THREE PHASE LINE COMMUTATED CONVERTER

Introduction

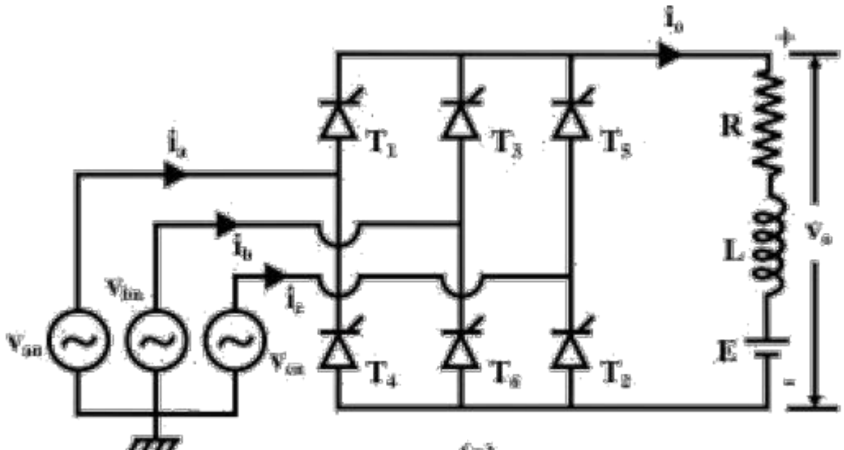
The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable out put dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called “phase controlled converters”. Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the “inverting mode”. The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as “Line commutated converter”. The same circuit while operating in the inverter mode requires load side counter emf. for commutation and are referred to as the “Load commutated inverter”.

In phase controlled rectifiers though the output voltage can be varied continuously the load harmonic voltage increases considerably as the average value goes down. Of course the magnitude of harmonic voltage is lower in three phase converter compared to the single phase circuit. Since the frequency of the harmonic voltage is higher smaller load inductance leads to continuous conduction. Input current wave shape become rectangular and contain 5th and higher order odd harmonics. The displacement angle of the input current increases with firing angle. The frequency of the harmonic voltage and current can be increased by increasing the pulse number of the converter which can be achieved by series and parallel connection of basic 6 pulse converters. The control circuit become considerably complicated and the use of coupling transformer and / or interphase reactors become mandatory.

With the introduction of high power IGBTs the three phase bridge converter has all but been replaced by dc link voltage source converters in the medium to moderately high power range. However in very high power application (such as HV dc transmission system, cycloconverter drives, load commutated inverter synchronous motor drives, static scherbius drives etc.) the basic B phase bridge converter block is still used. In this lesson the operating principle and characteristic of this very important converter topology will be discussed in source depth.

Operating principle of 3 phase fully controlled bridge converter

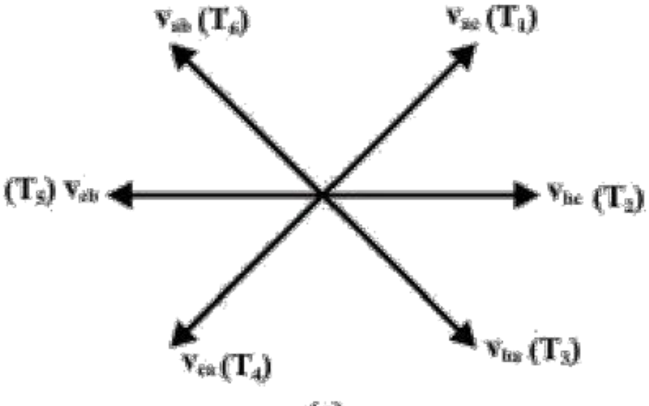
A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Fig. 13.1 (a)



(a)

Device / Mode	v_{T1}	v_{T2}	v_{T3}	v_{T4}	v_{T5}	v_{T6}	v_o
T_1T_2	0	0	v_{ba}	v_{ca}	v_{ca}	v_{cb}	v_{ac}
T_2T_3	v_{ab}	0	0	v_{ca}	v_{cb}	v_{cb}	v_{bc}
T_3T_4	v_{ab}	v_{ac}	0	0	v_{cb}	v_{ab}	v_{ba}
T_4T_5	v_{ac}	v_{ac}	v_{bc}	0	0	v_{ab}	v_{ca}
T_5T_6	v_{ac}	v_{bc}	v_{bc}	v_{ba}	0	0	v_{cb}
T_6T_1	0	v_{bc}	v_{ba}	v_{ba}	v_{ca}	0	v_{ab}
NONE	-	-	-	-	-	-	E

(b)



(c)

Fig. 13.1: operation of a three phase full controlled bridge converter
(a) circuit diagram,
(b) conduction table,
(c) phaser diagram of line voltages.

For any current to flow in the load at least one device from the top group (T_1, T_3, T_5) and one from the bottom group (T_2, T_4, T_6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct.

Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence $T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \rightarrow T_5 \rightarrow T_6 \rightarrow T_1$ with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence can not conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T_1T_2, T_2T_3, T_3T_4, T_4T_5, T_5T_6, T_6T_1. Each conduction mode is of 60° duration and appears in the sequence mentioned. The conduction table of Fig. 13.1 (b) shows voltage across different devices and the dc output voltage for each conduction interval. The phasor diagram of the line voltages appear in Fig. 13.1 (c). Each of these line voltages can be associated with the firing of a thyristor with the help of the conduction table-1. For example the thyristor T_1 is fired at the end of T_5 T_6 conduction interval. During this period the voltage across T_1 was v_{ac}. Therefore T_1 is fired α angle after the positive going zero crossing of v_{ac}. Similar observation can be made about other thyristors. The phasor diagram of Fig. 13.1 (c) also confirms that all the thyristors are fired in the correct sequence with 60° interval between each firing.

Fig. 13.2 shows the waveforms of different variables (shown in Fig. 13.1 (a)). To arrive at the waveforms it is necessary to draw the conduction diagram which shows the interval of conduction for each thyristor and can be drawn with the help of the phasor diagram of fig. 13.1 (c). If the converter firing angle is α each thyristor is fired "α" angle after the positive going zero crossing of the line voltage with which it's firing is associated. Once the conduction diagram is drawn all other voltage waveforms can be drawn from the line voltage waveforms and from the conduction table of fig. 13.1 (b). Similarly line currents can be drawn from the output current and the conduction diagram. It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore this converter is also called the "six pulse" converter. The input current on the other hand contains only odds harmonics of the input frequency other than the triplex (3^{rd}, 9^{th} etc.) harmonics. The next section will analyze the operation of this converter in more details.

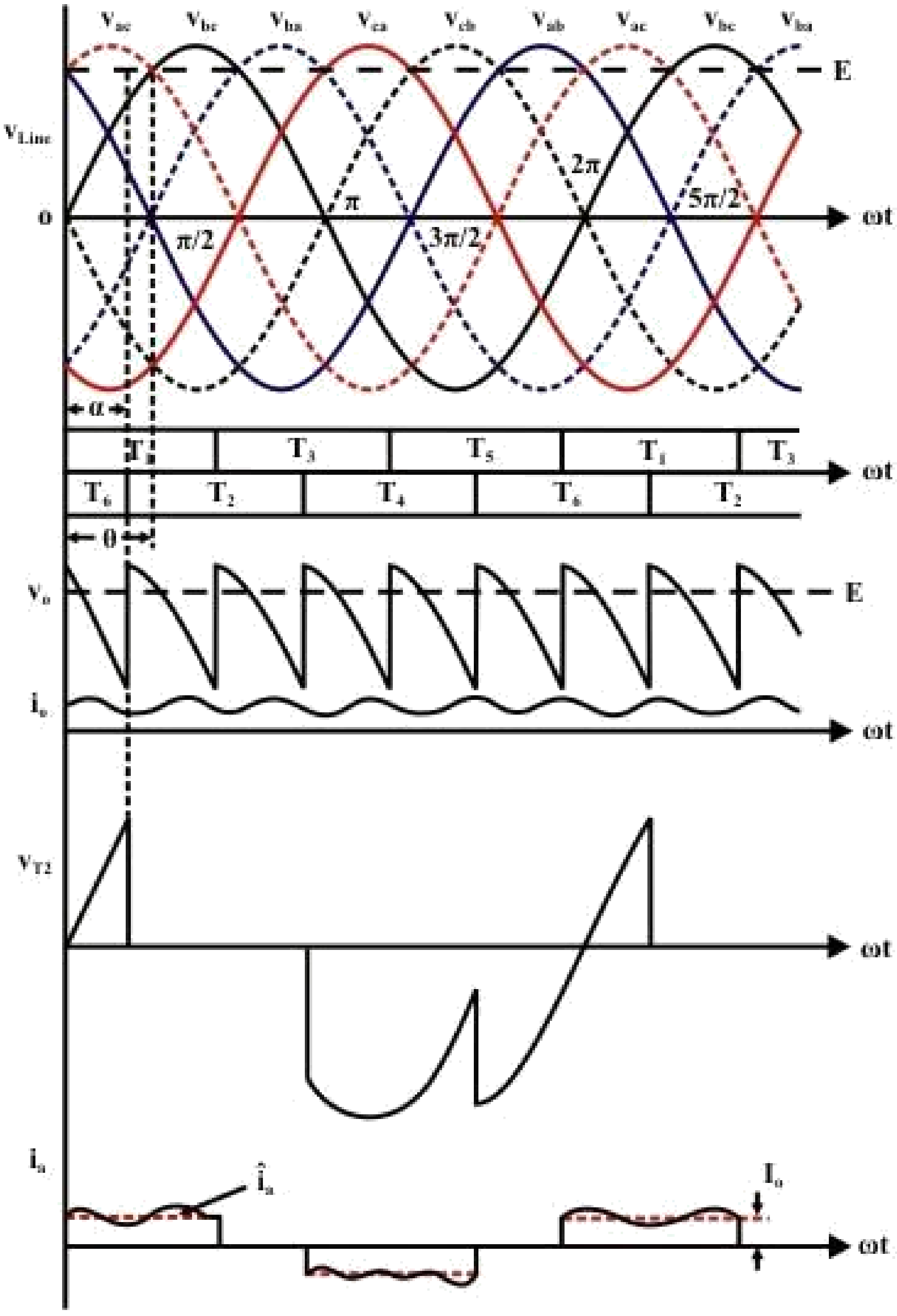


Fig. 13.2: Waveforms of three phase fully controlled converter 13.2.1 Analysis of the converter in the rectifier mode.

Analysis of the converter in the rectifier mode

The output voltage waveform can be written as

The input phase current i_a is expressed as

$$i_a = i_0 \qquad \alpha \le \omega t \le \alpha + \frac{\pi}{3}$$

$$i_a = -i_0 \qquad \alpha + \frac{2\pi}{3} \le \omega t \le \alpha + \frac{4\pi}{3}$$

$$i_a = i_0 \qquad \alpha + \frac{5\pi}{3} \le \omega t \le \alpha + 2\pi$$

$$i_a = 0 \qquad \text{otherwise}$$

From Fig. 13.2 it can be observed that i_0 itself has a ripple at a frequency six times the input frequency. The closed from expression of i_0, as will be seen later is some what complicated. However, considerable simplification in the expression of i_a can be obtained if i_0 is replaced by its average value I_0. This approximation will be valid provided the ripple on i_0 is small, i.e, the load is highly inductive. The modified input current waveform will then be i_a which can be expressed in terms of a fourier series as

To find out the condition for continuous conduction it is noted that in the limiting case of continuous conduction.

$i_0\big|_{\min} = 0$, Now if $\theta \le \alpha + \frac{\pi}{3}$ then i_0 is minimum at $\omega t = \alpha$. ∴ Condition for continuous conduction is $i_0\big|_{\omega t = \alpha} \ge 0$. However discontinuous conduction is rare in these conversions and will not be discussed any further.

Analysis of the converter in the inverting mode.

In all the analysis presented so far it has been assumed that $\alpha < 90°$. It follows from equation 13.2 that the output dc voltage will be positive in this case and power will be flowing from the three phase ac side to the dc side. This is the rectifier mode of operation of the converter. However if α is made larger than 90° the direction of power flow through the converter will reverse provided there exists a power source in the dc side of suitable polarity. The converter in that case is said to be operating in the inverter mode. It has been explained in connection with single phase converters that the polarity of EMF source on the dc side [Fig. 13.1(a)] would have to be reversed for inverter mode of operator. Fig. 13.3 shows the circuit connection and wave forms in the inverting mode of operation where the load current has been assumed to be continuous and ripple free.

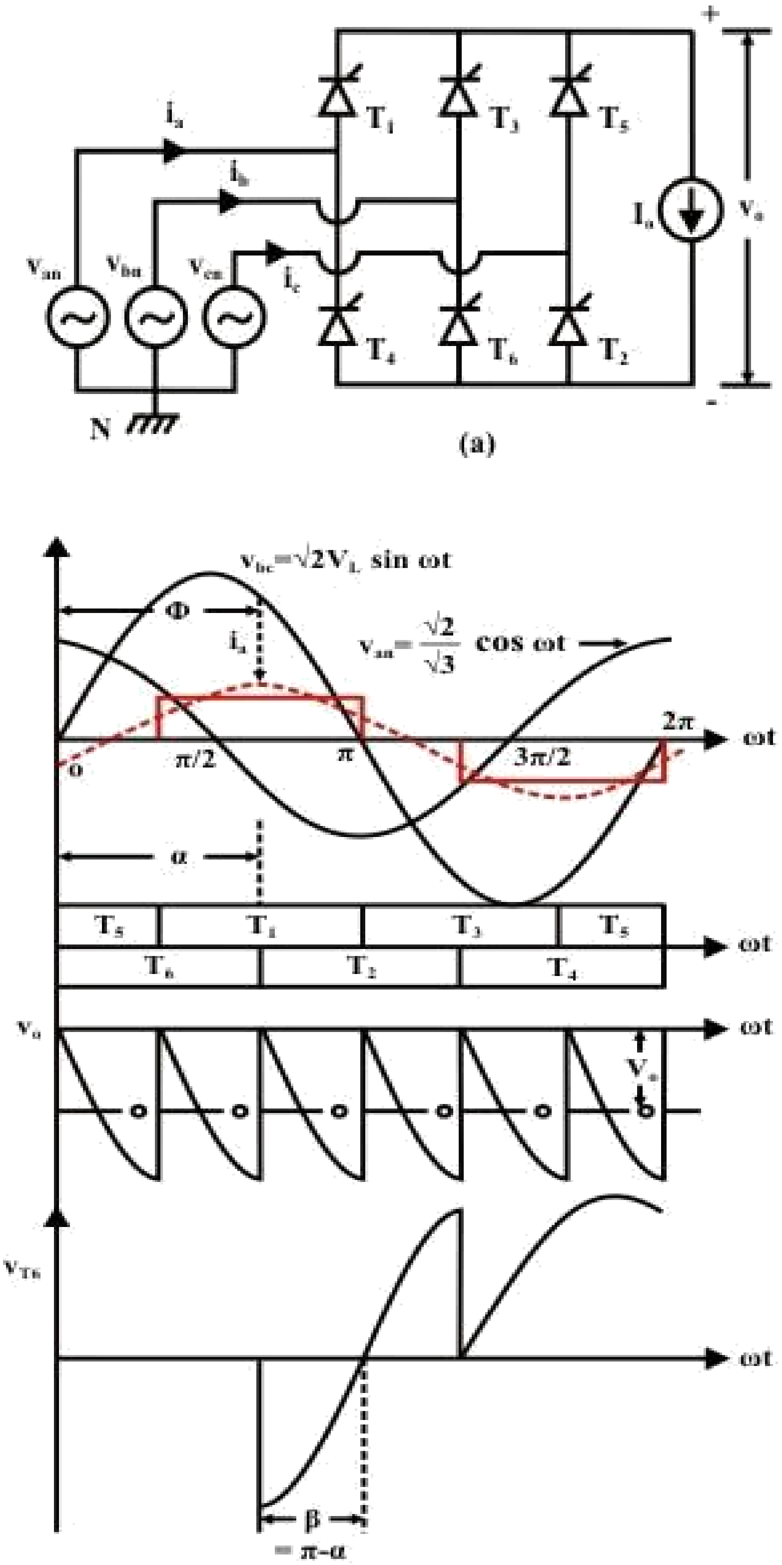


Fig. 13.3(b): Inverter mode of operation of the three phase fully controlled bridge converter
(a) circuit diagram
(b) waveforms.

Analysis of the converter in the inverting mode is similar to its rectifier mode of operation. The same expressions hold for the dc and harmonic compounds in the output voltage and current. The input supply current Fourier series is also identical to Equation 13.8. In particular

$$V_0 = \frac{32}{\pi} V_L \cos\alpha \qquad (13.24)$$

$$i_{a1} = \frac{23}{\pi} I_0 \cos(\omega t - \alpha) \qquad (13.25)$$

For values of α in the range 90° < α < 180° it is observed from Fig. 13.3(b) that the average dc voltage is negative and the displacement angle φ of the fundamental component of the input ac line current is equal to α > 90°. Therefore, power in the ac side flows from the converter to the source.

It is observed form Fig. 13.3(b) that an outgoing thyristor (thyristor T_6 in Fig. 13.3(b)) after commutation is impressed with a negative voltage of duration $\beta = \pi - \alpha$. For successful commutation of the outgoing thyristor it is essential that this interval is larger than the turn off time of the thyristor i.e,

$\beta \geq \omega t_q$, tq is the thyristor turn off time

Therefore $\pi - \alpha \geq \omega t_q$ or $\alpha \leq \pi - \omega t_q$.

Which imposes an upper limit on the value of α. In practice this upper value of α is further reduced due to commutation overlap.

Higher pulse number converters and dual converter

The three phase fully controlled converter is widely used in the medium to moderately high power applications. However in very large power applications (such as HV DC transmission systems) the device ratings become impractically large. Also the relatively low frequency (6th in the dc side, 5th and 7th in the ac side) harmonic voltages and currents produced by this converter become unacceptable. Therefore several such converters are connected in series parallel combination in order to increase the voltage / current rating of the resulting converter. Furthermore if the component converters are controlled properly some lower order harmonics can be eliminated both from the input and output resulting in a higher pulse converter.

Fig. 13.4(a) schematically represents series connection of two six pulse converters where as Fig. 13.4(b) can be considered to be a parallel connection. The inductance in between the converters has been included to limit circulating harmonic current. In both these figures CONV – I and CONV – II have identical construction and are also fired at the same firing angle α. Their input supplies also have same magnitude but displaced in phase by an angle φ. Then one can write

Now if cos 3Kφ = 0 for some K then the corresponding harmonic disappear from the fourier series expression of v_0.

In particular if φ = 30° then cos 3Kφ = 0 for K = 1, 2, 3, 5…….
This phase difference can be obtained by the arrangement shown in Fig.

13.4(c). Then

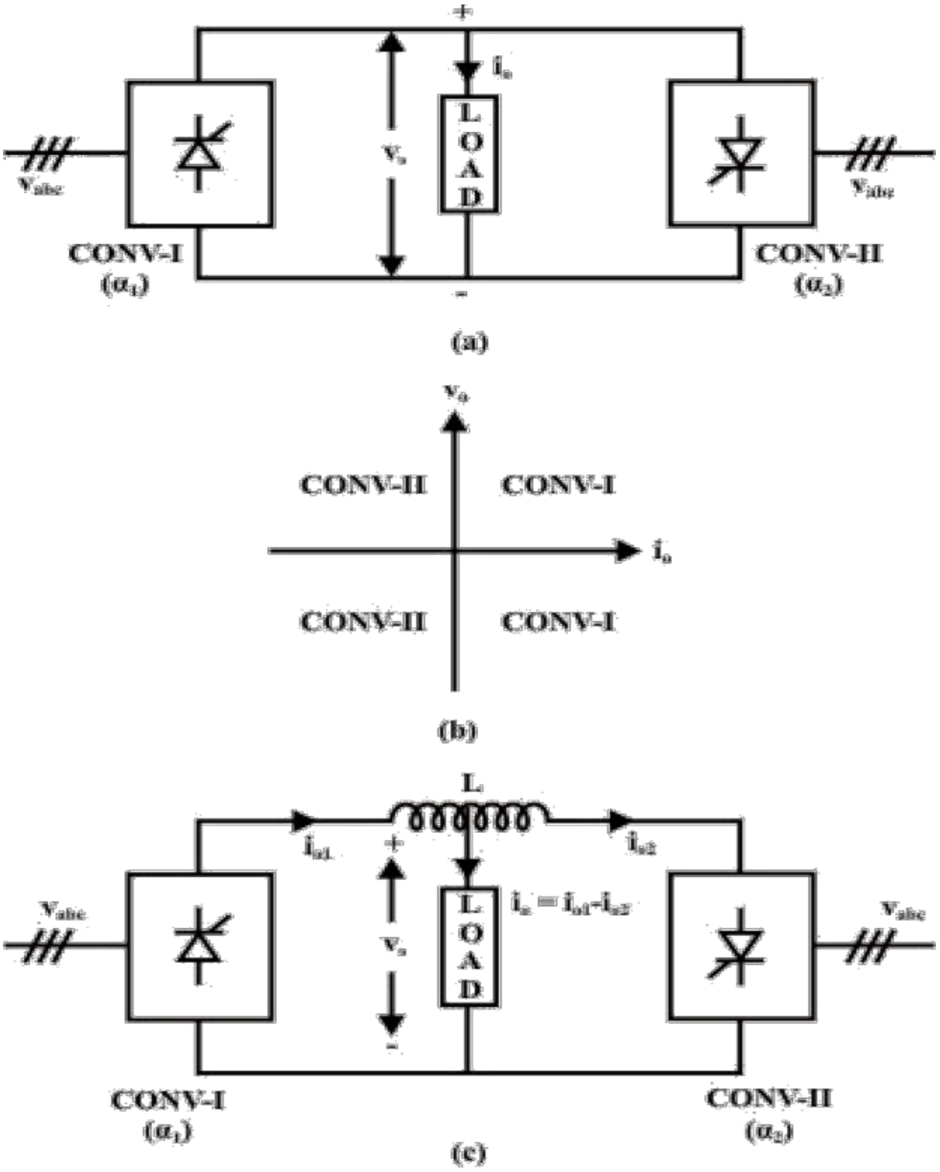
It can be seen that the frequency of the harmonics present in the output voltage has the
form 12ω, 24ω, 36ω ………..

Similarly it can be shown that the input side line current i_{ABC} have harmonic frequency of the form
11ω, 13ω, 23ω, 25ω, 35ω, 37ω, ………….

Which is the characteristic of a 12 pulse converter.

In a similar manner more number of 3 phase 6 pulse converters can be connected in series / parallel and the φ angle can be adjusted to obtain 18 and 24 pulse converters.

One of the shortcomings of a three phase fully controlled converter is that although it can produce both positive and negative voltage it can not supply current in both directions. However, some applications such as a four quadrant dc motor drive require this capability from the dc source. This problem is easily mitigated by connecting another three phase fully controlled converter in anti parallel as shown in Fig. 13.5 (a). In this figure converter -I supplies positive load current while converter-II supplies negative load current. In other words converter-I operates in the first and fourth quadrant of the output v – i plane whereas converter-II operates in the third and fourth quadrant. Thus the two converters taken together can operate in all four quadrants and is capable of supplying a four quadrant dc motor drive. The combined converter is called the Dual converter.



(a)

(b)

(c)

Fig. 13.5: Dual converter circuits
(a) non circulating type
(b) output V-I plane
(c) circulating current type

Obviously since converter-I and converter-II are connected in antiparallel they must produce the same dc voltage. This requires that the firing angles of these two converters be related as

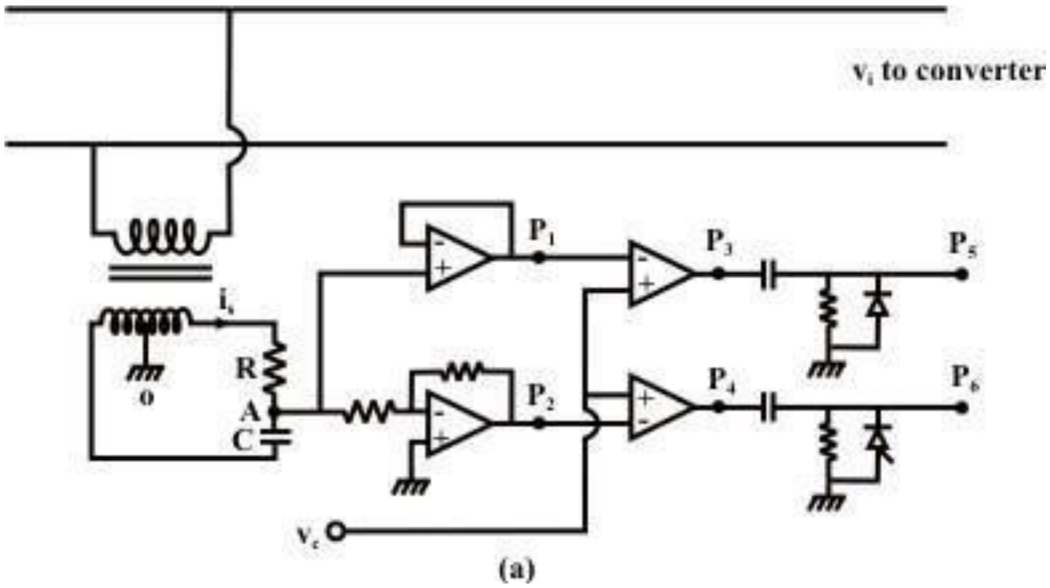
$$\alpha_2 = \pi - \alpha_1 \qquad (13.30)$$

Although Equations 13.30 ensures that the dc voltages produced by these converters are equal the output voltages do not match on an instantaneous basis. Therefore to avoid a direct short circuit between two different supply lines the two converters must never be gated simultaneously. Converter-I receives gate pulses when the load current is positive. Gate pulses to converter-II are blocked at that time. For negative load current converter-II thyristors are fired while converter-I gate pulses are blocked. Thus there is no circulating current flowing through the converters and therefore it is called the non-circulating current type dual converter. It requires precise sensing of the zero crossing of the output current which may pose a problem particularly at light load due to possible discontinuous conduction. To overcome this problem an interphase reactor may be incorporated between the two converters. With the interphase reactor in place both the converters can be gated simultaneously with $\alpha_2 = \pi - \alpha_1$. The resulting converter is called the circulating current type dual converter.

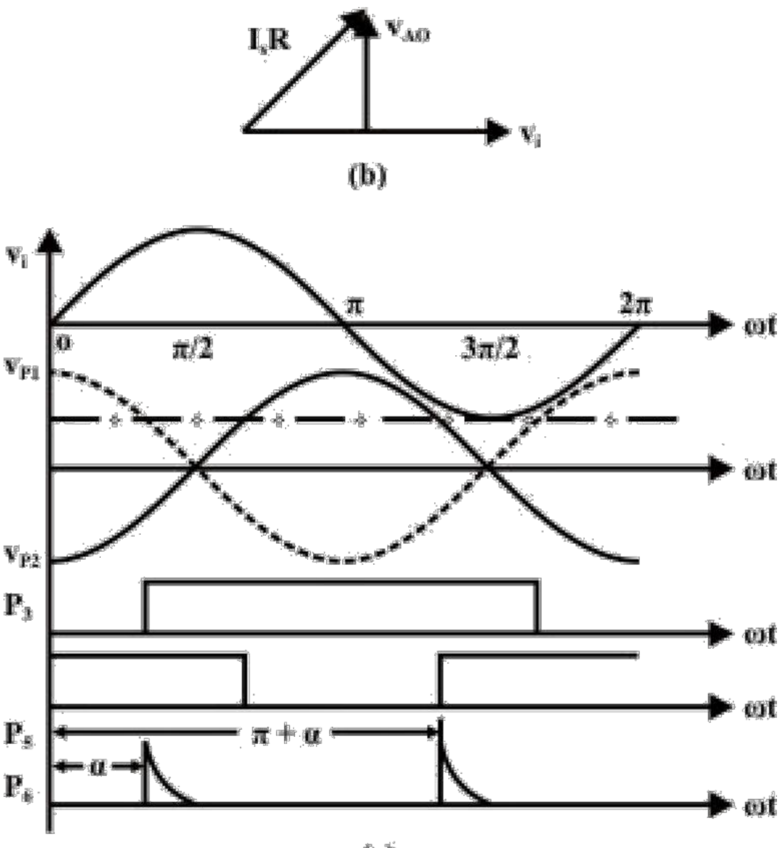
Gate Drive circuit for three phase fully controlled converter

Several schemes exist to generate gate drive pulses for single phase or three phase converters. In many application it is required that the output of the converter be proportional to a control voltage. This can be achieved as follows.

The following circuit can be used to generate "α" according to equation 13.32.



(a)



(b)

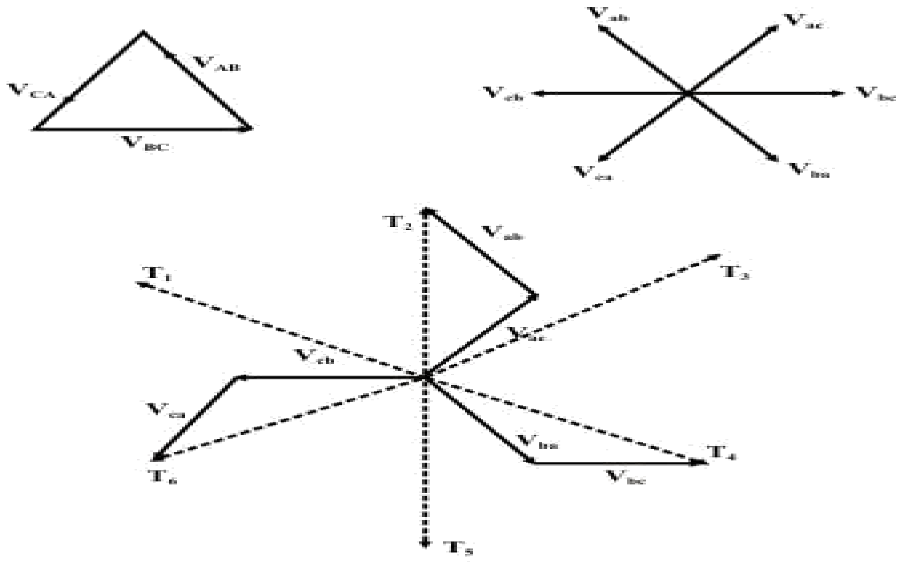
(c)

Fig. 13.6: Triggering circuit for single phase converter
(a) circuit diagram
(b) phasor diagram
(c) waveforms

In the circuit of Fig. 13.6(a) a phase shift network is used to obtain a waveform leading v_i by 90°. The phasor diagram of the phase shift circuit is shown in Fig. 13.6(b). The output of the phase shift waveform (and its inverse) is compared with v_c. The firing pulse is generated at the point when these two waveforms are equal. Obviously at-this instant

Therefore this method of generation of converter firing pulses is called "inverse cosine" control. The output of the phase shift network is called carrier waveform.

Similar technique can be used for three phase converters. However the phase shift network here consists of a three phase signal transformer with special connections as shown in Fig. 13.7.



(b)

Fig. 13.7: Carrier wave generation three phase converters
(a) Transformer connection
(b) phasor diagram.

The signal transformer uses three single phase transformer each of which has two secondary windings. The primary windings are connected in delta while the secondary windings are connected in zigzag. From Fig. 13.1 (c) T_2 is fired α angle after the positive going zero crossing of v_{bc}. Therefore, to implement inverse cosine the carrier wave for T_2 must lead v_{bc} by 90º. This waveform is obtained from zigzag connection of the winding segments a_1a_2 and c_1c_2 as shown in Fig. 13.7(a). The same figure also shows the zigzag connection for other phase. The voltage across each zigzag phase can be used to fire two thyristors belonging to the same phase leg using a circuit similar to Fig. 13.6 (a). The phase shift network will not be required in this case.