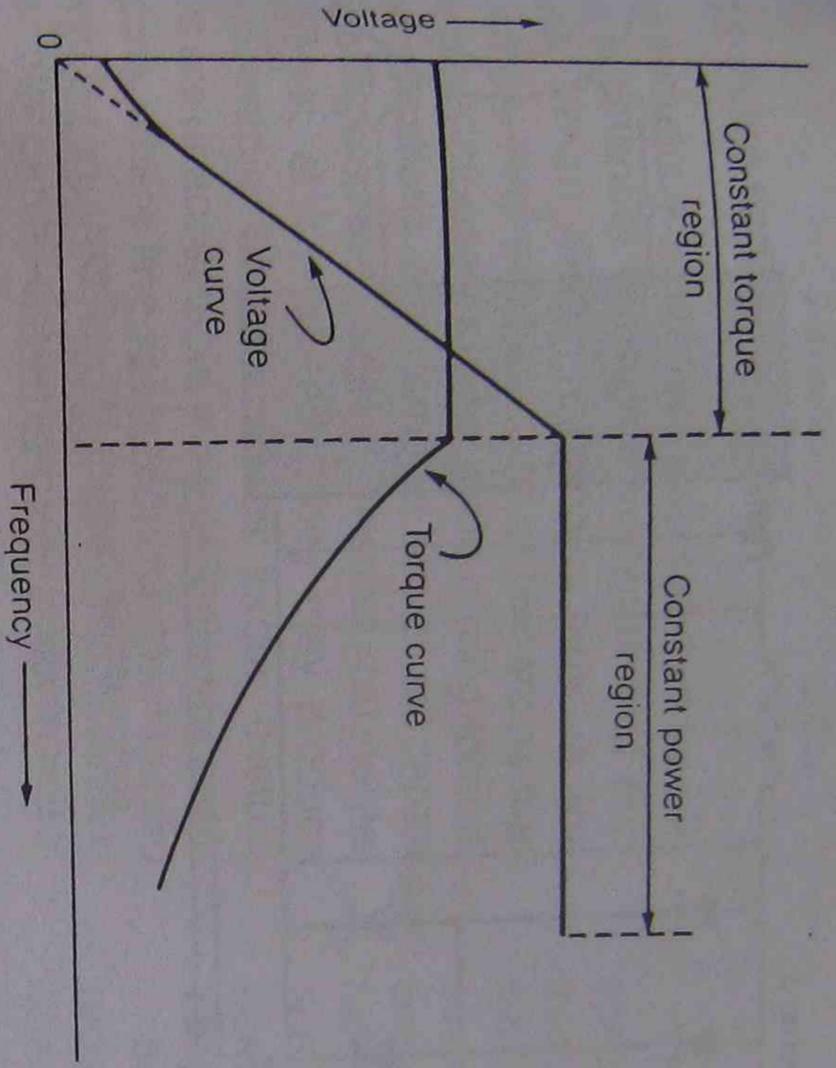


FIGURE 11-8 Voltage-frequency curve of induction motor

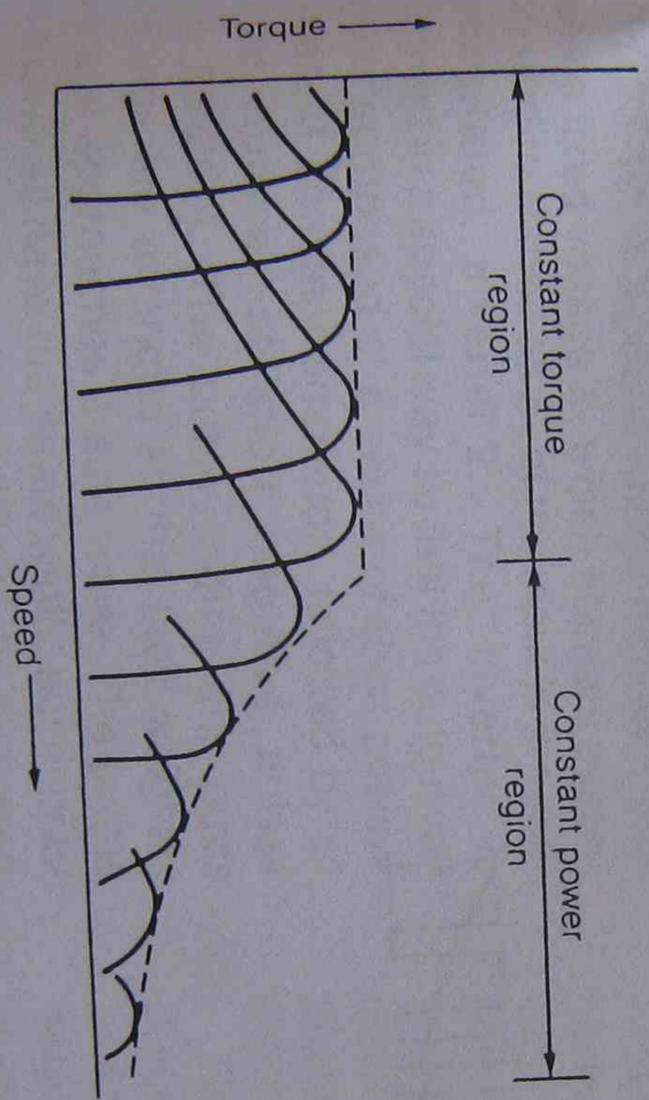


FIGURE 11-9 Torque-speed curves of induction motor with variable-voltage, variable-frequency power supply



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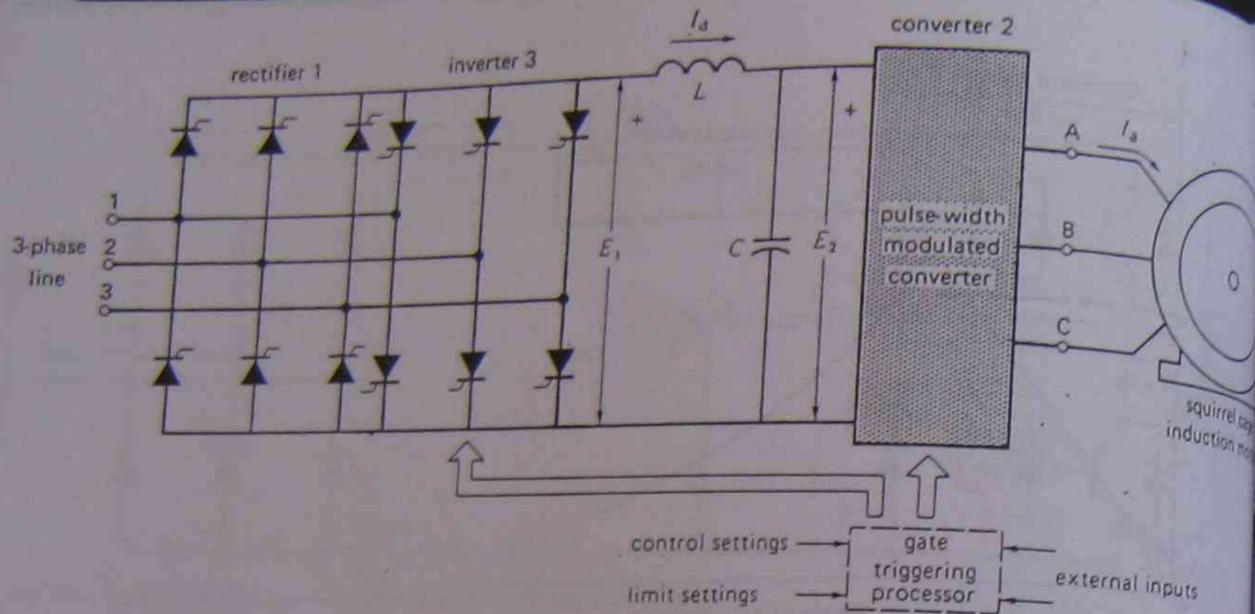


Figure 23-19  
Speed control by pulse width modulation.

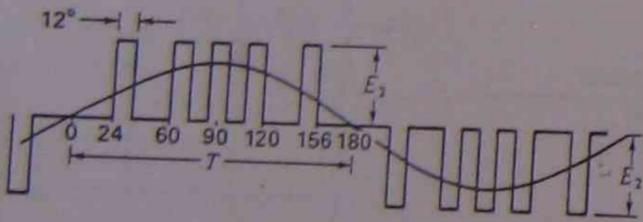


Figure 23-20a  
Voltage waveform across one phase.

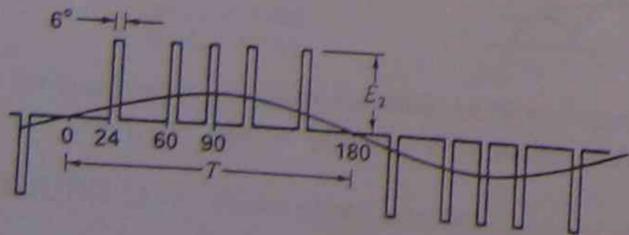


Figure 23-20b  
Waveform yielding the same frequency but half the voltage.

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## 23.9 Pulse width modulation

The frequency converters discussed so far create substantial harmonic voltages and currents. When these harmonics flow in the windings, they produce torque pulsations that are superimposed on the main driving torque. The pulsations are damped out at moderate and at high speeds owing to mechanical inertia. However, at low speeds, they may produce considerable vibration. Such torque fluctuations are unacceptable in some industrial applications, where fine speed control down to zero speed is required. Under these circumstances, the motor can be driven by *pulse width modulation* techniques.

To understand the technique, consider the voltage-fed frequency converter system shown in Fig. 23-19. A 3-phase bridge rectifier 1 produces a fixed voltage  $E_1$  which appears essentially undiminished as  $E_2$  at the input to the self-commutated inverter 2. The inverter is triggered in a special way so that the output voltage is composed of a series of short positive pulses of constant amplitude, followed by an equal number of short negative pulses (Fig. 23-20a). The pulse widths and pulse spacings are arranged so that their weighted average approaches a sine wave. The pulses as shown all have the same width, but in practice, the ones near the middle of the sine wave are made broader than those near the edges. By increasing the number of pulses per half cycle, we can make the output frequency as low as we please. Thus, to reduce the output frequency of Fig. 23-20a by a factor of 10, we increase the pulses per half-cycle from 5 to 50.

The pulse widths and pulse spacings are specially designed so as to eliminate the low-frequency voltage harmonics, such as the 3rd, 5th, and 7th harmonics. The higher harmonics, such as the 17th, 19th, etc., are unimportant because they are damped out, both mechanically and electrically. Such pulse width modulation produces output currents having very low harmonic distortion. Consequently, torque vibrations at low speeds are greatly reduced.

In some cases, the output voltage has to be reduced while maintaining the same output frequency. This is done by reducing all the pulse widths in proportion to the desired reduction in output voltage. Thus, in Fig. 23-20b, the pulses are half as wide as in Fig. 23-20a, yielding an output voltage half as great, but having the same frequency. We can therefore vary both the output frequency and output voltage using a fixed dc input voltage. As a result, a simple diode bridge rectifier can be used to supply the fixed dc link voltage. The power factor of the 3-phase supply line is therefore high.

\* Regenerative braking can be achieved, but during such power reversal, current  $I_d$  reverses while the polarity of  $E_2$  remains the same. Consequently, an extra inverter 3 has to be placed in reverse parallel with rectifier 1 in order to feed power back to the line (Fig. 23-19). Rectifier 1 is automatically blocked while inverter 3 is in operation, and vice versa.

Pulse-width modulation is effected by computer control of the gate triggering.

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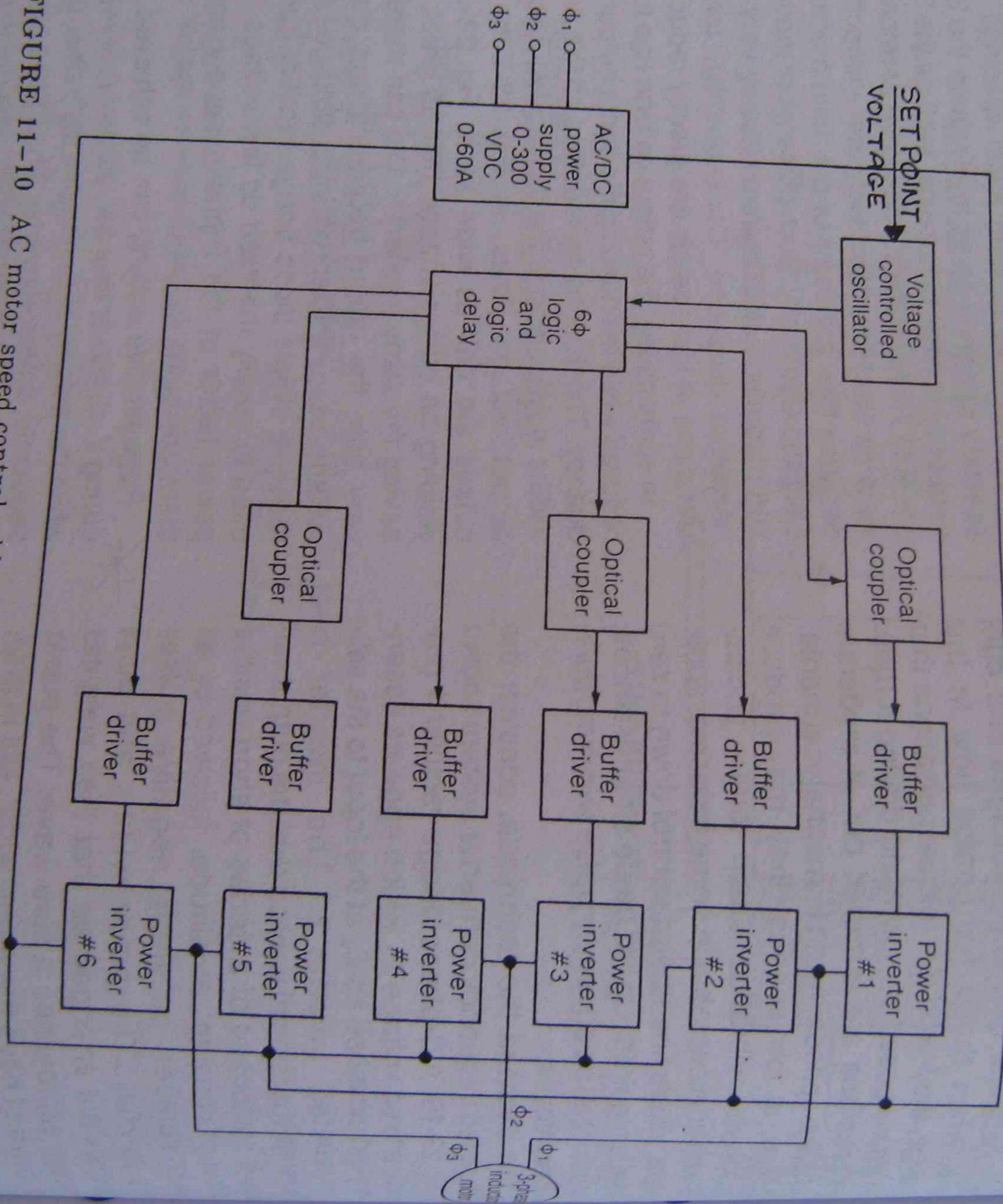


FIGURE 11-10 AC motor speed control—block diagram

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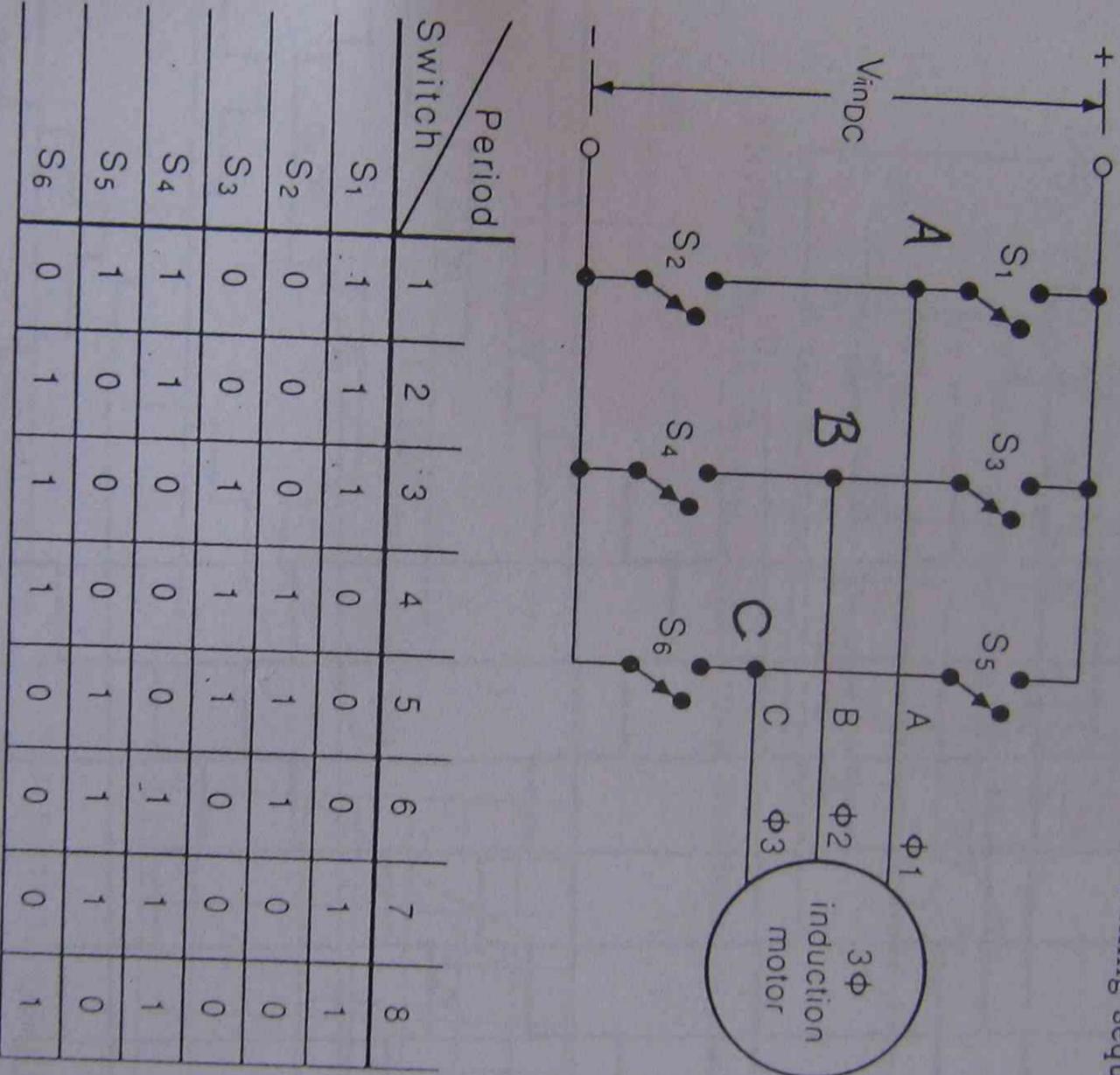
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# A.C. Motor Control.

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FIGURE 11-11 Six-step inverter simplified diagram and switching sequence



Key - 1 = on 0 = off

RELATES TO  
Fig 11-12  
6 STEPS  
THEN  
REPEAT

**Controlling the Motor** A block diagram of an AC motor speed controller is shown in Figure 11-10. The system receives a nominal AC input voltage that is converted to a variable DC output voltage. The output voltage is applied to a voltage-controlled oscillator that, in turn, produces a frequency proportional to the DC power supply output voltage. The output of the voltage-controlled oscillator is then used to drive the six-phase logic that will provide properly-timed pulsed outputs to the optical coupler, buffer drivers, and power inverters. Figure 11-11 shows a simplified six-step inverter diagram that will be used to show the proper switching sequence. Each of the switches shown in Figure 11-11 is actually a transistor or thyristor. The output voltage and current for a resistive load (connected in place of a motor) is shown in Figure 11-12. The current wave forms consist of six distinct steps when the switches are properly sequenced—hence, the name six-step.





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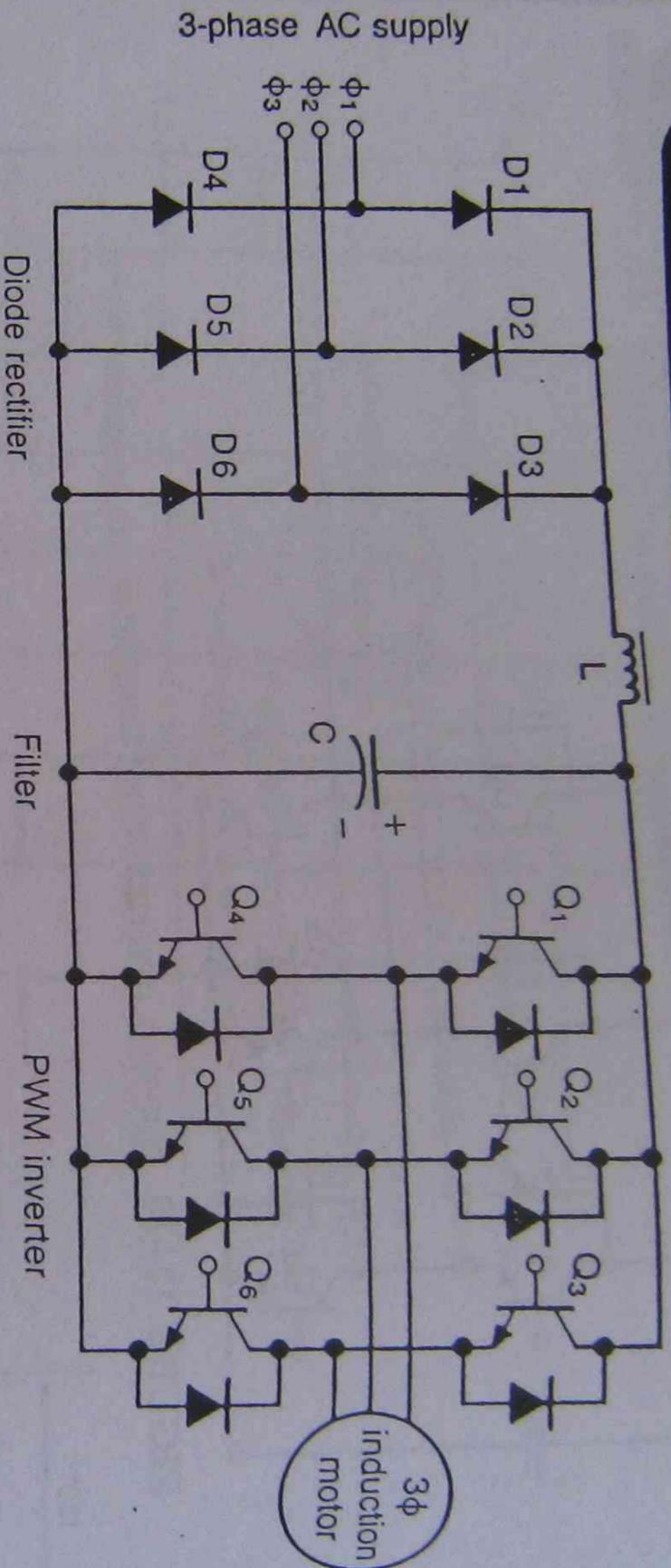


FIGURE 11-17 Variable-voltage, variable-frequency inverter

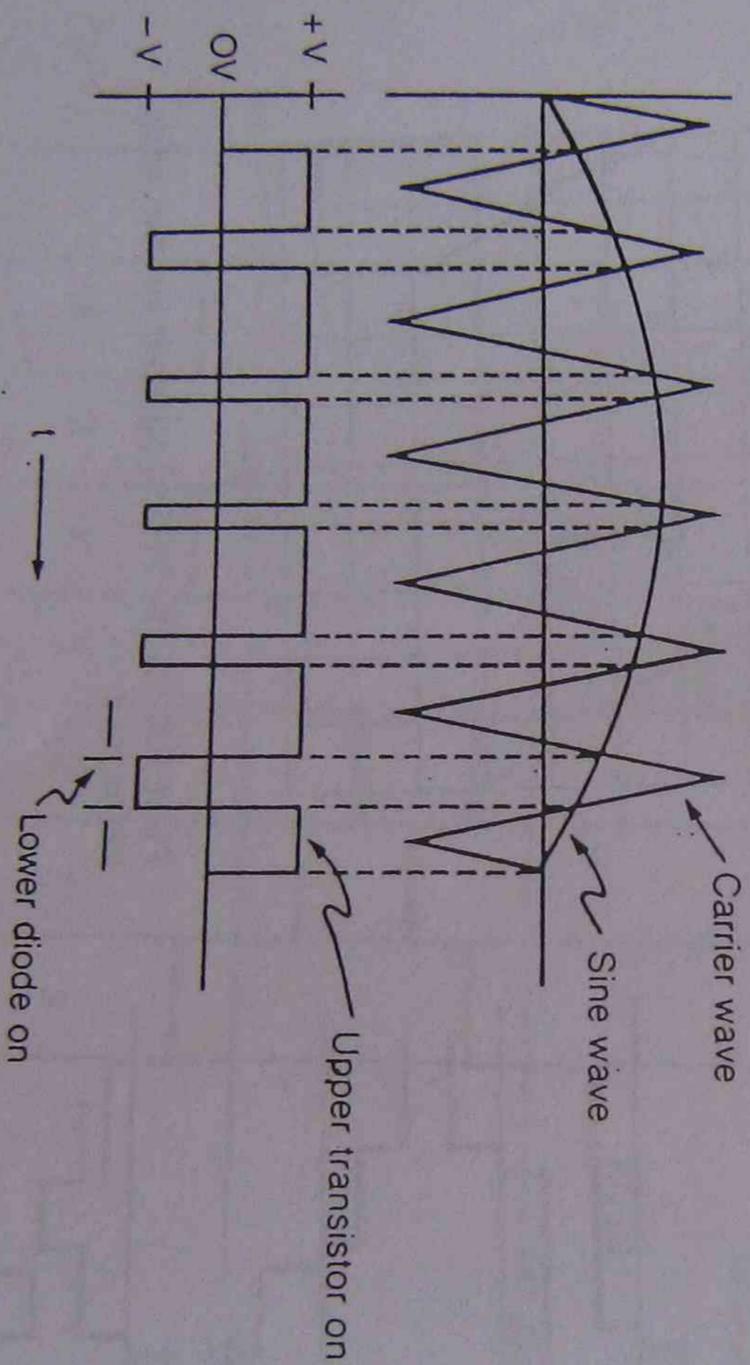


FIGURE 11-18 Pulse-width modulation by sine wave

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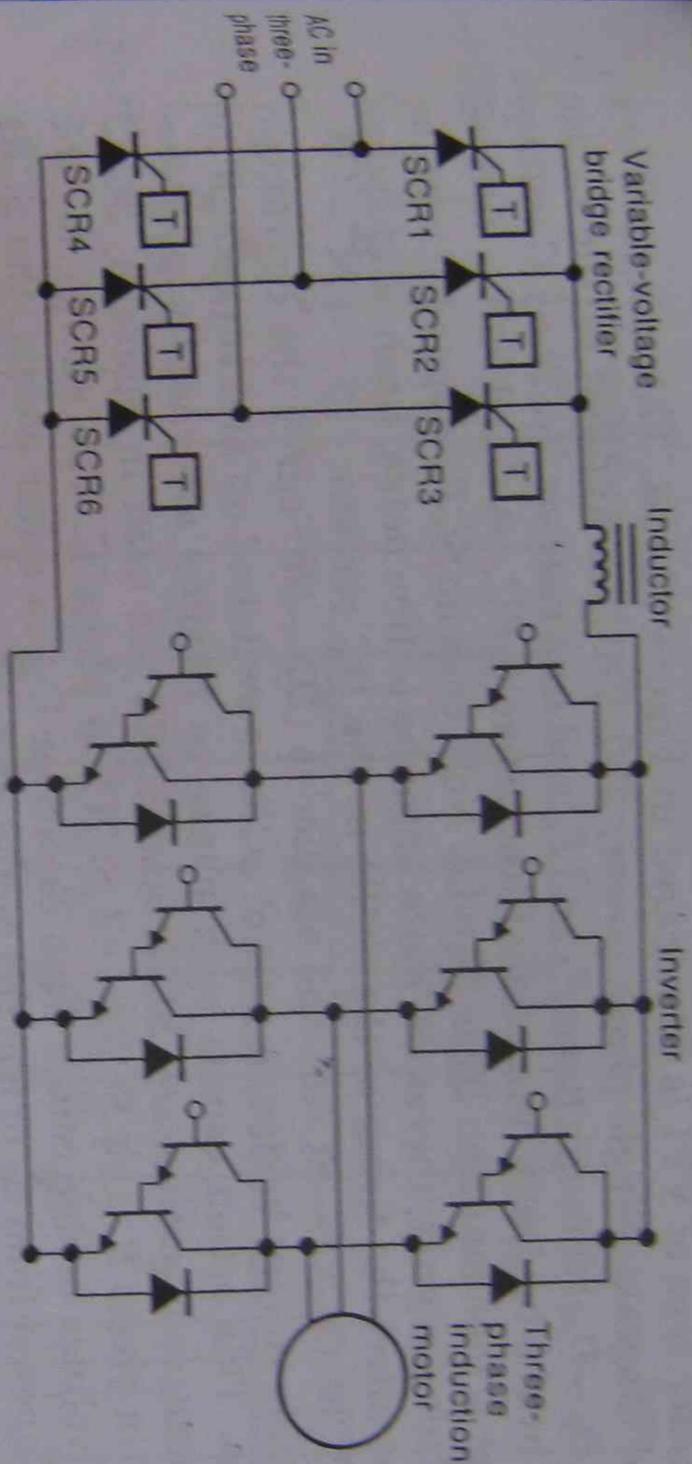


FIGURE 11-19 Variable-current, variable-frequency motor drive

## 11-2.4 Current Source Inverter (CSI)

The current source inverter (CSI), sometimes called the current-fed inverter, is very similar to the VVI circuit just discussed. Its name suggests that current, not voltage, is varied in this inverter. A large inductor is used in place of the large capacitor in the VVI.

The CSI requires a *stiff* DC current source as opposed to a voltage-fed inverter. In this case, stiff refers to the capability to provide a large amount of current without loading down the circuit. Figure 11-19 shows the power circuit of a current-fed inverter using power Darlingtontons as switches. A phase-controlled rectifier generates variable DC, which is converted to a current source by connecting a large inductor in series. A diode rectifier, followed by a DC chopper, can also make a variable DC source. The mode of control of the inverter could be either six-stepped or pulse-width modulated, similar to that of a voltage-fed inverter.

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Another type of VVI is illustrated in Figure 11-16. This diagram is a simplified diagram. Single-phase power, 220 VAC, is applied to the bridge rectifier ( $D_9-D_{12}$ ) through fuses  $F_1$  and  $F_2$  and line reactor  $L_1$ . The DC voltage produced by the bridge is filtered by filter capacitor  $C_4$ . A fixed value, filtered DC voltage is then found on lines 1 and 5. Note that no SCRs appear across the AC line. This design is, therefore, more immune to line noise, hash, and spikes that might affect the firing of the SCRs in the DC section.

Six SCRs ( $SCR1-SCR6$ ) and six diodes ( $D1-D6$ ) carry the current in the adjustable voltage bridge. A pair of SCRs is switched on and turned off for each phase. This action causes each phase to become alternately positive-negative-positive-negative, etc.  $SCR1$  and  $SCR2$  are used in phase A,  $SCR3$  and  $SCR4$  in phase B, and  $SCR4$  and  $SCR5$  in phase C. The energy for the adjustable voltage bridge comes from capacitor  $C_3$ . In other words, the SCRs are drawing power from  $C_3$  to run the motor, and they are continually trying to discharge  $C_3$ . The capacitor  $C_3$  is charged by the fixed voltage bridge.

Each pair of SCRs controlling each phase is turned on and commutated off in the proper timing sequence to supply three-phase power to the motor by the main control circuit board (not shown in the simplified diagram). The faster the switching on and commutating off, the higher the frequency.

The six SCRs in the fixed voltage bridge ( $SCR11-SCR16$ ) operate in parallel with their equivalents in the adjustable voltage bridge ( $SCR1-SCR6$ ). The purpose of the fixed voltage bridge is to furnish energy to  $C_3$  as the motor load uses it and to commute (turn off) the SCRs in the adjustable voltage bridge.

When an SCR in the adjustable voltage bridge, for example  $SCR1$ , is turned on, its equivalent in the fixed voltage bridge ( $SCR11$ ) can be turned on at 10 kHz rate. It will be turned on for one pulse any time  $C_3$  voltage is too low. When it is turned on for a pulse, energy comes from the DC line (lines 1 and 5) through  $X_1$  or  $X_2$ . Some of this energy goes to the motor, and the excess goes through the back diode ( $D1-D6$ ) and helps recharge  $C_3$ . If  $C_3$  voltage continues to be too low, another pulse of energy will be called for and once again the SCR in the fixed voltage bridge will be turned on. Up to 10,000 pulses of energy per second can be obtained from each SCR in the fixed voltage bridge in this manner.

To commutate off an SCR in the adjustable voltage bridge, for example  $SCR1$ , its gate is turned off. Then its mate in the fixed voltage bridge ( $SCR11$ ) is turned on for a pulse, causing current to flow. Some current flows to the motor; the excess flows through the back diode  $D1$ . This action shunts  $SCR1$ , causing it to stop conducting.

The SCRs in the fixed voltage bridge turn themselves off naturally after each pulse because they conduct into a tuned circuit. The voltage rises at the end of the pulse to block any further current flow.

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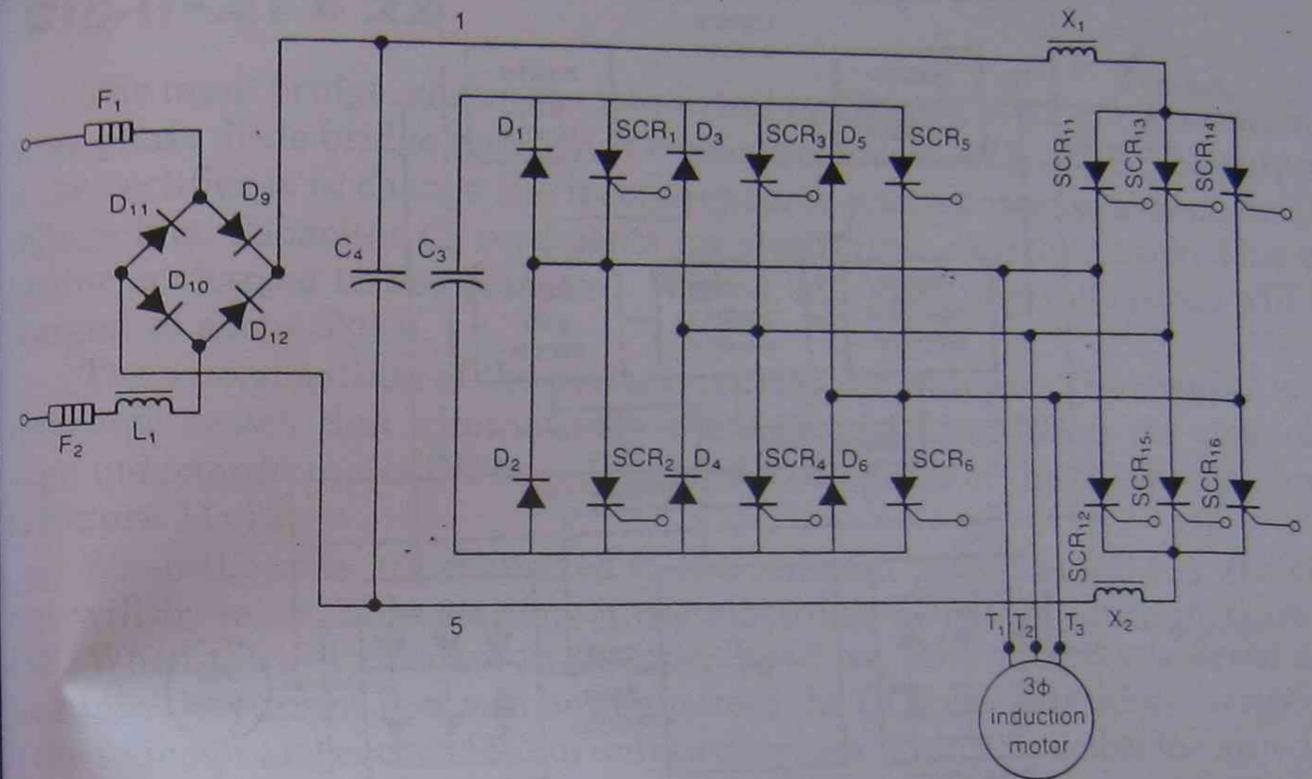
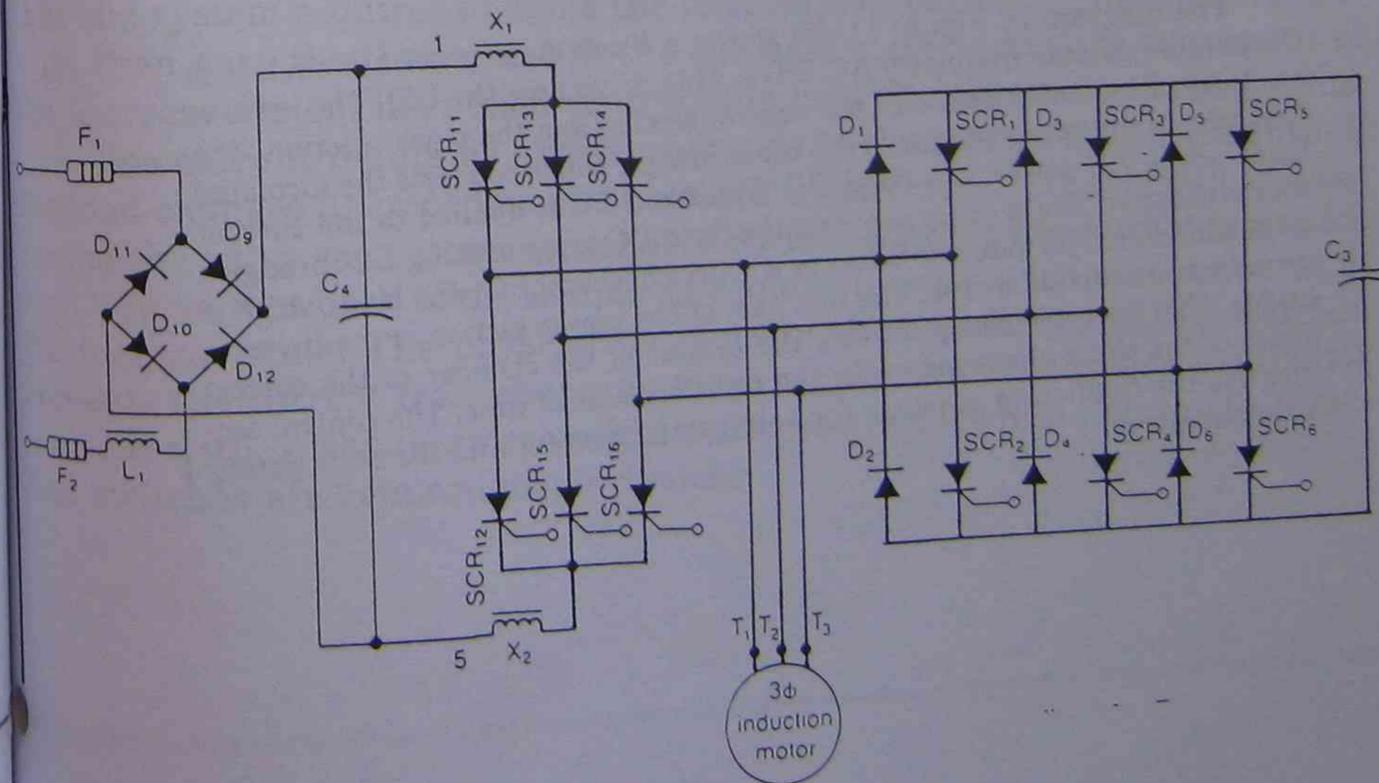


FIGURE 11-16 VVI AC motor drive using SCRs as switches



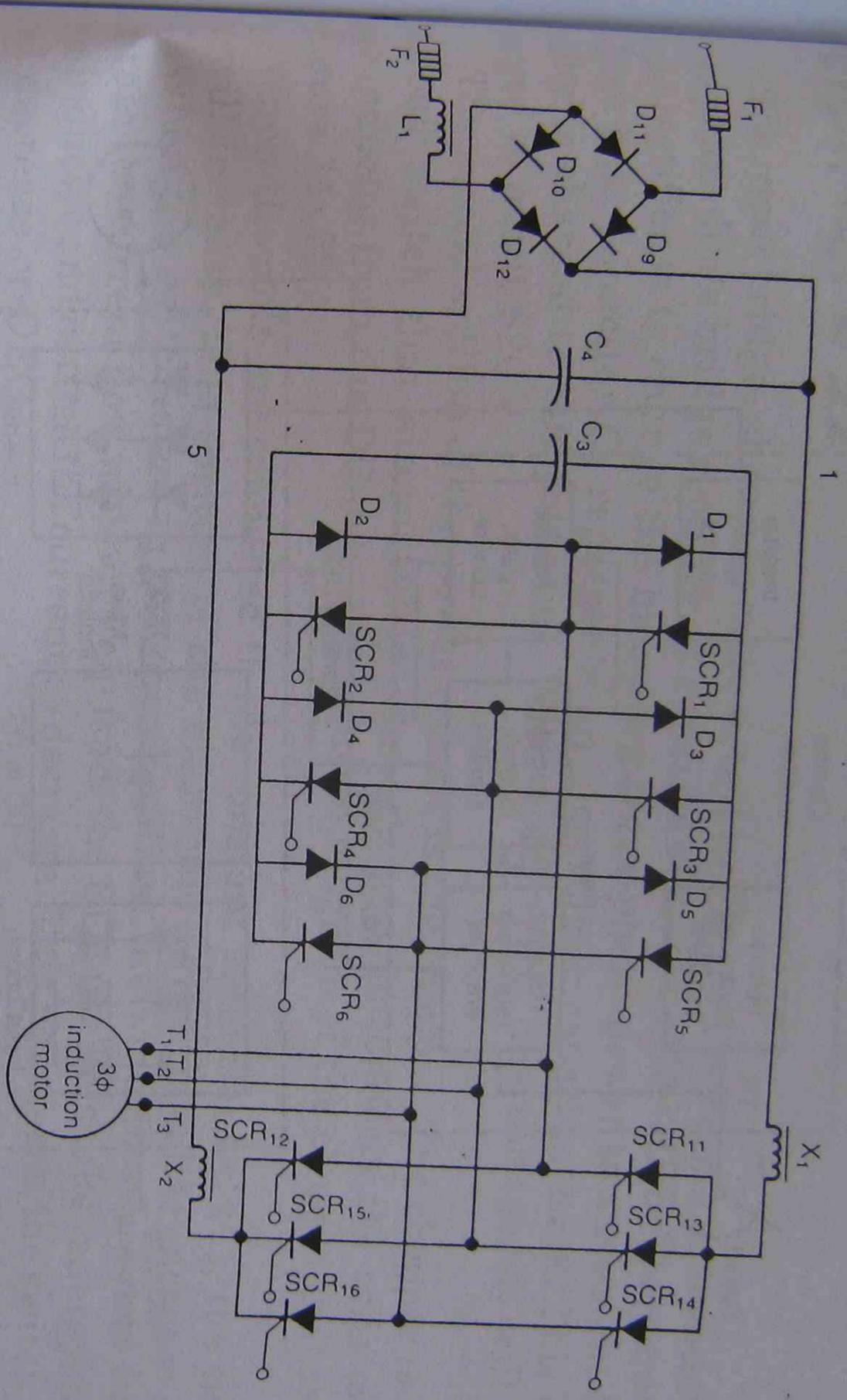
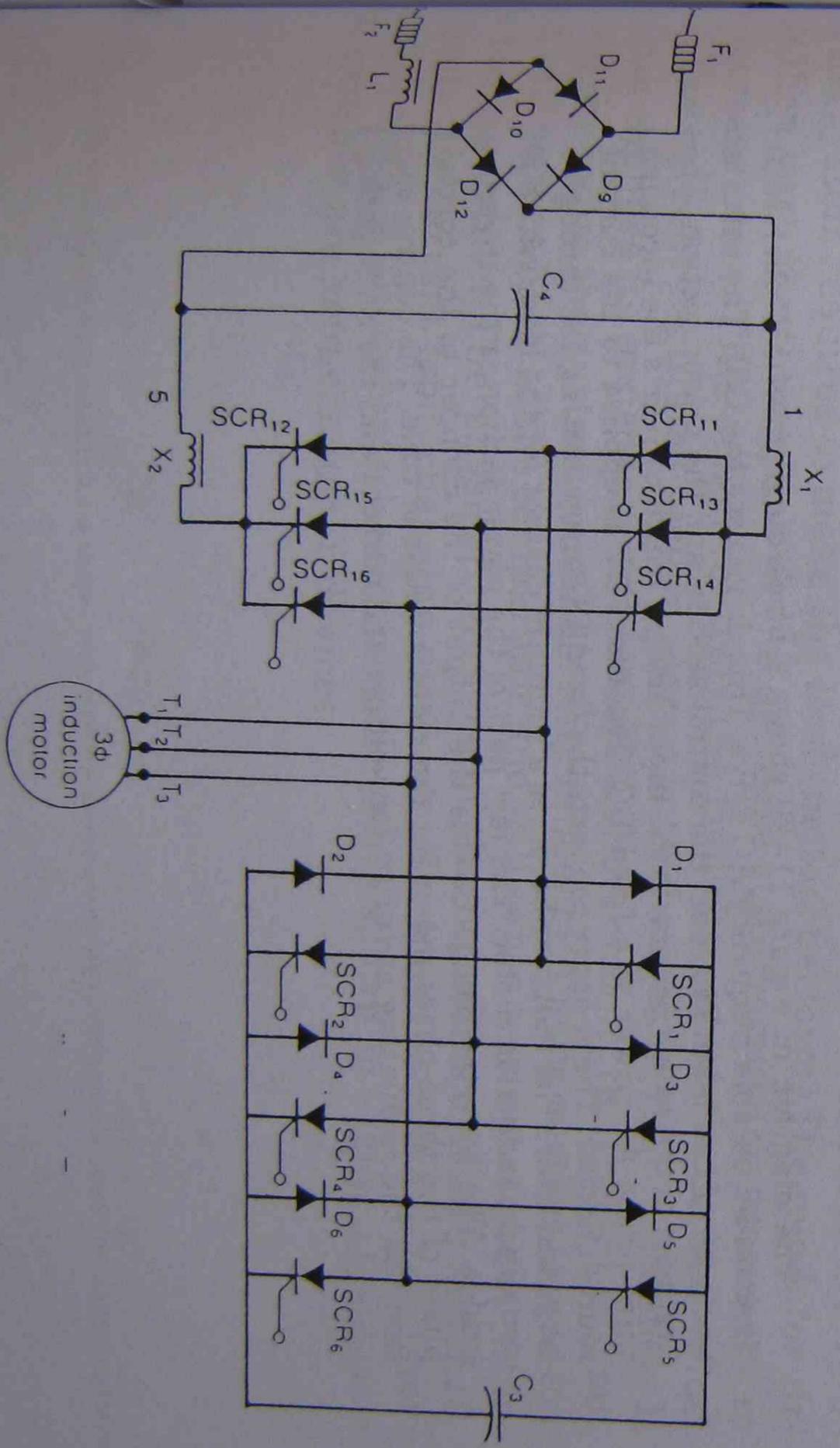


FIGURE 11-16 VVI AC motor drive using SCRs as switches



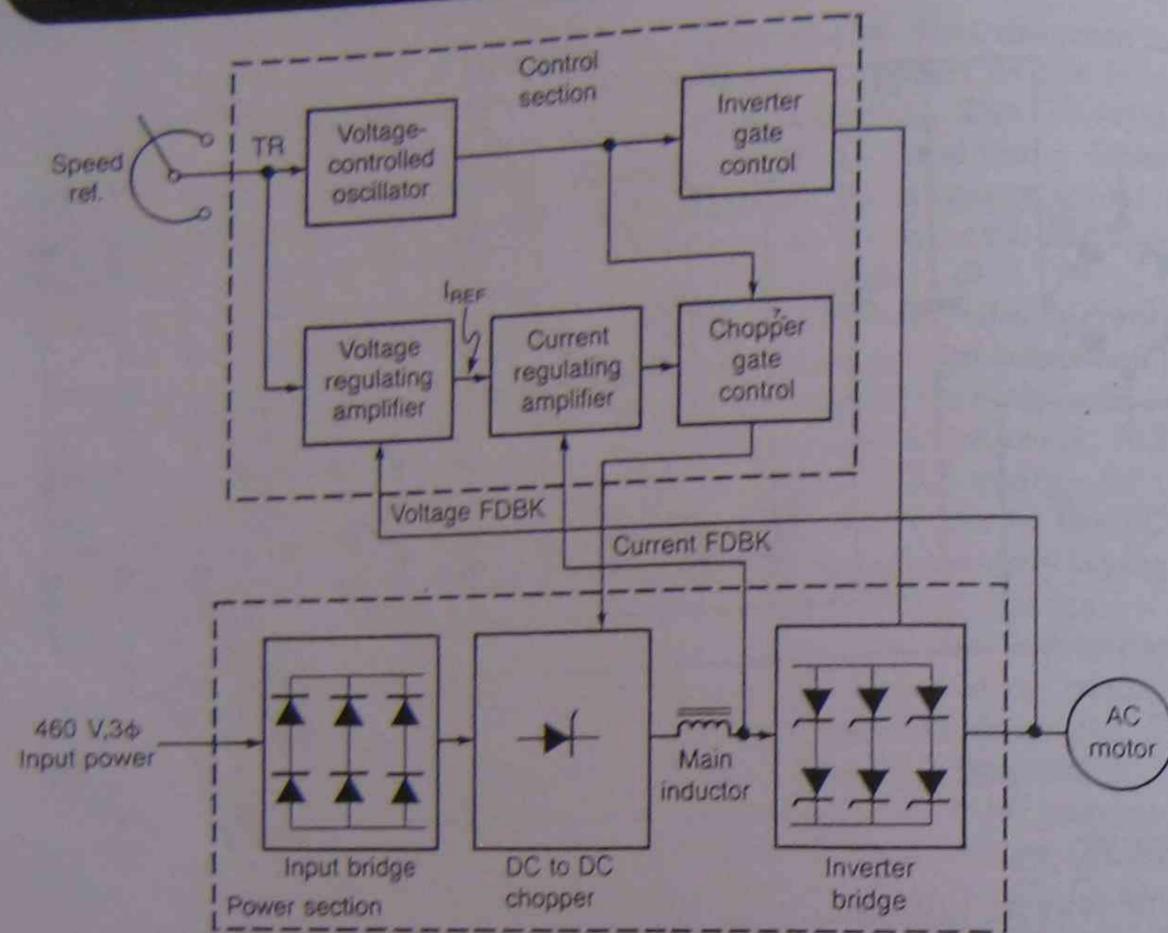


FIGURE 11-20 Graham 1580 CSI AC motor speed control (courtesy of Graham Co.)

The diagram in Figure 11-20 shows a block diagram of a Model 1580 Graham adjustable frequency AC drive. This drive uses the CSI. The drive is made up of two main sections: the control section and the power section. The first part of the power section is the input bridge, which converts the incoming three-phase AC power to a fixed DC. The fixed DC is applied to the current source chopper. The chopper converts the fixed DC to a pulsating DC through a large inductor. The inductor becomes a source of current for the load, which is usually an induction motor. The last part of the power section is the inverter bridge. The inverter bridge directs the output of the chopper to the correct phase of the three-phase motor for the right amount of time. The control section has the regulating circuitry for voltage and current and the SCR gating

FIGURE 11-21 & 22

The input bridge, shown in more detail in Figure 11-21, is a conventional three-phase diode bridge rectifier. It consists of diodes  $D13-D18$ . The purpose of the rectifier is to change the incoming three-phase power to a constant DC voltage bus. Capacitor  $C_1$  represents an electrolytic capacitor bank. This capacitor is charged to bus potential. With a 460 VAC line voltage,  $C_1$  will be charged to about 620 V.

The second section of the power circuit is the chopper. The chopper is an electronic switch that alternatively connects and disconnects the coils of a large inductor from the DC bus. A simplified diagram of the chopper is shown in Figure 11-22.

When the coils are connected to the constant potential DC bus, the current will increase. This position of the electronic switch is called increase or INC. When the switches are in the open position, the inductors  $L18$  and  $L19$  maintain the current flow without help from the DC bus. This takes energy out of the inductor and causes the current to decrease. This position of the switch is called decrease or DEC.

The load current is sensed by a Hall-effect device, which gives an output voltage proportional to the flux created by the load current. This proportional signal is then fed back to the regulator circuit where it is compared to a value that the system requires to make the load (motor) perform. The regulator circuits then vary the time spent in the decrease state versus the time spent in the increase state. This action controls the load current at the desired value.

The current-regulated section responds to changes in load impedance. If the load changes its impedance or becomes a short circuit, the current will not exceed the value the system demands. Any tendency for the current to rise too high will be sent back to the comparator and will cause less time to be spent in the increase state. The physical presence of the inductance of  $L18$  and  $L19$  prevents the current from changing more rapidly than the rate the regulator can cope with. Although mechanical switches are shown in Figure 11-22, actual switches are semiconductor devices.

# Topic -

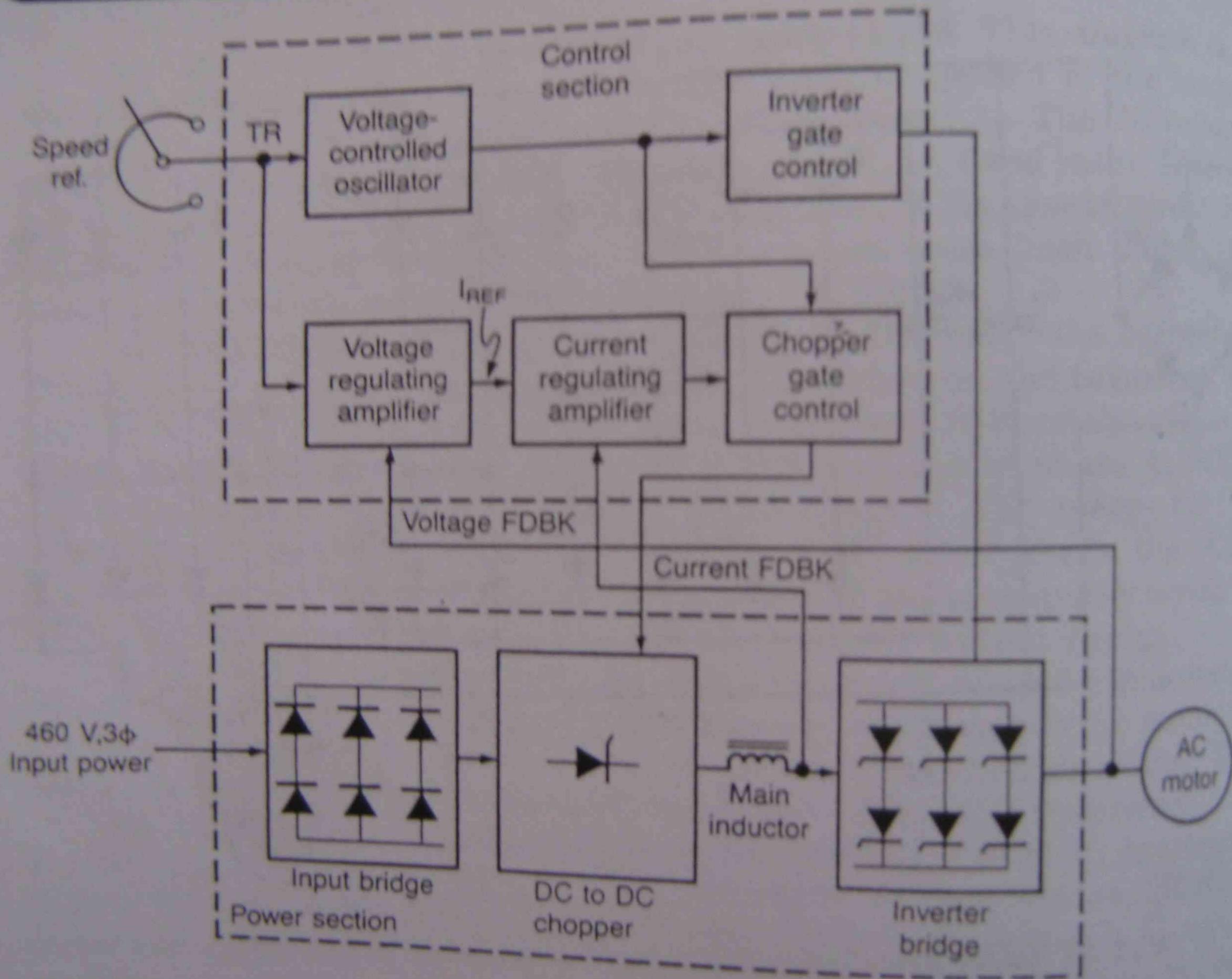


FIGURE 11-20 Graham 1580 GCR

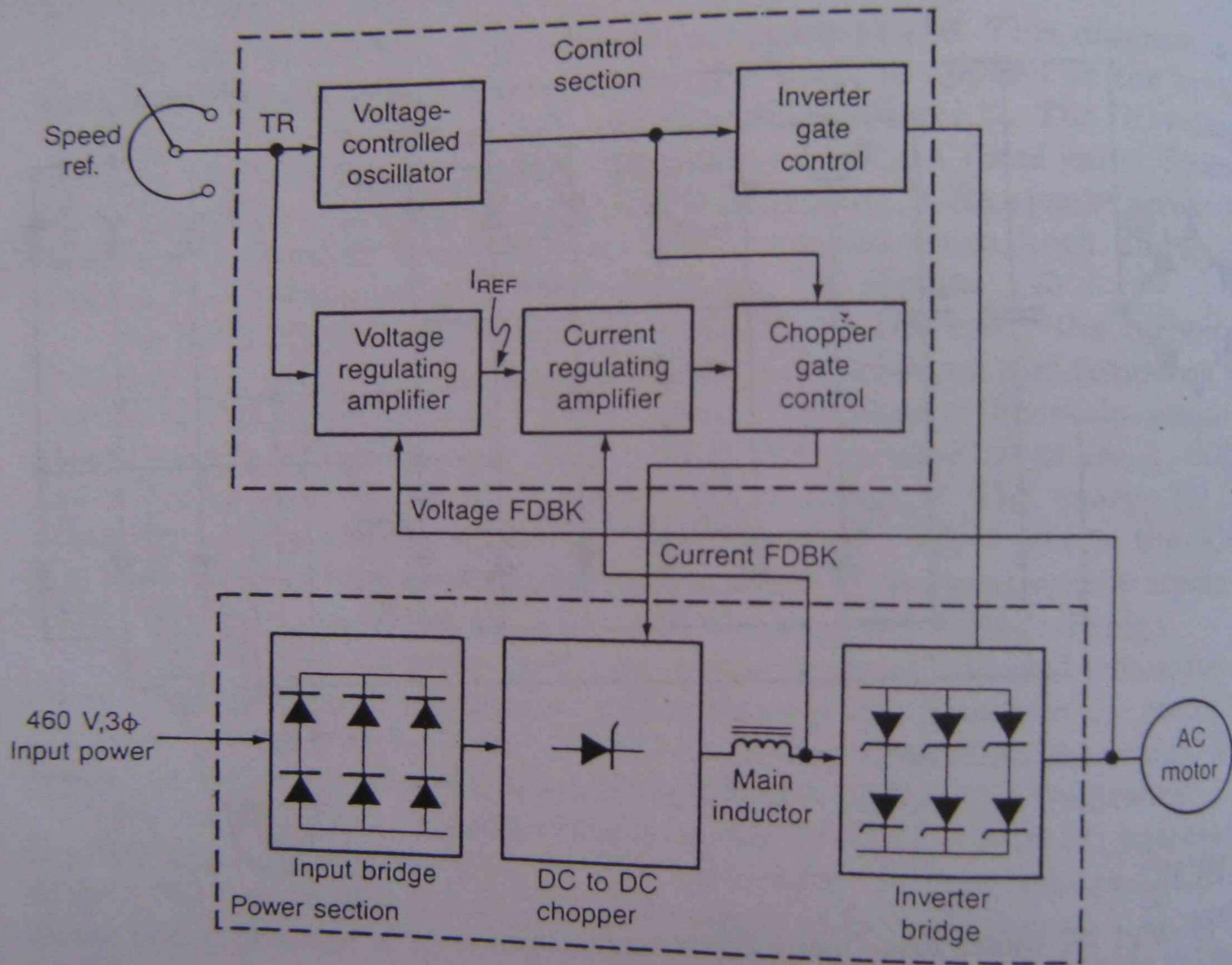


FIGURE 11-20 Graham 1580 CSI AC motor speed control (courtesy of Graham Co.)

The diagram in Figure 11-20 shows a block diagram of a CSI AC motor speed control system. The system consists of a control section and a power section. The control section includes a speed reference knob, a transformer, a voltage-controlled oscillator, a voltage regulating amplifier, a current regulating amplifier, an inverter gate control, and a chopper gate control. The power section includes an input bridge, a DC to DC chopper, a main inductor, and an inverter bridge. The output of the inverter bridge is connected to an AC motor. Feedback loops for voltage and current are also shown.

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# A.C. Motor Control.

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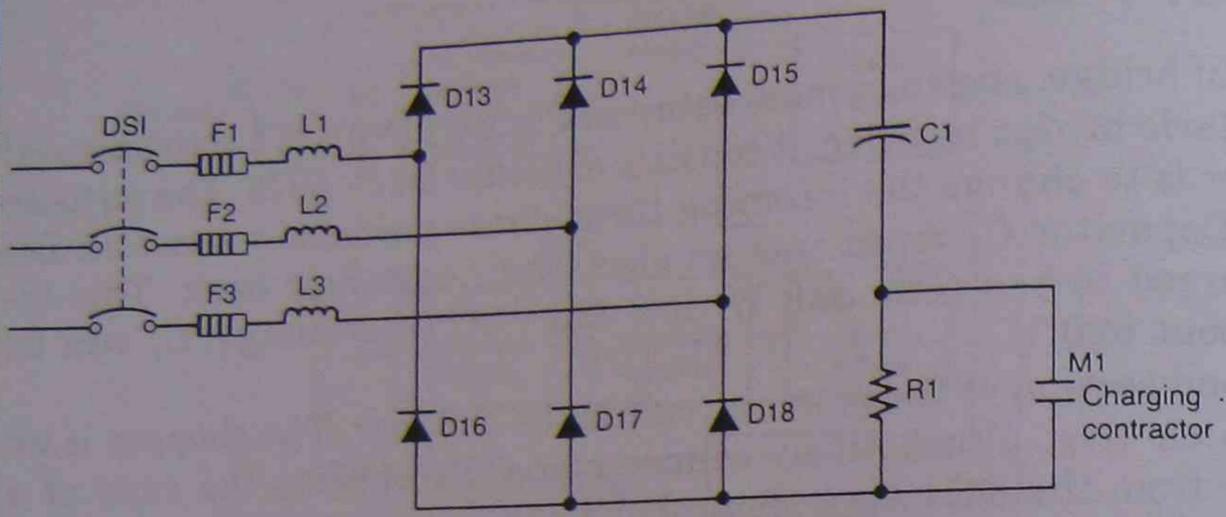


FIGURE 11-21 Input bridge, Graham CSI control (courtesy of Graham Co.)

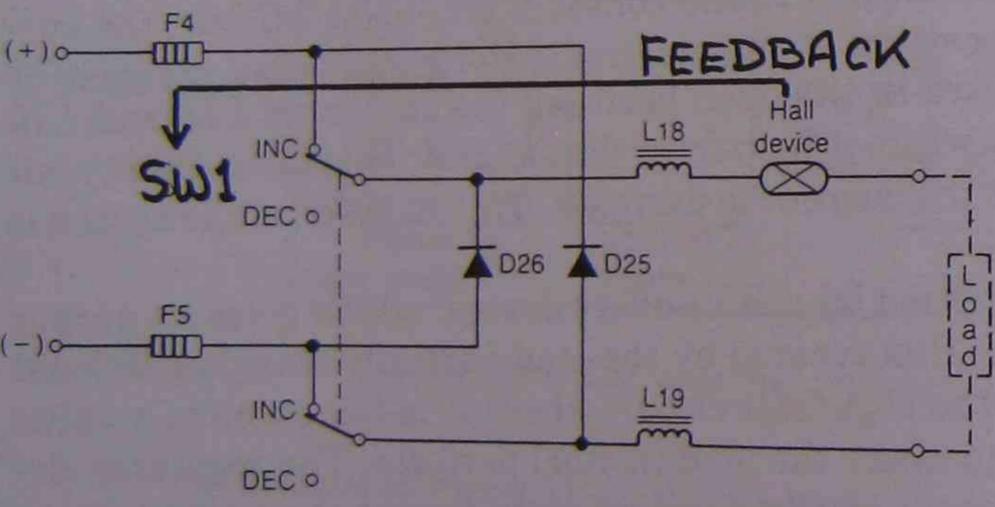


FIGURE 11-22 Chopper circuit, Graham CSI controller (courtesy of Graham Co.)

# A.C. Motor Control.

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## FIG 11-23

The schematic in Figure 11-23 is a simplified schematic of the inverter section. It is a six-step inverter with SCR1-6 switching the load current at the proper rate as determined by the control circuitry. The switching rate of the SCRs establishes the output frequency. Commutation capacitors C28 through C33 store energy necessary for turning off the SCRs by reversing their terminal voltage. Series diodes D1 through D6 isolate the capacitors from the load. Only two SCRs are on at any one time, with each one conducting the 120°. They are commutated when the adjacent SCRs in the next phase are fired in the order numbered.

The inductance of the motor is a significant factor in the commutating scheme. The inductance stores energy necessary for commutation, and this energy charges the capacitors for the next cycle. There is also a precharge circuit consisting of a diode and resistance in series with each capacitor. This precharge circuit is present to insure that enough capacitor voltage is present to commutate the SCRs during starting and low frequency operation.

The chopper controls the current in the inverter coming from L18. Even when there are two parallel paths for current, the sum of the two can never be greater than the output current from the chopper. The inverter controls only the time that the current flows through each motor phase.

The DC voltage at the input terminals of the inverter will vary with the demand of the load. At no load, the voltage will be near zero. At rated load, it will be maximum.

The response of the motor and the load and the applied current and frequency determine the counter EMF (CEMF) of the motor. It is approximately sinusoidal with a spike occurring each time an SCR is commutated. Figure 11-24 shows a typical phase current and voltage in the inverter section.

We can see that current flows for 120° in the positive direction, ceases for 60° and repeats, but in the negative direction. The positive current for phase 1 is when SCR1 conducts with either SCR3 or SCR5. Negative current is drawn when SCR4 conducts with either SCR3 or SCR5. The sawtooth on top of the current coincides with the chopper changing between the increase and decrease states.

# A.C. Motor Control.

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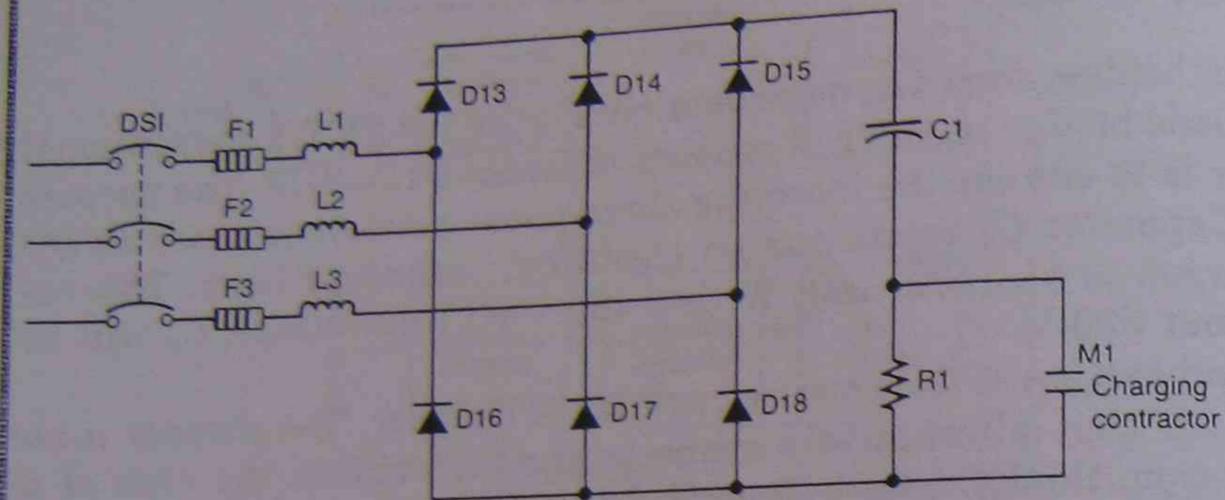


FIGURE 11-21 Input bridge, Graham CSI control (courtesy of Graham Co.)

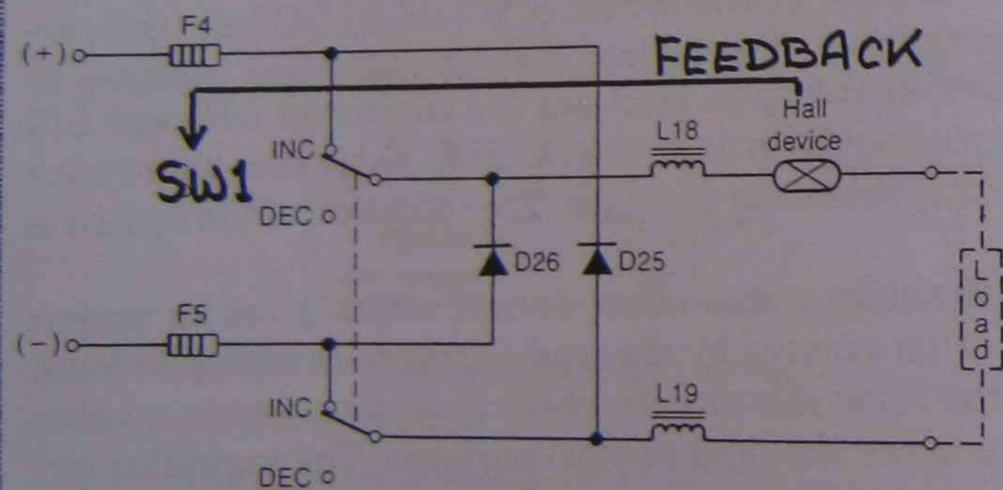


FIGURE 11-22 Chopper circuit, Graham CSI controller (courtesy of Graham Co.)

# A.C. Motor Control.

Topic - \_\_\_\_\_

## FIG 11-23

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We can see that current flows for  $120^\circ$  in the positive direction, ceases for  $60^\circ$  and repeats, but in the negative direction. The positive current for phase A is when *SCR1* conducts with either *SCR6* or *SCR2*. Negative current is drawn when *SCR4* conducts with either *SCR3* or *SCR5*. The sawtooth on top of the current coincides with the chopper changing between the increase and decrease states.