

Power Electronics

Unit-1 Devices

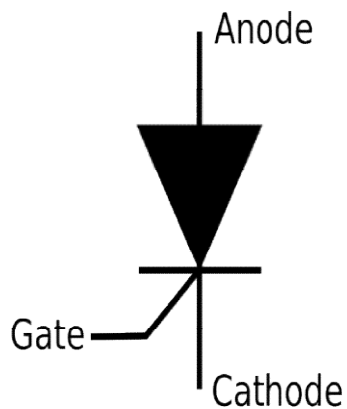
Unit-1 Chapter-1 Thyristor (or) SCR

1. Introduction of Thyristor
2. V-I Characteristics of SCR
 - (or) Static Characteristics of SCR
 - (or) Static V-I Characteristics of SCR
 - (or) Steady State Characteristics of SCR
3. Turning ON of SCR with Firing Circuits (Triggering Circuits)
 - * R Firing Circuit (or) Resistance Firing Circuit
 - * RC Firing Circuit (or) Resistance Capacitance Firing Circuit
4. Turning OFF (or) Commutation of SCR
 - * Introduction
 - * Current Commutation (or) Class-B Commutation (or) Resonant Pulse Commutation
 - * Voltage Commutation (or) Class-D Commutation (or) Impulse Commutation

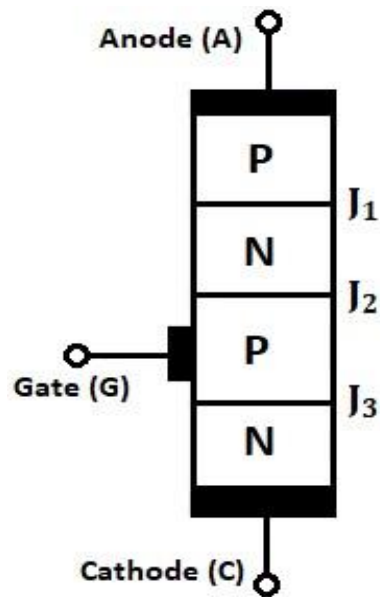
Introduction

THYRISTOR ==> THYRatron + transISTOR

- * Thyristor is a Power Semiconductor device which has characteristics similar to Thyatron and construction similar to Transistor.
- * Examples of Thyristors are SCR (Silicon Controlled Rectifier), GTO (Gate Turn Off Thyristor), RCT (Reverse Conducting Thyristor) etc.
- * SCR is the oldest and most commonly used Thyristor. Hence, many of the people call SCR as Thyristor.
- * SCR was invented by Bell Laboratories in the year 1956 and developed by General Electric Company (GEC) in the year 1957.
- * SCR is a Power Semiconductor device which has 4 layers (P, N, P, N), 3 junctions (J_1, J_2, J_3), 3 terminals (Anode A, Cathode K, Gate G).



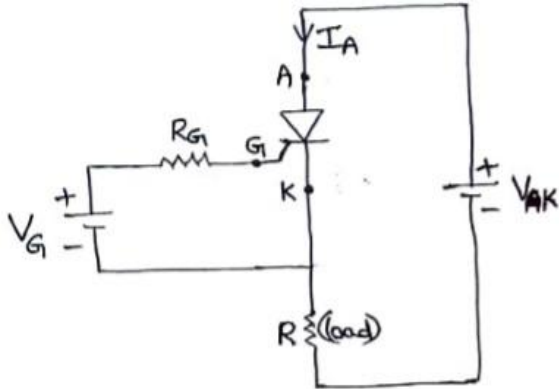
SCR Symbol



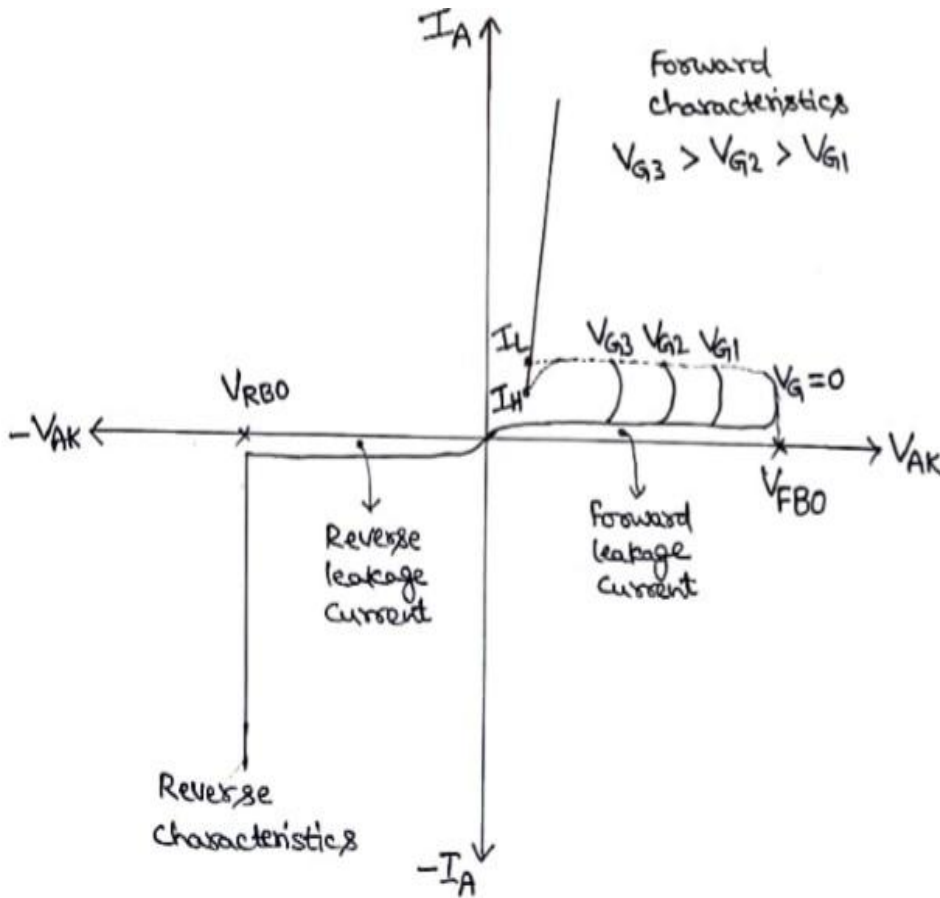
SCR Structure

V-I Characteristics of SCR
 (or) Static Characteristics of SCR
 (or) Static V-I Characteristics of SCR
 (or) Steady State Characteristics of SCR

Circuit Diagram



Characteristics



Here, V_{FBO} = Forward Break Over Voltage

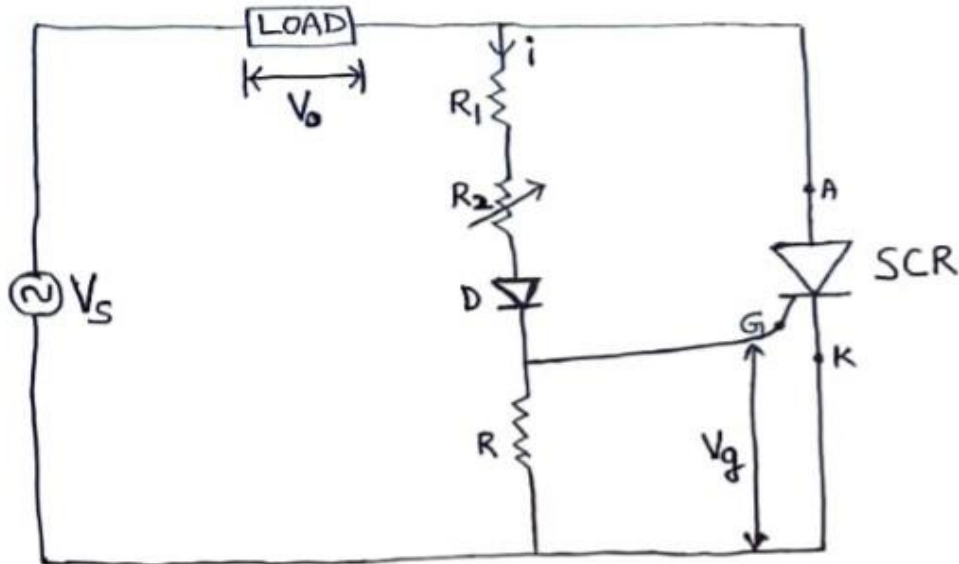
V_{RBO} = Reverse Break Over Voltage

I_L = Latching Current

I_H = Holding Current

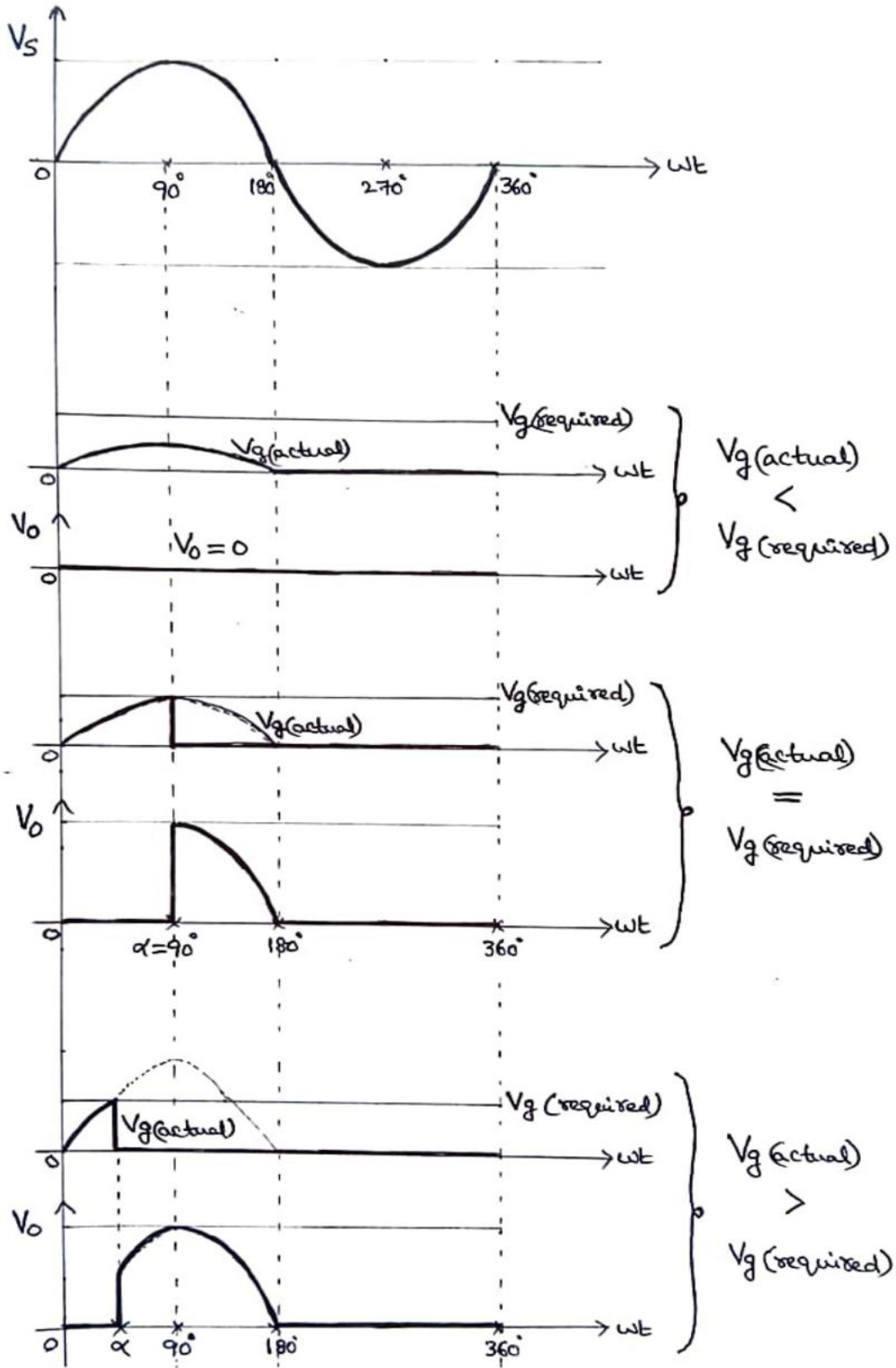
- * SCR has three junctions (J_1, J_2, J_3). Initially, the junctions J_1 and J_3 will be in forward bias and the junction J_2 , will be in reverse bias.
- * When the supply Voltage (V_S) is gradually increased, then, the forward voltage ($+V_{AK}$) gradually increases and a small forward leakage current flows through the SCR. When V_{AK} reaches a high value i.e. V_{FBO} , the junction J_2 will be break down and becomes forward bias. Hence, SCR comes to conduction state (or) ON state. This method of turning ON the SCR is known as Forward Voltage Triggering method.
- * The current at which SCR is turned ON is called as Latching Current (I_L). From that point onwards, the anode current I_A increases rapidly with a small change in V_{AK} .
- * If SCR is repeatedly turned ON by this Forward Voltage Triggering method, then, SCR may be damaged.
- * To reduce this risk, Gate Voltage has to be applied. Higher the gate voltage, lower the V_{AK} is required. This method of turning ON the SCR is known as Gate Triggering. This is the best method used in all practical applications.
- * To turn OFF the SCR, V_{AK} has to be reduced. When V_{AK} is gradually decreased, then, I_A also decreases. At a particular point, SCR comes to OFF state.
- * The current at which SCR is turned OFF is called as Holding Current (I_H).
- * When the reverse voltage ($-V_{AK}$) is gradually increased, then, a small reverse leakage current flows through the SCR. When ($-V_{AK}$) reaches a high value i.e. V_{RBO} , then, a large current flows through the SCR. Due to this, SCR may be damaged.

R Firing Circuit
(or) R Triggering Circuit
(or) Resistance Firing Circuit

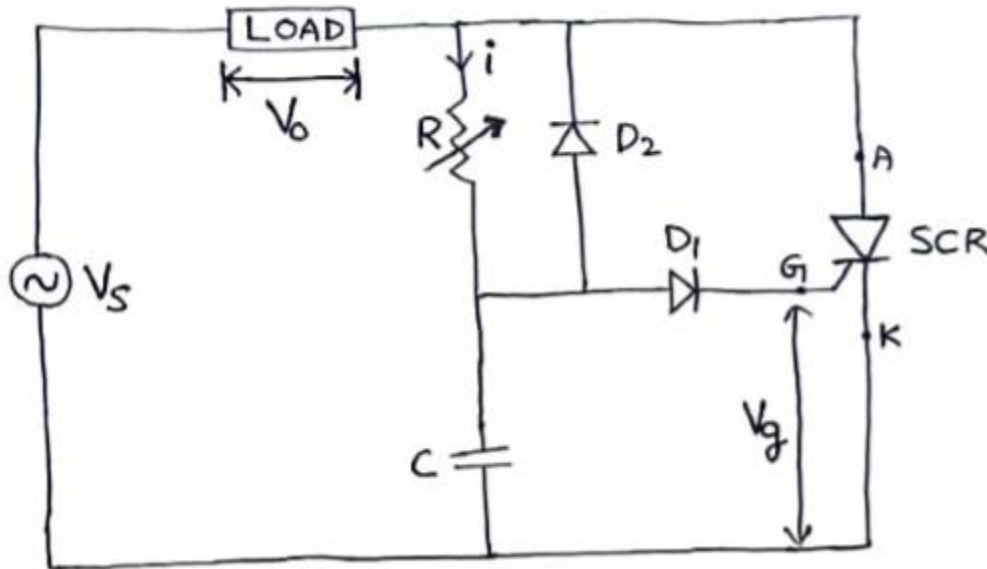


Here, R_2 = Variable Resistance (which varies from maximum to minimum)
 R = Resistance (which provides required gate voltage)
 R_1 = Resistance (which limits the current)
 D = Diode (which allows the current in positive half cycle of the supply)

- * When R_2 is maximum, then, the current (i) is minimum, $V_{g(\text{actual})} < V_{g(\text{required})}$. The SCR will be in OFF state.
- * When R_2 is decreased gradually, the current (i) increases.
- * At a particular value of R_2 , $V_{g(\text{actual})} = V_{g(\text{required})}$. This point is at $\alpha = 90^\circ$. The SCR will come to conduction state.
- * When R_2 is decreased gradually, then, the current (i) increases, the SCR will be in conduction state for ($\alpha < 90^\circ$)
- * The R triggering circuit provides firing angle control of ($\alpha : 0$ to 90°)
- * The R triggering circuit can be used for half wave rectifiers.



RC Firing Circuit
(or) RC Triggering Circuit
(or) Resistance Capacitance Firing Circuit



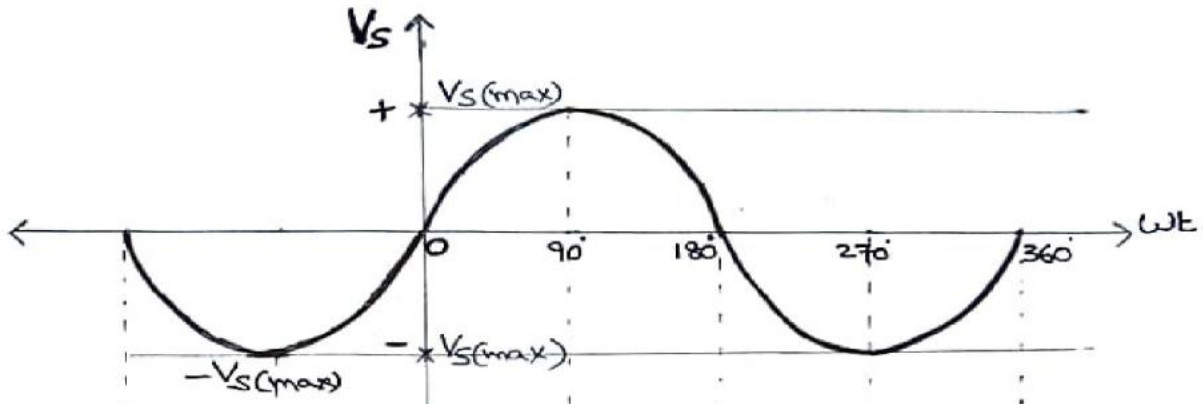
Here, R = Variable Resistance (which varies from maximum to minimum)

C = Capacitance (which produces required Gate Voltage)

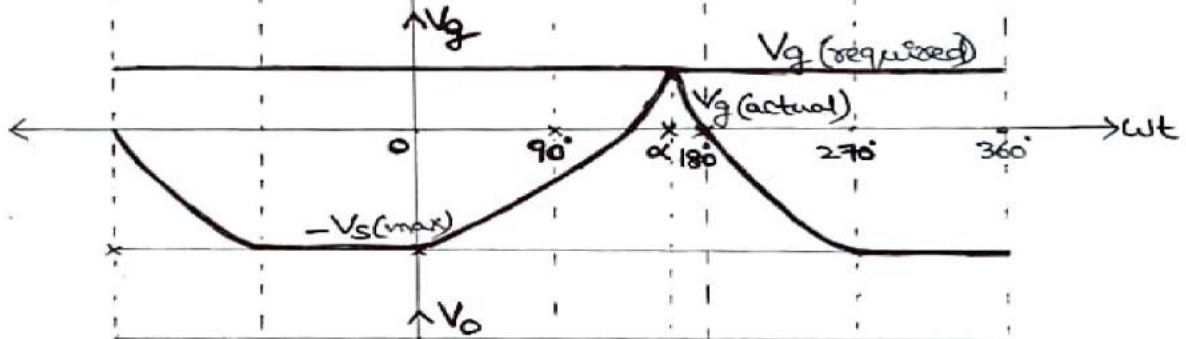
D_2 = Diode (which is used for capacitor charging)

D_1 = Diode (which is used for capacitor discharging)

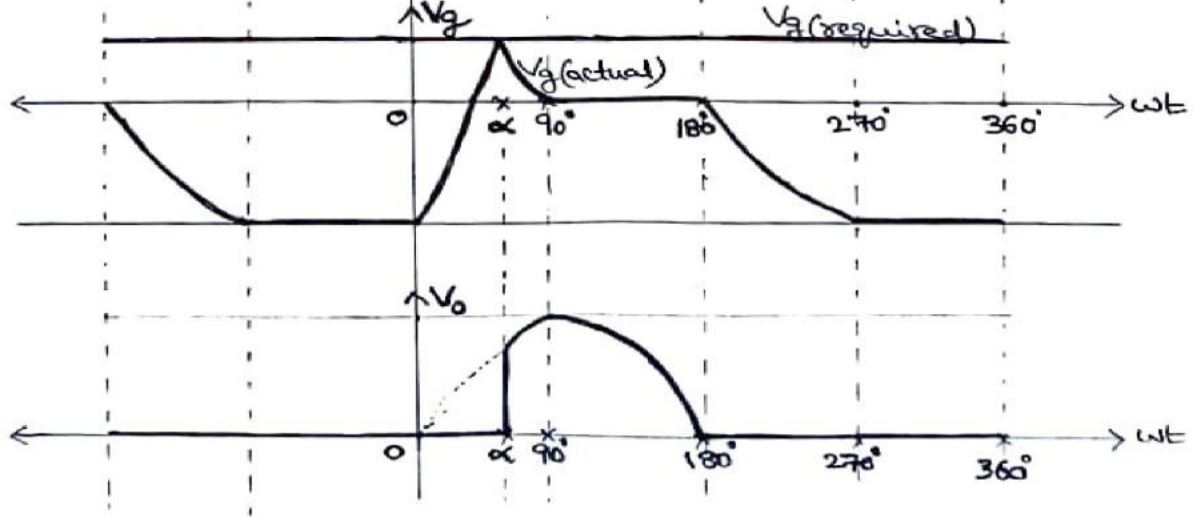
- * Initially, the capacitor charges to $(-V_{S(\max)})$ in the Negative half cycle of supply voltage V_s through the diode D_2 . The current path is $V_s \Rightarrow C \Rightarrow D_2 \Rightarrow V_s$.
- * In the Positive half cycle of supply voltage, when R is maximum, then, the current is minimum and time constant RC is maximum, the capacitor discharges very slowly and it produces required gate voltage at $(\alpha > 90^\circ)$
- * When R is minimum, then, the current is maximum and time constant RC is minimum, the capacitor discharges very fast and it produces required gate voltage at $(\alpha < 90^\circ)$
- * The RC triggering circuit provides firing angle control of $(\alpha : 0 \text{ to } 180^\circ)$
- * The RC triggering circuit can be used for half wave rectifiers.



$\alpha > 90^\circ$ when R is maximum

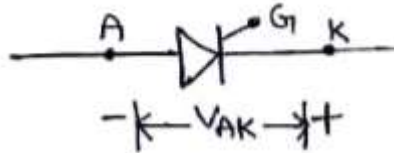


$\alpha < 90^\circ$ when R is minimum

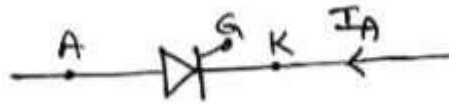


Commutation of SCR (or) Turning OFF of SCR

- * The SCR can be turned OFF by applying a reverse voltage or negative voltage across the SCR

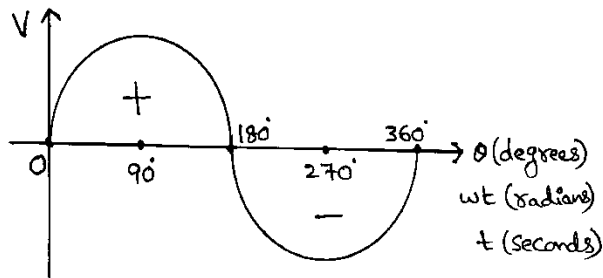


- * The SCR can be turned OFF by sending reverse current through the SCR



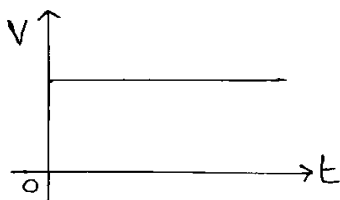
- * There are two types of commutation methods available for the SCR. (i) Natural Commutation (ii) Forced Commutation

(i) Natural Commutation



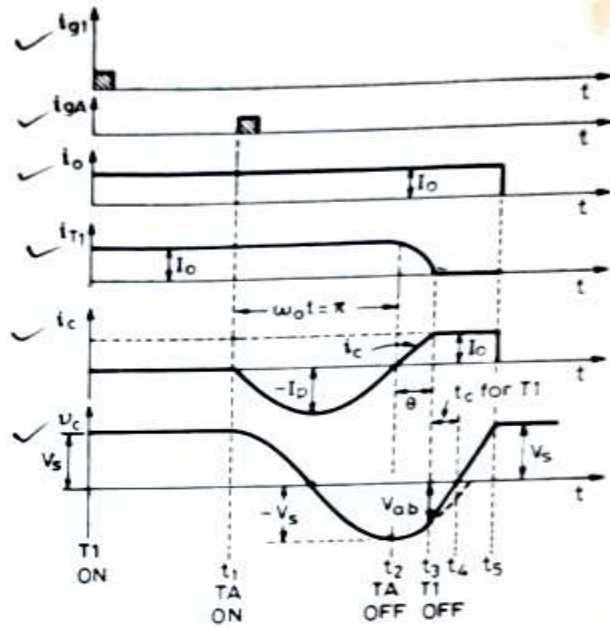
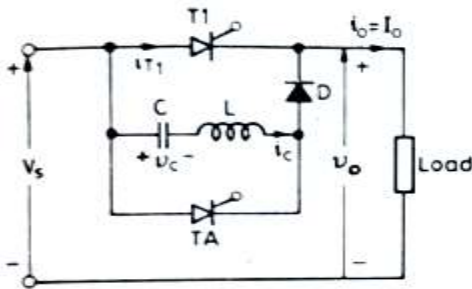
AC Supply voltage consists of positive half cycle and negative half cycle. The voltage of negative half cycle is called as reverse voltage. If AC supply is given to SCR, then, SCR will be in ON state in positive half cycle and SCR will be turned OFF naturally at the starting point of negative half cycle. This method of commutation is called as Natural Commutation.

(ii) Forced Commutation



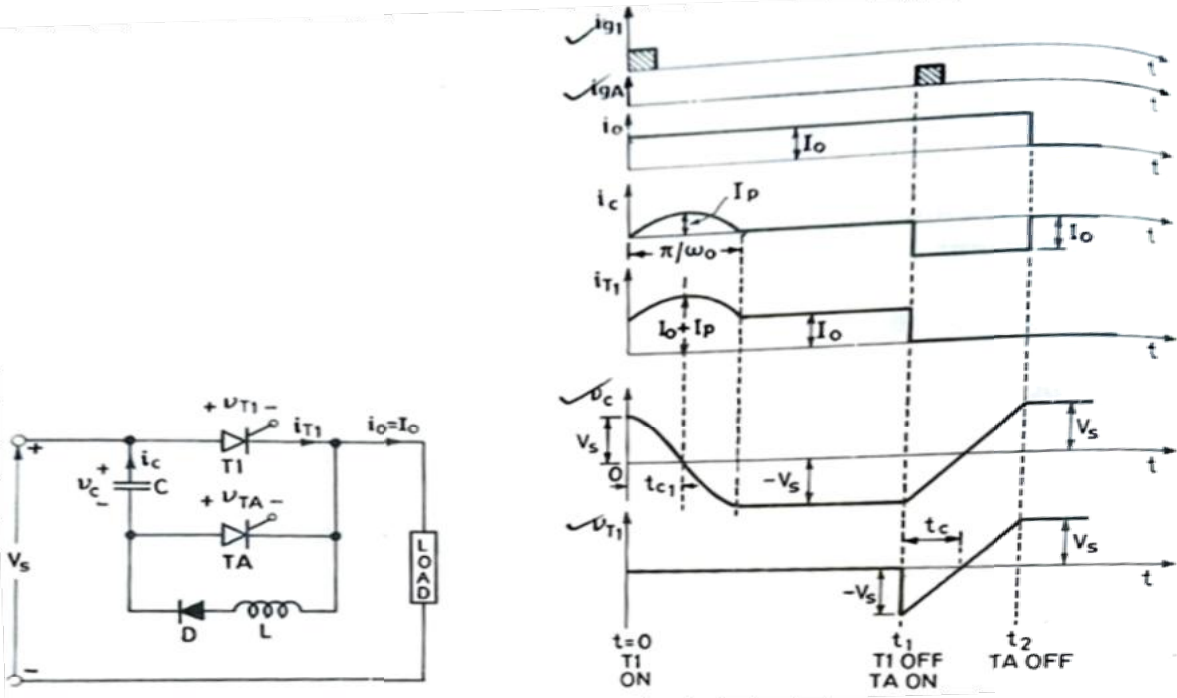
DC Supply Voltage does not consist of negative half cycle. So, if DC supply is given to SCR, then, an additional circuit must be connected across the SCR to generate reverse voltage and turn OFF the SCR forcibly. This method of commutation is called as Forced Commutation.

Current Commutation (or) Class-B Commutation (or) Resonant Pulse Commutation



- * Initially, the capacitor charges to a voltage V_S due to the source voltage (V_S) with left hand plate positive and right hand plate negative.
- * Initially, the main Thyristor T_1 and the auxiliary Thyristor T_A will be in OFF position.
- * When the main Thyristor T_1 is turned ON at ($t = 0$), a constant current (I_0) flows through the load. The current path is $V_{S(+)} \Rightarrow T_1 \Rightarrow \text{Load} \Rightarrow V_{S(-)}$.
- * To turn OFF the main Thyristor T_1 , the auxiliary Thyristor T_A is turned ON at ($t = t_1$). The capacitor discharges through the auxiliary Thyristor T_A , inductor L . The current path is $C \Rightarrow T_A \Rightarrow L \Rightarrow C$. The inductor stores energy during this process. Due to this inductor energy, the capacitor charges again to (V_S) with left hand plate negative and right hand plate positive.
- * The capacitor tries to discharge through inductor L , diode D , auxiliary Thyristor T_A . The current path is $C \Rightarrow L \Rightarrow T_A \Rightarrow C$. This discharge current is flowing in a reverse direction to the auxiliary Thyristor T_A . Due to this reverse current, the auxiliary Thyristor T_A will be turned OFF at ($t = t_2$).
- * The capacitor tries to discharge through inductor L , diode D , main Thyristor T_1 . The current path is $C \Rightarrow L \Rightarrow D \Rightarrow T_1 \Rightarrow C$. This discharge current is flowing in a reverse direction to the main Thyristor T_1 . Due to this reverse current, the main Thyristor T_1 will be turned OFF at ($t = t_3$).
- * As the Thyristors are turned OFF due to reverse current, this commutation method is called as Current Commutation.
- * The capacitor charges through inductor L , diode D , Load from ($t = t_3$) to ($t = t_5$). The current path is $V_{S(+)} \Rightarrow C \Rightarrow L \Rightarrow D \Rightarrow \text{Load} \Rightarrow V_{S(-)}$. From ($t = t_5$), there is no path for I_0 current and hence I_0 will be zero.

Voltage Commutation (or) Class-D Commutation (or) Impulse Commutation



- * Initially, the capacitor charges to a voltage V_S due to the source voltage (V_S) with upper plate positive and lower plate negative.
- * Initially, the main Thyristor T_1 and the auxiliary Thyristor T_A will be in OFF position.
- * When the main Thyristor T_1 is turned ON at ($t = 0$), a constant current (I_o) flows through the load. The current path is $V_{S(+)} \Rightarrow T_1 \Rightarrow \text{Load} \Rightarrow V_{S(-)}$.
- * The capacitor discharges through main Thyristor T_1 , inductor L and Diode D . The current path is $C \Rightarrow T_1 \Rightarrow L \Rightarrow D \Rightarrow C$. The inductor stores energy during this process. Due to this inductor energy, the capacitor charges again to (V_S) with upper plate negative and lower plate positive.
- * To turn OFF the main Thyristor T_1 , the auxiliary Thyristor T_A is turned ON at ($t = t_1$). The capacitor voltage appears as a reverse voltage to the main Thyristor T_1 . Due to this reverse voltage, the main Thyristor T_1 will be turned OFF at ($t = t_1$).
- * As the main Thyristor T_1 is turned OFF due to reverse voltage, this commutation method is called as Voltage Commutation.
- * The path for I_o current is $V_{S(+)} \Rightarrow C \Rightarrow T_A \Rightarrow \text{Load} \Rightarrow V_{S(-)}$. The capacitor voltage becomes positive i.e upper plate positive and lower plate negative. After that, there is no charging and discharging of capacitor, and the current passing through the auxiliary Thyristor T_A is zero and hence, the auxiliary Thyristor T_A will be turned off automatically. From ($t = t_2$), there is no path for I_o current and hence I_o will be zero.
- * From ($t = t_2$), there is no path for I_o current and hence I_o will be zero.

Power Electronics

Unit-1 Chapter-2 Other Devices

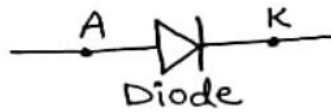
1. Diode
2. MOSFET (Metal Oxide Semiconductor Field Effect Transistor)
3. IGBT (Insulated Gate Bipolar Transistor)
4. Comparison between MOSFET and IGBT
5. Comparison between Transistor and Thyristor
6. Gallium Nitride Devices and Silicon Carbide Devices

Diode

Introduction:

Diode (or) Power Diode is an uncontrolled power semiconductor device which consists of two layers (P & N), two terminals (Anode "A" and cathode "K") and one P-N Junction.

Symbol:

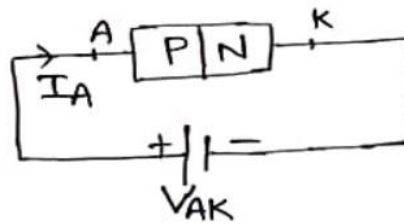


Structure:

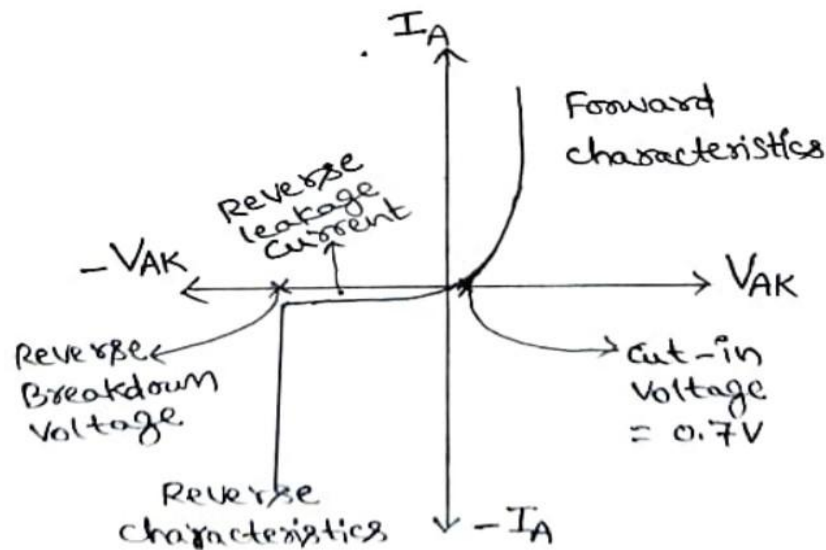


Static characteristics (or) V-I characteristics (or) steady state characteristics

(i) circuit diagram:



(ii) characteristics

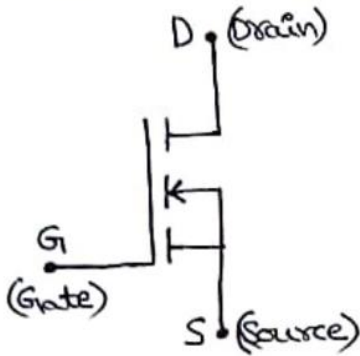


MOSFET

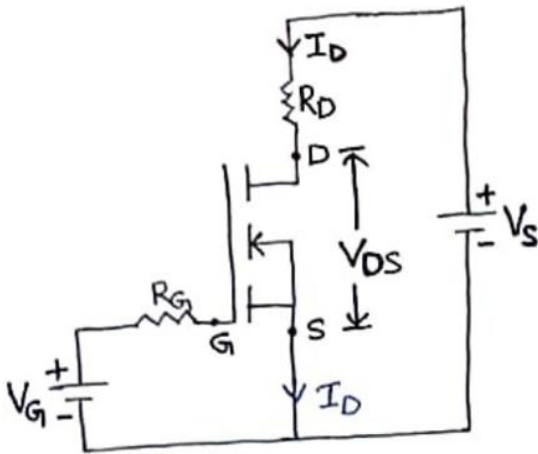
Introduction:

MOSFET means Metal oxide Semiconductor Field Effect Transistor. It has 3 terminals (Gate "G", Drain "D" and Source "S"). It is a voltage controlled device.

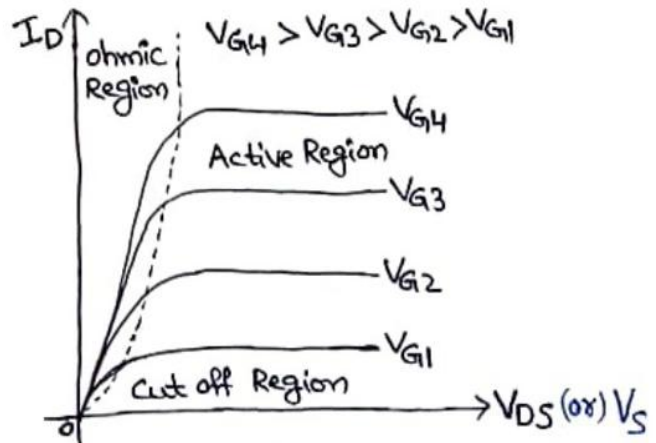
Symbol:



Characteristics circuit Diagram



Static characteristics (or) steady state characteristics (or) V-I characteristics



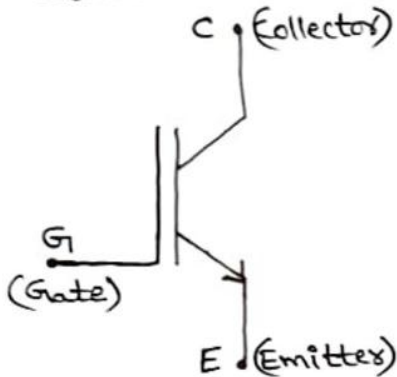
- * For lower values of V_{DS} , the curve is linear i.e. I_D increases.
- * For higher values of V_{DS} , the curve is flat i.e. I_D is constant.

IGBT

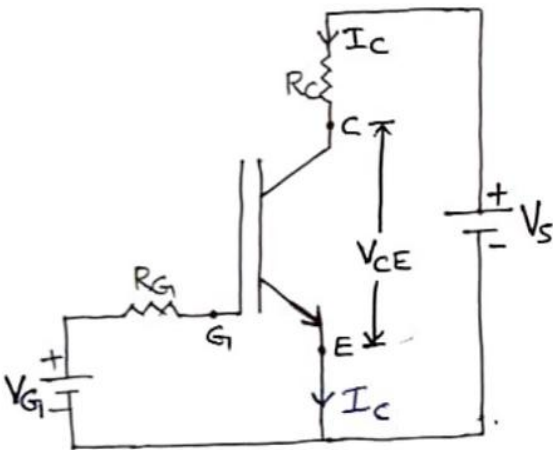
Introduction:

IGBT means Insulated Gate Bipolar Transistor.
It has 3 terminals (Gate "G", Collector "C" and Emitter "E").
It is a voltage controlled device.

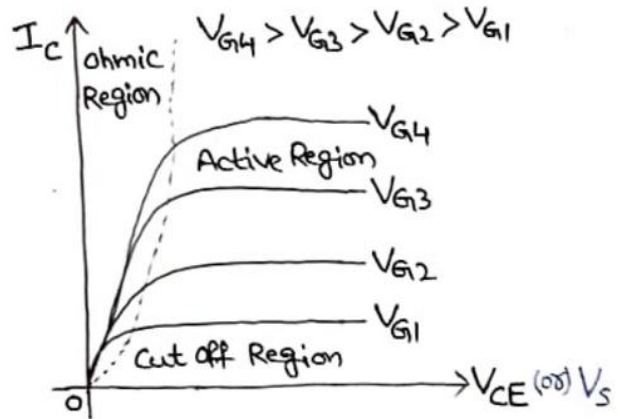
Symbol:



Characteristics Circuit Diagram



Static characteristics (or) steady state characteristics (or) V-I characteristics



- * For lower values of V_{CE} , the curve is linear i.e. I_C increases.
- * For higher values of V_{CE} , the curve is flat i.e. I_C is constant.

Comparison between MOSFET and IGBT

Sl. No.	MOSFET	IGBT
1	Metal Oxide Semiconductor Field Effect Transistor	Insulated Gate Bipolar Transistor
2	Maximum Ratings 500V, 140A, 250kHz	Maximum Ratings 1200V, 500A, 20kHz
3	High Switching Frequency (250KHz)	Low Switching Frequency (20KHz)
4	It has only one current path in its structure	It has two current paths in its structure
5	It is a unipolar device	It is a bipolar device
6	It is a unidirectional device and current flows from Drain to Source	It is a unidirectional device and current flows from Collector to Emitter
7	It is a voltage controlled device	It is a voltage controlled device
8	It is a Transistor	It is a Transistor
9	Applications are Inverter, UPS, SMPS	Applications are Inverter, UPS, SMPS

Comparison between Transistor and Thyristor

Sl. No.	Transistor	Thyristor
1	Examples MOSFET (Metal Oxide Semiconductor Field Effect Transistor), IGBT (Insulated Gate Bipolar Transistor), BJT (Bipolar Junction Transistor)	Examples SCR (Silicon Controlled Rectifier) RCT (Reverse Conducting Thyristor) GTO (Gate Turn Off Thyristor)
2	Ratings are low MOSFET (500V, 140A) IGBT (1200V, 500A)	Ratings are high SCR (10KV, 3000A)
3	Turn ON and Turn OFF is easy	Turn ON is easy & Turn OFF is not easy
4	Commutation circuit is not required	Communication circuit is required
5	When Gate Pulse is given, the Transistor will be turned ON. When Gate Pulse is removed, then, the Transistor will be turned OFF.	When Gate Pulse is given, the Transistor will be turned ON. When Gate Pulse is removed, then, the Thyristor will not be turned OFF.
6	ON state voltage drop is less	ON state voltage drop is more
7	It can not withstand to Surges	It can withstand to Surges
8	Size is less	Size is more
9	Cost is less	Cost is more

Gallium Nitride Devices and Silicon Carbide Devices

- * Gallium Nitride (GaN) and Silicon Carbide (SiC) are wide bandgap semiconductor materials used in power electronics, offering advantages over traditional silicon-based devices.
- * SiC is preferred for high-voltage, high-power applications like automotive traction inverters and industrial power supplies
- * GaN excels in high-frequency, lower-power applications like consumer and telecom power supplies, and electric vehicle (EV) onboard chargers.

Gallium Nitride (GaN) Devices:

- * High Frequency and Lower Power: GaN devices are particularly well-suited for high-frequency applications (above 100 kHz) and lower power levels (typically up to 650V).
- * High Power Density: GaN enables more compact and efficient power converters, leading to smaller chargers and power supplies.
- * Applications: Consumer power supplies (laptops, smartphones), telecom power supplies, server and data center power supplies, EV onboard chargers, and fast charging applications.
- * Advantages over SiC: GaN can offer higher switching frequencies and lower conduction losses than SiC in certain applications.

Silicon Carbide (SiC) Devices:

- * High Voltage and Power: SiC devices are known for their ability to handle high voltages (650V and above) and high currents, making them suitable for demanding applications like electric vehicle (EV) traction inverters, solar farms, and large industrial power supplies.
- * High Temperature Operation: SiC can operate at higher temperatures than silicon, enhancing reliability and performance in harsh environments.
- * Faster Switching Speed: SiC devices can switch faster than silicon, enabling more efficient power conversion and smaller component sizes.
- * Applications: High-power motor drives, large-scale power conditioners (e.g., for power generation), EV inverters, and industrial power supplies.

Power Electronics

Unit-2 Rectifiers (AC to DC Converters)

Unit-2 Chapter-1 1 ϕ Rectifiers

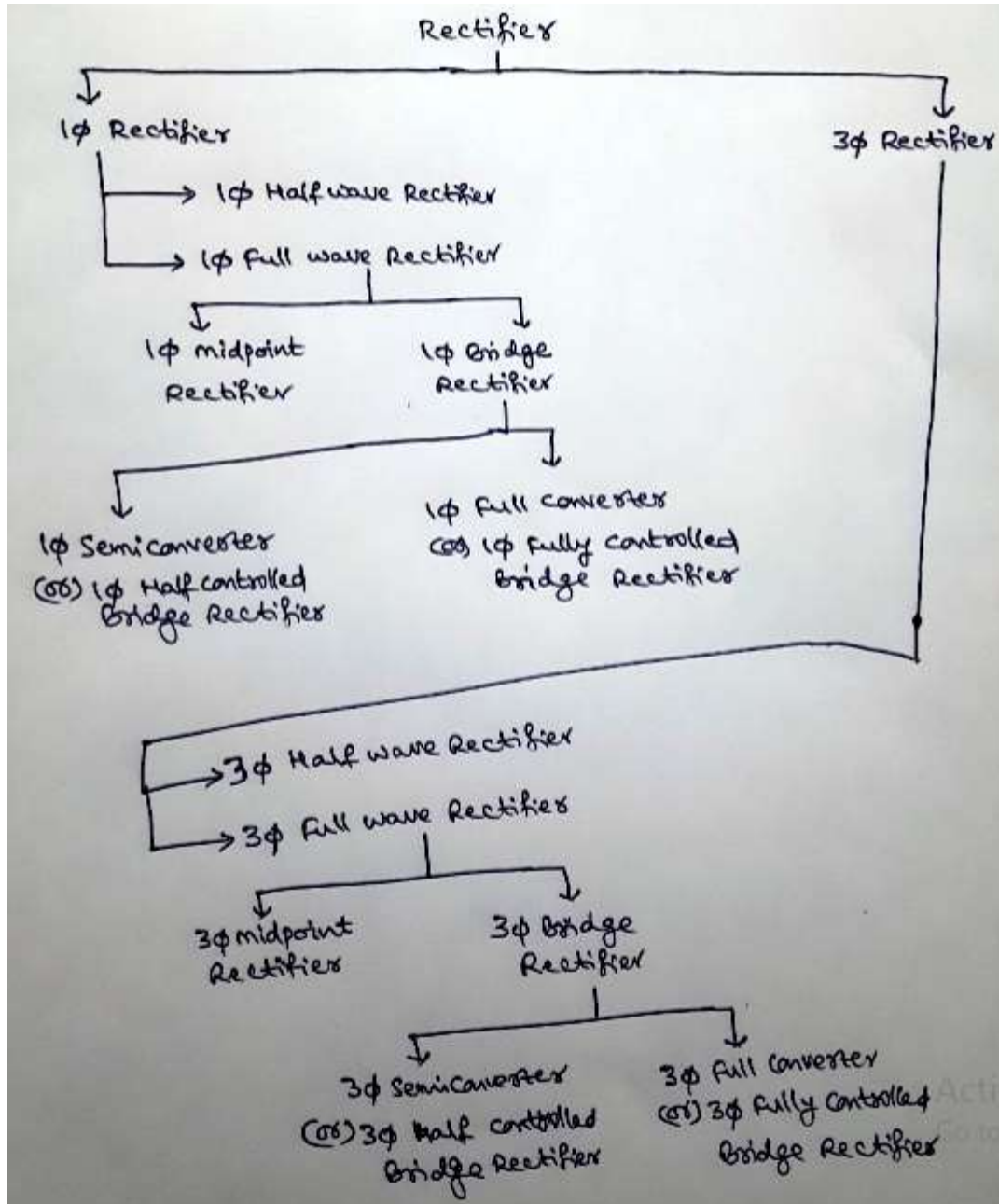
1. Introduction
2. 1 ϕ Half Wave Rectifier
 - (a) Resistive Load (R Load)
 - (b) Inductive Load (RL Load)
 - (c) RL Load and Free Wheeling Diode
3. 1 ϕ Full Converter (or) 1 ϕ Fully Controlled Bridge Rectifier
 - (a) Resistive Load (R Load)
 - (b) High Inductive Load (RL Load)
 - (c) RL Load and Free Wheeling Diode

Introduction

Definition of Rectifier: Rectifier is a Power Electronics Converter which converts fixed AC Voltage to Variable AC Voltage

Applications of Rectifiers: Battery Charging, Power Supplies, UPS, Inverter, DC Traction, HVDC Transmission etc.

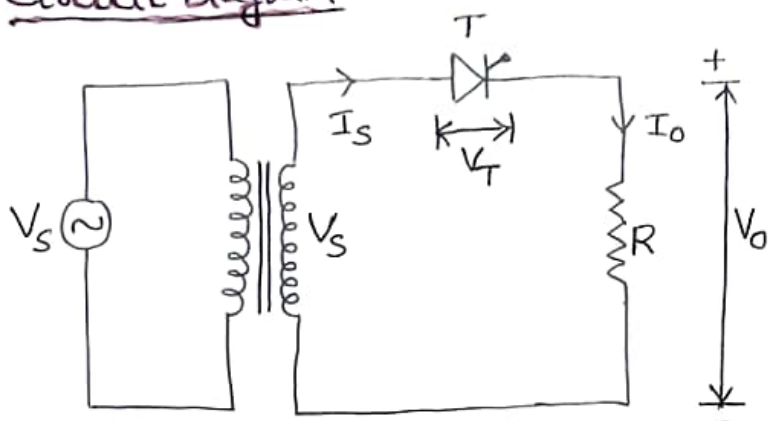
Classification of Rectifiers:



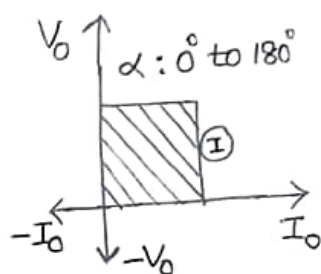
1 ϕ Half Wave Rectifier with R-Load

one pulse
one quadrant

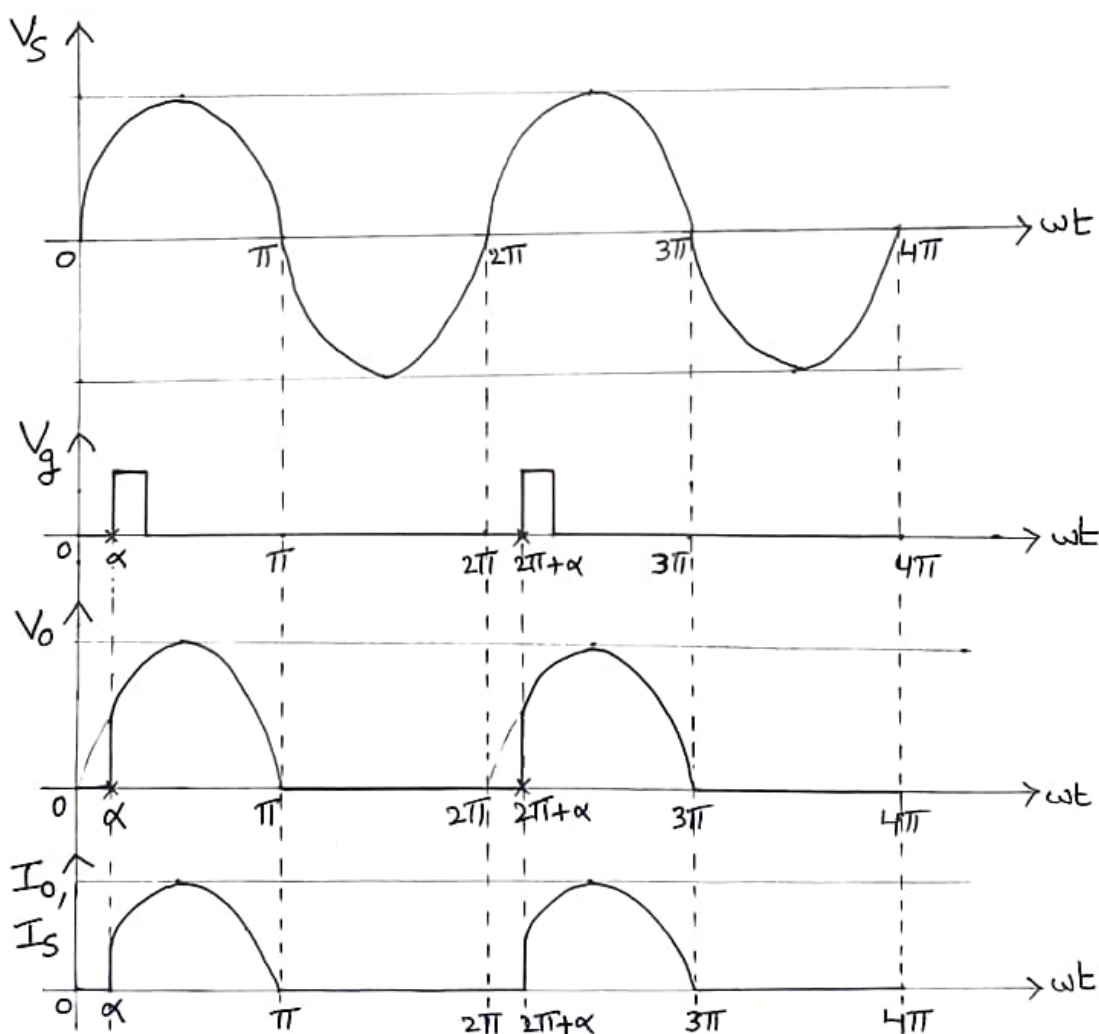
Circuit Diagram



Quadrant Diagram



Waveforms



Derivation

$$V_o(\text{avg}) = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_s d(\omega t) = \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t d(\omega t) = \frac{V_m}{2\pi} (1 + \cos \alpha)$$

$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{V_m}{2\pi R} (1 + \cos \alpha)$$

$$V_o(\text{rms}) = \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\pi} V_s^2 d(\omega t)}$$

$$I_o(\text{rms}) = V_o(\text{rms})/R$$

Derivation

$$\begin{aligned}\checkmark (i) V_o(\text{avg}) &= \frac{1}{2\pi} \int_{\alpha}^{\pi} V_s d(\omega t) \\ &= \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t d(\omega t) \\ &= \frac{V_m}{2\pi} \int_{\alpha}^{\pi} \sin \omega t d(\omega t) \\ &= \frac{V_m}{2\pi} (-\cos \omega t) \Big|_{\alpha}^{\pi} \\ &= -\frac{V_m}{2\pi} (\cos \omega t) \Big|_{\alpha}^{\pi} \\ &= -\frac{V_m}{2\pi} \cdot (\cos \pi - \cos \alpha) \\ &= -\frac{V_m}{2\pi} (-1 - \cos \alpha)\end{aligned}$$

$$V_o(\text{avg}) = \frac{V_m}{2\pi} (1 + \cos \alpha)$$

$$\checkmark (ii) I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{V_m}{2\pi R} (1 + \cos \alpha)$$

$$\begin{aligned}\times (iii) V_o(\text{rms}) &= \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\pi} V_s^2 d(\omega t)} = \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\pi} (V_m \sin \omega t)^2 d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{2\pi} \int_{\alpha}^{\pi} \sin^2 \omega t d(\omega t)} = \sqrt{\frac{V_m^2}{2\pi} \int_{\alpha}^{\pi} \frac{1 - \cos 2\omega t}{2} d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{4\pi} \int_{\alpha}^{\pi} (1 - \cos 2\omega t) d(\omega t)} = \sqrt{\frac{V_m^2}{4\pi} \left[\int_{\alpha}^{\pi} 1 \cdot d(\omega t) - \int_{\alpha}^{\pi} \cos 2\omega t d(\omega t) \right]}\end{aligned}$$

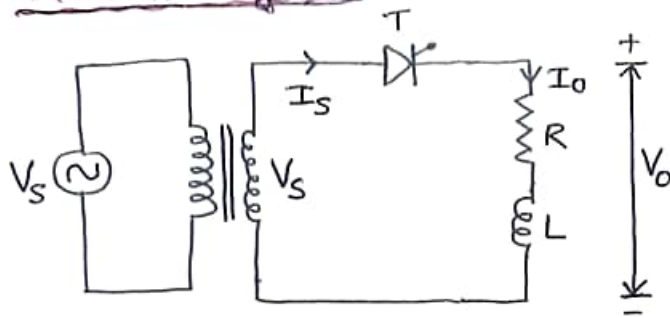
$$V_o(\text{rms}) = \frac{V_m}{2\sqrt{\pi}} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right] \frac{1}{2}$$

$$\times (iv) I_o(\text{rms}) = \frac{V_o(\text{rms})}{R}$$

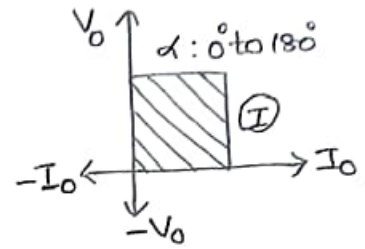
1 ϕ Half Wave Rectifier with RL-Load

one pulse
one quadrant

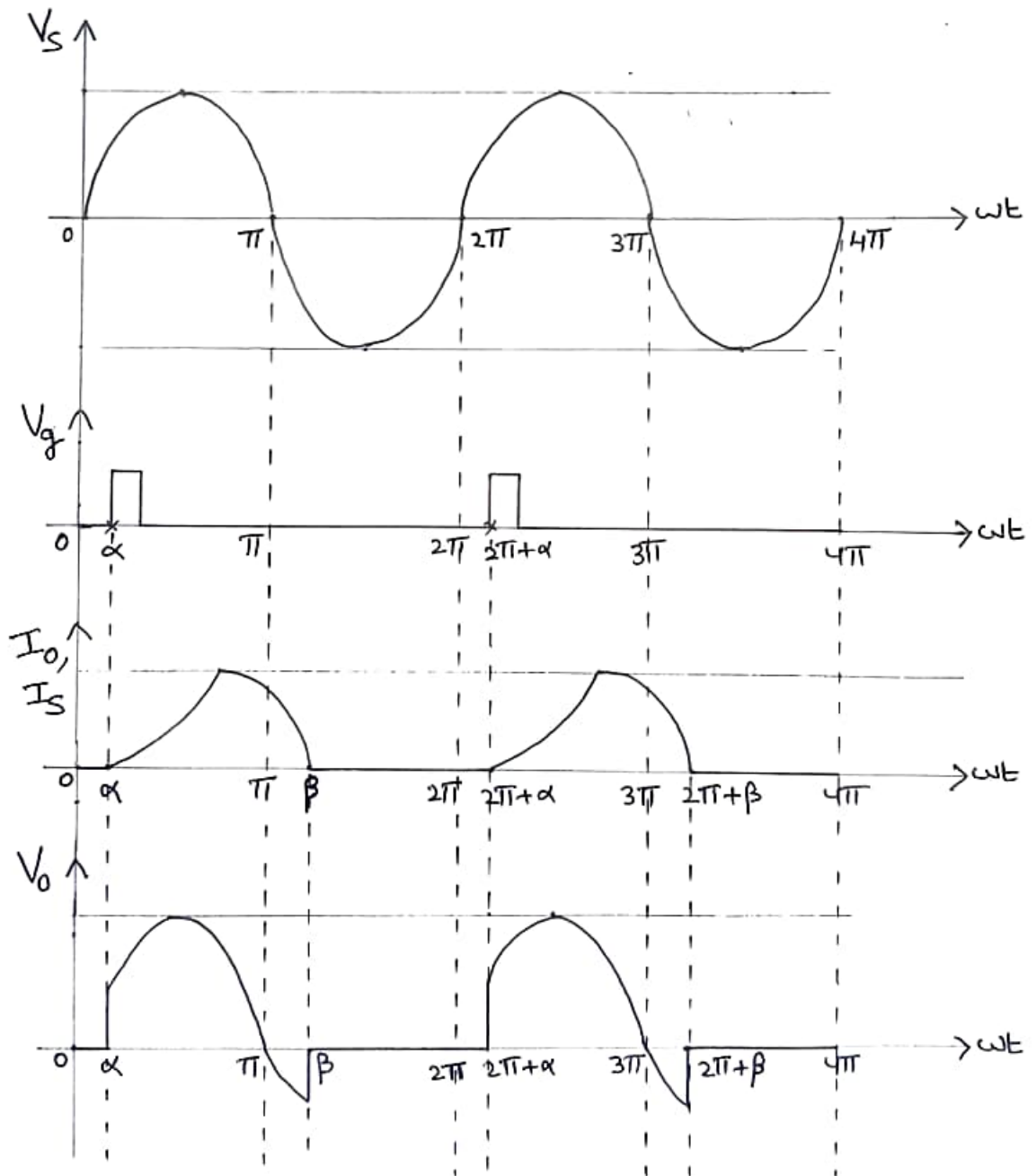
Circuit Diagram



Quadrant Diagram



Waveforms



Derivation

$$\begin{aligned}\checkmark (i) \quad V_{0(\text{avg})} &= \frac{1}{2\pi} \int_{\alpha}^{\beta} V_s \, d(\omega t) \\ &= \frac{1}{2\pi} \int_{\alpha}^{\beta} V_m \sin \omega t \, d(\omega t) \\ &= \frac{V_m}{2\pi} \int_{\alpha}^{\beta} \sin \omega t \, d(\omega t) \\ &= \frac{V_m}{2\pi} (-\cos \omega t) \Big|_{\alpha}^{\beta} \\ &= -\frac{V_m}{2\pi} (\cos \omega t) \Big|_{\alpha}^{\beta} \\ &= -\frac{V_m}{2\pi} (\cos \beta - \cos \alpha) \\ &= \frac{V_m}{2\pi} (\cos \alpha - \cos \beta)\end{aligned}$$

$$\therefore \boxed{V_{0(\text{avg})} = \frac{V_m}{2\pi} (\cos \alpha - \cos \beta)}$$

$$\checkmark (ii) \quad I_{0(\text{avg})} = \frac{V_{0(\text{avg})}}{R} = \frac{V_m}{2\pi R} (\cos \alpha - \cos \beta)$$

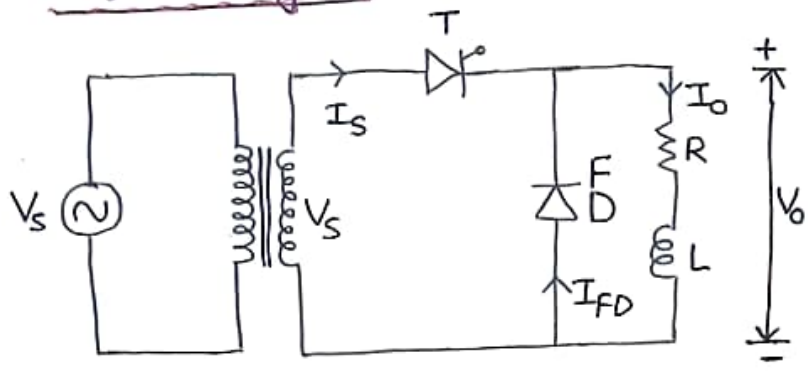
$$\begin{aligned}\times (iii) \quad V_{0(\text{rms})} &= \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\beta} V_s^2 \, d(\omega t)} = \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\beta} (V_m \sin \omega t)^2 \, d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{2\pi} \int_{\alpha}^{\beta} \sin^2 \omega t \, d(\omega t)} = \sqrt{\frac{V_m^2}{2\pi} \int_{\alpha}^{\beta} \frac{1 - \cos 2\omega t}{2} \, d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{4\pi} \int_{\alpha}^{\beta} (1 - \cos 2\omega t) \, d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{4\pi} \left[\int_{\alpha}^{\beta} 1 \, d(\omega t) - \int_{\alpha}^{\beta} \cos 2\omega t \, d(\omega t) \right]} \\ &= \sqrt{\frac{V_m^2}{4\pi} \left[(\omega t) \Big|_{\alpha}^{\beta} - \left(\frac{\sin 2\omega t}{2} \right) \Big|_{\alpha}^{\beta} \right]}\end{aligned}$$

$$\therefore \boxed{V_{0(\text{rms})} = \frac{V_m}{2\sqrt{\pi}} \left[(\beta - \alpha) - \frac{1}{2} (\sin 2\beta - \sin 2\alpha) \right]^{1/2}}$$

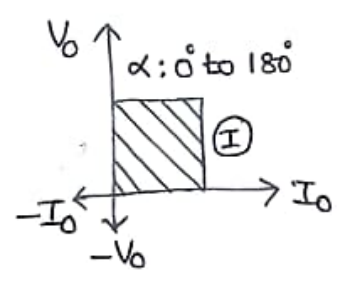
1 ϕ Half Wave Rectifier with RL-Load and Free wheeling Diode

one pulse
one quadrant

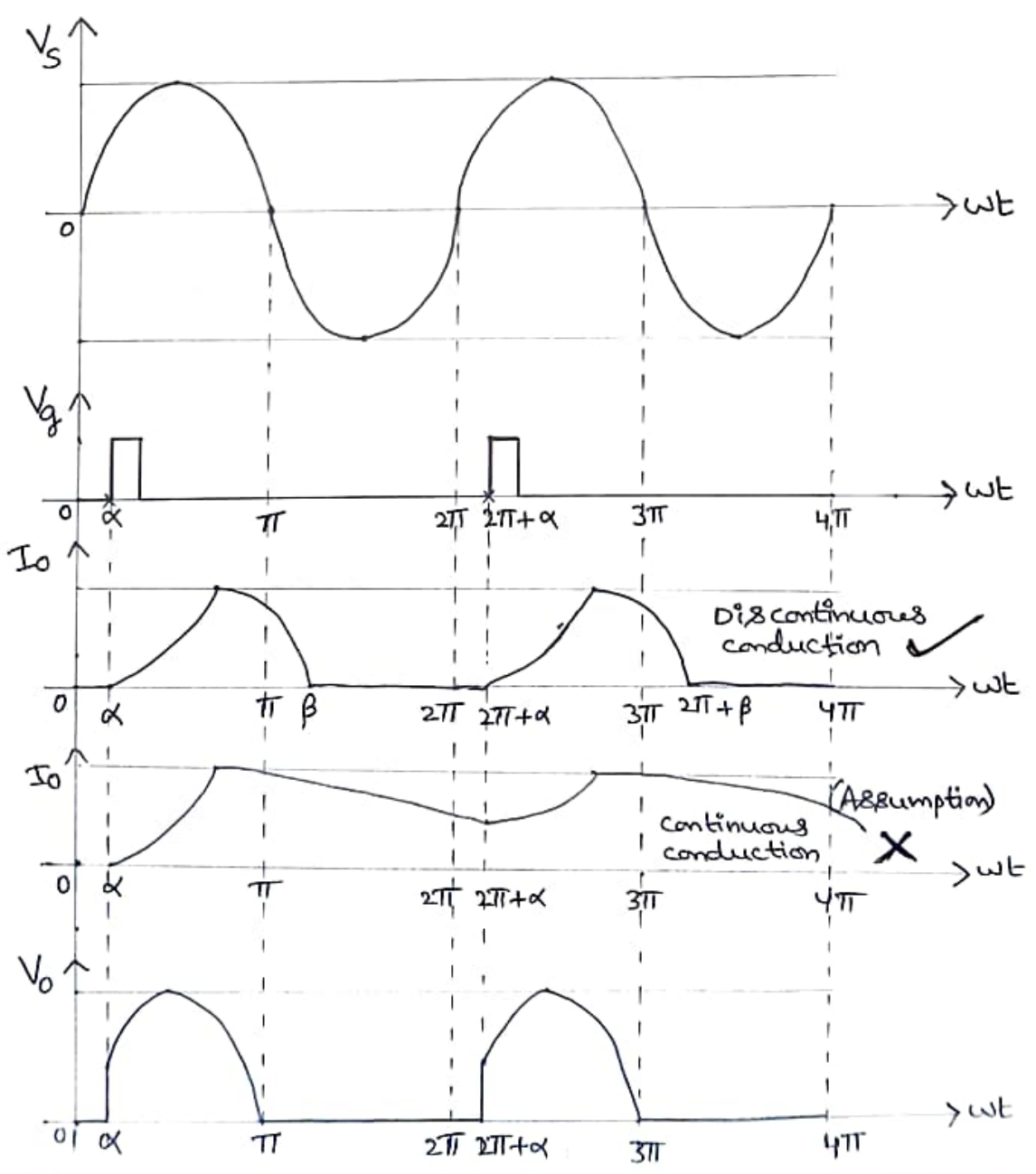
Circuit Diagram



Quadrant Diagram



Waveforms



Derivation

$$\begin{aligned}\checkmark (i) V_o(\text{avg}) &= \frac{1}{2\pi} \int_{\alpha}^{\pi} V_s d(\omega t) \\ &= \frac{1}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t d(\omega t) \\ &= \frac{V_m}{2\pi} \int_{\alpha}^{\pi} \sin \omega t d(\omega t) \\ &= \frac{V_m}{2\pi} (-\cos \omega t)_{\alpha}^{\pi} \\ &= -\frac{V_m}{2\pi} (\cos \omega t)_{\alpha}^{\pi} \\ &= -\frac{V_m}{2\pi} (\cos \pi - \cos \alpha) \\ &= -\frac{V_m}{2\pi} (-1 - \cos \alpha)\end{aligned}$$

$$\boxed{V_o(\text{avg}) = \frac{V_m}{2\pi} (1 + \cos \alpha)}$$

$$\checkmark (ii) I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{V_m}{2\pi R} (1 + \cos \alpha)$$

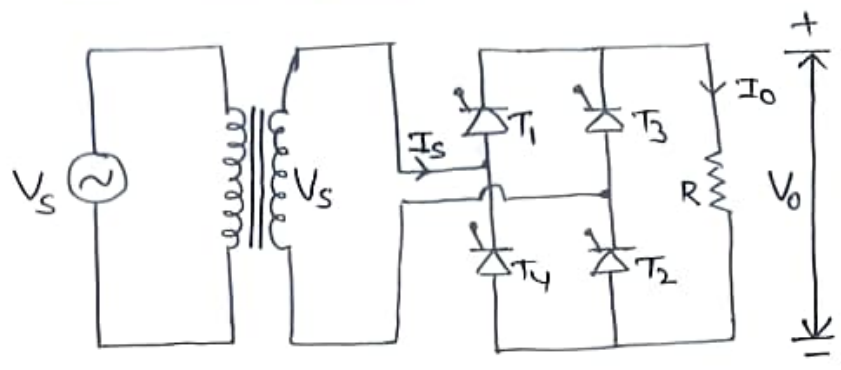
$$\begin{aligned}\times (iii) V_o(\text{rms}) &= \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\pi} V_s^2 d(\omega t)} = \sqrt{\frac{1}{2\pi} \int_{\alpha}^{\pi} (V_m \sin \omega t)^2 d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{2\pi} \int_{\alpha}^{\pi} \sin^2 \omega t d(\omega t)} = \sqrt{\frac{V_m^2}{2\pi} \int_{\alpha}^{\pi} \frac{1 - \cos 2\omega t}{2} d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{4\pi} \int_{\alpha}^{\pi} (1 - \cos 2\omega t) d(\omega t)} \\ &= \sqrt{\frac{V_m^2}{4\pi} \left[\int_{\alpha}^{\pi} 1 \cdot d(\omega t) - \int_{\alpha}^{\pi} \cos 2\omega t \cdot d(\omega t) \right]} \\ &= \sqrt{\frac{V_m^2}{4\pi} \left[(\omega t)_{\alpha}^{\pi} - \left(\frac{\sin 2\omega t}{2} \right)_{\alpha}^{\pi} \right]}\end{aligned}$$

$$\boxed{V_o(\text{rms}) = \frac{V_m}{2\sqrt{2\pi}} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]^{1/2}}$$

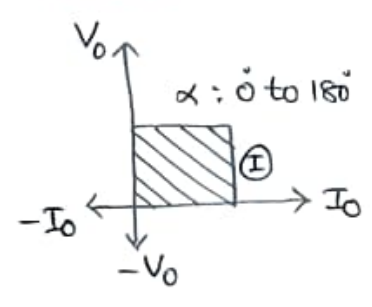
1 ϕ Full Converter with R-Load

Two pulse
one quadrant

Circuit Diagram



Quadrant Diagram



Derivation

~~$$V_o(\text{avg}) = \frac{1}{\pi} \int_{\alpha}^{\pi} V_s d(\omega t)$$

$$V_o(\text{avg}) = \frac{V_m}{\pi} (1 + \cos \alpha)$$

$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{V_m}{\pi R} (1 + \cos \alpha)$$

$$V_o(\text{rms}) = \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} V_s^2 d(\omega t)} = \frac{V_m}{\sqrt{2\pi}} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]^{\frac{1}{2}}$$~~

✓

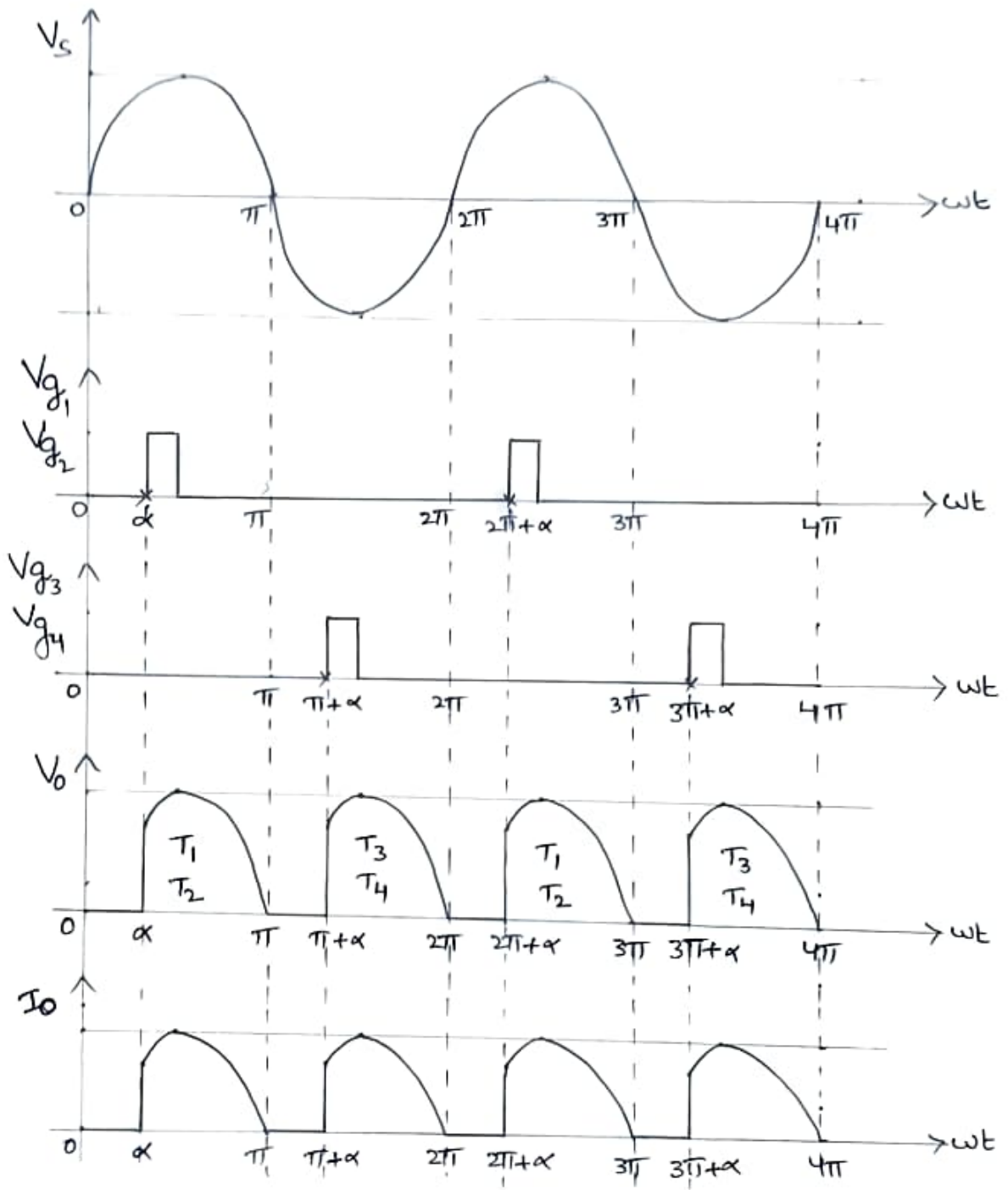
$$\begin{aligned}
 V_o(\text{avg}) &= \frac{1}{\pi} \int_{\alpha}^{\pi} V_s \cdot d(\omega t) \\
 &= \frac{1}{\pi} \int_{\alpha}^{\pi} V_m \cdot \sin \omega t \cdot d(\omega t) \\
 &= \frac{V_m}{\pi} \int_{\alpha}^{\pi} \sin \omega t \cdot d(\omega t) \\
 &= \frac{V_m}{\pi} (-\cos \omega t)_{\alpha}^{\pi} \\
 &= -\frac{V_m}{\pi} (\cos \omega t)_{\alpha}^{\pi} \\
 &= -\frac{V_m}{\pi} (\cos \pi - \cos \alpha) \\
 &= -\frac{V_m}{\pi} (-1 - \cos \alpha)
 \end{aligned}$$

$$V_o(\text{avg}) = \frac{V_m}{\pi} (1 + \cos \alpha)$$

✓

$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R}$$

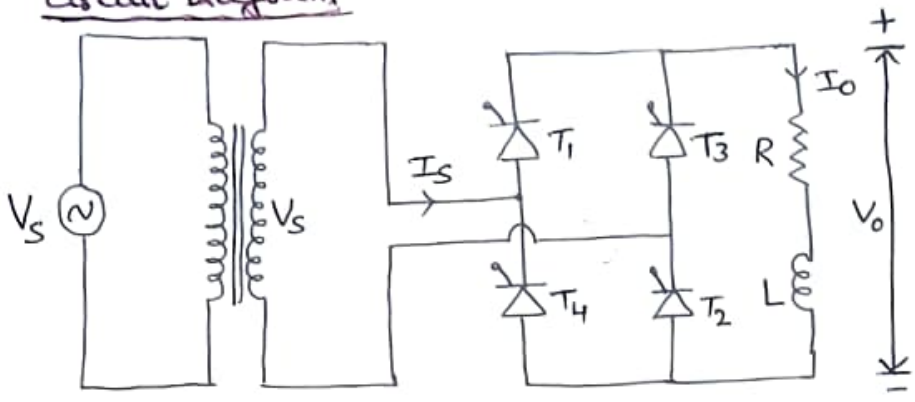
Waveforms



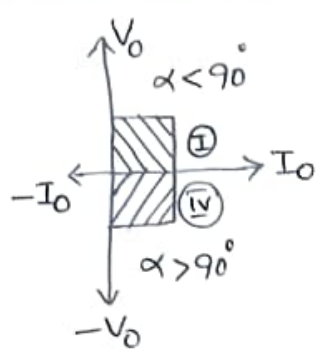
1 ϕ Full Converter with RL-Load

Two pulse
Two Quadrant

Circuit Diagram



Quadrant Diagram



Derivation

(i) Discontinuous conduction (for low inductance)

~~$$V_o(\text{avg}) = \frac{1}{\pi} \int_{\alpha}^{\beta} V_s d(\omega t)$$~~

~~$$V_o(\text{avg}) = \frac{V_m}{\pi} (\cos \alpha - \cos \beta)$$~~

~~$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{V_m}{\pi R} (\cos \alpha - \cos \beta)$$~~

~~$$V_o(\text{rms}) = \sqrt{\frac{1}{\pi} \int_{\alpha}^{\beta} V_s^2 d(\omega t)} = \frac{V_m}{\sqrt{2\pi}} \left[(\beta - \alpha) + \frac{1}{2} (\sin 2\beta - \sin 2\alpha) \right]^{\frac{1}{2}}$$~~

(ii) Continuous conduction (for high inductance)

~~$$V_o(\text{avg}) = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_s d(\omega t)$$~~

~~$$V_o(\text{avg}) = \frac{2V_m \cos \alpha}{\pi}$$~~

~~$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{2V_m \cos \alpha}{\pi R}$$~~

~~$$V_o(\text{rms}) = \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_s^2 d(\omega t)} = \frac{V_m}{\sqrt{2}}$$~~

$$V_o(\text{avg}) = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_s d(\omega t) = \frac{1}{\pi} \int_{\alpha}^{\pi+\alpha} V_m \sin \omega t d(\omega t) = \frac{V_m}{\pi} \int_{\alpha}^{\pi+\alpha} \sin \omega t d(\omega t)$$

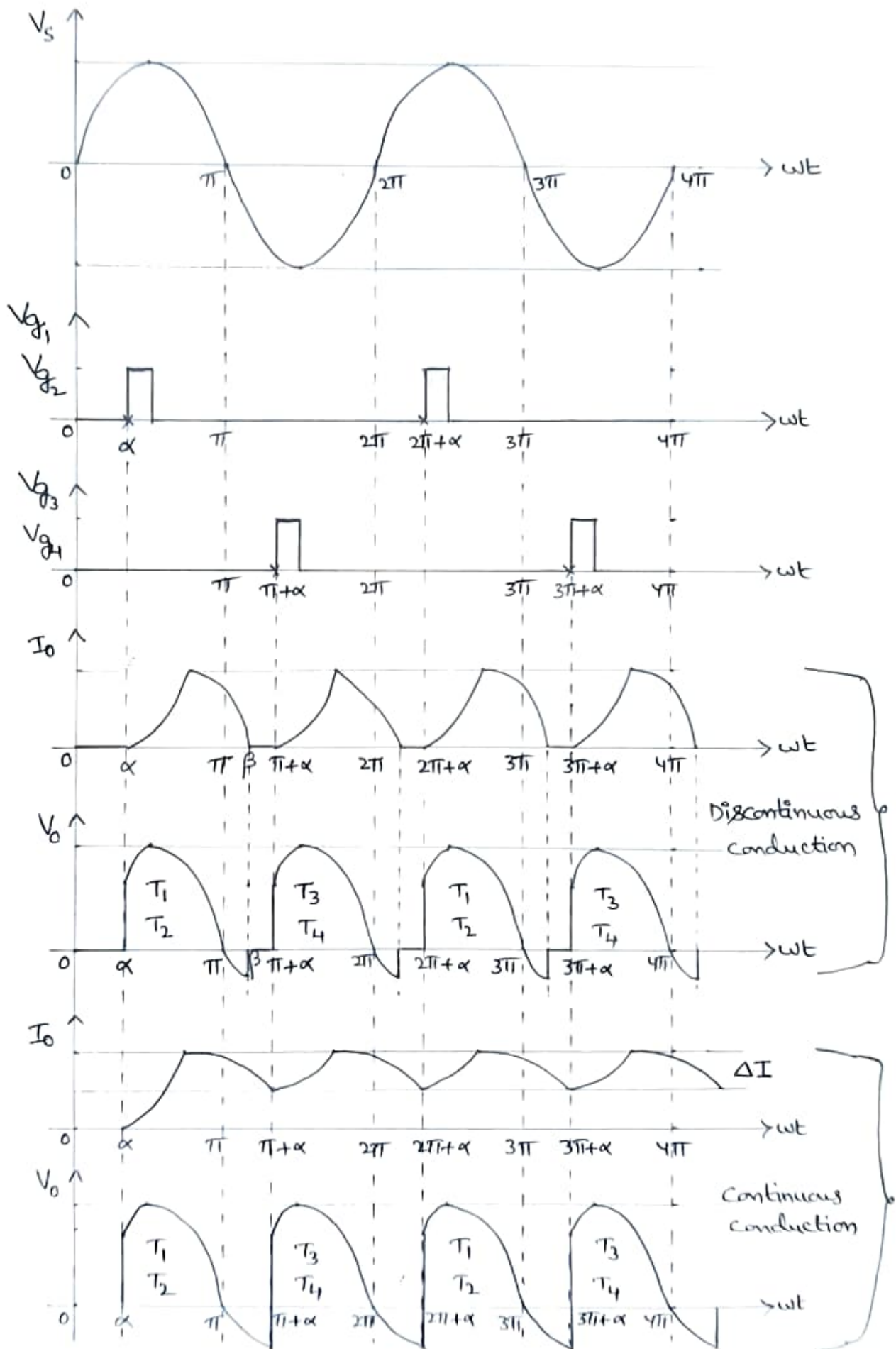
$$= \frac{V_m}{\pi} (-\cos \omega t)_{\alpha}^{\pi+\alpha} = -\frac{V_m}{\pi} (\cos \omega t)_{\alpha}^{\pi+\alpha} = -\frac{V_m}{\pi} (\cos(\pi+\alpha) - \cos \alpha)$$

$$= -\frac{V_m}{\pi} (-\cos \alpha - \cos \alpha) = -\frac{V_m}{\pi} (-2 \cos \alpha) = \frac{2V_m \cos \alpha}{\pi}$$

$$\therefore V_o(\text{avg}) = \frac{2V_m \cos \alpha}{\pi}$$

$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R}$$

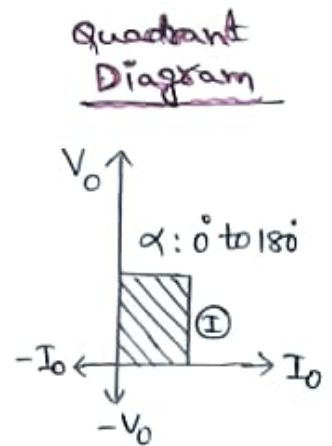
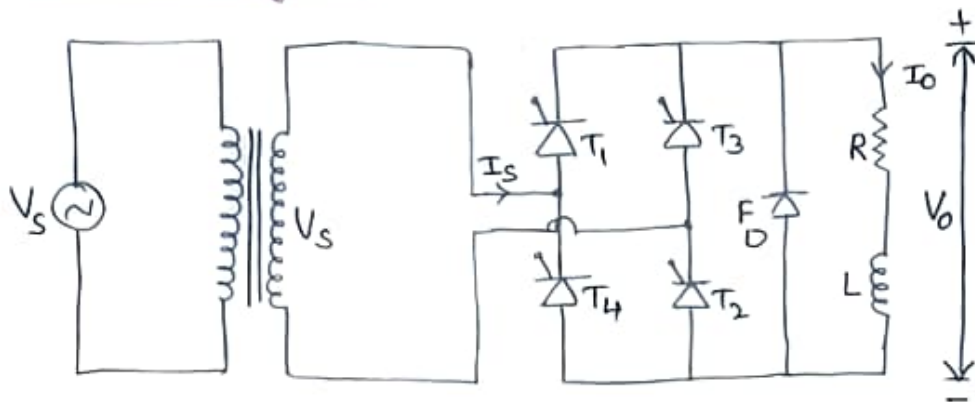
Waveforms



1 ϕ Full Converter with RL-Load and Freewheeling Diode

Two pulse
one quadrant

Circuit Diagram



Derivation

The 1 ϕ Full converter with RL-load and Freewheeling diode works in continuous conduction mode.

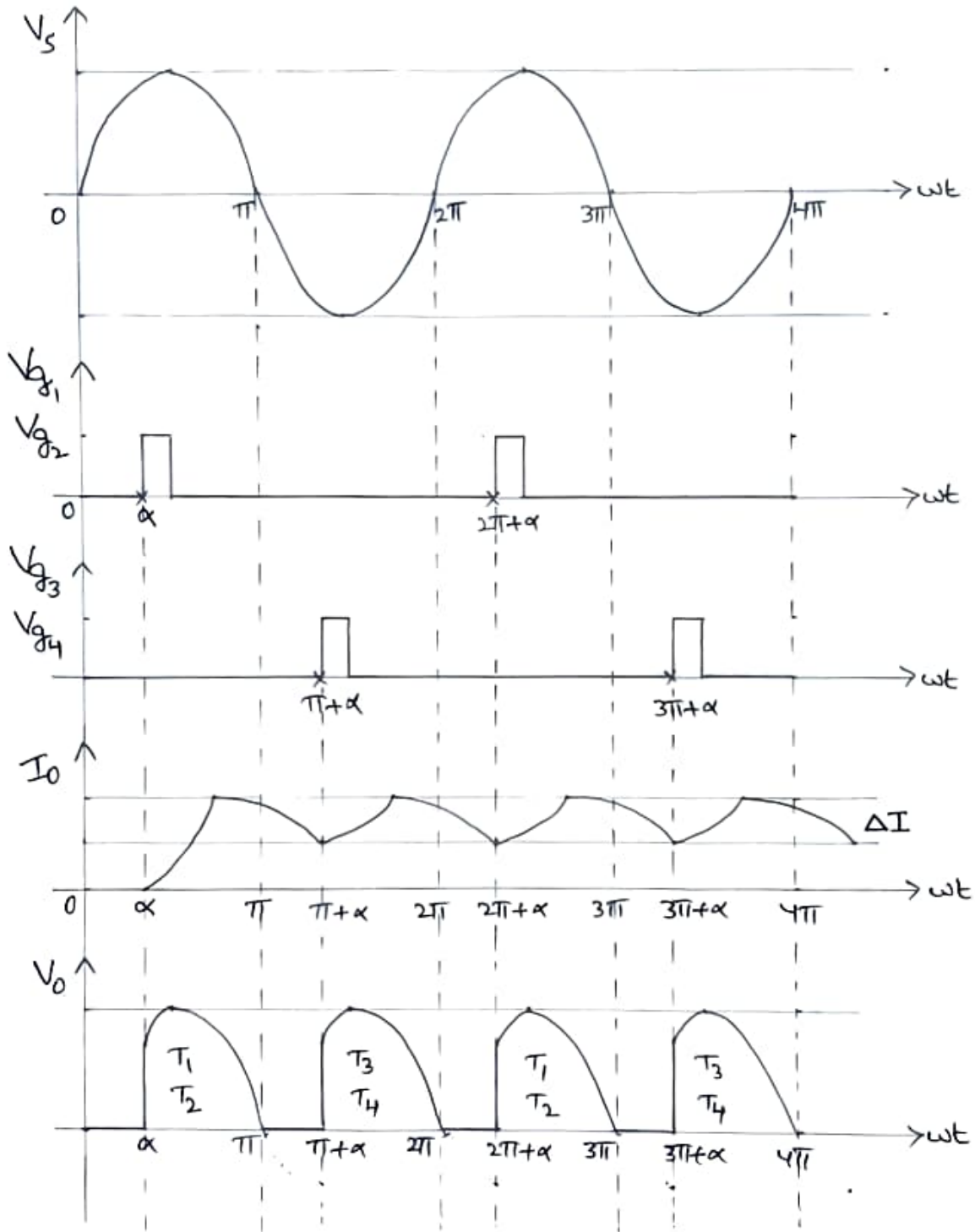
$$V_o(\text{avg}) = \frac{1}{\pi} \int_{\alpha}^{\pi} V_s d(\omega t)$$

$$V_o(\text{avg}) = \frac{V_m}{\pi} (1 + \cos \alpha)$$

$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{V_m}{\pi R} (1 + \cos \alpha)$$

$$V_o(\text{rms}) = \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} V_s^2 d(\omega t)} = \frac{V_m}{\sqrt{2\pi}} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]^{\frac{1}{2}}$$

Waveforms



Power Electronics

Unit-2 Rectifiers (AC to DC Converters)

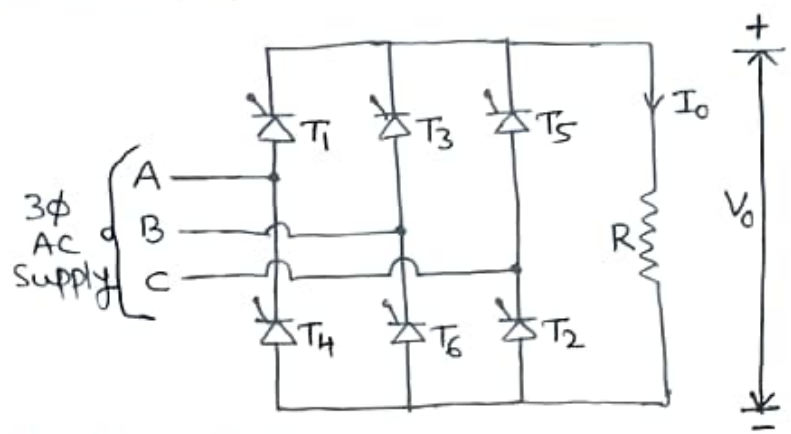
Unit-2 Chapter-2 3 ϕ Rectifiers and Other Topics

1. 3 ϕ Full Converter (or) 1 ϕ Fully Controlled Bridge Rectifier
 - (a) Resistive Load (R Load)
 - (b) High Inductive Load (RL Load)
2. Effect of Source Inductance in 1 ϕ Full Converter
3. Rectifier with Filter Capacitance
4. Dual Converter

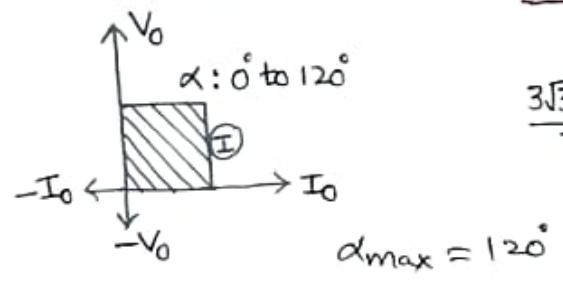
3 ϕ Full Converter with R-Load

Six Pulse
one Quadrant

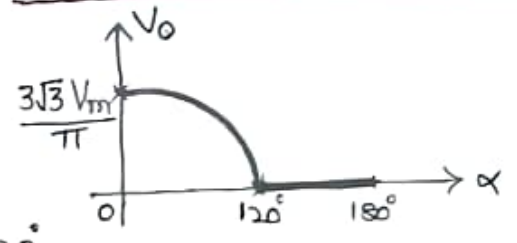
Circuit Diagram



Quadrant Diagram

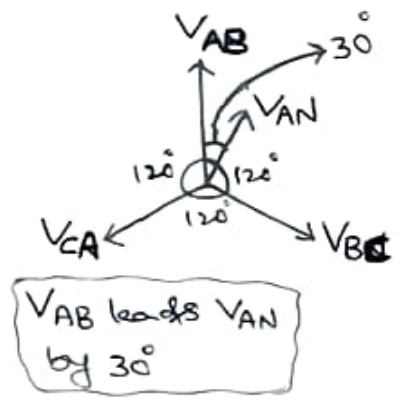


Control characteristics (V_0 vs α)



Switching Sequence Table

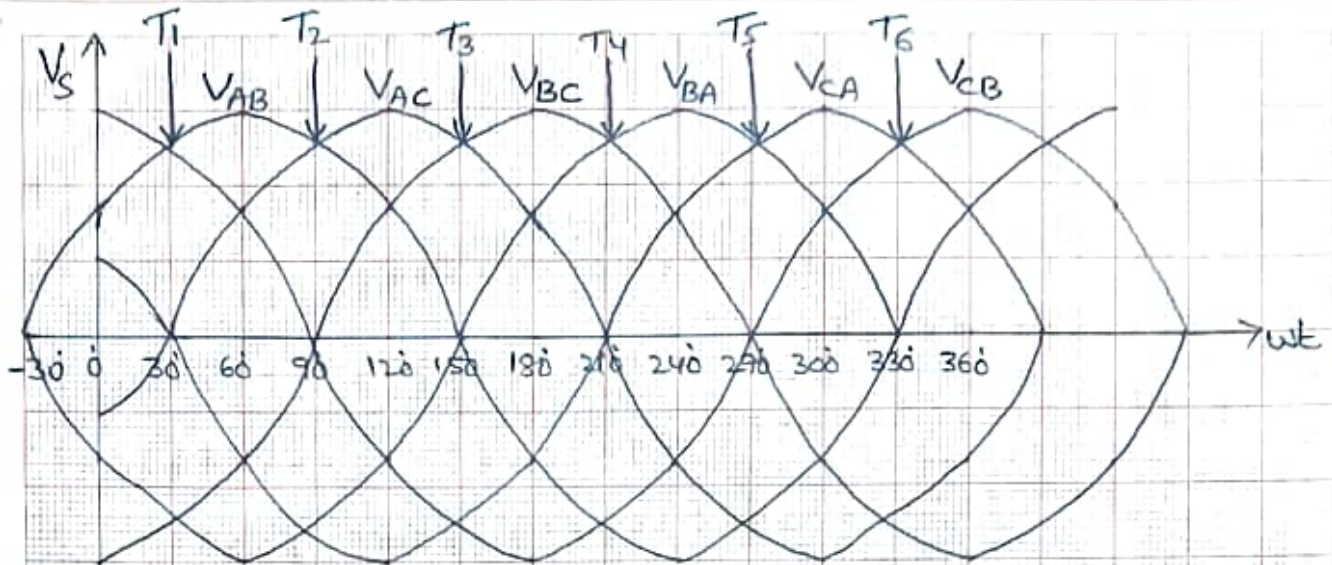
Sl. No.	Device	Turn-on Instant	conducting Pair	output voltage
1	T ₁	30° + α	T ₆ , T ₁	V _{AB}
2	T ₂	90° + α	T ₁ , T ₂	V _{AC}
3	T ₃	150° + α	T ₂ , T ₃	V _{BC}
4	T ₄	210° + α	T ₃ , T ₄	V _{BA}
5	T ₅	270° + α	T ₄ , T ₅	V _{CA}
6	T ₆	330° + α	T ₅ , T ₆	V _{CB}



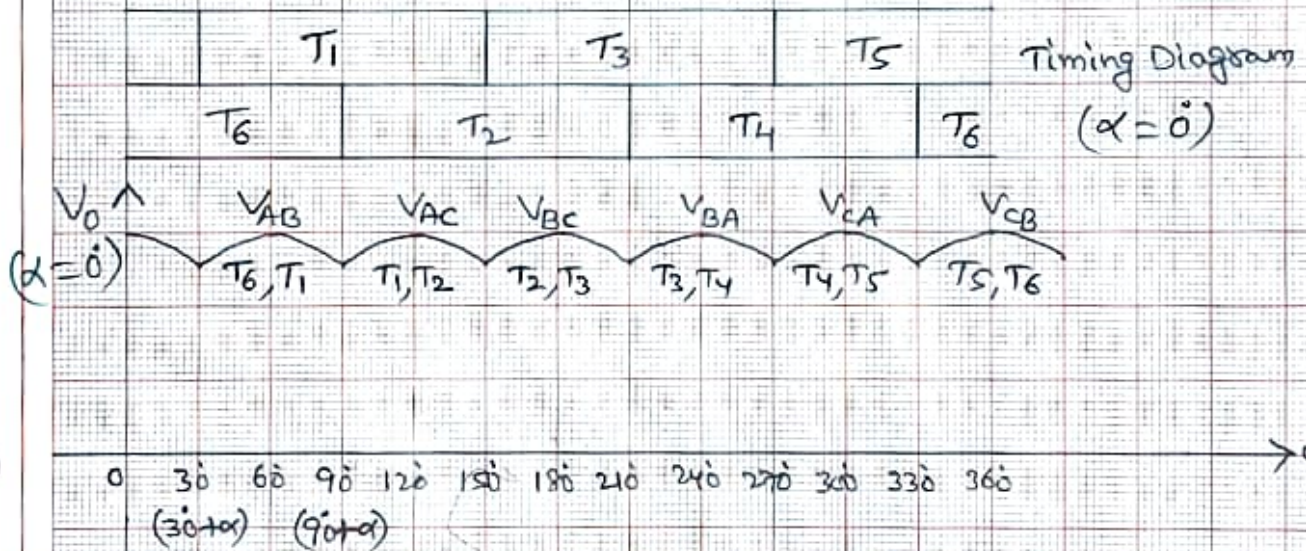
Range of Firing Angle (α)

For continuous conduction, $0^\circ \leq \alpha \leq 60^\circ$

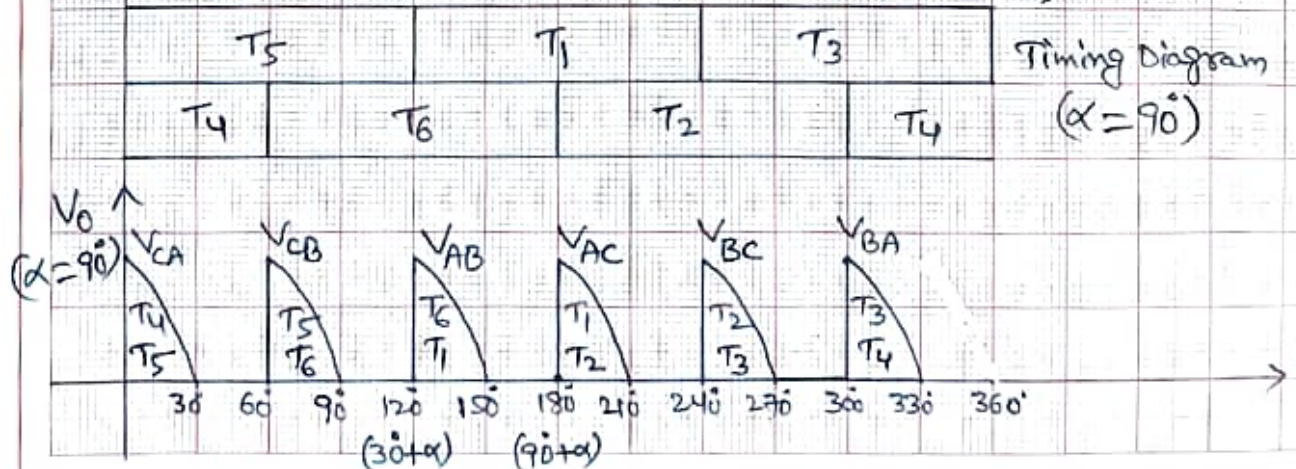
For discontinuous conduction, $60^\circ \leq \alpha \leq 120^\circ$



Continuous Conduction mode ($0 \leq \alpha \leq 60^\circ$)



Discontinuous conduction mode ($60^\circ \leq \alpha \leq 120^\circ$)



Derivation for Continuous Conduction mode ($0 \leq \alpha \leq 60^\circ$)

$$\begin{aligned}V_o(\text{avg}) &= \frac{1}{(\pi/3)} \int_{30^\circ+\alpha}^{90^\circ+\alpha} V_s d(\omega t) \\&= \frac{1}{(\pi/3)} \int_{30^\circ+\alpha}^{90^\circ+\alpha} \sqrt{3} V_m \sin(\omega t + 30^\circ) d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} \int_{30^\circ+\alpha}^{90^\circ+\alpha} \sin(\omega t + 30^\circ) d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} \int_{60^\circ+\alpha}^{120^\circ+\alpha} \sin \omega t d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} (-\cos \omega t) \Big|_{60^\circ+\alpha}^{120^\circ+\alpha} \\&= \frac{-3\sqrt{3} V_m}{\pi} (\cos \omega t) \Big|_{60^\circ+\alpha}^{120^\circ+\alpha} \\&= \frac{-3\sqrt{3} V_m}{\pi} [\cos(120^\circ+\alpha) - \cos(60^\circ+\alpha)] \\&= \frac{-3\sqrt{3} V_m}{\pi} [(\cos 120^\circ \cos \alpha - \sin 120^\circ \sin \alpha) - (\cos 60^\circ \cos \alpha - \sin 60^\circ \sin \alpha)] \\&= \frac{-3\sqrt{3} V_m}{\pi} \left[\left(-\frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha \right) - \left(\frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha \right) \right] \\&= \frac{-3\sqrt{3} V_m}{\pi} \left[2 \times -\frac{1}{2} \cos \alpha \right] \\&= \frac{-3\sqrt{3} V_m}{\pi} (-\cos \alpha)\end{aligned}$$

$$\boxed{V_o(\text{avg}) = \frac{3\sqrt{3} V_m}{\pi} \cos \alpha}$$

$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{3\sqrt{3} V_m}{\pi R} \cos \alpha$$

Derivation for Discontinuous Conduction mode ($60^\circ \leq \alpha \leq 120^\circ$)

$$\begin{aligned}V_o(\text{avg}) &= \frac{1}{(\pi/3)} \int_{30^\circ+\alpha}^{150^\circ} V_s d(\omega t) \\&= \frac{1}{(\pi/3)} \int_{30^\circ+\alpha}^{150^\circ} \sqrt{3} V_m \sin(\omega t + 30^\circ) d(\omega t) \\&= \frac{1}{(\pi/3)} \int_{60^\circ+\alpha}^{180^\circ} \sqrt{3} V_m \sin \omega t d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} \int_{60^\circ+\alpha}^{180^\circ} \sin \omega t d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} \left[-\cos \omega t \right]_{60^\circ+\alpha}^{180^\circ} \\&= \frac{-3\sqrt{3} V_m}{\pi} (\cos \omega t)_{60^\circ+\alpha}^{180^\circ} \\&= \frac{-3\sqrt{3} V_m}{\pi} [\cos 180^\circ - \cos(60^\circ+\alpha)] \\&= \frac{-3\sqrt{3} V_m}{\pi} [-1 - \cos(60^\circ+\alpha)]\end{aligned}$$

$$V_o(\text{avg}) = \frac{3\sqrt{3} V_m}{\pi} (1 + \cos(60^\circ+\alpha))$$

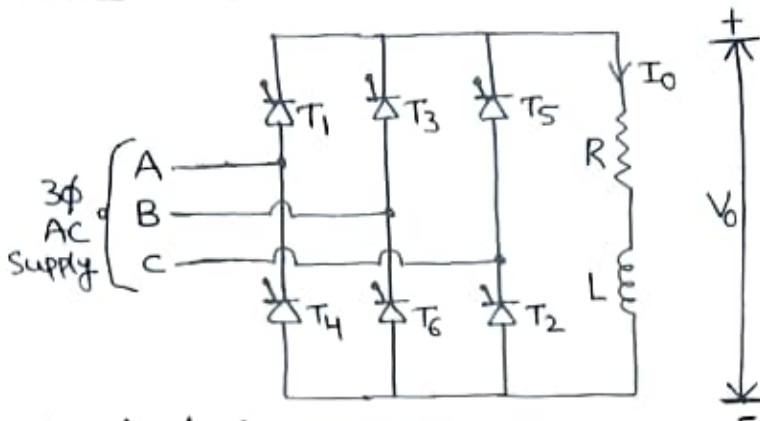
$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{3\sqrt{3} V_m}{\pi R} (1 + \cos(60^\circ+\alpha))$$

3 ϕ Full Converter with RL-Load

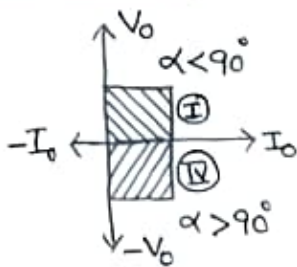
Six Pulse

Two Quadrant

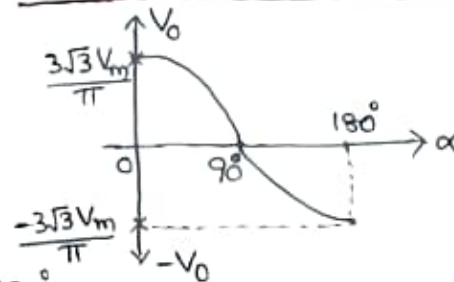
Circuit Diagram



Quadrant Diagram



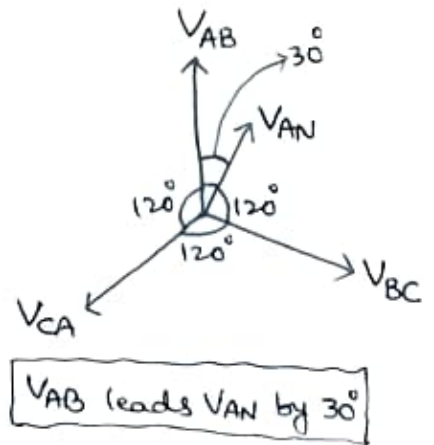
Control characteristics (V_0 vs α)



$$\alpha_{max} = 180^\circ$$

Switching Sequence Table

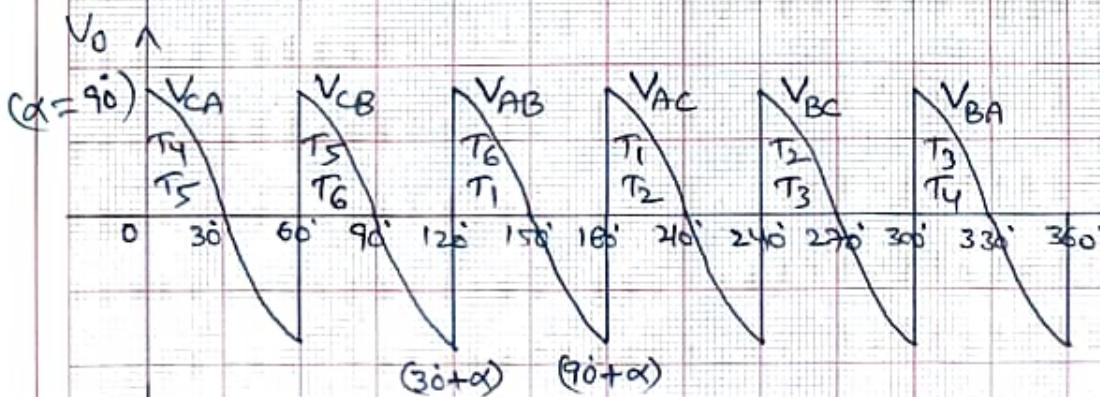
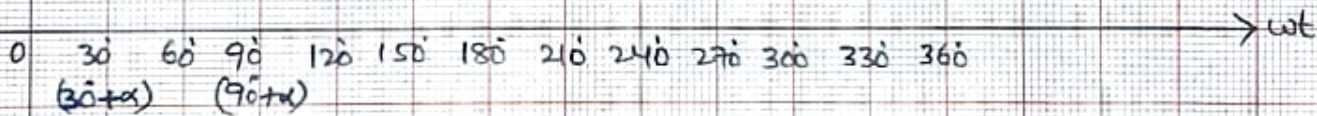
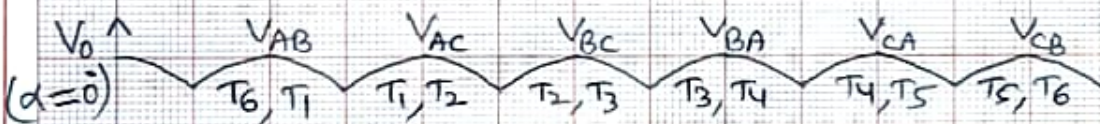
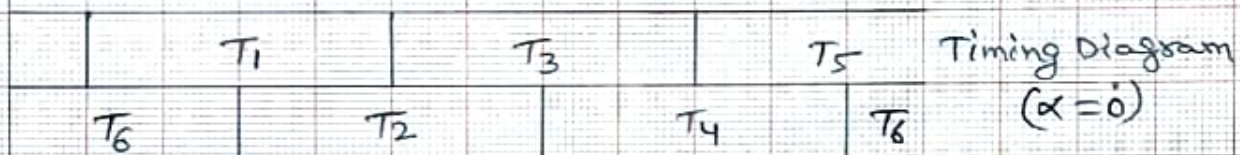
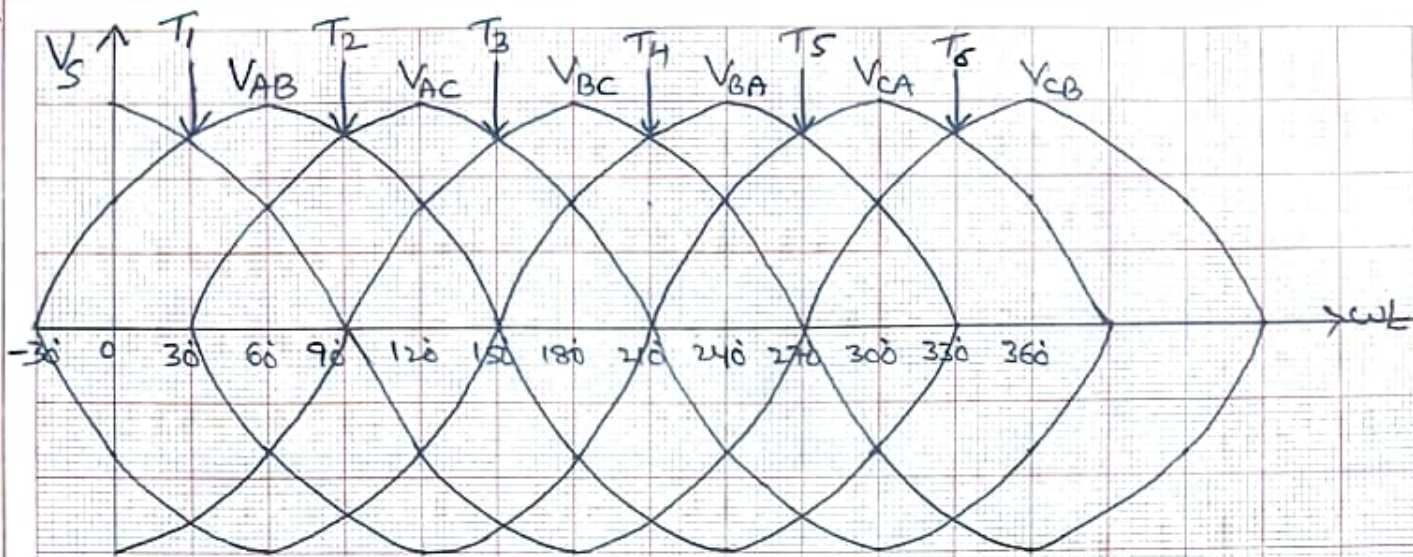
Sl. No.	Device	Turn-on Instant	conducting Pair	output Voltage
1	T_1	$30^\circ + \alpha$	T_6, T_1	V_{AB}
2	T_2	$90^\circ + \alpha$	T_1, T_2	V_{AC}
3	T_3	$150^\circ + \alpha$	T_2, T_3	V_{BC}
4	T_4	$210^\circ + \alpha$	T_3, T_4	V_{BA}
5	T_5	$270^\circ + \alpha$	T_4, T_5	V_{CA}
6	T_6	$330^\circ + \alpha$	T_5, T_6	V_{CB}



Range of Firing Angle (α)

For continuous conduction $0 \leq \alpha \leq 180^\circ$

Here, there is no discontinuous conduction.



Derivation

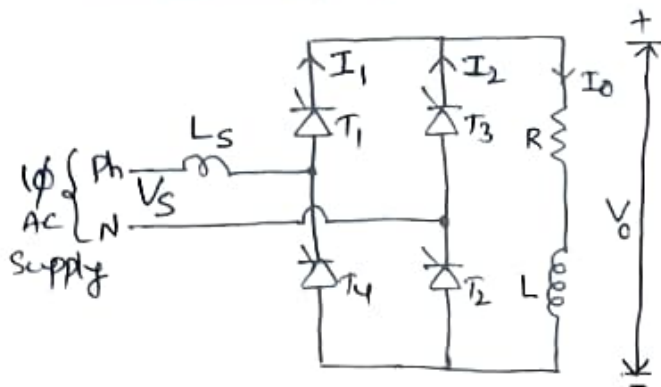
$$\begin{aligned}V_o(\text{avg}) &= \frac{1}{(\pi/3)} \int_{30^\circ+\alpha}^{90^\circ+\alpha} V_s d(\omega t) \\&= \frac{1}{(\pi/3)} \int_{30^\circ+\alpha}^{90^\circ+\alpha} \sqrt{3} V_m \sin(\omega t + 30^\circ) d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} \int_{30^\circ+\alpha}^{90^\circ+\alpha} \sin(\omega t + 30^\circ) d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} \int_{60^\circ+\alpha}^{120^\circ+\alpha} \sin \omega t d(\omega t) \\&= \frac{3\sqrt{3} V_m}{\pi} (-\cos \omega t) \Big|_{60^\circ+\alpha}^{120^\circ+\alpha} \\&= \frac{-3\sqrt{3} V_m}{\pi} (\cos \omega t) \Big|_{60^\circ+\alpha}^{120^\circ+\alpha} \\&= \frac{-3\sqrt{3} V_m}{\pi} [\cos(120^\circ+\alpha) - \cos(60^\circ+\alpha)] \\&= \frac{-3\sqrt{3} V_m}{\pi} [(\cos 120^\circ \cos \alpha - \sin 120^\circ \sin \alpha) - (\cos 60^\circ \cos \alpha - \sin 60^\circ \sin \alpha)] \\&= \frac{-3\sqrt{3} V_m}{\pi} \left[\left(-\frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha \right) - \left(\frac{1}{2} \cos \alpha - \frac{\sqrt{3}}{2} \sin \alpha \right) \right] \\&= \frac{-3\sqrt{3} V_m}{\pi} \left[2 \times -\frac{1}{2} \cos \alpha \right] \\&= \frac{-3\sqrt{3} V_m}{\pi} (-\cos \alpha)\end{aligned}$$

$$V_o(\text{avg}) = \frac{3\sqrt{3} V_m}{\pi} \cos \alpha$$

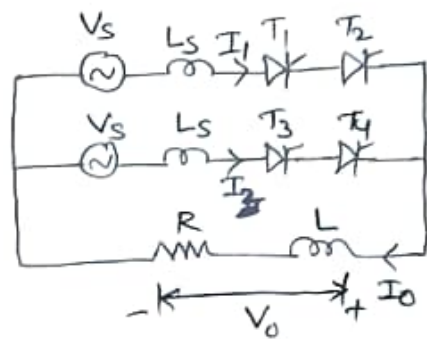
$$I_o(\text{avg}) = \frac{V_o(\text{avg})}{R} = \frac{3\sqrt{3} V_m}{\pi R} \cos \alpha$$

Effect of Source Inductance in π Full Converter

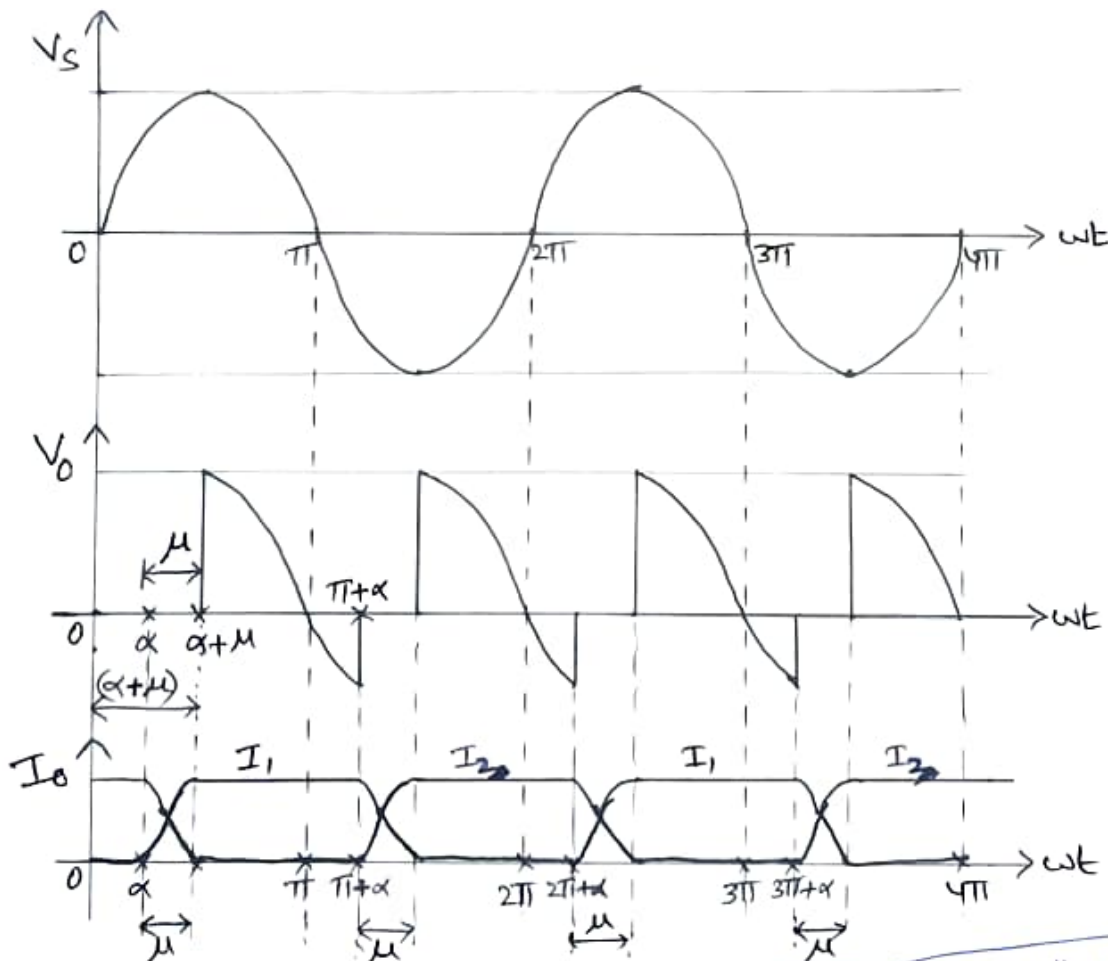
Circuit Diagram



Equivalent circuit



Waveforms



Derivation:

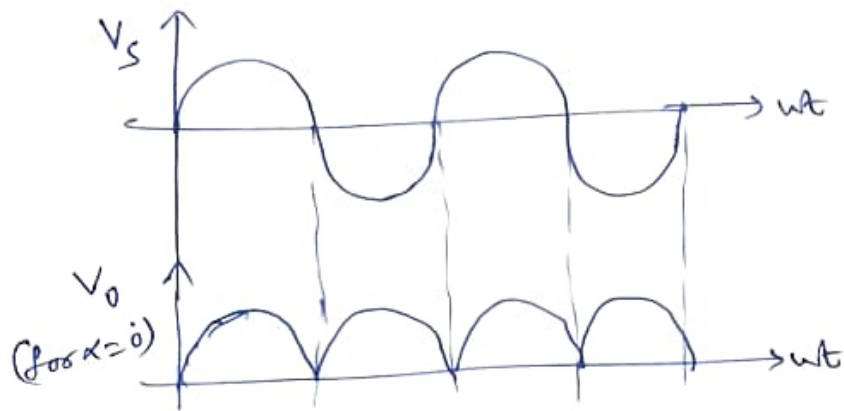
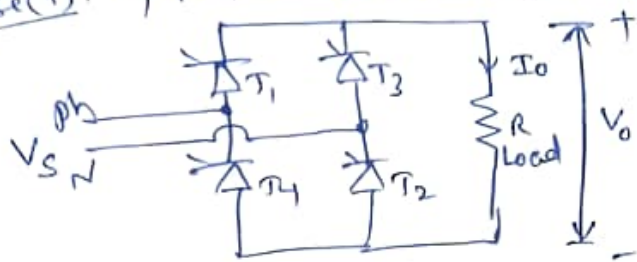
$$V_o(\text{avg}) = \frac{1}{\pi} \int_{\alpha+\mu}^{\pi+\alpha} V_s d(\omega t) = \frac{1}{\pi} \int_{\alpha+\mu}^{\pi+\alpha} V_m \sin \omega t d(\omega t)$$

The angle " μ " is called as overlap angle

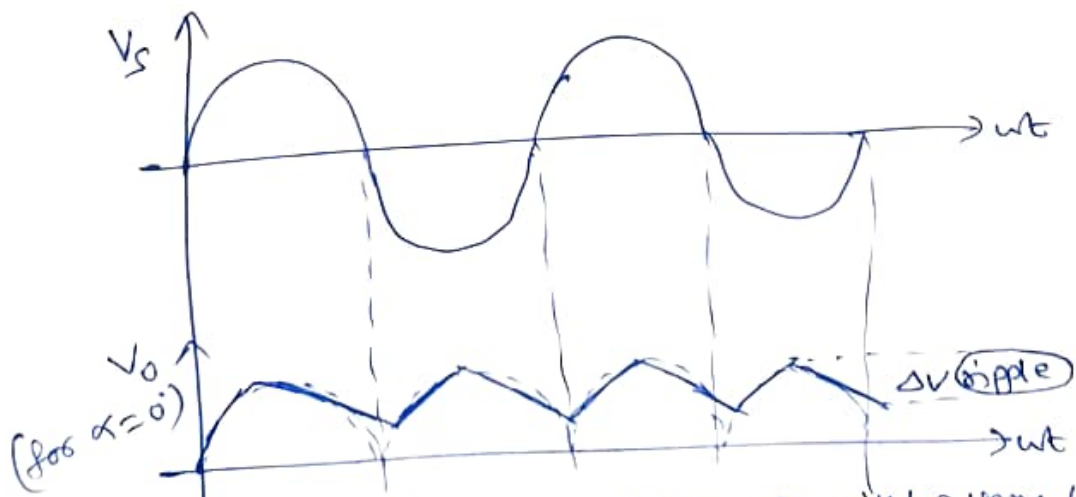
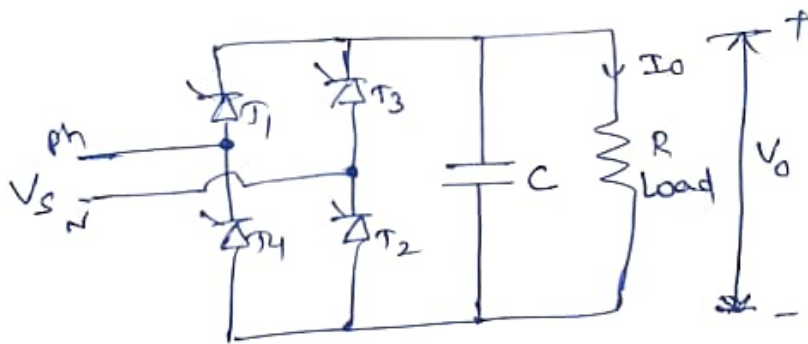
$$V_o(\text{avg}) = \frac{V_m}{\pi} [\cos \alpha + \cos(\alpha + \mu)]$$

Rectifier with Filter capacitance

Case (i): 1 ϕ Full converter without filter capacitance



Case (ii): 1 ϕ Full converter with filter capacitance (C)

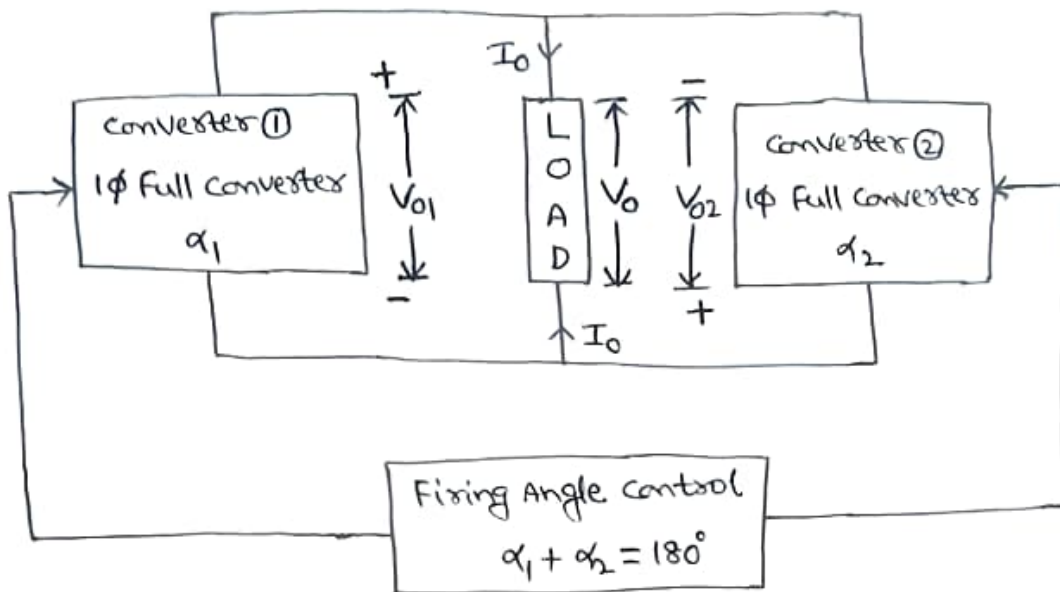


For high value of filter capacitance, ΔV will be very less.

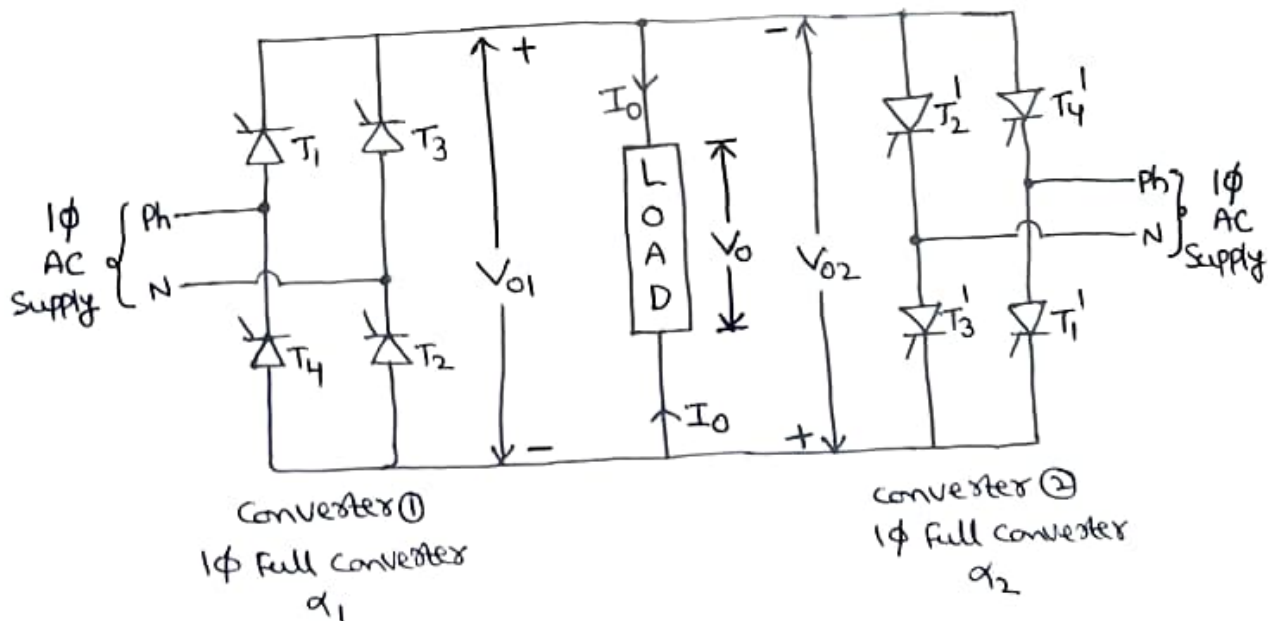


Dual converters

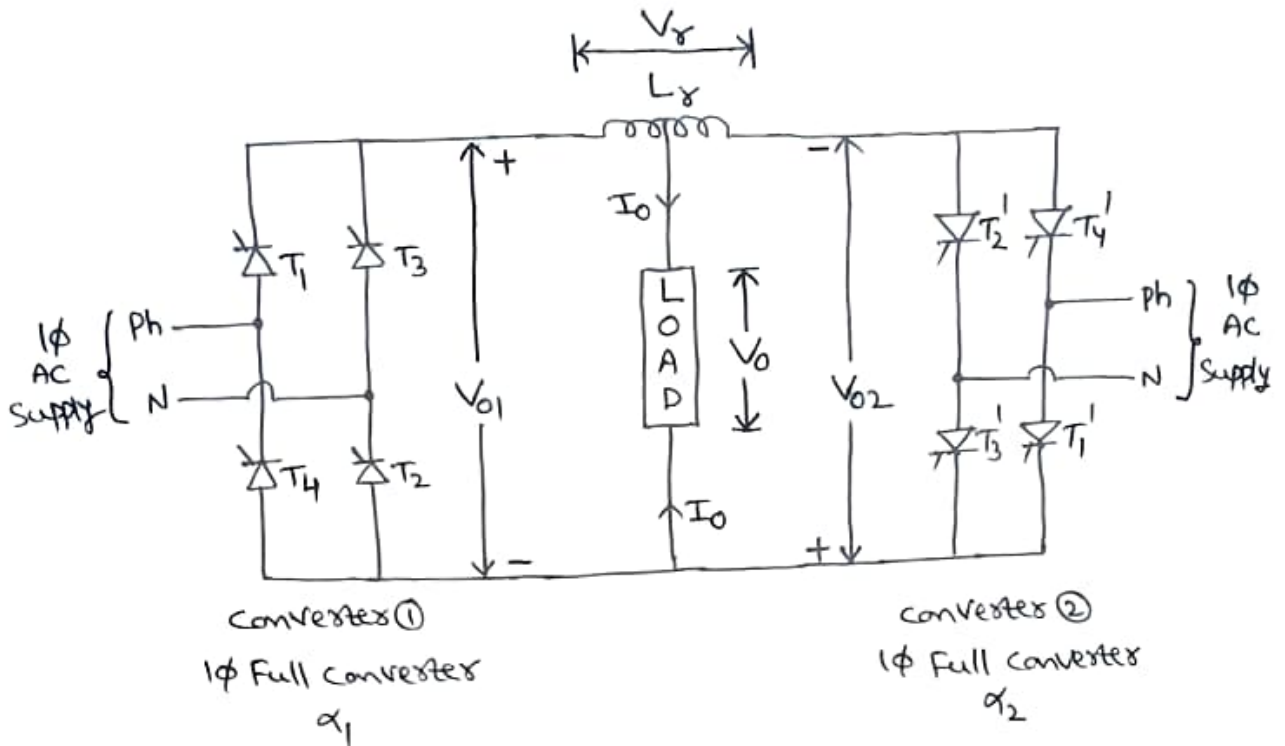
Ideal Dual converter



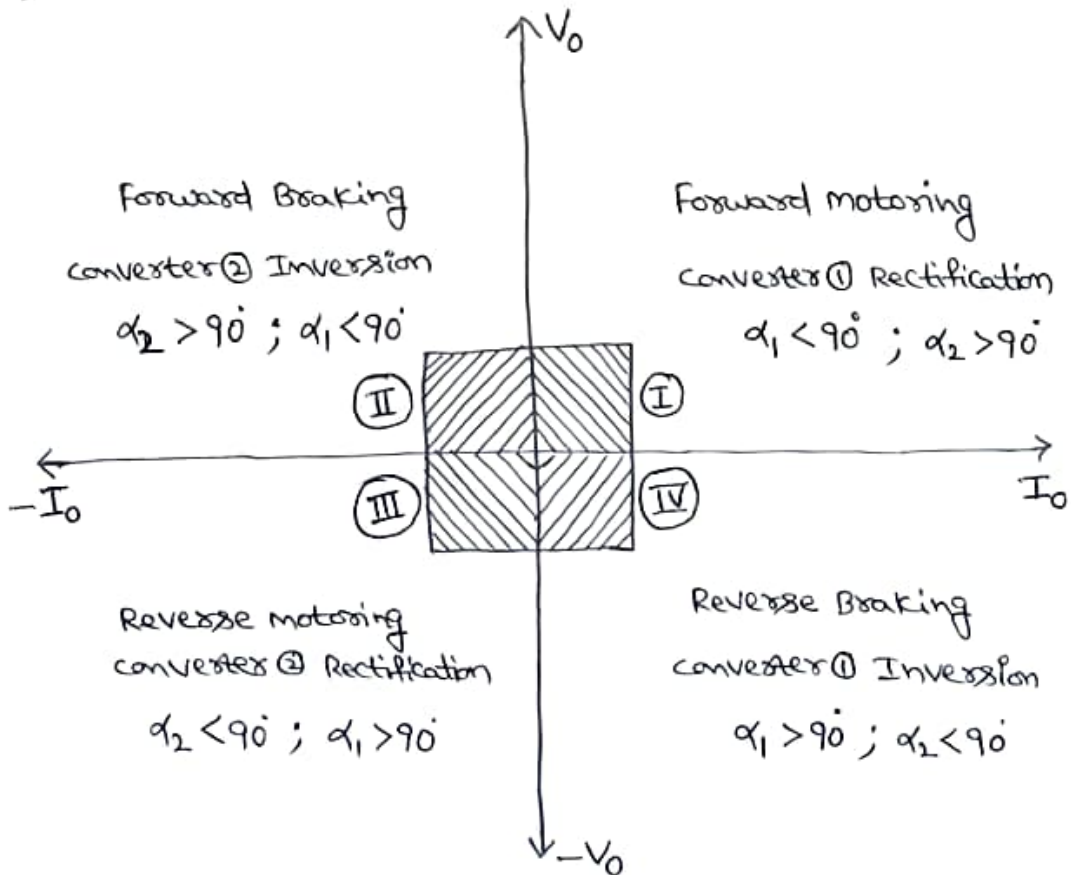
1 ϕ Dual converter in Non-circulating current mode



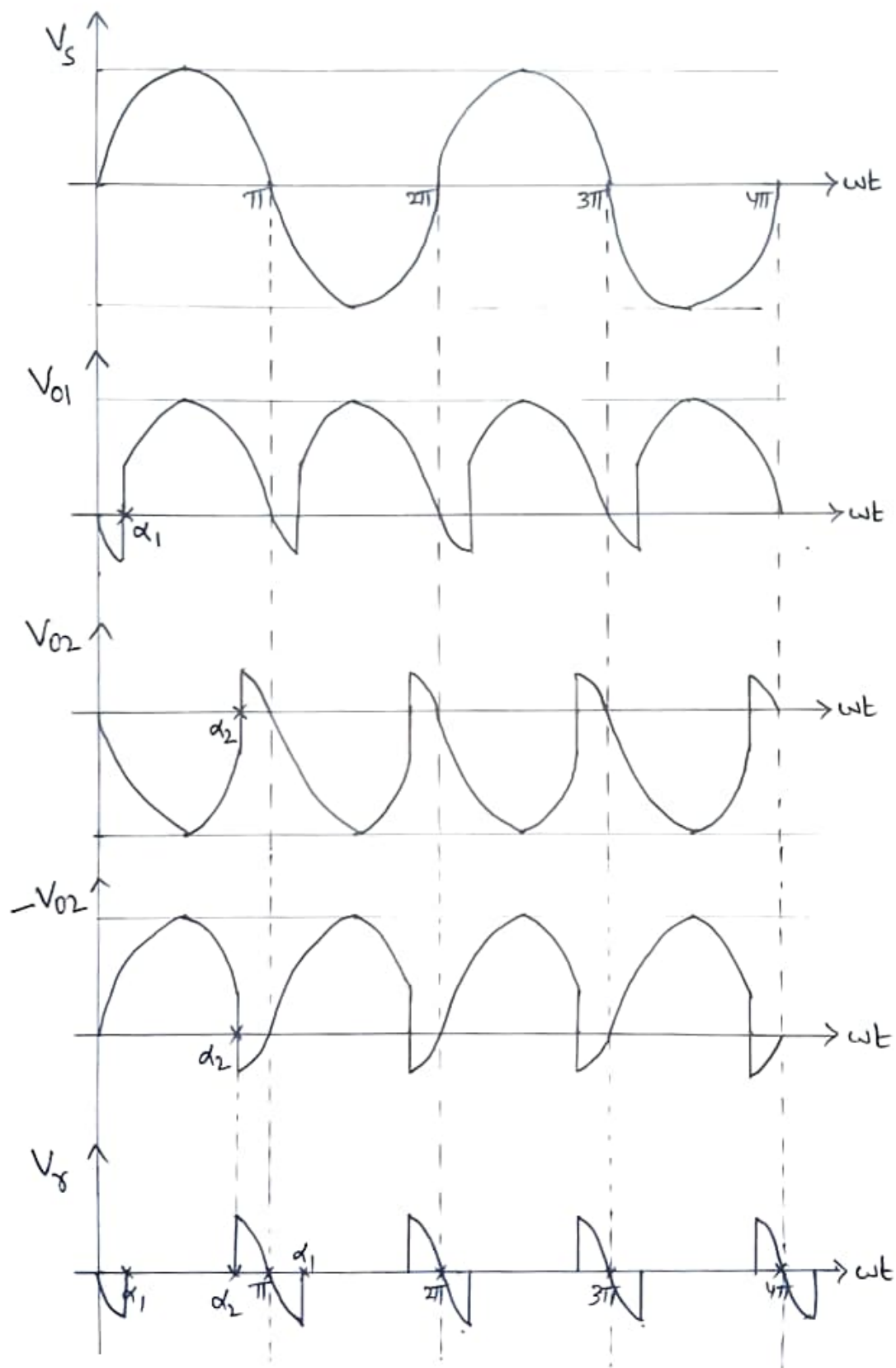
1 ϕ Dual converter in circulating current mode



Quadrant Diagram



Waveforms



Short Answer Questions

- * Rectifier is a Power Electronics Converter which converts fixed AC Voltage to Variable AC Voltage
- * Applications of Rectifiers are Battery Charging, Power Supplies, UPS, Inverter, DC Traction, HVDC Transmission etc.
- * Firing Angle is the angle at which the SCR is fired (or) triggered (or) Turned ON in the Rectifier Circuit. It is denoted by α (alpha). Firing Angle is also called as Phase Angle, Delay Angle, Triggering Angle.
- * Extinction Angle is the angle at which the load current becomes zero in discontinuous conduction mode in Rectifier Circuit. It is denoted by β (beta).
- * Conduction Angle is the angle during which the SCR conducts the load current. It is denoted by γ (gamma)
- * Overlap Angle is the angle which occurs in addition with delay angle (α) while turning ON the SCR when the effect of source inductance is considered. It is denoted by μ (mew)
- * In Half Wave Rectifier, the input voltage is V_s and the output voltage is (0 to $V_s/2$). Here, the maximum output voltage is $V_s/2$ only. This is the drawback of Half Wave Rectifier.
- * In Full Wave Rectifier, the input voltage is V_s and the output voltage is (0 to V_s). Here, the maximum output voltage is V_s . This is the advantage of Full Wave Rectifier.
- * In 1 \emptyset Half Wave Rectifier,
For Resistive Load (R Load), $V_{0(avg)} = \frac{V_m}{2\pi} (1 + \cos\alpha)$
For Inductive Load (RL Load), $V_{0(avg)} = \frac{V_m}{2\pi} (\cos\alpha - \cos\beta)$
- * In 1 \emptyset Fully Controlled Bridge Rectifier,
For Resistive Load (R Load), $V_{0(avg)} = \frac{V_m}{\pi} (1 + \cos\alpha)$
For high Inductive Load (RL Load), $V_{0(avg)} = \frac{2V_m}{\pi} \cos\alpha$
- * In 3 \emptyset Fully Controlled Bridge Rectifier
For R Load and RL Load, $V_{0(avg)} = \frac{3V_m}{\pi} \cos\alpha$
- * The output voltage (V_0) is high in 3 \emptyset Fully Controlled Bridge Rectifier when compared with 1 \emptyset Fully Controlled Bridge Rectifier. Hence, the output power is also high in 3 \emptyset Fully Controlled Bridge Rectifier when compared with 1 \emptyset Fully Controlled Bridge Rectifier.
- * Free Wheeling Diode eliminates the negative portion of output voltage waveform and improves the output voltage value. Free Wheeling Diode allows the SCR to be turned OFF at zero crossing points and reduces the burden on the SCR.

Power Electronics

Unit-3

DC Chopper

(Fixed DC Voltage to Variable DC Voltage)

1. Introduction
2. Step Down Chopper with Resistive Load (R Load)
 - (or) Buck Converter with R Load
 - (or) Principle of Chopper Control
3. Step Down Chopper with Inductive Load (RL Load)
 - (or) Buck Converter with RL Load
4. Step Up Chopper (same for R Load and RL Load)
 - (or) Boost Converter
5. Buck Boost Converter
6. Control Strategies
 - (a) Time Ratio Control (TRC)
 - (i) Constant Frequency Control (or) PWM Control
 - (ii) Variable Frequency Control
 - (b) Current Limit Control (CLC)

Introduction of DC Chopper

Definition of DC Chopper: DC Chopper is a Power Electronics Converter which converts fixed DC Voltage to Variable DC Voltage.

Applications of DC Chopper:

Regulated Power Supply (RPS), Electric Vehicles, Battery Charging etc.

Advantages of DC Chopper:

Smooth Control, Fast Response, High Efficiency

Disadvantages of DC Chopper:

For high power applications, SCR must be used. DC Chopper input is DC Supply. There will not be any negative voltage in DC Supply. Hence, SCR will not be turned OFF naturally for DC Supply. Hence, Forced Commutation circuit must be connected across SCR to turn it OFF.

Classification of DC Choppers:

- * Step Down Chopper
- * Step Up Chopper

CHOPPERS (DC to DC Converters)

Introduction: Chopper is a converter which converts fixed DC voltage into variable DC voltage.

Applications:

- (i) Sub-way cars
- (ii) Trolley Buses
- (iii) Battery operated vehicles
- (iv) Battery charging

Advantages:

- (i) Smooth control
- (ii) High Efficiency
- (iii) Fast Response
- (iv) Regeneration

Disadvantages:

- (i) For high power applications, SCRs must be used.
- (ii) Forced commutation is required to turn off SCRs.

Classification:

Classification (1):

- (i) step Down chopper
- (ii) step up chopper

Classification (2):

- (i) one Quadrant chopper
 - (a) First Quadrant chopper (Type A)
 - (b) second Quadrant chopper (Type B)
- (ii) Two Quadrant chopper
 - (a) Type C chopper
 - (b) Type D chopper
- (iii) Four Quadrant chopper (Type E)

Classification (3):

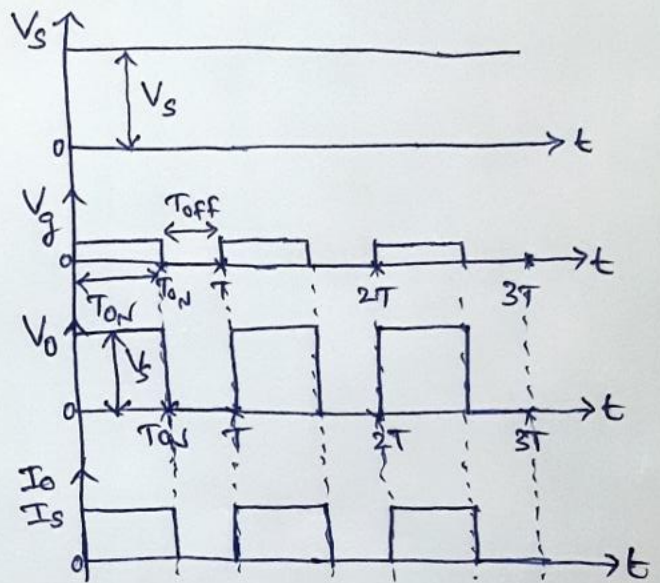
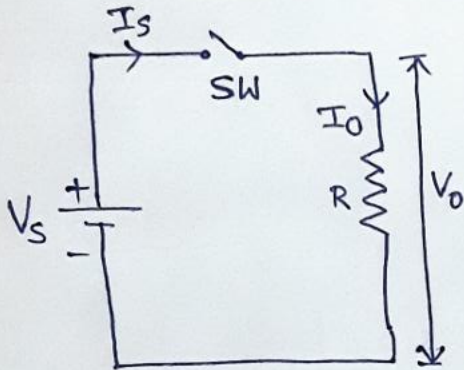
- (i) Forced commutated chopper
 - (a) Voltage commutated chopper
 - (b) Current commutated chopper
- (ii) Load commutated chopper

Classification :

- (i) Thyristor Based chopper (or) forced commutated chopper
 - (a) Jones chopper
 - (b) Morgan's chopper
 - (c) AC chopper
- (ii) Transistor Based chopper

Step Down chopper with R load : (Buck converter)

(a) Principle of chopper operation:



$$V_o(\text{avg}) = \frac{1}{T} \int_0^{T_{on}} V_s dt$$

$$\therefore V_o(\text{avg}) = \frac{1}{T} \times V_s \times \int_0^{T_{on}} (1) dt = \frac{1}{T} \times V_s \times (T_{on} - 0) = \frac{T_{on}}{T} V_s = \alpha V_s$$

$$\therefore \boxed{V_o = \alpha \cdot V_s}$$

Also, $\boxed{V_o = f \cdot T_{on} \cdot V_s}$

$$\boxed{I_o = \frac{V_o}{R}}$$

$$V_o(\text{rms}) = \sqrt{\frac{1}{T} \int_0^{T_{on}} V_s^2 dt}$$

$$\therefore \boxed{V_o(\text{rms}) = \sqrt{\alpha} \cdot V_s}$$

$$\boxed{I_o(\text{rms}) = \frac{V_o(\text{rms})}{R}}$$

$$\alpha = \frac{T_{on}}{T} = \text{Duty cycle (or) Duty Ratio}$$

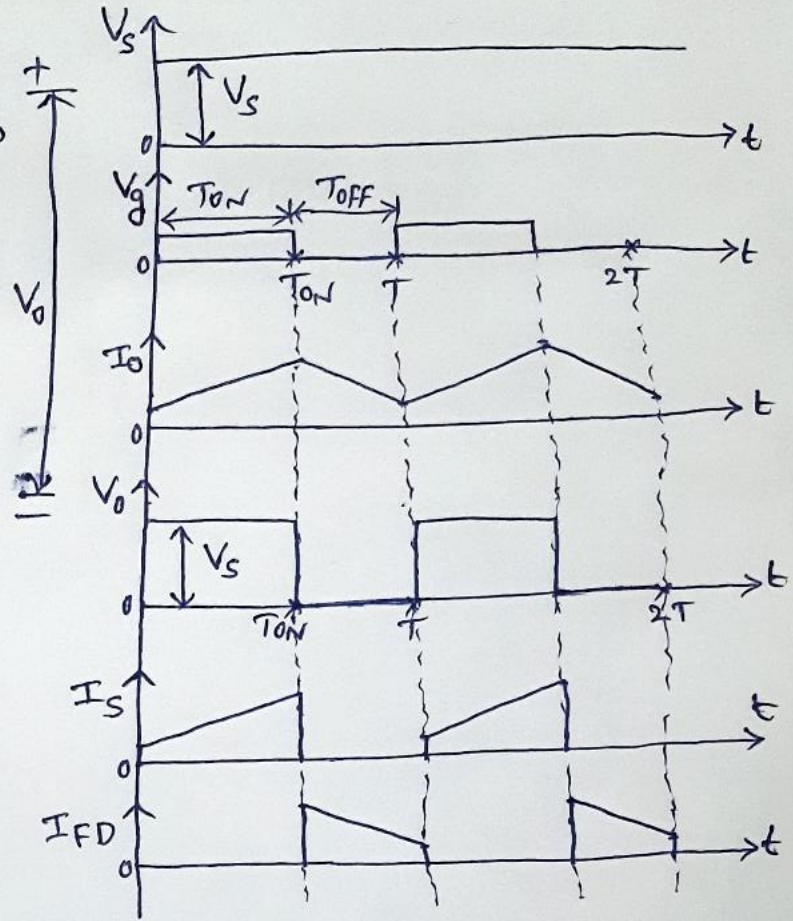
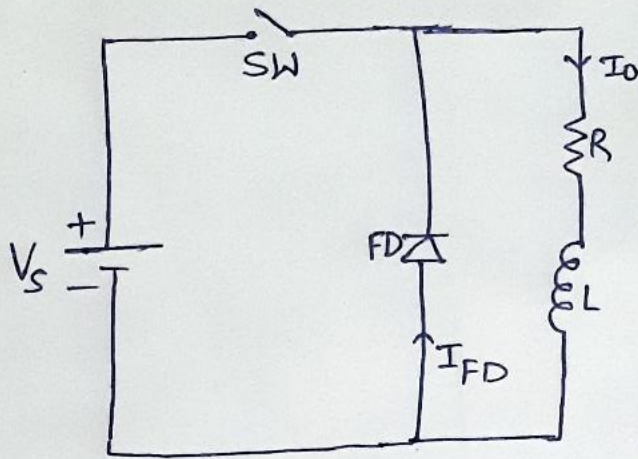
T_{on} = ON - Time

T_{off} = OFF - Time

$T = T_{on} + T_{off}$ = chopping period

$f = \frac{1}{T}$ = chopping frequency

Step Down chopper with RL load : (Buck Converter)



$$V_o(\text{avg}) = V_o = \frac{1}{T} \int_0^{T_{ON}} V_s dt$$

$$\therefore V_o = \frac{1}{T} \times V_s \times \int_0^{T_{ON}} (1) dt$$

$$\therefore V_o = \frac{1}{T} \times V_s \times (T_{ON} - 0)$$

$$\therefore V_o = \frac{T_{ON}}{T} \times V_s = \alpha V_s$$

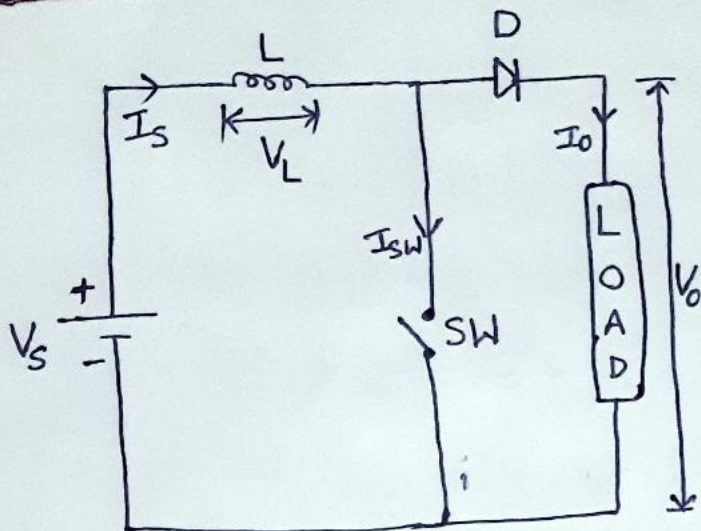
$$\therefore \boxed{V_o = \alpha V_s}$$

$$\boxed{I_o = \frac{V_o}{R}}$$

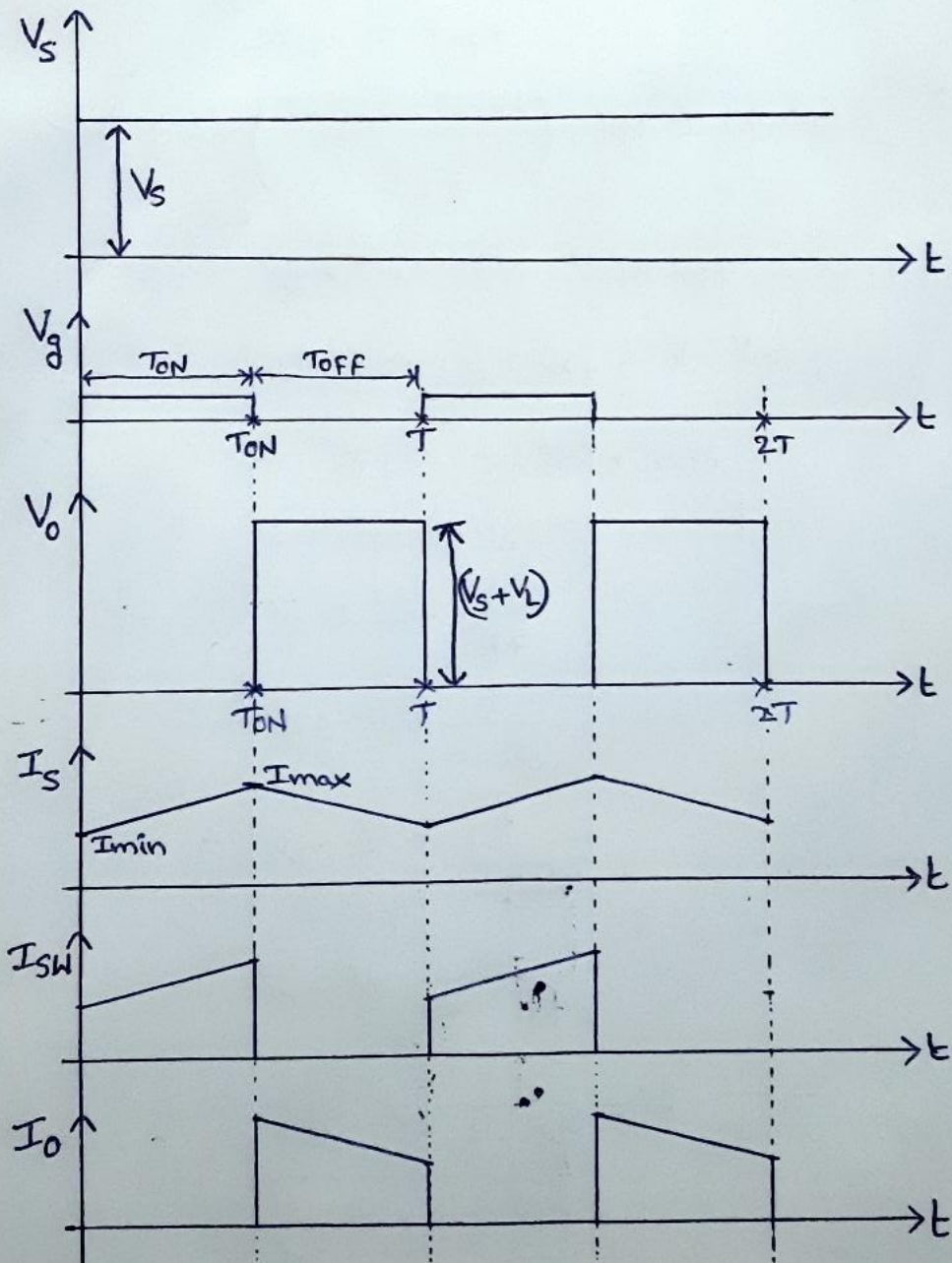
$$\boxed{V_o(\text{rms}) = \sqrt{\alpha} V_s}$$

$$\boxed{I_o(\text{rms}) = \frac{V_o(\text{rms})}{R}}$$

Step Up chopper (Boost converter)



Load = R-load
(os)
RL-load
(os)
RL-load



Energy stored in Inductor during T_{ON} period is

$$E_{ON} = V_L \times I_L \times T_{ON}$$

$$\therefore E_{ON} = (V_S) \times \left(\frac{I_{min} + I_{max}}{2} \right) \times T_{ON}$$

Energy released by Inductor during T_{OFF} period is

$$E_{OFF} = V_L \times I_L \times T_{OFF}$$

$$\therefore E_{OFF} = (V_0 - V_S) \times \left(\frac{I_{min} + I_{max}}{2} \right) \times T_{OFF}$$

Consider, the chopper has no losses, then,

$$E_{ON} = E_{OFF}$$

$$\therefore (V_S) \times \left(\frac{I_{min} + I_{max}}{2} \right) \times T_{ON} = (V_0 - V_S) \times \left(\frac{I_{min} + I_{max}}{2} \right) \times T_{OFF}$$

$$\therefore V_S \times T_{ON} = (V_0 - V_S) \times T_{OFF}$$

$$\therefore V_S \times T_{ON} = V_0 \times T_{OFF} - V_S \times T_{OFF}$$

$$\therefore V_0 \times T_{OFF} = V_S (T_{ON} + T_{OFF})$$

$$\therefore V_0 \times T_{OFF} = V_S \times T$$

$$\therefore V_0 = V_S \times \frac{T}{T_{OFF}}$$

$$\therefore V_0 = V_S \times \frac{T}{T - T_{ON}}$$

$$\therefore V_0 = V_S \times \frac{1}{\frac{T - T_{ON}}{T}}$$

$$\therefore V_0 = V_S \times \frac{1}{\frac{T}{T} - \frac{T_{ON}}{T}}$$

$$\therefore V_0 = V_S \times \frac{1}{1 - \frac{T_{ON}}{T}} = V_S \times \frac{1}{1 - \alpha}$$

$$\therefore \boxed{V_0 = \frac{1}{1 - \alpha} \times V_S}$$

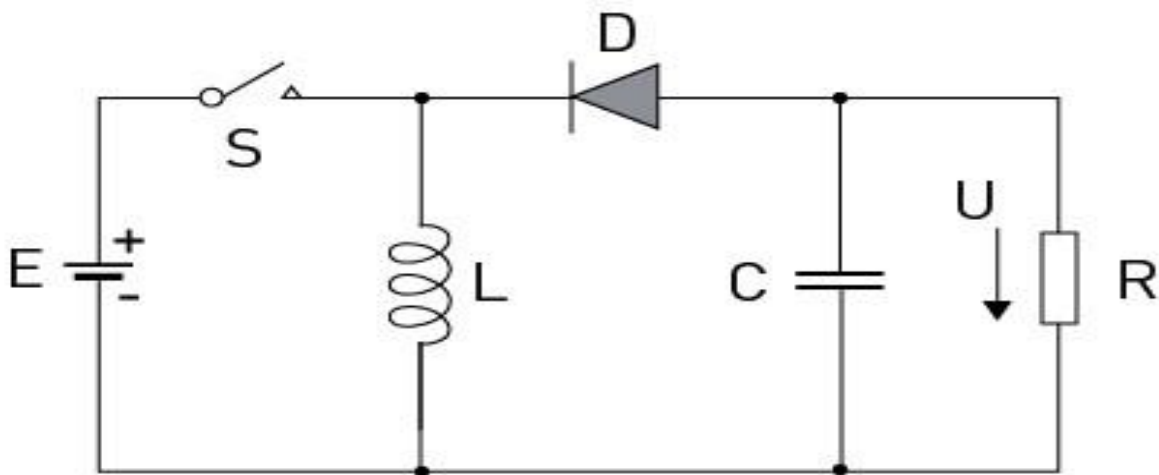
Buck-Boost Converter

The buck-boost converter is a type of DC-DC converter that can produce an output voltage that is either higher or lower than the input voltage, making it a versatile power conversion topology for various applications in power electronics where input voltage regulation and output voltage requirements may vary.

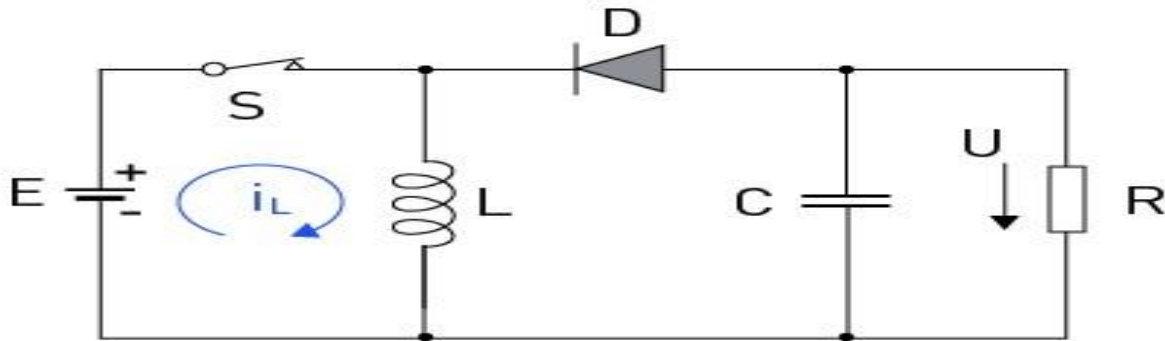
The buck-boost converter operates in two distinct modes: the "buck" mode, where the output voltage is lower than the input voltage, and the "boost" mode, where the output voltage is higher than the input voltage. The transition between these two modes is smooth, enabling the converter to maintain a stable output voltage under varying input conditions.

The buck-boost converter operates using a switch, typically a transistor, and a diode, which control current flow through an inductor and a capacitor. During the switch's ON state, energy is stored in the inductor, and during the OFF state, the energy is transferred to the output through the diode. The duty cycle of the switch, or the ratio of ON time to the total period of the switching cycle, determines the converter's output voltage. Adjusting the duty cycle allows the output voltage to be controlled and maintained at the desired level.

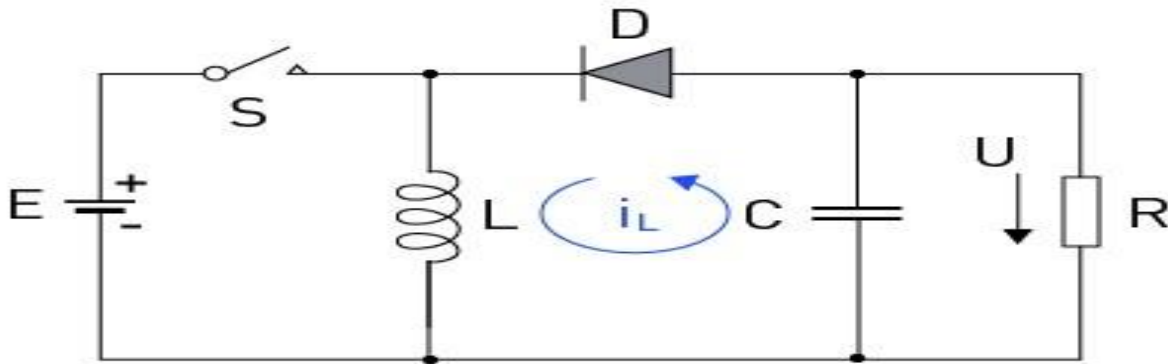
According to the converter's operating theory, magnetic energy obtained from the DC power source E builds up in the inductor over time. This energy is transferred to the load during the time. The positive terminal of the load voltage is connected to the negative terminal of the DC power source, indicating that this converter performs voltage inversion at the load. This is an important converter feature that may restrict where it can be used.



When the switch is turned on, the inductor is connected to the DC power source E , causing the inductor current to increase linearly from its minimum to maximum value. During this time, the diode is reverse-biased due to the sum of the voltage across the load V and the DC power source E , and therefore does not conduct.



When the switch is turned off, the inductor current is established through the diode D , transferring the magnetic energy of the inductor to the load. Under the influence of the load voltage V , the inductor current decreases from its maximum to minimum value.

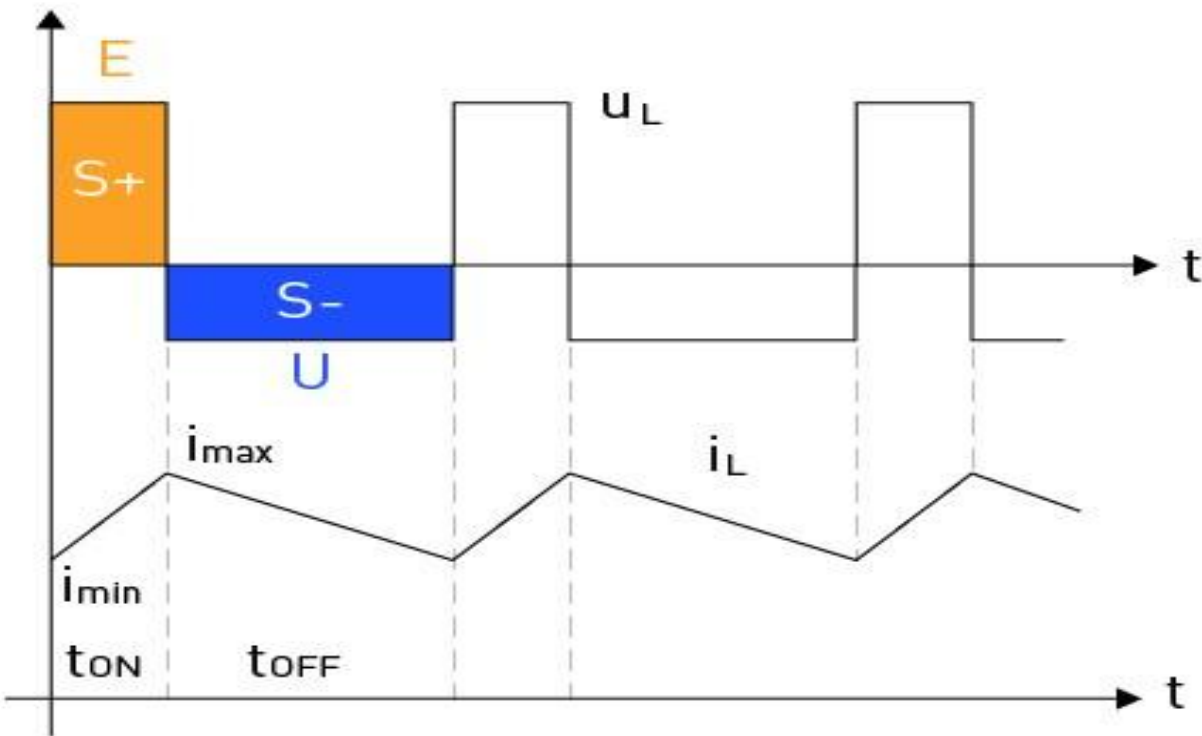


In steady state, the average value of the voltage across the inductor is zero, which implies:

$$S_+ = E \times T_{ON} = S_- = V \times T_{OFF}$$

$$\Rightarrow V = E \times T_{ON} / T_{OFF}$$

Therefore, this converter can operate as a step-down or step-up converter ($T_{ON} / T_{OFF} = 0 \dots \infty$). However, it should be noted that, as with the boost converter, the function of the voltage booster is limited by circuit losses.



Waveforms of Inductor Voltage and Inductor Current

The buck-boost converter has some similarities to both the boost converter and the buck converter in its circuit topology. The following are some of the main parts of the buck-boost converter:

Switch (S): Usually, a power transistor, such as a MOSFET, regulates the inductor's current flow. The converter's operating modes and output voltage depend on the switch's ON and OFF states.

Diode (D): When the switch is in the OFF position, it allows current to flow in only one direction, from the inductor to the output. The output capacitor can't discharge back to the input source thanks to the diode.

Inductor (L): Stores energy during the switch's ON state and releases it to the output during the OFF state. The inductor is crucial in smoothing the output voltage and current waveforms.

Capacitor (C): This component filters and smooths the output voltage waveform by storing and releasing energy. It helps maintain a stable output voltage by mitigating voltage ripple and transient responses.

Control Strategies :

(i) Time Ratio Control (TRC)

(a) Constant Frequency Control

(os) Pulse Width Modulation Control

(os) PWM Control

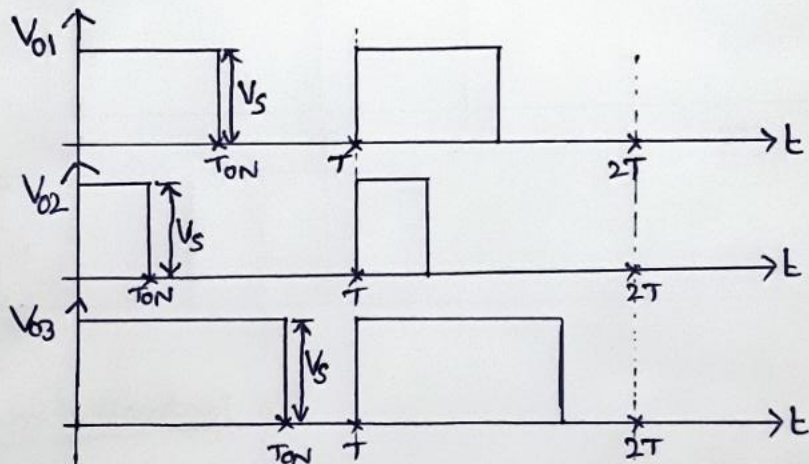
(b) Variable Frequency Control

(os) Frequency Modulation Control

(ii) Current Limit Control (CLC)

Constant Frequency Control :

In this type of Control strategy, the ON-time (T_{ON}) is varied. The chopping frequency (f) (os) chopping period (T) is kept constant.



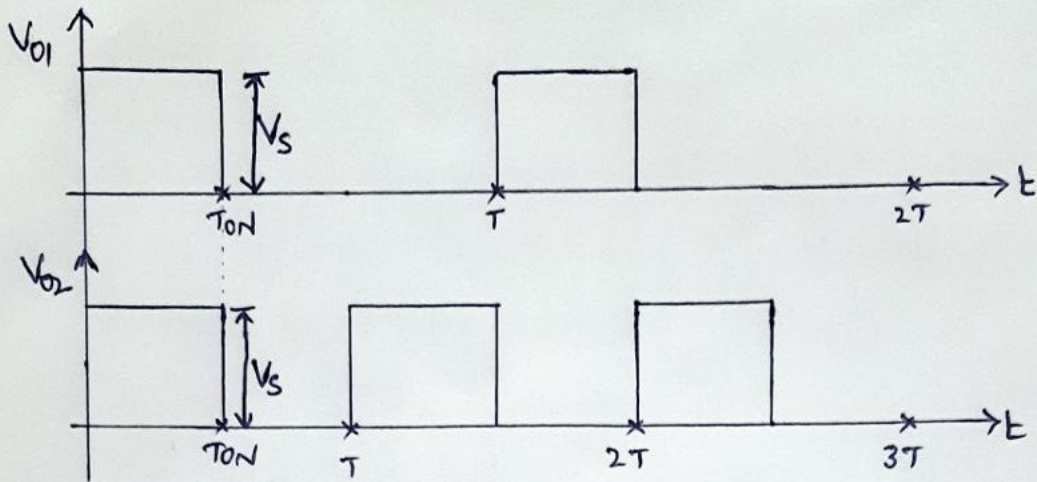
Variable Frequency control :

In this type of control strategy, the chopping frequency (f) (os) chopping period (T) is varied. The ON-time (T_{ON}) is kept constant (os) the off-time (T_{OFF}) is kept constant.

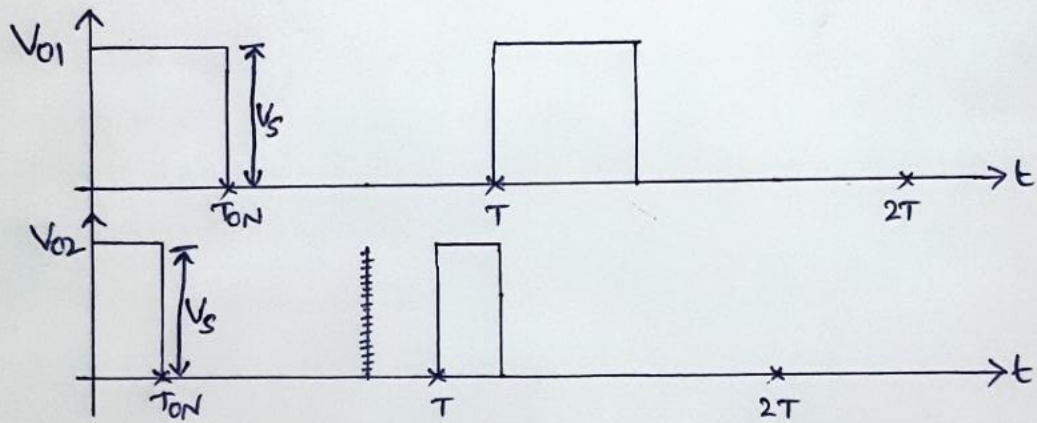
The disadvantages of Variable frequency control are,

- (i) Filter design is difficult
- (ii) There is a possibility of interference with signalling and telephone lines.
- (iii) If T_{OFF} is more, then the load current will be discontinuous, which is undesirable.

TON Constant :

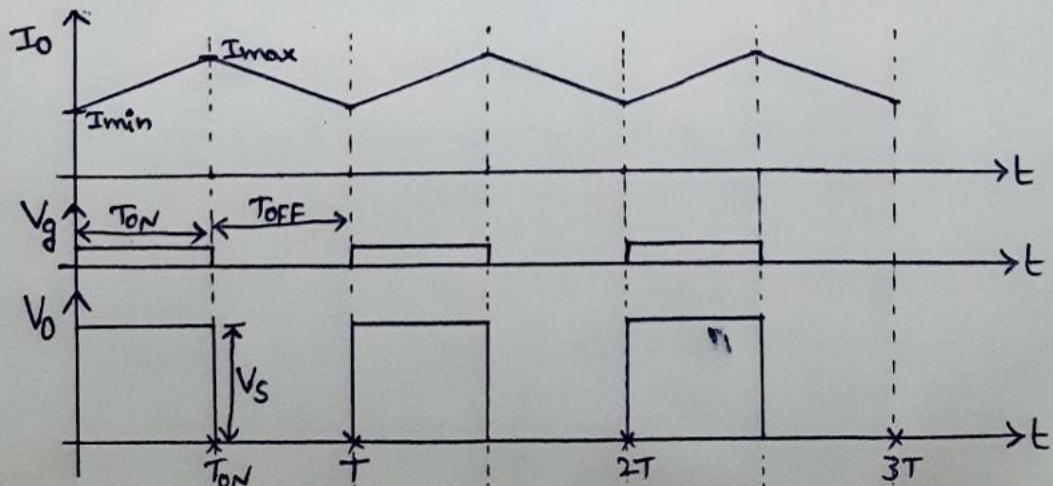


TOFF Constant :



Current Limit Control :

In this control technique, the switch is made ON & OFF so that the load current is maintained between two limits. When the current exceeds upper limit, the switch is made OFF. During T_{OFF} , the load current free wheels and decreases. When it reaches lower limit, the switch is made ON.



Power Electronics

Unit-4

Inverter

(Fixed DC Voltage to Variable AC Voltage)

1. Introduction
2. 1 \emptyset Half Bridge Inverter (or) 1 \emptyset Half Bridge VSI with Resistive Load (R Load)
3. 1 \emptyset Half Bridge Inverter (or) 1 \emptyset Half Bridge VSI with Inductive Load (RL Load)
4. 1 \emptyset Full Bridge Inverter (or) 1 \emptyset Full Bridge VSI with Resistive Load (R Load)
5. 1 \emptyset Full Bridge Inverter (or) 1 \emptyset Full Bridge VSI with Inductive Load (RL Load)

6. 3 \emptyset Voltage Source Inverter (VSI) with 180⁰ Conduction Mode
7. 3 \emptyset Voltage Source Inverter (VSI) with 120⁰ Conduction Mode

8. Voltage Control Techniques in Inverters
9. Pulse Width Modulation Techniques (Single PWM, Multiple PWM, Sine PWM)
10. 1 \emptyset Current Source Inverter (CSI)
11. 1 \emptyset Basic Series Inverter
12. 1 \emptyset Parallel Inverter

Single Phase Inverters

Introduction: 1ϕ Inverter converts fixed DC supply into variable 1ϕ AC supply at desired voltage and frequency. The inverter takes the DC supply from a battery (or) from a rectifier.

Classification of Inverters :

Classification (1) :

- (i) 1ϕ Inverter
- (ii) 3ϕ Inverter

Classification (2) :

- (i) Voltage Source Inverter (VSI)
 - (or) Voltage Fed Inverter (VFI)
- (ii) Current Source Inverter (CSI)
 - (or) Current Fed Inverter (CFI)

Classification (3) :

- (i) Line commutated Inverter
(Fully controlled Bridge Rectifier at $\alpha > 90^\circ$)
- (ii) Load commutated Inverter
- (iii) Forced commutated Inverter (By using SCR)
- (iv) Self commutated Inverter (By using MOSFET, IGBT, GTO)

Classification (4) :

- (i) Series Inverter
- (ii) Parallel Inverter
- (iii) Bridge Inverter
 - (a) Half Bridge Inverter
 - (b) Full Bridge Inverter

Classification (5) :

- (i) Mc Murray Half Bridge Inverter
- (ii) Modified Mc Murray Half Bridge Inverter
- (iii) Mc Murray Full Bridge Inverter
- (iv) Modified Mc Murray Full Bridge Inverter
- (v) Mc Murray - Bedford Half Bridge Inverter
- (vi) Modified Mc Murray - Bedford Half Bridge Inverter
- (vii) Mc Murray - Bedford Full Bridge Inverter
- (viii) Modified Mc Murray - Bedford Full Bridge Inverter

Applications of Inverters :

- (i) Variable Speed AC Motor Drives
- (ii) Induction Heating
- (iii) Uninterruptible Power Supplies
- (iv) Standby Power Supplies

Advantages of Inverters :

- (i) Variable AC output voltage can be obtained.
- (ii) Variable AC output frequency can be obtained.
- (iii) Pulse Width Modulation (PWM) techniques can be used.
- (iv) The sinusoidal output can be obtained by using latest techniques.
- (v) Harmonics in output voltage can be reduced by using high speed power semiconductor devices.

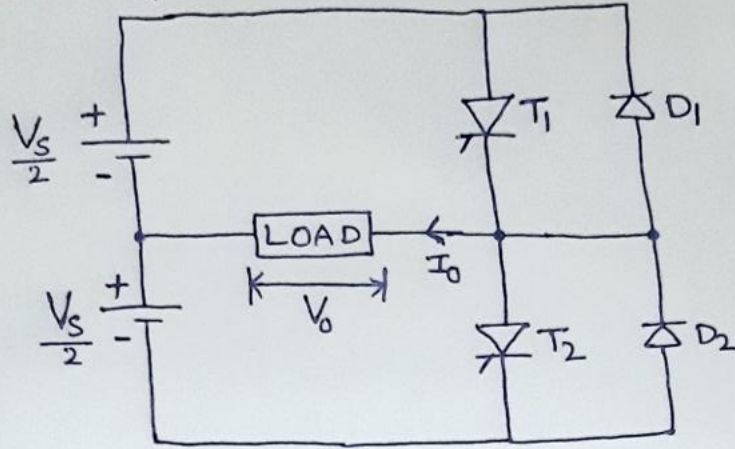
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Disadvantages of Inverters :

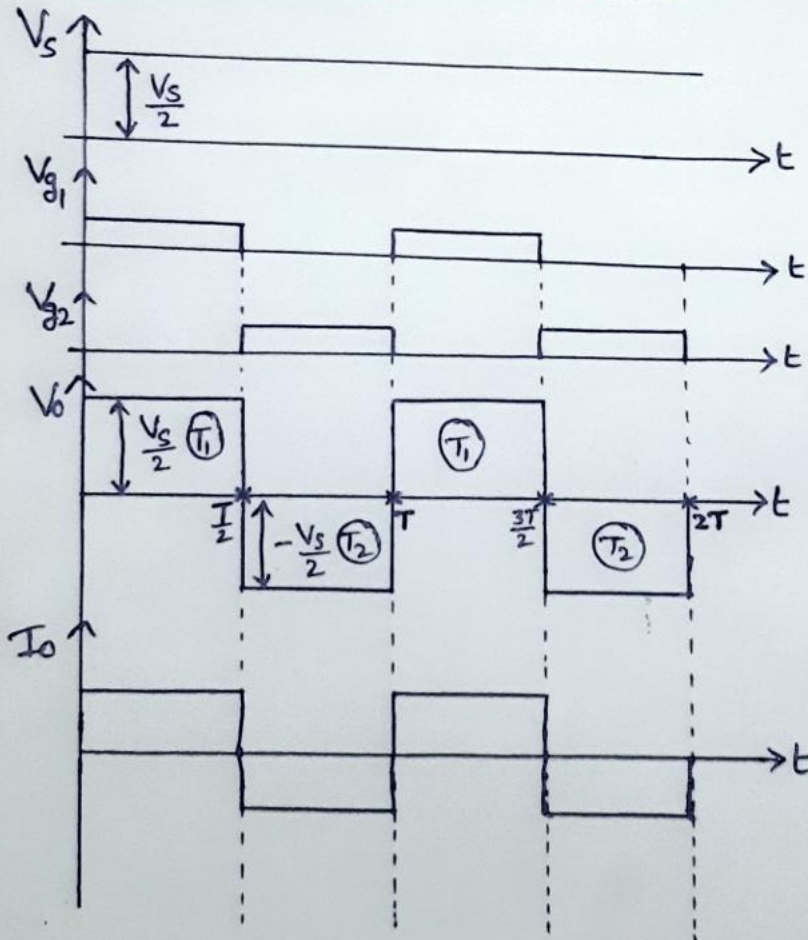
- (i) To get sinusoidal output, the cost of inverter will be increased.
- (ii) Filters must be connected at the output side to reduce harmonics.

1 ϕ Half Bridge Inverter (or) 1 ϕ Half Bridge VSI:

Circuit Diagram:



Waveforms for Resistive Load (R-Load):



$$V_o(\text{rms}) = \sqrt{\frac{1}{T} \int_0^{T/2} \left(\frac{V_s}{2}\right)^2 dt} = \sqrt{\frac{2}{T} \times \left(\frac{V_s}{2}\right)^2 \times \int_0^{T/2} (1) dt}$$

$$\therefore \boxed{V_o(\text{rms}) = \frac{V_s}{2}}$$

Waveforms for Inductive Load (RL-Load) :

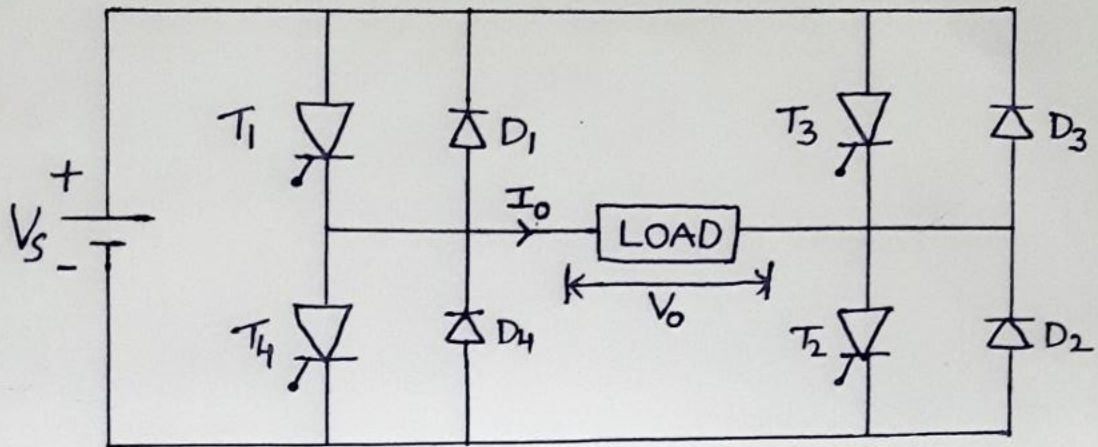


$$V_o(\text{rms}) = \sqrt{\frac{1}{T/2} \int_0^{T/2} \left(\frac{V_s}{2}\right)^2 dt}$$

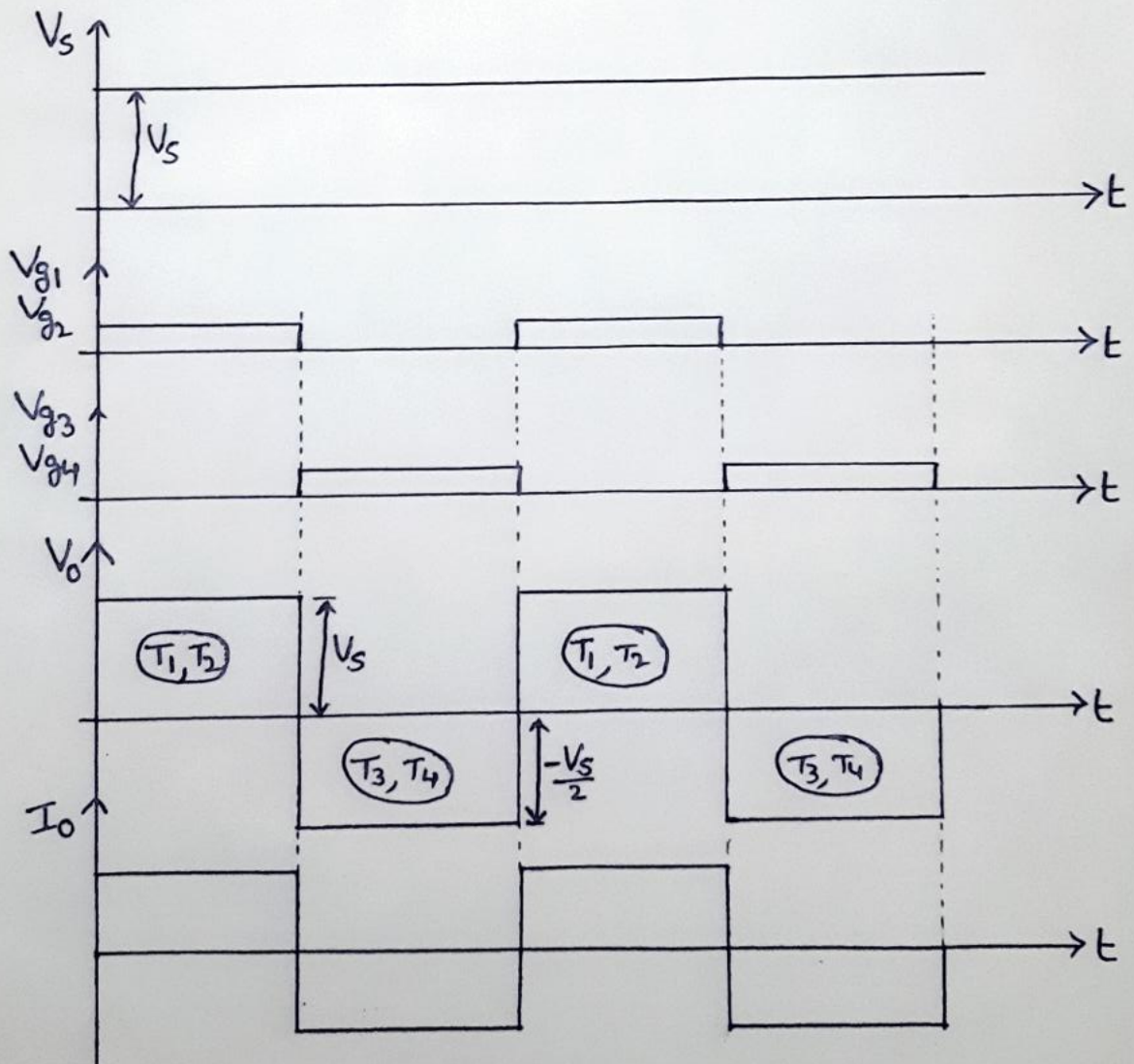
$$\therefore \boxed{V_o(\text{rms}) = \frac{V_s}{2}}$$

1 ϕ Full Bridge Inverter (or) 1 ϕ Full Bridge VSI :

Circuit Diagram :



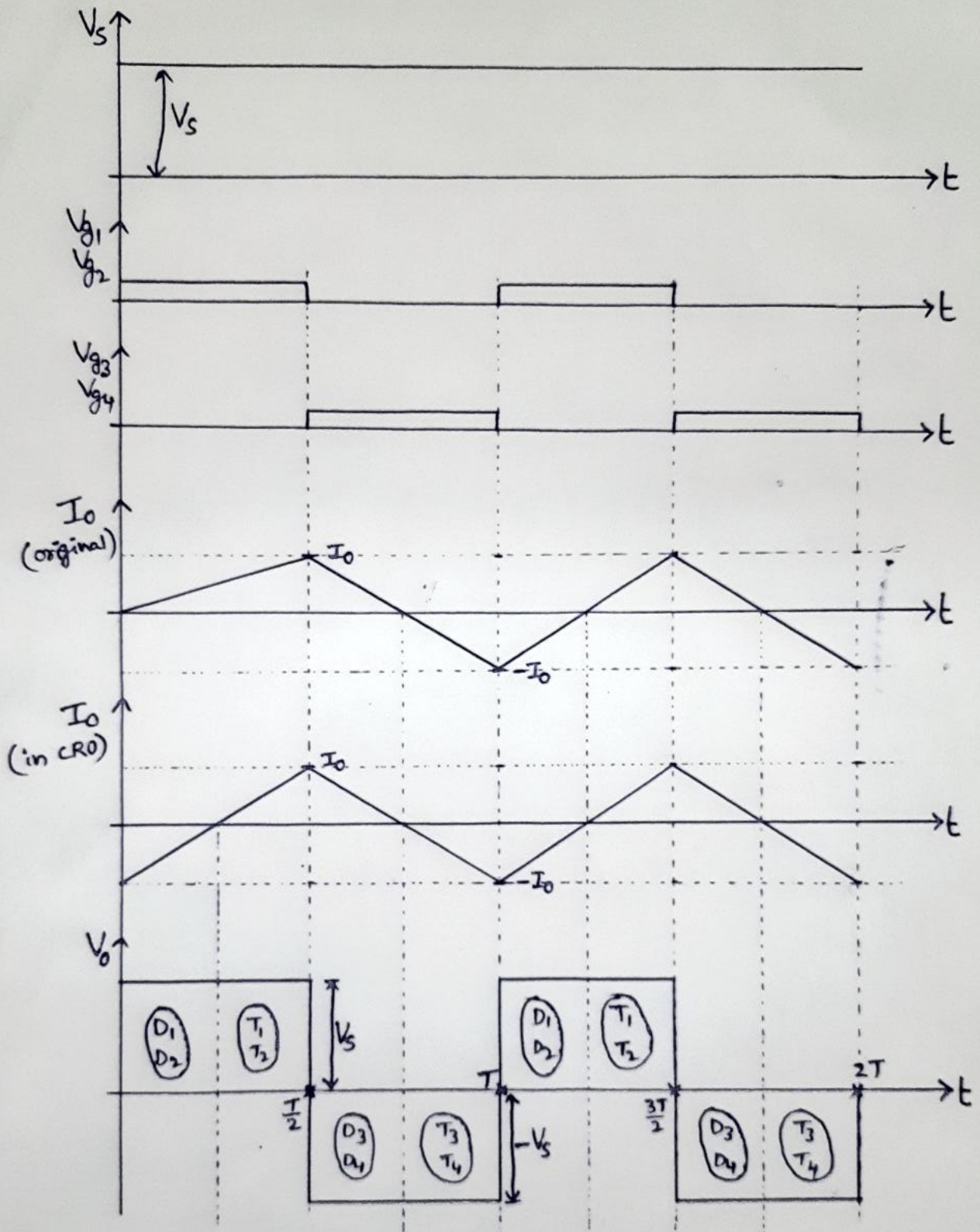
Waveforms for Resistive Load (R-Load) :



$$V_o(\text{rms}) = \sqrt{\frac{1}{T/2} \int_0^{T/2} (V_s)^2 dt}$$

$$\therefore V_o(\text{rms}) = V_s$$

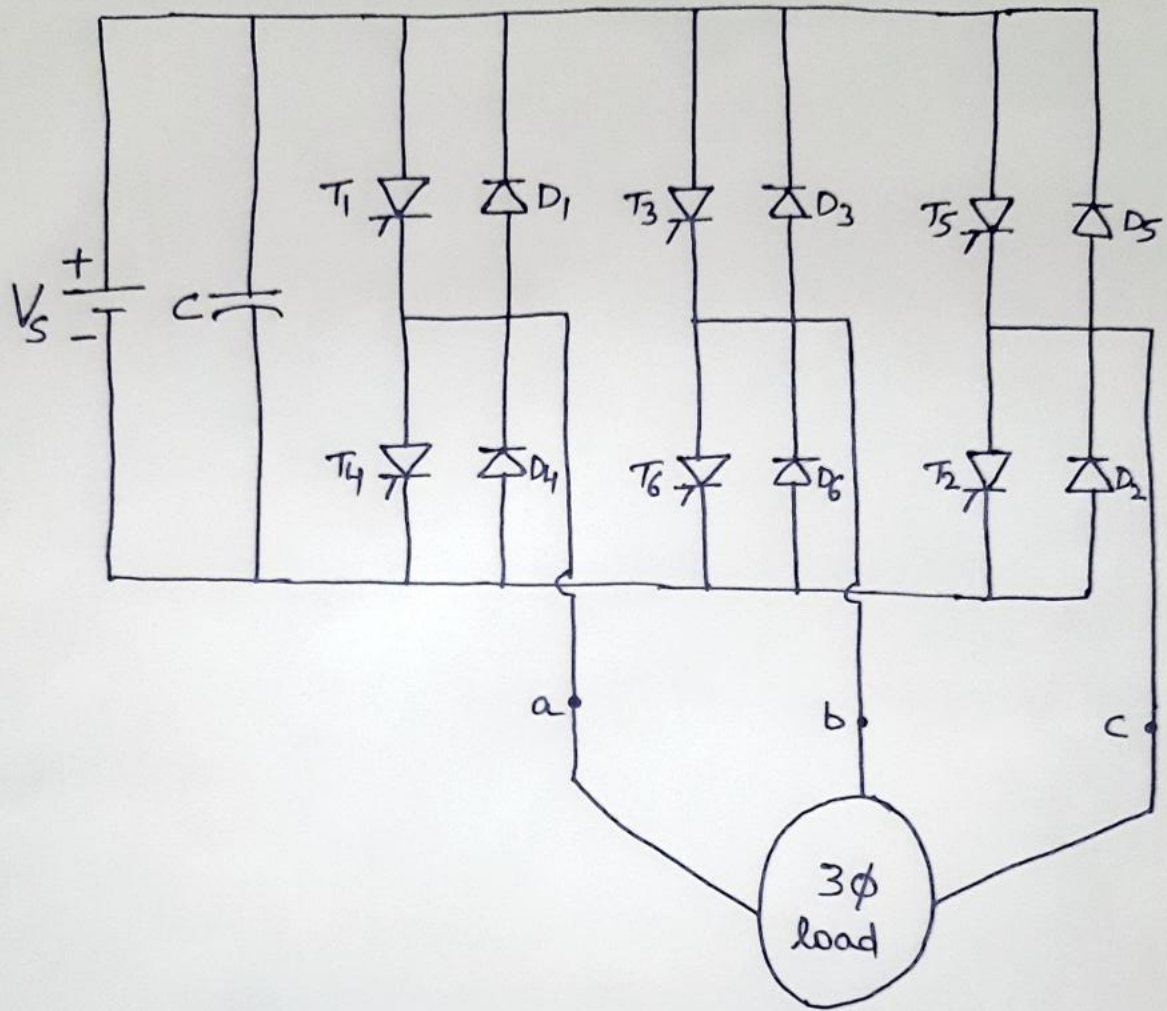
Waveforms for Inductive Load (RL-Load):



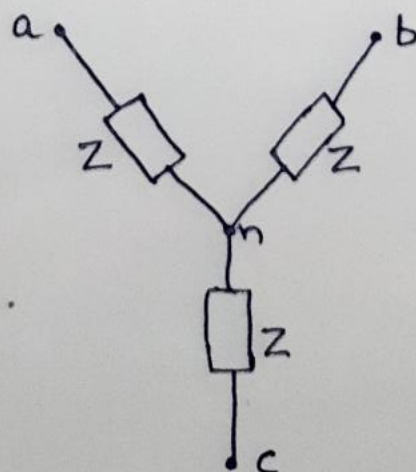
$$V_o(\text{rms}) = \sqrt{\frac{1}{T/2} \int_0^{T/2} (V_s)^2 dt}$$

$$\therefore \boxed{V_o(\text{rms}) = V_s}$$

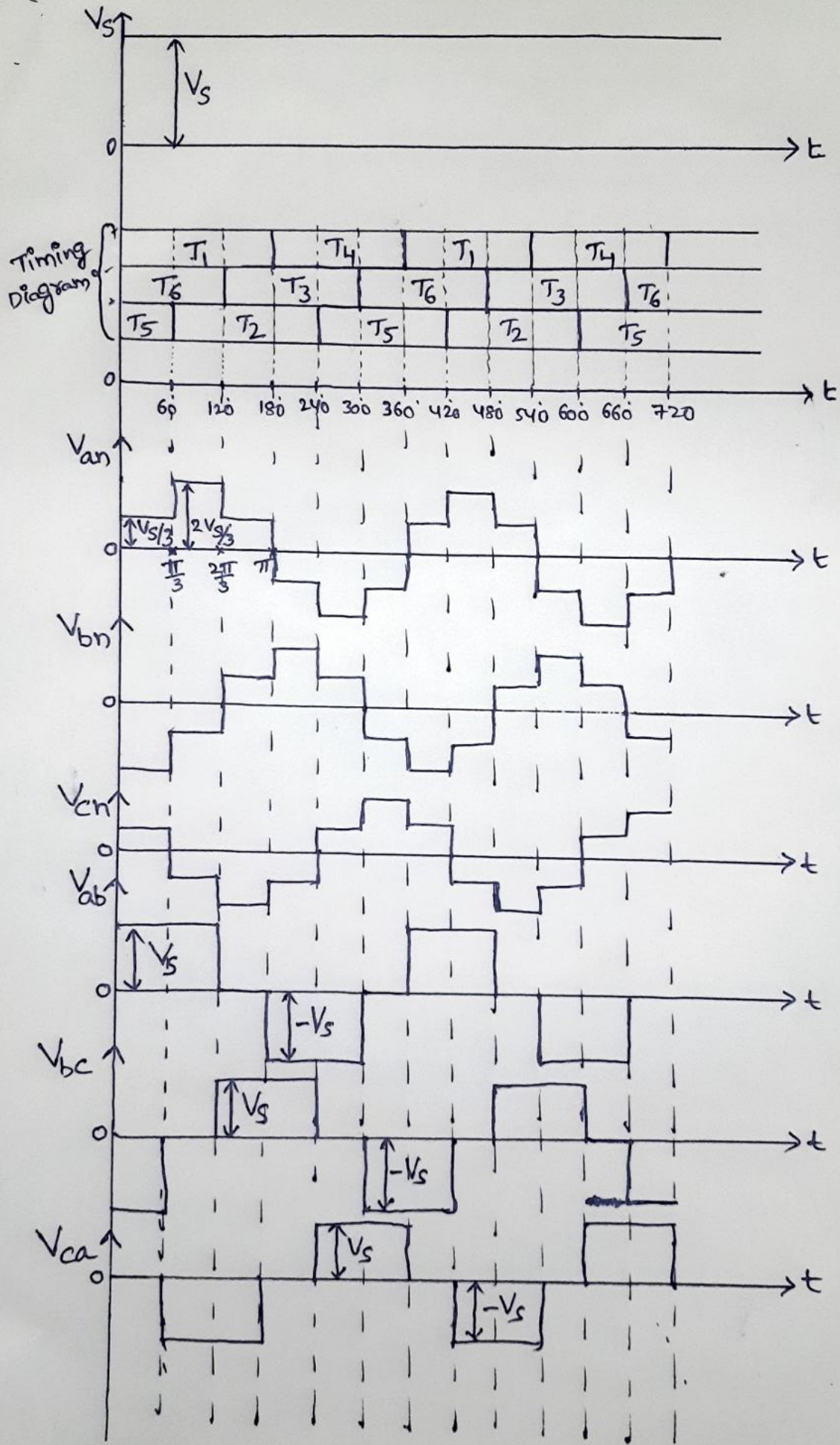
3 ϕ VSI with 180 $^\circ$ conduction Mode:



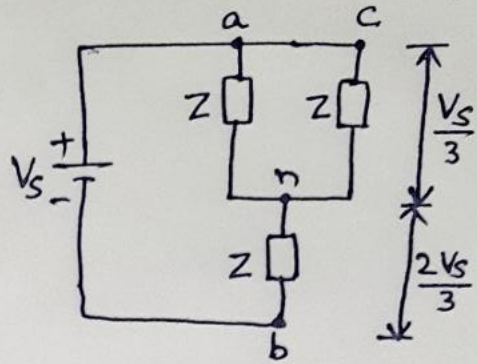
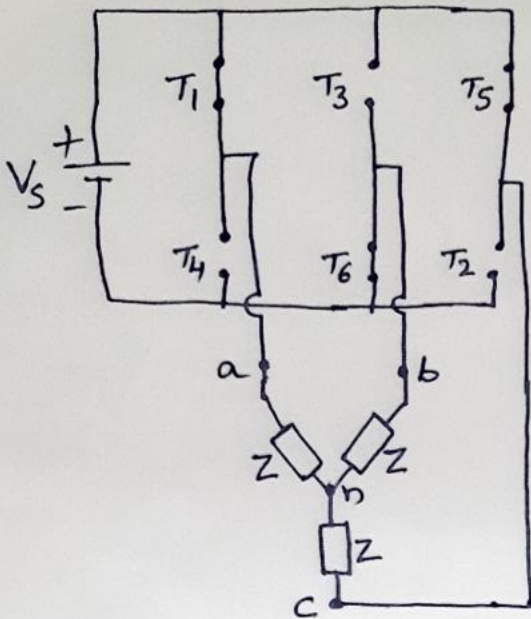
In 3 ϕ VSI circuit diagram, SCRs (T_1, T_2, T_3, T_4, T_5 & T_6) are connected. These SCRs are called as switching devices (or) switches. In recent days, MOSFET & IGBT are used as switches. The 3 ϕ load can be represented as



Z = Impedance of load per phase



Step I (0° to 60°):

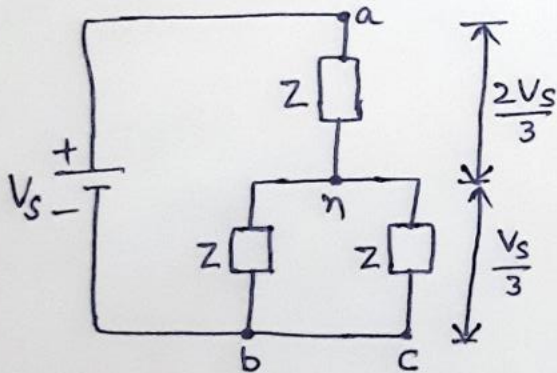


$$V_{an} = \frac{V_s}{3}$$

$$V_{bn} = -\frac{2V_s}{3}$$

$$V_{cn} = \frac{V_s}{3}$$

Step II (60° to 120°):

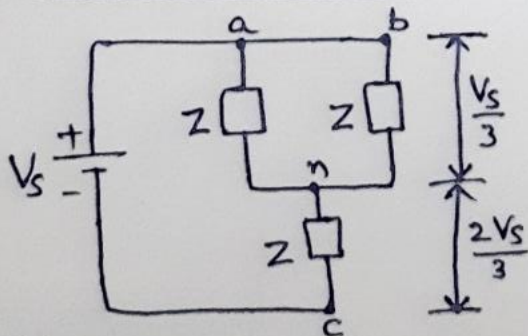


$$V_{an} = \frac{2V_s}{3}$$

$$V_{bn} = -\frac{V_s}{3}$$

$$V_{cn} = -\frac{V_s}{3}$$

Step III (120° to 180°):



$$V_{an} = \frac{V_s}{3}$$

$$V_{bn} = \frac{V_s}{3}$$

$$V_{cn} = -\frac{2V_s}{3}$$

Line voltages:

$$V_{ab} = V_{an} - V_{bn}$$

$$V_{bc} = V_{bn} - V_{cn}$$

$$V_{ca} = V_{cn} - V_{an}$$

Derivation :

Consider Van waveform for derivation purpose.

Also, consider star connected load. ($V_L = \sqrt{3} V_{ph}$ & $I_L = I_{ph}$)

$$V_o(\text{rms})/ph = V_{ph} = \left[\frac{1}{\pi} \left\{ \left(\frac{V_s}{3} \right)^2 \cdot \frac{\pi}{3} + \left(\frac{2V_s}{3} \right)^2 \cdot \frac{\pi}{3} + \left(\frac{V_s}{3} \right)^2 \cdot \frac{\pi}{3} \right\} \right]^{\frac{1}{2}}$$

$$\therefore V_{ph} = \left[\frac{1}{\pi} * \frac{\pi}{3} \left\{ \frac{V_s^2}{9} + \frac{4V_s^2}{9} + \frac{V_s^2}{9} \right\} \right]^{\frac{1}{2}}$$

$$\therefore V_{ph} = \left[\frac{1}{\pi} * \frac{\pi}{3} * \frac{6V_s^2}{9} \right]^{\frac{1}{2}}$$

$$\therefore V_{ph} = \left[\frac{2}{9} V_s^2 \right]^{\frac{1}{2}}$$

$$\therefore V_{ph} = \frac{\sqrt{2}}{3} V_s$$

$$\therefore \boxed{V_{ph} = 0.4714 V_s}$$

$$I_{ph} = \frac{V_{ph}}{R} = \frac{0.4714 V_s}{R}$$

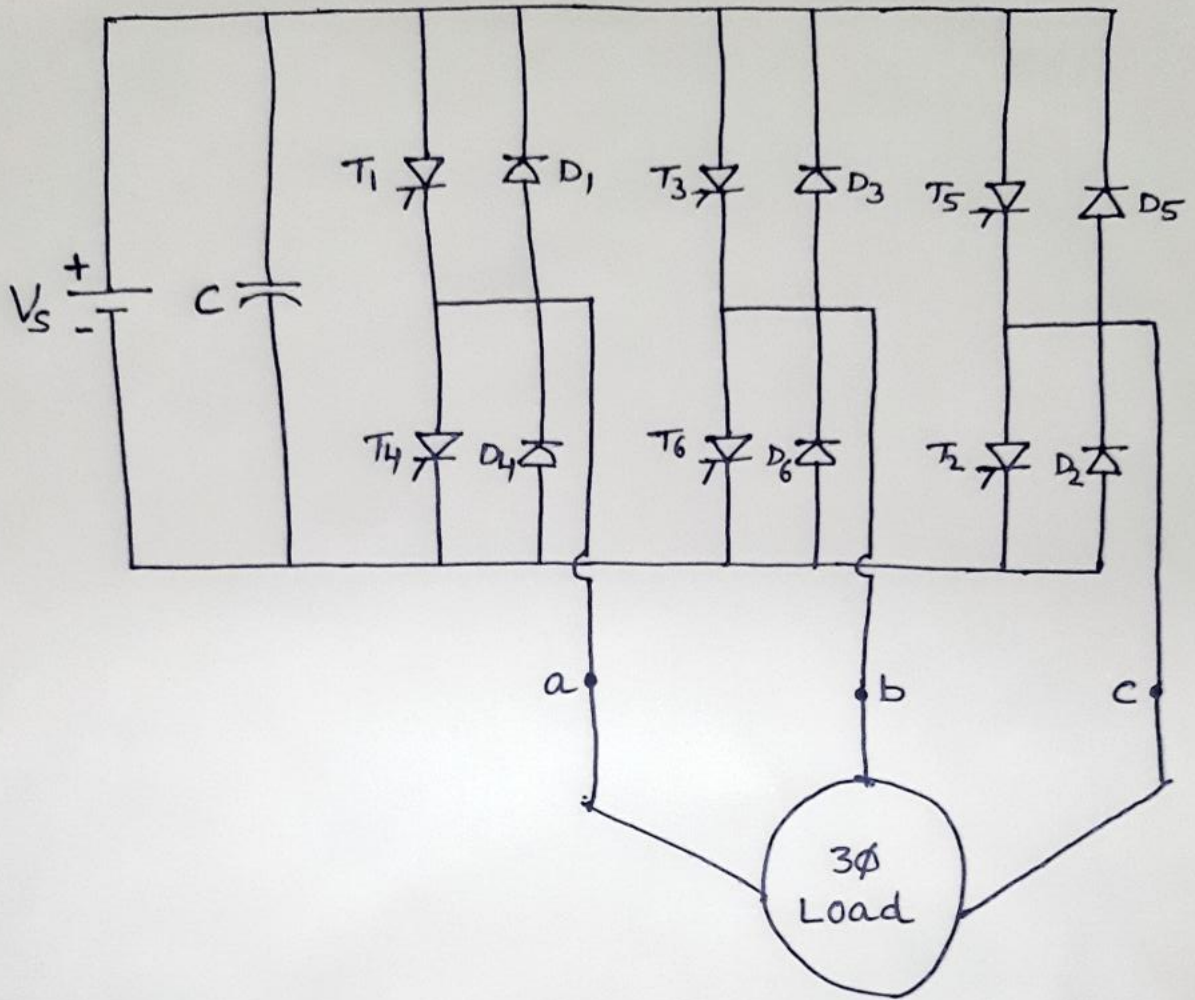
$$\therefore \boxed{I_{ph} = \frac{0.4714 V_s}{R}}$$

$$V_o(\text{rms})(\text{line}) = V_L = \sqrt{3} V_{ph} = \sqrt{3} * 0.4714 V_s$$

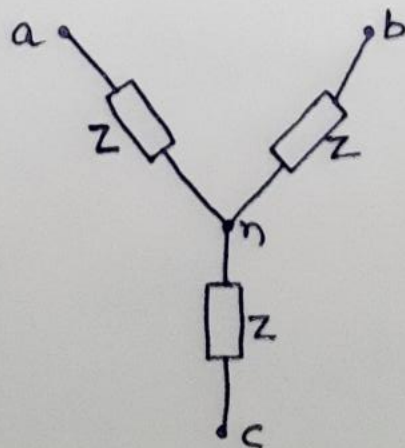
$$\therefore \boxed{V_L = 0.8165 V_s}$$

$$I_L = I_{ph} \quad \therefore \boxed{I_L = \frac{0.4714 V_s}{R}}$$

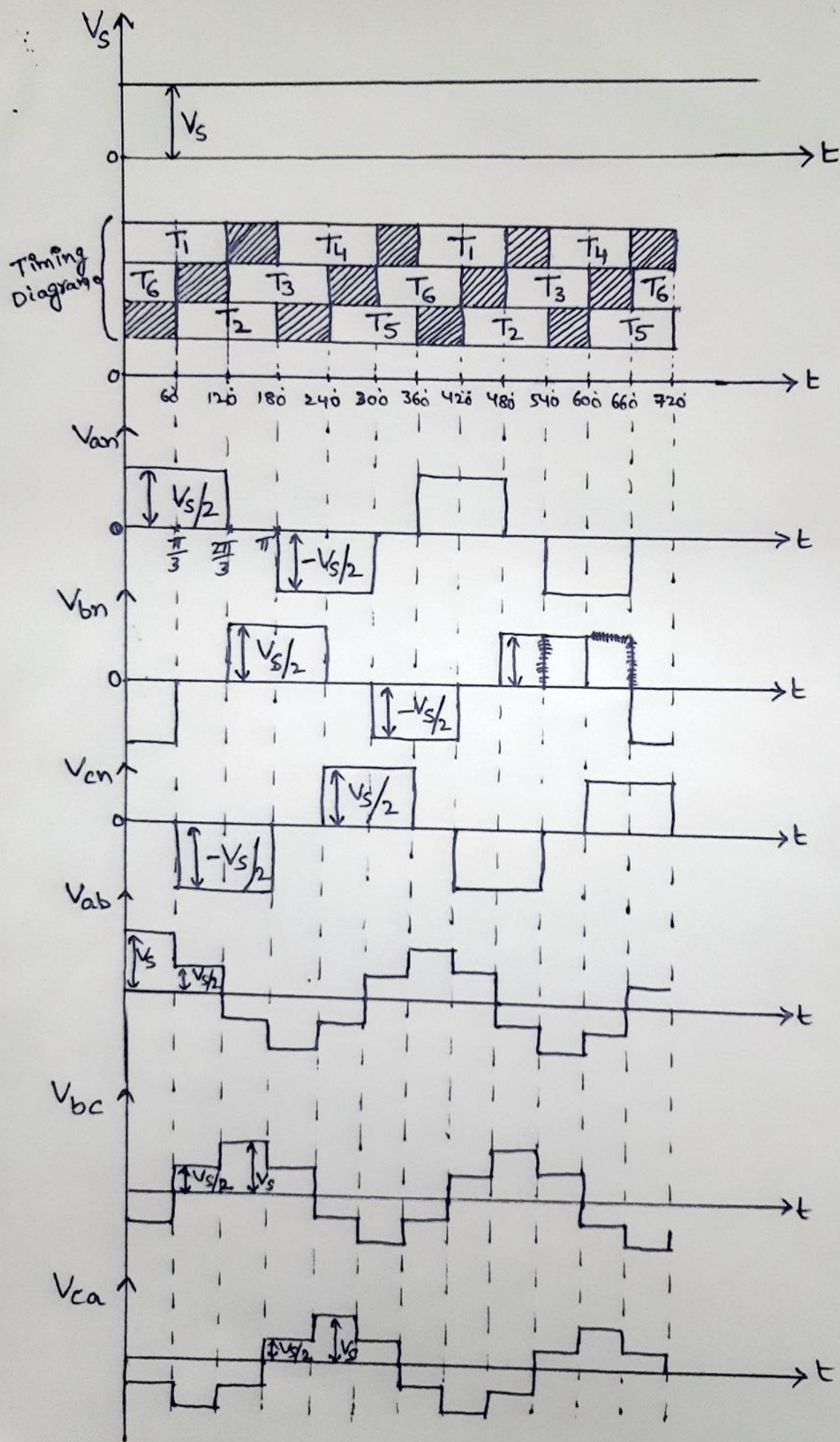
3 ϕ VSI with 120 $^\circ$ conduction Mode:



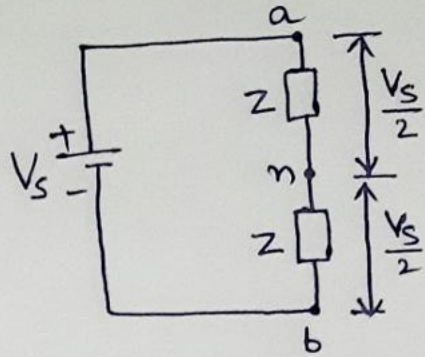
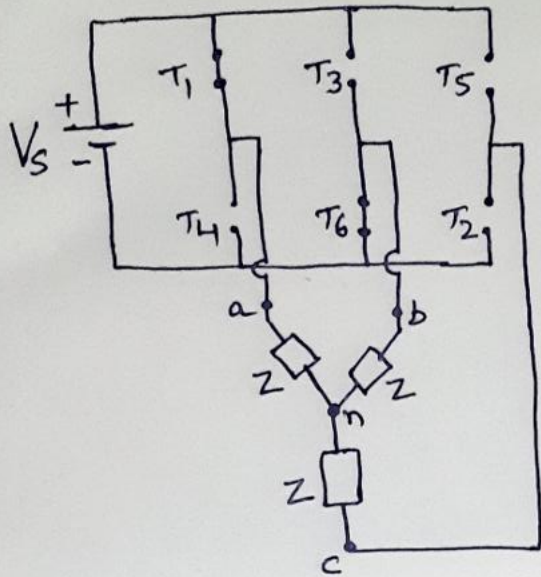
In 3 ϕ VSI circuit diagram, SCRs (T_1, T_2, T_3, T_4, T_5 & T_6) are connected. These SCRs are called as switching devices (or) switches. In recent days, MOSFET & IGBT are used as switches. The 3 ϕ load can be represented as



Z = Impedance of load per phase



Step I (0° to 60°):

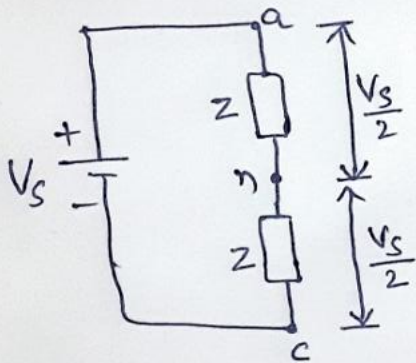


$$V_{an} = \frac{V_s}{2}$$

$$V_{bn} = -\frac{V_s}{2}$$

$$V_{cn} = 0$$

Step II (60° to 120°):

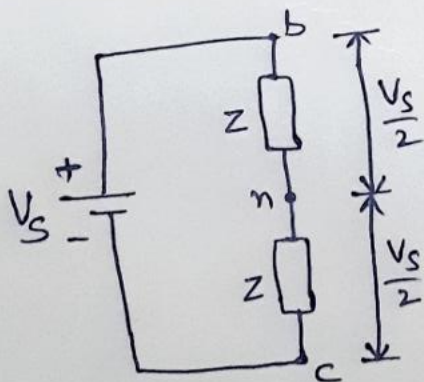


$$V_{an} = \frac{V_s}{2}$$

$$V_{bn} = 0$$

$$V_{cn} = -\frac{V_s}{2}$$

Step III (120° to 180°):



$$V_{an} = 0$$

$$V_{bn} = \frac{V_s}{2}$$

$$V_{cn} = -\frac{V_s}{2}$$

Line Voltages:

$$V_{ab} = V_{an} - V_{bn}$$

$$V_{bc} = V_{bn} - V_{cn}$$

$$V_{ca} = V_{cn} - V_{an}$$

Derivation:

Consider V_{an} waveform for derivation purpose.

Also, consider star connected load. ($V_L = \sqrt{3} V_{ph}$ & $I_L = I_{ph}$)

$$V_{o(\text{rms})/ph} = V_{ph} = \left[\frac{1}{\pi} \left\{ \left(\frac{V_s}{2} \right)^2 * \frac{2\pi}{3} \right\} \right]^{\frac{1}{2}}$$

$$\therefore V_{ph} = \left[\frac{1}{\pi} * \frac{V_s^2}{4} * \frac{2\pi}{3} \right]^{\frac{1}{2}}$$

$$\therefore V_{ph} = \left[\frac{V_s^2}{6} \right]^{\frac{1}{2}}$$

$$\therefore V_{ph} = \frac{V_s}{\sqrt{6}}$$

$$\therefore \boxed{V_{ph} = 0.4082 V_s}$$

$$I_{ph} = \frac{V_{ph}}{R} = \frac{0.4082 V_s}{R}$$

$$\therefore \boxed{I_{ph} = \frac{0.4082 V_s}{R}}$$

$$V_{o(\text{rms})}(\text{line}) = V_L = \sqrt{3} V_{ph} = \sqrt{3} * 0.4082 V_s$$

$$\therefore \boxed{V_L = 0.7071 V_s}$$

$$I_L = I_{ph} \quad \therefore \boxed{I_L = \frac{0.4082 V_s}{R}}$$

Comparison of 180° Mode & 120° Mode :

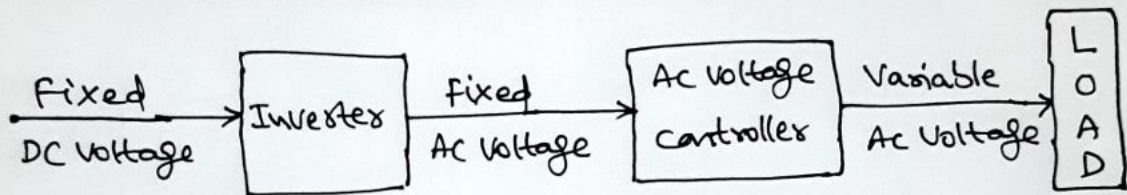
	180° Conduction Mode	120° Conduction Mode
①	Each Thyristor conducts for 180°.	Each Thyristor conducts for 120°.
②	There is no commutation interval for proper and reliable operation of Inverter.	There is commutation interval of 60° for proper and reliable operation of Inverter.
③	Utility Factor = UF = 33.33%	Utility Factor = UF = 28.9%
④	Possibility of two series thyristors conducting simultaneously is more.	Possibility of two series thyristors conducting simultaneously is less.
⑤	$V_L = 0.8165 V_s$ $V_{ph} = 0.4714 V_s$ $I_o = 0.4714 V_s / R$	$V_L = 0.7071 V_s$ $V_{ph} = 0.4082 V_s$ $I_o = 0.4082 V_s / R$

Voltage Control Techniques

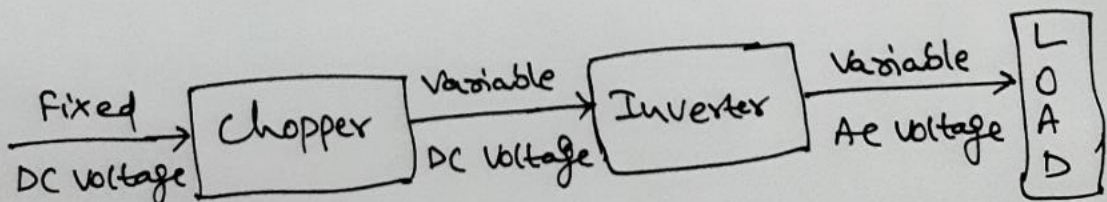
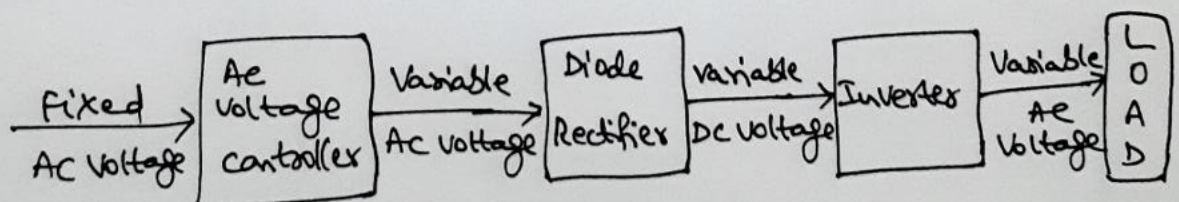
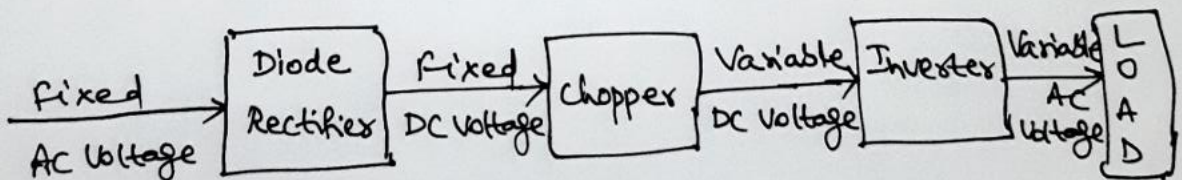
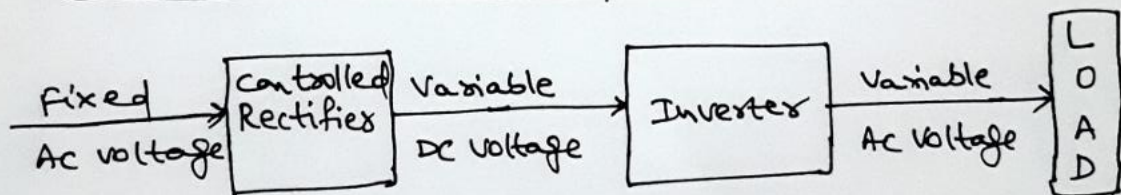
- (i) External control of AC output voltage
- (ii) External control of DC Input voltage
- (iii) Internal control (or) pulse width modulation control (or) PWM control

- (a) Single pwm
- (b) Multiple pwm
- (c) Sinusoidal pwm (or) Sine pwm (or) SPWM

(i) External Control of AC output voltage

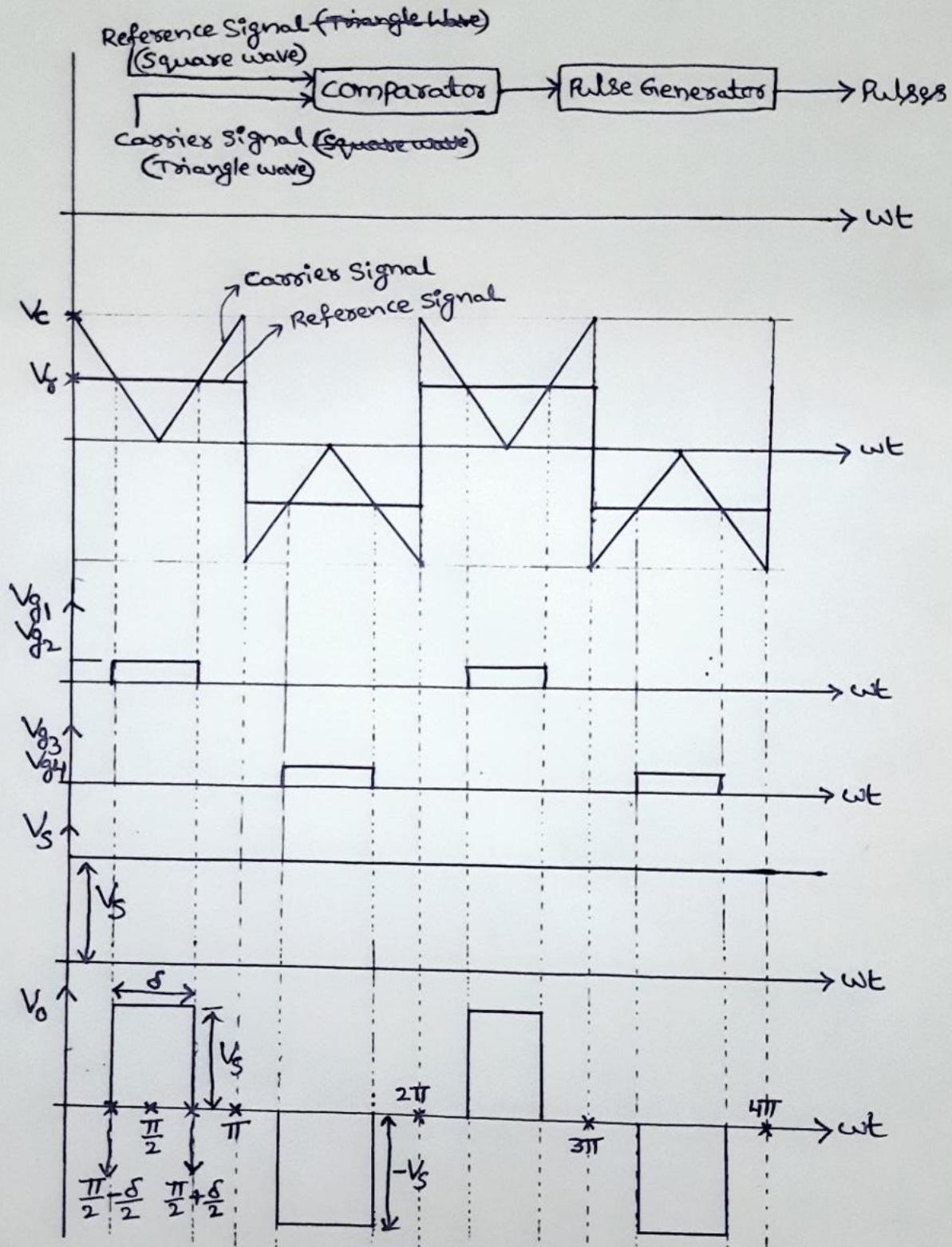


(ii) External control of DC Input voltage



Pulse Width Modulation (PWM) Techniques :

Single PWM Technique :



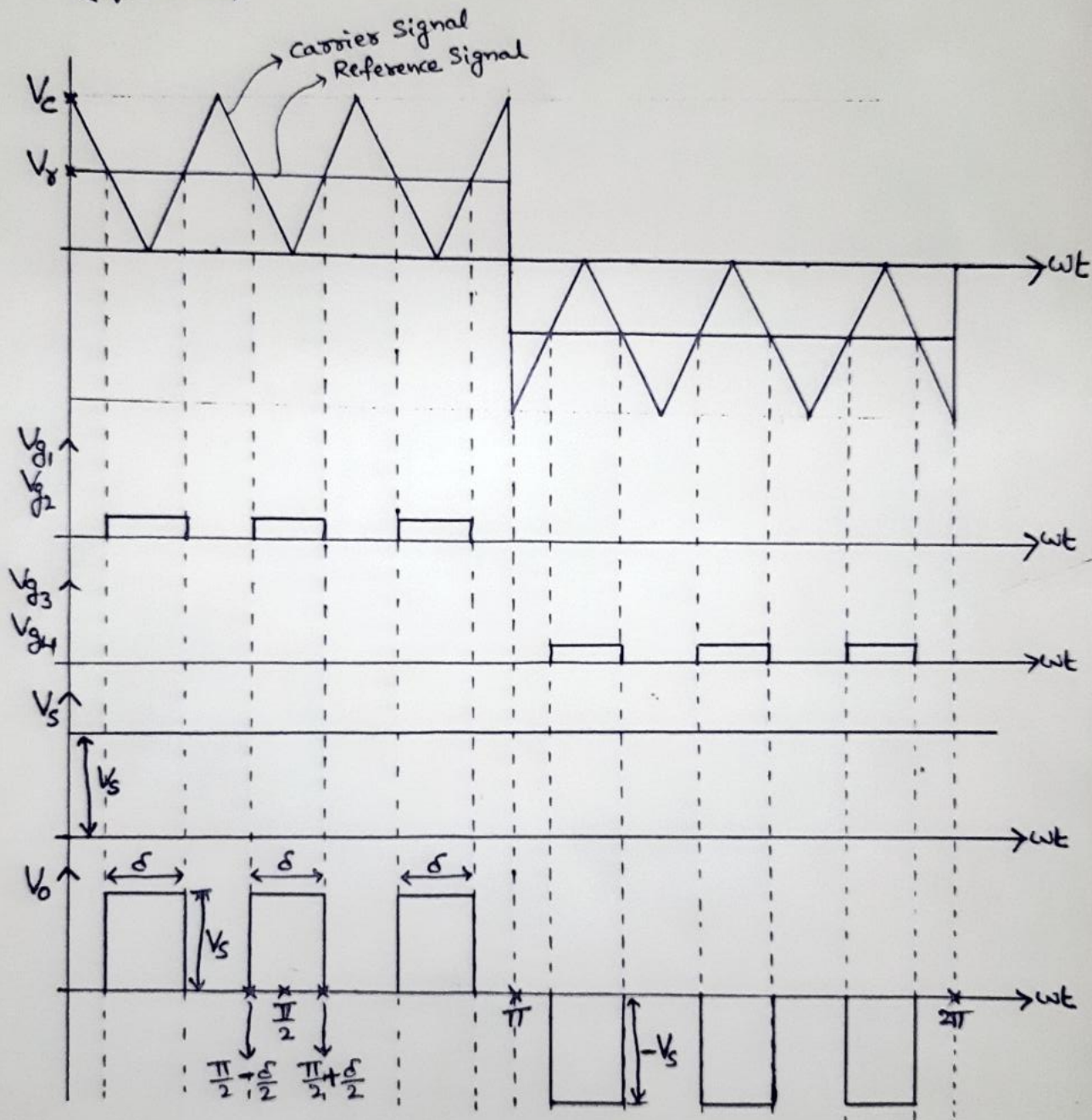
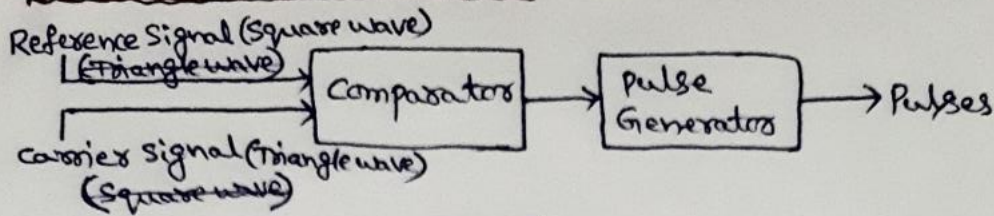
$$V_0(\text{rms}) = \sqrt{\frac{1}{\pi} \int_{\frac{\pi}{2} - \frac{\delta}{2}}^{\frac{\pi}{2} + \frac{\delta}{2}} (V_s)^2 d(\omega t)}$$

$$\therefore V_0(\text{rms}) = V_s \sqrt{\frac{\delta}{\pi}}$$

If $\delta = 0$ then $V_0 = 0$; If $\delta = \pi$ then $V_0 = V_s$.

\therefore By varying δ from (0 to π); V_0 can be varied from (0 to V_s).

Multiple PWM Technique:

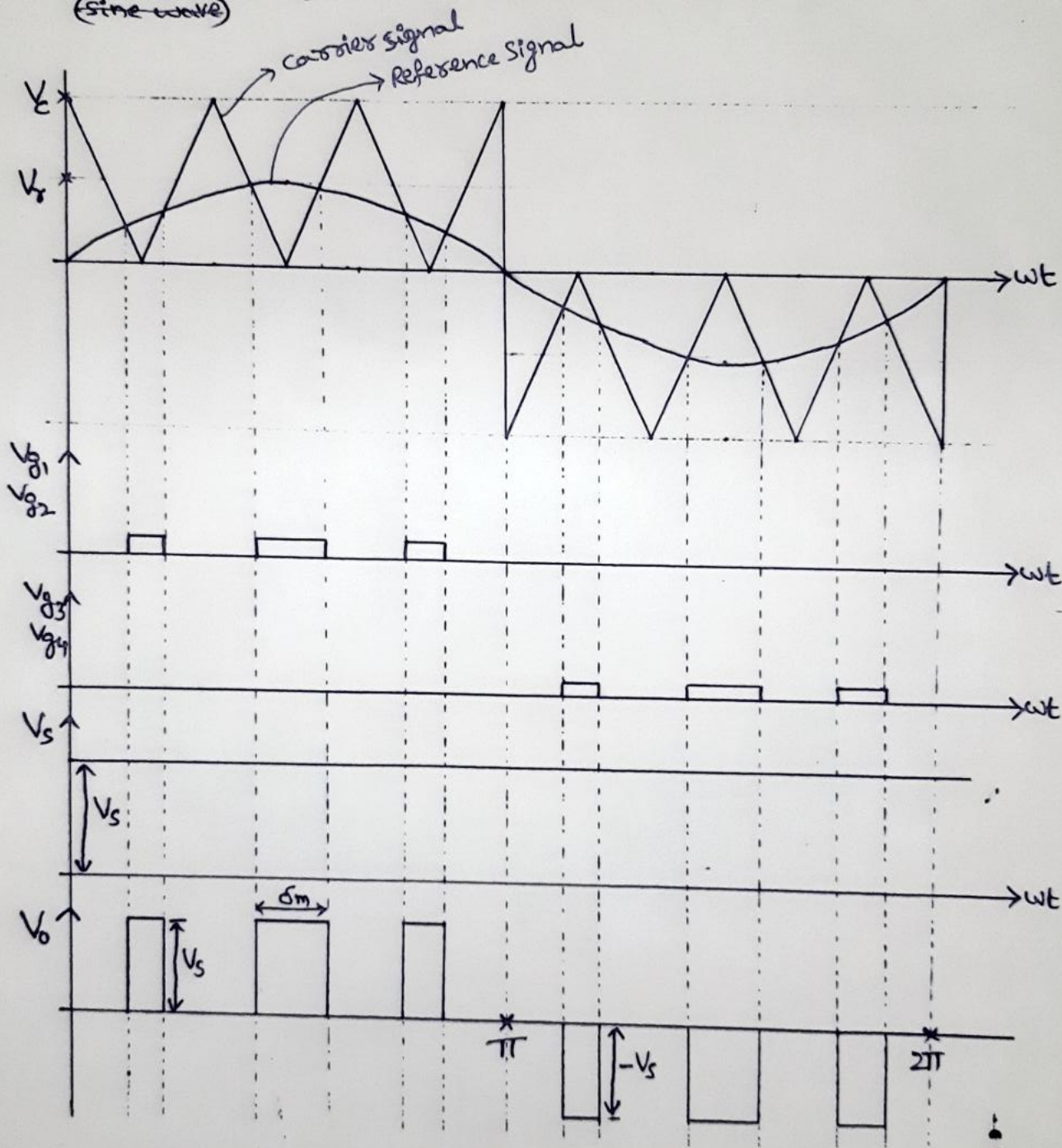
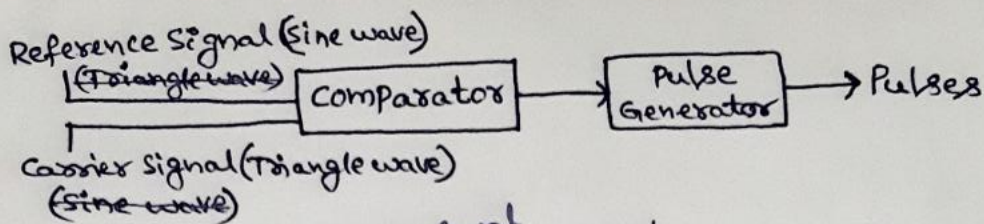


$$V_o(\text{rms}) = \sqrt{\frac{1}{\pi} \times P \times \int_{\frac{\pi}{2} - \frac{\delta}{2}}^{\frac{\pi}{2} + \frac{\delta}{2}} (V_s)^2 d(wt)}$$

$$\therefore V_o(\text{rms}) = V_s \sqrt{\frac{P\delta}{\pi}}$$

Here, P = No. of pulses per half cycle of V_o wave.

Sinusoidal PWM (or) Sine PWM (or) SPWM :



$$V_o(\text{rms}) = \frac{1}{\sqrt{2}} V_s \sqrt{\sum_{m=1}^P \frac{\delta_m}{\pi}}$$

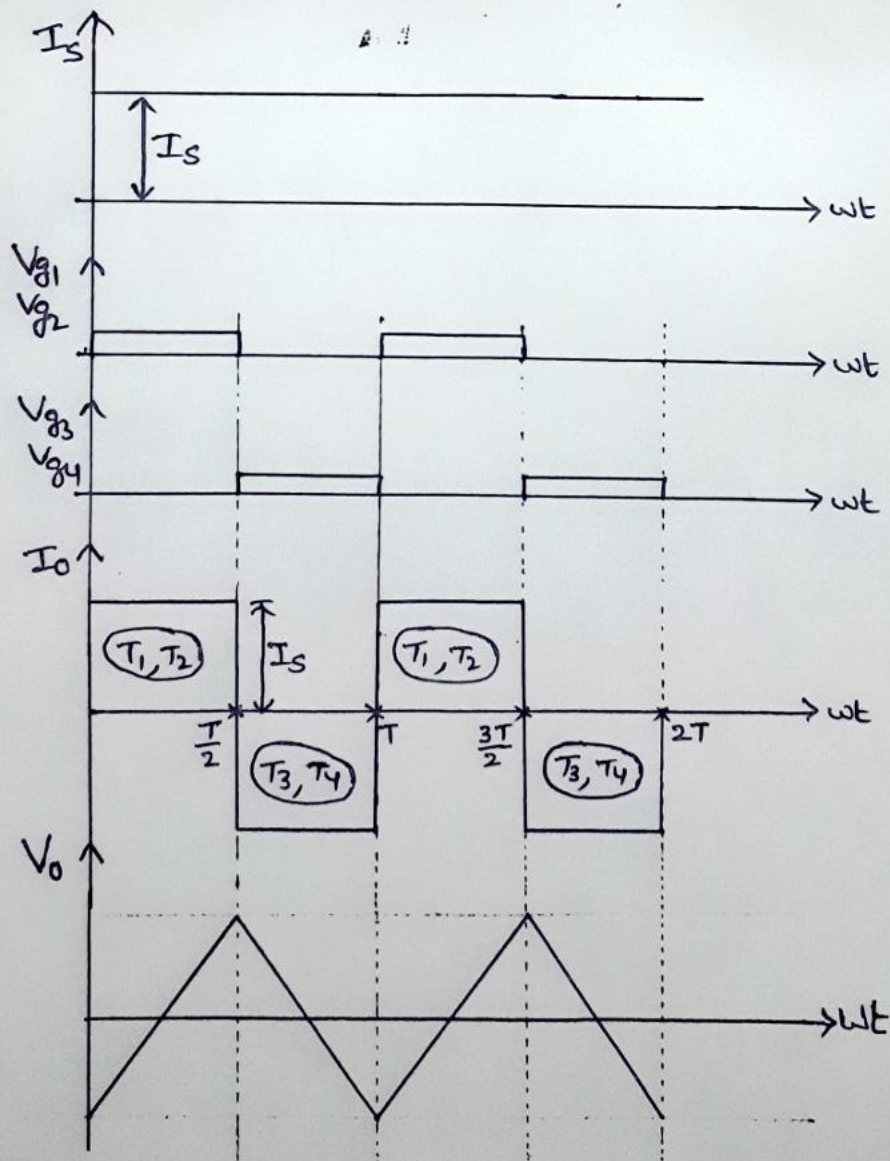
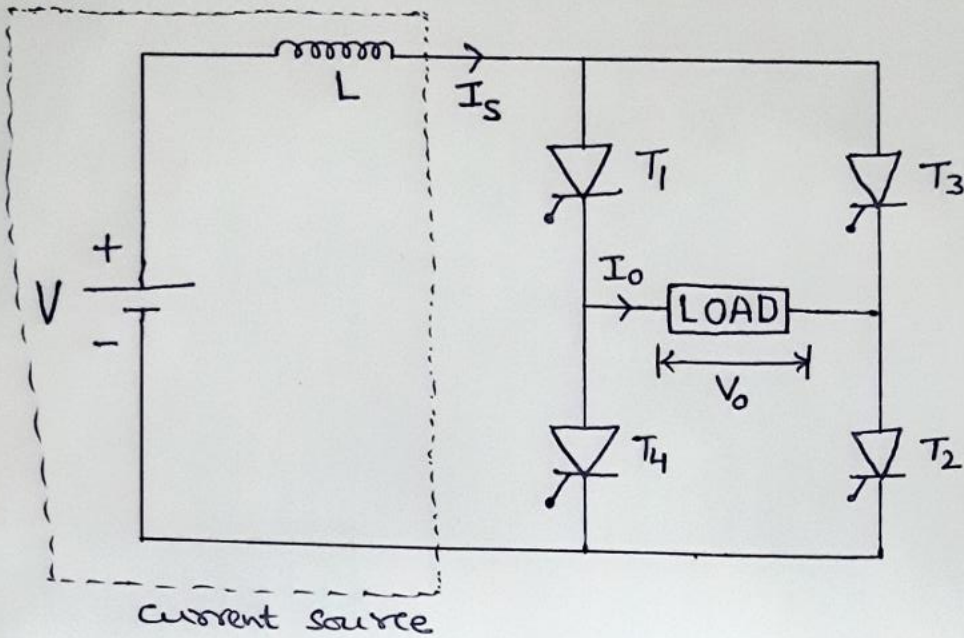
; Here, P = no. of pulses per half cycle of V_o wave
 $m = \text{pulse numbers} = 1, 2, 3, \dots$

$$\text{Modulation Index (M)} = \frac{V_o}{V_c}$$

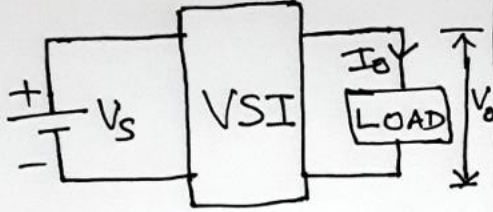

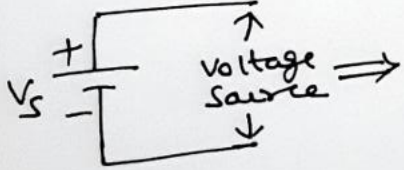
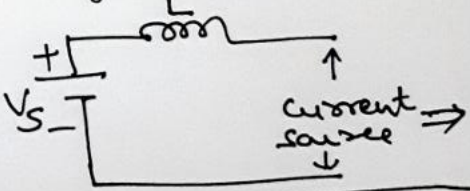
When $V_o = 0$; $M = 0$
 When $V_o = V_c$; $M = 1$

\therefore By varying M from (0 to 1); V_o can be varied.

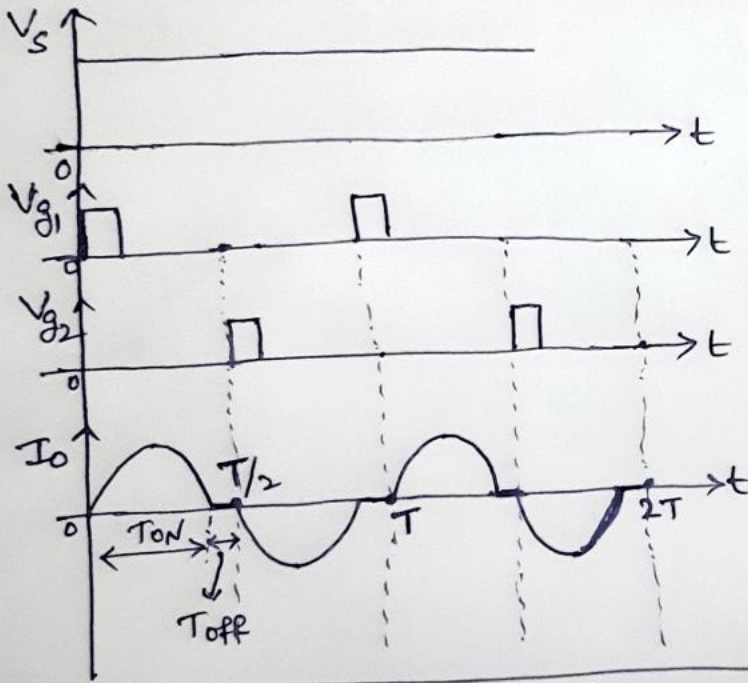
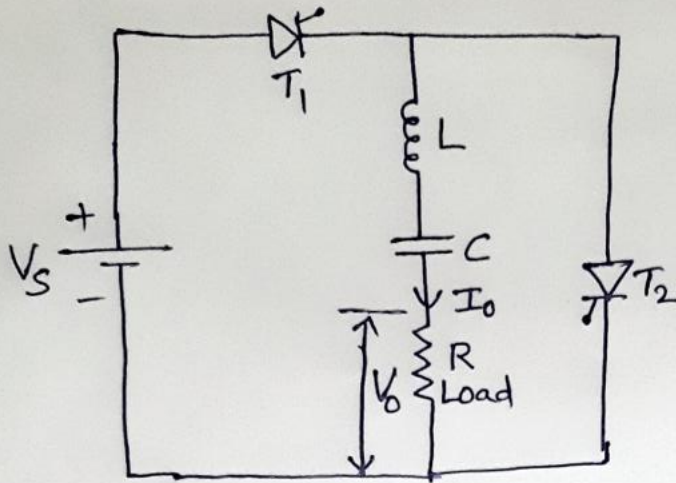
1 ϕ Current Source Inverter (1 ϕ CSI)



Comparison between VSI and CSI

Sl.No.	Voltage Source Inverter VSI	Current Source Inverter CSI
1	VSI is a converter which converts fixed DC voltage into variable AC voltage	CSI is a converter which converts fixed DC current into variable AC current
2		
3	Voltage source is easily available 	Current source has to be obtained by connecting an inductor in series with voltage source 
4	output voltage can be controlled by varying the pulse width of gate pulses.	output voltage depends on load impedance
	output current depends on load impedance	output current can be controlled by varying the input current

Basic Series Inverter



* Initially T_1 and T_2 are off.
 * when T_1 is ON, current path is

$I_o : V_s \rightarrow T_1 \rightarrow L \rightarrow C \rightarrow R \rightarrow V_s$
 capacitor charges

circuit will be in underdamped condition.
 Hence, T_1 will be turned off automatically, when I_o becomes zero.

* when T_2 is ON, current path is

$I_o : C \rightarrow L \rightarrow T_2 \rightarrow R \rightarrow C$
 capacitor discharges.

T_1 will be turned off automatically, when I_o becomes zero.

* The commutating component "Capacitor (C)" is in series with load. Hence, this inverter is called as Series Inverter.

* Series Inverter can work at high frequencies.

* Series Inverters are used in Induction heating.

* The disadvantage (or) limitation of Series Inverter
 • Output waveform has more distortion, more ripples, poor regulation.

Problem: calculate the output frequency of a basic series inverter with the following parameters: $L = 10\text{mH}$, $C = 0.4\mu\text{F}$, $R = 300\Omega$, $T_{off} = 0.2\text{ms} = 0.2 \times 10^{-3}\text{sec}$

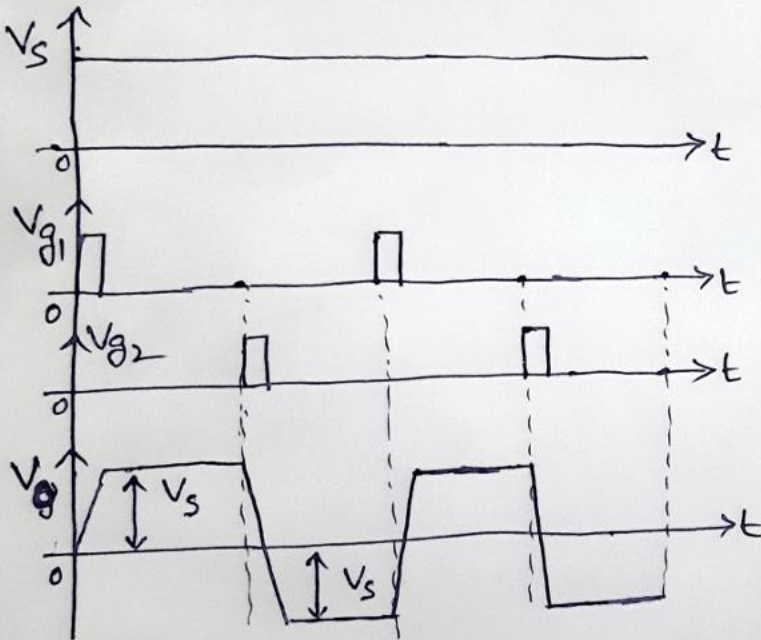
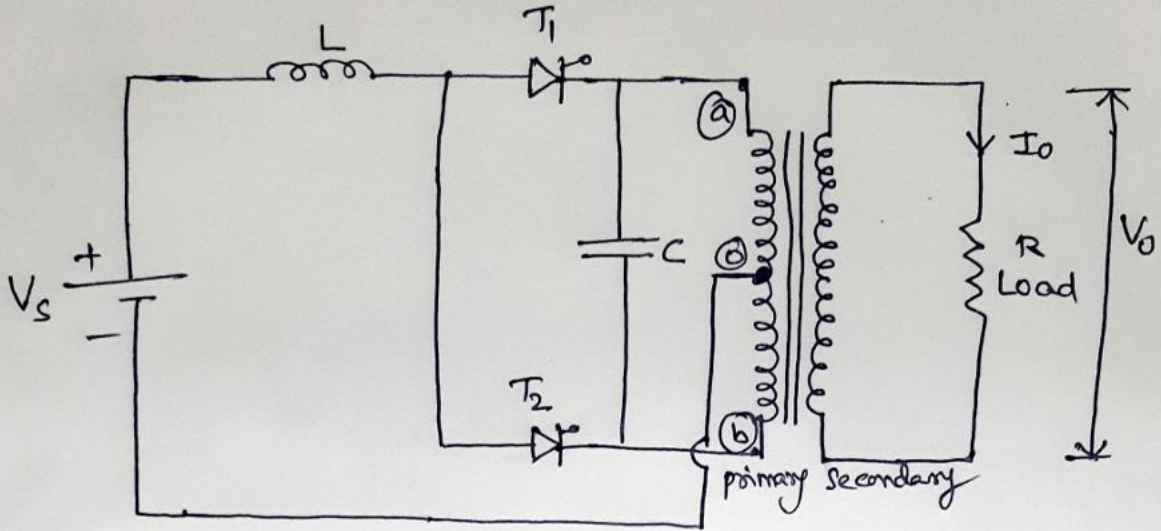
Solution: frequency = $f = \frac{1}{2(T_{on} + T_{off})}$

$$\text{where } T_{on} = \frac{\pi}{\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}}$$

$$= \frac{3.14}{\sqrt{\frac{1}{10 \times 10^{-3} \times 0.4 \times 10^{-6}} - \left(\frac{300}{2 \times 10 \times 10^{-3}}\right)^2}} = 0.628 \times 10^{-3}\text{sec}$$

$$\therefore f = \frac{1}{2(0.628 \times 10^{-3} + 0.2 \times 10^{-3})} = \underline{\underline{737\text{Hz}}}$$

Parallel Inverter

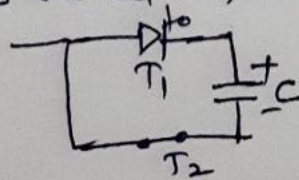


The commutating component "capacitor (C)" is in parallel with load. Hence, this Inverter is called as parallel Inverter.

- * Initially T_1 and T_2 are in off condition.
- * when T_1 is turned ON, the current path is

$V_s \rightarrow L \rightarrow T_1 \rightarrow \textcircled{a} \rightarrow \textcircled{b} \rightarrow V_s$
 capacitor charges $\begin{matrix} + \\ | \\ - \end{matrix}$ This voltage appears across load. (positive voltage)

- * when T_2 is turned ON, the capacitor voltage appears across T_1 .



This capacitor voltage appears as reverse voltage to T_1 . Hence, T_1 will be off.

Then, ~~the~~ the current path is $V_s \rightarrow L \rightarrow T_2 \rightarrow \textcircled{b} \rightarrow \textcircled{a} \rightarrow V_s$.
 capacitor charges $\begin{matrix} - \\ | \\ + \end{matrix}$ This voltage appears across load. (negative voltage)

Power Electronics

Unit-5

(1 \emptyset AC Voltage Controller & 1 \emptyset Cyclo Converter)

Unit-5 Chapter-1

1 \emptyset AC Voltage Controller

(Fixed AC Voltage to Variable AC Voltage with Constant Frequency)

1. Introduction
2. 1 \emptyset AC Voltage Controller with Resistive Load (R Load)
(or) Principle of Phase Control in 1 \emptyset AC Voltage Controller
3. 1 \emptyset AC Voltage Controller with Inductive Load (RL Load)
4. Power Factor in 1 \emptyset AC Voltage Controller
5. 1 \emptyset AC Voltage Controller using TRIAC
6. Integral Cycle Control (or) ON – OFF Control in 1 \emptyset AC Voltage Controller

Introduction of AC Voltage Controller

Definition of AC Voltage Controller: AC Voltage Controller is a Power Electronics Converter which converts fixed AC Voltage to Variable AC Voltage with constant frequency.

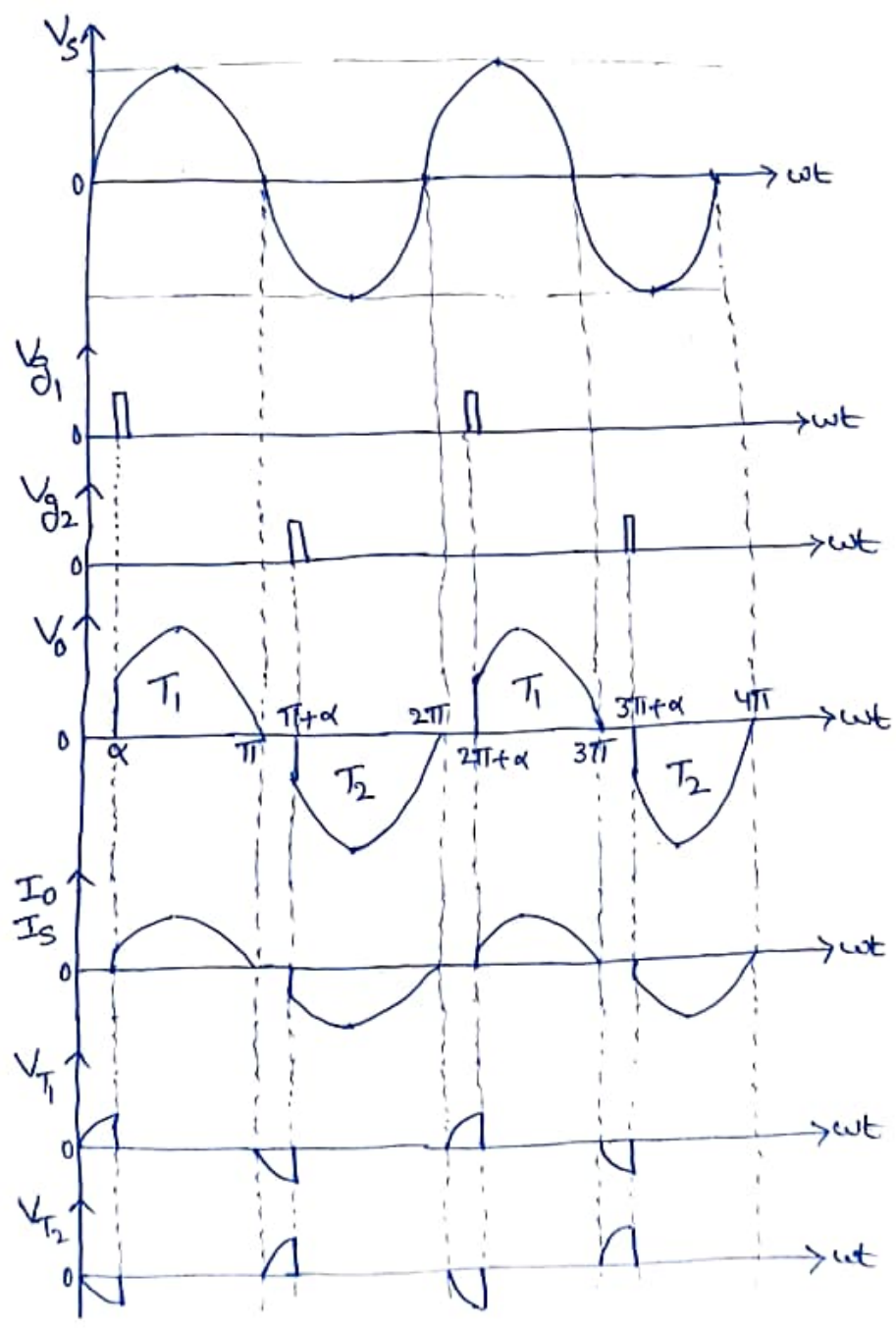
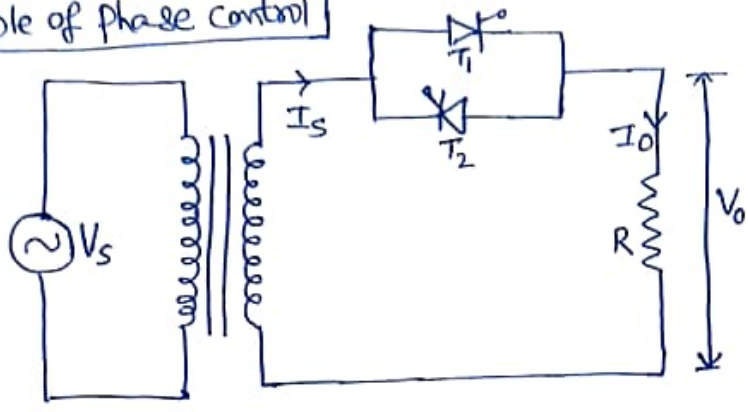
Applications of AC Voltage Controllers: Speed control of AC Motors, Starting of Induction Motors, Lighting Control (controlling the lighting of Bulbs in theaters, auditoriums, homes etc.), Transformer Tap changing, Domestic and Industrial Electric Heating (Ovens, Heaters etc.) etc.

Classification of AC Voltage Controllers:

- * 1 \emptyset AC Voltage Controller
- * 3 \emptyset AC Voltage Controller

1 ϕ AC Voltage controller with R load

Principle of phase control



Derivation

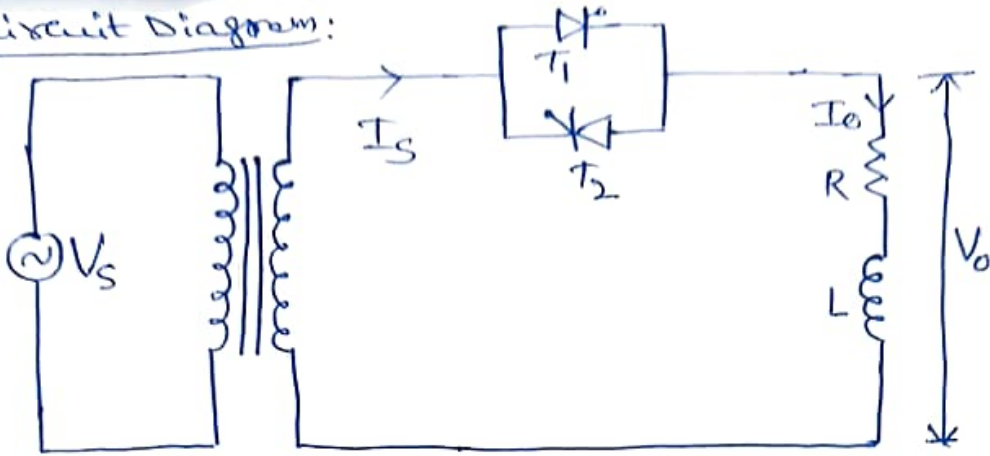
$$\begin{aligned}V_o(\text{rms}) &= \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} V_s^2 \cdot d(\omega t)} \\&= \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} (V_m \sin \omega t)^2 \cdot d(\omega t)} \\&= \sqrt{\frac{1}{\pi} \int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \cdot d(\omega t)} \\&= \sqrt{\frac{V_m^2}{\pi} \int_{\alpha}^{\pi} \sin^2 \omega t \cdot d(\omega t)} \\&= \sqrt{\frac{V_m^2}{\pi} \int_{\alpha}^{\pi} \frac{1 - \cos 2\omega t}{2} \cdot d(\omega t)} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[\int_{\alpha}^{\pi} 1 \cdot d(\omega t) - \int_{\alpha}^{\pi} \cos 2\omega t \cdot d(\omega t) \right]} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[(\omega t)_{\alpha}^{\pi} - \left(\frac{\sin 2\omega t}{2} \right)_{\alpha}^{\pi} \right]} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[(\pi - \alpha) - \left(\frac{\sin 2\pi}{2} - \frac{\sin 2\alpha}{2} \right) \right]} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]}\end{aligned}$$

$$\therefore V_o(\text{rms}) = \frac{V_m}{\sqrt{2}} * \sqrt{\frac{1}{\pi} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]}$$

$$I_o(\text{rms}) = \frac{V_o(\text{rms})}{R}$$

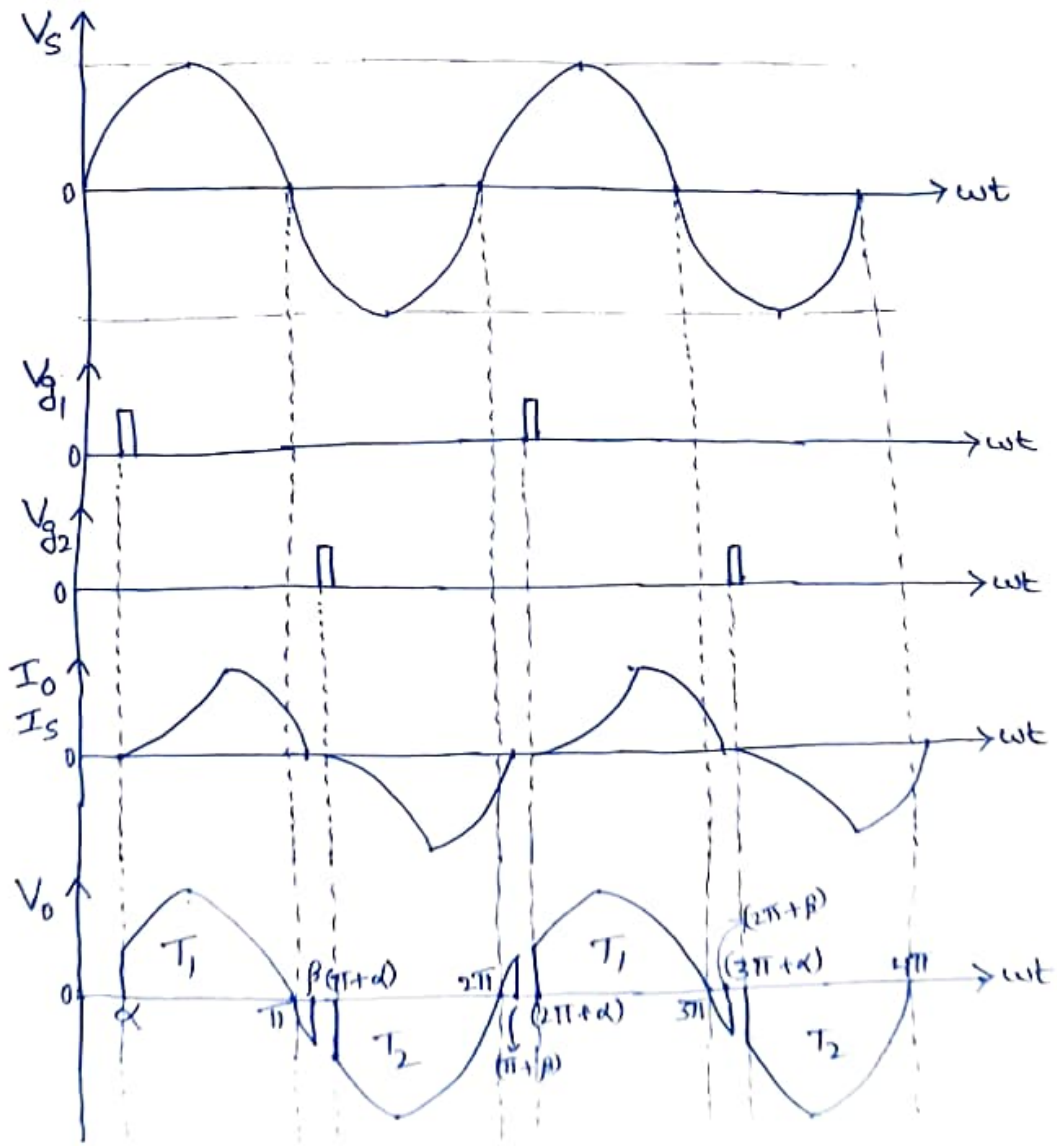
1 ϕ AC Voltage Controller with RL load

Circuit Diagram:



Waveforms

Discontinuous conduction mode:



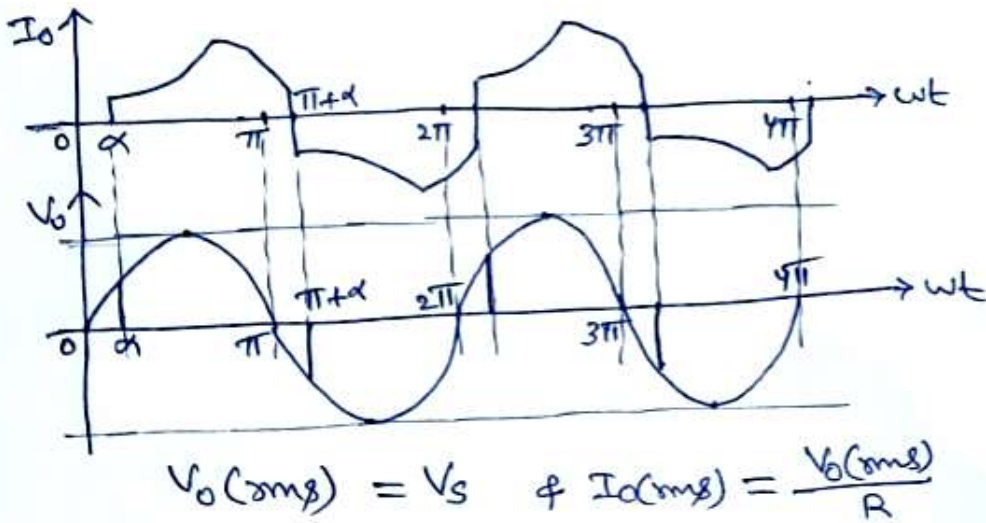
Derivation:

$$\begin{aligned}V_o(\text{rms}) &= \sqrt{\frac{1}{\pi} \int_{\alpha}^{\beta} V_s^2 \cdot d(\omega t)} \\&= \sqrt{\frac{1}{\pi} \int_{\alpha}^{\beta} (V_m \sin \omega t)^2 \cdot d(\omega t)} \\&= \sqrt{\frac{1}{\pi} \int_{\alpha}^{\beta} V_m^2 \sin^2 \omega t \cdot d(\omega t)} \\&= \sqrt{\frac{V_m^2}{\pi} \int_{\alpha}^{\beta} \sin^2 \omega t \cdot d(\omega t)} \\&= \sqrt{\frac{V_m^2}{\pi} \int_{\alpha}^{\beta} \frac{1 - \cos 2\omega t}{2} \cdot d(\omega t)} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[\int_{\alpha}^{\beta} 1 \cdot d(\omega t) - \int_{\alpha}^{\beta} \cos 2\omega t \cdot d(\omega t) \right]} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[(\omega t) \Big|_{\alpha}^{\beta} - \left(\frac{\sin 2\omega t}{2} \right) \Big|_{\alpha}^{\beta} \right]} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[(\beta - \alpha) - \left(\frac{\sin 2\beta}{2} - \frac{\sin 2\alpha}{2} \right) \right]} \\&= \sqrt{\frac{V_m^2}{2\pi} \left[(\beta - \alpha) + \frac{1}{2} (\sin 2\alpha - \sin 2\beta) \right]}\end{aligned}$$

$$\therefore V_o(\text{rms}) = \frac{V_m}{\sqrt{2}} * \sqrt{\frac{1}{\pi} \left[(\beta - \alpha) + \frac{1}{2} (\sin 2\alpha - \sin 2\beta) \right]}$$

$$I_o(\text{rms}) = \frac{V_o(\text{rms})}{R}$$

Continuous conduction mode



Power factor of 1 ϕ AC voltage controller :

Power factor is defined as the ratio of Real Power to Apparent power of 1 ϕ AC voltage controller.

$$\therefore \text{power factor} = \text{PF} = \frac{\text{Real Power}}{\text{Apparent Power}}$$

For ideal condition in AC voltage controller,
Input power = output power

$$V_s I_s \cos \theta_s = V_o(\text{rms}) I_o(\text{rms}) \cos \theta_o$$

Here, $I_s = I_o(\text{rms})$ & $\cos \theta_o = 1$ for R-load

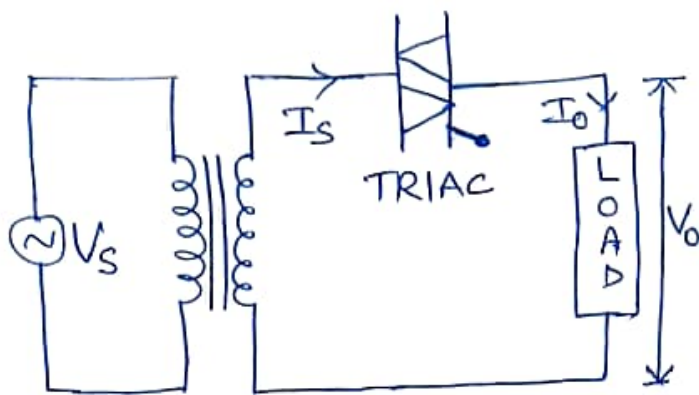
$$\therefore V_s \cos \theta_s = V_o(\text{rms})$$

$$\therefore \cos \theta_s = \frac{V_o(\text{rms})}{V_s} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{1}{\pi} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]} \div V_s$$

We know that $V_s = \frac{V_m}{\sqrt{2}}$

$$\therefore \text{Power factor} = \cos \theta_s = \sqrt{\frac{1}{\pi} \left[(\pi - \alpha) + \frac{1}{2} \sin 2\alpha \right]}$$

1 ϕ AC Voltage controller using TRIAC :



TRIAC is a switching device which is similar to two SCRs connected in Anti-parallel.

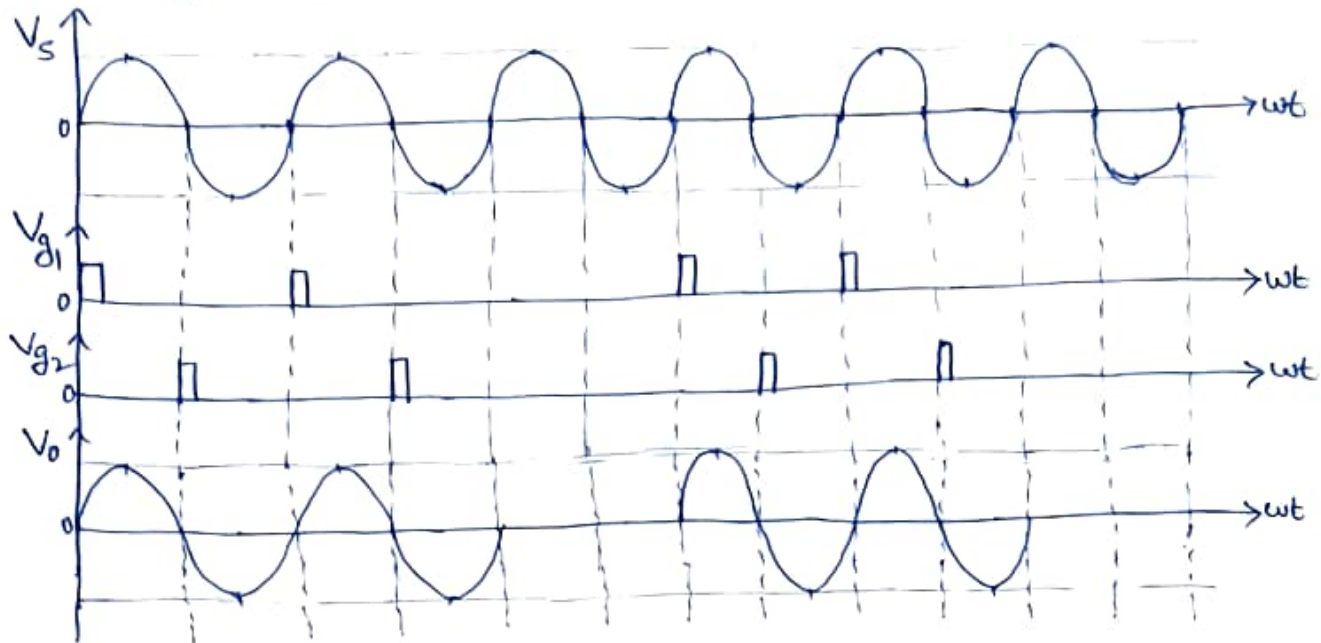
* Waveforms for 1 ϕ AC voltage controller using TRIAC are exactly same as 1 ϕ Full wave AC voltage controller using two Antiparallel SCRs.

Comparison between TRIAC based 1 ϕ AC voltage controller & Two Anti-Parallel SCRs based 1 ϕ AC voltage controller

Sl. No.	TRIAC based 1 ϕ AC voltage controller	Two Anti-parallel SCRs based 1 ϕ AC voltage controller
1	Only one switching device (TRIAC) is required	Two switching devices (SCRs) are required
2	Cost is less	Cost is more
3	One Heat sink is required	Two heat sinks are required
4	Size is less	Size is more
5	If TRIAC is damaged, then output will not come	If one SCR is damaged, then output will come with one SCR atleast.

Integral cycle control (or) ON-OFF control

In this method, the load will be connected to the source for some ON-cycles (n) and the load will be disconnected to the source for some off-cycles (m). Here, n & m are also called as integral cycles.



Integral cycle control is also called as on-off control, burst firing control, zero-voltage switching control, cycle selection control, cycle synchopation control.

In the above waveforms,

$$n = \text{no. of ON-cycles} = 2$$

$$m = \text{no. of off-cycles} = 1$$

$$V_o(\text{rms}) = \sqrt{\frac{n}{2\pi(n+m)} \int_0^{2\pi} V_s^2 \cdot d(\omega t)}$$

$$\begin{aligned} \therefore V_o(\text{rms}) &= \sqrt{\frac{n}{2\pi(n+m)} \int_0^{2\pi} (V_m \sin \omega t)^2 \cdot d(\omega t)} \\ &= \sqrt{\frac{n \cdot V_m^2}{2\pi(n+m)} \int_0^{2\pi} \sin^2 \omega t} \end{aligned}$$

$$\begin{aligned}
\therefore V_o(\text{avg}) &= \sqrt{\frac{n \cdot V_m^2}{2\pi(n+m)} \cdot \int_0^{2\pi} \frac{1 - \cos 2\omega t}{2} \cdot d(\omega t)} \\
&= \sqrt{\frac{n \cdot V_m^2}{4\pi(n+m)} \left[\int_0^{2\pi} 1 \cdot d(\omega t) - \int_0^{2\pi} \cos 2\omega t \cdot d(\omega t) \right]} \\
&= \sqrt{\frac{n \cdot V_m^2}{4\pi(n+m)} \cdot \left[(2\pi - 0) - \left(\frac{\sin 2\omega t}{2} \right) \Big|_0^{2\pi} \right]} \\
&= \sqrt{\frac{n \cdot V_m^2}{4\pi(n+m)} \cdot \left[(2\pi - 0) - \left(\frac{\sin 4\pi}{2} - \frac{\sin(0)}{2} \right) \right]} \\
&= \sqrt{\frac{n \cdot V_m^2}{4\pi(n+m)} * 2\pi} \\
&= \sqrt{\frac{n \cdot V_m^2}{2(n+m)}}
\end{aligned}$$

$$\therefore V_o(\text{rms}) = \frac{V_m}{\sqrt{2}} \cdot \sqrt{\frac{n}{n+m}} = V_s \cdot \sqrt{K}$$

where, $V_s = \frac{V_m}{\sqrt{2}}$ & $K = \frac{n}{n+m}$

$$\therefore \boxed{V_o(\text{rms}) = V_s \cdot \sqrt{K}}$$

$$I_o(\text{rms}) = \frac{V_o(\text{rms})}{R}, \quad P_o = \frac{V_o(\text{rms})^2}{R}$$

Power factor = \sqrt{K}

Average value of Thyristor current = $I_T(\text{avg}) = \frac{K \cdot I_m}{\pi}$

RMS Value of Thyristor current = $I_T(\text{rms}) = \frac{\sqrt{K} \cdot I_m}{2}$

Power Electronics

Unit-5

(1 \emptyset AC Voltage Controller & 1 \emptyset Cyclo Converter)

Unit-5 Chapter-2

1 \emptyset Cyclo Converter

(Fixed AC Voltage and Frequency to Variable AC Voltage and Frequency)

1. Introduction
2. 1 \emptyset Mid Point Type Step Down Cyclo Converter with Resistive Load (R Load)
3. 1 \emptyset Mid Point Type Step Down Cyclo Converter with Inductive Load (RL Load)
4. 1 \emptyset Bridge Type Step Down Cyclo Converter with Resistive Load (R Load)
5. 1 \emptyset Bridge Type Step Down Cyclo Converter with Inductive Load (RL Load)
6. 1 \emptyset Mid Point Type Step Up Cyclo Converter (same for R Load and RL Load)
7. 1 \emptyset Bridge Type Step Up Cyclo Converter (same for R Load and RL Load)

Introduction of Cyclo Converter

Definition of Cyclo Converter: Cyclo Converter is a Power Electronics Converter which converts fixed AC Voltage and Frequency to Variable AC Voltage and Frequency.

Applications of Cyclo Converters: Speed control of AC Motors, Washing Machines, Water Pumps, Industrial Applications (Cement Mills, Rolling Mills, Grinding Mills etc), Speed Control of Propulsion Motors in Ships etc.

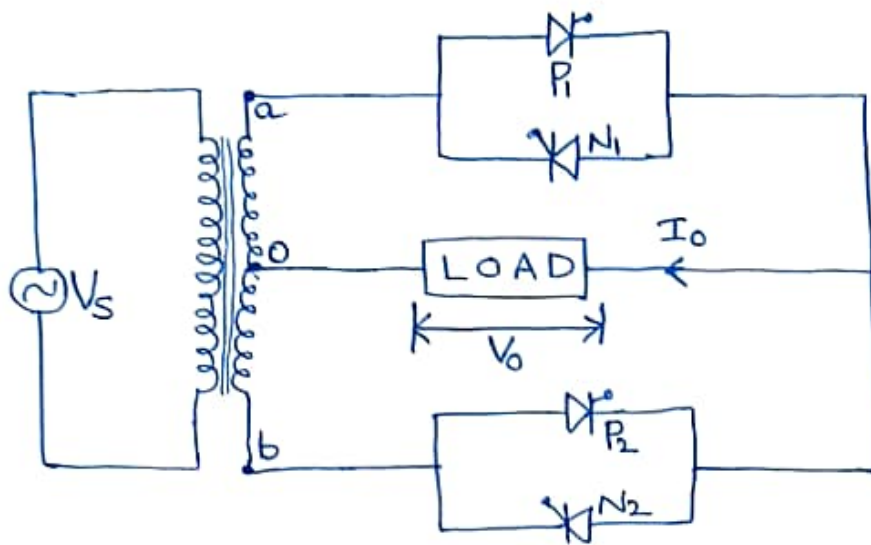
Classification of Cyclo Converters:

Classification1 ==> 1 \emptyset Cyclo Converter, 3 \emptyset Cyclo Converter

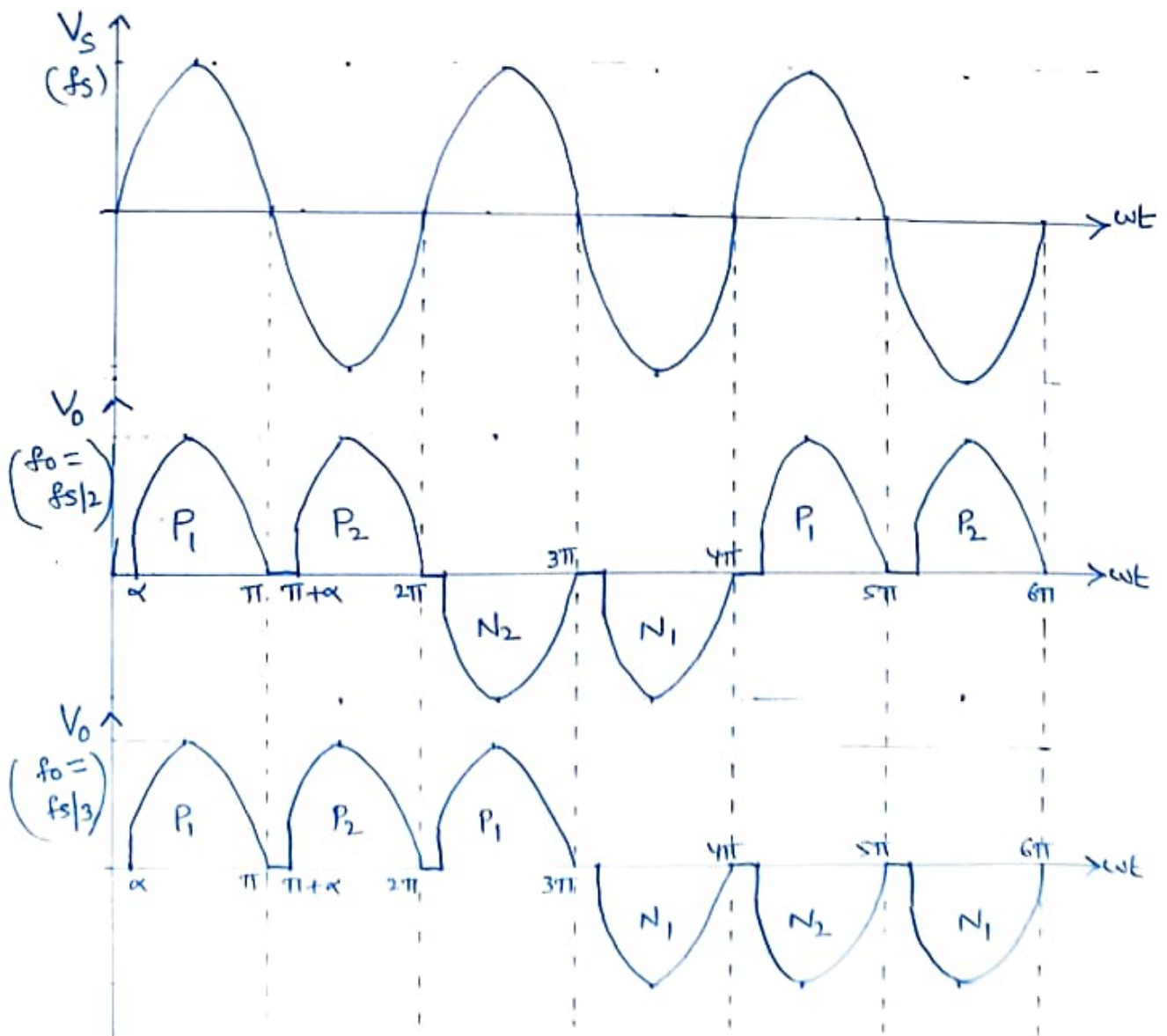
Classification2 ==> Mid Point Type Cyclo Converter, Bridge Type Cyclo Converter

Classification3 ==> Step Down Cyclo Converter, Step Up Cyclo Converter

1 ϕ Mid Point Type Step Down Cycloconverter:

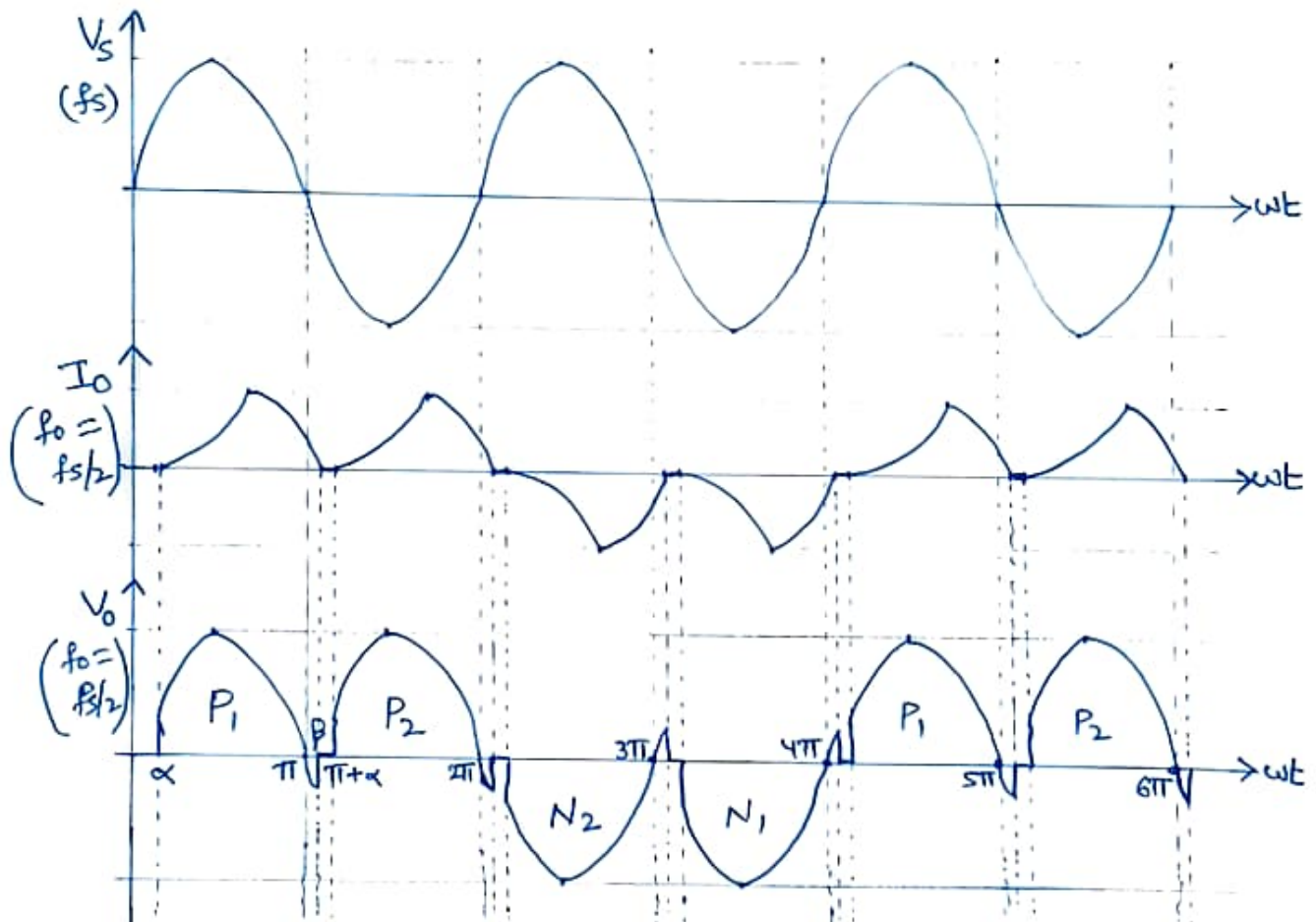


(a) Resistive Load (R-Load):

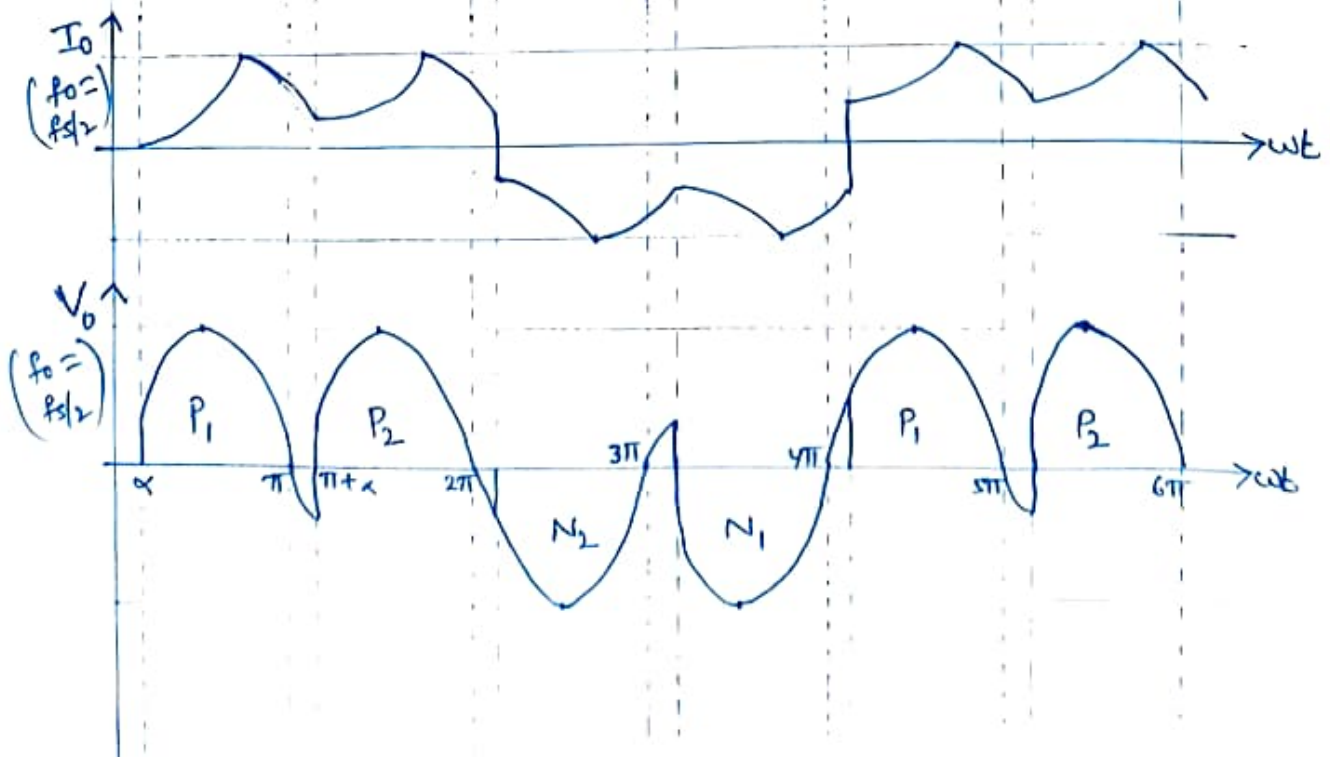


(b) Inductive Load [RL Load] :

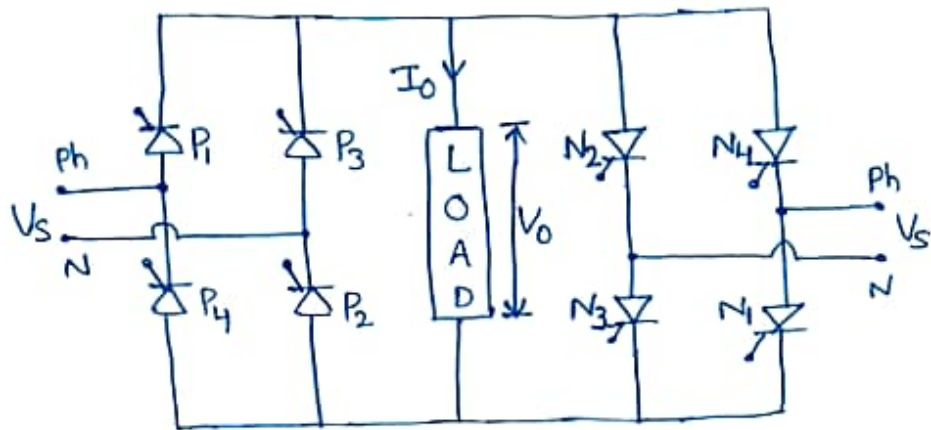
(i) Discontinuous conduction :



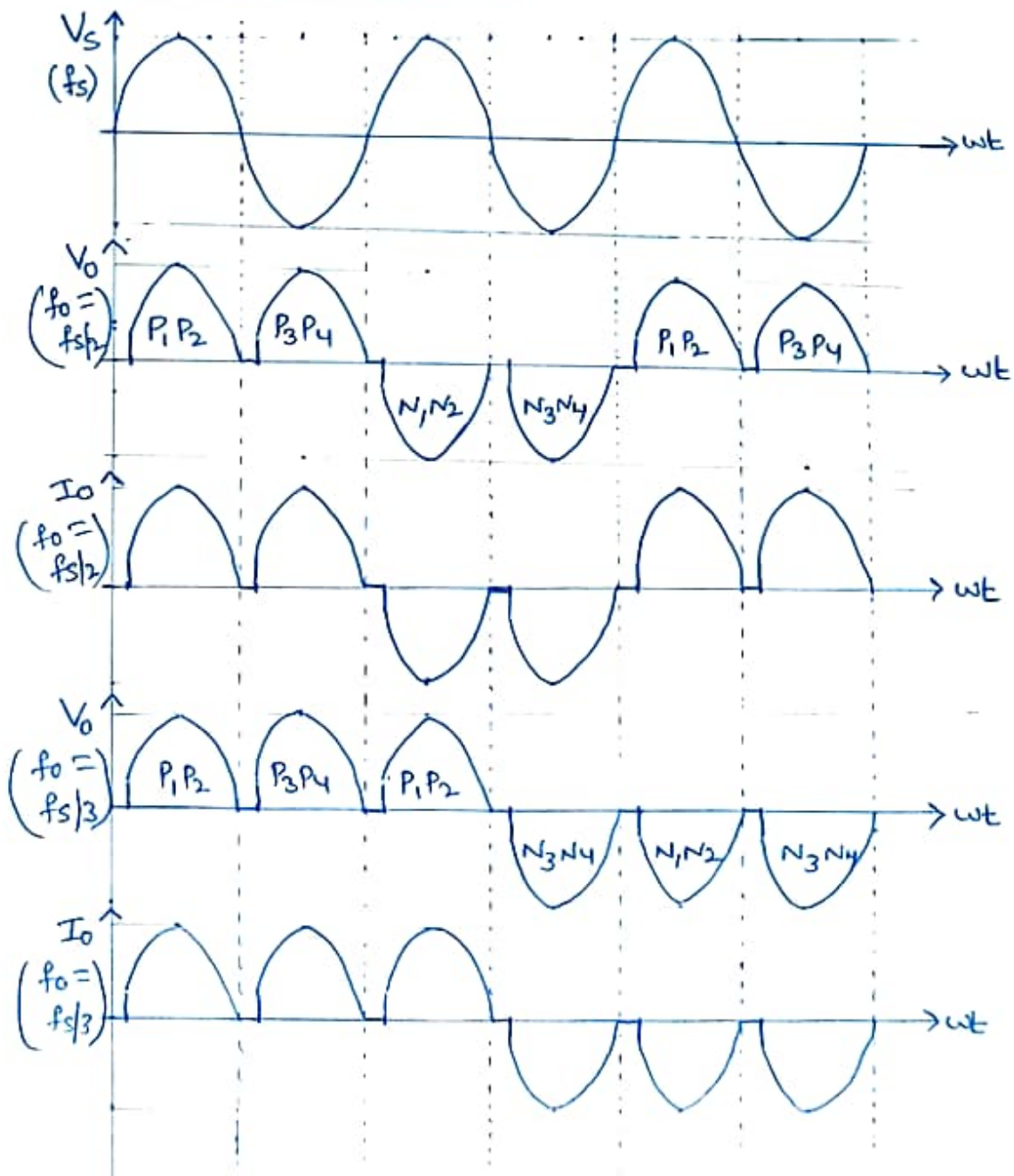
(ii) Continuous conduction :



1 ϕ Bridge Type Step Down Cycloconverter :

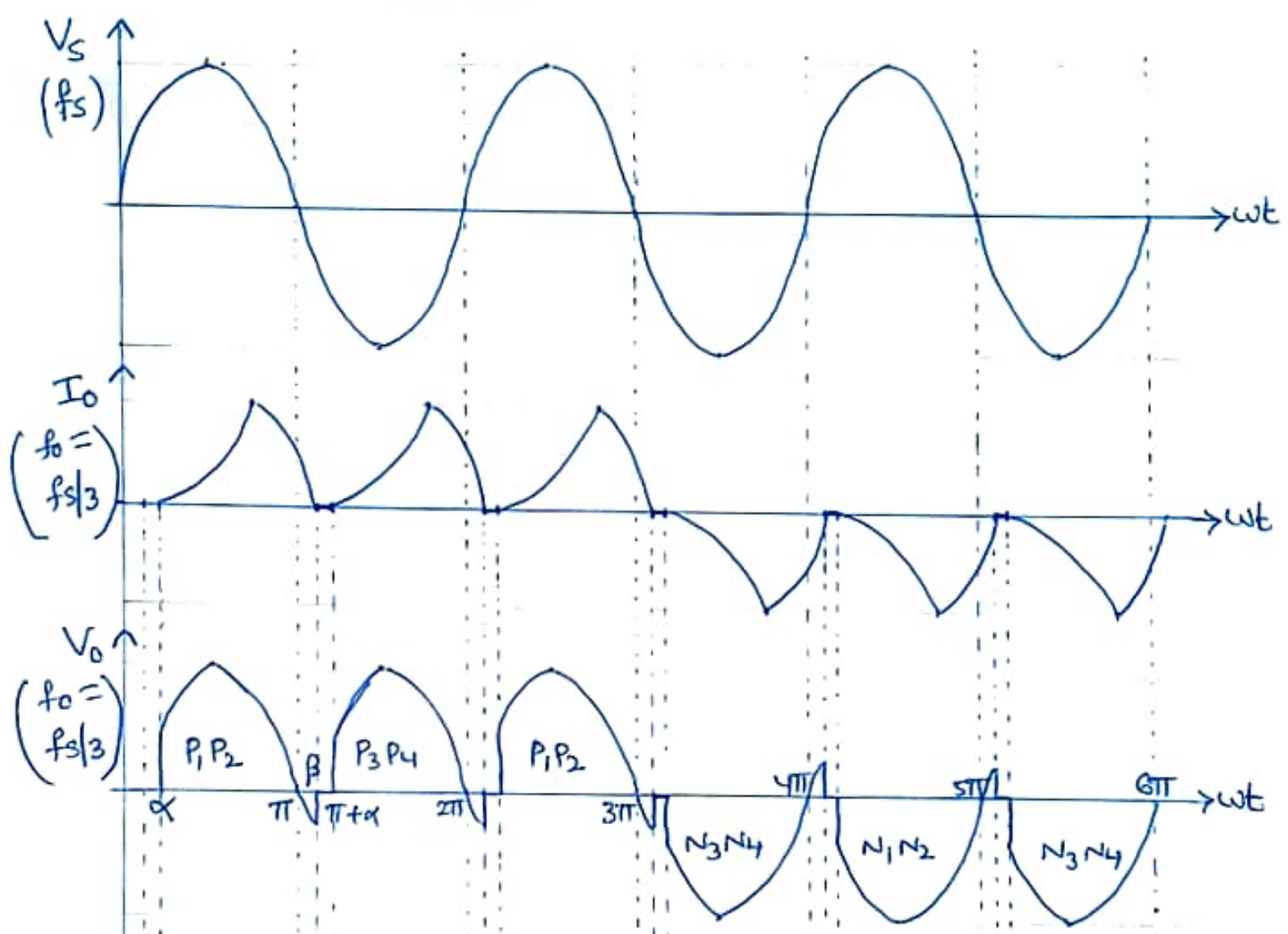


(a) Resistive Load (R-Load) :

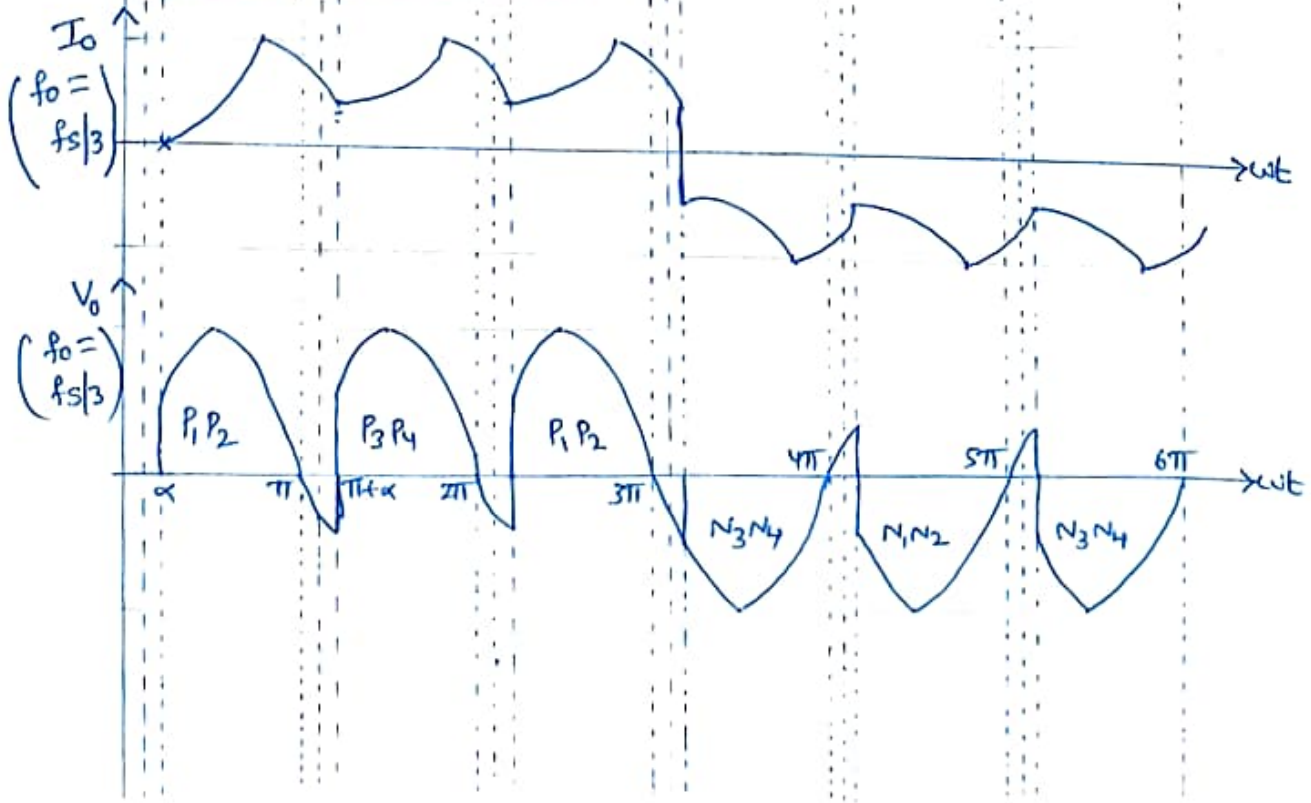


(b) Inductive Load [RL Load] :

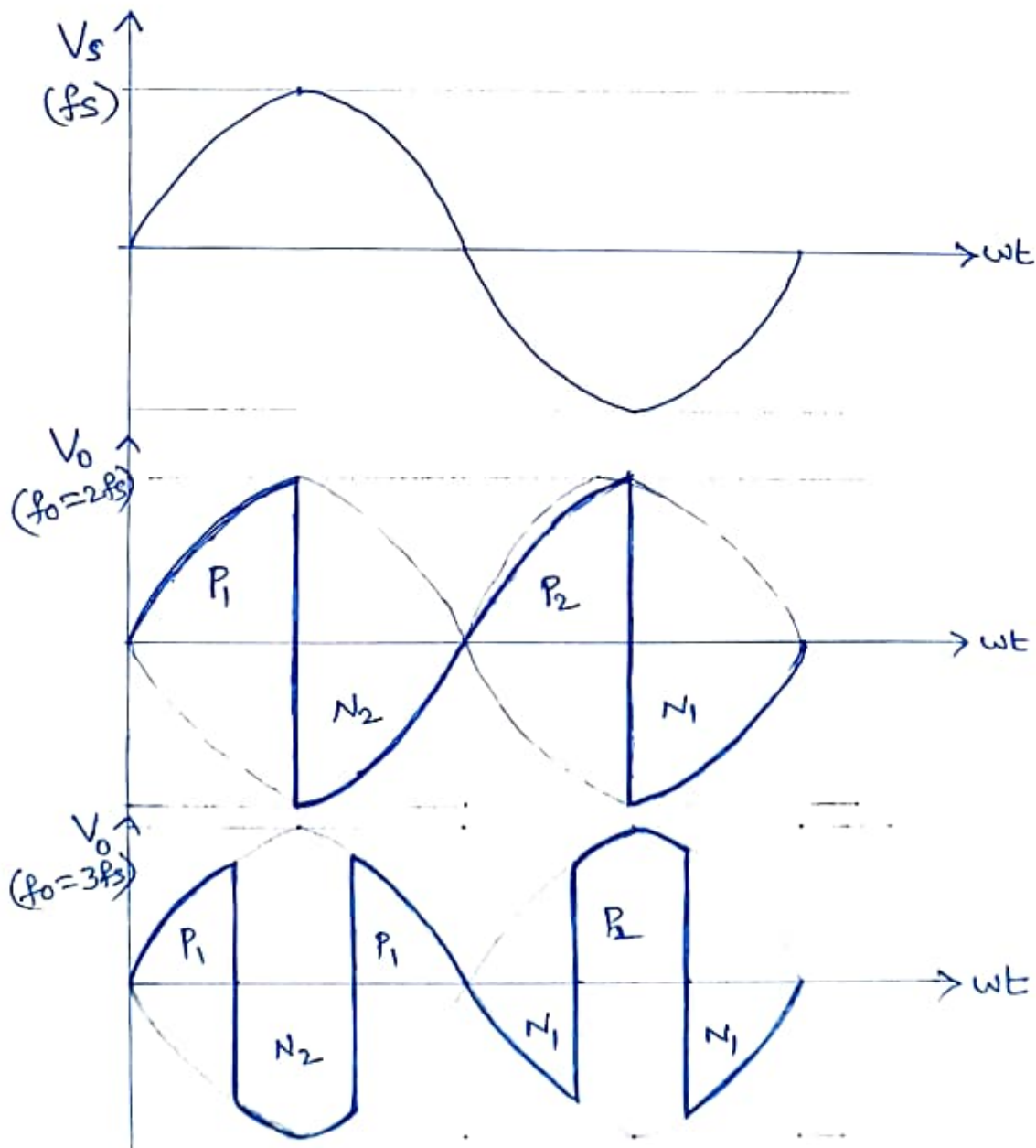
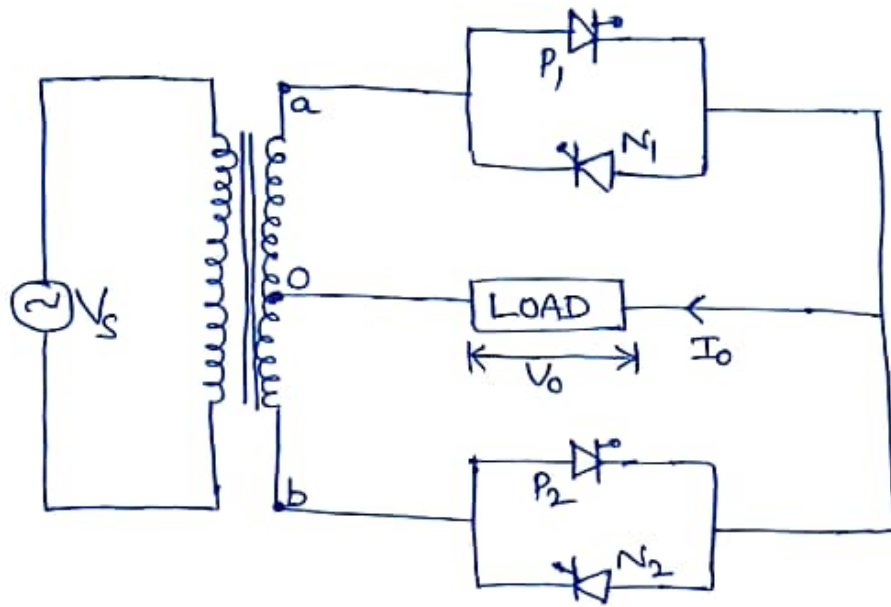
(i) Discontinuous Conduction :



(ii) Continuous Conduction :



1 ϕ Mid Point Type Step Up cycloconverter:



1 ϕ Bridge Type Step Up cycloconverter:

