NBKRIST

POWER ELECTRONICS LECTURE NOTES

UNIT-6

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

UNIT-VI

AC voltage controller: Single phase two SCR's in anti-parallel - with R and RL loads- derivation of RMS load voltage- current and power factor.

Cyclo-converters: Single phase midpoint and bridge configuration cycle-converters with R and RL loads (step up and step down).

AC VOLTAGE CONTROLLERS

6.1 Introduction

AC voltage controller is a type of thyristor power converter which is used to convert a fixed voltage AC input supply to obtain a variable voltage AC output with constant frequency as shown in fig 6.1. The RMS value of the ac output voltage and the ac power flow to the load is controlled by varying (adjusting) the trigger angle ‘α’

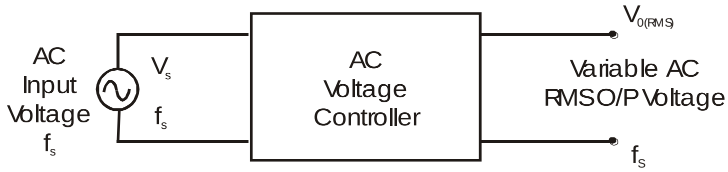


Fig :6.1 basic block diagram

There are two different types of thyristor control used in practice to control the ac power flow

- On-Off control
- Phase control

6.1.1 ON-OFF CONTROL

In On-Off control technique Thyristors are used as switches to connect the load circuit to the ac supply (source) for a few cycles of the input ac supply and then to disconnect it for few input cycles. The Thyristors thus act as a high speed contactor (or high speed ac switch).

6.1.2 PHASE CONTROL

In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle. That is the ac supply voltage is chopped using Thyristors during a part of each input cycle. By controlling the phase angle or the trigger angle ‘α’ (delay angle), the output RMS voltage across the load can be controlled. The trigger delay angle ‘α’ is defined as the phase angle (the value of ωt) at which the thyristor turns on and the load current begins to flow.

Thyristors in ac voltage controllers are line commutated (phase commutated or naturally commutated) since the input supply is ac. When the input ac voltage reverses and becomes negative during the negative half cycle the current flowing through the conducting thyristor decreases and falls to zero. Thus the ON thyristor naturally turns off, when the device current falls to zero.

Phase controls Thyristors which are relatively inexpensive, converter grade Thyristors which are slower than fast switching inverter grade Thyristors are normally used.

For applications up to 400Hz, if TRIAC’s are available to meet the voltage and current ratings of a particular application, TRIAC’s are more commonly used. Due to ac line commutation or natural commutation, there is no need of extra commutation circuitry or components and the circuits for ac voltage controllers are very simple.

6.1.3 TYPE OF AC VOLTAGE CONTROLLERS

The ac voltage controllers are classified into two types based on the type of input ac supply applied to the circuit.

- Single Phase AC Controllers.
- Three Phase AC Controllers.

Single phase ac controllers operate with single phase ac supply voltage of 230V RMS at 60Hz in our country. Three phase ac controllers operate with 3 phase ac supply of 400V RMS at 60Hz supply frequency.

Each type of controller may be sub divided into

- Uni-directional or half wave ac controller.
- Bi-directional or full wave ac controller.

In brief different types of ac voltage controllers are

- Single phase half wave ac voltage controller (uni-directional controller).
- Single phase full wave ac voltage controller (bi-directional controller).
- Three phase half wave ac voltage controller (uni-directional controller).
- Three phase full wave ac voltage controller (bi-directional controller).

6.1.4 APPLICATIONS OF AC VOLTAGE CONTROLLERS

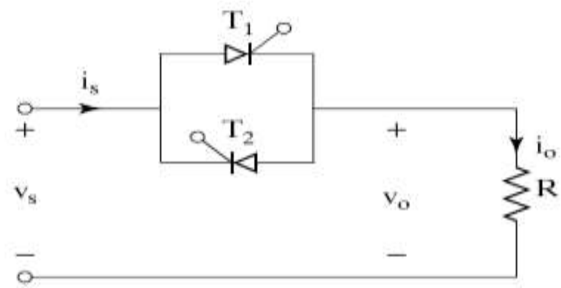
- Lighting / Illumination control in ac power circuits.
- Induction heating.
- Industrial heating & Domestic heating.
- Transformers tap changing (on load transformer tap changing).
- Speed control of induction motors (single phase and poly phase ac induction motor control).
- AC magnet controls.

6.2 Principle of On-Off Control Technique (Integral Cycle Control)

The basic principle of on-off control technique is explained with reference to a single phase full wave ac voltage controller circuit shown below figure 6.2. The thyristor switches T_1 and T_2 are turned on by applying appropriate gate trigger pulses to connect the input ac supply to the load for 'n' number of input cycles during the time interval t_{ON}. The thyristor switches T_1 and T_2 are turned off by blocking the gate trigger pulses for 'm' number of input cycles during the time interval t_{OFF}. The ac controller ON time t_{ON} usually consists of an integral number of input cycles.

Thyristors are turned ON precisely at the zero voltage crossings of the input supply. The thyristor T_1 is turned on in positive half cycle and the thyristor T_2 is turned on in negative half cycle by applying gating signal to the gates of T_1 and T_2, during t_{ON} in the respective half cycles. The load current flows during T_{ON} and it is in bi-directional (alternating load current flow).

This type of control is used in applications which have high mechanical inertia and high thermal time constant (Industrial heating and speed control of ac motors). Due to zero voltage and zero current switching of Thyristors, the harmonics generated by switching actions are reduced.



$R = R_L$ **= Load Resistance**

Fig:6.2 Single phase full wave AC voltage controller circuit

Example: Referring to the waveforms of ON-OFF control technique in the below diagram fig 6.3,
$n =$ Two input cycles. Thyristors are turned ON during t_{ON} for two input cycles.
$m =$ One input cycle. Thyristors are turned OFF during t_{OFF} for one input cycle

For a sine wave input supply voltage, $v_s = V_m \sin \omega t = \sqrt{2} V_S \sin \omega t$

$V_S =$ RMS value of input ac supply = $\frac{V_m}{\sqrt{2}}$ = RMS phase supply voltage.

If the input ac supply is connected to load for 'n' number of input cycles and disconnected for 'm' number of input cycles, then

$t_{ON} = n \times T, \quad t_{OFF} = m \times T$ Where $T = \frac{1}{f}$ = input cycle time (time period) and

f = input supply frequency.

t_{ON} = controller on time = $n \times T$; t_{OFF} = controller off time = $m \times T$.

T_O = Output time period = $\left(t_{ON} + t_{OFF}\right) = \left(nT + mT\right)$.

We can show that,

Output RMS voltage $V_{O(RMS)} = V_{i(RMS)} \sqrt{\frac{t_{ON}}{T_O}} = V_S \sqrt{\frac{t_{ON}}{T_O}}$

Where $V_{i(RMS)}$ the RMS is input supply voltage = V_S .

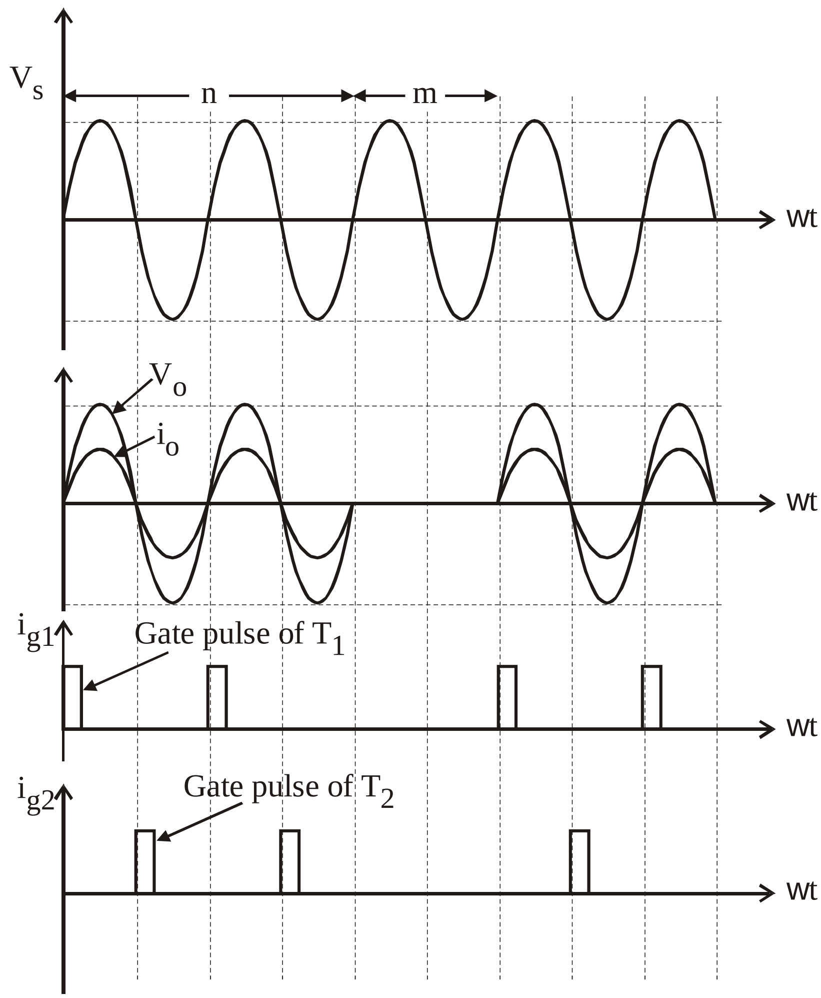


Fig.: 6.3 Waveforms of On-Off Control

6.3 Performance Parameters of Ac Voltage Controllers

- **RMS Output (Load) Voltage**

$$V_{O(RMS)} = \left[\frac{n}{2\pi(n+m)} \int_0^{2\pi} V_m^{\,2} \sin^2 \omega t.d(\omega t) \right]^{1/2}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{n}{(m+n)}} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

$$V_{O(RMS)} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

Where $V_S = V_{i(RMS)}$ = RMS value of input supply voltage.

- **Duty Cycle**

$$k = \frac{t_{ON}}{T_O} = \frac{t_{ON}}{\left(t_{ON} + t_{OFF}\right)} = \frac{nT}{(m+n)T}$$

Where, $k = \frac{n}{(m+n)}$ = duty cycle (d).

- **RMS Load Current**

$$I_{O(RMS)} = \frac{V_{O(RMS)}}{Z} = \frac{V_{O(RMS)}}{R_L};$$

for a resistive load $Z = R_L$.

- **Output AC (Load) Power**

$$P_O = I^2_{O(RMS)} \times R_L$$

- **Input Power Factor**

$$PF = \frac{P_O}{VA} = \frac{\text{output load power}}{\text{input supply volt amperes}} = \frac{P_O}{V_S I_S}$$

$$PF = \frac{I^2_{O(RMS)} \times R_L}{V_{i(RMS)} \times I_{in(RMS)}};$$

$I_S = I_{in(RMS)} =$ RMS input supply current.

The input supply current is same as the load current $I_{in} = I_O = I_L$

Hence, RMS supply current = RMS load current; $I_{in(RMS)} = I_{O(RMS)}$.

$$PF = \frac{I^2_{O(RMS)} \times R_L}{V_{i(RMS)} \times I_{in(RMS)}} = \frac{V_{O(RMS)}}{V_{i(RMS)}} = \frac{V_{i(RMS)}\sqrt{k}}{V_{i(RMS)}} = \sqrt{k}$$

$$PF = \sqrt{k} = \sqrt{\frac{n}{m+n}}$$

- **The Average Current of Thyristor** $I_{T(Avg)}$

Average thyristor current is shown in below figure 6.4

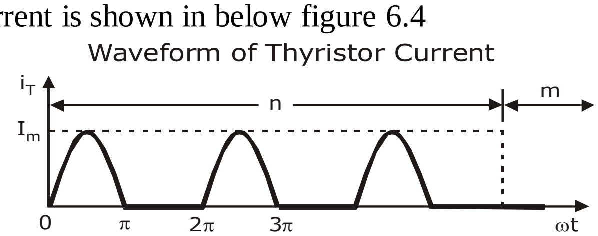


Fig 6.4 Average current of thyristor

$$I_{T(Avg)} = \frac{I_m n}{\pi(m+n)} = \frac{k.I_m}{\pi},$$

Where $I_m = \frac{V_m}{R_L}$ = maximum or peak thyristor current and k = duty cycle $= \frac{t_{ON}}{(t_{ON}+t_{OFF})} = \frac{n}{(n+m)}$

- **RMS Current of Thyristor** $I_{T(RMS)}$

$$I_{T(RMS)} = \frac{I_m}{2}\sqrt{\frac{n}{(m+n)}} = \frac{I_m}{2}\sqrt{k}$$

$$I_{T(RMS)} = \frac{I_m}{2}\sqrt{k}$$

6.5 Single phase full wave AC voltage controller with resistive load:

Single phase full wave AC voltage controller circuit using two SCRs or a single TRIAC is generally used in most of the ac control applications. A single phase full wave ac voltage controller with a resistive load is shown in the figure 6.5 below. It is possible to control the ac power flow to the load in both the half cycles by adjusting the trigger angle α. Hence the full wave ac voltage controller is also referred to as to a bi-directional controller.

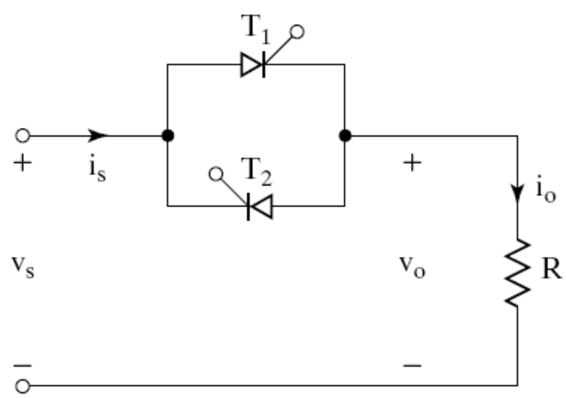


Fig 6.5 Single phase full wave AC voltage controller circuit using two SCR's

The thyristor T_1 is forward biased during the positive half cycle of the input supply voltage. The thyristor T_1 is triggered at a delay angle of α. Considering the on thyristor T_1 as an ideal closed switch the input supply voltage appears across the load resistor R and the output voltage, v_O is same as input voltage, v_S during $\omega t = \alpha$ to π radians. The load current flows through the conducting thyristor T_1 and through the load resistor R in the downward direction in this period. At $\omega t = \pi$, when the input voltage falls to zero the thyristor current falls to zero and hence T_1 naturally turns off. No current flows in the circuit during $\omega t = \pi$ to $(\pi + \alpha)$.

The thyristor T_2 is forward biased during the negative cycle of input supply and when thyristor T_2 is triggered at a delay angle ($\pi + \alpha$), the output voltage follows the negative half cycle of input from $\omega t = (\pi + \alpha)$ to 2π. When T_2 is on, the load current flows in the reverse direction (upward direction). The time interval between the gate trigger pulses of T_1 and T_2 is kept at π radians. At $\omega t = 2\pi$ the input supply voltage falls to zero and hence the load current also falls to zero and thyristor T_2 turns off naturally. Respective waveforms are shown in figure 6.7 .

Instead of using two SCR's in parallel, a TRIAC can be used for full wave ac voltage control as shown in figure 6.6.

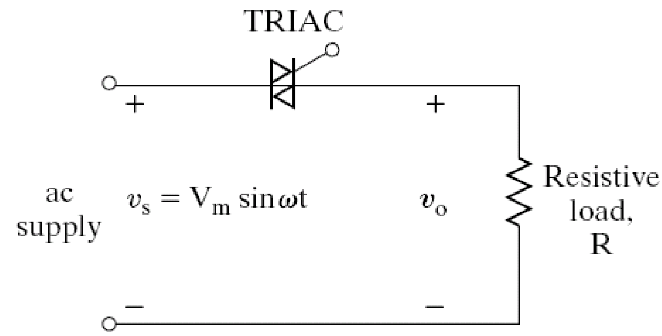


Fig 6.6: Single phase full wave AC voltage controller circuit using TRIAC

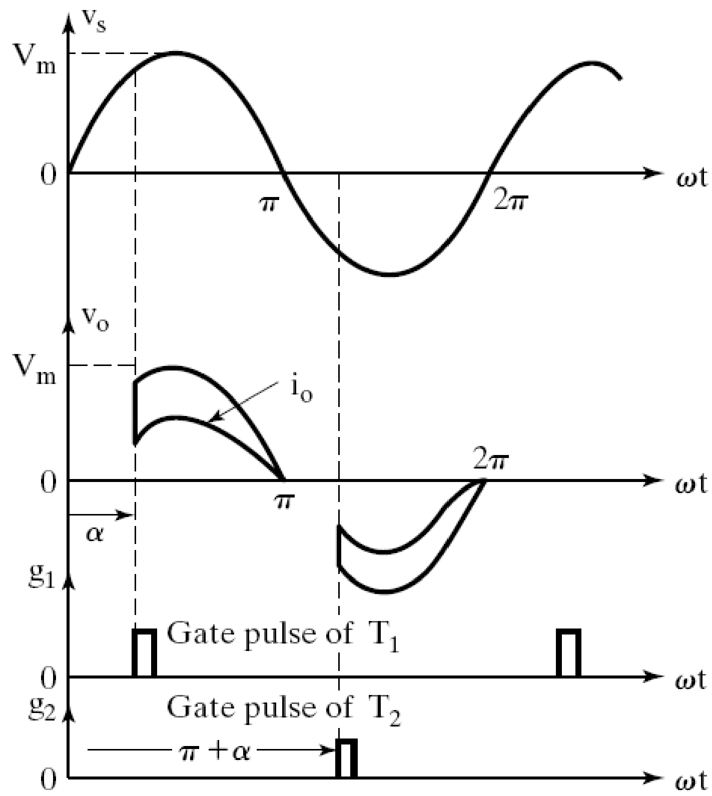


Fig 6.7 out put voltage waveforms

- For a sine wave input supply voltage,

$v_S = V_m \sin \omega t = \sqrt{2} V_S$

Where V_S = RMS value of input ac supply = $V_m/\sqrt{2}$ = RMS phase supply voltage,

- Output load voltage is given by

$$V_{L(RMS)} = V_S \sqrt{\frac{1}{\pi}\left[(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]}$$

6.5.1 Control Characteristic of Single Phase Full-Wave AC Voltage Controller with Resistive Load

The control characteristic is the plot of RMS output voltage $V_{O(RMS)}$ versus the trigger angle α ; which can be obtained by using the expression for the RMS output voltage of a full-wave ac controller with resistive load.

$$V_{O(RMS)} = V_S \sqrt{\frac{1}{\pi}\left[(\pi - \alpha) + \frac{\sin 2\alpha}{2}\right]} \quad ; \quad \text{Where} \quad V_S = \frac{V_m}{\sqrt{2}} = \text{RMS value of input supply voltage}$$

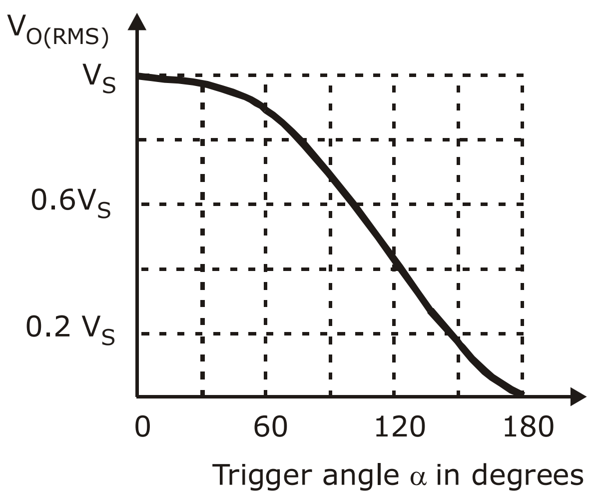


Fig 6.8 control characteristics

We can notice from the figure, that we obtain a much better output control characteristic by using a single phase full wave ac voltage controller. The RMS output voltage can be varied from a maximum of 100% V_S at $\alpha = 0$ to a minimum of '0' at $\alpha = 180^0$. Thus we get a full range output voltage control by using a single phase full wave ac voltage controller.

6.6 Single phase full wave AC voltage controller with R-L load:

- In practice most of the loads are of RL type. For example a single phase full wave ac voltage controller controlling the speed of a single phase ac induction motor, the load which is the induction motor winding is an RL type of load, where R represents the motor winding resistance and L represents the motor winding inductance.
- A single phase full wave ac voltage controller circuit with an RL load using two thyristors T_1 and T_2 connected in parallel is shown in the figure below.
- The thyristor T_1 is forward biased during the positive half cycle of input supply. The thyristor T_1 is triggered at a delay angle of α, by applying a suitable gate trigger pulse to T_1 when is forward biased. The output voltage across the load follows the input supply voltage when T_1 is on. The load current flows through the load in the downward direction. This load current pulse flowing through T_1 can be considered as the positive current pulse. Due to the inductance in the load, the load current flowing through T_1 would not fall to zero at $\omega t = \pi$, when the input supply voltage starts to become negative.

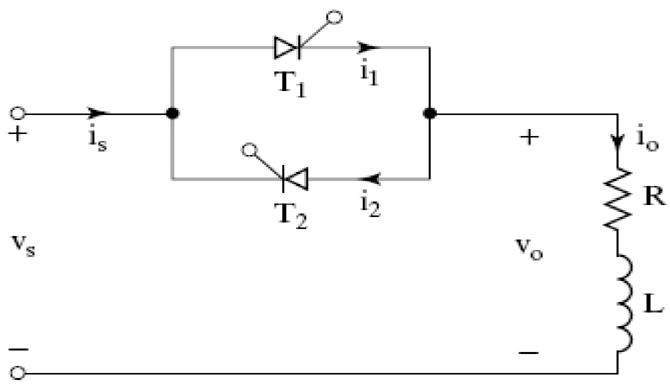


Fig 6.9 Single phase full wave AC voltage controller with RL load

- The thyristor T_1 will continue to conduct the load current until all the inductive energy stored in the load inductor L is completely utilized and the load current through T_1 falls to zero at $\omega t = \beta$, where β is called as the extinction angle, at which the load current falls to zero. The thyristor T_1 conducts from $\omega t = \alpha$ to β. Waveforms of single phase full wave ac voltage controller with RL load for α>ø are shown in the figures below. Discontinuous load current operation occurs for α>ø and $\beta < (\pi+\alpha)$.

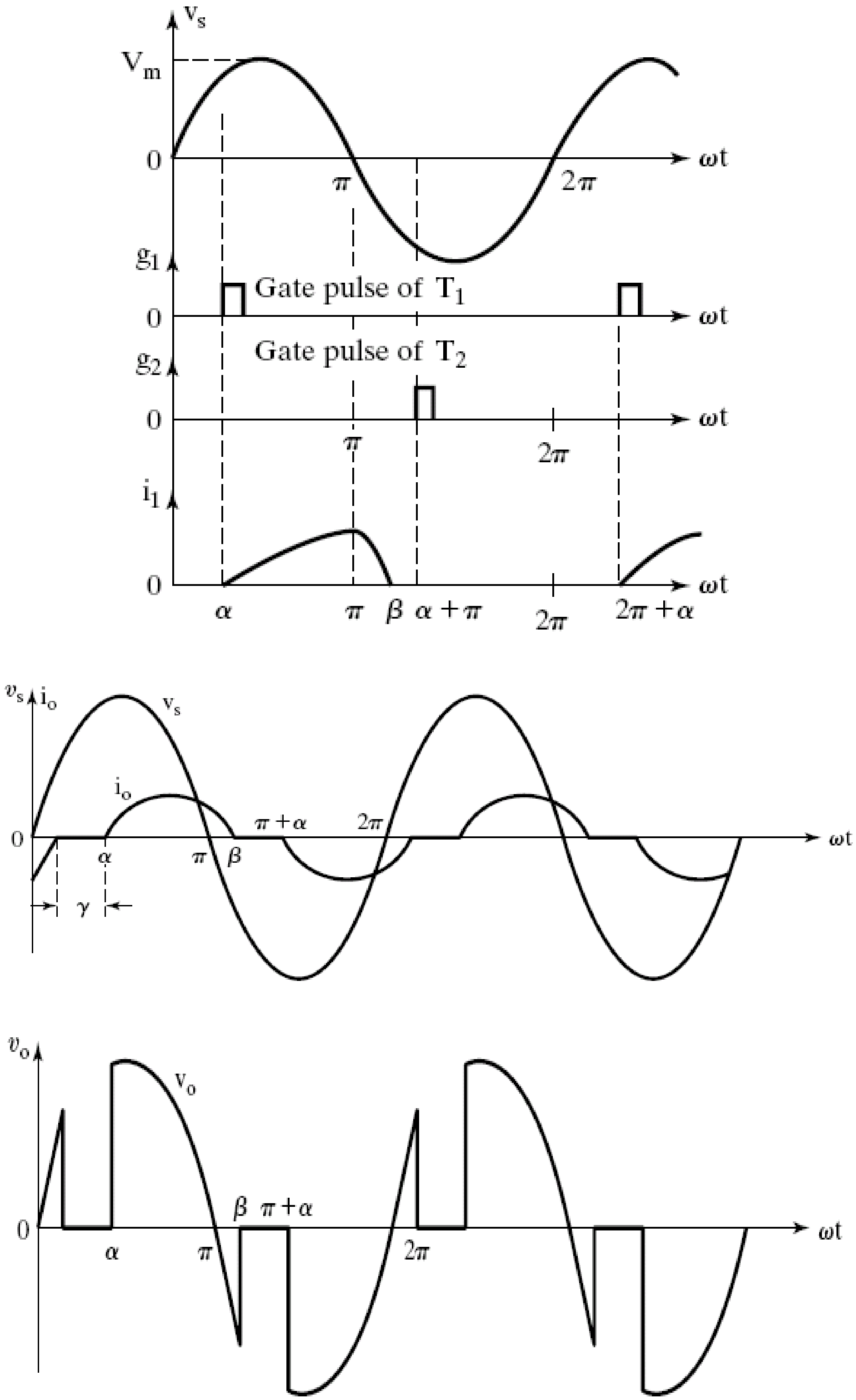


Fig 6.10 Single phase full wave AC voltage controller with RL load waveforms

➢ For a sine wave input supply voltage,

$v_S = V_m \sin \omega t = \sqrt{2} V_S$

Where V_S = RMS value of input ac supply = $V_m/\sqrt{2}$ = RMS phase supply voltage,

- Output load voltage is given by

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}}\left[\frac{1}{\pi}\left\{(\beta-\alpha)+\frac{\sin 2\alpha}{2}-\frac{\sin 2\beta}{2}\right\}\right]^{1/2}$$

- This circuit, AC voltage controller can be used to regulate the RMS voltage across the terminals of an ac motor. It can be used to control the temperature of a furnace by varying the RMS output voltage.
- For very large load inductance 'L' the SCR may fail to commutate, after it is triggered and the load voltage will be a full sine wave (similar to the applied input supply voltage and the output control will be lost) as long as the gating signals are applied to the thyristors T_1 and T_2. The load current waveform will appear as a full continuous sine wave and the load current waveform lags behind the output sine wave by the load power factor angle ϕ as shown in figure 6.11.

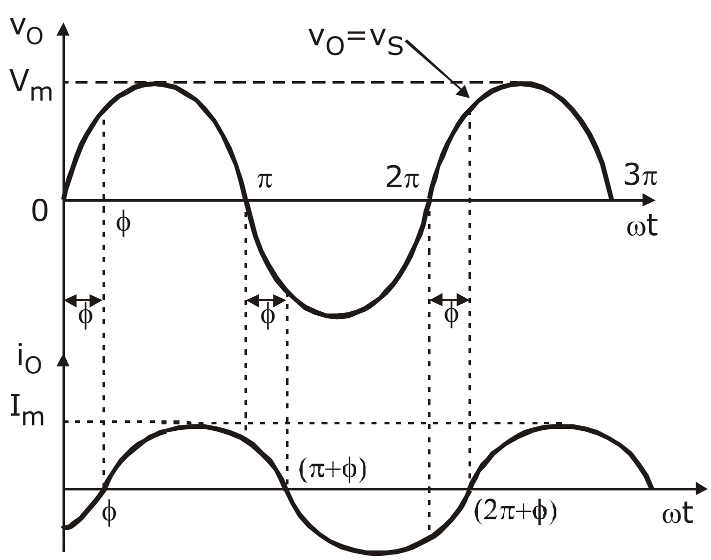


Fig 6.11 load current waveforms if L is large

CYCLO-CONVERTERS

6.2 Introduction

- Traditionally, ac-ac conversion using power semiconductor switches is done in two different ways: 1- in two stages (ac-dc and then dc-ac) as in dc link converters or 2- in one stage (ac-ac) cycloconverters as shown in figure 6.21. Cycloconverters are used in high power applications driving induction and synchronous motors. They are usually phase-controlled and they traditionally use thyristors due to their ease of phase commutation.

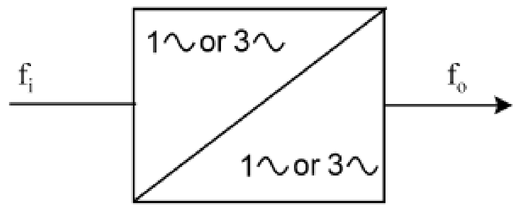


Fig 6.21 block diagram of cyclo converter

- There are other newer forms of cyclo-conversion such as ac-ac matrix converters and high frequency ac-ac converters and these use self-controlled switches. These converters, however, are not popular yet.

Applications of cycloconverter are:

- Cement mill drives
- Ship propulsion drives
- Rolling mill drives
- Scherbius drives
- Ore grinding mills
- Mine winders

6.21 Advantages and Disadvantages of Cyclo-converter:

6.21(a) 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 frequencies, since it is fabricated from a large number of segments of the supply waveform. This is often preferable for very low speed applications.

6.21(b) 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.

6.22 Principle of Operation of Single Phase Cyclo-converter:

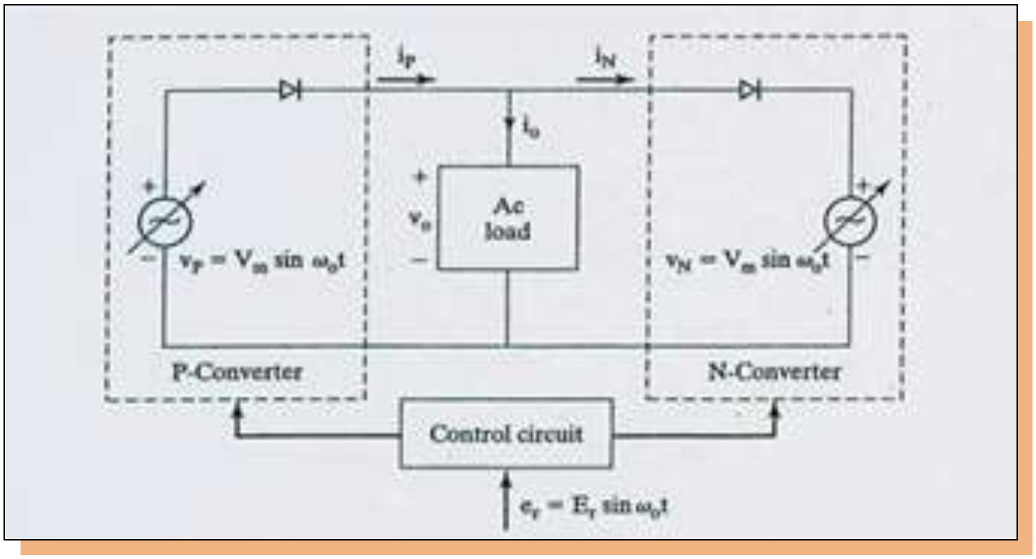


Fig 6.22 equivalent circuit of cyclo converter

A cyclo-converter is a direct frequency changer that converts ac power at one frequency at one frequency to ac power at another frequency to ac to ac conversion without any intermediate dc link.

They are again classified as:

1. Step Up Cyclo-Converter
2. Step Down Cyclo-Converter

6.23 Step Up Cyclo-Converter

a) Mid-point step-up cyclo-converter

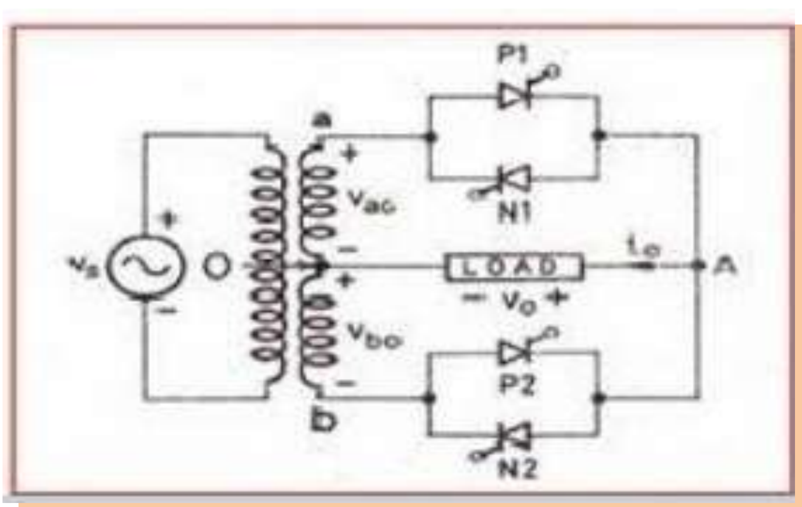


Fig_6.23: Step Up Cyclo-Converter midpoint connection

P1,P2 -> Positive Group Thyristor

N1,N2 -> Negative Group Thyristor

In Single Phase Step Up Cyclo Converter, during a positive half cycle of supply voltage terminal A is positive with respect to terminal B so that SCRs P_1 and N_2 are forward biased from wt = 0 to wt = π. SCR P_1 is turned on at wt = 0, so that load voltage is positive. At certain instant wt_1, P_1 is forced commutated and N_2 is turned on by providing a gate signal to it and it remains in a conduction state and load voltage is negative.

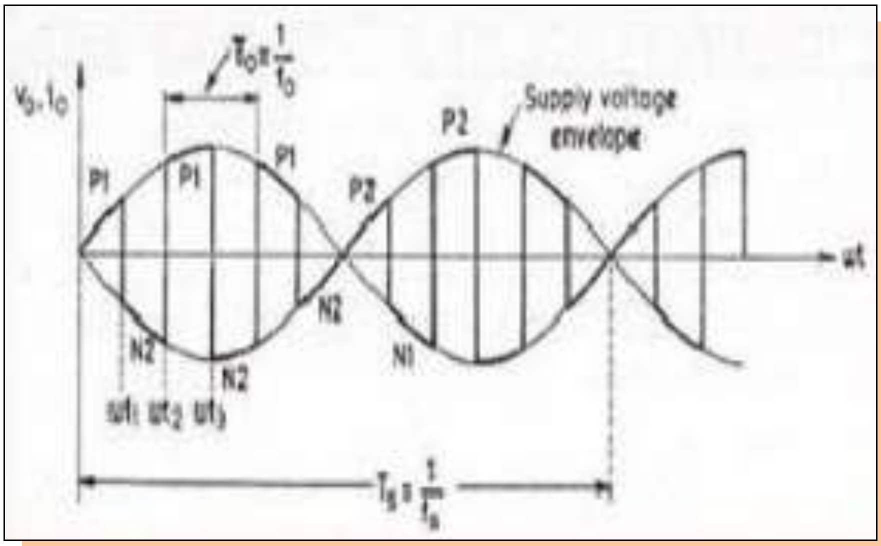


Fig6.24 step up cyclo converter waveforms (fo=6fs)

Similarly, at wt_2, N_2 is forced commutated and P_1 is turned on and load voltage is positive. So, we can repeat this process by turning on and turning off the Positive Group Thyristor in the appropriate time interval. When wt = π, terminal B is positive with respect to terminal A; both SCR P_2 and N_1 are therefore forward biased from wt = π to 2π. In the same way, P2 and N1 are turned on and off in a certain sequence.

Thus, by switching the positive group thyristor and Negative group thyristor in a certain appropriate sequence as mentioned above, the frequency of the output voltage is increased certain times than frequency of input voltage.

Similarly for Bridge type Cycloconverter, circuit diagram as shown in fig. 6.26 and related wave forms are shown in fig. 6.26.

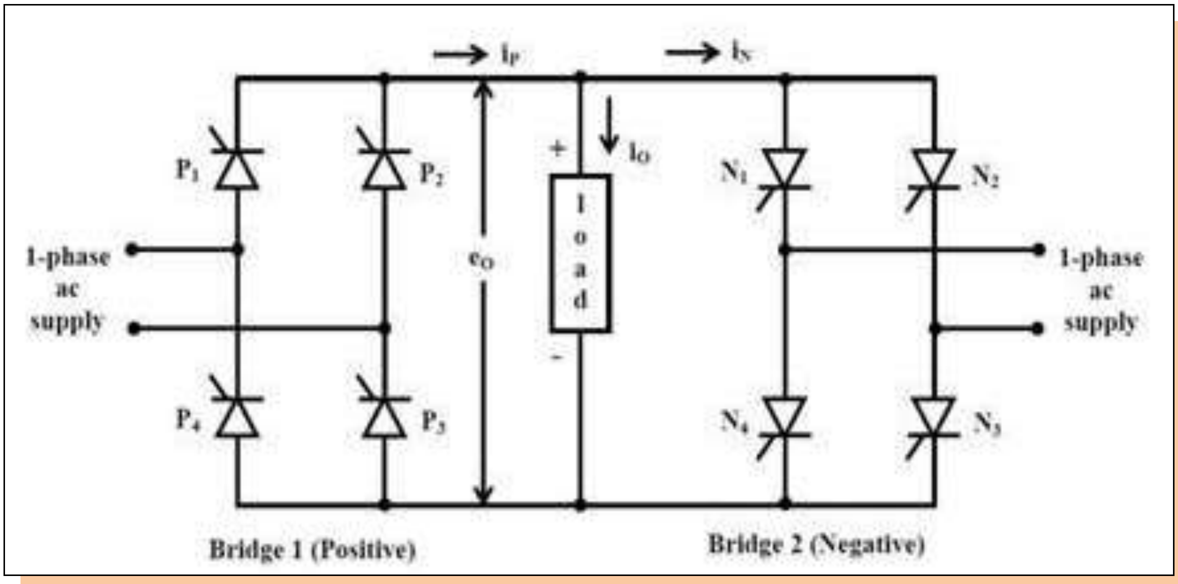


Fig_6.26: Step Up Bridge type Cyclo-Converter connection

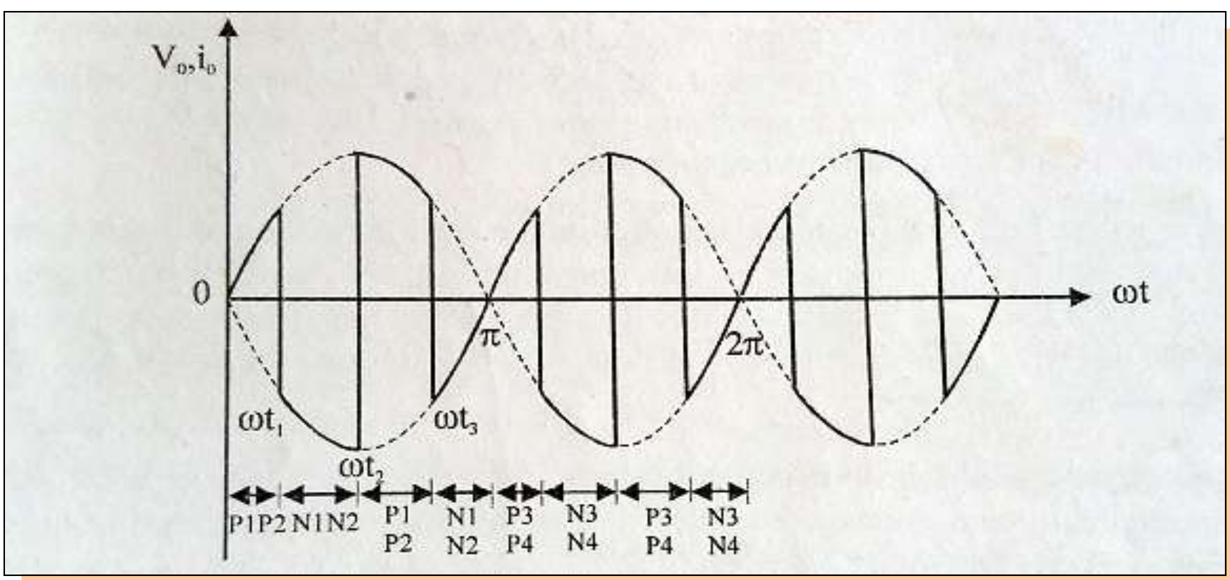


Fig6.26 step up cyclo converter waveforms for Bride type cyclo conveter (fo=4fs)

5.24 Step Down Cyclo-Converter

a) Bridge type Step Down Cyclo-Converter

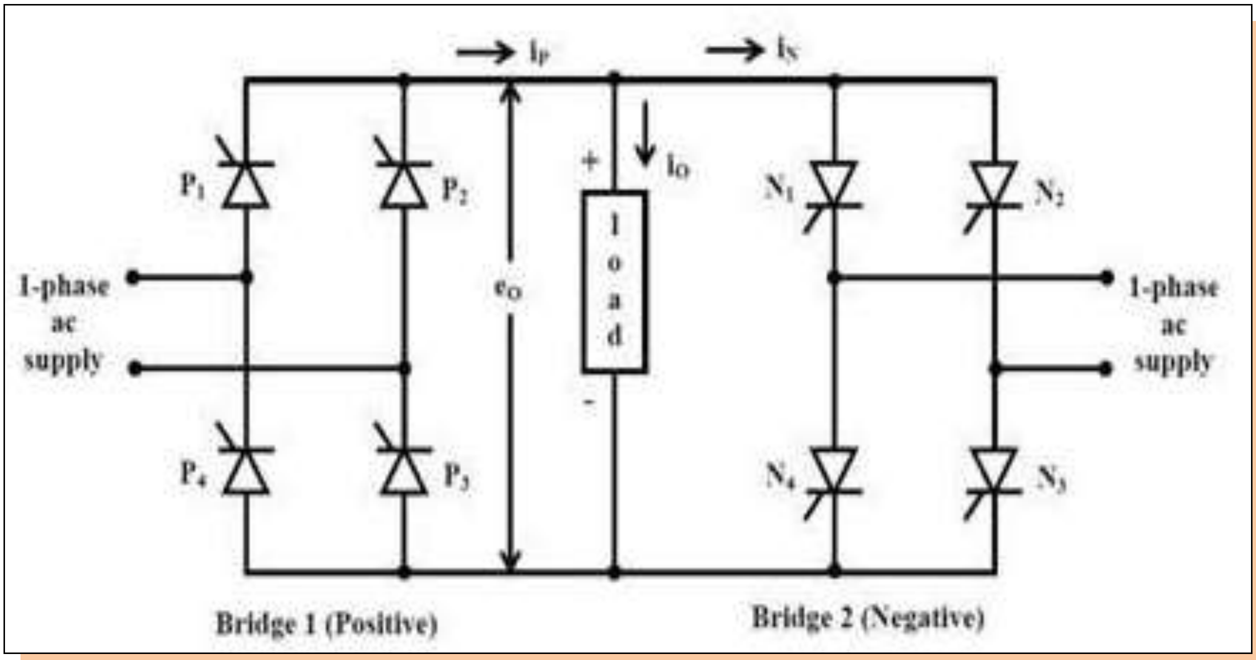


Fig 6.27: Bridge type Step Down Cyclo-Converter circuit diagram

In this converter, two single phase controlled converters are operated as a bridge rectifier and they are named as P-Converter and N-Converter where P and N mean positive and negative. Thus P-Converter gives positive output voltage while N-Converter gives negative output voltage. However, their delay angles are such that the output voltage of P-Converter is equal to the output voltage of N-Converter.

Gating Sequence

During the first period of output frequency $T_o/2$, P-Converter operates at a delay angle $\alpha_p = \alpha$ i.e by gating T_1 and T_2 at α and T_3 and T_4 at $(\pi + \alpha)$. During the negative half cycle, $T_o/2$, N-Converter operating at delay angle of $\alpha_n = \alpha$ i.e by gating T_1' and T_2' at $3\pi + \alpha$ and T_3' and T_4' at $4\pi + \alpha$ as shown in figure 6.28 for $f_o = ½ f_s$.

Similarly the related wave forms are shown for RL load to discontinues and continuous current conduction as shown in figs. 6.29 and 6.30 respectively.

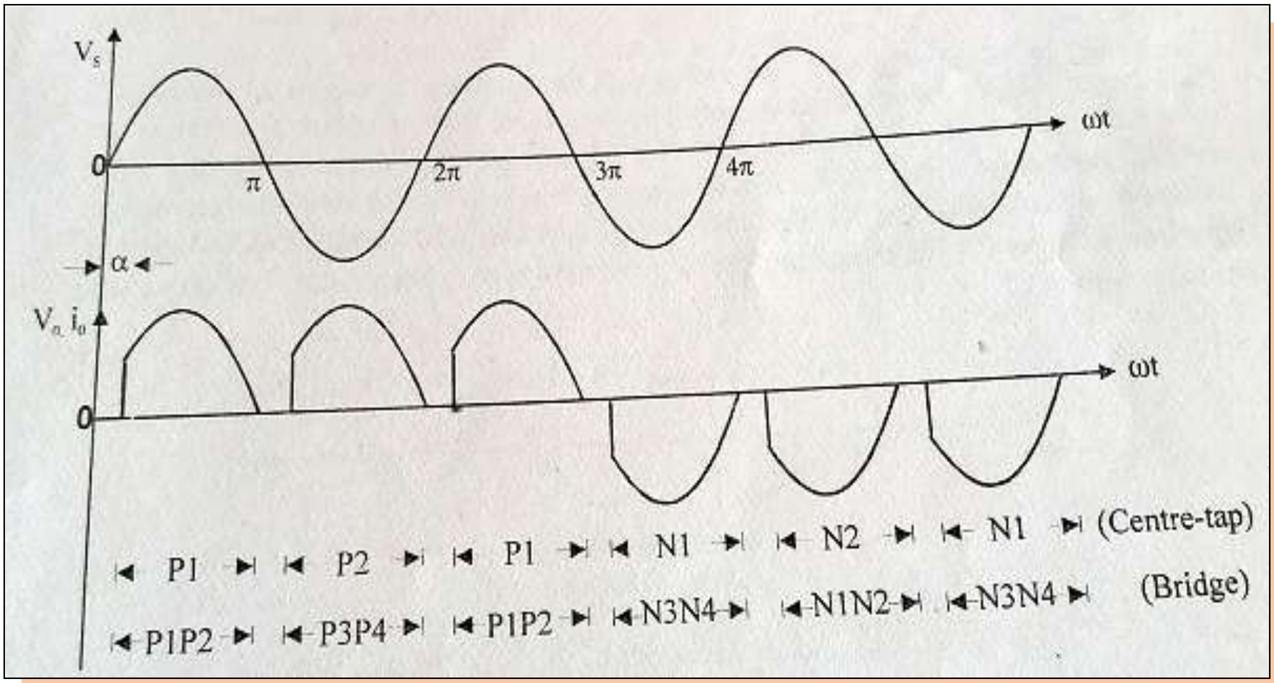


Fig 6.28 Related wave forms for step down cyclo-converter with Resistive load.

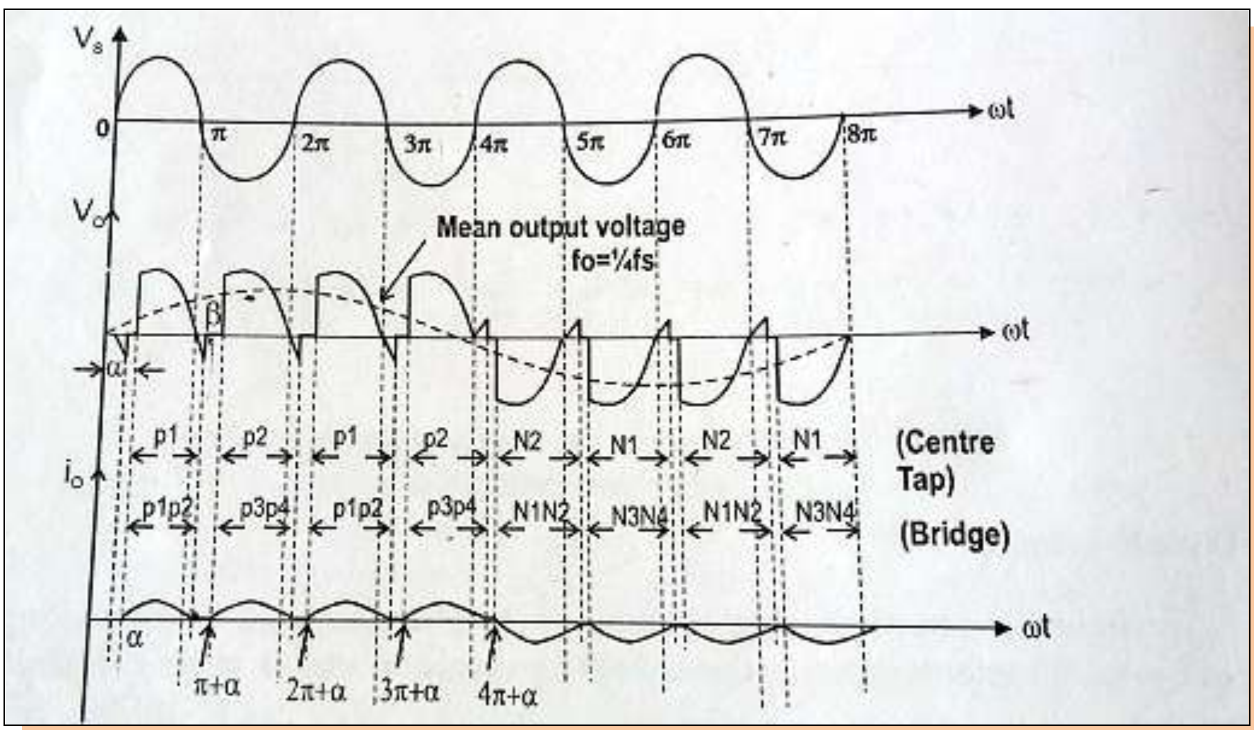


Fig 6.29 Voltage and current wave forms for step down cyclo - converter with discontinuous load current mode of operation

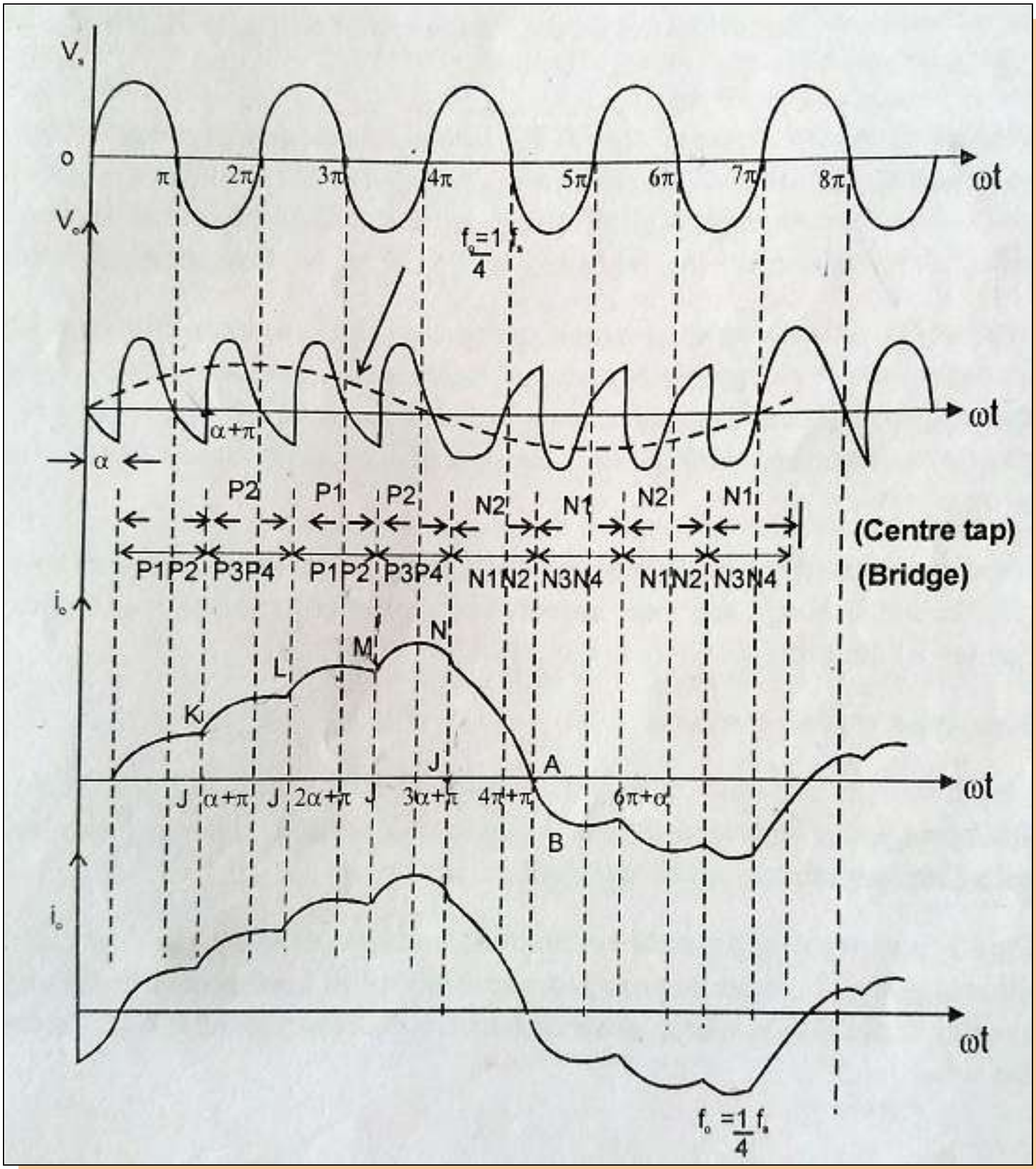


Fig 6.30 Voltage and current wave forms for step down cyclo - converter with continuous load current mode of operation

Similarly the fig. 6.31 shows Mid-point step-down cyclo-converter and operates the P1, P2 switches to generate positive pulse in output voltage and operates the N1, N2 switches to generate negative pulse in output voltage. The voltage and current wave forms for R and RL loads are as shown in Figs. 6.28, 6.29 and 6.30.

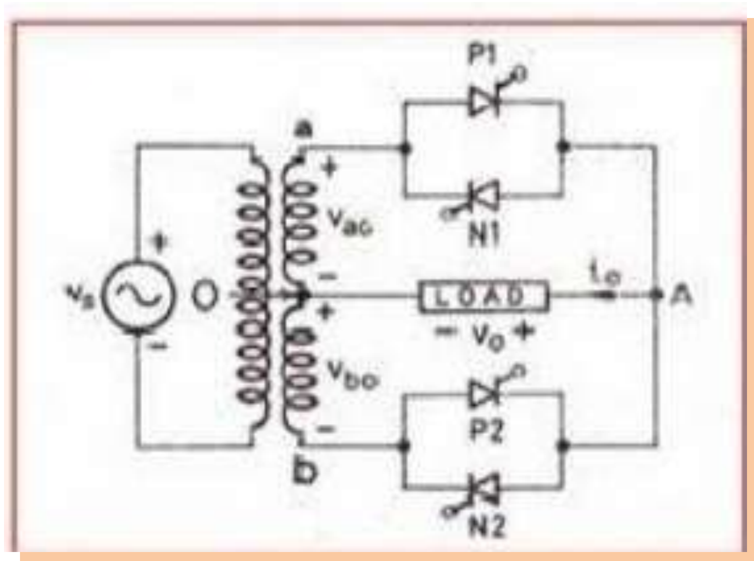


Fig. 6.13 Mid-point step-down cyclo-converter circuit diagram