10

Cycloconverters

10.1 Introduction

SCRs are extensively used in AC to AC energy conversion in the fields of very high power applications *viz.*, traction, steel plant and other process plant drives. AC to AC converters take power from one ac system and deliver the power to another ac system with waveforms of different amplitude, frequency and or phase. The AC system can be single or polyphase depending upon the application. A *cycloconverter* is a converter used for conversion from AC to AC at different frequency level and consists of two thyristor converters connected back to back [Fig. 10.1(*a*)].

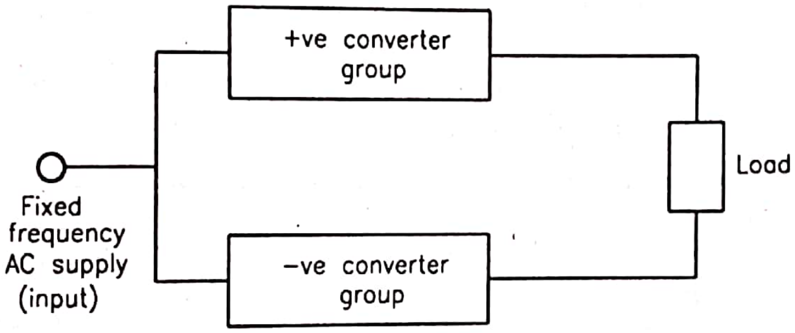

Fig. 10.1(*a*). Layout of Cycloconverter.

The waveform of the AC output across the load is shown in Fig. 10.1(*b*) [the load being assumed resistive type]

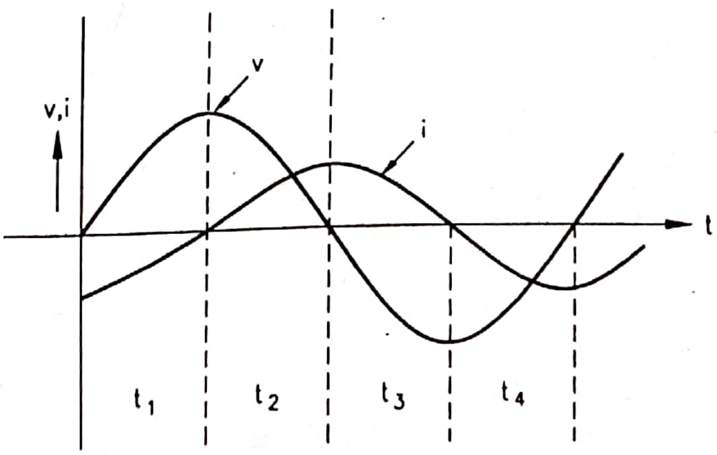

Fig. 10.1(*b*). Load voltage and current waveform.

t_1 = –ve converter group working (inverting)
t_2 = +ve converter group working (rectifying)
t_3 = + ve converter group working (inverting)
t_4 = –ve converter group working (rectifying).

The cycloconverter in Fig. 10.1(*a*) being a single input single output with a pure resistive load, the corresponding circuit diagram is shown in Fig. 10.2(*a*)

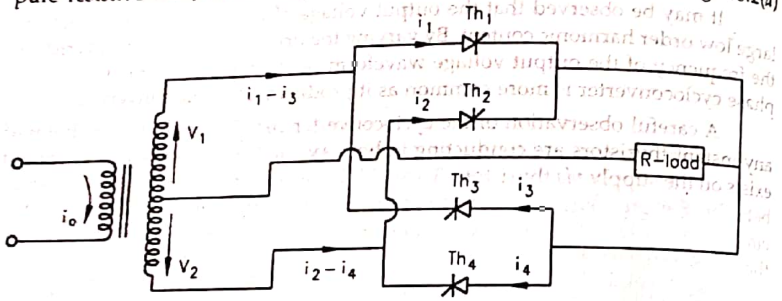

Fig. 10.2(*a*). Single phase cycloconverter : operation.

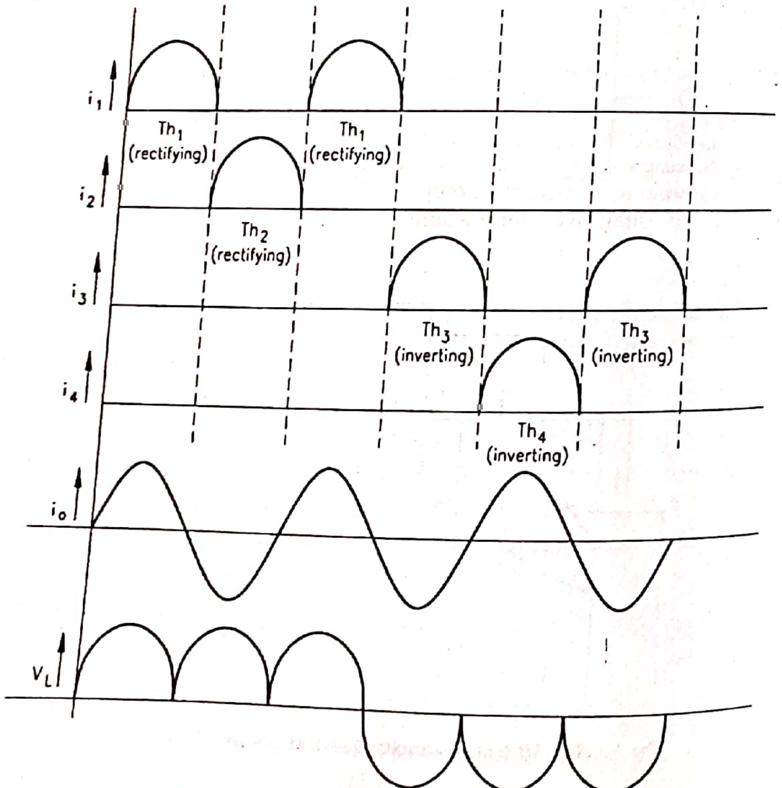

Fig. 10.2(*b*). Waveforms of thyristor currents and load voltage.

while the voltage and current waveforms are shown in Fig. 10.2(*b*) , the positive group of converters conduct for three half cycles while the negative group conducts for the next three half cycles.

The thyristors conduct with firing angle of 0° *i.e.*, like diodes. The output voltage wave has $\frac{1}{3}$rd frequency of the input (the load voltage magnitude being governed by the transformer turn ratio). The current from the supply (i_s) is a continuous sine wave.

It may be observed that the output voltage of the cycloconverter contains large low order harmonic content. By varying the firing sequence of the thyristors, the frequency of the output voltage waveform can be varied. In practice, a polyphase cycloconverter is more common as it produces a flexible converter.

A careful observation of the cycloconverter circuits would reveal that if at any instant thyristors are conducting in both +ve and –ve groups, a short circuit exists on the supply *via* thyristors. To avoid this problem, a reactor can be inserted between the groups in order to limit the circulating current (the firing control circuitry can also be arranged so that neither group is fired while current flows in the other group).

Phase delaying of the thyristors' conduction is also possible. The thyristors then do not conduct for its full period but for a limited period from the instant of firing. This phase controlled operation reduces the harmonic content of the load-voltage waveforms.

10.2 Three-phase Three-pulse Cycloconverter with Resistive Load

Fig. 10.3(*a*) represents a three phase three pulse cyclo-converter when positive group of converters are designated as *P* and negative group as *N*. The waveforms being shown in Fig. 10.3(*b*), the thyristors are fired at such angles as to follow the sine wave pattern at output (the fundamental wave). Since the load is resistive, the voltage waveform would contain zero period. Each group (positive

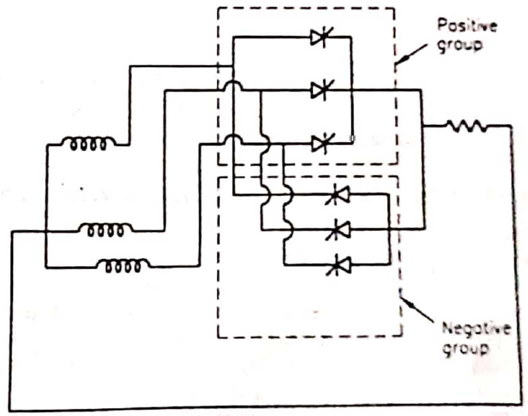

Fig. 10.3(*a*). Schematic of three phase three pulse cycloconverter.

or negative) of thyristors fire for the inputs of five half cycles. The output of the negative group differs in waveform to that of the positive group as the output wave in not composed of a whole number of input cycles (here one output cycle occupies just less than five input cycles). The current waveforms lead to unbalance in the supply.

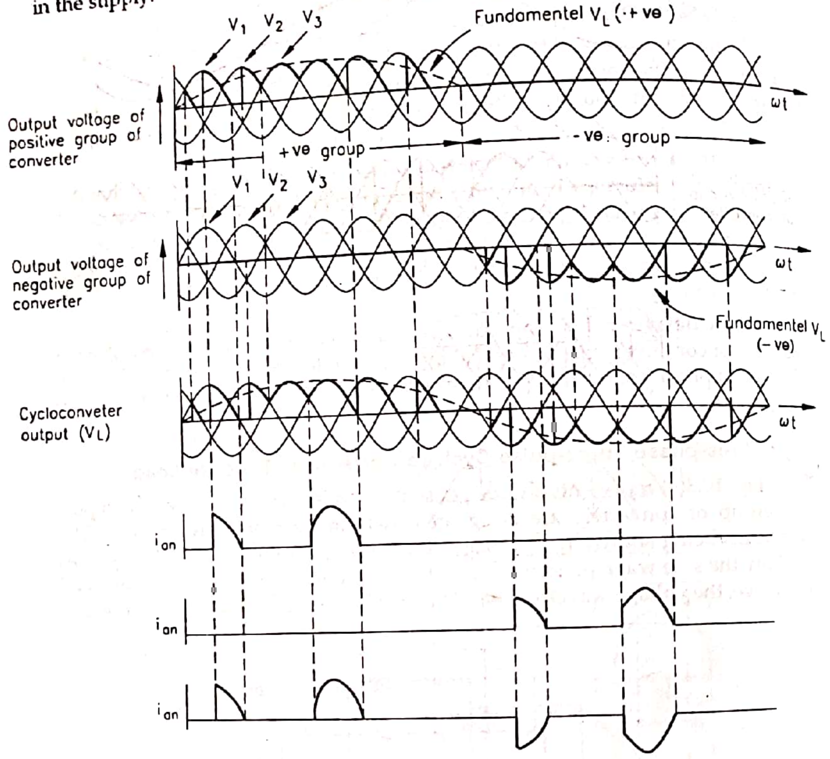

Fig. 10.3(*b*). Cycloconverter Outputs.

10.3 Operation of a three phase three pulse Cycloconverter with R-L Load

Assuming the load to be inductive, the output voltage waveforms and input phase current waveforms are shown in Fig. 10.4. The load current is lagging the voltage and as the direction of load current determines which group would conduct, the group *on-periods* are delayed relative to the desired output voltage. The thyristors in the groups are fired in such a way so that the output as close as possible to a sinewave is generated. The lagging load current takes each group into the inversion mode and the group will cease conduction when the load current reverses. Due to overlap, the current would likely to be continued (though the lower inductance in the load may render the load current discontinuous). The

input current waves are not sinusoidal and are heavily distorted, it even changes waves shape in every cycle (however, when the input and output frequencies are in exact multiple, the wave form will repeat over each period of output frequency).

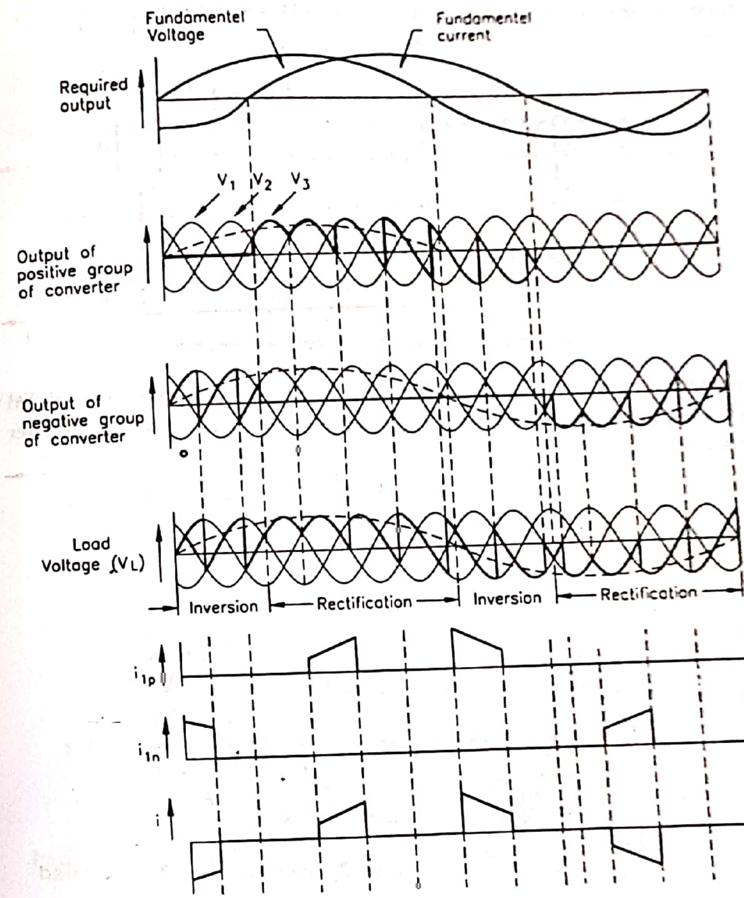

Fig. 10.4. Waveform of three phase three pulse cycloconverter with inductive load.

10.4 Three-phase Six-pulse Cycloconverter

Fig. 10.5 represents a three phase six pulse cycloconverter whose output voltage V_0 for a fixed firing angle α is given by $V_0 = 3\frac{V_{m_L}}{\pi}\cos\alpha = V_{do}\cos\alpha$, where V_{mL} is the amplitude of the line to line input voltage. As the firing angle α is

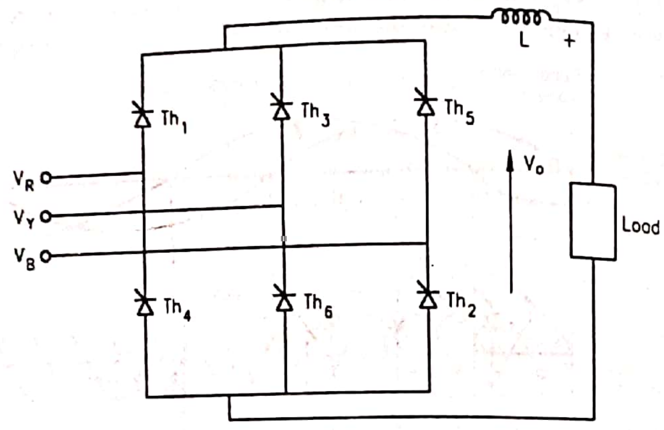

Fig. 10.5. Three phase six pulse cycloconverter operation.

increased from 0 to π, the output voltage varies from V_{do} to $-V_{do}$. If α is modulated slowly compared to the input frequency f_i, the output voltage of the cycloconverter is a sine wave (Fig. 10.6).

$$\alpha = \cos^{-1}\left(\frac{V_0}{V_{do}} \sin \omega_0 t\right).$$

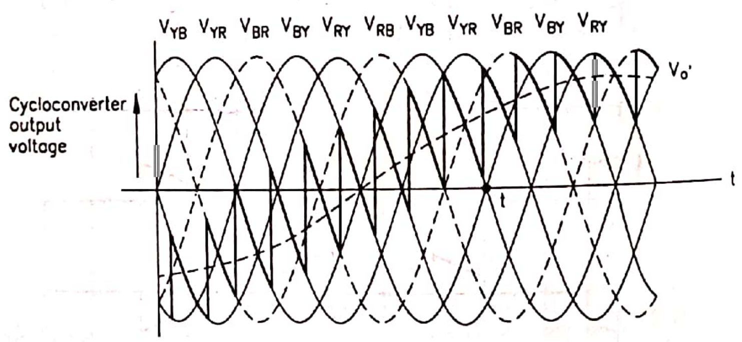

Fig. 10.6. Output voltage of a three phase six pulse cycloconverter.

In a practical cycloconverter circuit, the function for α is generally implemented indirectly by comparing the line to line voltage with the desired output waveform V_0' and turning on the next thyristor when the voltage V_0 would be closer to V_0'. Just before instant t (Fig. 10.6), V_{YB} is connected to the output through Th_3 and Th_2. The next commutation is form Th_2 to Th_4, connecting V_{YR} to the output. At this time t, V_{YB} and V_{YR} are equidistant from V_0'. However, V_{YB} is diverging while V_{YR} is converging on V_0'. Then Th_4 is triggered and V_0 assumes the value of V_{YR}. The next firing is initiated by comparing $(V_{BR} - V_0')$ with $(V_0' - V_{YR})$. This continues comparing.

The cycloconverter described above is a two *quadrant positive converter* as the current through the load is always unidirectional though the output voltage alternates between positive and negative amplitudes. Fig. 10.7 represents the negative converter. It is also a *two quadrant converter* but the direction of current through the load is just the reverse to that of the previous one.

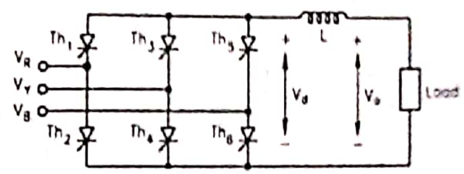

Fig. 10.7(*a*). Two quadrant cycloconverter schematic

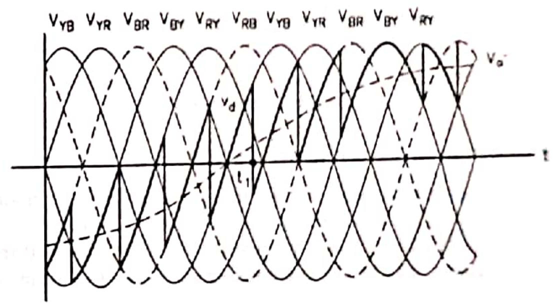

Fig. 10.7(*b*). Output waveform.

10.5 Four Quadrant (Bilateral) Cycloconverter

In order to obtain a *bilateral load current*, a negative and a positive cycloconverter are to be placed in parallel. The direction of the thyristors are inverted for the negative converter with respect to the positive converter. Because the SCRs are inverted, the output voltage takes a negative step at commutation. This combined circuit is known as *Four quadrant cycloconverter*. The circuit diagrams as well as the waveforms are shown in Fig. 10.8(*a*) and (*b*). It may be noted that the direction of the step change in V_d at the point of commutation indicates which converter is operating at any point in the cycle. At t_0, operation shifts from the negative to the positive converter.

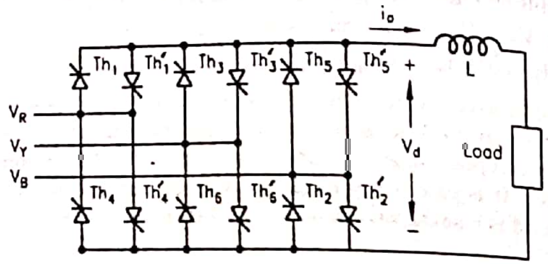

Fig. 10.8(a). Four quadrant cycloconverter schematic.

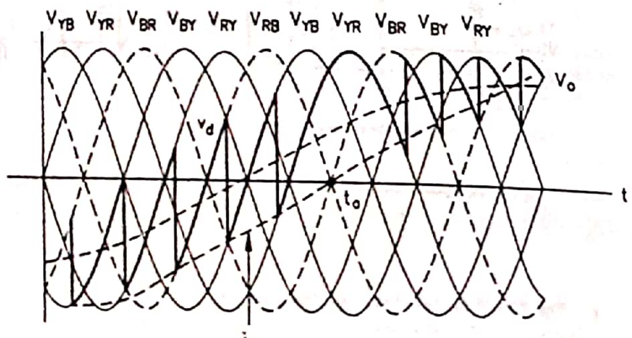

Fig. 10.8(b). Output waveform.

10.6 Cycloconverters with Polyphase Outputs

High power applications involve the use of *polyphase output generating cycloconverters*. Fig. 10.9 represents 3 pulse phase controlled converters in order to generate three output voltages. Each converter has six thyristors (three carrying positive load currents and three negative load currents). The input voltages are

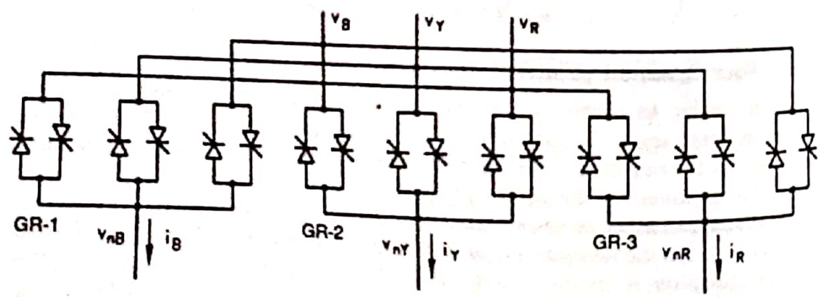

Fig. 10.9. Three pulse polyphase output cycloconverter bridge.

line to neutral voltages. Fig. 10.10 shows the waveform at phase *R*, *Y* and *B* of the cycloconverter. If may be noted that each three pulse converter has only three input voltages and the commutation occur half as often as with the six pulse circuit. Fig. 10.11 represents the *R*–phase line current for the loads.

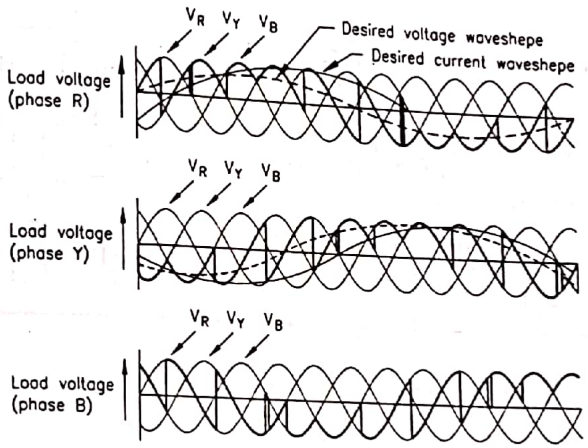

Fig. 10.10. Waveform of output voltage of phase *R*, γ and *B* of the three pulse polyphase output cycloconverter.

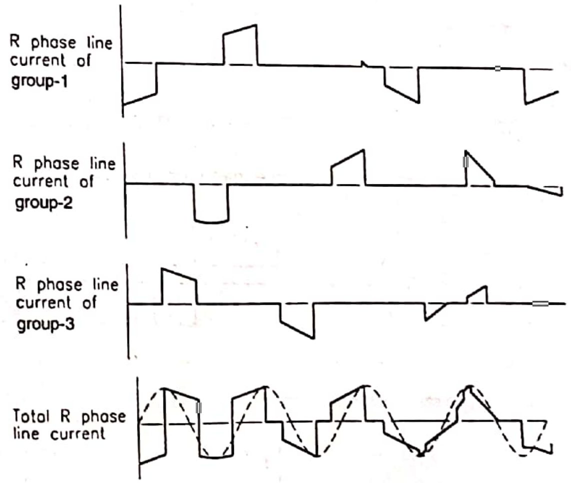

Fig. 10.11. R-Phase line current of the three pulse polyphase output cycloconverter.

Fig. 10.12 represents the schematic of six pulse bridge cycloconverter for polyphase output while Fig. 10.13 represent the load voltage waveform.

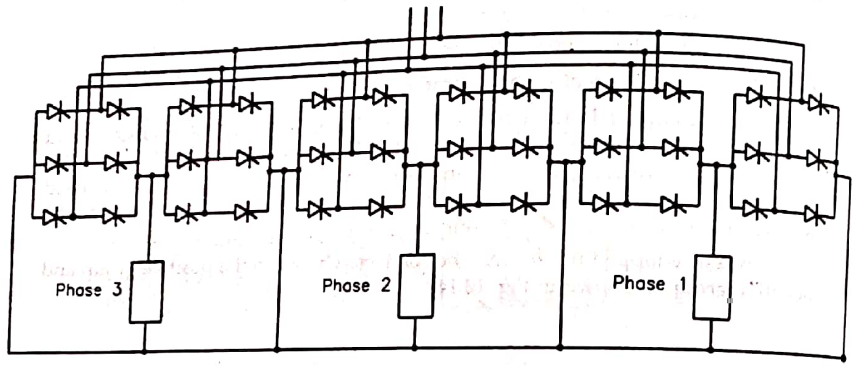

Fig. 10.12. Six-pulse bridge cycloconverter for polyphase output.

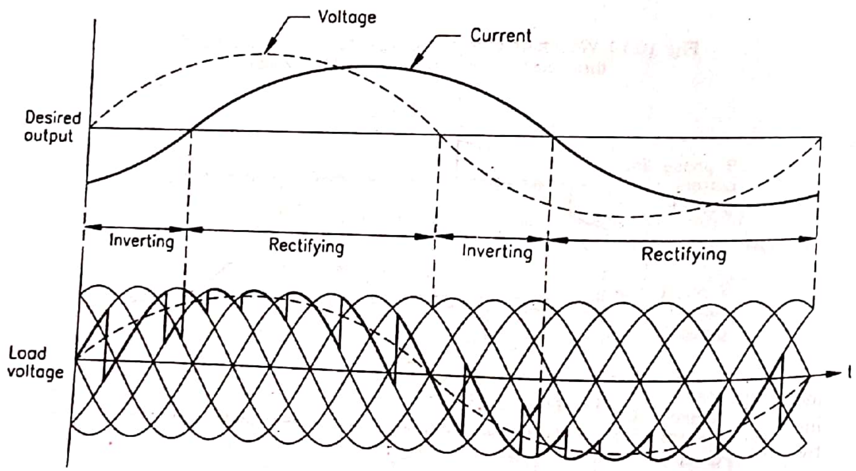

Fig. 10.13. Load voltage waveform of six pulse bridge cycloconverter for polyphase output.

It may be evident that the higher the pulse number, the closer is the output waveform to the desired sinusoidal waveform. In practice the output frequency is generally limited to one half to one third of the input frequency. The peak voltage at the output is the mean value of the direct voltage which each group can provide.

When a polyphase output cycloconverter is used to feed a balanced load, the input current is much more evenly balanced. The total load current is not identical in each cycle and the fundamental component of the load current lags the supply voltage slight more than the load power factor angle. The commutation of the thyristors are natural and the firing must be adjusted such that the output of the cycloconverter voltage is nearly sinusoidal.

10.7 Circulating current mode operation of Four Quadrant Cycloconverters

For a four quadrant operation of a cycloconverter, both the positive and negative groups conduct continuously with rectifying and inverting modes. The mean between two groups is fed to the load and some of the ripples get cancelled in the combination of two groups. The two group voltages should ideally be mostly identical sinewaves at the output frequency, but in opposition.

A centre tapped reactor may be connected between the positive group and negative group as shown in Fig. 10.14.

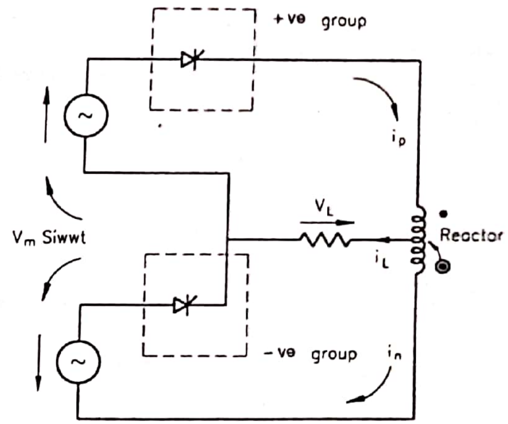

Fig. 10.14. Four quadrant cycloconverter circuit simplified.

The circulating current mode operation exists when there is a flow of harmonic current between positive and negative group of converters. A non-circulating current mode also exists when the flow of current is blocked between these two groups.

During conduction of +ve group of converters, the delay angle being α^+, the delay angle becomes α^- while negative group of converters conduct. The mean output voltage of the converter group is maintained equal to the back e.m.f. of the inverter group provided $\alpha^+ = (180° - \alpha^0)$. This avoids the circulating of large low frequency currents between these groups. However, the instantaneous voltages of these two groups vary to some extent and harmonic currents circulate unless they are suppressed or limited. The production of group currents may be explained following the operation of the cycloconverter as shown in Fig. 10.14.

At start of conduction for the +ve group, the growth of i_p (the positive group current) induces a voltage across the reactor that is reflected in the negative group converter circuit. However, the reverse bias of the thyristors prevent the current in the negative group to flow. After i_p reaches its peak and starts to fall, a reverse voltage gets induced in the reactor and the current i_n (the negative group current) starts flowing. This is possible to utilise the stored energy of the reactor. With fall of i_p, i_n starts rising in equal rate and in the reverse half cycle, i_p falls to zero while i_n rises to the peak. Hence the load current become $i_L (= i_p - i_n)$ and each group current has a mean value equal to the half of maximum value of load current. The load current is superimposed by the circulating current and causes higher loading of each group.

Circulating current mode operation is allowed only when the load current is low so that continuous load current with a better waveform can be maintained. At higher levels of load current the circulating current mode operation would be prevented either using a reactor or by using proper control circuitry in the firing angle control.

10.8 Cycloconverter Circuit Equations

In case there is no firing delay in a half wave phase controlled cycloconverter, the average direct voltage output ($V_{dc(0)}$) given by

$$\boxed{V_{dc(0)} = V_m\left(\frac{m}{\pi}\right)\sin\left(\frac{\pi}{m}\right)}$$

where V_m is the peak ac value of the input wave, m being the number of phases.

On the other hand if the delay angle of the converter thyristors are slowly varied, the output voltage per phase $V_{dc(\alpha)}$ for continuous current conduction is given by

$$\boxed{V_{dc(\alpha)} = V_m\left[\left(\frac{m}{\pi}\right)\sin\left(\frac{\pi}{m}\right)\right]\cos\alpha}$$

where α is the delay angle.

[In practical thyristorised cycloconverters, the firing angle of the positive group cannot be reduced to zero as this corresponds to firing angle of 180° delayed firing is not acceptable because sufficient margin must be allowed for commutation overlap as well as for the thyristor recovery time. Similarly, the firing delay angle of the positive group cannot be reduced below a finite value].

10.9 Advantages and Disadvantages of Cycloconverters

The following list gives the chief advantages and disadvantages of cycloconverters over dc link inverters.*

* A *dc link inverter* has two power controllers connected in cascade. Their role is to convert the input frequency to another value of output frequency using the "medium" of high frequency. First the input waveform is rectified to give a dc waveform. This waveform is then inverted to get ac waveform at the output. AC or DC converters can be controlled independently.

Advantages

(*i*) Frequency conversion in a single power state is possible in cycloconverters while dc line converters require two power stages.

(*ii*) In cycloconverters, both voltage and frequency are controllable while in dc link inverters only frequency is controllable.

(*iii*) Cycloconverters are naturally commutated circuits while additional commutation circuits are needed in dc link inverter circuits if SCRs are to be used.

(*iv*) At lower frequency, the total harmonic distortion is lower in cycloconverters than usual dc link inverters.

(*v*) Isolation of a defective SCR does not require the cycloconverter to be switched off. On the other hand, for the dc link inverter, it is to be switched off to replace a thyristor.

(*vi*) In cycloconverter, the power transfer is bidirectional while in dc link inverter it is unidirectional unless the inverter is ready to reverse the power flow.

Disadvantages

(*i*) Cycloconverter operation is possible only for frequencies less than half of the input frequency. On the other hand, for dc link inverters wide range of operating frequencies is possible.

(*ii*) Cycloconverter requires a large number of SCRs while the dc link inverter requires lesser number of SCRs.

(*iii*) Complex control circuitry is needed in cycloconverter while the control circuitry in dc link inverter is much simpler.

(*iv*) At smaller load currents, the cycloconverter may create problem in firing delay control. This does not occur in dc link inverter control.

10.10 Factors affecting the harmonics in Cycloconverters

Following factors usually have the governing role on the *harmonics* of cycloconverters :

(*a*) Number of pulses per cycle

(*b*) Circulating or non-circulating mode of operation.

(*c*) Continuous or discontinuous conduction.

(*d*) Effect of overlap.

(*e*) Effect of load power factor.

(*f*) Control methods.

Example 10.1. *Why the output frequency of a cycloconverter is significantly lower than the input frequency ?*

Solution. Since the cycloconverter is a phase controlled AC-AC converter producing the desired output AC voltage by selecting segments of the input voltage (*i.e.*, synthesizing the output wave from segments of input wave) utilizing natural commutation, the output frequency becomes significantly lower than the input frequency.

Example 10.2. *How the firing pulses in a cycloconverter should be arranged to get a low frequency output voltage nearly sinusoidal ?*

Solution. The output of a cycloconverter is given by

$$V_0 = V_{0\,(max)} \cos\alpha \qquad \text{if } \alpha \text{ is held constant. [}\alpha \text{ being the firing angle]}$$

On the other hand if α be modulated, the average output will vary according to the relation

$$V_0 = V_{0\,(max)} \cos\left(\frac{\pi}{2} + \theta(t)\right)$$

$$= V_{0\,(max)} \sin\theta(t)$$

Variation of $\sin\theta(t)$ in accordance to the equation $\sin\theta(t) = \sin\omega_0 t$ yields an average sine wave output. For controlling the output voltage, the maximum excursion of α around π/2 is controlled causing the control of output voltage by depth of modulation.

Example 10.3. *In a cyclo-converter what is the relation between triggering angles of the thyristors of bilateral converters and why ?*

Solution. In a bilateral converter if one converter is operated at a time while the other is inoperative, it is not essential to vary the trigger pulses of the other. But the trigger circuits are kept operative in such a way that when both the converters are simultaneously operated, the average output voltage of both the converters remains same though instantaneous values may differ. Assuming α_p and α_n to the firing angles of positive and negative converter, in continuous conduction, it is required that

$$\alpha_p + \alpha_n = \pi$$

or,

$$\alpha_p = \pi - \alpha_n.$$

This firing angle relation must be maintained between the triggering angles of the two (positive and negative) converters.

Example 10.4. *A three pulse polyphase cycloconverter feeds a single phase load at 230 V, 25 A at a p.f. 0.8. lag. What is the supply voltage ?*

Solution. The output voltage being given by

$$V_{0\,(\alpha)} = V_m\left[\left(\frac{m}{\pi}\right)\sin\left(\frac{\pi}{m}\right)\right]\cos\alpha,$$

its peak value is $\left[\left(\frac{m}{\pi}\right)\sin\left(\frac{\pi}{m}\right)\times\sqrt{2}\,V_{r.m.s.}\right]$ where $V_{r.m.s.}$ is the supply voltage.

Here $\quad 230\sqrt{2} = \frac{3}{\pi}\sin\left(\frac{\pi}{3}\right)\times\sqrt{2}\,V_{r.m.s.}$

[since peak value = $230\sqrt{2}$ volts, m = 3]

$$\therefore \quad V_{r.m.s.} = 230\sqrt{2}\times\frac{\pi}{3}\Big/\left(\sin\frac{\pi}{3}\right)\sqrt{2}$$

$$= 278 \text{ volts.}$$

Example 10.5. *What is the thyristor rating for the cycloconverter of Ex. 10.4 ?*

Solution. The worst case will appear when the output frequency is very low and a converter group is acting as a rectifier feeding a dc load for a sufficiently prolonged period, the current being equal to the maximum value of the cycloconverter load.

Since the maximum value of the load becomes $(25\sqrt{2})$ A, for the thyristor,

$$I_{r.m.s.} = \frac{25\sqrt{2}}{\sqrt{3}} = 20.41 \text{ A}$$

$$PIV = \sqrt{3}\,V_{max} = \sqrt{3}\times 278\times\sqrt{2}$$

$$= 681 \text{ V}$$

(at higher value of *PIV* rating may be selected with a conservative design)

Example 10.6. *A three pulse cycloconverter has output voltage of 250 V to feed a single phase load at 50 A. If the load p.f. is unity, find the input power per phase and the power factor.*

Solution. Input power/phase

$$= \frac{1}{3}\,250\times 50\times 1 = 4.17 \text{ kW.}$$

[∵ the cycloconverter is three pulse hence the power expression must be multiplied by $\frac{1}{3}$. Also, $\cos\phi$ = unity and $V = 250$ V, $I = 50$ A]

Again from the given data, the peak value being $\left(\frac{m}{\pi}\right)\sin\left(\frac{\pi}{m}\right)\sqrt{2}\,V_{r.m.s.}$

$$\sqrt{2}\times 250 = \frac{3}{\pi}\sin\left(\frac{\pi}{3}\right)\times\sqrt{2}\,V_{r.m.s.}$$

$$\therefore \quad V_{r.m.s.} = \frac{\sqrt{2}\times 250\,\pi/3}{\sqrt{2}\times\sin\left(\frac{\pi}{3}\right)} = 302 \text{ V.}$$

Since the load conduction is for 1/3 period,

$$I_{r.m.s.} = \left[\frac{50^2}{3}\right]^{1/2} = 29 \text{ A.}$$

∴ Input power $= V_{r.m.s.}\times I_{r.m.s.} = 302\times 29 = 8.76$ kW.

P.F. (power factor) of the cycloconverter

$$= \frac{4.17}{8.76} = 0.48.$$

Example 10.7 *A three pulse cycloconverter is fed from a 440 V three phase supply having a reactance of 0.2 Ω /phase. Obtain the output load voltage for the firing delay angle 0°. Assume the load current to be 20 A and assume overlap.*

Solution. The relationship between the overlap angle (μ), load current I, supply voltage V_m and the commutation reactance X_c for a n pulse converter operating with a firing delay angle delay angle α is given by

$$IX_c = V_m \sin\frac{\pi}{m}[\cos\alpha - \cos(\alpha+\mu)]$$

Here, $I = 20\text{ A}, X_c = 0.2\ \Omega/\text{ph},$

$\alpha = 0°, n = 3, V_m = 440\sqrt{2}.$

∴ We find $20\times 0.2 = 440\sqrt{2}\sin\frac{\pi}{3}[1-\cos\mu]$

or, $$\frac{4}{440\sqrt{2}}\times\frac{1}{\sin\frac{\pi}{3}} = 1-\cos\mu$$

or, $\cos\mu = 0.9925$. ∴ $\mu = 7.02°$

∴ $$V_{mean} = \frac{3\times 440\sqrt{2}}{2\pi}\sin\frac{\pi}{3}(1+\cos 7.02)$$

$$\left[\because V_{mean} = \frac{3V_m}{2\pi}\sin\frac{\pi}{m}(1+\cos\mu)\right]$$

[max. volts across the load]

Here $V_{mean} = 258.55$ volts

and load voltage $= \frac{V_{mean}}{\sqrt{2}} = 182.85$ Volts.

10.11 OUTPUT VOLTAGE EQUATION FOR A CYCLOCONVERTER

A cycloconverter is basically a dual converter operated to produce an alternating output voltage. Each thyristor in the cycloconverter works as a phase controlled converter with a varying firing angle.

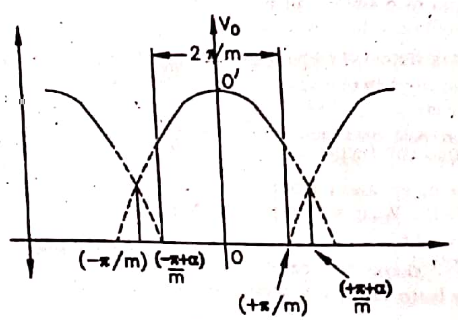

Fig. 10.15.

It is evident that for an m–phase half wave converter, each phase conducts for $\frac{2\pi}{m}$ radians in one cycle of 2π radians (Fig. 10.15). With time origin OO′ taken at the peak value of the supply voltage, the instantaneous phase voltage is given by

$$v = V_m\cos\omega t = \sqrt{2}\,V_{ph}\cos\omega t$$

[V_{ph} is the *rms* phase voltage of the supply].

For α = 0°; the conduction takes place from $\left(-\frac{\pi}{m}\right)$ to $\left(+\frac{\pi}{m}\right)$. For any firing angle α, the conduction is from $\left(-\frac{\pi}{m}+\alpha\right)$ to $\left(\frac{\pi}{m}+\alpha\right)$. Thus, average value of the output dc voltage V_{dc} equals to the average height of the shaded-area in the given figure and is expressed as

$$V_{dc} = \frac{m}{2\pi}\int_{-\frac{\pi}{m}+\alpha}^{\frac{\pi}{m}+\alpha} V_m\cos\omega t\,.\,d(\omega t).$$

$$= V_m\left[\left(\frac{m}{\pi}\right)\sin\frac{\pi}{m}\right]\cos\alpha.$$

For firing angle α = 0, the average value of the direct voltage $V_{dc(0)}$ is given as

$$V_{dc(0)} = V_m\left(\frac{m}{\pi}\right)\sin\frac{\pi}{m}\left(=\sqrt{2}\,V_{ph}\frac{m}{\pi}\sin\frac{\pi}{m}\right).$$

EXERCISE

1. What is a cycloconverter ? Explain its operation.
2. What is the difference between the operation of the three phase three pulse cycloconverter with *R* load *RL* load ?
3. Draw a circuit diagram to explain the operation of a six pulse cycloconverter ? What is the output voltage wave shape ?
4. Describe the operation of a four quadrant cycloconverter.
5. Draw the waveform of output voltages of phases of a three pulse polyphase output cycloconverter.
6. Write a short note on "circulating current mode operation of four quadrant cycloconverter."
7. A three pulse polyphase cycloconverter feeds a single phase load at 200 V, 20 A at a p.f. of 0.9 lag. What is the supply voltage ?
   [**Hint.** Ref. Ex. 10.4.]
8. A three pulse cycloconverter has output voltage of 400 V to feed a single phase load at 40 A. If the load p.f. is unity. Find the input power per phase and the power factor.
   [**Hint.** Ref. Ex. 10.6.]