UNIT -4TH

AC to AC Voltage Converters

Introduction to Cycloconverters

Instructional Objectives

Study of the following:

- The cyclo-converter circuits − basic principle of operation
- The circuit for the single-phase to single-phase cyclo-converter using thyristors
- The operation of the above cyclo-converter circuit, along with the voltage waveforms

Introduction

Earlier in the last three (4.1-4.3) lessons (first half) of this module, the circuit and operation of ac to ac voltage controllers − both single-phase and three-phase, were described in detail. The devices used are either triac, or thyristors connected back to back. In this lesson (4.4) − first one in the second half of this module, the cyclo-converter is introduced as a type of power controller, where an alternating voltage at supply frequency is converted directly to an alternating voltage at load frequency (normally lower), without any intermediate dc stage. As will be shown in the last (fifth) module, an alternating voltage at any frequency (output) is obtained using an inverter as a power controller from a dc voltage fed at its input. This input, i.e. dc voltage, is again obtained using a rectifier (converter) with ac voltage (normally at supply frequency) fed at its input. This type has been described in module 2. Note that this is a two -stage process with an intermediate dc stage. Now-a-days, the power switching devices used in the inverter circuit belong to transistor family (termed as self-commutated ones), starting with power transistors, whereas thyristors are still being used in the converter (rectifier) circuits. These devices are called force-commutated ones, when used in dc chopper circuits (described in module 3), but in this case, i.e. converter circuits, line commutation takes place. As stated earlier, the output frequency of the cyclo-converter is limited to about one-third of supply (line) frequency of 50 Hz.

Initially, the basic principle of operation used in a cyclo-converter is discussed. Then, the circuit of a single-phase to single-phase cyclo-converter using thyristors is presented. This is followed by describing the operation of the above cyclo-converter circuit, along with voltage waveforms. The readers at this stage, have gone through the following lessons − single-phase fully controlled converter using thyristors, for obtaining dc output voltage from ac supply (#2.2), and ac to ac voltage controllers − both single-phase and three-phase, using either triac, or thyristors connected back to back (#4.1-4.3). In the above cases, the output voltage obtained is, in the form of phase-controlled one, as can be observed from the waveforms shown in the above lessons. In the present case, the output voltage of the cyclo-converter circuit (single-phase) using thyristors, is synthesized from the above phase-controlled voltage waveforms, so as to obtain an ac waveform (output) of low frequency, with the input being an ac voltage of higher frequency, say line. The angle, at which the thyristors are triggered, is controlled to obtain the desired waveform.

Keywords: Single-phase to single-phase cyclo-converter using thyristors, Voltage waveforms.

Cyclo-converter

Basic Principle of Operation

The basic principle of operation of a cyclo-converter is explained with reference to an equivalent circuit shown in Fig. 29.1. Each two-quadrant converter (phase-controlled) is represented as an alternating voltage source, which corresponds to the fundamental voltage component obtained at its output terminals. The diodes connected in series with each voltage source, show the unidirectional conduction of each converter, whose output voltage can be either positive or negative, being a two-quadrant one, but the direction of current is in the direction as shown in the circuit, as only thyristors − unidirectional switching devices, are used in the two converters. Normally, the ripple content in the output voltage is neglected.

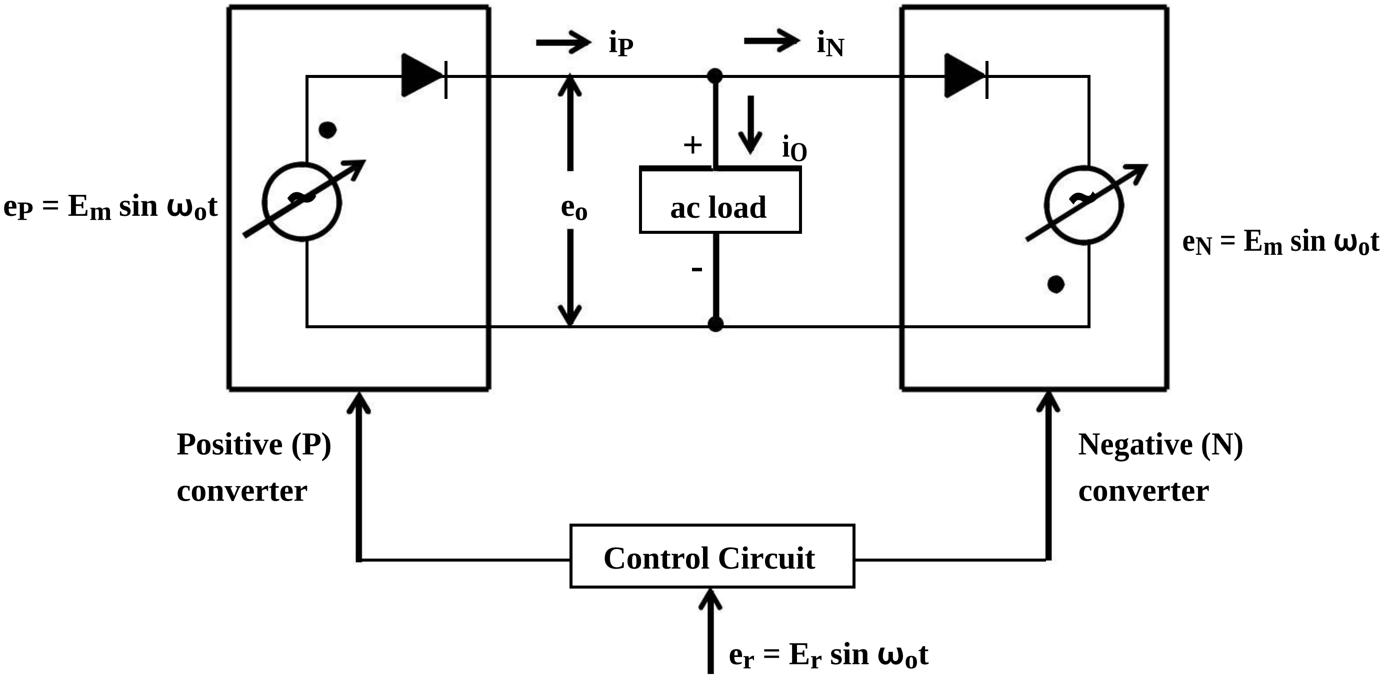
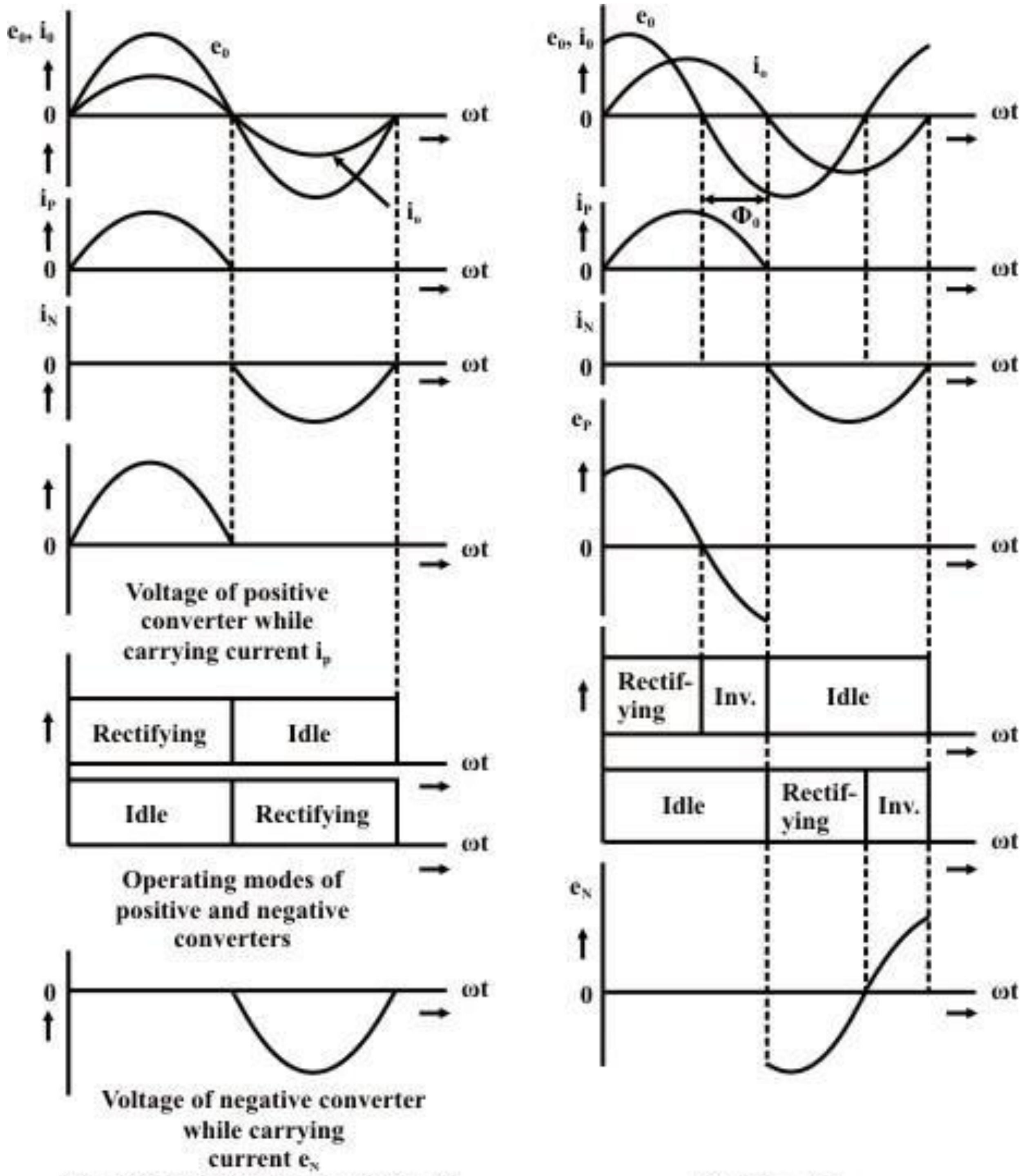


Fig. 29.1: Equivalent circuit of cyclovonverter

The control principle used in an ideal cyclo-converter is to continuously modulate the firing angles of the individual converters, so that each produces the same sinusoidal (ac) voltage at its output terminals. Thus, the voltages of the two generators (Fig. 29.1) have the same amplitude, frequency and phase, and the voltage of the cyclo-converter is equal to the voltage of either of these generators. It is possible for the mean power to flow either 'to' or 'from' the output terminals, and the cyclo-converter is inherently capable of operation with loads of any phase angle − inductive or capacitive. Because of the uni-directional current carrying property of the individual converters, it is inherent that the positive half-cycle of load current must always be carried by the positive converter, and the negative half-cycle by the negative converter, regardless of the phase of the current with respect to the voltage. This means that each two-quadrant converter operates both in its rectifying (converting) and in its inverting region during the period of its associated half-cycle of current.

The output voltage and current waveforms, illustrating the operation of an ideal cyclo-converter circuit with loads of various displacement angles, are shown in Fig. 29.2. The displacement angle of the load (current) is 0° (Fig. 29.2a). In this case, each converter carries the load current only, when it operates in its rectifying region, and it remains idle throughout the whole period in which its terminal voltage is in the inverting region of operation. In Fig. 29.2b, the displacement angle of the load is 60° lagging. During the first 120° period of each half-cycle of load current, the associated converter operates in its rectifying region, and delivers power to the load. During the latter 60° period in the half-cycle, the associated converter operates in its inverting region, and under this condition, the load is regenerating power back into the cyclo-converter output terminals, and hence, into the ac system at the input side. These two are illustrative cases only. Any other case, say capacitive load, with the displacement angle as leading, the operation changes with inverting region in the first period of the half-cycle as per displacement angle, and the latter period operating in rectifying region. This is not shown in Fig. 29.2, which can be studied from a standard text book.



(a) Load displacement angle $\Phi_o = 0°$

(b) $\Phi_o = -60°$

Single-phase to Single-phase Cyclo-converter

The circuit of a single-phase to single-phase cyclo-converter is shown in Fig. 29.3. Two full-wave fully controlled bridge converter circuits, using four thyristors for each bridge, are connected in opposite direction (back to back), with both bridges being fed from ac supply (50 Hz). Bridge 1 (P – positive) supplies load current in the positive half of the output cycle, while bridge 2 (N – negative) supplies load current in the negative half. The two bridges should not conduct together as this will produce short -circuit at the input. In this case, two thyristors come in series with each voltage source. When the load current is positive, the firing pulses to the thyristors of bridge 2 are inhibited, while the thyristors of bridge 1 are triggered by giving pulses at their gates at that time. Similarly, when the load current is negative, the thyristors of bridge 2 are triggered by giving pulses at their gates, while the firing pulses to the thyristors of bridge 1 are inhibited at that time. This is the circulating-current free mode of operation. Thus, the firing angle control scheme must be such that only one converter conduct at a time, and the change over of firing pulses from one converter to the other, should be periodic according to the output frequency. However, the firing angles the thyristors in both converters should be the same to produce a symmetrical output.

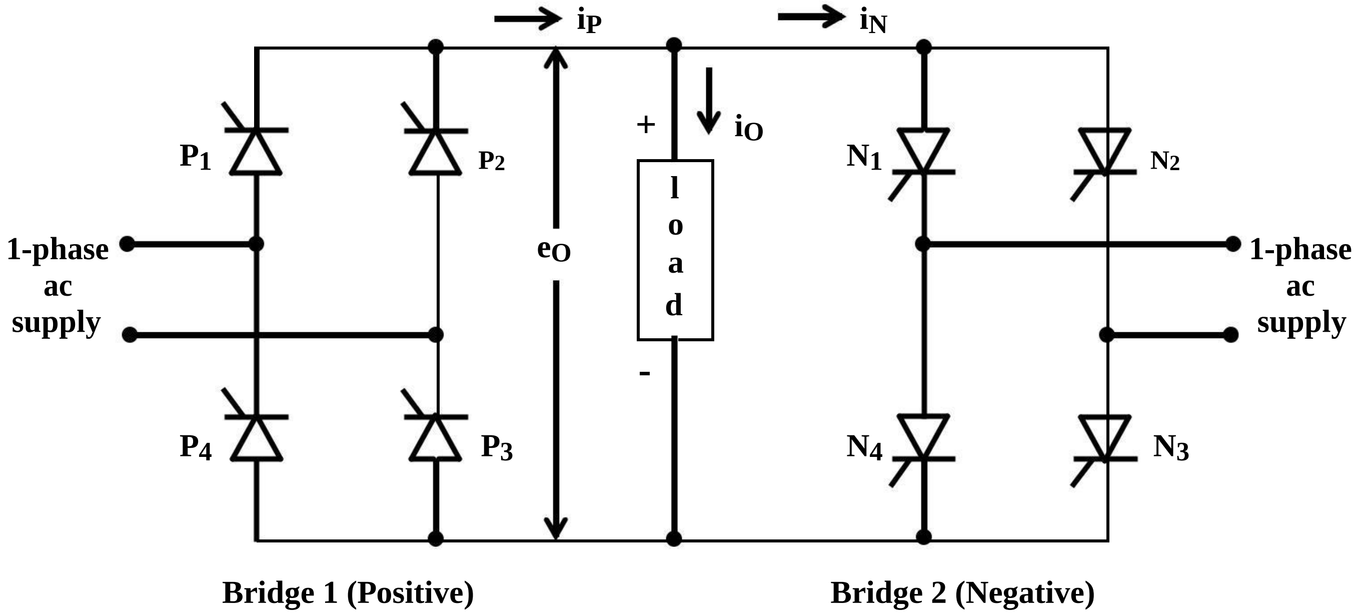


Fig. 29.3: Single-phase to single-phase cycloconverter (using thyristor bridges)

When a cyclo-converter operates in the non-circulating current mode, the control scheme is complicated, if the load current is discontinuous. The control is somewhat simplified, if some amount of circulating current is allowed to flow between them. In this case, a circulating current limiting reactor is connected between the positive and negative converters, as is the case with dual converter, i.e. two fully controlled bridge converters connected back to back, in circulating-current mode. The readers are requested to refer to any standard text book. This circulating current by itself keeps both converters in virtually continuous conduction over the whole control range. This type of operation is termed as the circulating-current mode of operation. The operation of the cyclo-converter circuit with both purely resistive (R), and inductive (R-L) loads is explained.

Resistive (R) Load: For this load, the load current (instantaneous) goes to zero, as the input voltage at the end of each half cycle (both positive and negative) reaches zero (0). Thus, the conducting thyristor pair in one of the bridges turns off at that time, i.e. the thyristors undergo natural commutation. So, operation with discontinuous current (Fig. 29.4) takes place, as current flows in the load, only when the next thyristor pair in that bridge is triggered, or pulses are fed at respective gates. Taking first bridge 1 (positive), and assuming the top point of the ac supply as positive with the bottom point as negative in the positive half cycle of ac input, the odd-numbered thyristor pair, P_1 & P_3 is triggered after phase delay (α_1), such that current starts flowing through the load in this half cycle. In the next (negative) half cycle, the other thyristor pair (even- numbered), P_2 & P_4 in that bridge conducts, by triggering them after suitable phase delay from the start of zero-crossing. The current flows through the load in the same direction, with the output voltage also remaining positive. This process continues for one more half cycle (making a total of three) of input voltage ($f_1 = 50$ Hz). From three waveforms, one combined positive half cycle of output voltage is produced across the load resistance, with its frequency being one-third of input frequency ($f_2 = f_1 / 3 = 16\frac{2}{3}$ Hz). The following points may be noted. The firing angle (α) of the converter is first decreased, in this case for second cycle only, and then again increased in the next (third) cycle, as shown in Fig. 29.4b. This is, because only three cycles for each half cycle is used. If the output frequency needed is lower, the number of cycles is to be increased, with the firing angle decreasing for some cycles, and then again increasing in the subsequent cycles, as described earlier.

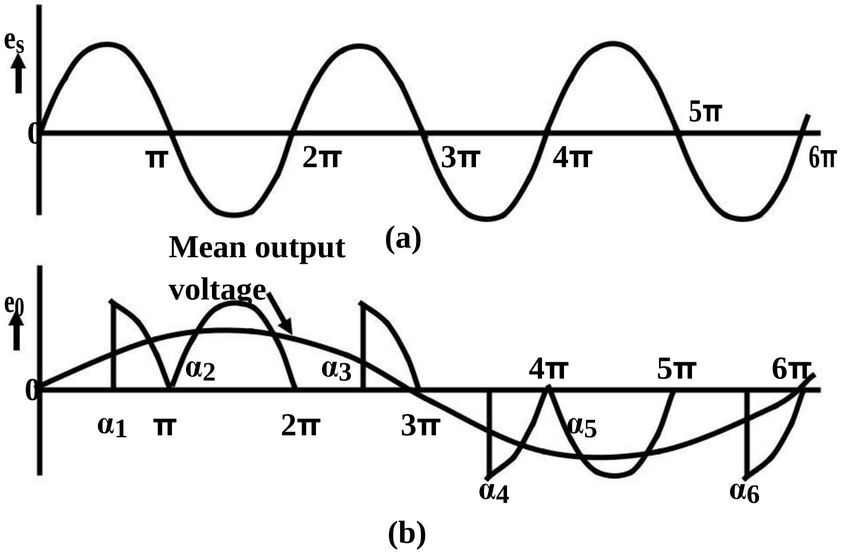


Fig. 29.4: Input (a) and output (b) voltage waveforms of a cyclo-converter with an output frequency of $16\frac{2}{3}$ Hz for resistive (R) load

To obtain negative output voltage, in the next three half cycles of input voltage, bridge 2 is used. Following same logic, if the bottom point of the ac supply is taken as positive with the top point as negative in the negative half of ac input, the odd-numbered thyristor pair, N_1 & N_3 conducts, by triggering them after suitable phase delay from the zero -crossing. Similarly, the even-numbered thyristor pair, N_2 & N_4 conducts in the next half cycle. Both the output voltage and current are now negative. As in the previous case, the above process also continues for three consecutive half cycles of input voltage. From three waveforms, one combined negative half cycle of output voltage is produced, having same frequency as given earlier. The pattern of firing angle − first decreasing and the increasing, is also followed in the negative half cycle. One positive half cycle, along with one negative half cycle, constitute one complete cycle of output (load) voltage waveform, its frequency being $16\frac{2}{3}$ Hz as stated earlier. The ripple frequency of the output voltage/ current for single–phase full-wave converter is 100 Hz, i.e., double of the input frequency. It may be noted that the load (output) current is discontinuous (Fig. 29.4c), as also load (output) voltage (Fig. 29.4b). The supply (input) voltage is shown in Fig. 29.4a. Only one of two thyristor bridges (positive or negative) conducts at a time, giving <u>non-circulating current mode of operation</u> in this circuit.

Inductive (R-L) Load: For this load, the load current may be continuous or discontinuous depending on the firing angle and load power factor. The load voltage and current waveforms are shown for continuous and discontinuous load current in Fig. 29.5 and 29.6 respectively.

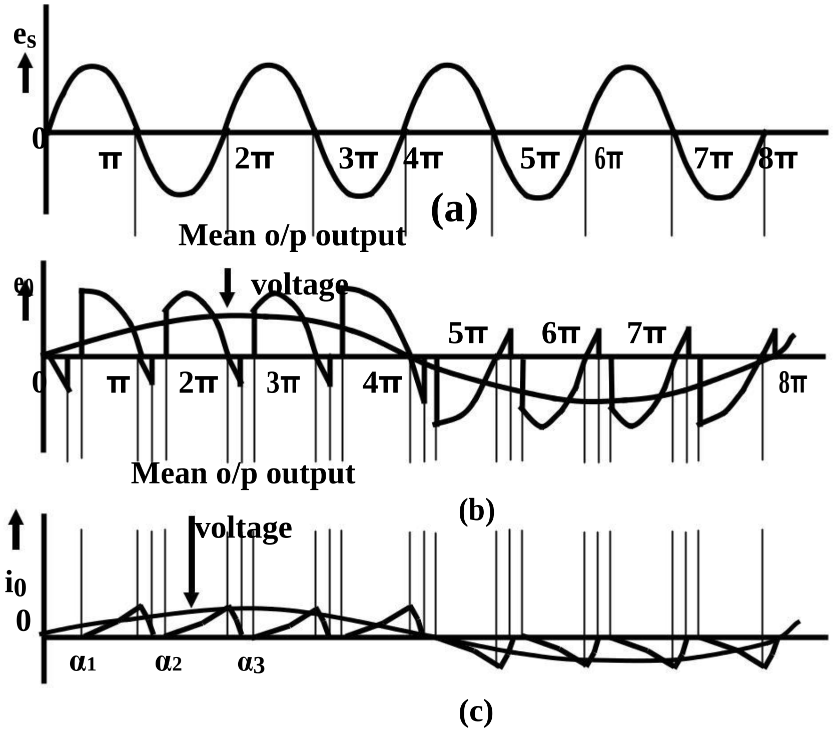


Fig. 29.5: Input (a) and output (b) voltage, and current (c) waveforms for a cyclo-converter with discontinuous

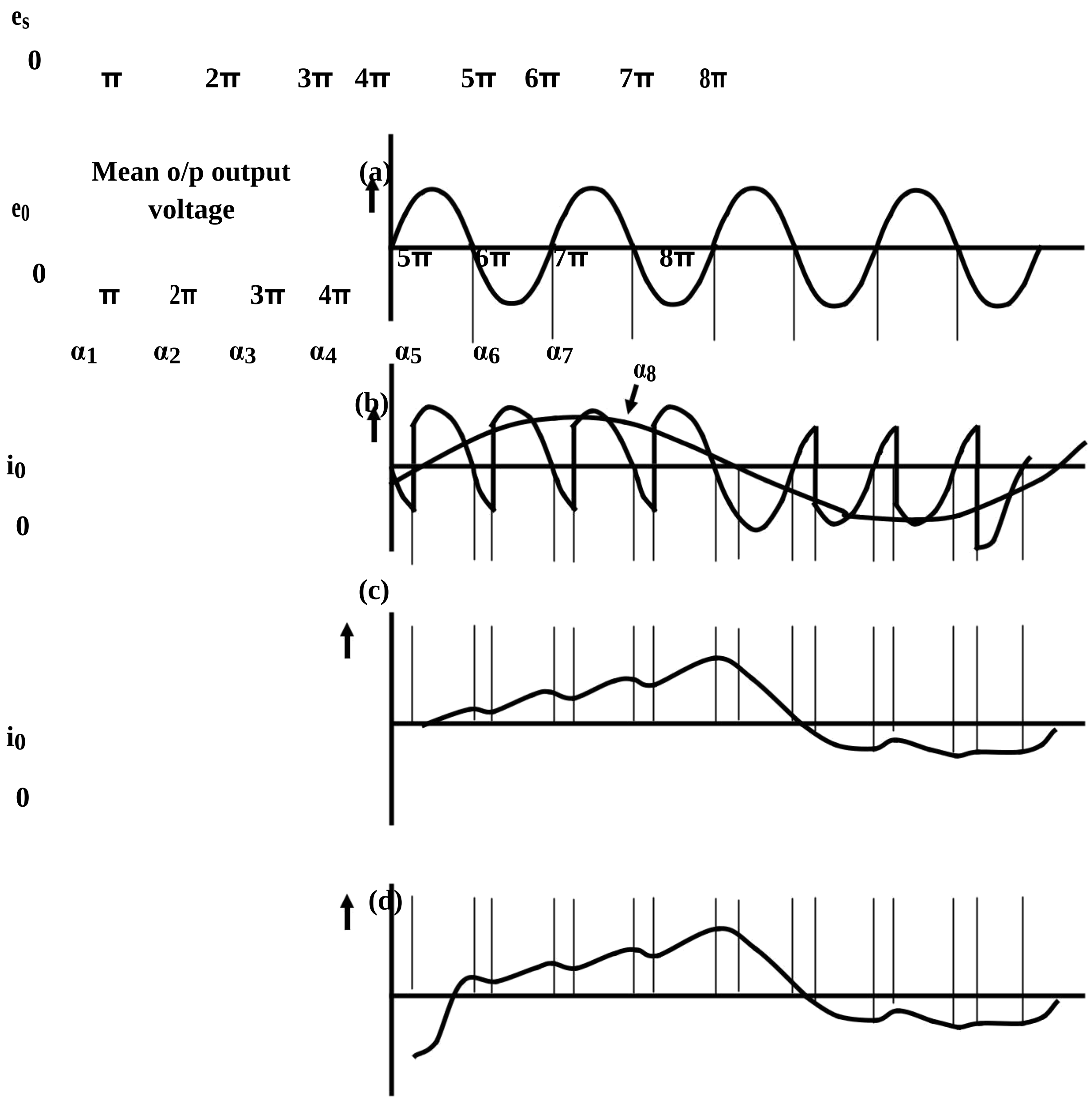


Fig. 29.6: Input (a) and output (b) voltage, and current (c, d) waveforms for a cyclo-converter with continuous load current.

(a) Discontinuous load current

The load current in this case is discontinuous, as the inductance, L in series with the resistance, R, is low. This is somewhat similar to the previous case, but difference also exists as described. Here, also non-circulating mode of operation takes place, with only one of the bridges − #1 (positive), or #2 (negative), conducting at a time, but two bridges do not conduct at the same time, as this will result in a short circuit. In this case, the output frequency is assumed as ($f_2 = 12.5$ Hz), the input frequency being same as ($f_1 = 50$ Hz), i.e., $f_1 = 4 \cdot f_2$, or $f_2 = f_1 / 4$. So, four positive half cycles, or two full cycles of the input to the full-wave bridge converter (#1), are required to produce one positive half cycle of the output waveform, as the output frequency is one-fourth of the input frequency as given earlier. As in the previous case with resistive load, taking bridge 1, and assuming the top point of the ac supply as positive, in the positive half cycle of ac input, the odd-numbered thyristor pair, P_1 & P_3, is triggered after phase delay ($\theta = \omega t = \alpha_1$), such that current starts flowing the inductive load in this half cycle. But here, the current flows even after the input voltage has reversed (after $\theta = \pi$), till it reaches zero at ($\theta = \beta_1$) with $(\pi + \alpha_2) > \beta_1 > \pi$, due to inductance being present in series with resistance, its value being low. It may be noted that the thyristor pair is, thus, naturally commutated. In the next (negative) half cycle, the other thyristor pair (even-numbered), P_2 & P_4, is triggered at $(\pi + \alpha_2)$. The current flows through the load in the same direction, with the output voltage also remaining positive. The current goes to zero at $(\pi + \beta_2)$, with $(\pi + \alpha_3) > \beta_2 > \pi$. This procedure continues for the next two half cycles, making a total of four positive half cycles. From these four waveforms, one combined positive half cycle of output voltage is produced across the inductive load. The firing angle (α) of the converter is first decreased, in this case for second half cycle only, kept nearly same in the third one, and finally increased in the last (fourth) one, as shown in Fig. 29.5b.

To obtain negative output voltage, in the next four half cycles of output voltage, bridge 2 is used. Following same logic, if the bottom point of the ac supply is taken as positive in the negative half of ac input, the odd-numbered thyristor pair, N_1 & N_3 conducts, by triggering them after phase delay ($\theta = 4 \cdot \pi + \alpha_1$). The current flows now in the opposite (negative) direction through the inductive load, with the output voltage being also negative. The current goes to zero at ($4 \cdot \pi + \beta_1$), due to load being inductive as given earlier. Similarly, the even-numbered thyristor pair, N_2 & N_4 conducts in the next half cycle, after they are triggered at ($5 \cdot \pi + \alpha_2$). The current goes to zero at ($5 \cdot \pi + \beta_2$). Both the output voltage and current are now negative. As in the previous case, the above process also continues for two more half cycles of input voltage, making a total of four. From these four waveforms, one combined negative half cycle of output voltage is produced with same output frequency. The pattern of firing angle − first decreasing and then increasing, is also followed in the negative half cycle. It may be noted that the load (output) current is discontinuous (Fig. 29.5c), as also load (output) voltage (Fig. 29.5b). The supply (input) voltage is shown in Fig. 29.5a. One positive half cycle, along with one negative half cycle, constitute one complete cycle of output (load) voltage waveform, its frequency being 12.5 Hz as stated earlier. The ripple frequency remains also same at 100 Hz, with the ripple in load current being filtered by the inductance present in the load.

(b) Continuous load current

As given above, the load current is discontinuous, as the inductance of the load is low. If the inductance is increased, the current will be continuous. Most of the points given earlier are applicable to this case, as described. To repeat, non-circulating mode of operation is used, i.e., only one of the bridges − #1 (positive), or #2 (negative), conducts at a time, but two bridges do not conduct at the same time, as this will result in a short circuit. Also, the ripple frequency in the voltage and current waveforms remains same at 100 Hz. The output frequency is one-fourth of input frequency (50 Hz), i.e., 12.5 Hz. So, for each half-cycle of output voltage waveform, four half cycles of input supply are required. Taking bridge 1, and assuming the top point of the ac supply as positive, in the positive half cycle of ac input, the odd-numbered thyristor pair, P_1 & P_3, is triggered after phase delay ($\theta = \omega t = \alpha_1$), such that current starts flowing the inductive load in this half cycle. But here, the current flows for about one complete half cycle, i.e., up to the angle, $(\pi + \alpha_1)$ or $(\pi + \alpha_2)$, whichever is higher, even after the input voltage has reversed, due to the high value of load inductance. In the next (negative) half cycle, the other thyristor pair (even-numbered), P_2 & P_4, is triggered at $(\pi + \alpha_2)$. At that time, reverse voltage is applied across each of the conducting thyristors, P_1/P_3, and the thyristors turn off. The current flows through the load in the same direction, with the output voltage also remaining positive. Also, the current flows for about one complete half cycle, i.e., up to the angle, $(\pi + \alpha_2)$ or $(\pi + \alpha_3)$, whichever is higher. This procedure continues for the next two half cycles, making a total of four positive half cycles. From these four waveforms, one combined positive half cycle of output voltage is produced across the inductive load. The firing angle (α) of the converter is first decreased, in this case for second half cycle only, kept nearly same in the third one, and finally increased in the last (fourth) one, as shown in Fig. 29.6b.

To obtain negative output voltage, in the next four half cycles of output voltage, bridge 2 is used. Following same logic, if the bottom point of the ac supply is taken as positive in the negative half of ac input, the odd-numbered thyristor pair, N_1 & N_3 conducts, by triggering them after phase delay $(\theta = 4 \cdot \pi + \alpha_1)$. The current flows now in the opposite (negative) direction through the inductive load, with the output voltage being also negative. The current flows for about one complete half cycle, i.e., up to the angle, $(5 \cdot .\pi + \alpha_1)$ or $(5 \cdot \pi + \alpha_2)$, whichever is higher, as the load is inductive. Similarly, the even-numbered thyristor pair, N_2 & N_4 conducts in the next half cycle, after they are triggered at $(5 \cdot \pi + \alpha_2)$. As described earlier, both the conducting thyristors turn off, as reverse voltage is applied across each of them. Both the output voltage and current are now negative. Also, the current flows for about one complete half cycle, i.e. up to the angle, $(5 \cdot \pi + \alpha_2)$ or $(5 \cdot \pi + \alpha_3)$, whichever is higher. As in the previous case, the above process also continues for two more half cycles of input voltage, making a total of four. From these four waveforms, one combined negative half cycle of output voltage is produced with same output frequency of 12.5 Hz. The pattern of firing angle − first decreasing and then increasing, is also followed in the negative half cycle. It may be observed that the load (output) current is continuous (Fig. 29.6c), as also load (output) voltage (Fig. 29.6b). The load (output) current is redrawn in Fig. 29.6d, under steady state condition, while the supply (input) voltage is shown in Fig. 29.6a. One positive half cycle, along with one negative half cycle, constitute one complete cycle of output (load) voltage waveform.

Advantages and Disadvantages of Cyclo-converter Advantages

1. In a cyclo-converter, ac power at one frequency is converted directly to a lower frequency in a single conversion stage.
2. Cyclo-converter functions by means of phase commutation, without auxiliary forced commutation circuits. The power circuit is more compact, eliminating circuit losses associated with forced commutation.
3. Cyclo-converter is inherently capable of power transfer in either direction between source and load. It can supply power to loads at any power factor, and is also capable of regeneration over the complete speed range, down to standstill. This feature makes it preferable for large reversing drives requiring rapid acceleration and deceleration, thus suited for metal rolling application.
4. Commutation failure causes a short circuit of ac supply. But, if an individual fuse blows off, a complete shutdown is not necessary, and cyclo-converter continues to function with somewhat distorted waveforms. A balanced load is presented to the ac supply with unbalanced output conditions.

5. Cyclo-converter delivers a high quality sinusoidal waveform at low output fre-quencies, since it is fabricated from a large number of segments of the supply waveform. This is often preferable for very low speed applications.
6. Cyclo-converter is extremely attractive for large power, low speed drives.

Disadvantages

1. Large number of thyristors is required in a cyclo-converter, and its control circuitry becomes more complex. It is not justified to use it for small installations, but is economical for units above 20 kVA.
2. For reasonable power output and efficiency, the output frequency is limited to one-third of the input frequency.
3. The power factor is low particularly at reduced output voltages, as phase control is used with high firing delay angle.

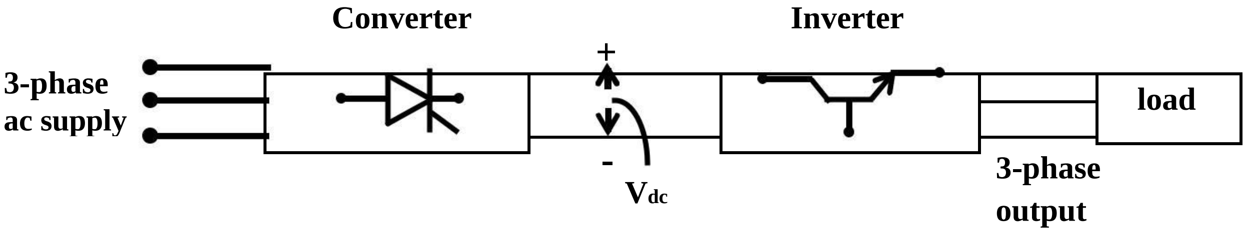


Fig. 29.7: DC link converter

The cyclo-converter is normally compared with dc link converter (Fig. 29.7), where two power controllers, first one for converting from ac input at line frequency to dc output, and the second one as inverter to obtain ac output at any frequency from the above dc input fed to it. The thyristors, or switching devices of transistor family, which are termed as self-commutated ones, usually the former, which in this case is naturally commutated, are used in controlled converters (rectifiers). The diodes, whose cost is low, are used in uncontrolled ones. But now-a -days, switching devices of transistor family are used in inverters, though thyristors using force commutation are also used. A diode, connected back to back with the switching device, may be a power transistor (BJT), is needed for each device. The number of switching devices in dc link converter depends upon the number of phases used at both input and output. The number of devices, such as thyristors, used in cyclo-converters depends on the types of connection, and also the number of phases at both input and output. It may be noted that all features of a cyclo-converter may not be available in a dc link converter. Similarly, certain features, like Pulse Width Modulation (PWM) techniques as used in inverters and also converters, to reduce the harmonics in voltage waveforms, are not applied in cyclo-converters. The various circuits used and their operational aspects are discussed in detail in the next (last) module (#5) on DC to AC Converters termed as Inverters.

Advantages and Disadvantages of DC Link Converter

Advantages

1. The output frequency can be varied from zero to rated value, with the upper frequency limit, being decided by the turn-off time of the switching devices, which is quite low due to the use of transistors in recent time.

2. .The control circuit here is simpler, as compared to that used in cyclo-converter.
3. It has high input power factor, if diode rectifier is used in the first stage. If phase-controlled thyristor converter is used, power factor depends upon phase angle delay.
4. It is suitable for higher frequencies, as given earlier.

Disadvantages

1. The conversion is in two stages, using two power controllers − one as converter and other as inverter, as stated earlier.
2. Forced commutation is required for the inverter, if thyristors are used, even though phase control is used in converter, where natural commutation takes place.
3. The feature of regeneration is somewhat difficult, and also is involved to incorporate in a dc link converter.
4. The output waveform of the inverter is normally a stepped one, which may cause non-uniform rotation of an ac motor at very low frequencies (< 10 Hz). The distorted waveform also causes system instability at low frequencies. This can be reduced by using PWM technique as given earlier.

In this lesson, the first one in the second half of this module (#4), the cyclo-converter is first introduced, along with the basic principle of operation. The circuit and the operation of single-phase to single-phase cyclo-converter, with both resistive and inductive loads, are described in detail, with voltage and current waveforms. The current is discontinuous, with resistive and inductive (with low value of inductance) loads, but can be continuous, if the inductance is higher. In the next lesson, the circuit and operation of three-phase to single-phase cyclo-converter, followed by three-phase to three-phase one, will be described in detail.