The diodes have the following advantages

- High mechanical and thermal reliability
- High peak inverse voltage
- Low reverse current
- Low forward voltage drop
- High efficiency
- Compactness.

1.9 POWER TRANSISTORS

Power transistors are devices that have controlled turn-on and turn-off characteristics. These devices are used a switching devices and are operated in the saturation region resulting in low on-state voltage drop. They are turned on when a current signal is given to base or control terminal. The transistor remains on so long as the control signal is present. The switching speed of modern transistors is much higher than that of thyristors and are used extensively in dc-dc and dc-ac converters. However their voltage and current ratings are lower than those of thyristors and are therefore used in low to medium power applications.

Power transistors are classified as follows

- Bipolar junction transistors(BJTs)
- Metal-oxide semiconductor filed-effect transistors(MOSFETs)
- Static Induction transistors(SITs)
- Insulated-gate bipolar transistors(IGBTs)

1.9.1 BIPOLAR JUNCTION TRANSISTORS

The need for a large blocking voltage in the off state and a high current carrying capability in the on state means that a power BJT must have substantially different structure than its small signal equivalent. The modified structure leads to significant differences in the I-V characteristics and switching behavior between power transistors and its logic level counterpart.

1.9.2 POWER TRANSISTOR STRUCTURE

If we recall the structure of conventional transistor we see a thin p-layer is sandwiched between two n-layers or vice versa to form a three terminal device with the terminals named as Emitter, Base and Collector.

The difference in the two structures is obvious.

A power transistor is a vertically oriented four layer structure of alternating p-type and n-type. The vertical structure is preferred because it maximizes the cross sectional area and through which the current in the device is flowing. This also minimizes on-state resistance and thus power dissipation in the transistor.

The doping of emitter layer and collector layer is quite large typically 10^{19} cm^{-3}. A special layer called the collector drift region (n^{-}) has a light doping level of 10^{14}.

The thickness of the drift region determines the breakdown voltage of the transistor. The base thickness is made as small as possible in order to have good amplification capabilities, however if the base thickness is small the breakdown voltage capability of the transistor is compromised.

APPLICATIONS

Widely used in medium power applications such as DC and AC motor drives, UPS systems, Power supplies for solenoids, relays and contractors.

Though IGBT’s are more expensive than BJT’s, they have lower gate drive requirements, lower switching losses. The ratings up to 1200V, 500A.

SERIES AND PARALLEL OPERATION

Transistors may be operated in series to increase their voltage handling capability. It is very important that the series-connected transistors are turned on and off simultaneously. Other wise, the slowest device at turn-on and the fastest devices at turn-off will be subjected to the full voltage of the collector emitter circuit and the particular device may be destroyed due to high voltage. The devices should be matched for gain, transconductance, threshold voltage, on state voltage, turn-on time, and turn-off time. Even the gate or base drive characteristics should be identical.

Transistors are connected in parallel if one device cannot handle the load current demand. For equal current sharings, the transistors should be matched for gain, transconductance, saturation voltage, and turn-on time and turn-off time. But in practice, it is not always possible to meet these requirements. A reasonable amount of current sharing (45 to 55% with two transistors) can be obtained by connecting resistors in series with the emitter terminals as shown in the figure 10.

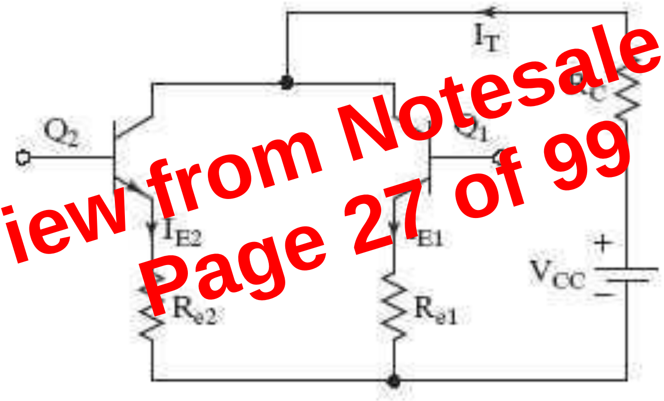


Fig. 10: Parallel connection of Transistors

The resistor will help current sharing under steady state conditions. Current sharing under dynamic conditions can be accomplished by connecting coupled inductors. If the current through Q_1 rises, the $l\, di/dt$ across L_1 increases, and a corresponding voltage of opposite polarity is induced across inductor L_2 . The result is low impedance path, and the current is shifted to Q_2 . The inductors would generate voltage spikes and they may be expensive and bulky, especially at high currents.

During turn-on, the collector rise and the di/dt is

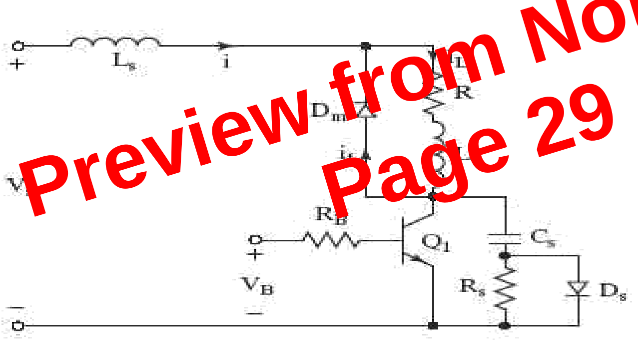
$$\frac{di}{dt} = \frac{I_L}{t_r} = \frac{I_{cs}}{t_r} \quad ...(1)$$

During turn off, the collector emitter voltage must rise in relation to the fall of the collector current, and is

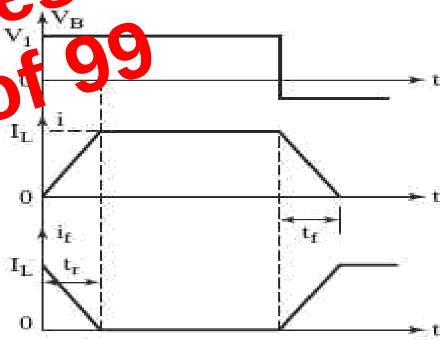
$$\frac{dv}{dt} = \frac{V_s}{t_f} = \frac{V_{cc}}{t_f} \quad ...(2)$$

The conditions di/dt and dv/dt in equation (1) and (2) are set by the transistor switching characteristics and must be satisfied during turn on and turn off. Protection circuits are normally required to keep the operating di/dt and dv/dt within the allowable *limits of transistor. A typical switch with* di/dt and dv/dt protection is shown in figure *(a), with operating wave forms in figure (b). The RC network across the transistor is known as the snubber circuit or snubber and limits the* dv/dt . The inductor L_S , which *limits the* di/dt , is sometimes called series snubber.

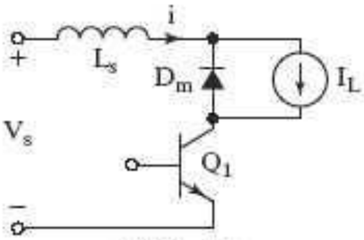
Let us assume that under steady state conditions the load current I_L is free wheeling through diode D_m , which has negligible reverse reco`very time. When transistor Q_1 is turned on, the collector current rises and current of diode D_m falls, because D_m will behave as short circuited. The equivalent circuit during turn on is shown in figure below



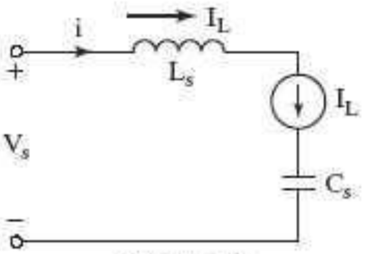
(a) Protection circuits



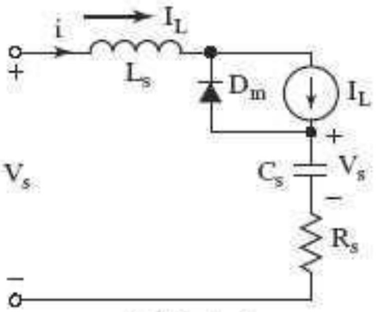
(b) Waveforms



(a) Mode 1



(b) Mode 2



(c) Mode 3

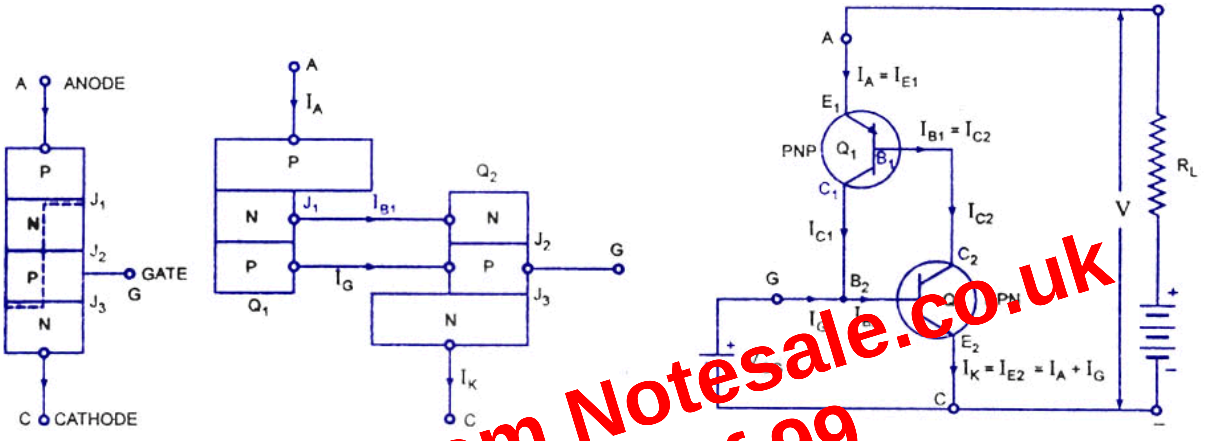
2.1Two Transistor analogy of SCR

The principle of thyristor operation can be explained with the use of its two-transistor model (or two-transistor analogy). Fig. 4.15 (a) shows schematic diagram of a thyristor. From this figure, two-transistor model is obtained by bisecting the two middle layers, along the dotted line, in two separate halves as shown in Fig. 4.15 (b). In this figure, junctions J1 – j2and J2 -J3 can be considered to constitute pnp and npn transistors separately. The circuit representation of the two-transistor model of a thyristor is shown in Fig. 4.15 (c).

In the off-state of a transistor, collector current Ic is related to emitter current IE as

$I_C = \alpha I_E + I_{CBO}$

where α is the common-base current gain and I_{CB0} is the common-base leakage current of collector-base junction of a transistor.



SCR Split-up into Two Transistors Two Transistor Equivalent Circuit of An SCR

Two Transistor Model of An SCR

For transistor Q_1 in Fig. 4.15 (c), emitter current I_E = anode current I_a and I_C = collector current I_{C1}. Therefore, for Q_1

$I_{C1} = \alpha_1 I_a + I_{CBO1}$ ……..(4.3)

where α_1 = common-base current gain of Q_1

and I_{CBO1} = common-base leakage current of Q_1

Similarly, for transistor Q_2, the collector current I_{C2} is given by

$I_{C2} = \alpha_2 I_k + I_{CBO2}$ …(4.4)

After thyristor is turned on, all the four layers are filled with carriers and all junctions are forward biased. Under these conditions, thyristor has very low impedance and is in the forward on-state.

(ii) **Forward-voltage triggering** : If the forward anode to cathode voltage is increased, the collector to emitter voltages of both the transistors are also increased. As a result, the leakage current at the middle junction J_2 of thyristor increases, which is also the collector current of Q_2 as well as Q_1 With increase in collector currents I_{C1} and I_{C2} due to avalanche effect, the emitter currents of the two transistors also increase causing $\alpha_{1+}\alpha_2$ to approach unity. This leads to switching action of the device due to regenerative action. The forward-voltage triggering for turning-on a thyristor may be destructive and should therefore be avoided.

(iii) **dv/dt triggering** : The reversed biased junction J_2 behaves like a capacitor because of the space-charge present there. Let the capacitance of this junction be Cj. For any capacitor, i = C dv/dt.In case it is assumed that entire forward voltage v_a appears across reverse biased junction J_2 then charging current across the junction is given by

$i = Cj\ dv_a /dt$

This charging or displacement current across junction J_2 is collector currents of Q_2 and Q_1 Currents I_{C2}, I_{C1} will induce emitter current in Q_2, Q_1 In case rate of rise of anode voltage is large, the emitter currents will be large and as a result, $\alpha_{1+}\alpha_2$ will approach unity leading to eventual switching action of the thyristor.

(iid **Temperature triggering** : At high temperature, the forward leakage current across junction J_2 rises. This leakage current serves as the collector junction current of the component transistors Q_1 and Q_2. Therefore, an increase in leakage current I_{CI}, I_{C2} leads to an increase in the emitter currents of $Q_l\ Q_2$. As a result, $(\alpha_{1+}\alpha_2)$ approaches unity. Consequently, switching action of thyristor takes place.

(v) **Light triggering** : When light is thrown on silicon, the electron-hole pairs increase. In the forward-biased thyristor, leakage current across J_2 increases which eventually increases $\alpha_{1+}\alpha_2$ to unity as explained before and switching action of thyristor occurs.

As stated before, gate-triggering is the most common method for turning-on a thyristor. Light-triggered thyristors are used in HVDC applications.

The operational differences between thyristor-family and transistor family of devices may now be summarised as under :

i) Once a thyristor is turned on by a gate signal, it remains latched in on-state due to internal regenerative action. However, a transistor must be given a continuous base signal to remain in on-state.

ii) In order to turn-off a thyristor, a reverse voltage must be applied across its anode-cathode terminals. However, a transistor turns off when its base signal is removed.

2.2 Different Firing Circuits of SCR:

One common application of the uni junction transistor is the triggering of the other devices such as the SCR, triac etc. The basic elements of such a triggering circuit are shown in figure. The resistor R_E is chosen so that the load line determined by R_E passes through the device characteristic in the negative resistance region, that is, to the right of the peak point but to the left of the valley point, as shown in figure. If the load line does not pass to the right of the peak point P, the device cannot turn on.

For ensuring turn-on of UJT

$R_E < V_{BB} - V_p / I_P$

This can be established as below

Consider the peak point at which $I_{RE} = I_p$ and $V_E = V_P$

(the equality $I_{RE} = I_P$ is valid because the charging current of capacitor, at this instant is zero, that is, the capacitor, at this particular instant, is changing from a charging state to a discharging state). Then $V_E = V_{BB} - I_{RE} R_E$

So, $R_{E(MAX)} = V_{BB} - V_E / I_{RE} = V_{BB} - V_p / I_P$ *at the peak point.*

At the valley point, V

$I_E = I_V$ and $V_E = V_V$ so that

$V_E = V_{BB} - I_{RE} R_E$

So $R_{E(MIN)} = V_{BB} - V_E / I_{RE} = V_{BB} - V_V / I_V$ or for ensuring turn-off.

$R_E >= V_{BB} - V_V / I_V$

So, the range of resistor R_E is given as

$V_{BB} - V_P / I_P > R_E > V_{BB} - V_V / I_V$

The resistor R is chosen small enough so as to ensure that SCR is not turned on by voltage V_R when emitter terminal E is open or $I_E = 0$

The voltage $V_R = RV_{BB}/R + R_{BB}$ for open-emitter terminal.

The capacitor C determines the time interval between triggering pulses and the time duration of each pulse. By varying R_E, we can change the time constant R_E C and alter the point at which the UJT fires. This allows us to control the conduction angle of the SCR, which means the control of load current.

UNIT-III

SINGLE PHASE HALF CONTROLLED CONVERTERS

UNIT-IV

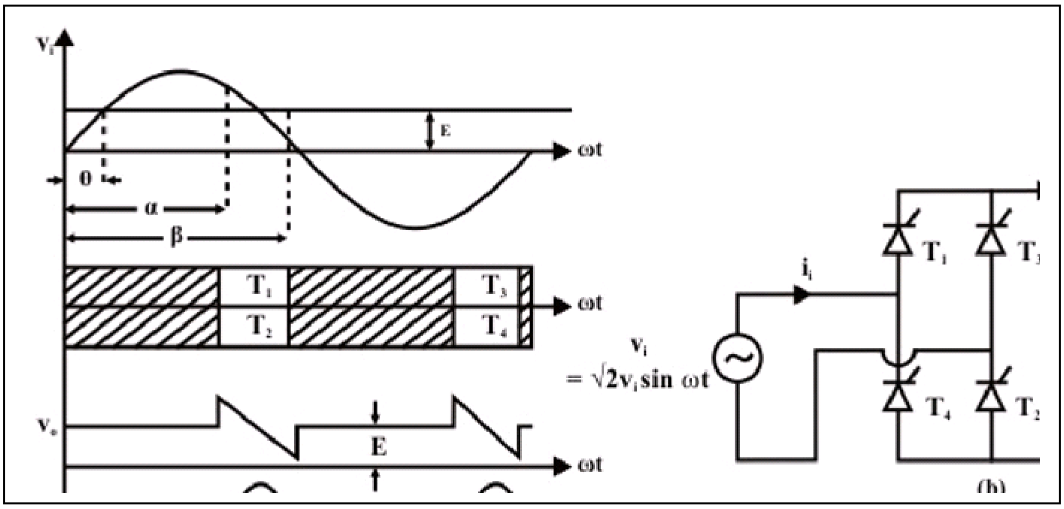
SINGLE PHASE FULLY CONTROLLED CONVERTERS

Answer: (i) continuous, discontinuous; (ii) two; (iii) load; (iv) twice; (v) firing.

4.5 Operation in the discontinuous conduction mode

So far we have assumed that the converter operates in continuous conduction mode without paying attention to the load condition required for it. In figure 10.4 the voltage across the R and L component of the load is negative in the region $\pi - \theta \le \omega t \le \pi + \alpha$. Therefore i_0 continues to decrease till a new pair of thyristor is fired at $\omega t = \pi + \alpha$. Now if the value of R, L and E are such that i_0 becomes zero before $\omega t = \pi + \alpha$ the conduction becomes discontinuous. Obviously then, at the boundary between continuous and discontinuous conduction the minimum value of i_0 which occurs at $\omega t = \alpha$ and $\omega t = \pi + \alpha$ will be zero. Putting this condition in (10.26) we obtain the condition for continuous conduction as.

Fig 10.6 shows waveforms of different variables on the boundary between continuous and discontinuous conduction modes and in the discontinuous conduction mode. It should be stressed that on the boundary between continuous and discontinuous conduction modes the load current is still continuous. Therefore, all the analysis of continuous conduction mode applies to this case as well. However in the discontinuous conduction mode i_0 remains zero for certain interval. During this interval none of the thyristors conduct. These intervals are shown by hatched lines in the conduction diagram of Fig 10.6(b). In this conduction mode i_0 starts rising from zero as T_1T_2 are fired at $\omega t = \alpha$. The load current continues to increase till $\omega t = \pi - \theta$. After this, the output voltage v_0 falls below the emf E and i_0 decreases till $\omega t = \beta$ when it becomes zero. Since the thyristors cannot conduct current in the reverse direction i_0 remains at zero till $\omega t = \pi + \alpha$ when T_3 and T_4 are fired. During the period $\beta \le \omega t \le \pi + \alpha$ none of the thyristors conduct. During this period v_0 attains the value E.
Performance of the rectifier such as V_{OAV}, V_{ORMS}, I_{OAV}, I_{ORMS} etc can be found in termsofα,β



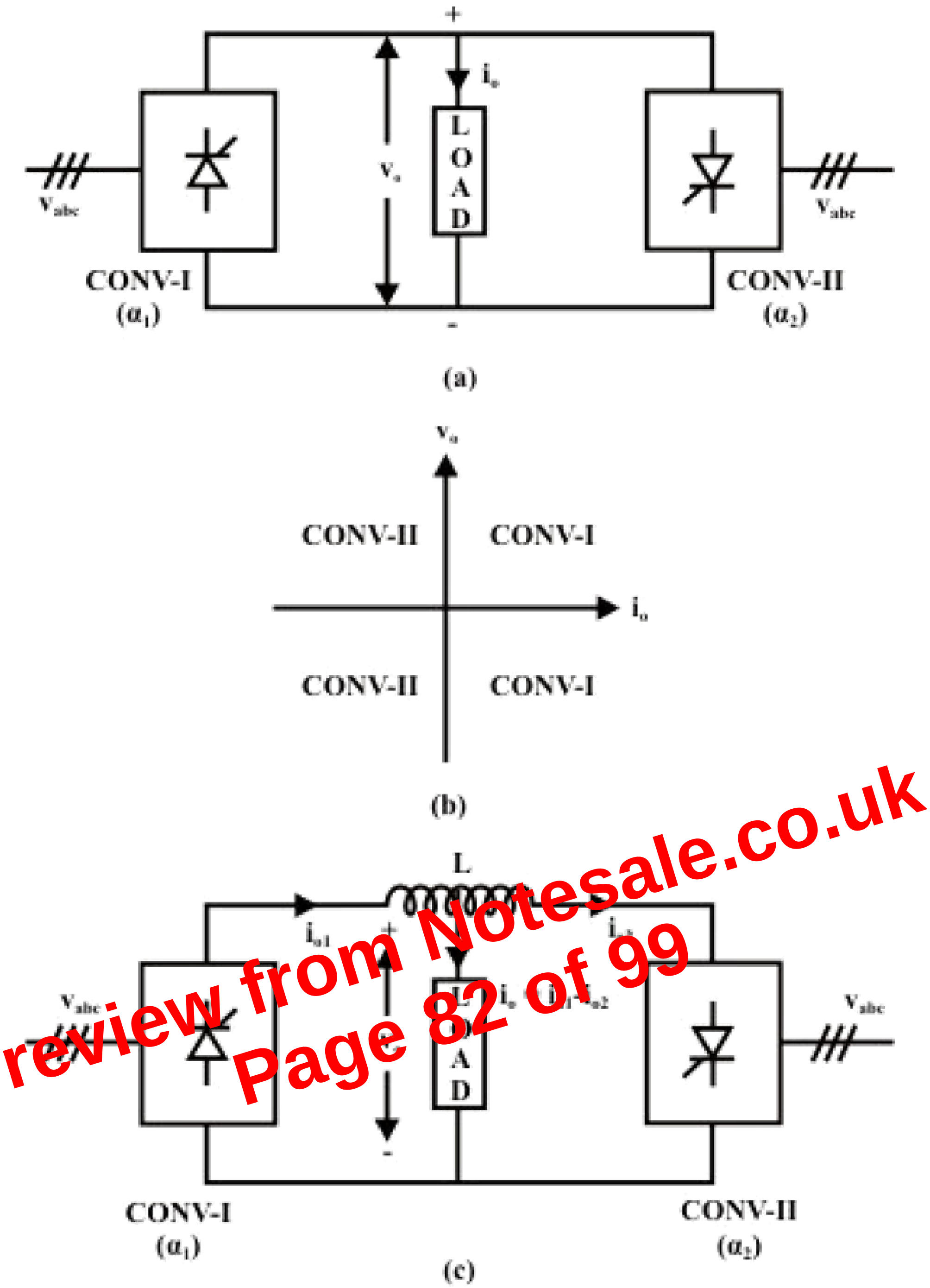


Fig. 13.5: Dual converter circuits
(a) non circulating type
(b) output V-I plane
(c) circulating current type

harmonic of the input frequency in addition to the dc component.

- The input current of a three phase fully controlled converter contains only odd harmonics other than tripler harmonics.
- The input current displacement factor of a three phase fully controlled converter is $\cos\alpha$. α being the firing angle.
- In the continuous conduction mode a three phase fully controlled converter may operate in the inverting mode by increasing α beyond 90°.
- In the inverting mode the firing angle should be less than 180° for safe commutation of the thyristors.
- Several units of three phase fully controlled converters can be connected in series parallel to form higher pulse number (12, 18, 24 etc) converters.
- In higher pulse number converters all component converters are fired at the same firing angle while their input supplies are phase shifted from one another by a predetermined angle.
- Two three phase fully controlled converter can be connected in anti parallel to form a dual converter which can operate in all four quadrants of the V-I plane.
- Dual converters can be of circulating and non circulating current type.
- Fully controlled converters employ “inverse casine control” strategy for generating firing pulses which gives linear relationship between the output voltage and the control voltage. In a three phase fully controlled converter, a three phase delta/zig-zag connected signal transformer is used to generate the required carrier waves for this purpose.

UNIT-VI

AC VOLTAGE CONTROLLERS & CYCLO CONVERTERS

6.1Cycloconverters

In Figs. 3.2 and 3.3, the two typical types of cycloconverters are presented. In the first case there are two three-phase midpoint controlled rectifiers connected back to back. The second case shows two three-phase bridge rectifier converters connected back to back. Both are used for three-phase to three-phase conversion. In Fig. 3.4 the single-phase output voltage and current waves are presented for the

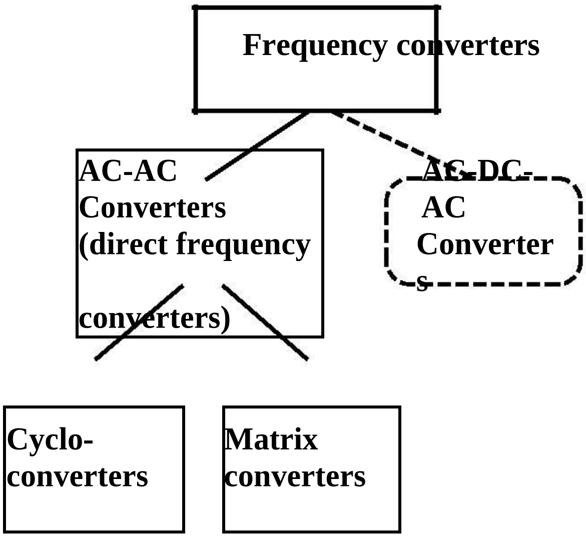


FIGURE 3.1 Classification of frequency converters.

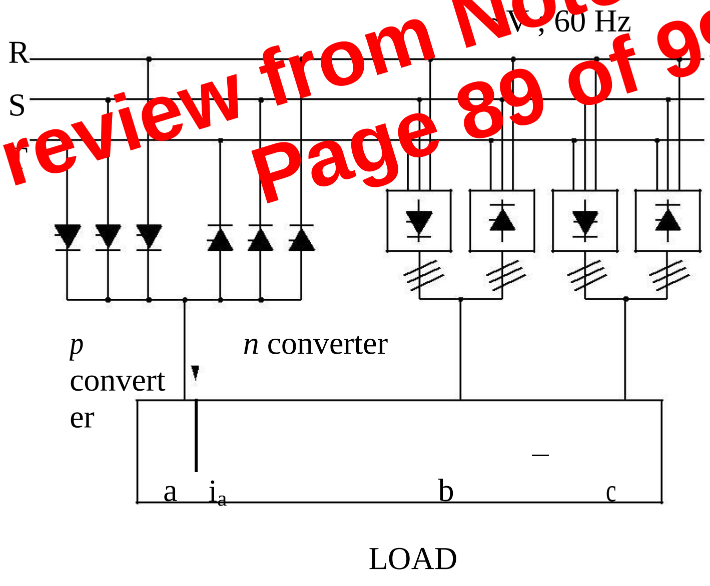


FIGURE 3.2 Cycloconverter scheme with three-phase midpoint controlled rectifier.

The phase control of the *p* and *n* converters is modulated by a sine or trapezoidal wave. The content of the harmonics for sine modulation is lower; however, the maximum value of the output voltage is lower than that for trapezoidal modulation. During every cycle of the output voltage both of the converters must work as rectifiers and inverters.

The shape of the output voltage goes from bad to worse with an increase in the output voltage and the output frequency. If the frequency reaches the well-defined value the current harmonics become unacceptable. This frequency is usually 33% of supply frequency for three-phase midpoint (Fig. 3.2) and 50% for three-phase bridge (Fig. 3.3) converters.

The cycloconverter is usually used for three-phase, high-power, low-speed synchronous motor drives and rarely employed for induction motor drives.

6.2 AC VOLTAGE CONTROLLERS

6.1 Introduction

AC to AC voltage converters operates on the AC mains essentially to regulate the output voltage. Portions of the supply sinusoid appear at the load while the semiconductor switches block the remaining portions. Several topologies have emerged along with voltage regulation methods, most of which are linked to the development of the semiconductor devices.

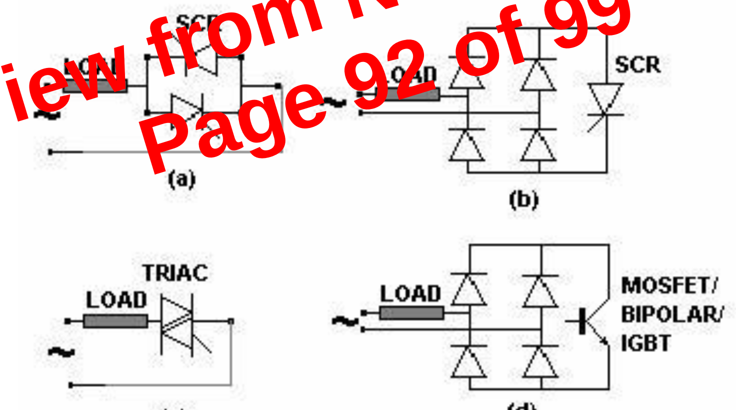


Fig 26.1 Some single phase AC-AC voltage regulator topologies. (a) Back-to -back SCR; (b) One SCR in (a) replaced by a four-diode full wave diode bridge; (c) A bi-directionally conducting TRIAC; (d) The SCR in (b) replaced by a transistor.

6.4 Operation with inductive loads

With inductive loads the operation of the PAC is illustrated in Fig 26.5. The current builds up from zero in each cycle. It quenches not at the zero crossing of the applied voltage as with the resistive load but after that instant. The supply voltage thus continues to be impressed on the load till the load current returns to zero. A single-pulse trigger for the TRIAC 26.1 (c) or the anti-parallel SCR (b) has no effect on the devices if it (or the anti-parallel device) is already in conduction in the reverse direction. The devices would fail to conduct when they are intended to, as they do not have the supply voltage forward biasing them when the trigger pulse arrives. A single pulse trigger will work till the trigger angle $\alpha > \varphi$, where φ is the power factor angle of the inductive load. A train of pulses is required here. The output voltage is controllable only between triggering angles φ and 180^o.

The load current waveform is further explained in Fig. 26.6. The current is composed of two components. The first is the steady state component of the load current, i_{ss} and the second, i_{tr} is the transient component.

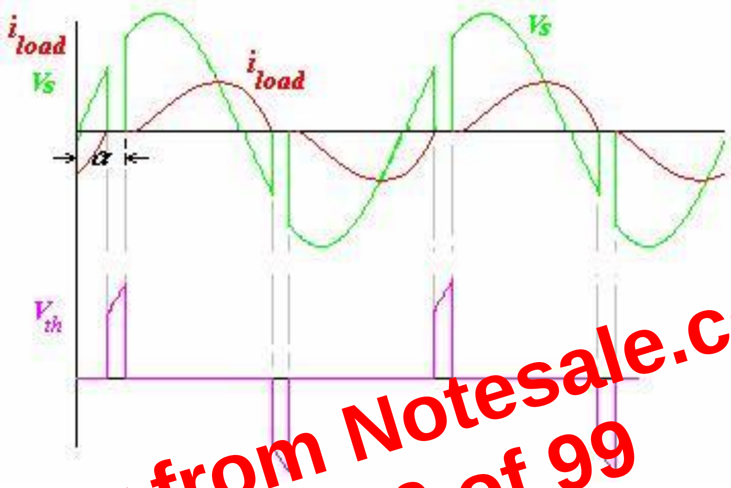


Fig. 26.6 Operation of a single phase PAC with an inductive load

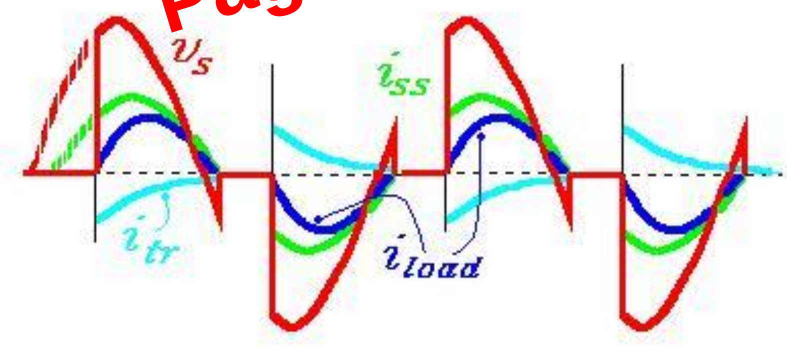


Fig 26.7 Load current for a single phase AC-AC converter with a R_L load. V_s - supply voltage, i_{ss} -steady state current component , i_{tr} - transient current component and i_{load} - load current (= i_{ss} + i_{tr}).

With an inductance in the load the distinguishing feature of the load current is that it must always start from zero. However, if the switch could have permanently kept the load connected to the supply the current would have become a sinusoidal one phase shifted from the voltage by the phase angle of the load, φ. This current restricted to the half periods of conduction is called the 'steady-state component' of load current i_{ss}. The 'transient component' of load current i_{tr}, again in each half cycle, must add up to zero with this i_{ss} to start from zero. This condition sets the initial value of the transient component to that of the steady state at the instant that the SCR/TRIAC is triggered. Fig. 26.6 illustrates these relations.

When a device is in conduction, the load current is governed by the equation

$$L\frac{di}{dt} + Ri = v_s$$

$$i_{load} = \frac{\sqrt{2}V}{Z}\left[\sin(\omega t - \varphi) + \sin(\alpha - \varphi)e^{-\frac{R}{L}(\alpha/\omega - t)}\right]$$

Since at $t = 0$, $i_{load} = 0$ and supply voltage $v_s = \sqrt{2}V\sin\omega t$ the solution is of the form

The instant when the load current extinguishes is called the extinction angle β. It can be inferred that there would be no transients in the load current if the devices are triggered at the power factor angle of the load. The load current I that case is perfectly sinusoidal.

26.5 AC-AC Chopper

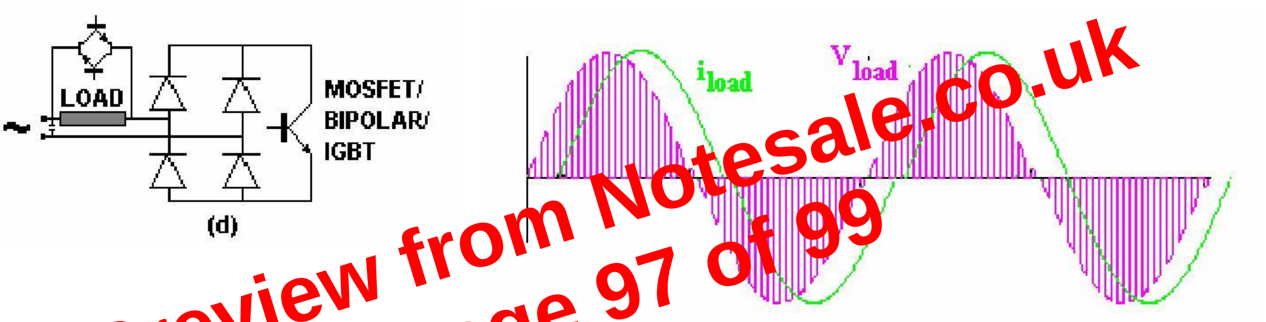


Fig. 26.8 A complete Transistorised AC-AC chopper topology of the version shown in Fig. 26.1 and the corresponding load voltage and current waveforms for an inductive load. The output voltage is shown to be about 50% for a 0.5 Duty Ratio chopping.

The AC-AC converter shown in Fig 26.1 has to be augmented with two additional controlled devices clamping the load as indicated in Fig. 26.7. A large capacitor across the supply terminals is also to be inserted. These devices which are mostly transistors of the same variety as used for the chopper are necessary to clamp the voltages generated by the switching-off of the current carrying inductors in the load while the input capacitor takes care of the line inductances. The harmonics in the line current and load voltage waveforms are significantly different from those with the PACs. Mostly switching frequency harmonics are present in both the waveforms.