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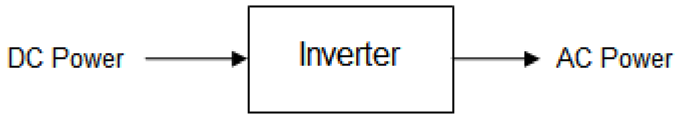
Inverters

After completion of this chapter students will able to learn

- Applications of Inverter
- The operation of voltage driver, current driver, single phase half bridge and full bridge inverters
- Three phase inverters
-

Introduction

It is a device that converts DC power into AC power at desired output voltage and frequency.



Classification of Inverters

Inverters can be classified into many types depending on source, types of load, output characteristics, different PWM techniques and no of output.

- According to the source of Inverter:
- **Voltage Source Inverter** – If the DC input is voltage source then it is called voltage source inverter. It has the capability of controlling AC output voltage. It has stiff dc voltage source at its input terminal i.e. dc source has negligible impedance.
- **Current Source Inverter -** If the DC input is current source then it is called current source inverter. It has the capability of controlling AC output current. It is fed with adjustable current from dc source of high impedance i.e. from a stiff dc current. In this case output current waves are not affected by the load.

- According to the type of load inverters
  1) Single Phase Inverter
     a) Half-Bridge Inverter
     b) Full – Bridge Inverter
  2) Three Phase Inverter
     a) 180-degree mode
     b) 120-degree mode

- According to the type of output characteristics
  i) Square Wave Inverter
  ii) Sine Wave Inverter
  iii) Modified Sine Wave Inverter

- According to different PWM techniques
  a) Simple Pulse Width Modulation (SPWM)
  b) Multiple Pulse Width Modulation (MPWM)
  c) Sinusoidal Pulse Width Modulation (SPWM)
  d) Modified Sinusoidal Pulse Width Modulation (MSPWM)

- According to the no of Output levels
  1) Regular Two-level Inverter
  2) Multilevel Inverter

Applications

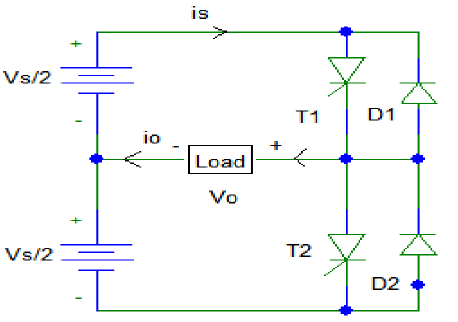
- Adjustable – speed ac drives
- UPS for computers
- Induction heating
- stand by aircrafts power supply
- HVDC transmission line
- Power grid

Single Phase Voltage Source Inverters

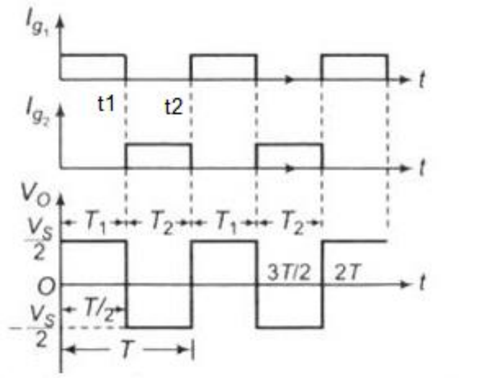
- **Single Phase Bridge Inverters**

Single Phase bridge inverters are mainly two types, (i) Single Phase half-bridge inverters (ii) Single Phase full-bridge inverters.

Single Phase Half Bridge Inverter (Load is resistive in nature)



Single Phase Half Bridge Inverter

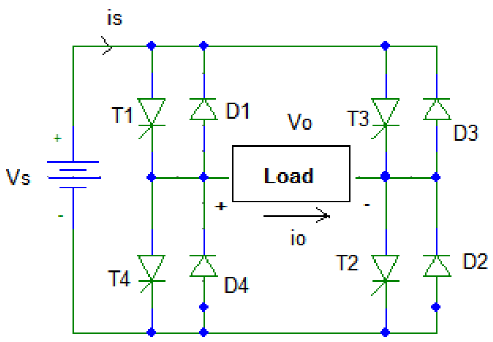


Waveforms of gate pulses and output voltage

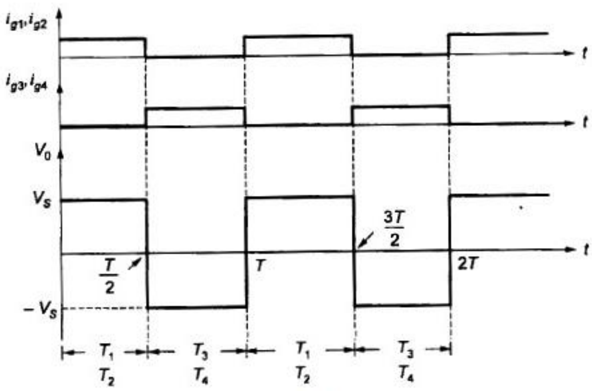
At 0$\leq t \leq t_1$, T_1 is triggered. So, T_1 is short circuited i.e. T_1 = ON. In that time source current will pass through load voltage i.e. $V_0 = \frac{V_S}{2}$.

At $t_1 \leq t \leq t_2$, T_2 is triggered. So, T_2 is short circuited i.e. T_2 = ON. In that time source current will pass through load voltage i.e. $V_0 = -\frac{V_S}{2}$. So, current will flow in opposite direction through load.

Single Phase Full Bridge Inverter



Single Phase Full-Bridge Inverter



Single Phase Full Bridge Inverter

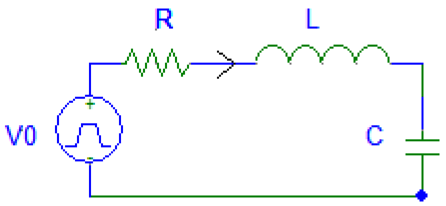
At 0$\leq t \leq T/2$, T_1 and T_2 are both triggered. So, T_1 and T_2 are short circuited i.e. T_1 , T_2= ON. In that time source current will pass through load voltage i.e. $V_0 = V_S$. here, load is purely resistive nature.

At $T/2 \leq t \leq T$, T_3 and T_4 are both triggered. So, T_3 and T_4 is short circuited i.e. T_3 , T_4 = ON. In that time source current will pass through load voltage i.e. $V_0 = -V_S$. So, current will flow in opposite direction through load.

Diode D_1, D_2, D_3 and D_4 are called Feedback Diodes and they functions only when the load is other than Resistive Load.

Steady State Analysis of Single Phase Inverter

In all previous cases, load does not depend nature of load. But here let the load consists of a RLC in series. In this circuit model, load current would settle down to steady state condition and vary periodically according to the waveform shown below.



Case I : Load is purely resistive

Bothe V_0 and I_0 produce square wave and each switching device will conduct for 180°.

Case II: Load is purely Inductive in nature

Here, $i_0 = \frac{1}{L}\int V_S dt = \frac{V_S}{L}t$ As, voltage is square wave in nature so integration of square wave will produce triangular wave. So, each switching device and freewheeling diode will conduct for 90° or $\frac{T}{4}$.

Case III : RL Load

Here, output voltage is square wave in nature.

$$V_S = Ri(t) + L\frac{di(t)}{dt}$$

Or, $\frac{V_S}{s} = RI(S) + sLI(S)$ [Laplace transform in both side]

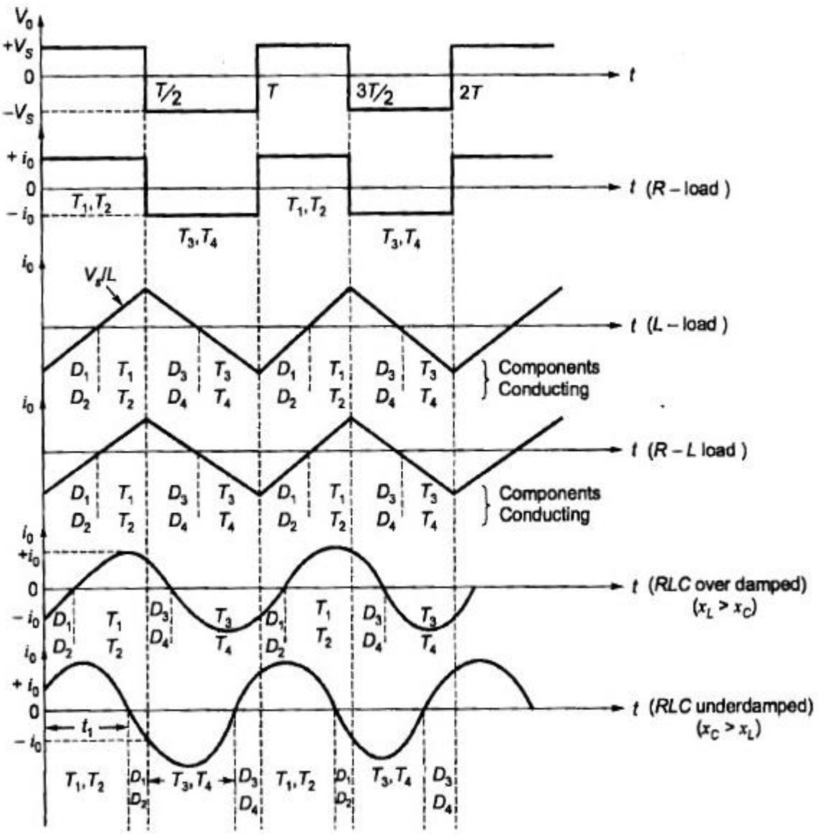
Or, $I(s) = \frac{V_S}{S(SL+R)}$

Or, $= \frac{V_S}{R}.\frac{R/L}{S(S+\frac{R}{L})}$

Or, $= \frac{V_S}{R}.[\frac{1}{S} - \frac{1}{S+R/L}]$

Or, i(t) = $\frac{V_S}{R}(1 - e^{-\frac{R}{L}t})$ [after inverse Laplace transform]

So, magnitude of current will decrease slightly and current curve will follow this equation.



Case IV : RLC Load

When $(X_L > X_C)$, nature of the response is Overdamped i.e. $\zeta > 1$. $v_{0=}$ Square wave and $i_0 =$ sinusoidal in nature. The characteristics equation of 2nd order series RLC System is given by

$S^2 + \frac{R}{L}s + \frac{1}{LC} = 0$ by comparing this equation with $S^2 + 2\zeta\omega_n S + \omega_n{}^2 = 0$ we get

$\omega_n = \frac{1}{\sqrt{LC}}; \zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$. Therefore, $R > 2\sqrt{\frac{C}{L}}$.

Forced Commutation is required because to turn OFF the switches T_1, T_2 at t=T/2, anode current should comes to zero – Due to load it is not possible because current becomes zero after the voltage becomes zero.

When $(X_L < X_C)$, nature of the response is Underdamped i.e. $\zeta < 1$. $So, \zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$ and $R < 2\sqrt{\frac{C}{L}}$.
Here, output voltage is Half-wave symmetric.

Forced Commutation is not required because to turn OFF the switches T_1, T_2 at t=T/2, anode current should comes to zero – Due to load it is possible because current becomes zero before the voltage becomes zero.

Three Phase Bridge Inverter

Three phase inverter is basically a six-step bridge inverter. It uses minimum six thyristors. Step is defined as a change in the firing angle from one thyristor to next thyristor in proper sequence. For one cycle of 360°, each step would be of 60° intervals for a six step inverter. It means that SSR will gated at regular interval of 60° in proper sequence so that three phase ac voltage is synthesized at the output terminals of a six step inverters. Here, commutations and snubber circuits are ignored for simplicity and easier calculation.

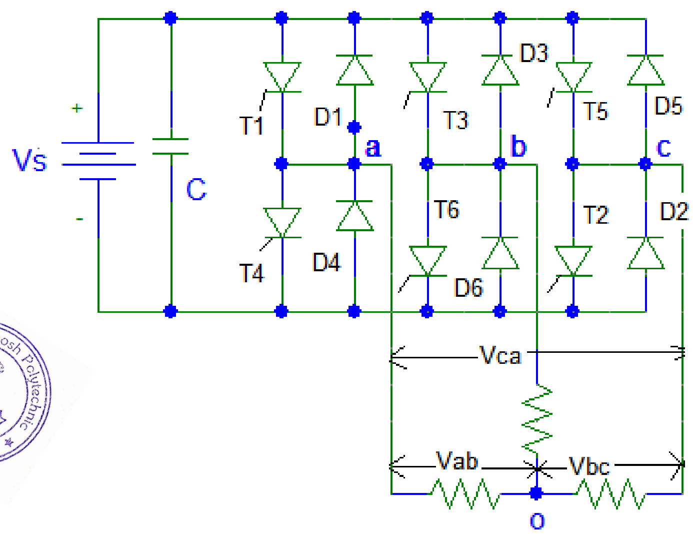
Circuit consists of three half bridge inverters arranged side by side. Load is assumed to be star connected. The SRCs are numbered in the sequence in which they are triggered to obtain voltages V_{ab}, V_{bc}, V_{ca} at the output terminals a, b, c of the inverters.

There are two possible way of gating the thyristos. In one way, each SCR conducts for 180° and in another way each SCR conducts for 120°. But in both ways, gating signal applied and removed at 60° intervals of the output voltage waveform. Therefore, both these modes require six step bridge inverter.

Three Phase 180° Mode Voltage Source Inverter

In this case, each SCR will conduct for 180° of a cycle. Thyristor pair in each arm i.e. (T1, T4); (T3, T6)and (T5, T2) are turned on with a time of interval of 180°. It means that T1 conducts for 180° and T4 conducts for the next 180° of a cycle. Thyristor in the upper group i.e. T1, T3, T5 conduct at an interval of 120° $(= \frac{360°}{2})$. It implies that, if T1 is triggered at $\omega t = 0°$, then T3 must be fired at

$\omega t = 120°$ and T5 at $\omega t = 240°$. same is true for lower group of inverters.



Three Phase Bridge Inverter using SCR

In this table, 1st row shows that T1 from the upper group conducts for 180°, T4 for next 180° and repeats in this way.

In 2nd row, T3 starts conducting 120° after T1 starts conducting. After T3 conduction for 180°, T6 conducts for next 180° and so on.

In the 3rd row, T5 starts conducting 120° after T3 or 240° after T1. After T5 conducts 180, T2 conducts for next 180° intervals and so on.

In this manner, the pattern of firing six SCRs is identified. T5, T6, T1 should be gated for step 1; T6, T1 T2 for step II; T1, T2, T3 for step III; T2, T3, T4 for step IV; T3, T4, T5 for step V; T4, T5, T6 for step VI. Then the process repeats again.

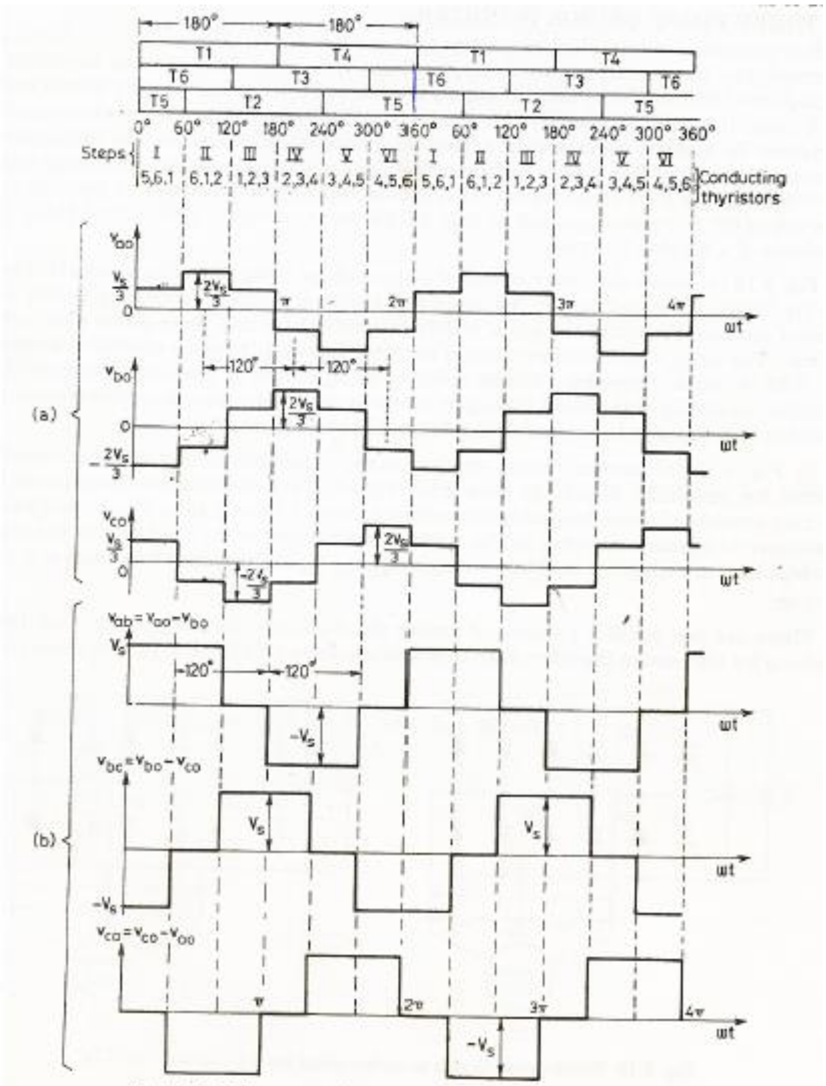


Fig. 8.20. Voltage waveforms for 180° mode 3-phase VSI

During conduction of SCR, it is treated as close switch and non – conducting SCR acts as open switch. When upper group of SCRs are connected positive side of the battery then a, b, c terminals are also positive and lower group of SCRs are connected to the negative side of the battery then terminals are negative.

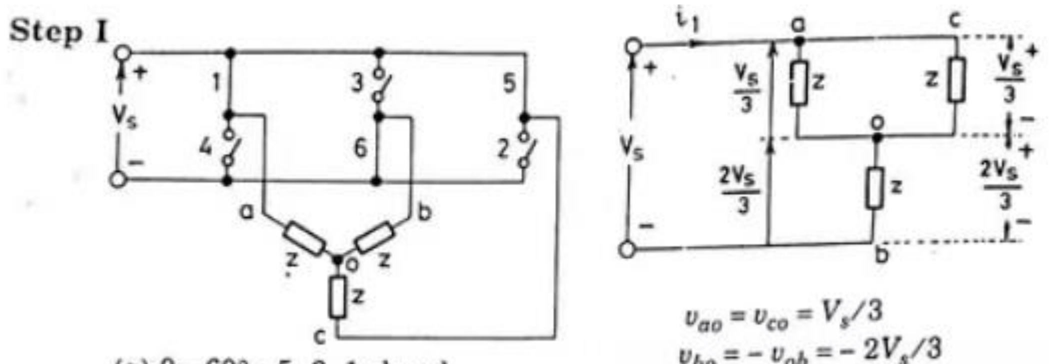
During step I: $0° \leq \omega t \leq 60°$

T5, T6, T1 are conducting where T5 and T1 i.e. a and c terminal are positive in nature and b terminal is negative in nature. So,

$$i_1 = \frac{V_s}{R + \frac{R}{2}}$$

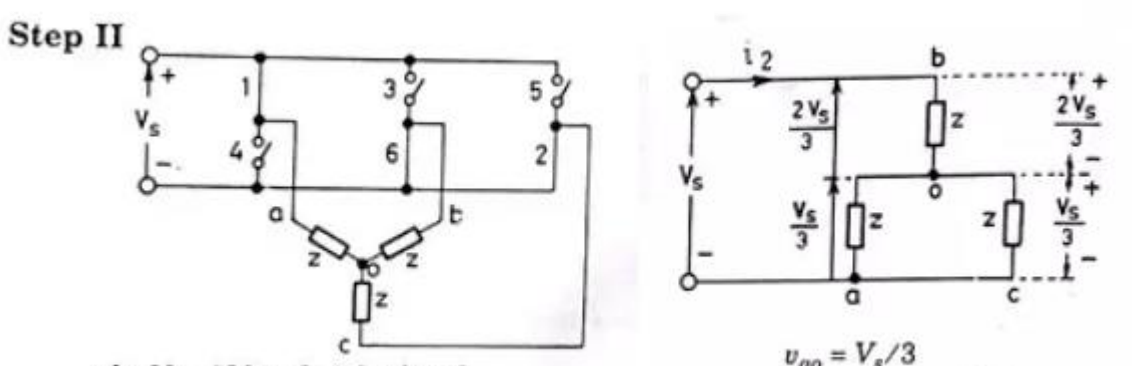
$v_{ao} = v_{co} = i_1 . \frac{R}{2}$ and

$v_{ob} = i_1 . R = \frac{2V_s}{3}$. Illustration is given below



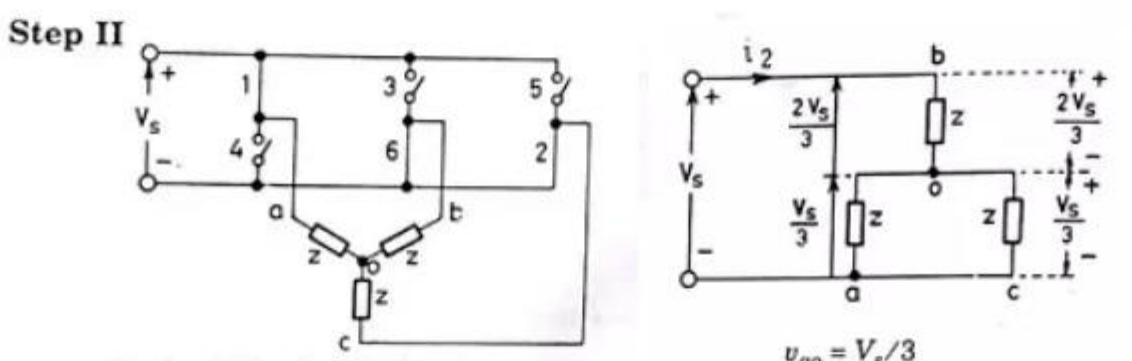
(a) 0—60° ; 5, 6, 1 closed.

Similarly, during **Step – II :** $60° \leq \omega t \leq 120°$, T6, T1 and T2 are conducting in nature. So,



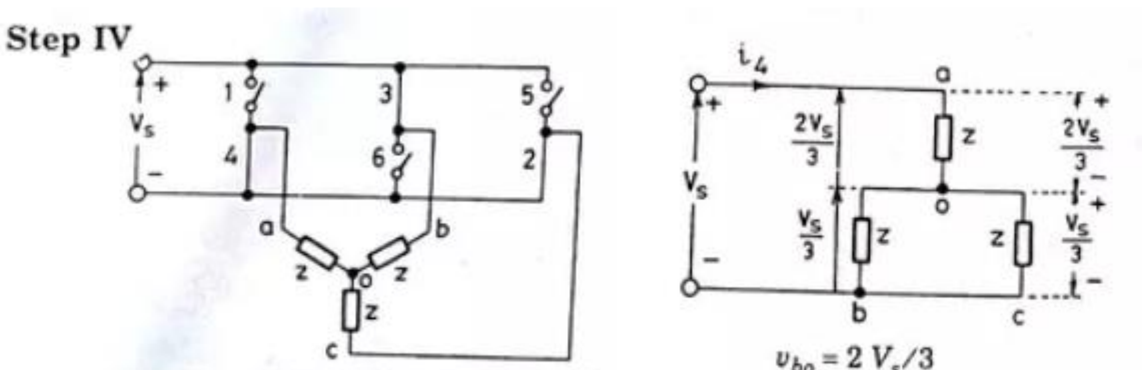
(b) 60—120° ; 6, 1,2 closed.

Step – III : $120° \leq \omega t \leq 180°$, T1, T2 and T3 are conducting in nature. So,



(b) 60—120° ; 6, 1,2 closed.

Step – IV : $180° \leq \omega t \leq 240°$, T1, T2 and T3 are conducting in nature. So,



(d) 180—240° ; 2, 3, 4 closed.

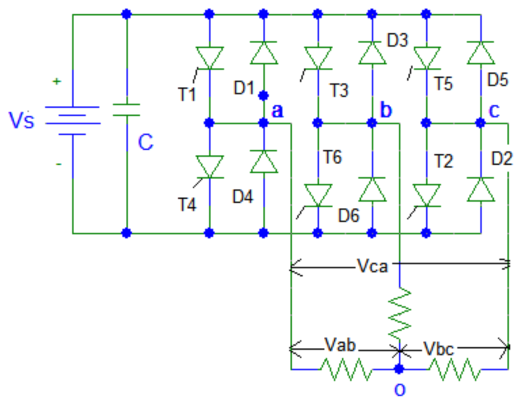
Similarly, **Step – V :** $240° \leq \omega t \leq 300°$, T3, T4 and T5 are conducting in nature. So, $v_{ao} = -\frac{2V_s}{3}$ and

$v_{bo} = v_{co} = \frac{V_s}{3}$.

Similarly, **Step – VI :** $300° \leq \omega t \leq 360°$, T4, T5 and T6 are conducting in nature. So, $v_{co} = \frac{2V_s}{3}$ and $v_{bo} = v_{ao} = -\frac{V_s}{3}$. The function of diodes D1 to D6 is to allow the flow of currents through them when the load is reactive in nature.

Three – Phase 120° Mode Voltage Source Inverter

For 120° mode voltage source inverter, each thyristor conducts for 120° of a cycle. In this case, it requires also six steps, each of 60° duration, for completing one cycle of the output ac voltage.



Three Phase Bridge Inverter using SCR

1st row shows that T1 conducts for 120° of a cycle and for the next 60° neither T1 nor T4 conducts. Now, T4 turned on at $\omega t = 180°$ and conducts for 120° duration i.e. T4 remains on from 180° to 300°. Again both SCRs are in non-conducting stage for the duration of 60° starting from 300° to 360°. So, T1 will turn on again at ωt = 360°.

Firing sequence and output waveforms are given below:

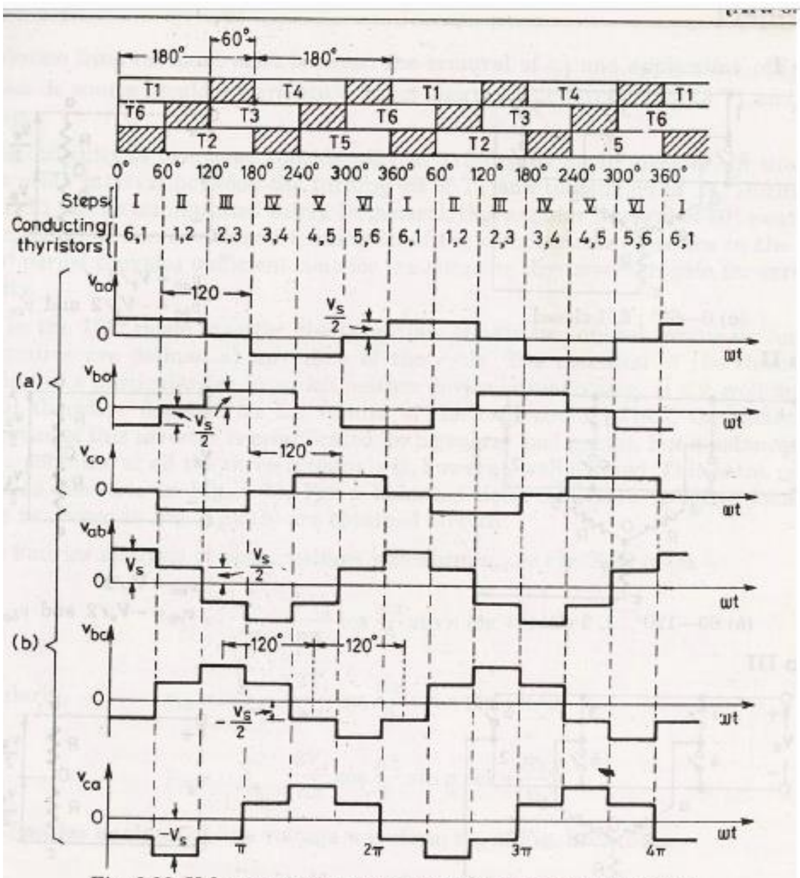


Fig. 8.22. Voltage waveforms for 120°mode six-step 3-phase VSI.

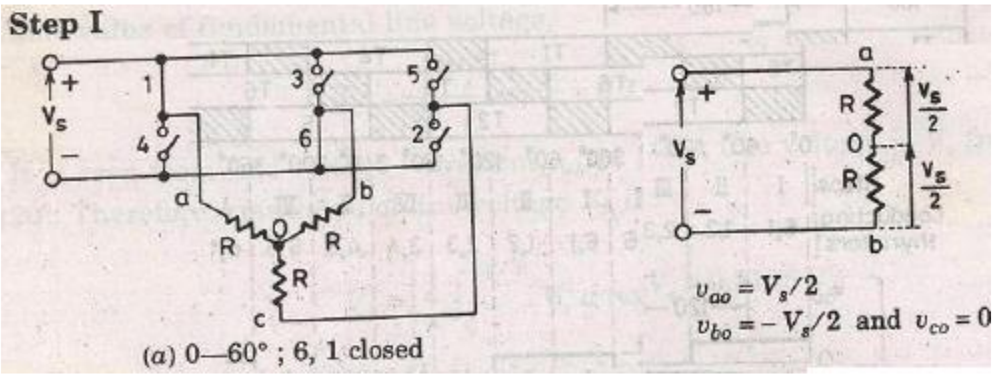
In the 2nd row, T3 starts conducting 120° after turned on T1 as in 180° mode inverter. Now, T3 conducts for 120° duration, then 60° interval elapses during which neither T3 nor T6 conducts. So, T6 starts conducting at ωt = 300°.

In this way 3rd row completed.

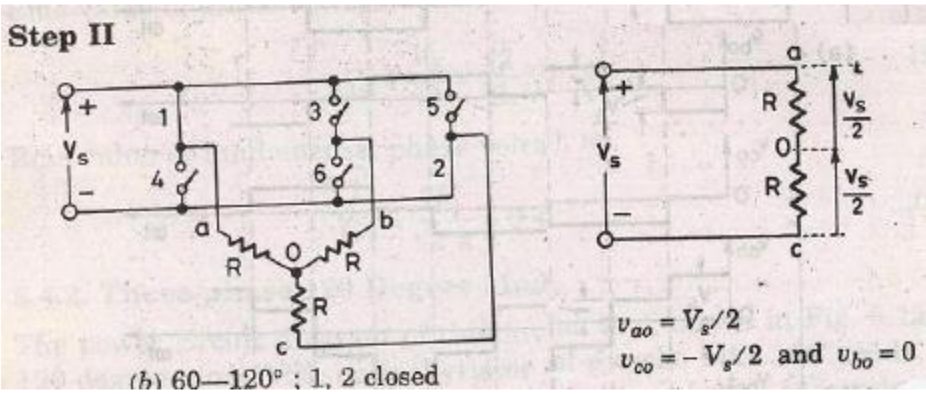
Now, T6, T1 should be gated for step I; T1, T2 for step II; T2, T3 for step III and so on.

The sequence of firing the six SCRs is same as before. During each step only two SCRs conduct for the inverter – one from upper group and other from.

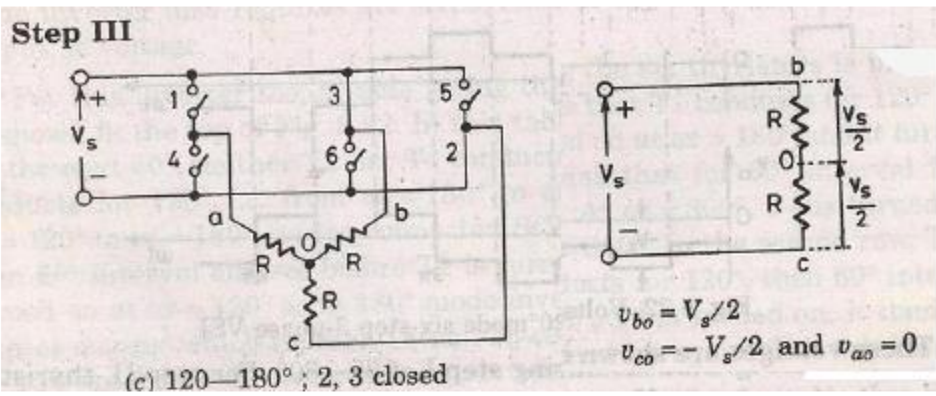
Step I : for $0° \leq \omega t \leq 60°$ only T6 and T1 conducts. So, a terminal is connected to positive side of the battery, b terminal is connected to the negative side of the battery and c terminal is not connected to anywhere. Therefore, $v_{ao} = \frac{V_s}{2}$; $v_{bo} = -\frac{V_s}{2}$ and $v_{co} = 0$.



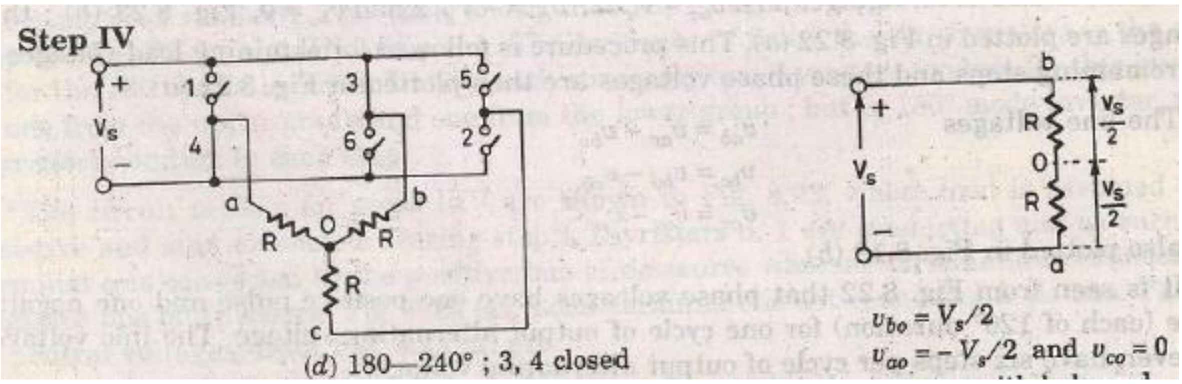
Step II : for $60° \leq \omega t \leq 120°$ only T1 and T2 conducts. So, a terminal is connected to positive side of the battery, c terminal is connected to the negative side of the battery and b terminal is not connected to anywhere. Therefore, $v_{ao} = \frac{V_s}{2}$; $v_{co} = -\frac{V_s}{2}$ and $v_{bo} = 0$.



Step III : for $120° \leq \omega t \leq 180°$ only T2 and T3 conducts. So, b terminal is connected to positive side of the battery, c terminal is connected to the negative side of the battery and a terminal is not connected to anywhere. Therefore, $v_{bo} = \frac{V_s}{2}$; $v_{co} = -\frac{V_s}{2}$ and $v_{ao} = 0$.



Step IV : for $180° \leq \omega t \leq 240°$ only T3 and T4 conducts. So, b terminal is connected to positive side of the battery, a terminal is connected to the negative side of the battery and c terminal is not connected to anywhere. Therefore, $v_{bo} = \frac{V_s}{2}$; $v_{ao} = -\frac{V_s}{2}$ and $v_{co} = 0$.



(d) 180—240° ; 3, 4 closed

Similarly, **Step V :** 240°≤ $\omega t \leq$ 300°, T4 and T5 are conducting in nature. $v_{co} = \frac{V_s}{2}$; $v_{ao} = -\frac{V_s}{2}$ and $v_{bo} = 0$.

Similarly, **Step VI :** 300°≤ $\omega t \leq 360°$, T5 and T6 are conducting in nature. So, $v_{co} = \frac{V_s}{2}$; $v_{bo} = -\frac{V_s}{2}$ and $v_{co} = 0$. The function of diodes D1 to D6 is to allow the flow of currents through them when the load is reactive in nature.

In this inverter, there is 60° interval in between T1 and T4. So, during this interval T1 can be commutated safely. It provides sufficient time for the outgoing thyristor to regain forward blocking capability.

Here, potentials of two output terminals are connected to the dc source where third terminal is not connected to anywhere. So, the analysis of this inverter depends on the nature of load. Hence, load is resistive and delta connected.

Current Source Inverters

Here, current source is constant and adjustable. The amplitude of output current of this inverter is independent of load. But, the magnitude of output voltage and its output waveform is dependent upon the nature of the load impedance. The dc input to current source inverter is obtained from a fixed voltage ac source through a controlled rectifier bridge or through diode bridge and a chopper. In order to make current input ripple free L-filter is used before applied.

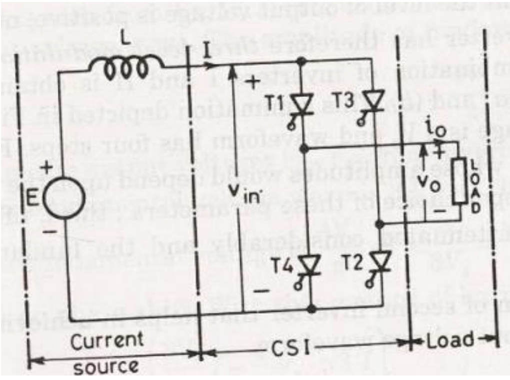
This type of inverters does not use any feedback diode. Commutation circuit is simple as it contains only capacitors. As power semiconductors in a current source inverters (CSI) have to withstand reverse voltage, devices such as GTOs, power transistors, power MOSFETs cannot be used.

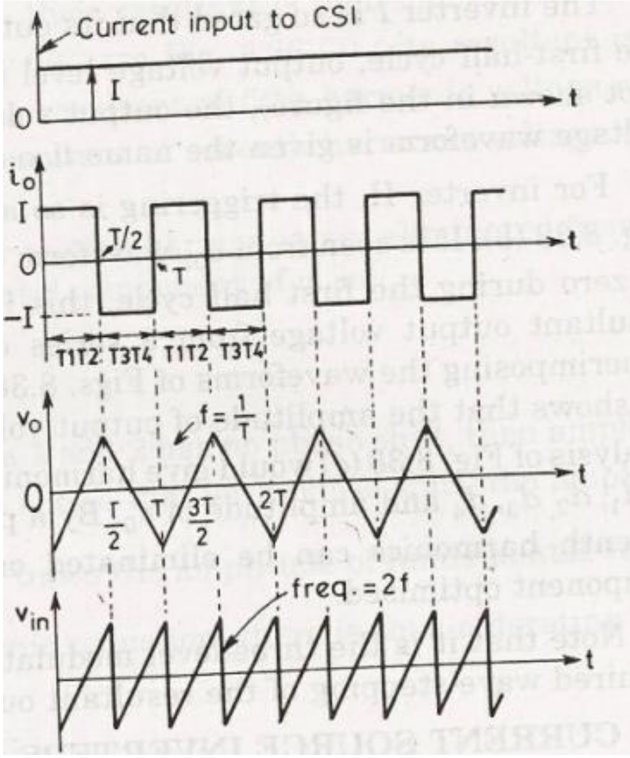
This can be used in

- speed control of ac motors
- Induction heating
- Lagging VAr compensation
- Synchronous motor heating etc.

Single Phase CSI with Ideal Switches

Here a thyristor is assumed to an ideal switch with zero commutation time. The source consists of a voltage source (E) and a large inductance (L) in series with it. The function of high impedance reactor in series with voltage source is to maintain a contain current at the input terminals of CSI.





When, T1, T2 = ON Load current $i_0 = +I$.
When, T3, T4 = ON Load current $i_0 = -I$.

The output frequency of i_0 can be varied by Controlling the frequency of triggering the Thyristor pairs T1, T2 and T3, T4. The magnitude of output current is constant square wave and does not depend on load.

If the load is purely capacitive, then $v_0 = \int i_0 dt$. So, output voltage is triangular in nature. CSI may be load or force commutated. Loa commutation is possible when load power factor is leading. For lagging power factor load, forced commutation is essential.