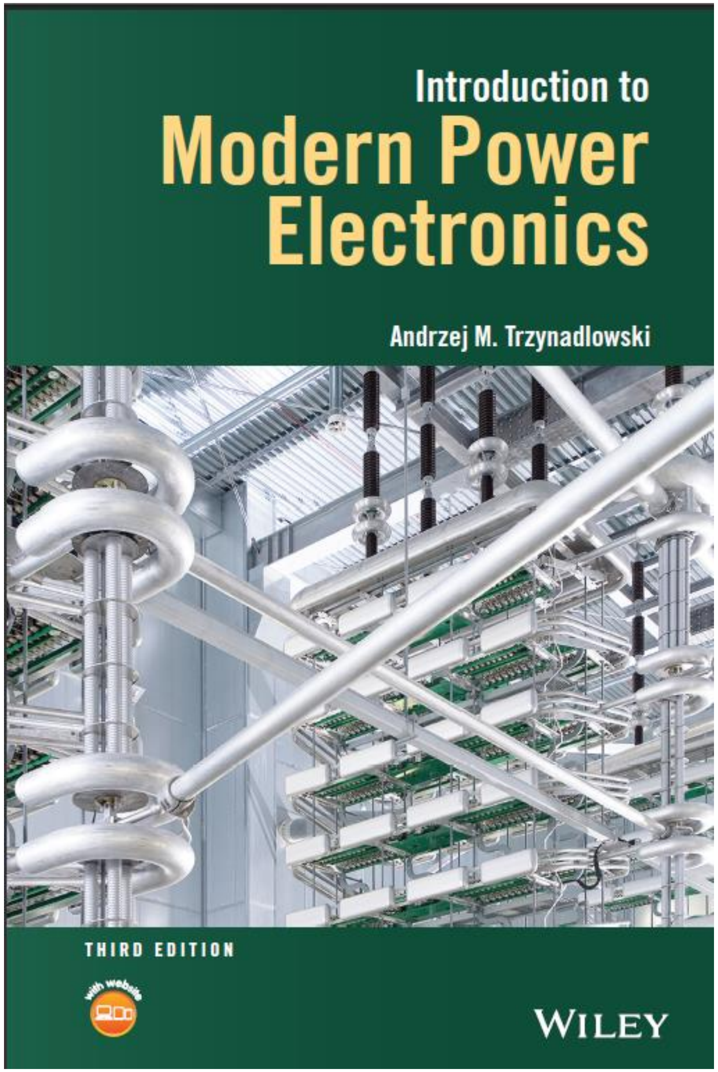
Introduction to Modern Power Electronics

Chap.-5
AC to AC Converters

Dr. U. T. Shami

Information about the Text Book



The Front View of Our Text Book

Title:
Introduction to Modern Power Electronics

Author:
Andrzej M. Trzynadlowski

Third Edition.
Publisher: Wiley

In this slide presentation we will cover chapter 5.

5.1 AC VOLTAGE CONTROLLERS

Ac voltage controllers are based on pairs of antiparallel-connected power switches. When SCRs or triacs are used, phase control is employed, and the controller belongs in the class of line-commutated power electronic converters. Fully-controlled switches are used in force-commutated, PWM ac voltage controllers, whose advantages are similar to those of PWM rectifiers.

5.1.1 Phase-Controlled Single-Phase AC Voltage Controller

Figure 5.1 is a circuit diagram of a phase-controlled single-phase ac voltage controller. In low-power converters, a triac is used instead of the two antiparallel-connected SCRs shown. An RL load is assumed in subsequent considerations. When one of the SCRs is conducting, the other SCR is reverse biased by the voltage drop across the conducting SCR. Only one path of the current exists, so the input current, i_i, equals the output current, i_o. With either SCR conducting, the input and output terminals of the converter are connected directly, and the output voltage, v_o, equals the input voltage, v_i.

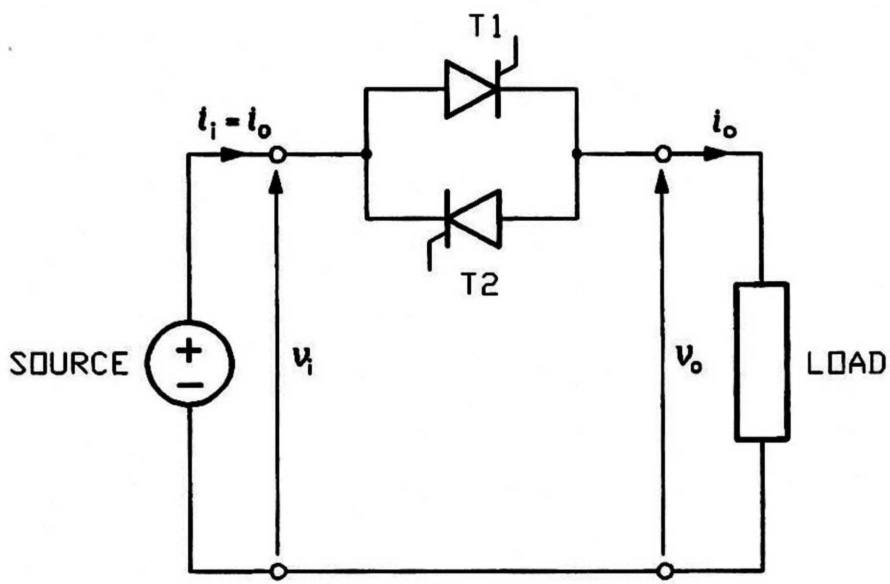


Figure 5.1 Single-phase ac voltage controller.

Output Voltage and Current Selected voltage and current waveforms are shown in Figure 5.2. When SCR T1 is forward biased and fired at a certain firing angle, α_f, the current conducted initially increases thanks to the positive input voltage, but eventually drops to zero, somewhat later than the voltage does. Now the input voltage

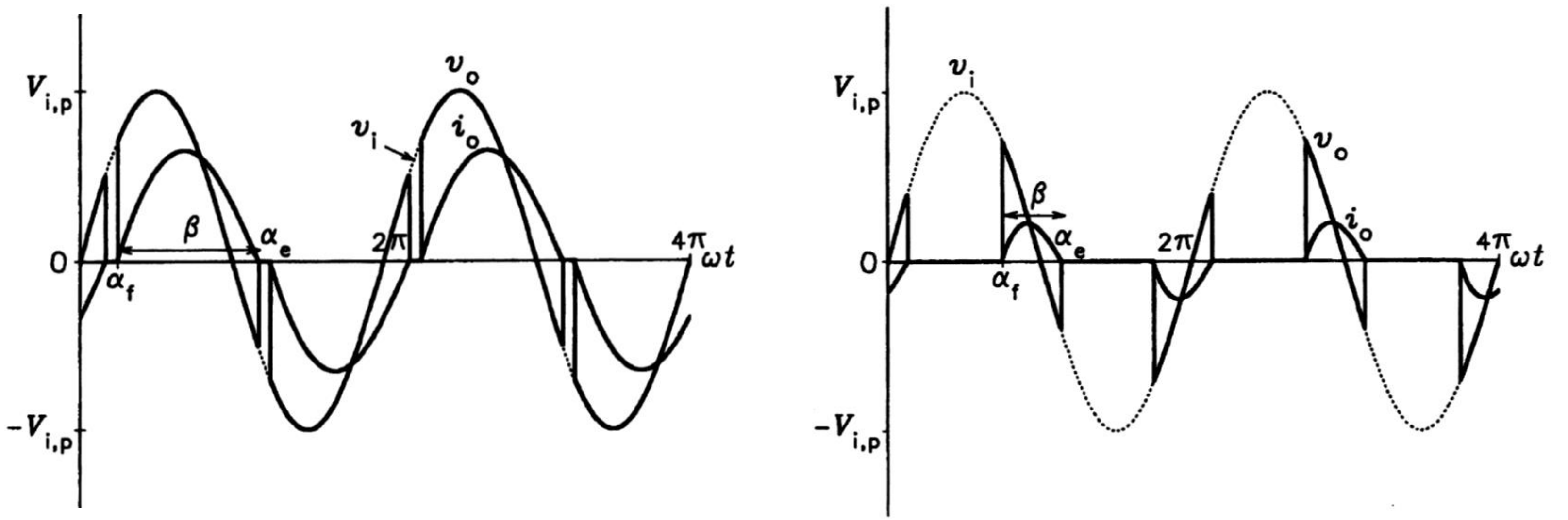
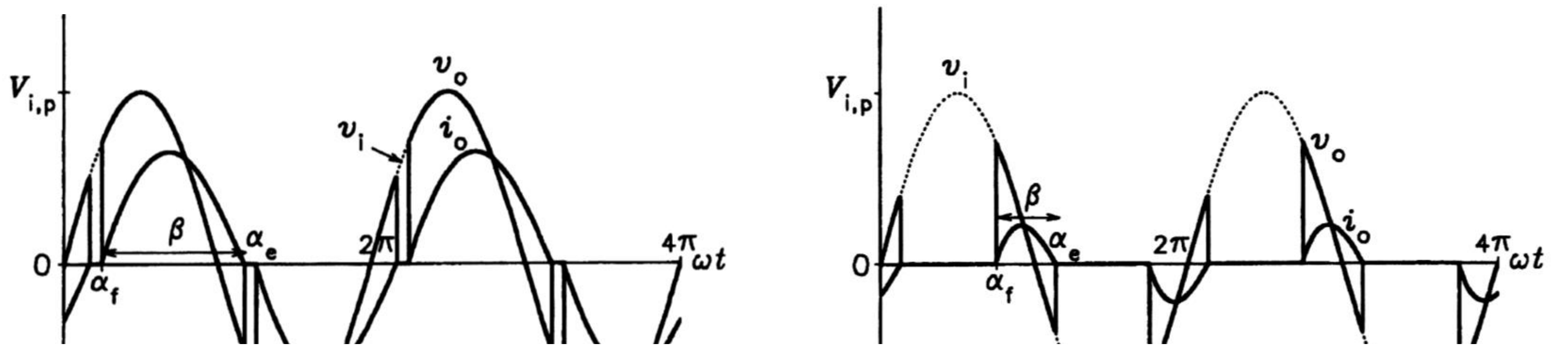


Figure 5.2 Waveforms of output voltage and current of a single-phase ac voltage controller ($\varphi = 30°$): (a) $\alpha_f = 45°$; (b) $\alpha_f = 135°$.



$$i_o(\omega t) = \frac{V_{i,p}}{Z}\left[\sin(\omega t - \varphi) - e^{(\omega t - \alpha_f)/\tan\varphi}\sin(\alpha_f - \varphi)\right] \qquad (5.2)$$

Figure 5.2 controller

($\varphi = 30°$): (a

$$V_o = \sqrt{\frac{1}{\pi}\int_0^{\pi} v_o^2(\omega t)\, d\omega t} = \sqrt{\frac{1}{\pi}\int_0^{\pi} (V_{i,p}\sin\omega t)^2\, d\omega t}$$

$$= V_{i,p}\sqrt{\frac{1}{\pi}\left[\alpha_e - \alpha_f - \frac{1}{2}(\sin 2\alpha_e - \sin 2\alpha_f)\right]}$$

Voltage Control

If $\varphi = 0$ (purely resistive load), Eq. (5.2) yields

$$i_o(\omega t) = \frac{V_{i,p}}{R} \sin \omega t \tag{5.3}$$

and the extinction angle is π radians. Conversely, if $\varphi = \pi/2$ (purely inductive load), then

$$i_o(\omega t) = \frac{V_{i,p}}{\omega L}(\cos \alpha_f - \cos \omega t) \tag{5.4}$$

and the extinction angle is $2\pi - \alpha_f$, as $\cos \alpha_f - \cos(2\pi - \alpha_f) = 0$.

Substituting the values of α_e obtained in Eq. (5.1), the envelope of control characteristics can be expressed as

$$V_{o(\varphi=0)}(\alpha_f) \leq V_o(\alpha_f) \leq V_{o(\varphi=\pi/2)}(\alpha_f) \tag{5.5}$$

where

$$V_{o(\varphi=0)}(\alpha_f) = V_i \sqrt{\frac{1}{\pi}\left(\pi - \alpha_f + \frac{1}{2} \sin 2\alpha_f\right)} \tag{5.6}$$

and

$$V_{o(\varphi=\pi/2)}(\alpha_f) = \sqrt{2}\, V_{o(\varphi=0)}(\alpha_f). \tag{5.7}$$

Voltage Control

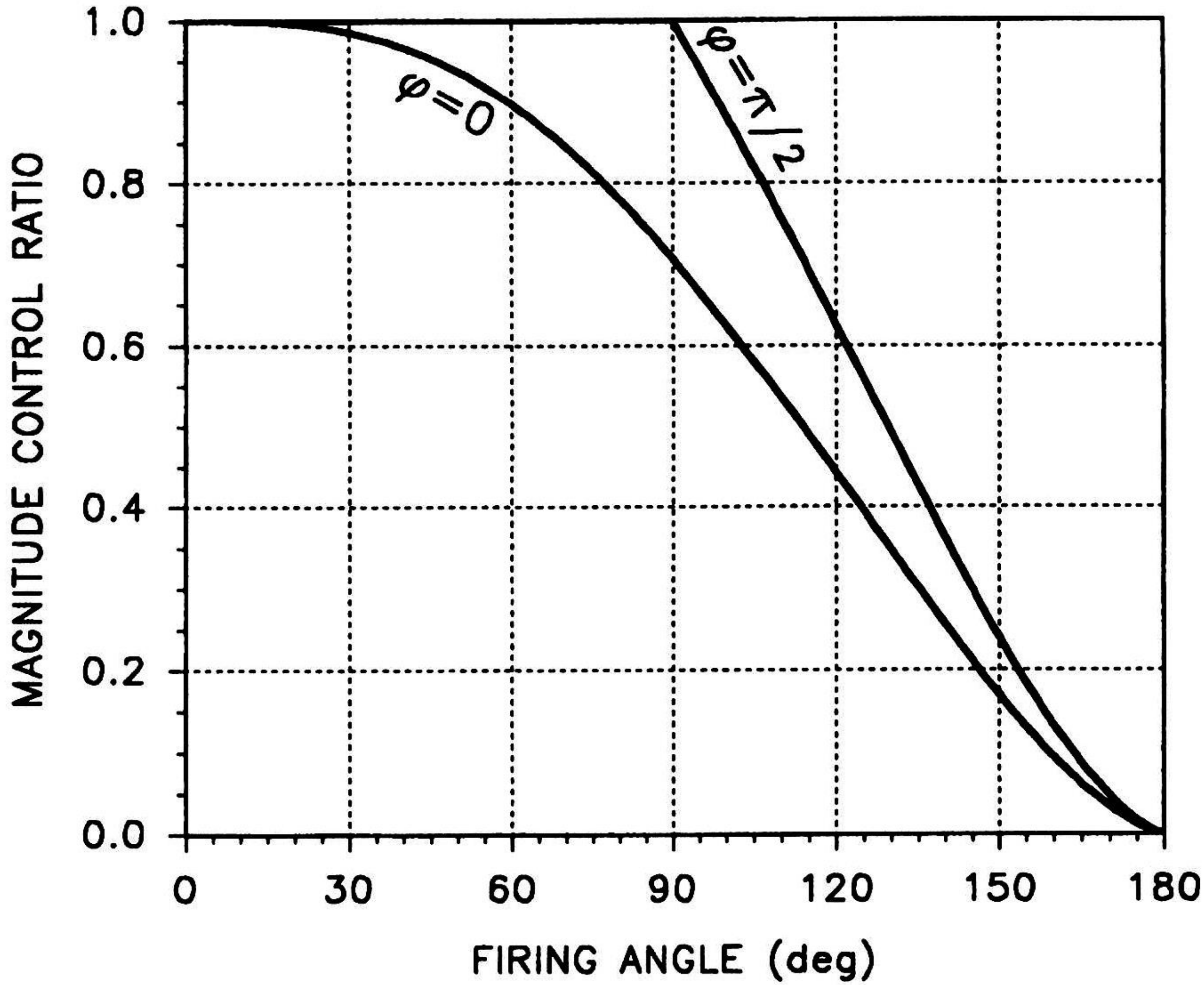


Figure 5.3 Envelope of control characteristics, $V_o = f(\alpha_f)$, of a single-phase ac voltage controller.

Voltage Control

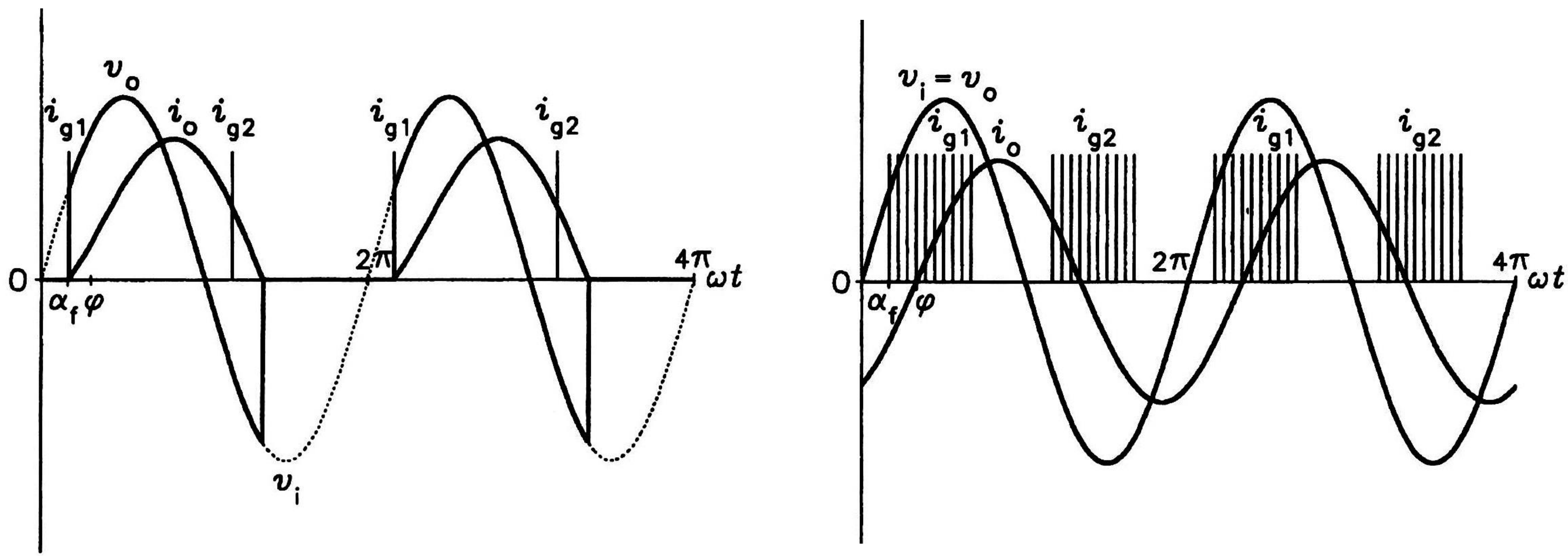


Figure 5.4 Operation of a single-phase ac voltage controller with (a) a single-pulse gate signal; (b) a multipulse gate signal.

Voltage Control

$$\alpha'_f = \pi - \beta = \pi - \alpha_e + \alpha_f.$$

angle, α_f, can be expressed

$$\alpha_f = \alpha'_f + \alpha_e - \pi$$

and substituted in Eq. (5.1), to yield

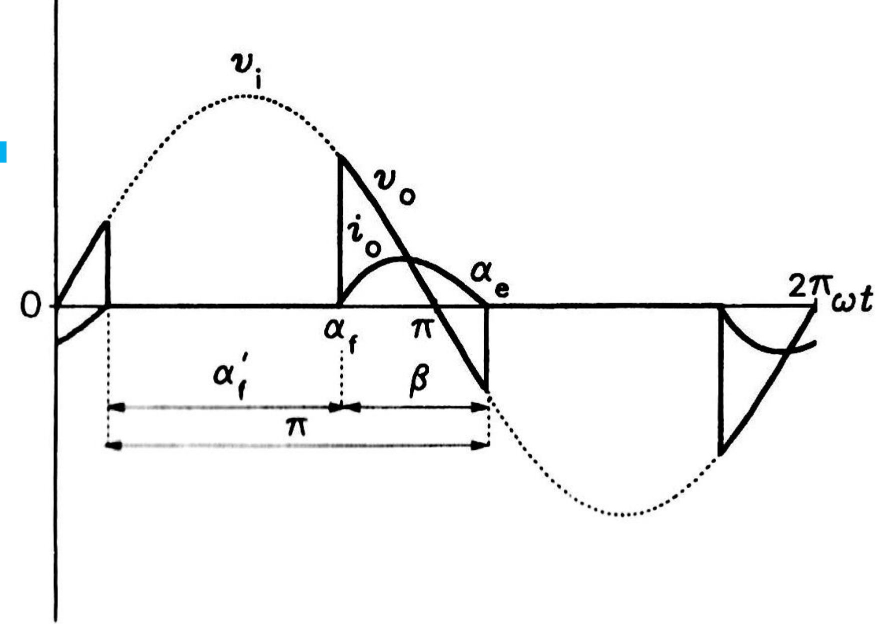


Figure 5.5 Definition of a control angle.

$$V_o = V_i\sqrt{\frac{1}{\pi}[\pi - \alpha'_f + \sin\alpha'_f\ \cos(2\alpha_e + \alpha'_f)]}.$$

where

$$V_{o(\varphi=\pi/2)}(\alpha'_f) \le V_o(\alpha'_f) \le V_{o(\varphi=0)}(\alpha'_f)$$

$$V_{o(\varphi=\pi/2)}(\alpha'_f) = V_i\sqrt{\frac{1}{\pi}(\pi - \alpha'_f - \sin\alpha'_f)}$$

$$V_{o(\varphi=0)}(\alpha'_f) = V_i\sqrt{\frac{1}{\pi}\left(\pi - \alpha'_f + \frac{1}{2}\sin 2\alpha'_f\right)}.$$

Power Factor

Power Factor The input power factor, PF, of a lossless ac voltage controller can be expressed as

$$PF = \frac{P_o}{S_i} = \frac{RI_o^2}{V_i I_i} = \frac{ZI_o}{V_i} \cos \varphi. \tag{5.14}$$

Then PF $= V_o/V_i = M$ (magnitude control ratio). Thus, based on Eq. (5.6),

$$PF_{(\varphi=0)}(\alpha_f) = \sqrt{\frac{1}{\pi}\left(\pi - \alpha_f + \frac{1}{2}\sin 2\alpha_f\right)}. \tag{5.15}$$

It can be seen that similar to phase-controlled rectifiers, phase-controlled ac voltage controllers are characterized by the decreasing quality of the input current with an increase in the firing angle. The input power factor decreases and the total harmonic distortion of the input current increases.

5.1.2 Phase-Controlled Three-Phase AC Voltage Controllers

Fully Controlled Three-Phase AC Voltage Controller Operation of the fully controlled three-phase ac voltage controller, shown in Figure 5.7, is more complicated than that of the single-phase converter. Note, for example, that to get the controller started, two triacs must be fired simultaneously to provide the path for current necessary to maintain the on-state of triacs.

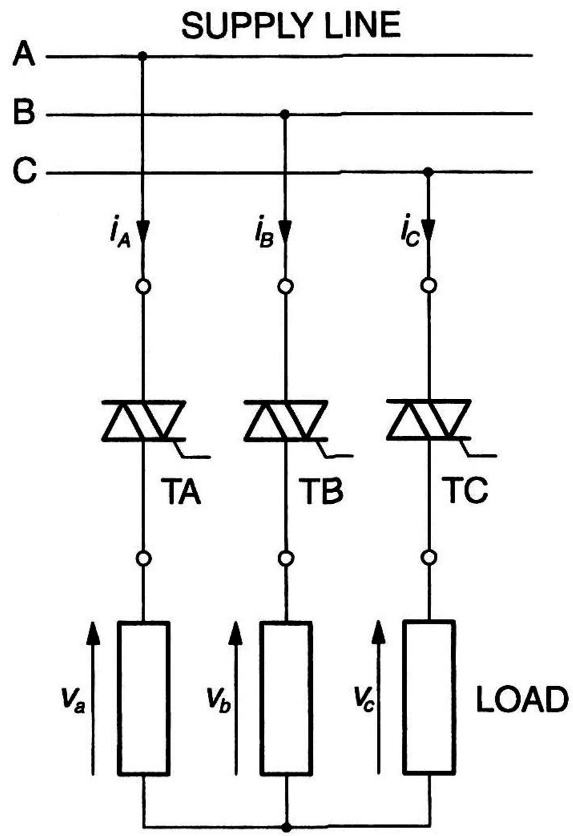


Figure 5.7 Fully controlled three-phase ac voltage controller.

Fully Controlled Three-Phase AC Voltage Controller

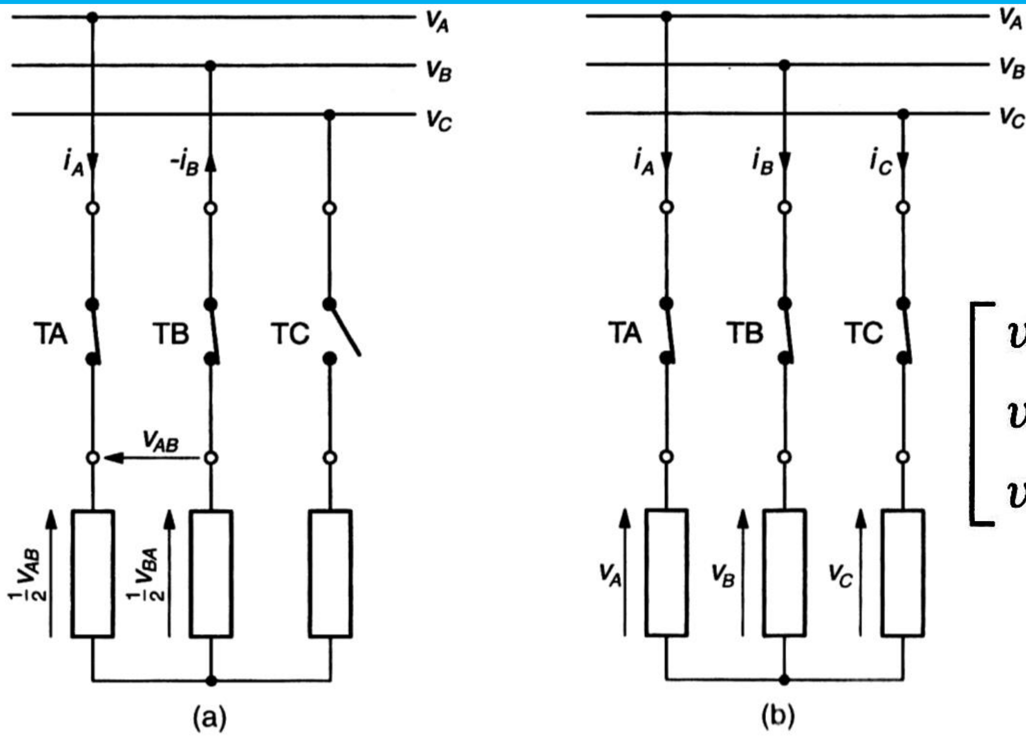


Figure 5.8 Voltage and current distribution in a fully controlled three-phase ac voltage controller: (a) two triacs conducting; (b) three triacs conducting.

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{2}\begin{bmatrix} a & -b & -c \\ -a & b & -c \\ -a & -b & c \end{bmatrix}\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix}$$

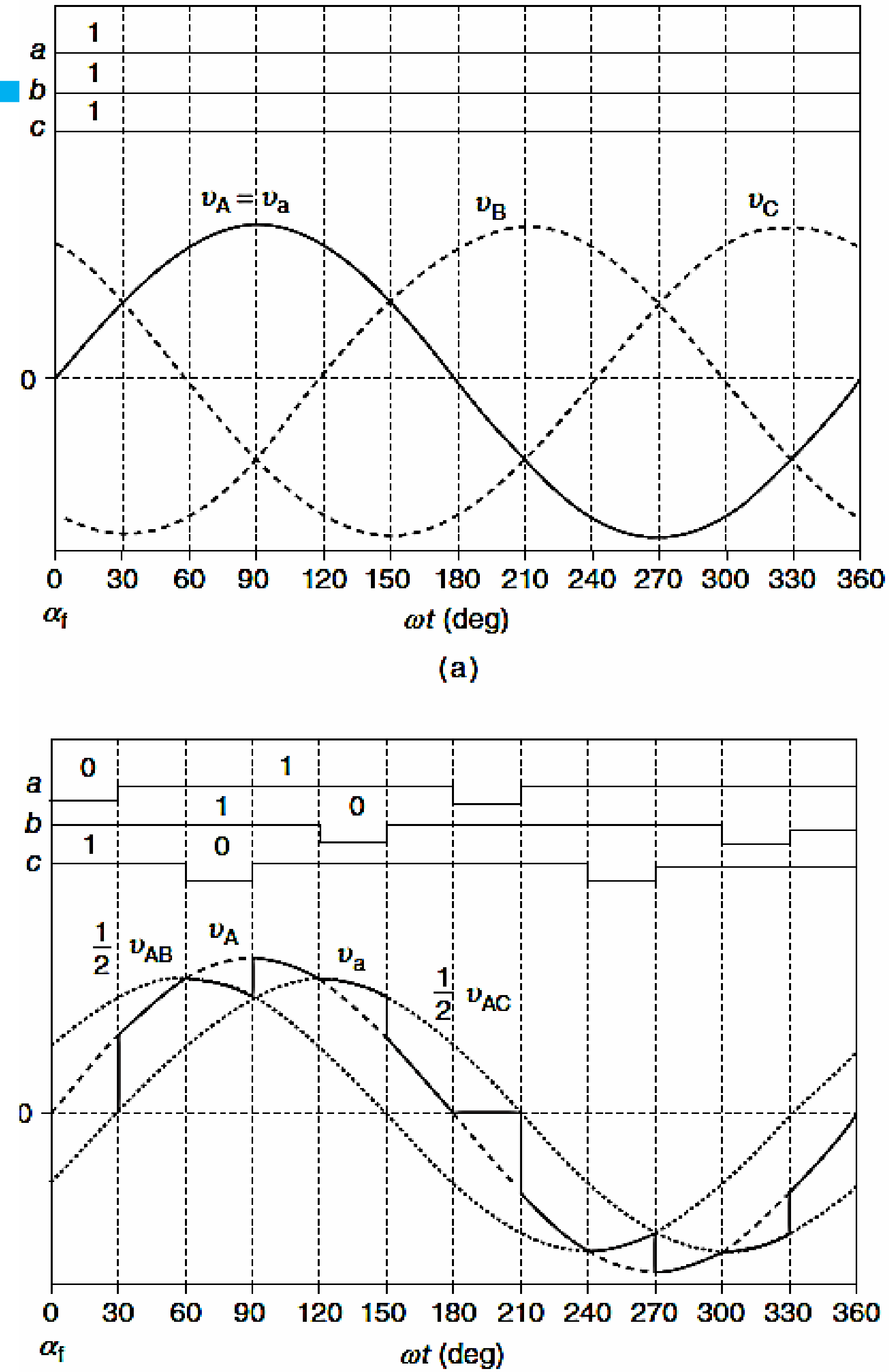
Mode 1 ($0° \le \alpha_f < 60°$): two or three triacs conducting (in either direction)

Mode 2 ($60° \le \alpha_f < 90°$): two triacs conducting

Mode 3 ($90° \le \alpha_f < 150°$): none or two triacs conducting

Operation of the controller

with Resistive Load



Operation of the controller with Resistive Load

Operation of the controller with large firing angles is illustrated in Figure 5.10. An example waveform of the output voltage at $\alpha_f = 75°$ is shown in Figure 5.10a and that at $\alpha_f = 120°$ in Figure 5.10b.

For completeness, formulas for the rms output voltage, V_o, of the fully controlled ac voltage controller with purely resistive and purely inductive loads are provided below without derivation.

Resistive load:

$$V_o = V_i \sqrt{\frac{1}{\pi}\left[\pi - \frac{3}{2}\alpha_f + \frac{3}{4}\sin(2\alpha_f)\right]} \tag{5.17}$$

for $0 \leq \alpha_f < 60°$,

$$V_o = V_i \sqrt{\frac{1}{\pi}\left[\frac{\pi}{2} + \frac{3\sqrt{3}}{4}\sin\left(2\alpha_f + \frac{\pi}{6}\right)\right]} \tag{5.18}$$

for $60° \leq \alpha_f < 90°$, and

$$V_o = V_i \sqrt{\frac{1}{\pi}\left[\frac{5}{4}\pi - \frac{3}{2}\alpha_f + \frac{3}{4}\sin\left(2\alpha_f + \frac{\pi}{3}\right)\right]} \tag{5.19}$$

for $90° \leq \alpha_f < 150°$.

Operation of the controller with Inductive Load

Inductive load:

$$V_o = V_i \sqrt{\frac{1}{\pi}\left[\frac{5}{2}\pi - 3\alpha_f + \frac{3}{2}\sin(2\alpha_f)\right]} \tag{5.20}$$

for $90° \leq \alpha_f < 120°$, and

$$V_o = V_i \sqrt{\frac{1}{\pi}\left[\frac{5}{2}\pi - 3\alpha_f + \frac{3}{2}\sin(2\alpha_f +)\right]} \tag{5.21}$$

for $120° \leq \alpha_f < 150°$.

The Envelope of Control Characteristics

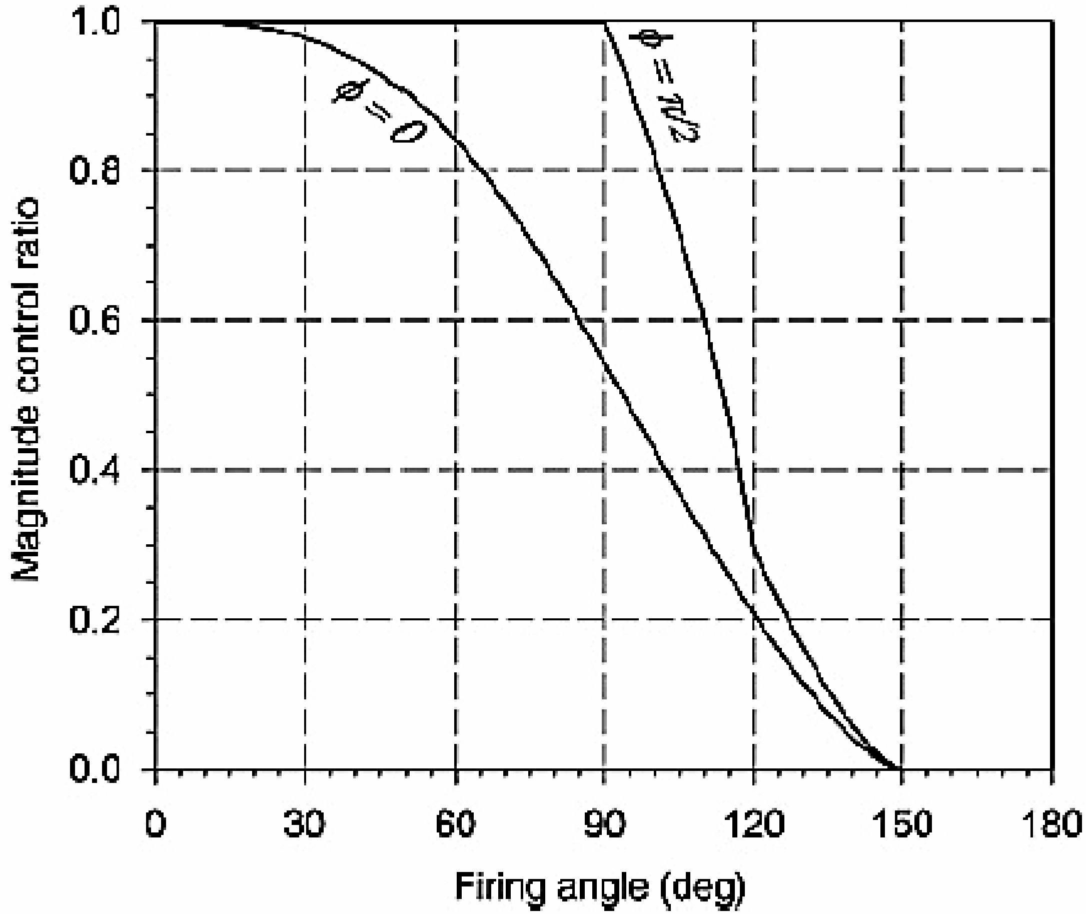


Figure 5.11 Envelope of control characteristics, $V_o = f(\alpha_f)$, of a fully controlled three-phase ac voltage controller.

Other Types of Three-Phase AC Voltage Controllers 1

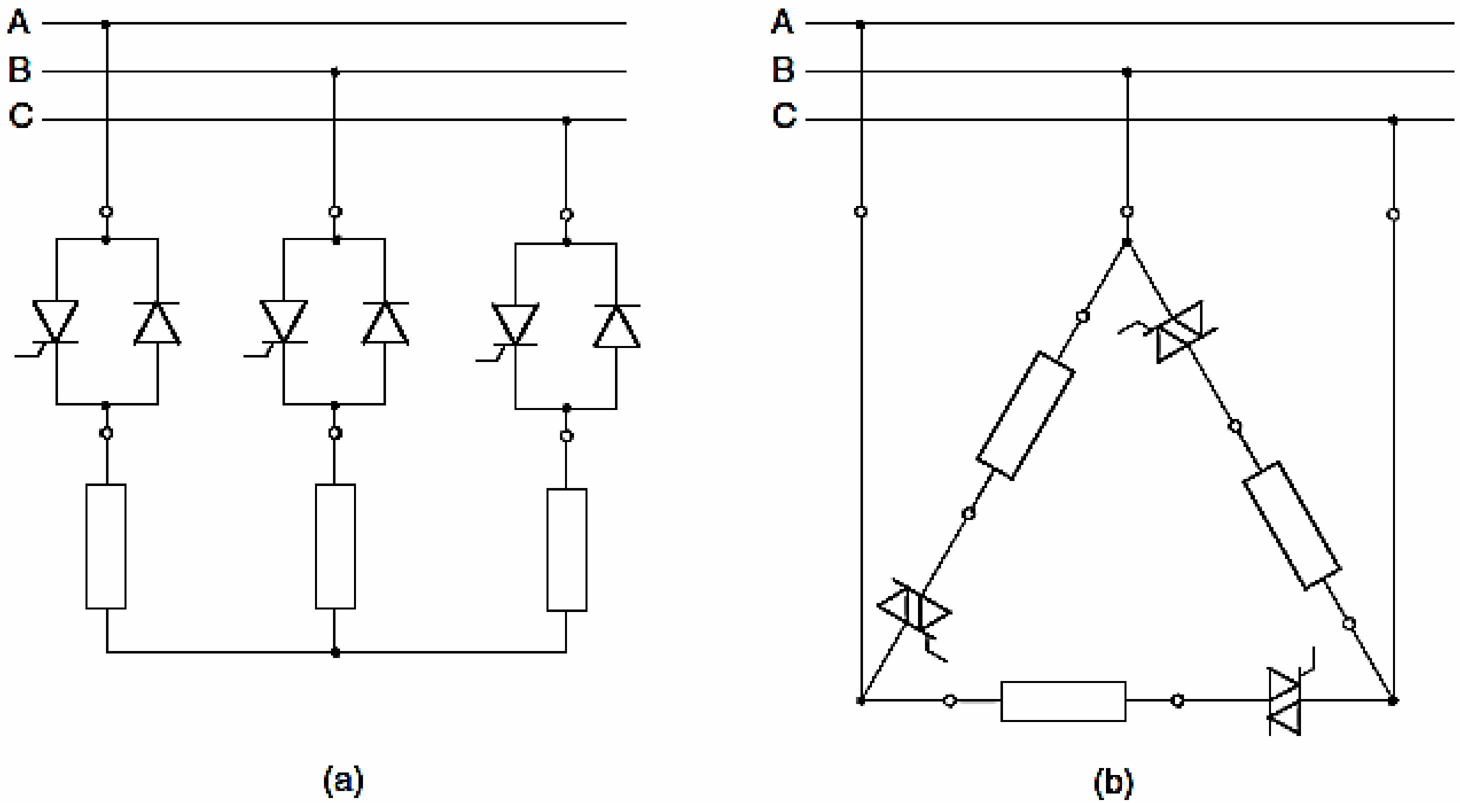


Figure 5.13 Three-phase ac voltage controllers connected before the load: (a) half controlled, (b) delta connected.

Other Types of Three-Phase AC Voltage Controllers 2

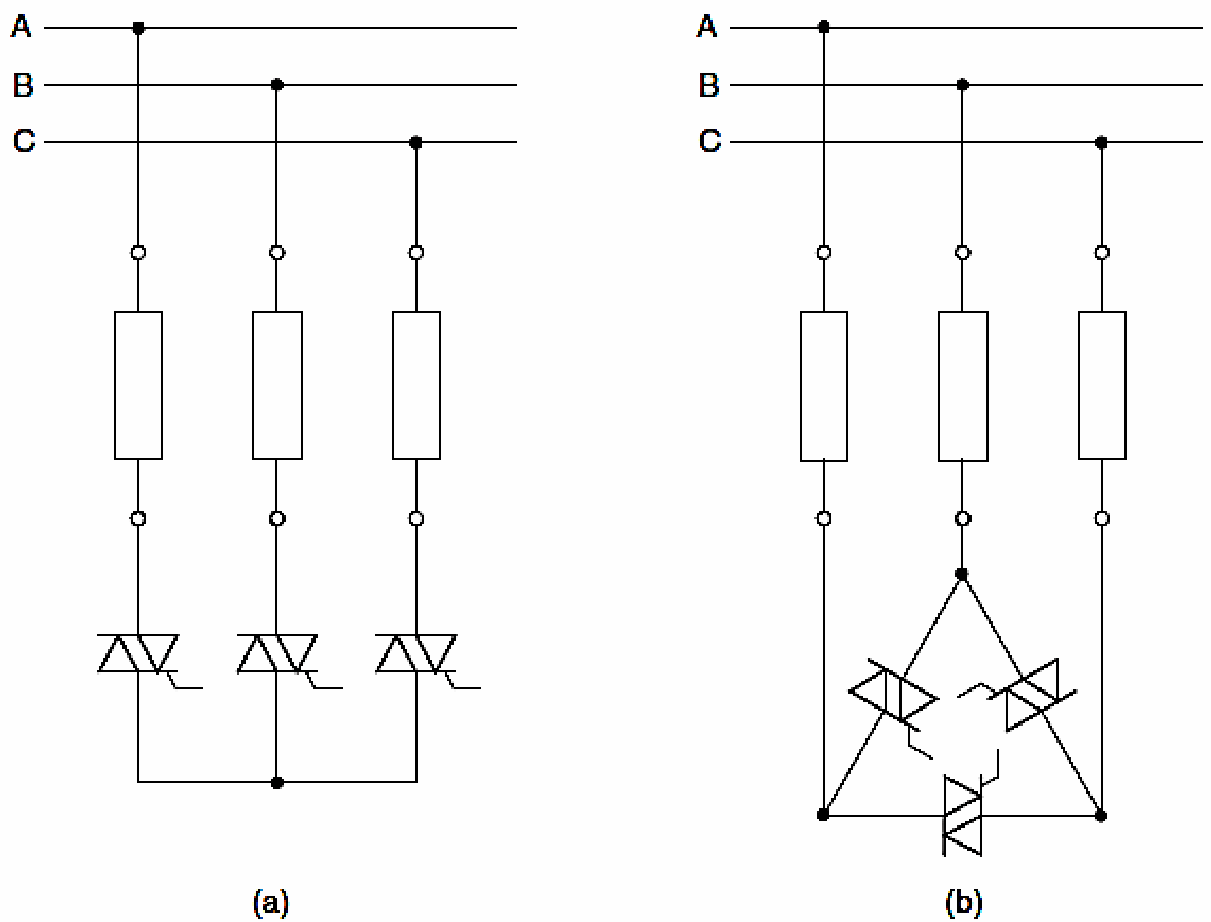


Figure 5.14 Three-phase ac voltage controllers connected after the load: (a) wye connected, (b) delta connected.

Other Types of Three-Phase AC Voltage Controllers 3

The circuit diagram of a four-wire ac voltage controller is shown in Figure 5.15. The load is connected in wye, and the neutrals of the load and supply line are connected. As such, the converter operates as three independent single-phase ac voltage controllers, whose operating properties have already been described in Section 5.1.1.

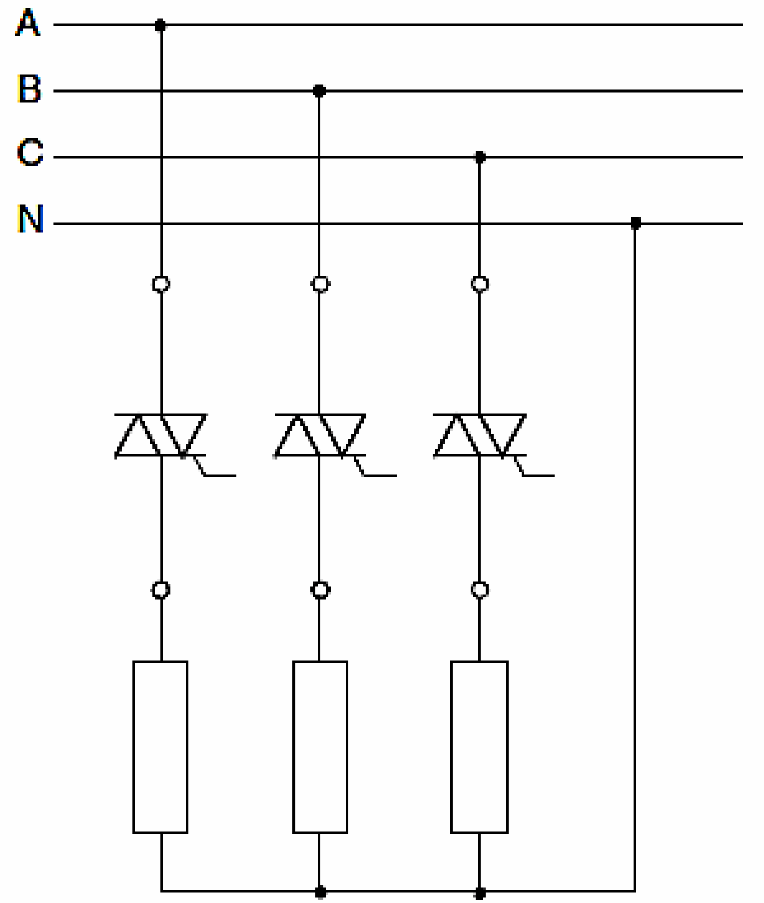
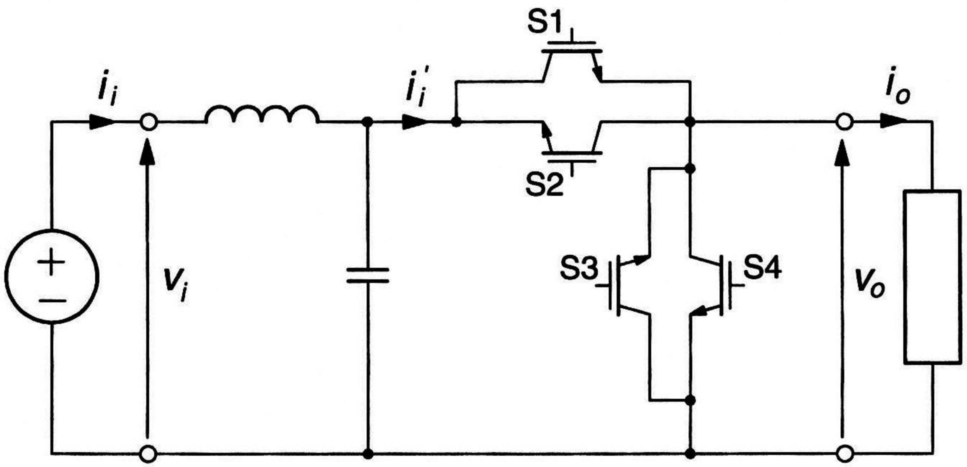


Figure 5.15 Three-phase four-wire ac voltage controller.

5.1.3 PWM AC Voltage Controllers

The circuit diagram of a single-phase PWM ac voltage controller, also known as an *ac chopper*, is shown in Figure 5.17. An input filter such as that used for PWM rectifiers is required to attenuate the high-frequency harmonic currents drawn from the power system. The inductance provided by the power system is often sufficient, so that only the capacitor is installed. Ac choppers have been developed to improve the input power factor, control characteristics, and quality of the output current.

5.1.3 PWM AC Voltage Controllers



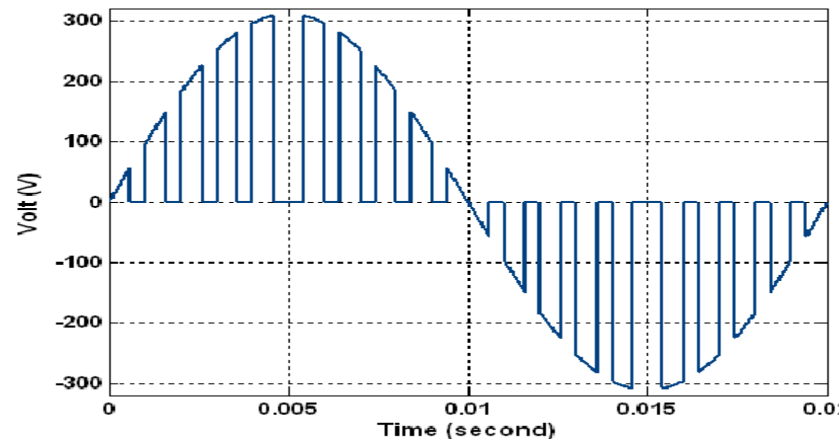


Figure 5.17 Single-phase ac chopper with an input filter.

The switches are turned on and off many times within a cycle of the input voltage. Assigning switching variables x_1 through x_4 to switches S1 through S4, respectively, the duty ratios for switches S1 and S2 in the nth switching interval, $d_{1,n}$ and $d_{2,n}$, are

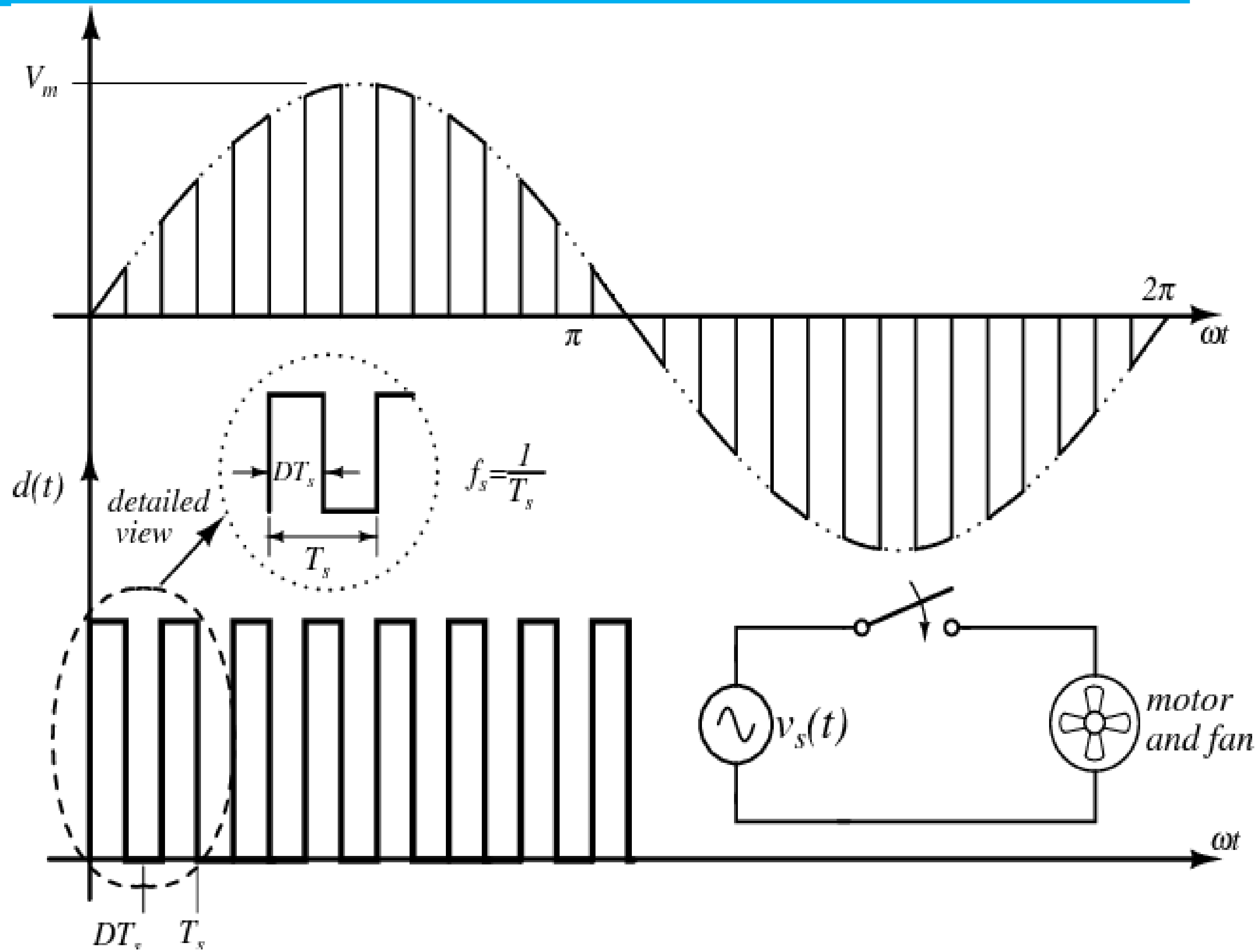
$$d_{1,n} = \begin{cases} F(m, \alpha_n) & \text{for } 0 < \alpha_n \leq \pi \\ 0 & \text{otherwise} \end{cases}$$

$$d_{2,n} = \begin{cases} F(m, \alpha_n) & \text{for } \pi < \alpha_n \leq \pi \\ 0 & \text{otherwise} \end{cases}$$

and for switches S3 and S4

$$x_3 = \bar{x}_1$$
$$x_4 = \bar{x}_2.$$

5.1.3 PWM AC Voltage Controllers



5.1.3 PWM AC Voltage Controllers

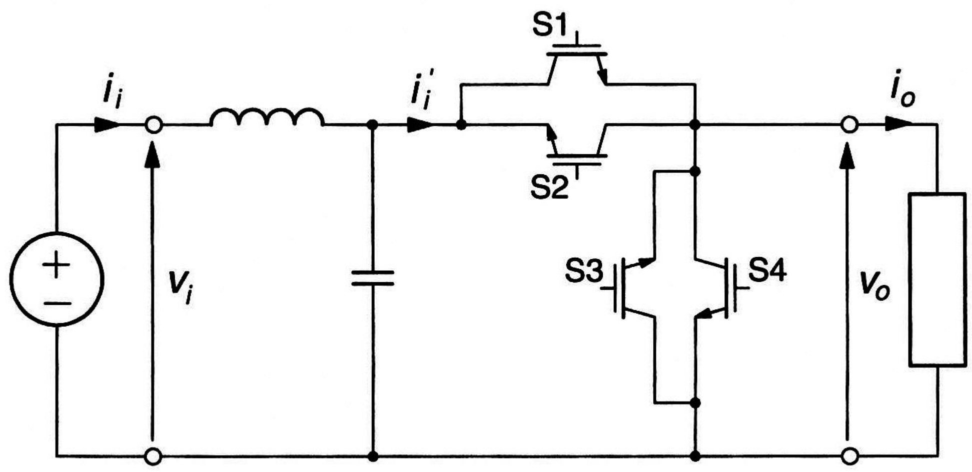
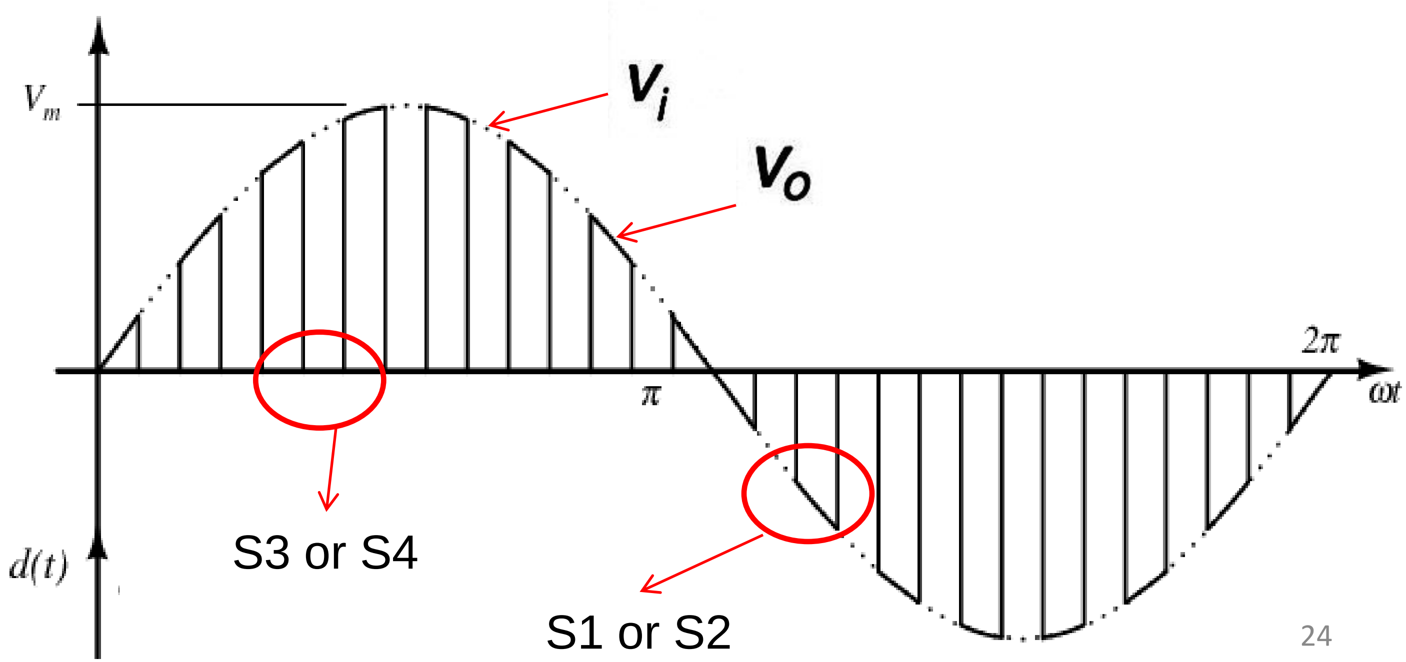
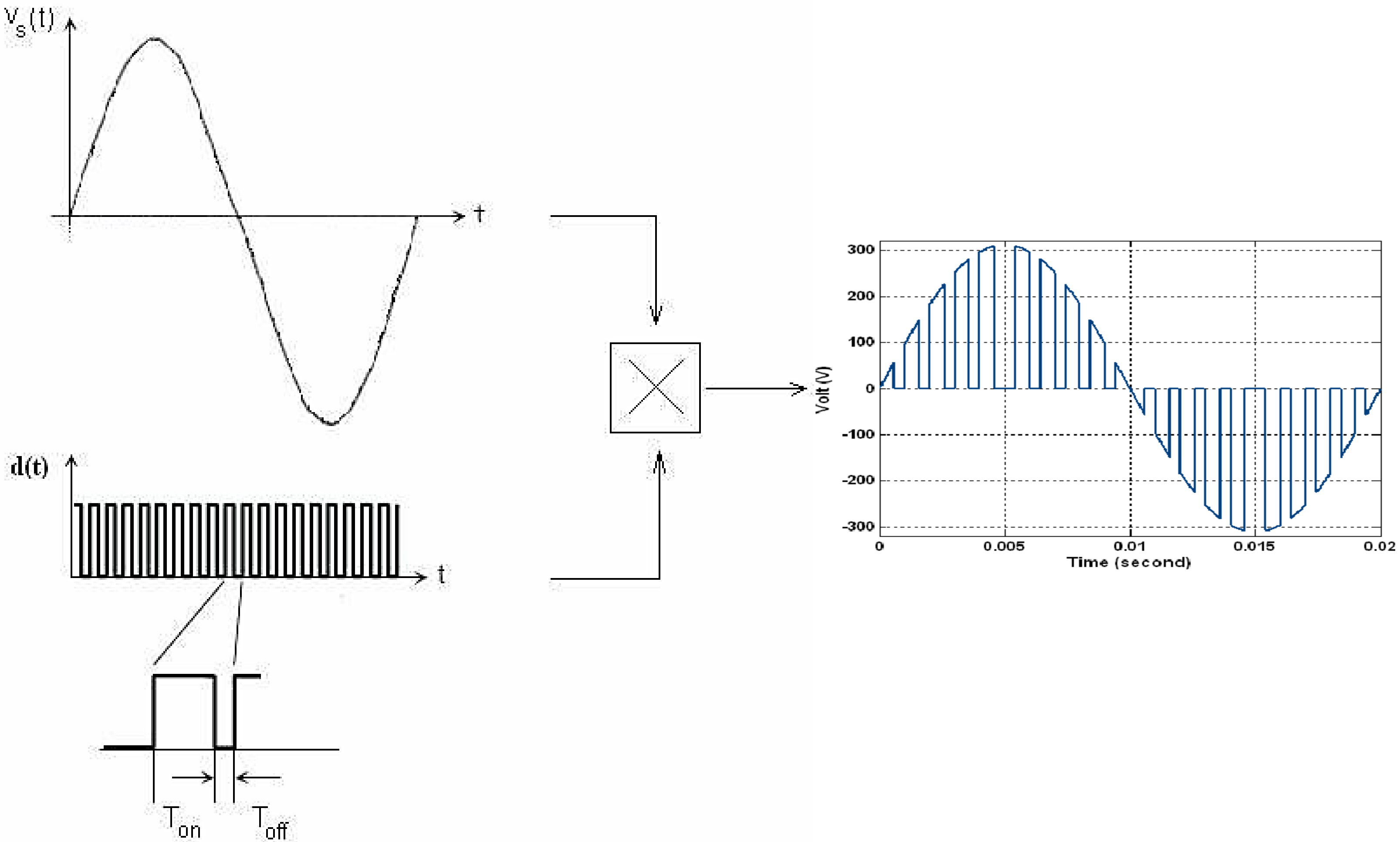


Figure 5.17 Single-phase ac chopper with an input filter.



5.1.3 PWM AC Voltage Controllers



5.1.3 PWM AC Voltage Controllers

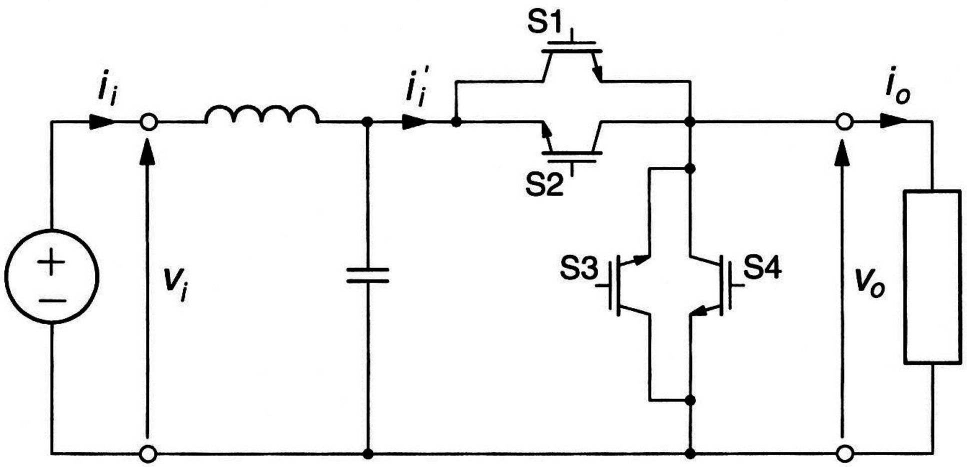
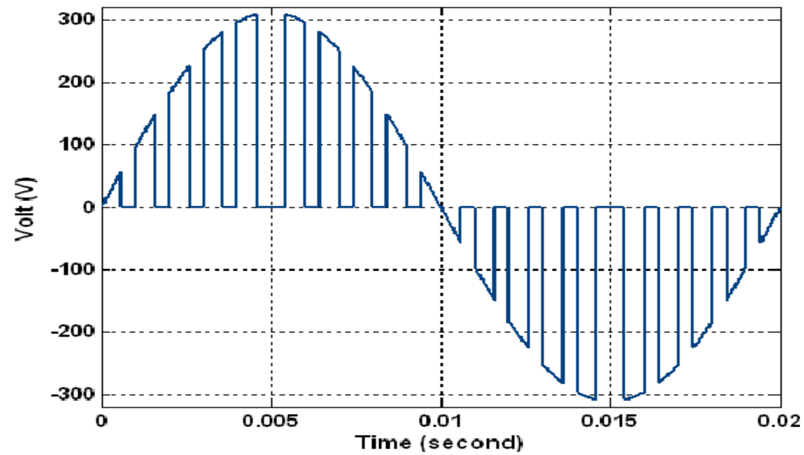
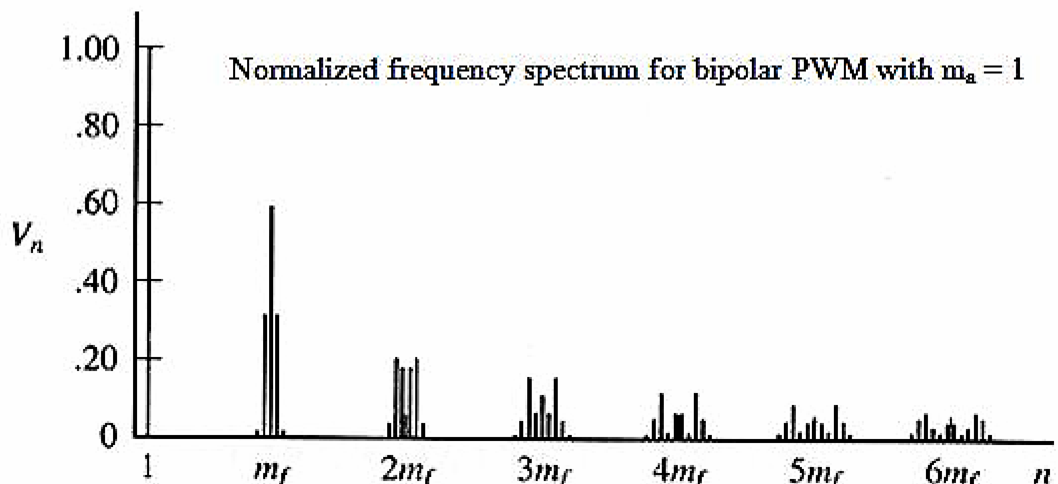


Figure 5.17 Single-phase ac chopper with an input filter.





5.1.3 PWM AC Voltage Controllers

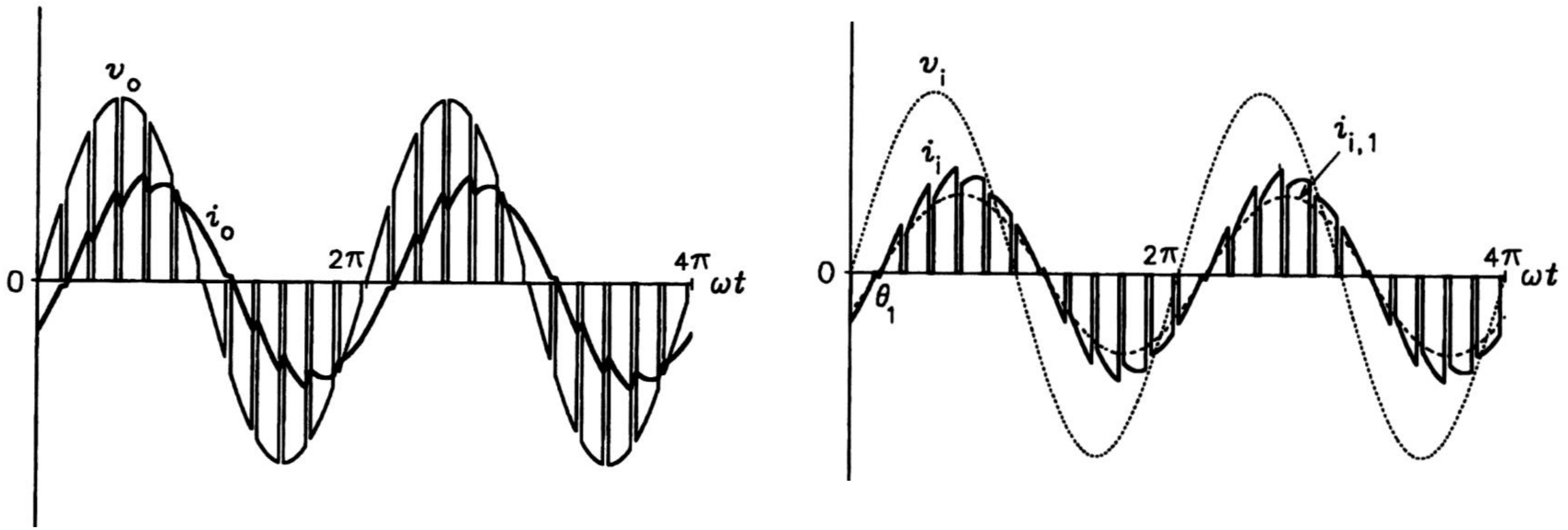


Figure 5.18 Waveforms of voltages and currents in a single-phase ac chopper: (a) output voltage and current; (b) input voltage and current (after the input filter) and the fundamental output current.

5.1.3 PWM AC Voltage Controllers

It can be proved that the magnitude control ratio, M, equals $\sqrt{m}$, that is,

$$V_o = \sqrt{m} V_i \tag{5.27}$$

which results in the control characteristic shown in Figure 5.18. However, the ratio, $V_{o,1}/V_{i,1}$, of fundamentals of the output and input voltages equals the modulation index m.

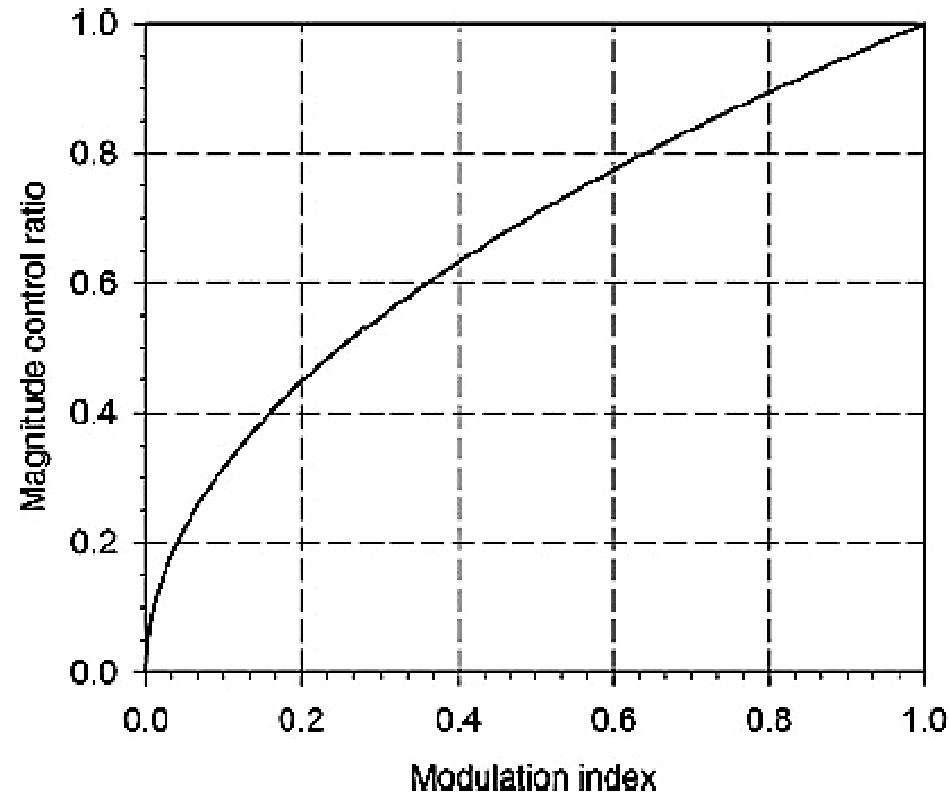


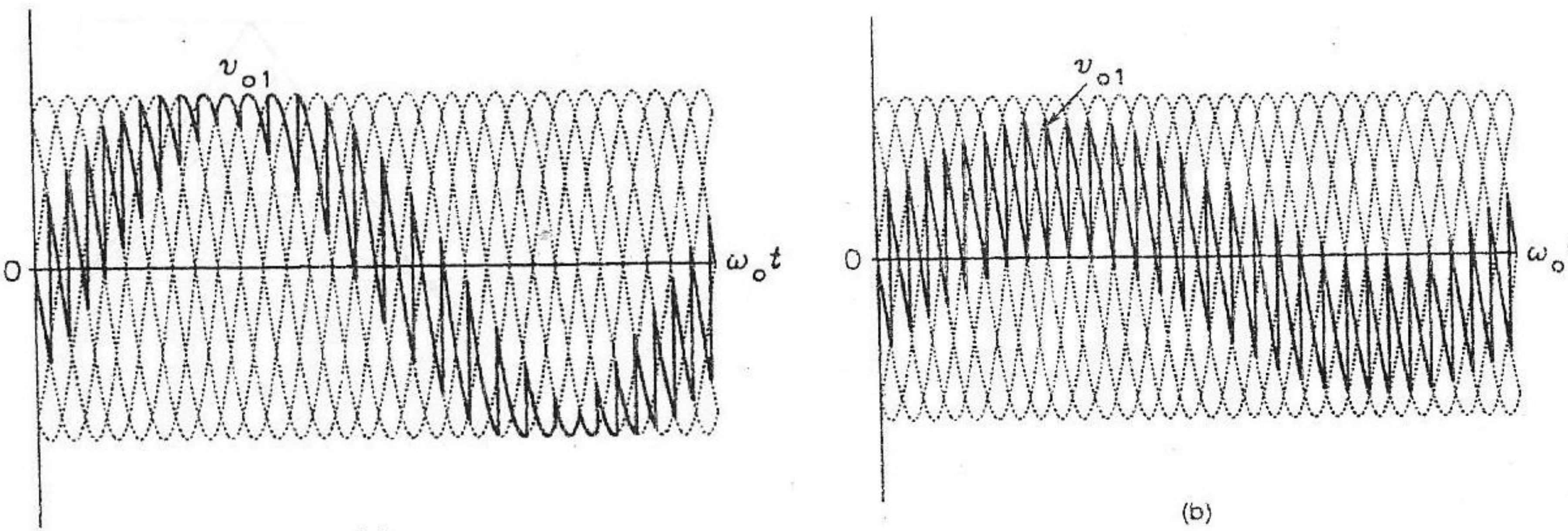
Figure 5.18 Control characteristic of the ac chopper.

5.2 CYCLOCONVERTERS

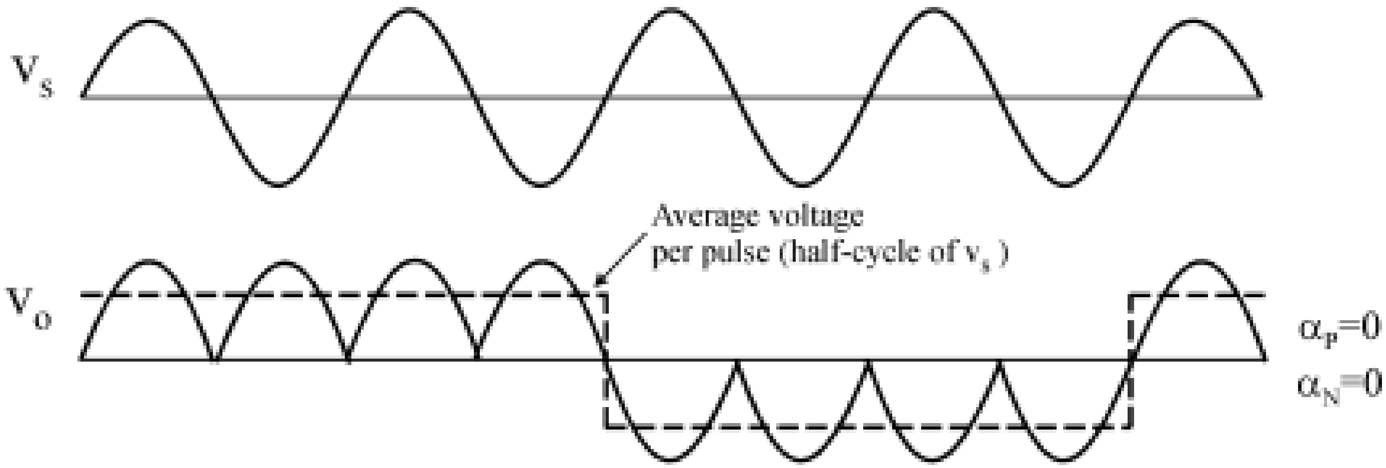
1. Cycloconverters are frequency changers that convert AC power of specific frequency and voltage to different frequency and voltage of AC power without any intermediate DC link. A cycloconverter is a naturally commutated converter in which the output frequency and voltage can be controlled independently and continuously. It consists of back to back connected controlled rectifiers whose output voltage and frequency can be controlled by tuning firing angles of rectifiers.
2. A cycloconverter provides direct a.c./a.c. conversion, while using large number of power devices and poorer output waveforms.
3. The frequency range is restricted to be less than the mains frequency.
4. The output waveshape consists of many unwanted harmonics.
5. However, the cycloconverter has certain features which make it superior to inverters for large, slow-speed drives. It allows energy to be transferred in either direction, and the large number of devices is no handicap when load currents are so large that parallel devices would have to be used in an inverter.
6. It is mainly used in electric traction, AC motors having variable speed and induction heating.

5.2 CYCLOCONVERTERS

Cycloconverters are ac-to-ac power converters in which the output frequency is a fraction of the input frequency. A single-phase two-pulse generic cycloconverter in a simple trapezoidal mode of operation resulting in an integer ratio of the input frequency to output frequency was shown in Examples 1.1 and 1.2. Practical cycloconverters have a three-phase output, although a hypothetical single-phase six-pulse cycloconverter will be used to illustrate the operating principles. The number of phases of a cycloconverter indicated applies to the *output*, the input being typically of the three-phase type.



(a) (b)



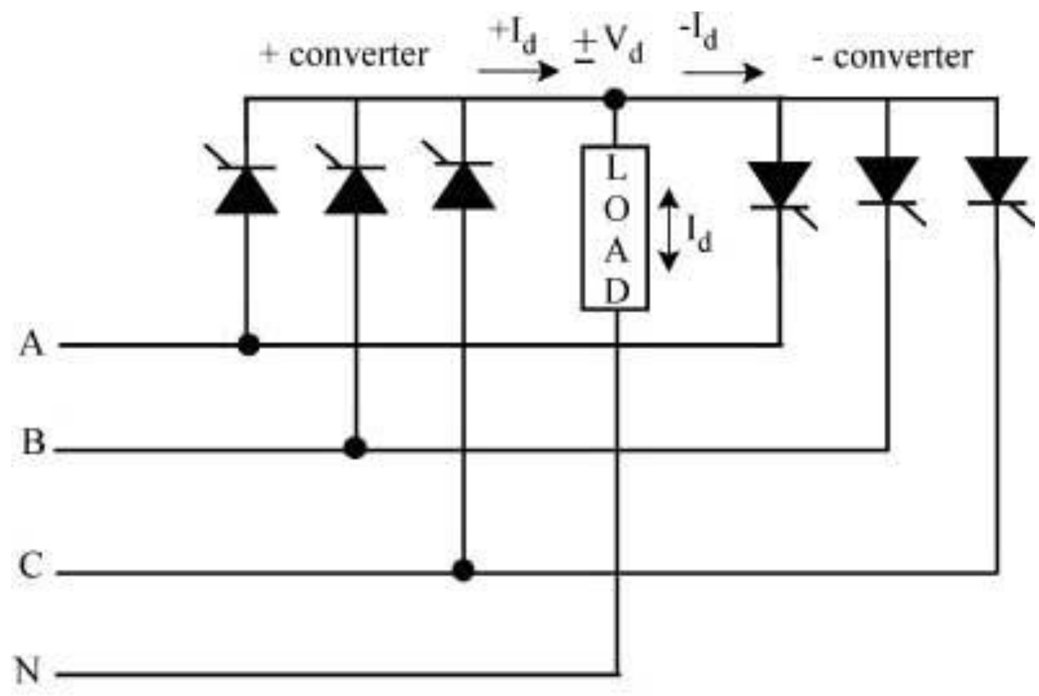


Fig. 4 3ϕ-1ϕ half-wave cycloconverter

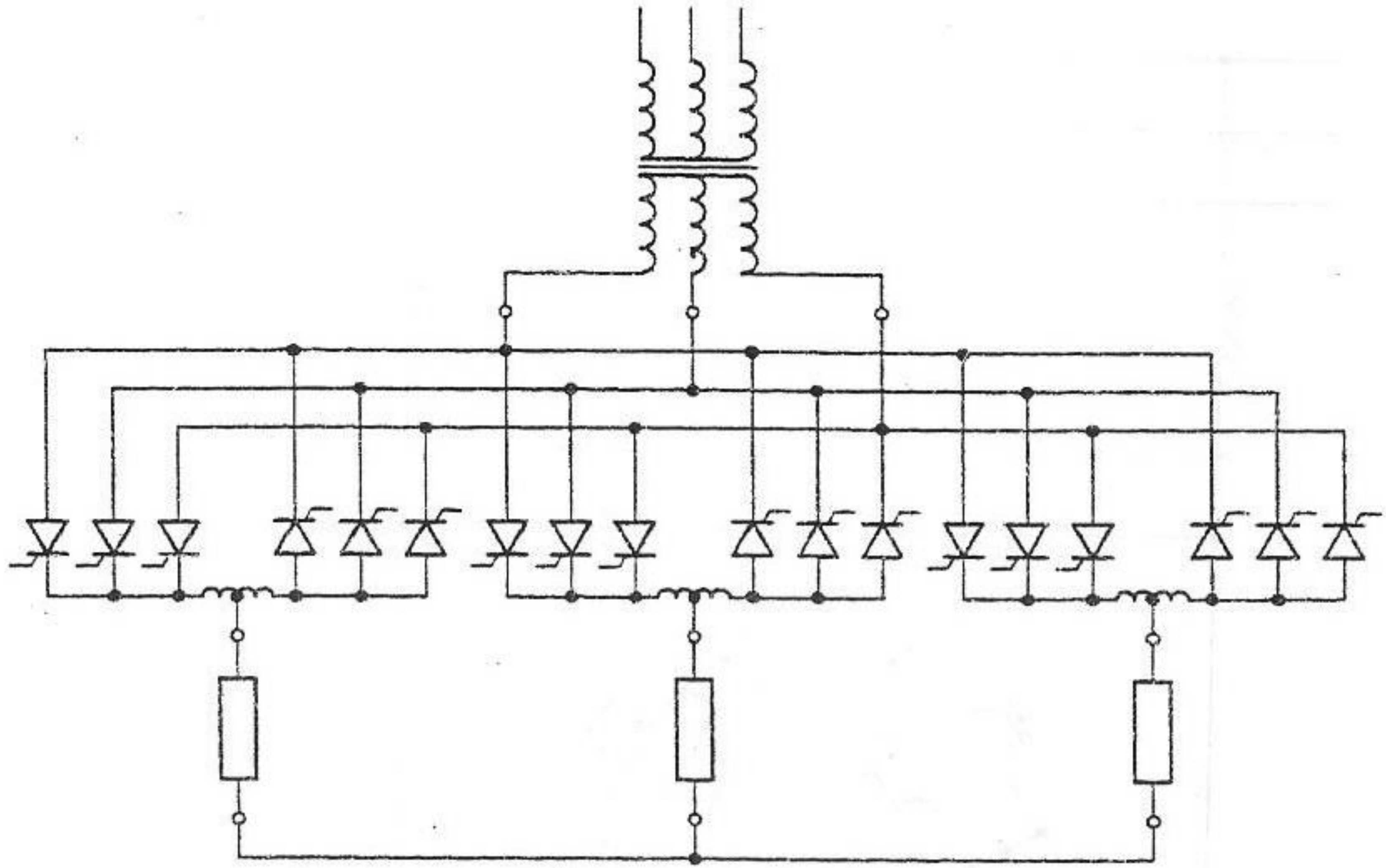
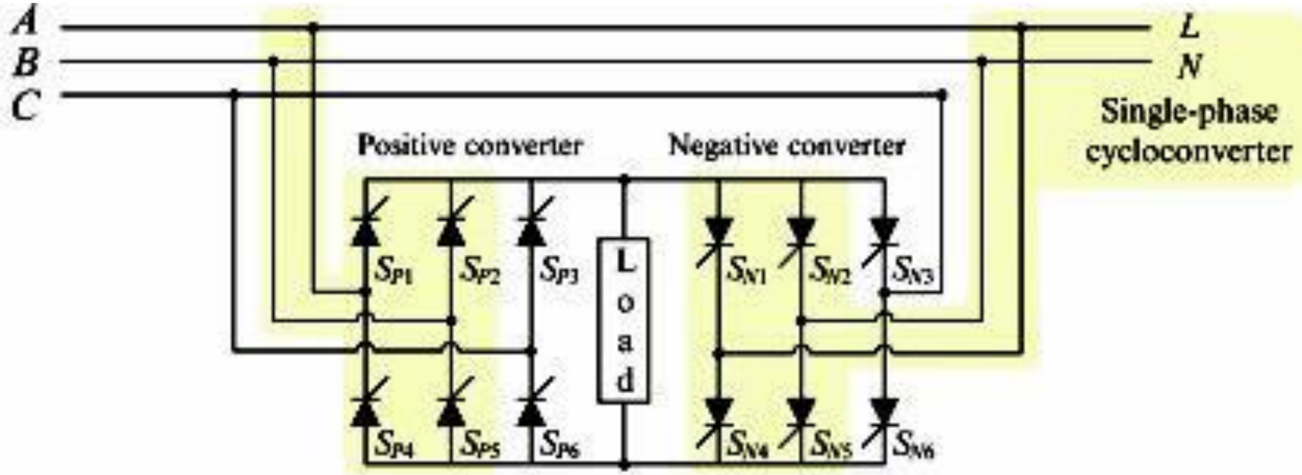
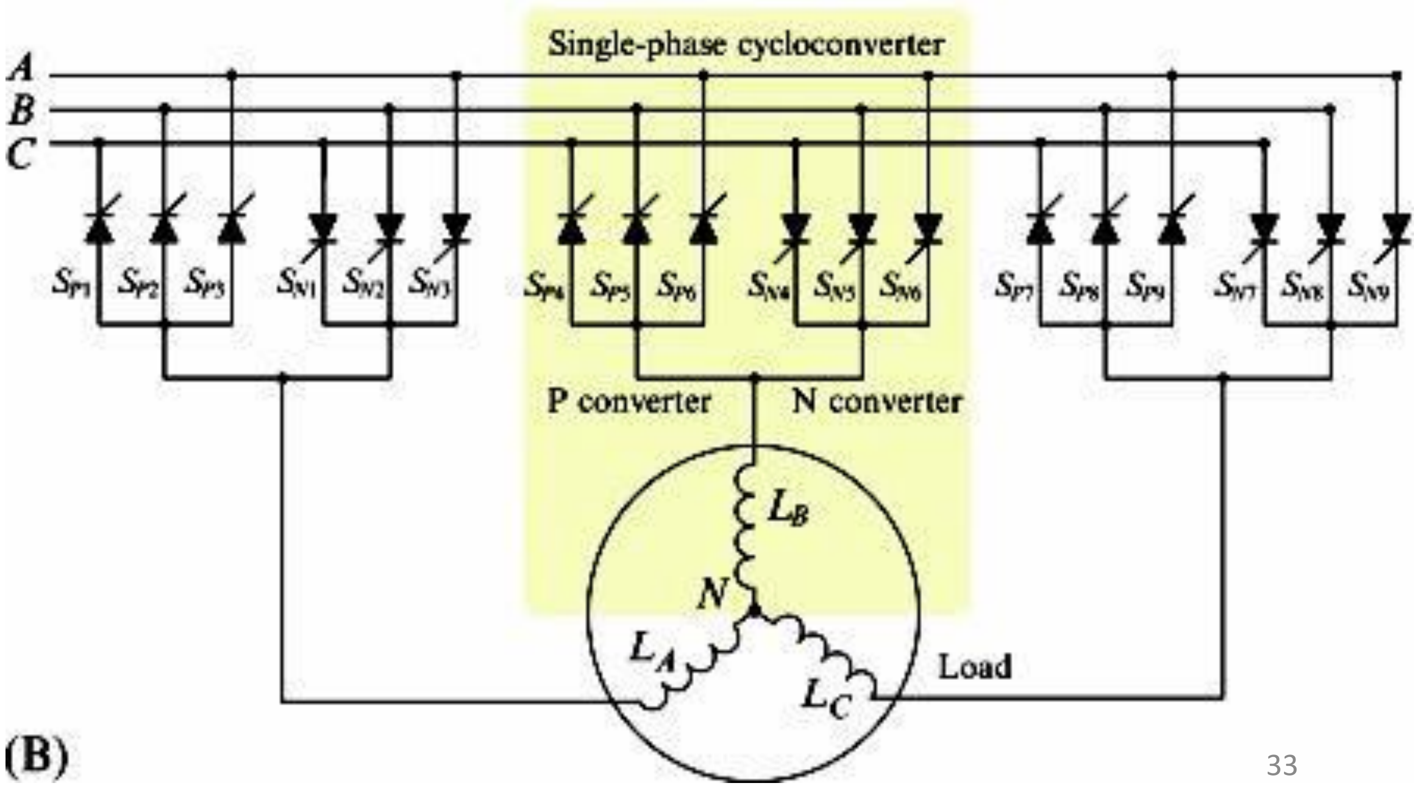


Figure 5.24 Three-phase three-pulse cycloconverter.


A
B
C
L
N
Single-phase cycloconverter
Positive converter
Negative converter
Load
S_{P1} S_{P2} S_{P3} S_{P4} S_{P5} S_{P6}
S_{N1} S_{N2} S_{N3} S_{N4} S_{N5} S_{N6}
(A)


Single-phase cycloconverter
A
B
C
S_{P1} S_{P2} S_{P3} S_{N1} S_{N2} S_{N3}
S_{P4} S_{P5} S_{P6} S_{N4} S_{N5} S_{N6}
S_{P7} S_{P8} S_{P9} S_{N7} S_{N8} S_{N9}
P converter
N converter
L_B
N
L_A
L_C
Load
(B)

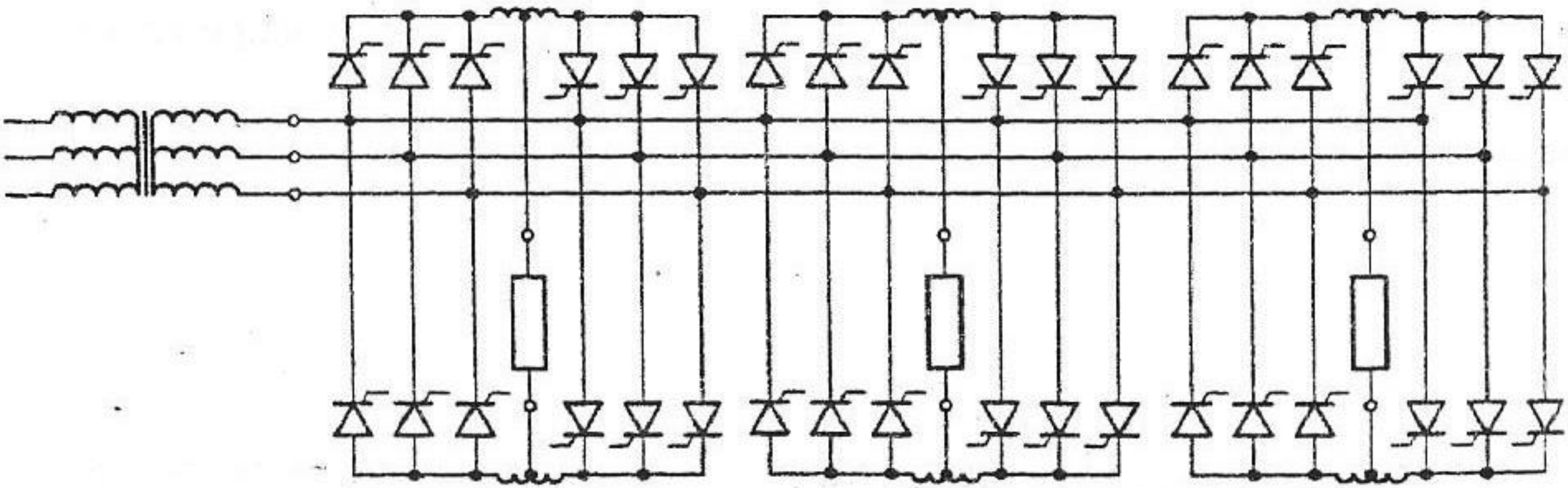


Figure 5.25 Three-phase six-pulse cycloconverter with isolated phase loads.

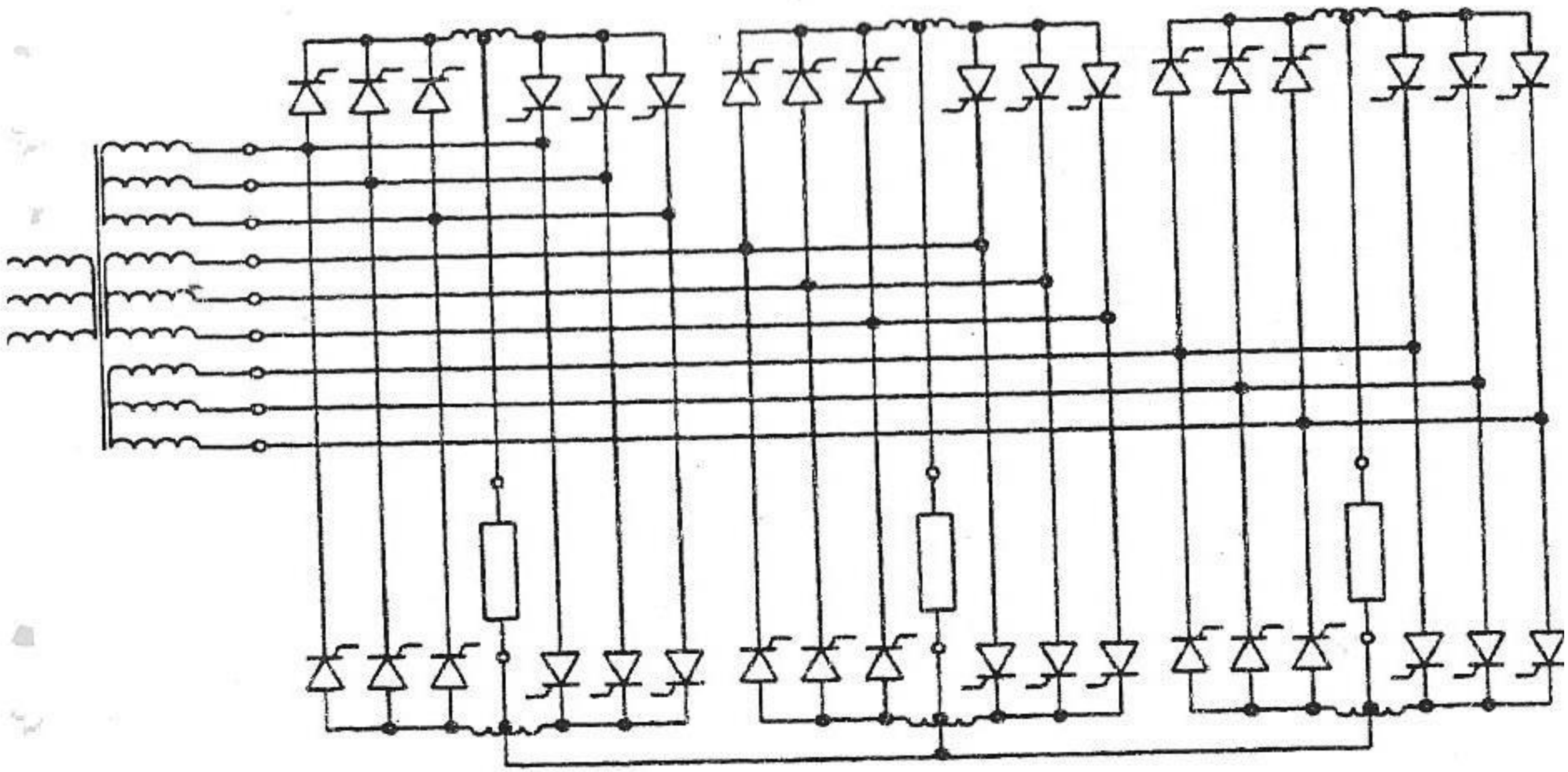
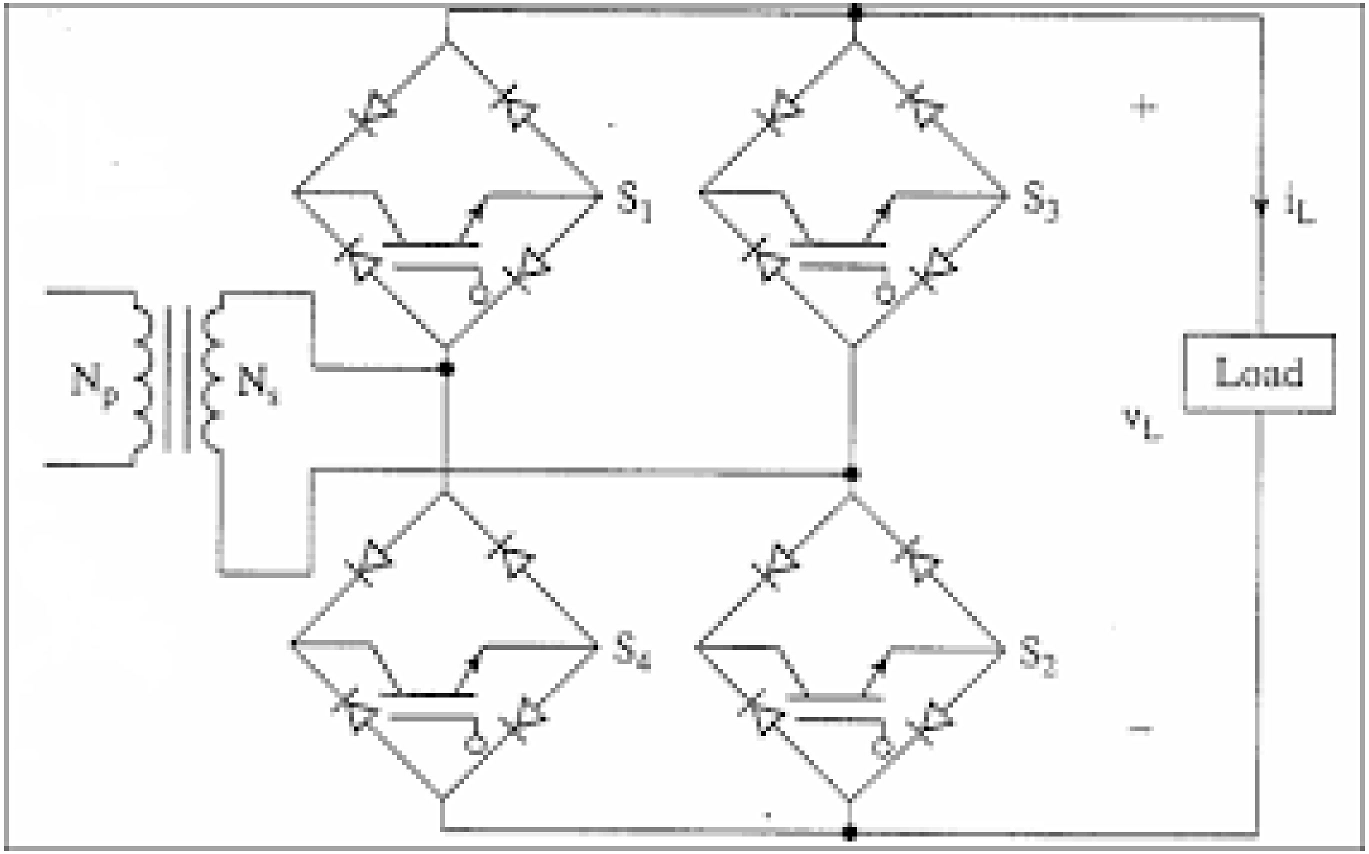


Figure 5.26 Three-phase six-pulse cycloconverter with interconnected phase loads.



S_1
S_3
S_4
S_2
N_p
N_s
Load
i_L
v_L
+
−

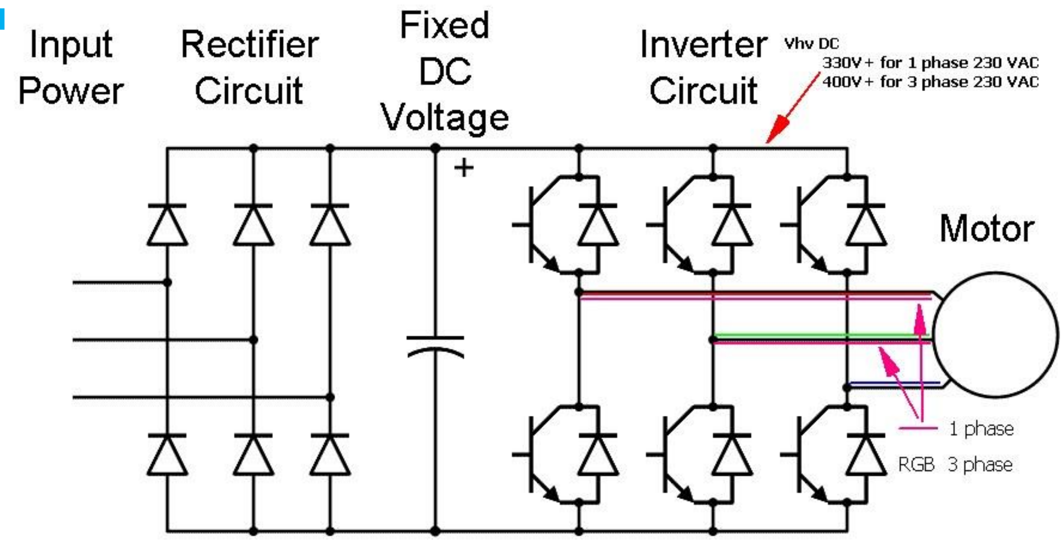
5.3 MATRIX CONVERTERS

The matrix converter has several advantages over traditional rectifier-inverter type power frequency converters. It provides sinusoidal input and output waveforms, with minimal higher order harmonics and no sub-harmonics; it has inherent bi-directional energy flow capability; the input power factor can be fully controlled. Last but not least, it has minimal energy storage requirements, which allows to get rid of bulky and lifetime-limited energy-storing capacitors

But the matrix converter has also some disadvantages. First of all it has a maximum input output voltage transfer ratio limited to approx 87 % for sinusoidal input and output waveforms. It requires more semiconductor devices than a conventional AC-AC indirect power frequency converter, since no monolithic bi-directional switches exist and consequently discrete unidirectional devices, variously arranged, have to be used for each bi-directional switch.

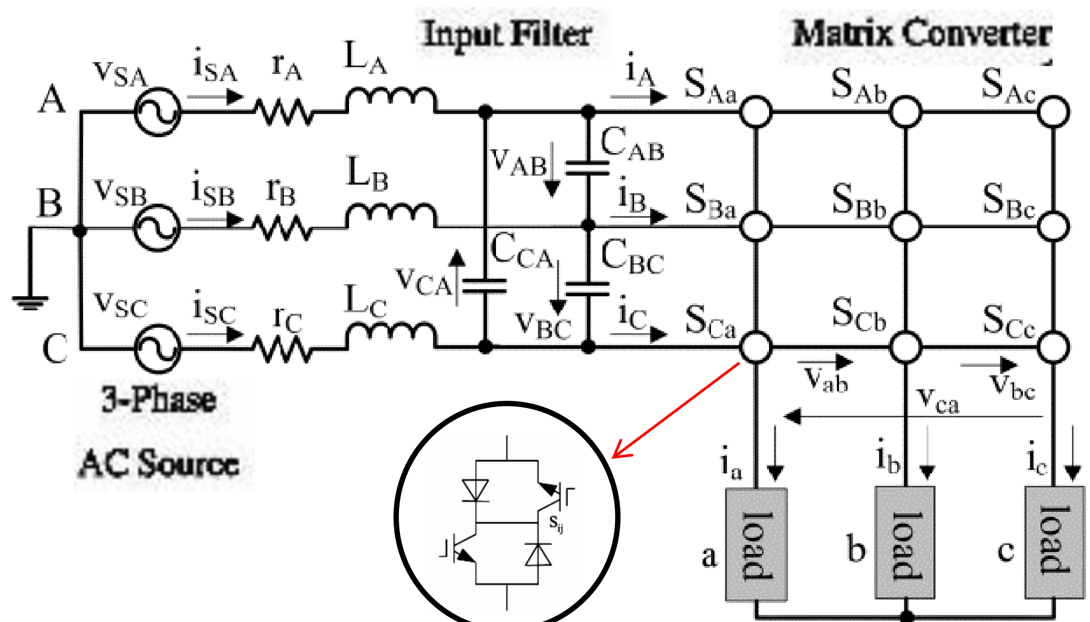
5.3 MATRIX CONVERTERS

Circuit Comparison



Traditional AC to DC to AC converter(inverter)

Three-Phase Matrix converter



5.3 MATRIX CONVERTERS

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} x_{Aa} & x_{Ba} & x_{Ca} \\ x_{Ab} & x_{Bb} & x_{Cb} \\ x_{Ac} & x_{Bc} & x_{Cc} \end{bmatrix} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix}$$

$$v_n = \frac{1}{3}(v_a + v_b + v_c).$$

line-to-neutral output voltages, v_{an}, v_{bn}, and v_{cn}, can be expressed

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix}$$

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} x_{Aa} & x_{Ab} & x_{Ac} \\ x_{Ba} & x_{Bb} & x_{Ab} \\ x_{Ca} & x_{Cb} & x_{Cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

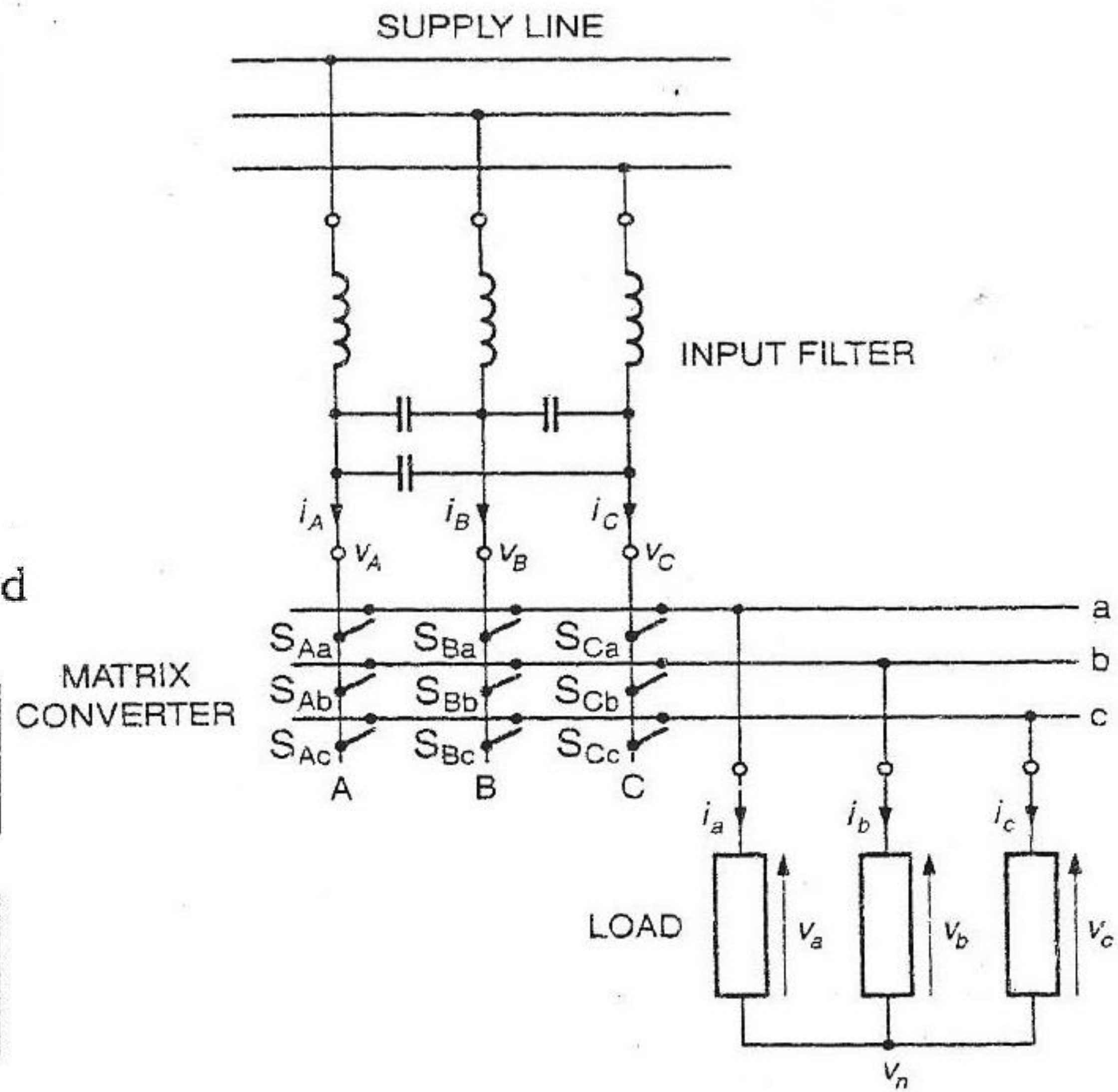


Figure 5.27 Three-phase to three-phase (3Φ–3Φ) matrix converter.

5.3 MATRIX CONVERTERS

TABLE 5.1 Switching Pattern for 3Φ–3Φ Matrix Converter with Space Vector PWM

Switching Subcycle	Rectifier State	Inverter State	t_n / T_{sw}
1	X_I	X_V	$d_{XI} d_{XV}/2$
2	X_I	Y_V	$d_{XI} d_{YV}/2$
3	Y_I	Y_V	$d_{YI} d_{YV}/2$
4	Y_I	X_V	$d_{YI} d_{XV}/2$
5	Z_I	Z_V	$1 - (d_{XI} + d_{YI})(d_{XV} + d_{YV})$
6	Y_I	X_V	$d_{YI} d_{XV}/2$
7	Y_I	Y_V	$d_{YI} d_{YV}/2$
8	X_I	Y_V	$d_{XI} d_{YV}/2$
9	X_I	X_V	$d_{XI} d_{XV}/2$

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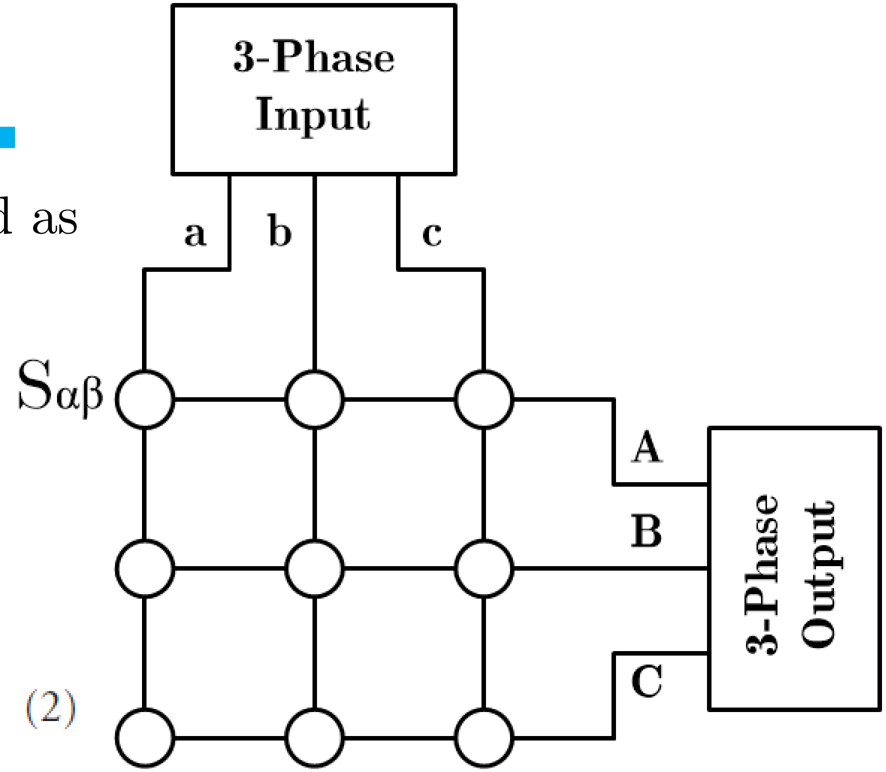
The switch function, Sαβ, can be defined as

$$S_{\alpha\beta} = \begin{cases} 0 & S_{\alpha\beta} : \text{open}, \\ 1 & S_{\alpha\beta} : \text{close}, \end{cases} \qquad (1)$$

$$\alpha \in \{a, b, c\}, \ \beta \in \{A, B, C\}.$$



The restriction is expressed as

$$S_{a\beta} + S_{b\beta} + S_{c\beta} = 1. \qquad (2)$$

The output voltages and input currents of the matrix converter can be represented by the switching function S and the transposed S^T, such as

$$[V_{\text{out}}] = [S] \times [V_{\text{in}}],$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{12} & S_{22} & S_{32} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix},$$

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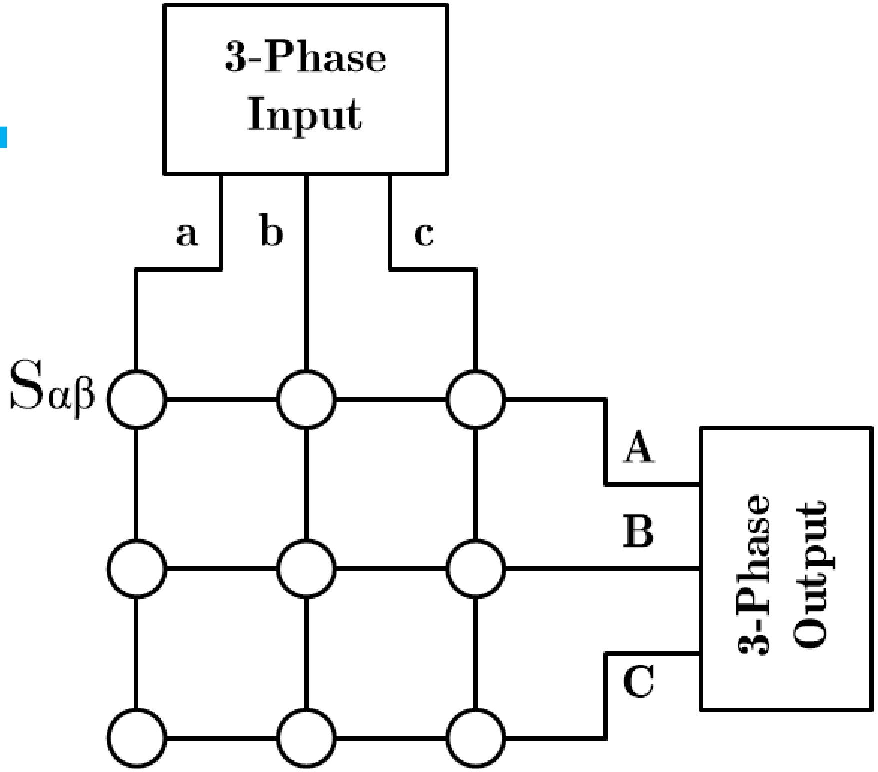

$$[I_{\text{in}}] = \left[S^T\right] \times [I_{\text{out}}],$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} . \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix},$$

where V_a, V_b, and V_c are input phase voltages; V_A, V_B and V_C are output phase voltages; I_a, I_b, and I_c are input currents; I_A, I_B, and I_C are output currents.

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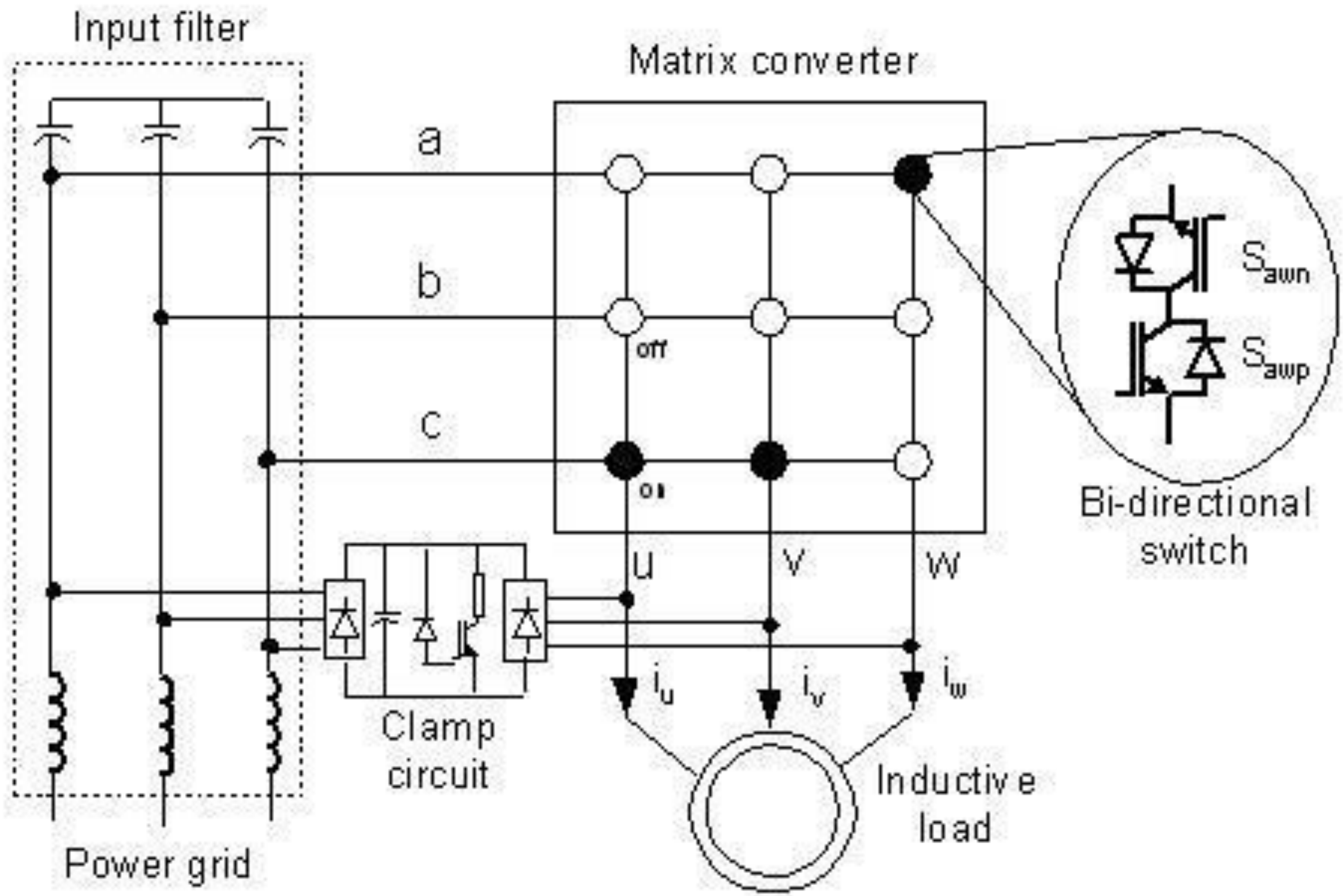

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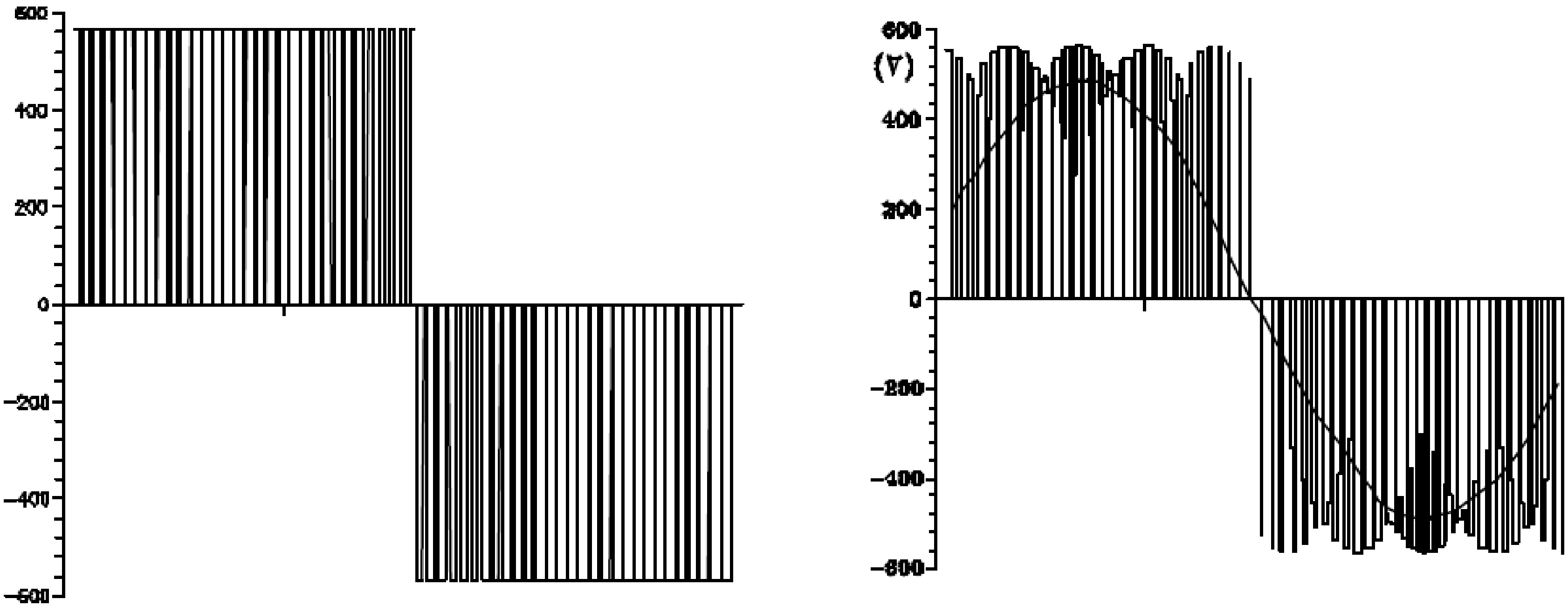

a) VSI

b) Matrix converter

Fig.2.2 Output voltage waveforms generated by a VSI and a matrix converter

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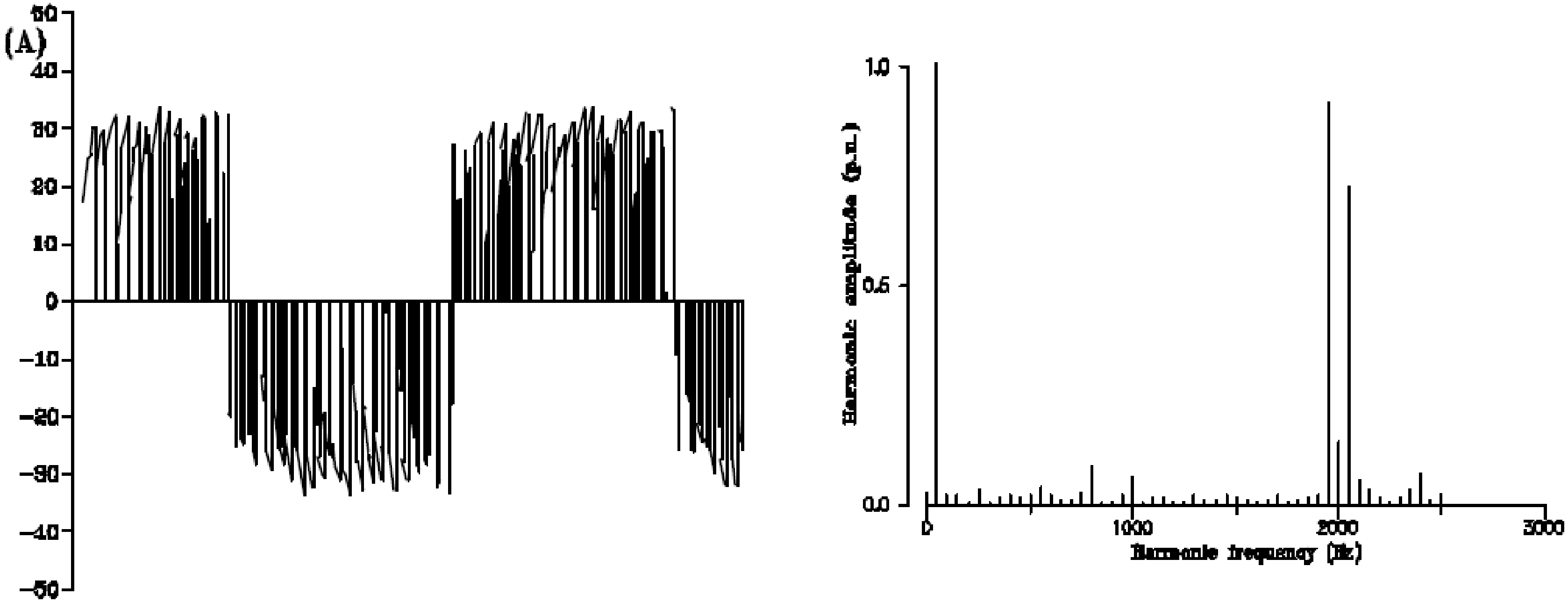

Fig.2.3 Matrix converter input current and harmonic spectrum. Switching frequency 2kHz.

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The input power factor control

The input power factor control capability is another attractive feature of matrix converters, which holds for most of the control algorithms proposed in literature [2], [3], [8]-[11]. Despite of this common capability it is worth noting that a basic difference exists with respect to the load displacement angle dependency.

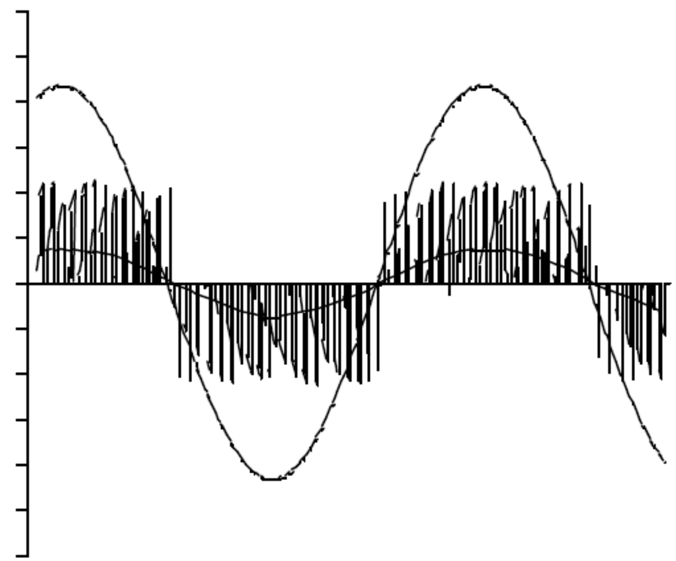

Fig.2.4 Matrix converter input line-to-neutral voltage, instantaneous input current and its average value. Switching frequency 2kHz.

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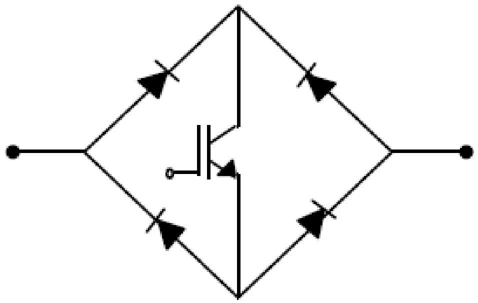
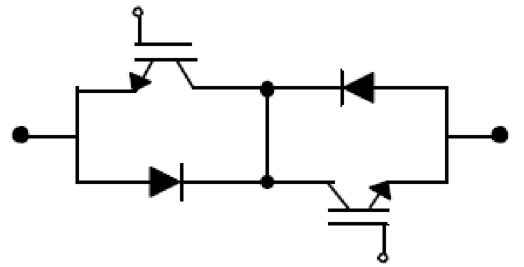
Implementation of the Matrix Converter

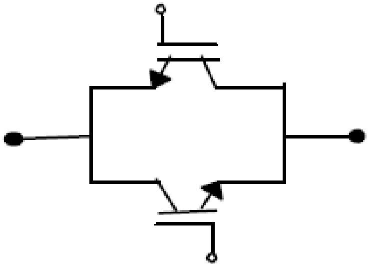
The bi-directional switch realization and commutation



a) Diode bridge with a single IGBT



b) Two anti-paralleled IGBT with series diodes



c) Two anti-paralleled NPT-IGBT's with reverse blocking capability

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