UNIT I
POWER SEMICONDUCTOR DEVICES

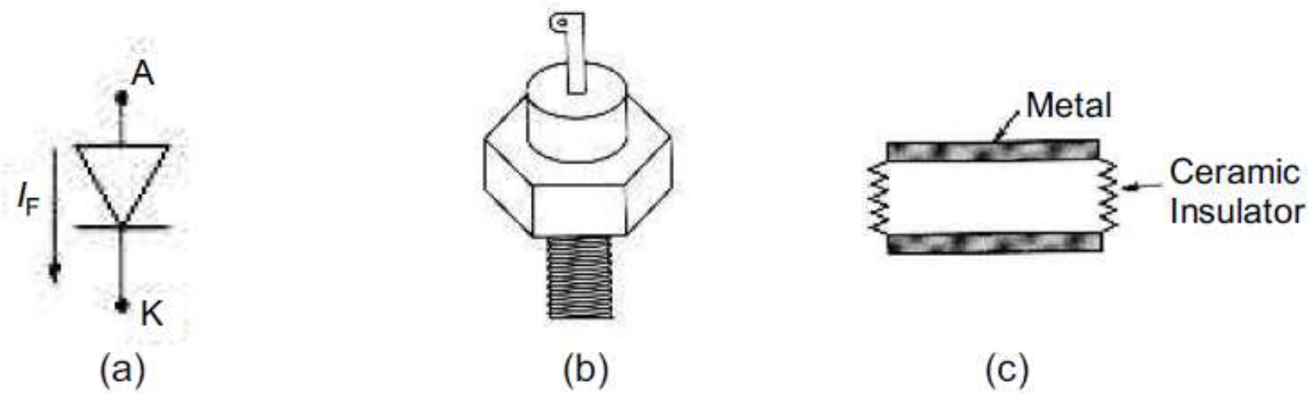
TOPICS COVERED

- SEMICONDUCTOR DEVICES
- CONTROLLED RECTIFIERS
- DC CHOPPERS
- INVERTERS
- AC CHOPPERS

SEMICONDUCTOR DEVICES

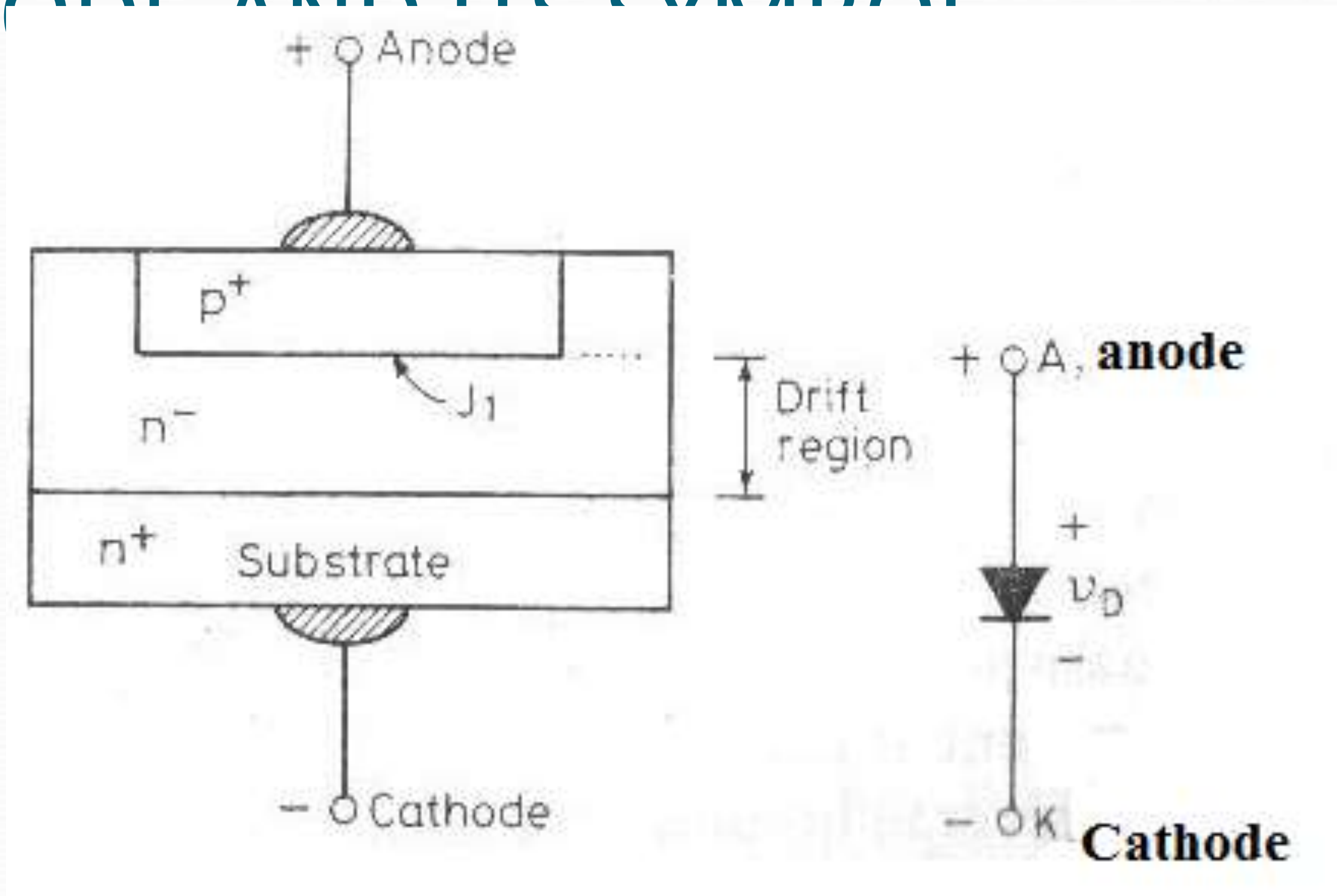
- POWER DIODE
- POWER TRANSISTORS
  - POWER BJT
  - POWER MOSFET
  - IGBT
  - SIT
- THYRISTORS
  - SCR
  - TRIAC
  - GTO
  - SITH
  - MCT

POWER DIODE

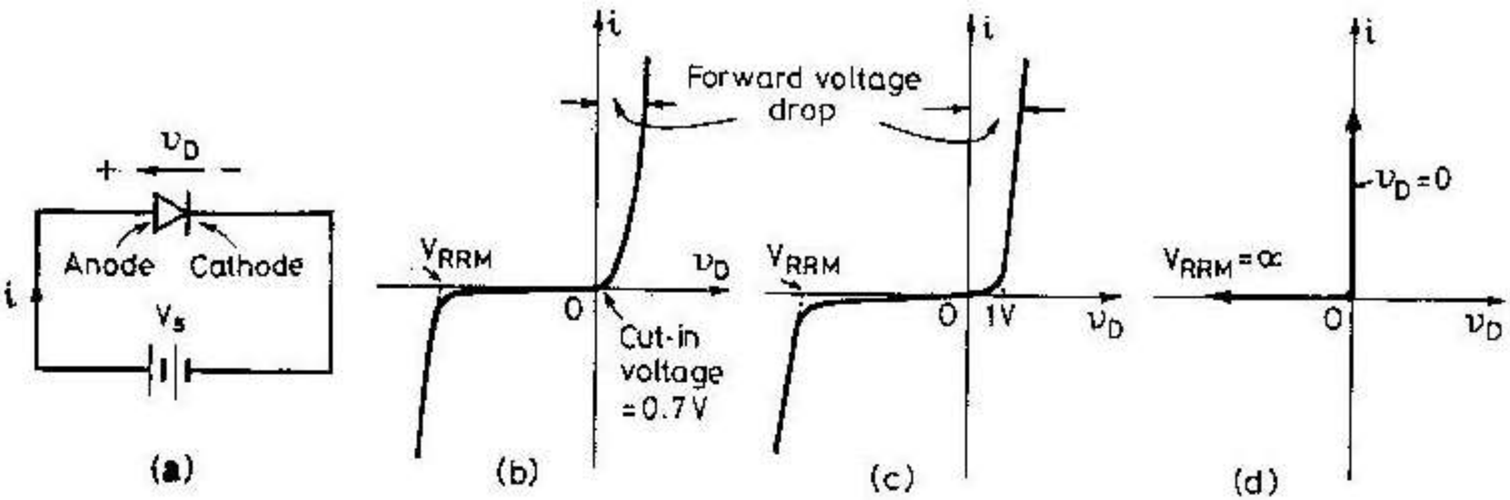


Power diode: (a) symbol; (b) and (c) types of packaging.

STRUCTURAL FEATURES OF POWER DIODE AND ITS SYMBOL



V-I CHARACTERISTICS OF SIGNAL DIODE, POWER DIODE AND IDEAL DIODE



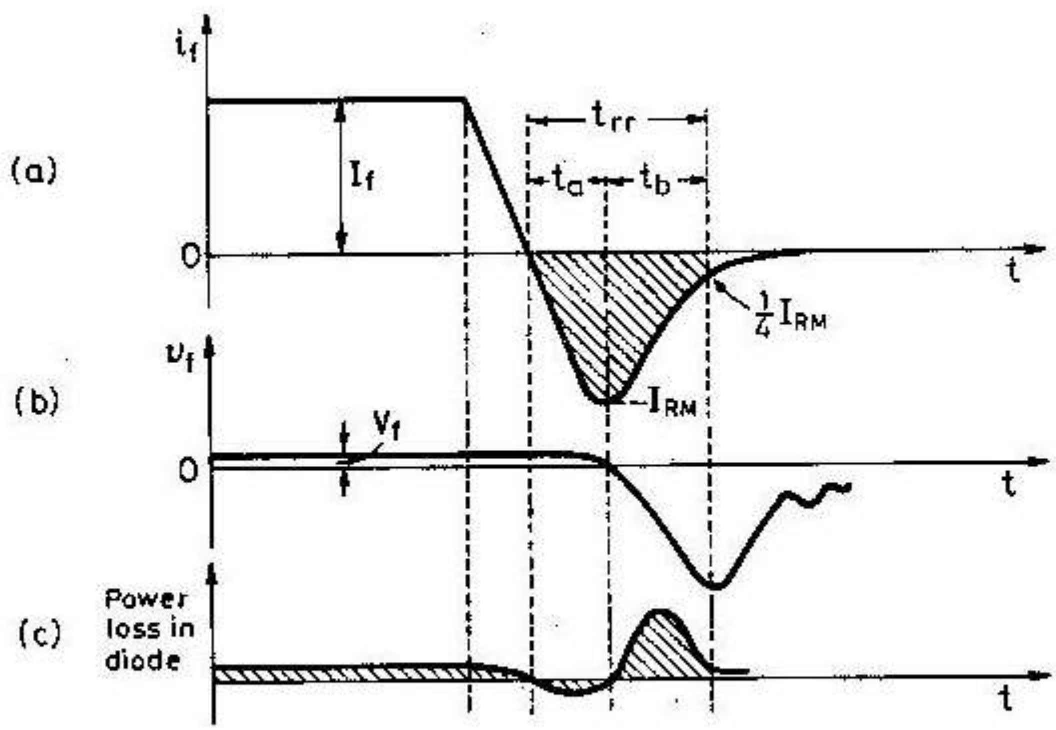
(a) Forward biased Power Diode

(b) V-I Charateristics of Signal Diode

(c) V-I Characteristics of Power Diode

(d)V-I Characteristics of Ideal Diode

REVERSE RECOVERY CHARACTERISTICS



(a)Variation of Forward Current If (b) Forward Voltage DropVf (c) Power loss in the Diode

POWER TRANSISTORS

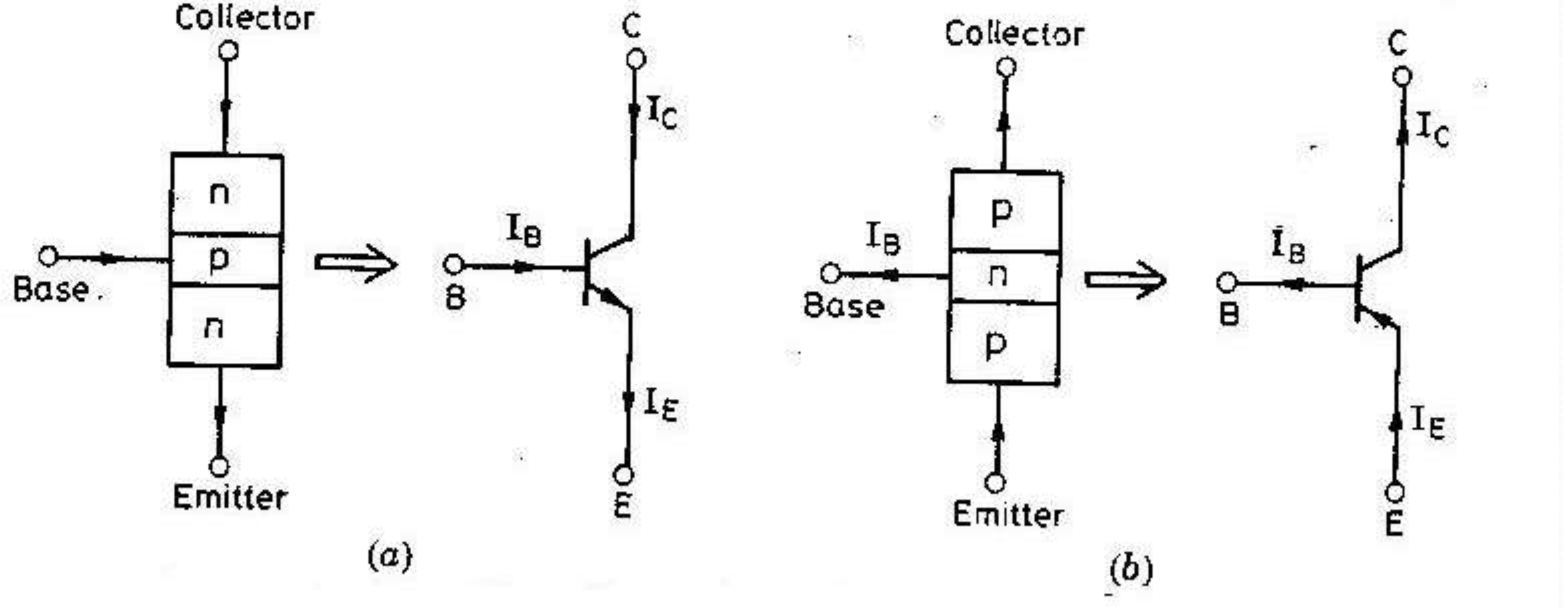
FOUR TYPES

- Bipolar junction Transistor(**BJT**)
- Metal Oxide Semiconductor Field Effect Transistor(**MOSFET**)
- Insulated Gate Bipolar Transistors(**IGBT**) and
- Static Induction Transistor (**SIT**)

POWER BJT

- **Three layer ,Two Junction** npn or pnp type
- **Bipolar** means current flow in the device is due to the movement of BOTH holes and Electrons.

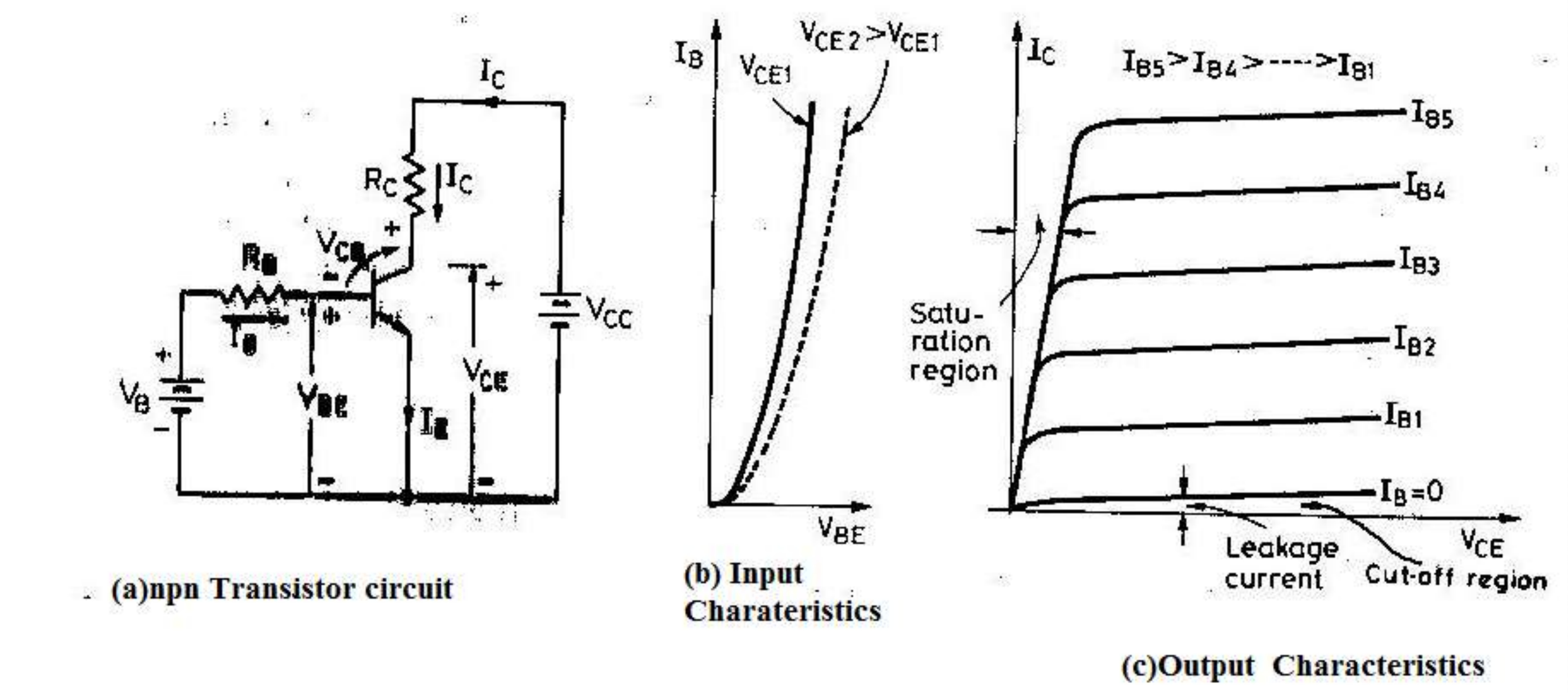
POWER BJT



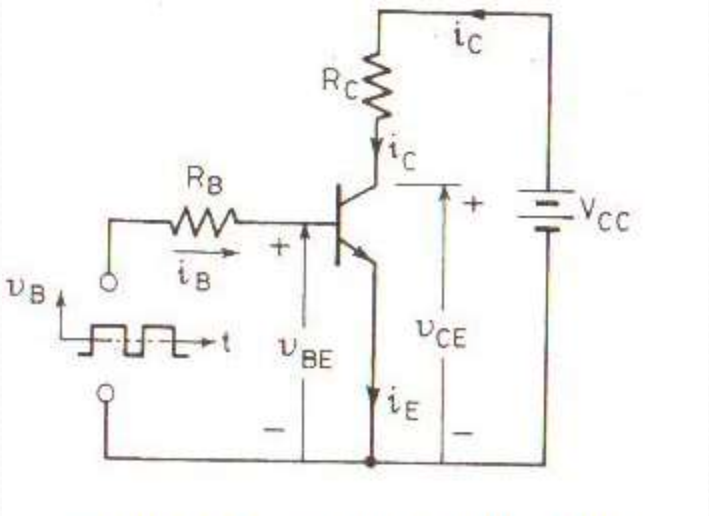
(a) npn type

(b) pnp type

V-I CHARACTERISTICS OF POWER BJT

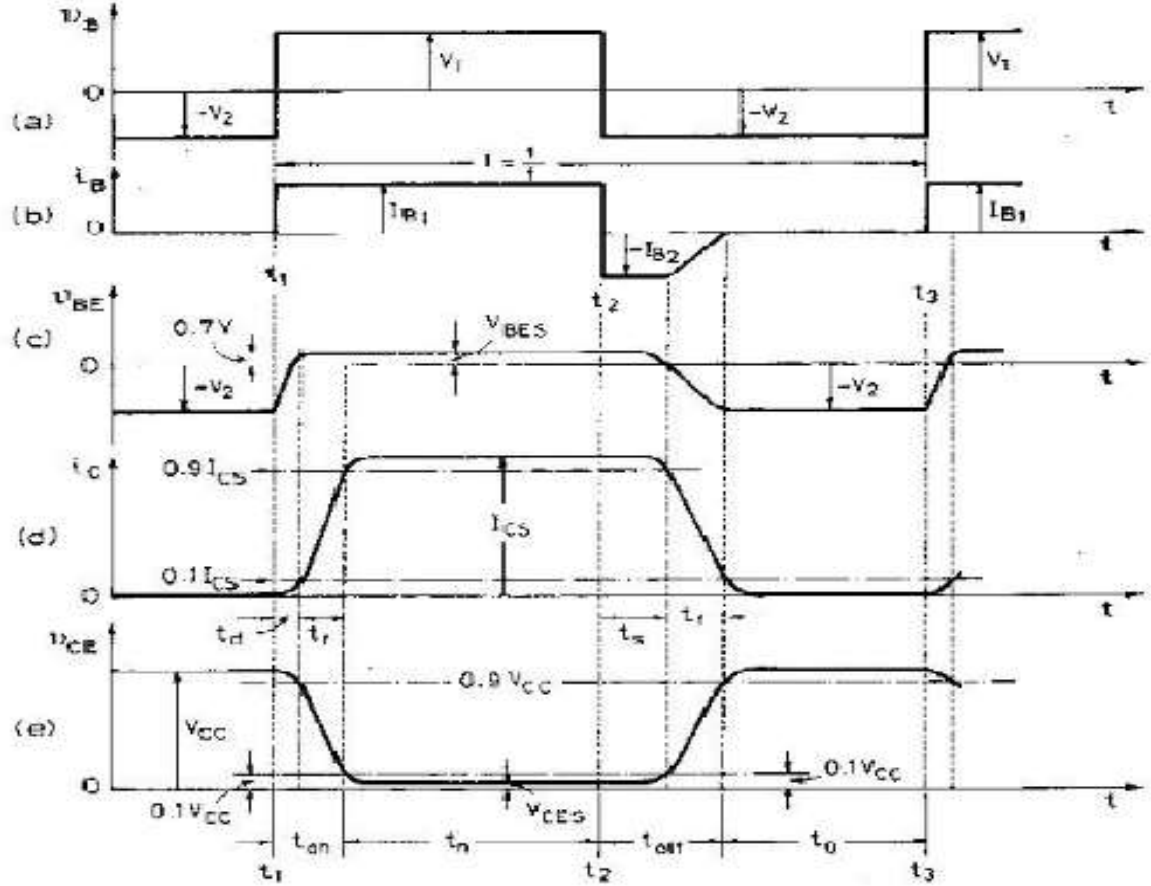


SWITCHING CHARACTERISTICS CIRCUIT FOR BJT



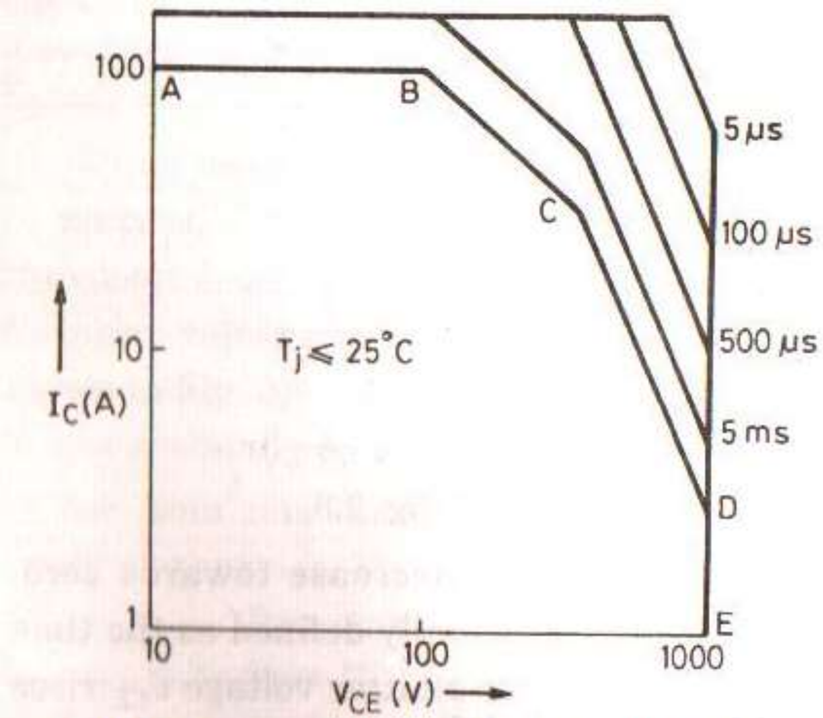
npn transistor with resistive load

SWITCHING CHARACTERISTICS OF POWER BJT

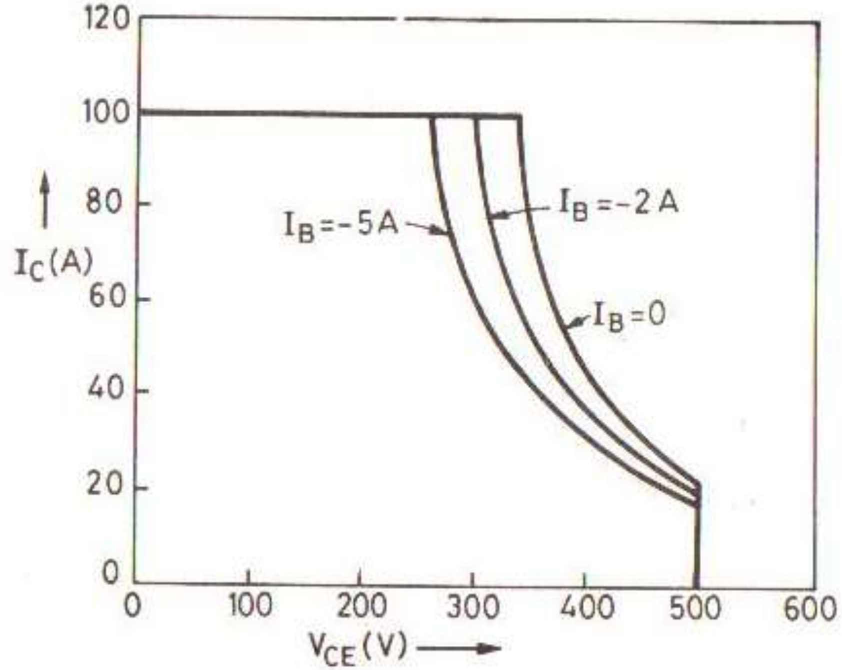


Switching waveforms of Power BJT

SAFE OPERATING AREA FOR POWER BJT

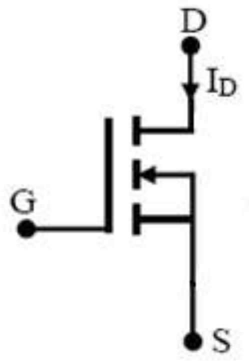


FBSOA-Forward biased Safe Operating Area



RBSOA-Reverse Block Safe Operating Area

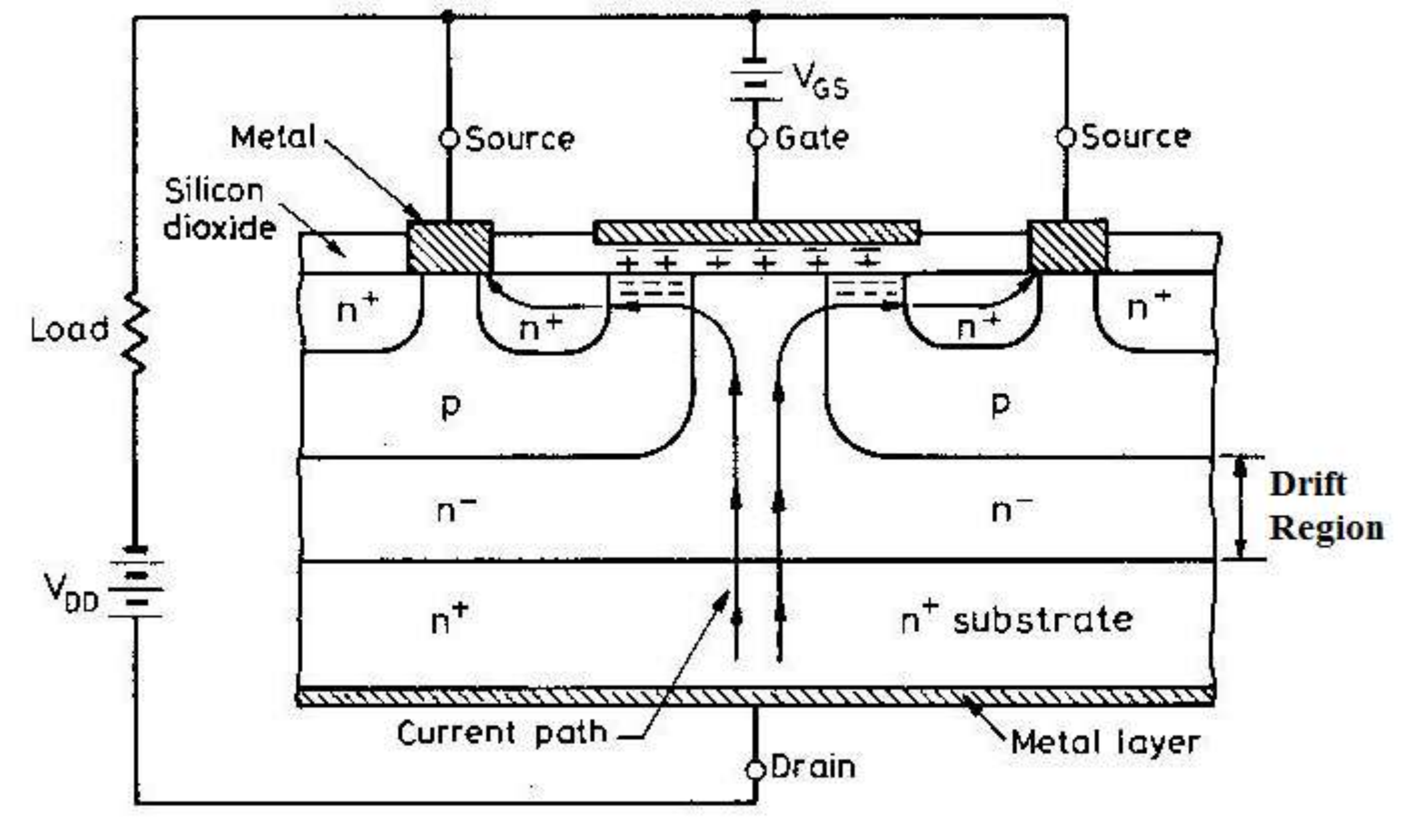
POWER MOSFET



POWER MOSFET

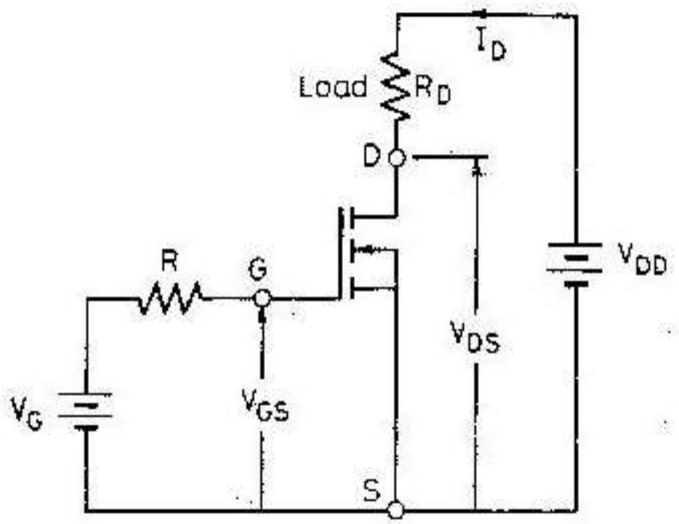
- THREE TERMINALS – DRAIN,SOURCE AND GATE
- VOLTAGE CONTROLLED DEVICE
- GATE CIRCUIT IMPEDANCE IS HIGH (OF THE ORDER OF MEGA OHM).HENCE GATE CAN BE DRIVEN DIRECTLY FROM MICROELECTRONIC CIRCUITS.
- USED IN LOW POWER HIGH FREQUENCY CONVERTERS,SMPS AND INVERTERS

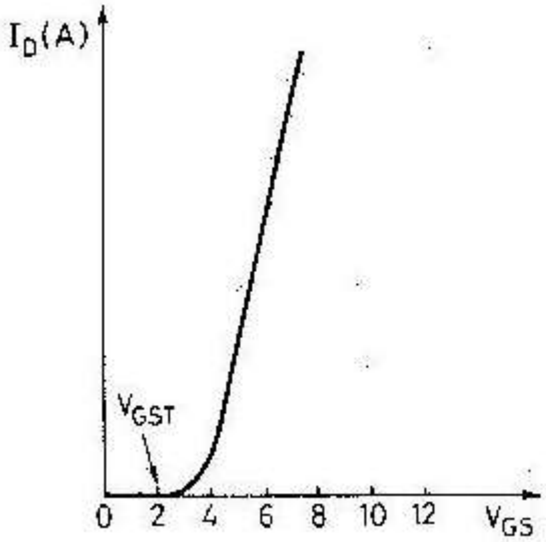
BASIC STRUCTURE OF n-CHANNEL POWER MOSFET



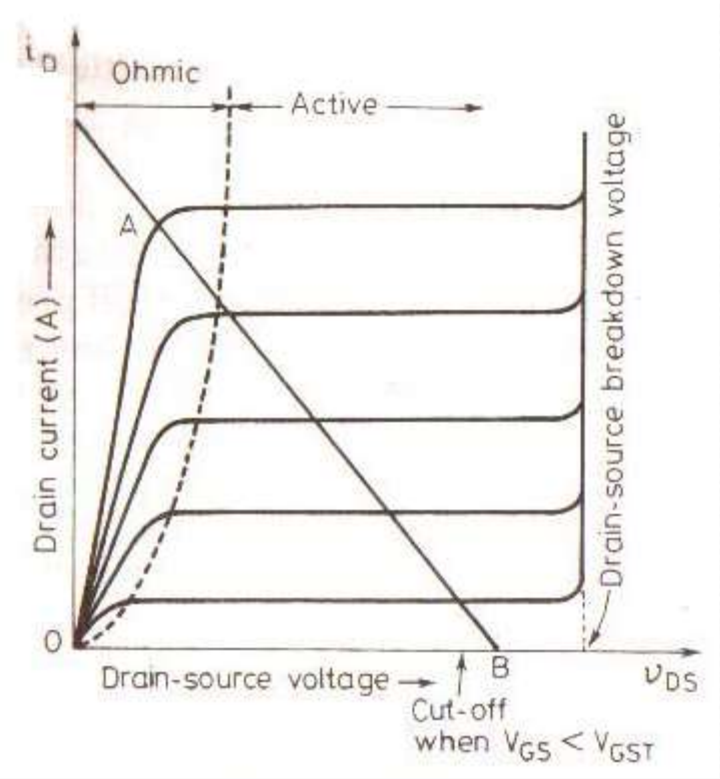
BASIC STRUCTURE OF n-CHANNEL POWER MOSFET

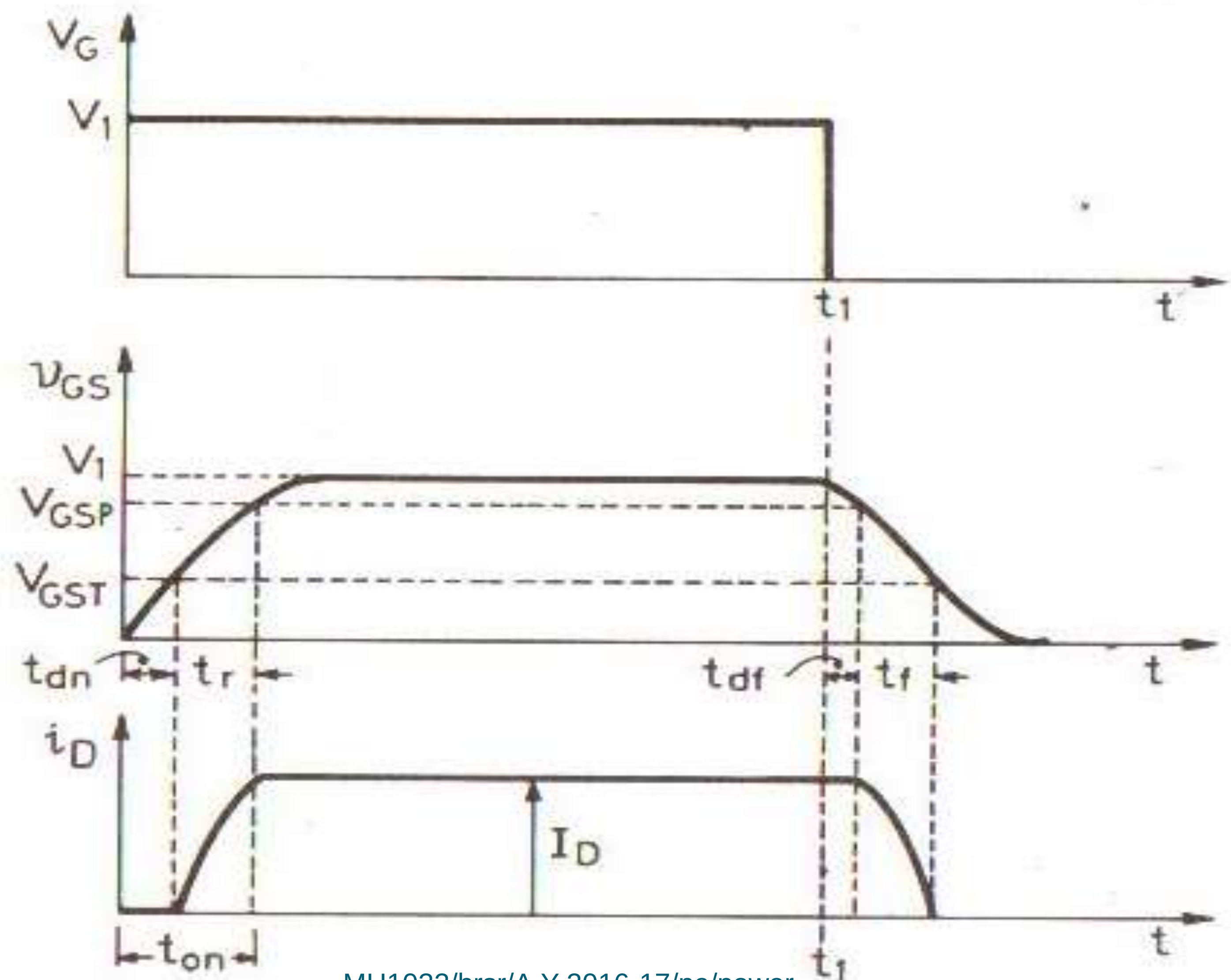
MOSFET TRANSFER CHARACTERISTICS





MOSFET OUTPUT CHARACTERISTICS





V_G
V_1
t_1
t
v_{GS}
V_1
V_{GSP}
V_{GST}
t_{dn}
t_r
t_{df}
t_f
t
i_D
I_D
t_{on}
t_1
t

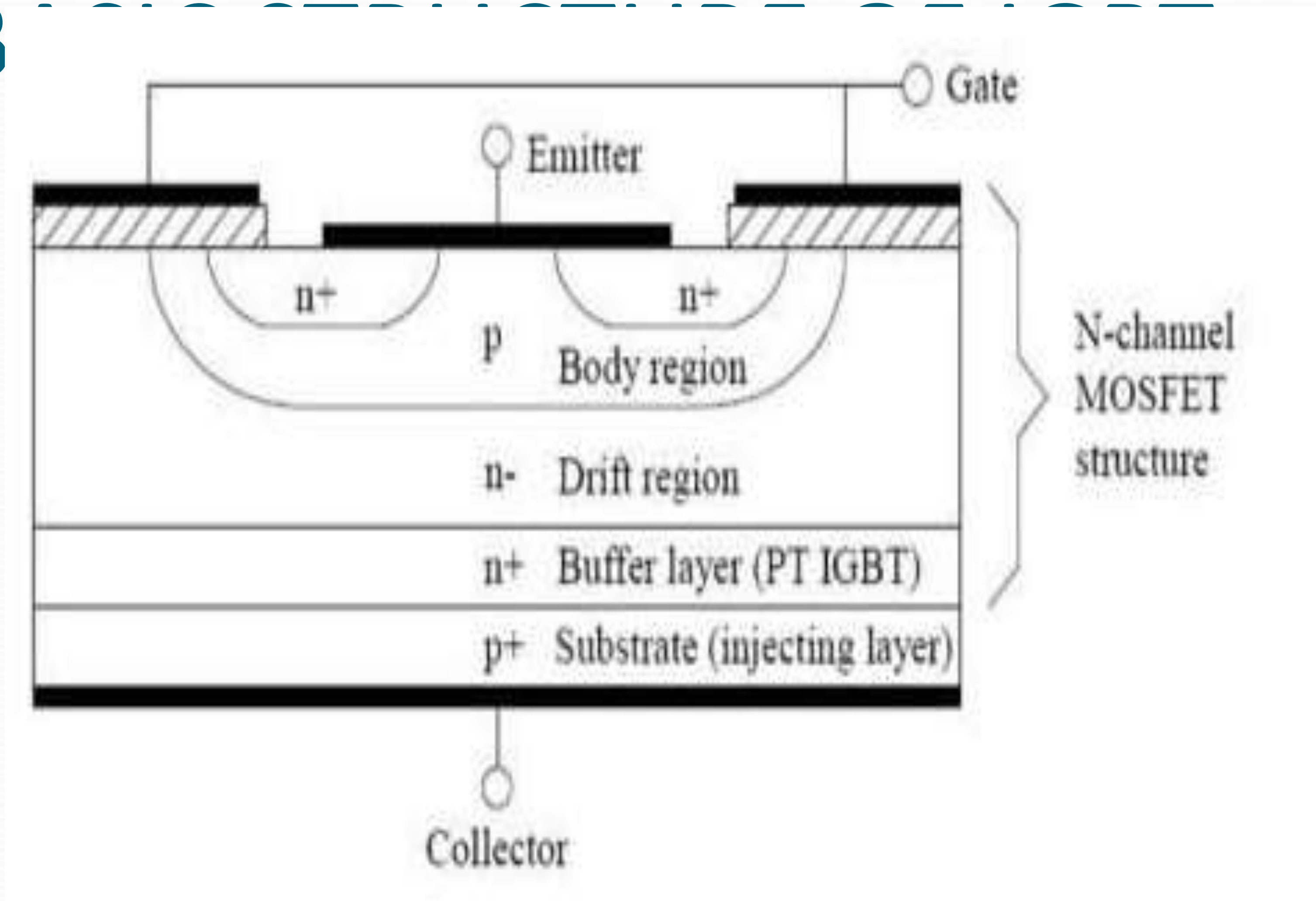
COMPARISON OF BJT AND MOSFET

S.No	BJT	MOSFET
1	BIPOLAR DEVICE	UNIPOLAR DEVICE
2	LOW INPUT IMPEDANCE(KILO OHM)	HIGH INPUT IMPEDANCE (MEGA OHM)
3	HIGH SWITCHING LOSSES BUT LOWER CONDUCTION LOSSES	LOWER SWITCHING LOSSES BUT HIGH ON-RESISTANCE AND CONDUCTION LOSSES
4	CURRENT CONTROLLED DEVICE	VOLTAGE CONTROLLED DEVICE
5	NEGATIVE TEMPERATURE COEFFICIENT OF RESISTANCE.PARALLEL OPERATION IS DIFFICULT.CURRENT SHARING RESISTORS SHOULD BE USED.	POSITIVE TEMPERATURE COEFFICIENT OF RESISTANCE. PARALLEL OPERATION IS EASY
6	SECONDARY BREAKDOWN OCCURS.	SECONDARY BREAKDOWN DOES NOT OCCUR.

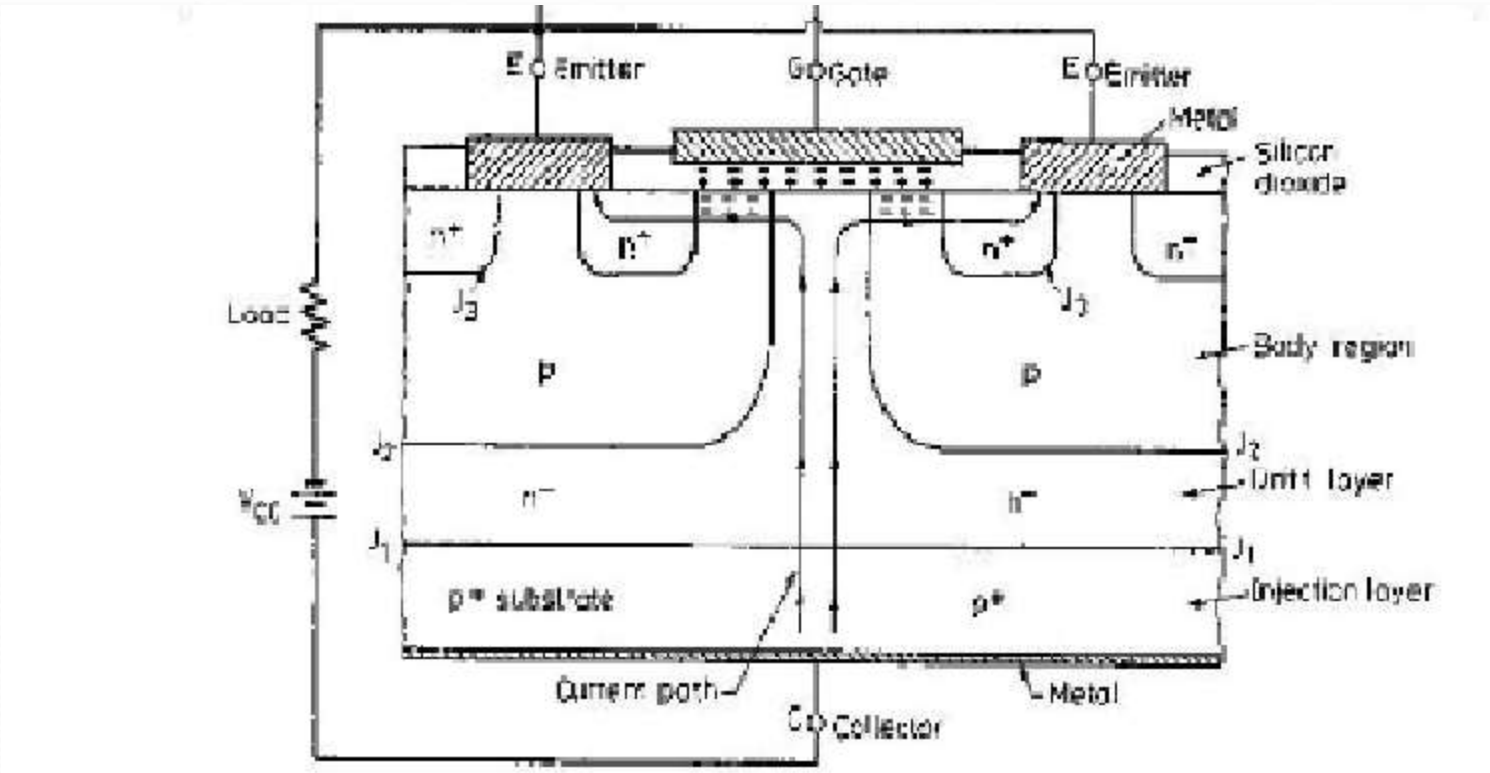
INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

- COMBINES THE BEST QUALITIES OF BOTH **BJT** AND **MOSFET**
- HAS HIGH INPUT IMPEDANCE AS MOSFET AND HAS LOW ON-STATE POWER LOSS AS IN BJT
- OTHER NAMES
  - ✓ **MOSIGT** (METAL OXIDE INSULATED GATE TRANSISTOR),
  - ✓ **COMFET** (CONDUCTIVELY-MODULATED FIELD EFFECT TRANSISTOR),
  - ✓ **GEMFET** (GAIN MODULATED FIELD EFFECT TRANSISTOR),
  - ✓ **IGT** (INSULATED GATE TRANSISTOR)

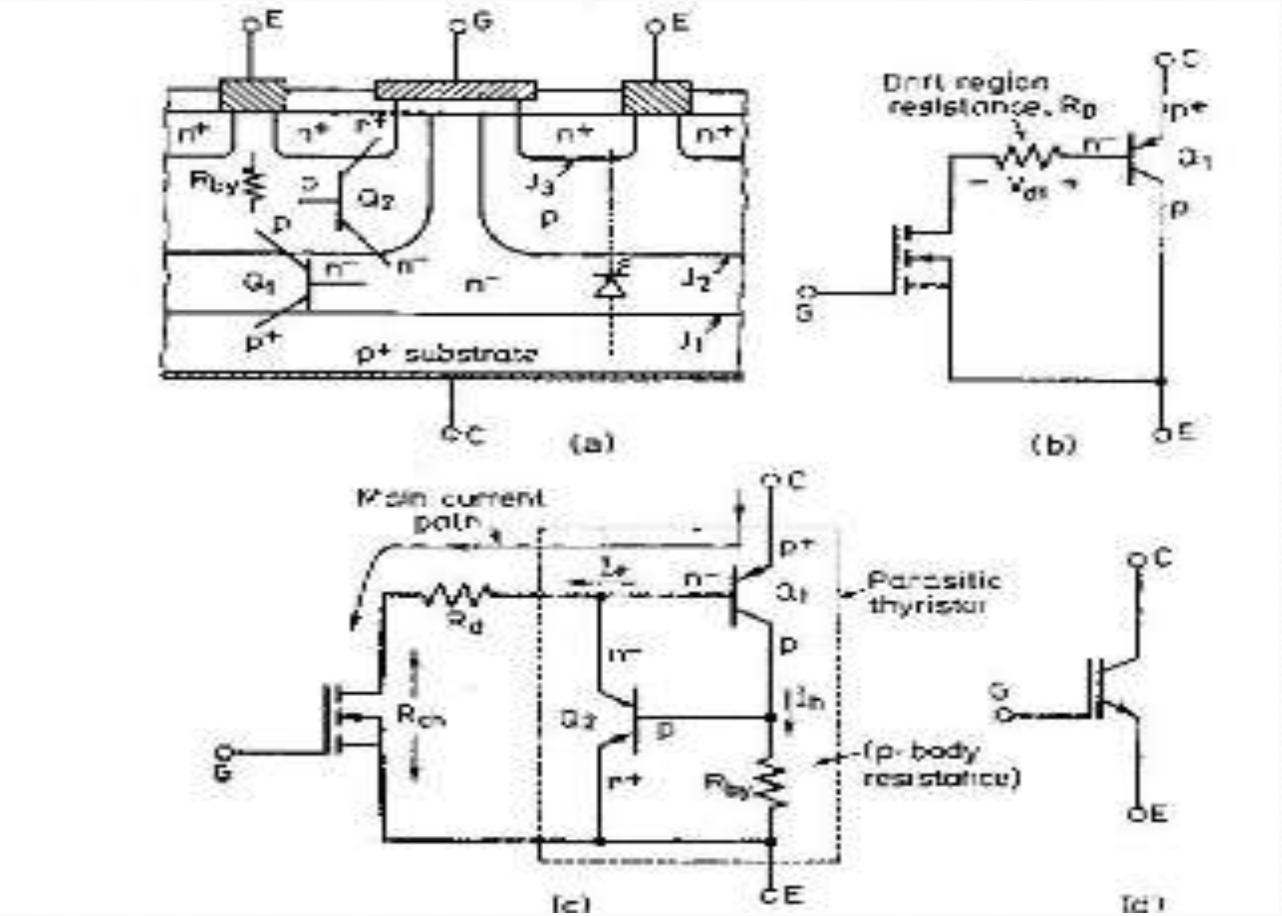
B


Gate
Emitter
n+
n+
p
Body region
n- Drift region
n+ Buffer layer (PT IGBT)
p+ Substrate (injecting layer)
N-channel
MOSFET
structure
Collector

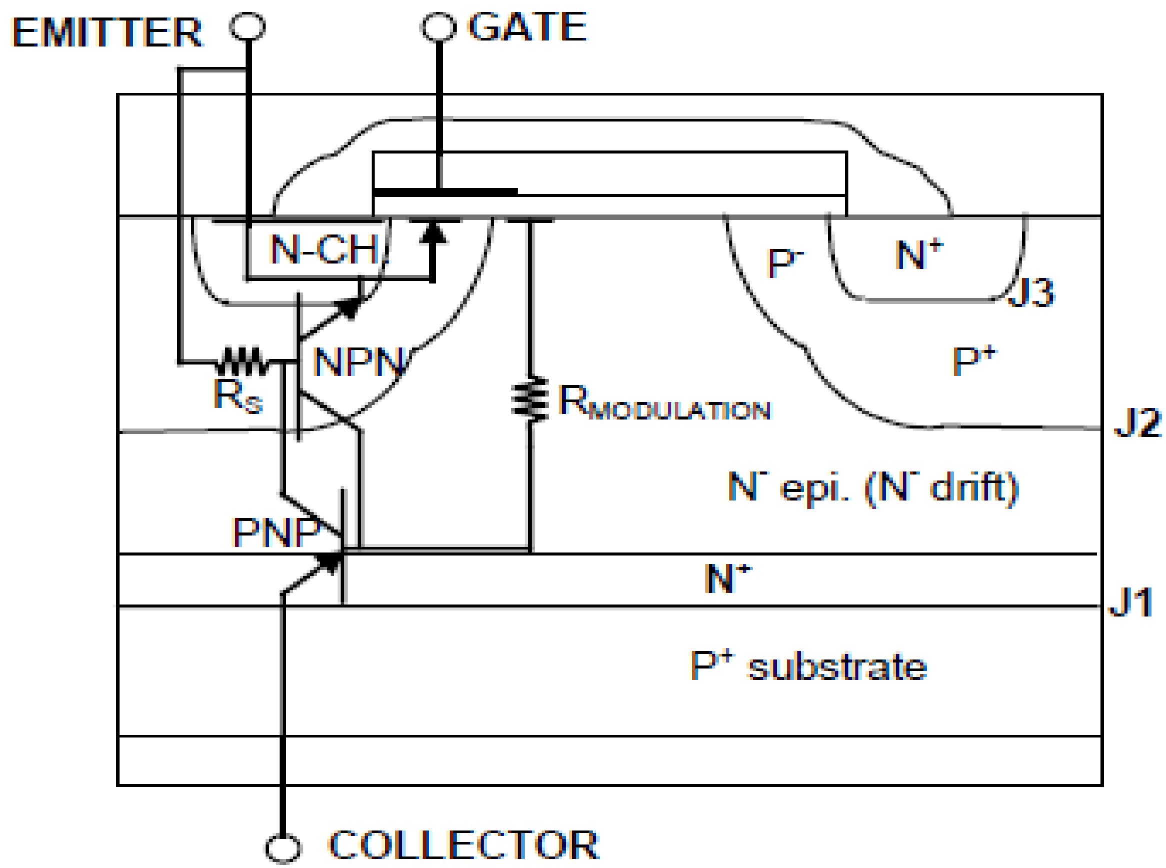
BASIC STRUCTURE OF IGBT



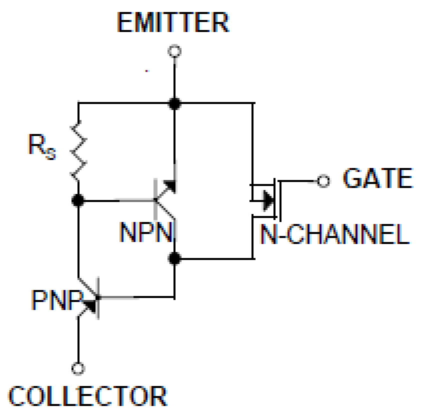
EQUIVALENT CIRCUIT OF IGBT



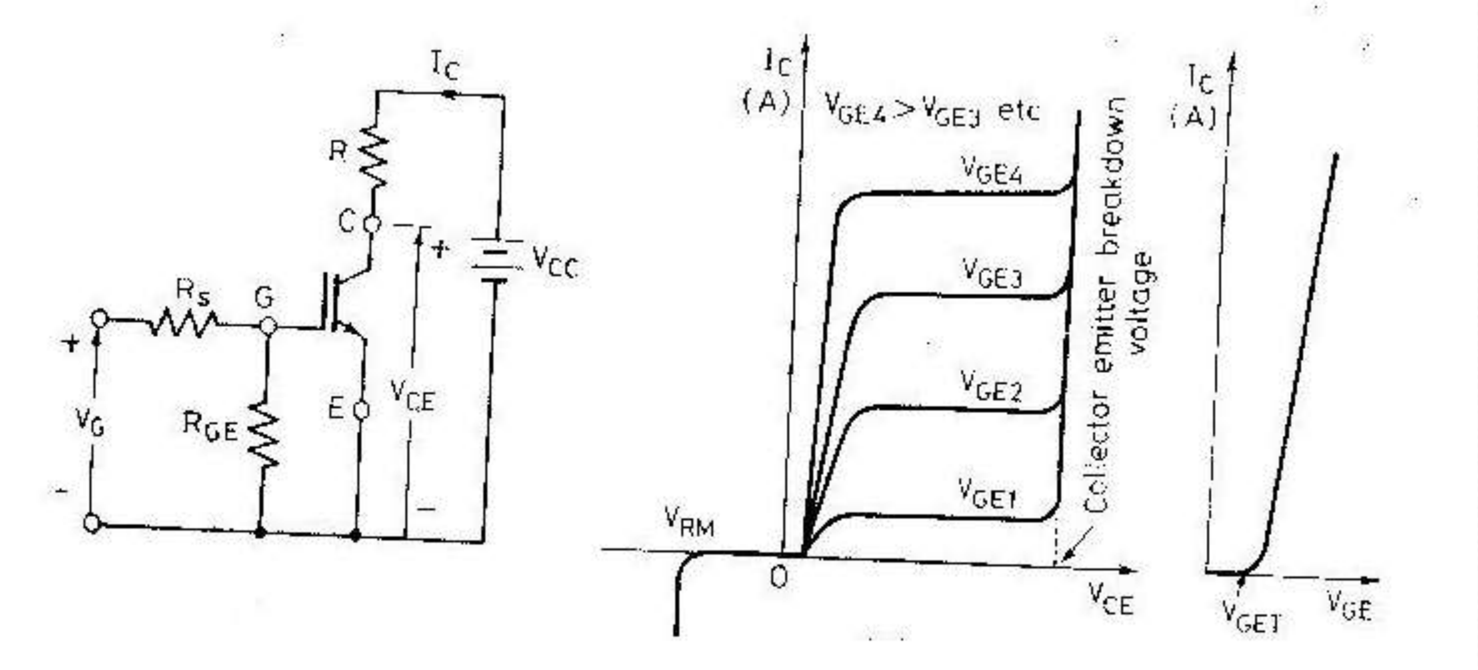
BASIC STRUCTURE OF IGBT



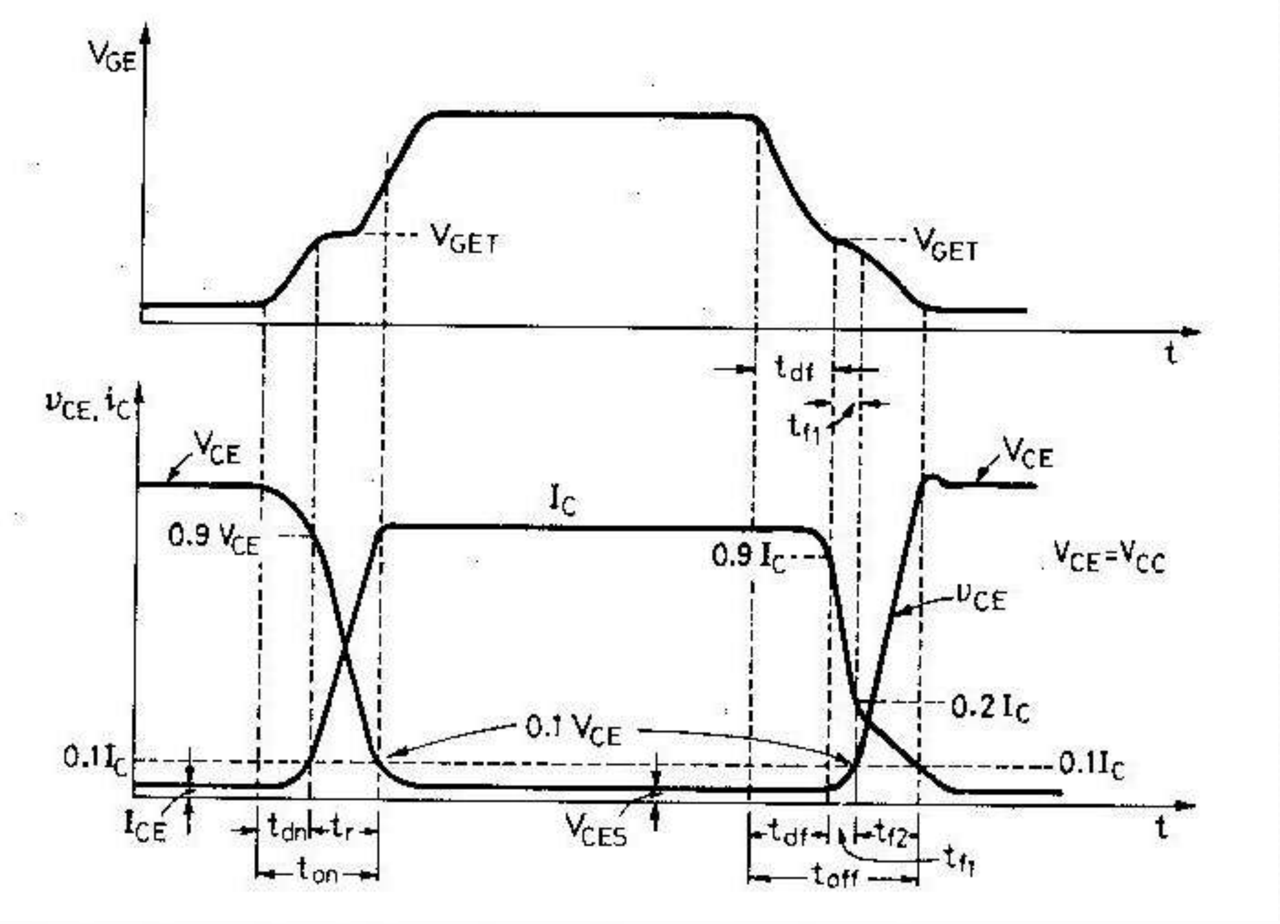
EQUIVALENT CIRCUIT OF IGBT



V-I AND TRANSFER CHARACTERISTICS OF IGBT



SWITCHING CHARACTERISTICS OF IGBT



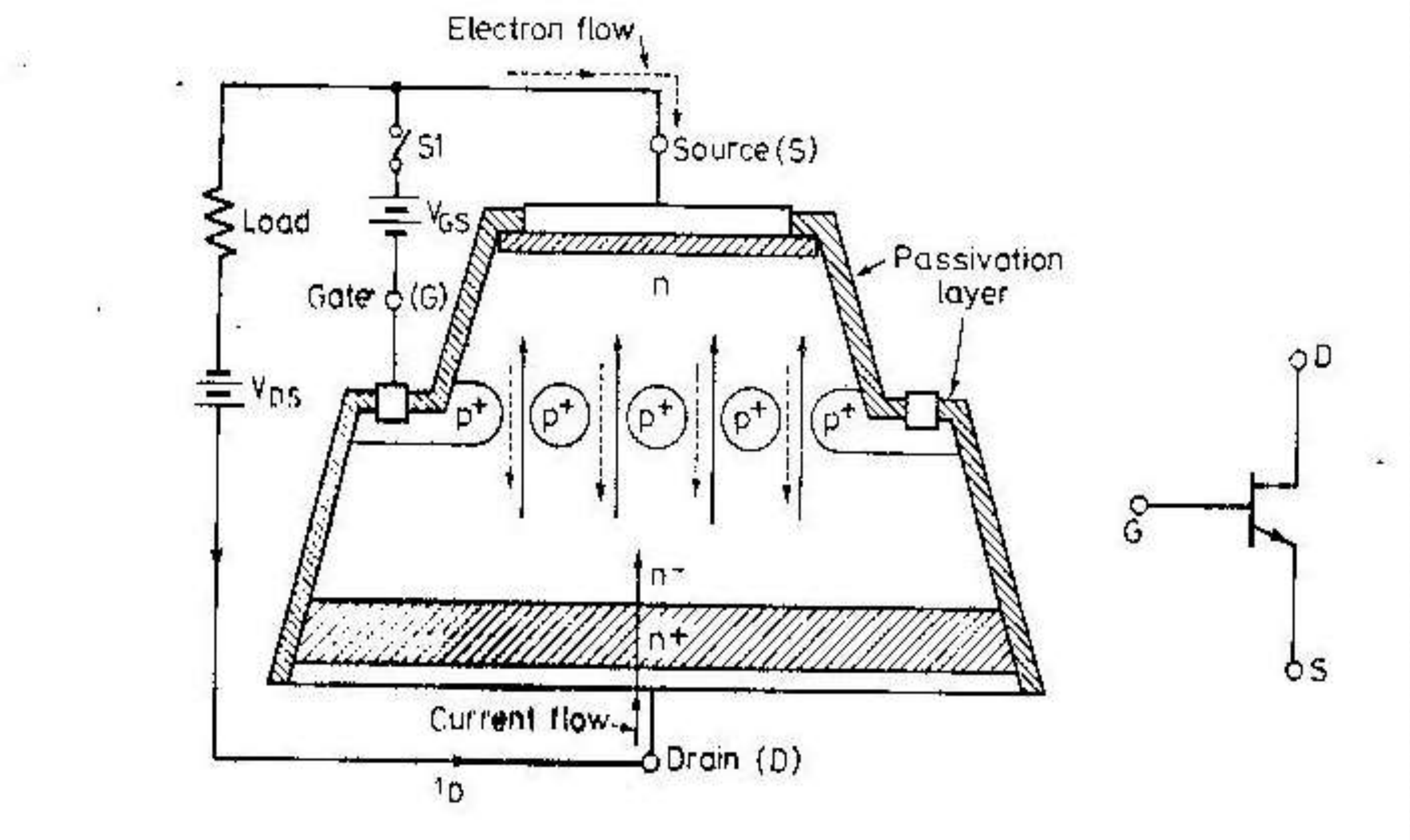
APPLICATIONS OF IGBT

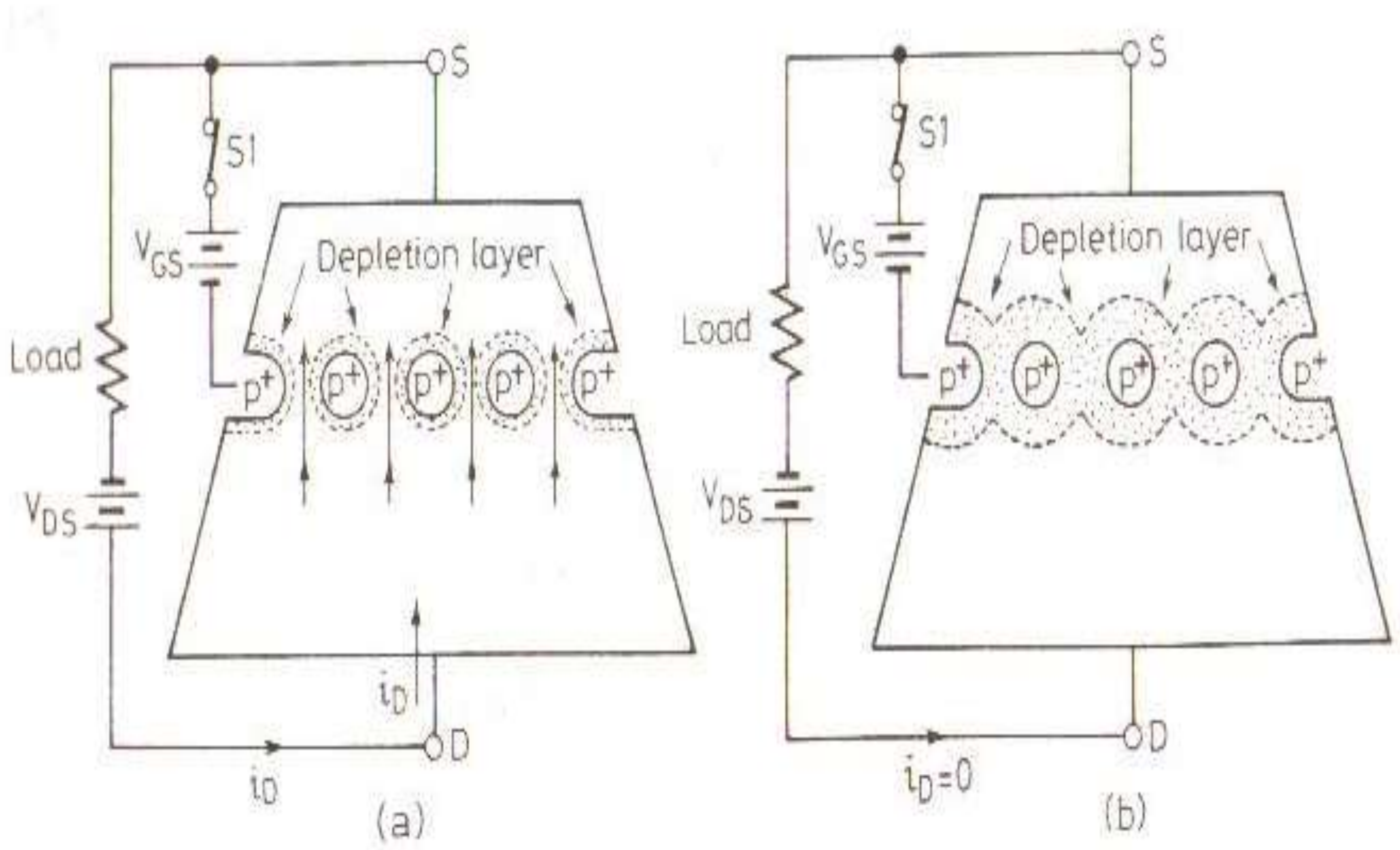
- DC AND AC MOTOR DRIVES
- UPS SYSTEMS,POWER SUPPLIES
- DRIVES FOR SOLENOIDS,RELAYS AND CONTACTORS

COMPARISON OF IGBT WITH MOSFET

S.No	MOSFET	IGBT
1.	THREE TERMINALS ARE GATE,SOURCE AND DRAIN	THREE TERMINALS ARE GATE,EMITTER AND COLLECTOR
2.	HIGH INPUT IMPEDANCE	HIGH INPUT IMPEDANCE
3.	VOLTAGE CONTROLLED DEVICE	VOLTAGE CONTROLLED DEVICE
4.	RATINGS AVAILABLE UPTO 500V,140A	RATINGS AVAILABLE UPTO 1200V,500A
5.	OPERATING FREQUENCY IS UPTO I MHz	OPERATING FREQUENCY IS UPTO 50KHz
6.	WITH RISE IN TEMPERATURE,THE INCREASE IN ON-STATE RESISTANCE IN MOSFET IS MORE PRONOUNCED THAN IGBT.SO, ON-STATE VOLTAGE DROP AND LOSSES RISE RAPIDLY IN MOSFET THAN IN IGBT ITH RISE IN TEMPERATURE	
7.	WITH RISE IN VOLTAGE,THE INCREMENT IN ON-STATE VOLTAGE DROP IS	

BASIC STRUCTURE OF STATIC INDUCTION TRANSISTOR(SIT)





(a)Lower reverse bias,load current is reduced due to depletion layer
(b) Higher reverse bias,expanded depletion layer stops current flow

WORKING OF SIT

- SIT IS A NORMALLY ON DEVICE
- IF V_{GS} =0 AND V_{DS} IS PRESENT ,ELECTRONS WOULD FLOW FROM SOURCE TO n,P^+,n^-, n^+ AND REACH DRAIN.DRAIN CURRENT FLOWS FROM D TO S.
- IF V_{GS} = NEGATIVE, P^+n^- JUNCTIONS GET REVERSE BIASED.DEPLETION REGION IS FORMED AROUND P+ ELECTRODES AND THIS REDUCES THE CURRENT FLOW FROM ITS VALUE WHEN V_{GS} =0.
- AT SOME HIGHER VALUE OF REVERSE BIAS VOLTAGE V_{GS} ,THE DEPLETION LAYER WOULD GROW TO SUCH AN EXTENT AS TO CUT OFF THE CHANNEL COMPLETELY AND LOAD CURRENT WOULD BE ZERO.

STATIC INDUCTION TRANSISTOR(SIT)

- IT IS A HIGH POWER,HIGH FREQUENCY DEVICE.
- LARGE DROP IN SIT MAKES IT UNSUITABLE FOR GENERAL POWER ELECTRONIC APPLICATIONS.
- A 1500V,180A SIT HAS A CHANNEL RESISTANCE OF 0.5 Ω GIVING 90V CONDUCTION DROP AT 180A.AN EQUIVALENT THYRISTOR OR GTO DROP MAY BE AROUND 2V.
- TYPICAL T_{ON} AND T_{OFF} TIMES ARE VERY LOW AROUND 0.35μs.
- HIGH CONDUCTION DROP WITH VERY LOW TURN-ON AND TURN-OFF TIMES RESULT IN LOW ON-OFF ENERGY LOSSES.THIS MAKES SIT SUITABLE FOR HIGH POWER,HIGH FREQUENCY APPLICATIONS.

APPLICATIONS OF SIT

- AM/FM TRANSMITTERS
- INDUCTION HEATERS
- HIGH VOLTAGE LOW CURRENT POWER SUPPLIES
- ULTRASONIC GENERATORS
- TYPICAL RATINGS AVAILABLE - 1200V,300AWITH TURN ON AND TURN OFF TIMES AROUND 0.25 TO 0.35 μs AND 100KHz OPERATING FREQUENCY.

THYRISTORS
SILICON CONTROLLED RECTIFIER (SCR)

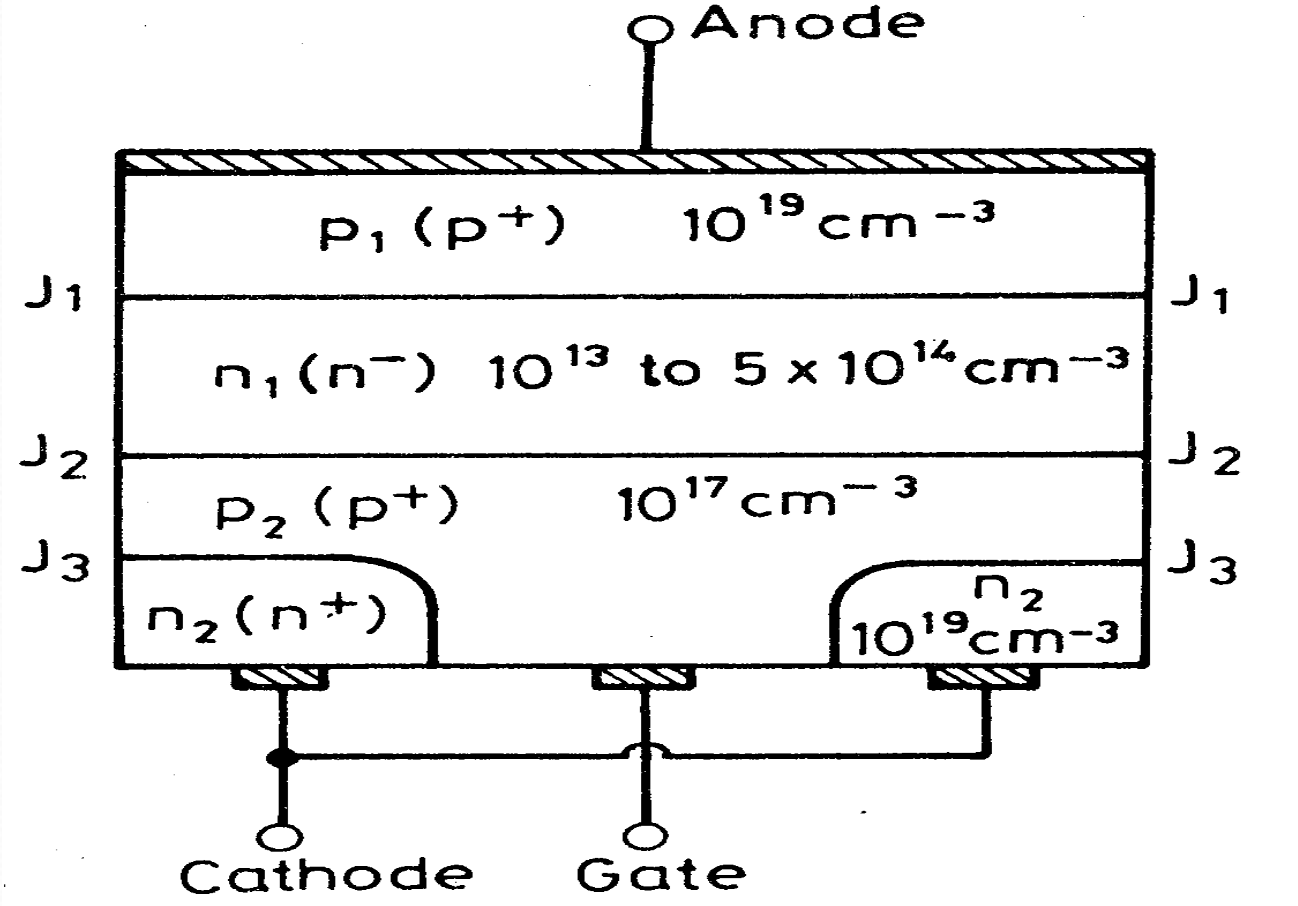
- Three terminal, four layers (P-N-P-N)
- Can handle high currents and high voltages, with better switching speed and improved breakdown voltage .
- Name 'Thyristor', is derived by a combination of the capital letters from **THYRatron** and **transISTOR**.
- Has characteristics similar to a thyratron tube

  But from the construction view point belongs to transistor (pnp or npn device) family.

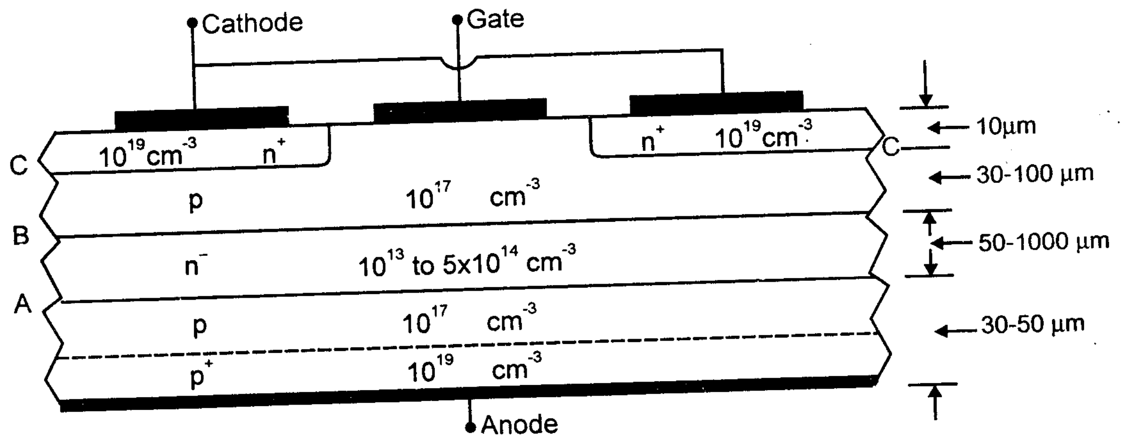
THYRISTORS

- TYPICAL RATINGS AVAILABLE ARE 1.5KA & 10KV WHICH RESPONDS TO 15MW POWER HANDLING CAPACITY.
- THIS POWER CAN BE CONTROLLED BY A GATE CURRENT OF ABOUT 1A ONLY.

BASIC STRUCTURE OF SCR



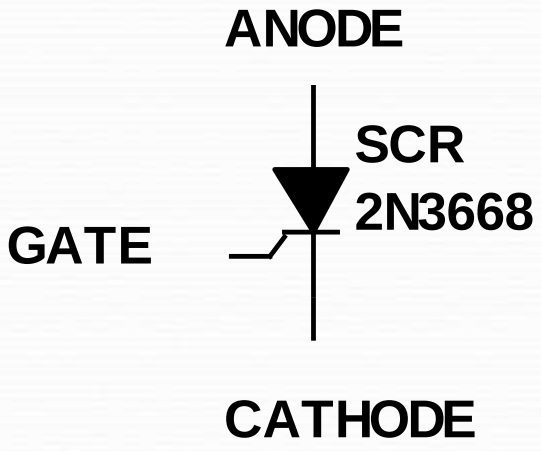
BASIC STRUCTURE OF SCR CONTD…



(a) Vertical cross-section of thyristor

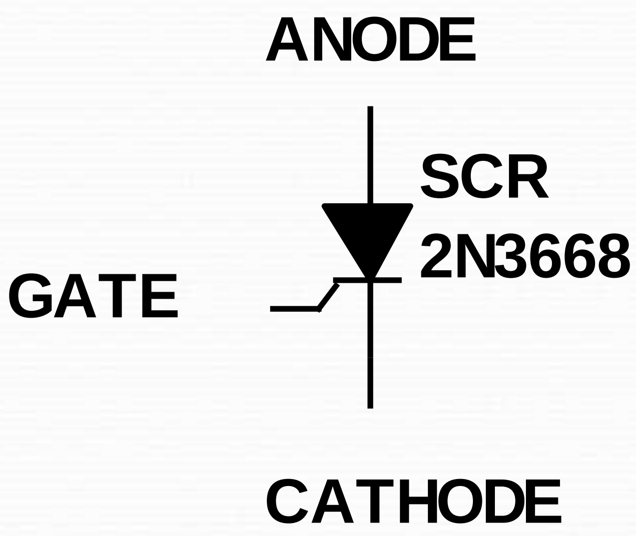
SCR / Thyristor

- Circuit Symbol and Terminal Identification



SCR / Thyristor

- Anode and Cathode terminals as conventional pn junction diode
- Gate terminal for a controlling input signal



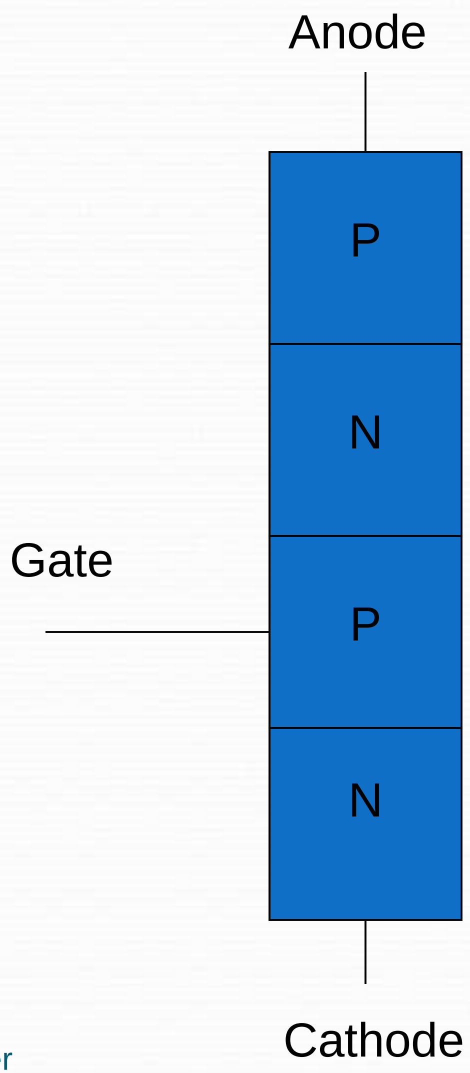
SCR/ Thyristor

- An SCR (Thyristor) is a “controlled” rectifier (diode)
- Control the conduction under forward bias by applying a current into the Gate terminal
- Under reverse bias, looks like conventional pn junction diode

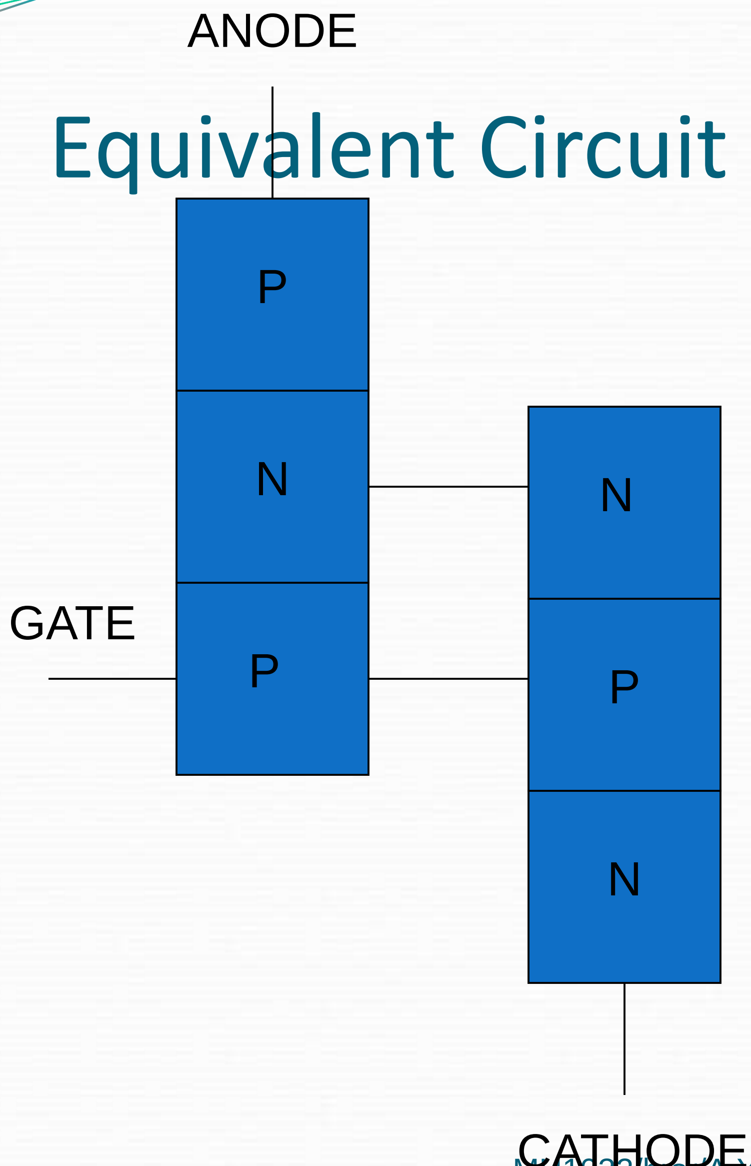
SCR / Thyristor

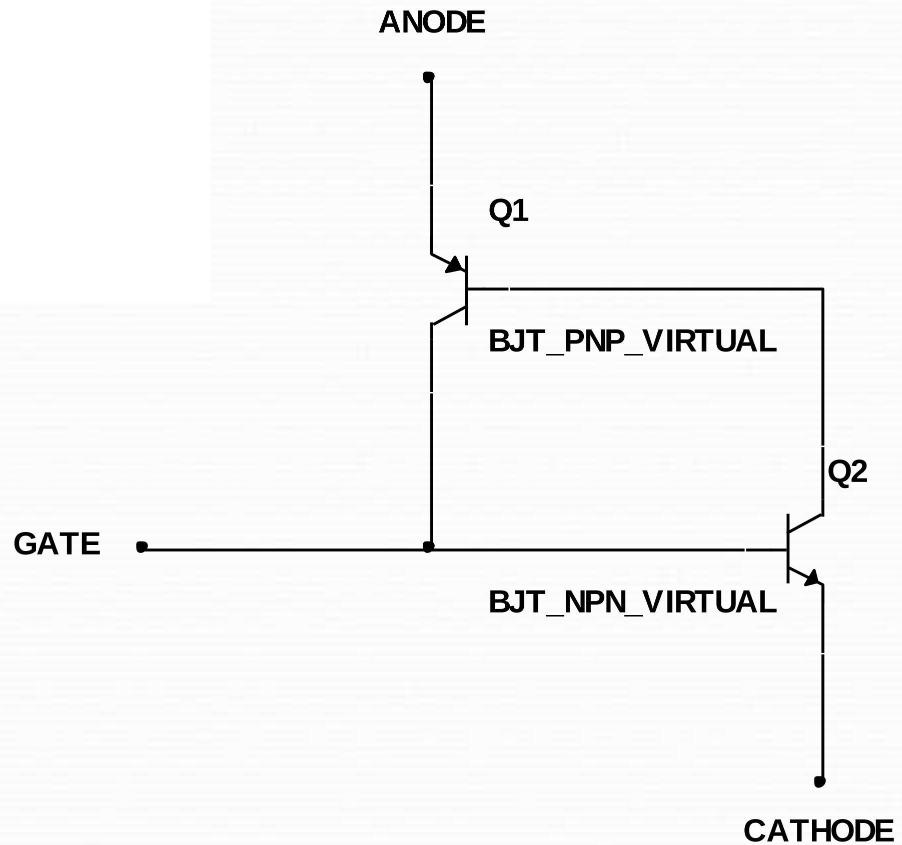
- 4-layer (pnpn) device
- Anode, Cathode as for a conventional pn junction diode

- Cathode Gate brought out for controlling input



Equivalent Circuit

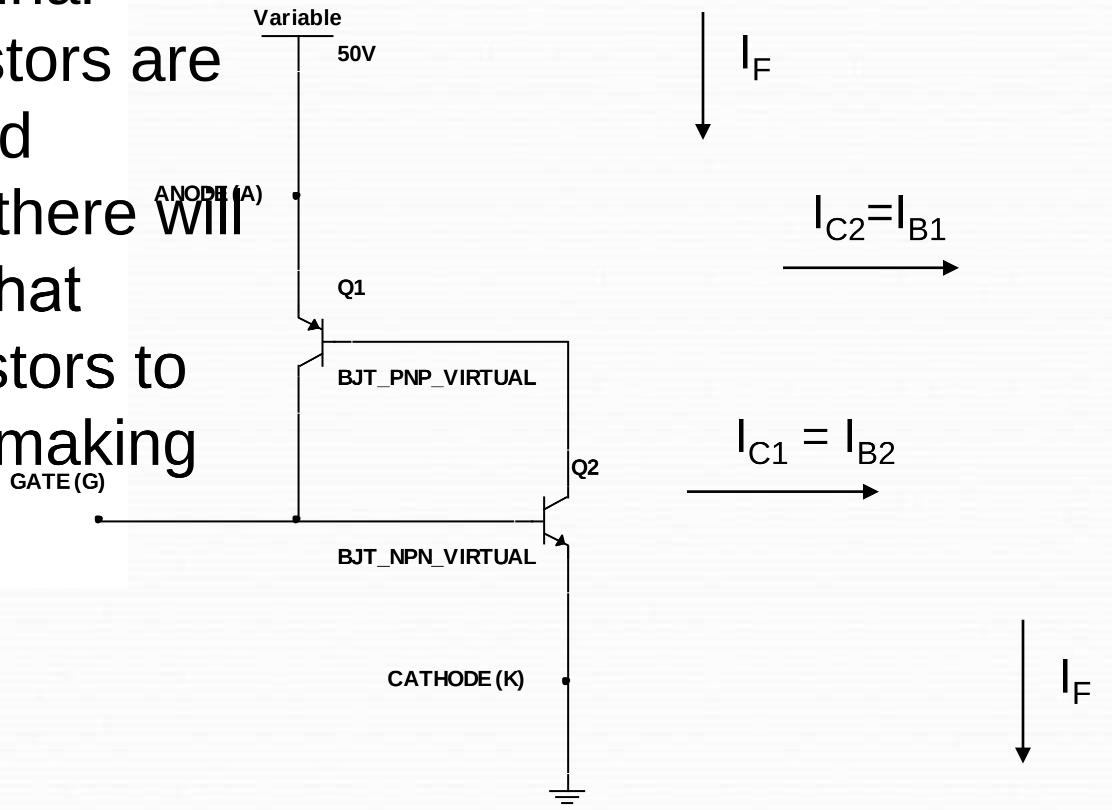




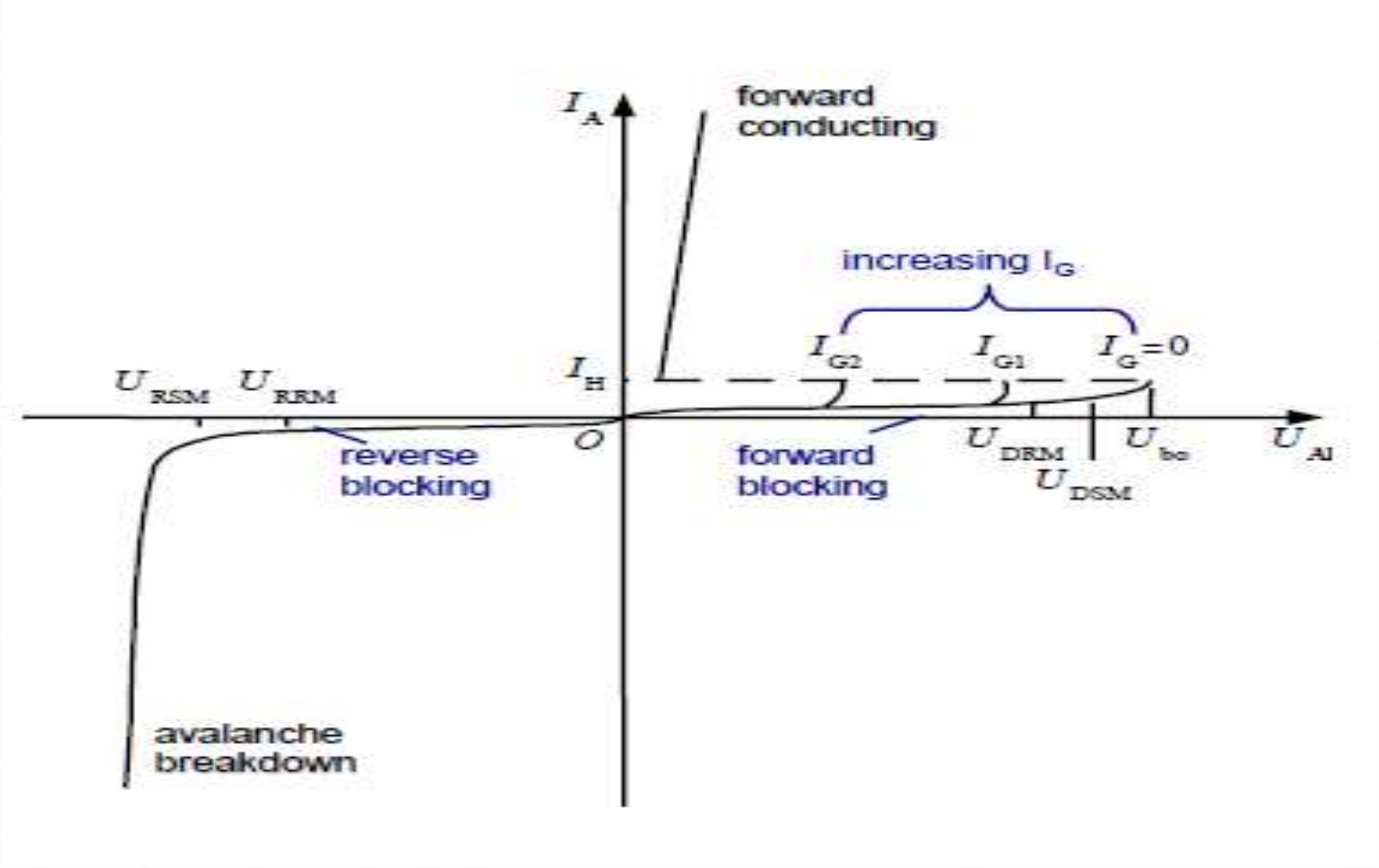
Apply Biasing

With the Gate terminal OPEN, both transistors are OFF. As the applied voltage increases, there will be a "breakdown" that causes both transistors to conduct (saturate) making $I_F > 0$ and $V_{AK} = 0$.

$V_{Breakdown} = V_{BR(F)}$



V-I CHARACTERISTICS OF SCR



Apply a Gate Current

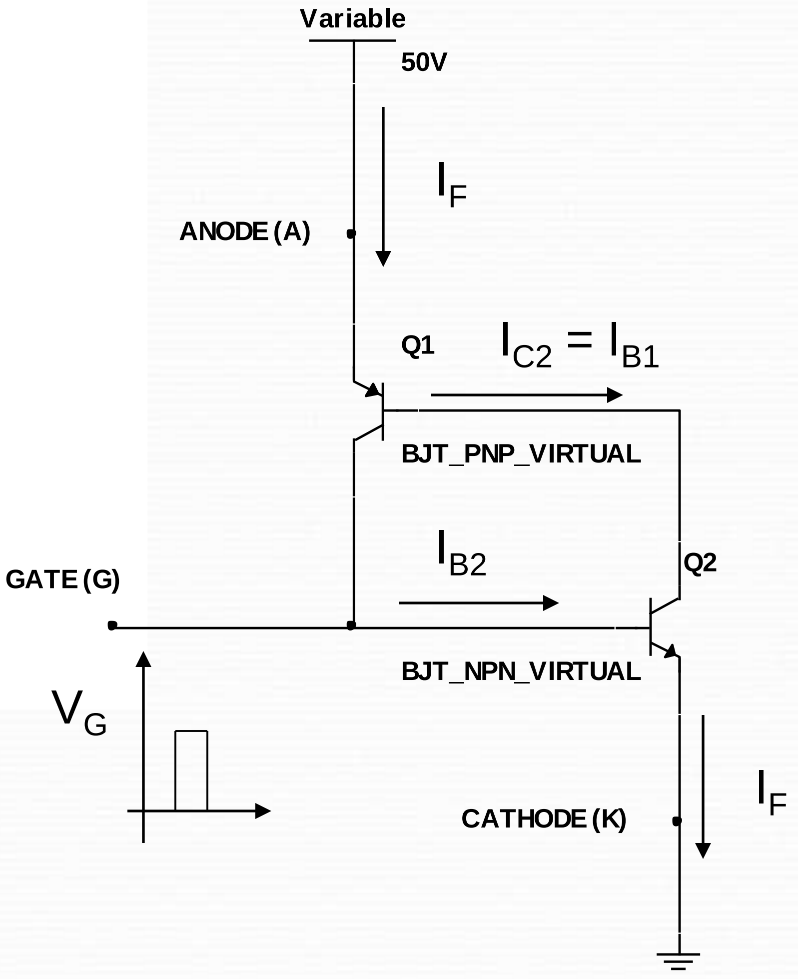
For $0 < V_{AK} < V_{BR(F)}$:

Turn Q_2 ON by applying a current into the Gate

This causes Q_1 to turn ON, and eventually both transistors SATURATE

$V_{AK} = V_{CEsat} + V_{BEsat}$

If the Gate pulse is removed, Q_1 and Q_2 still stay ON!

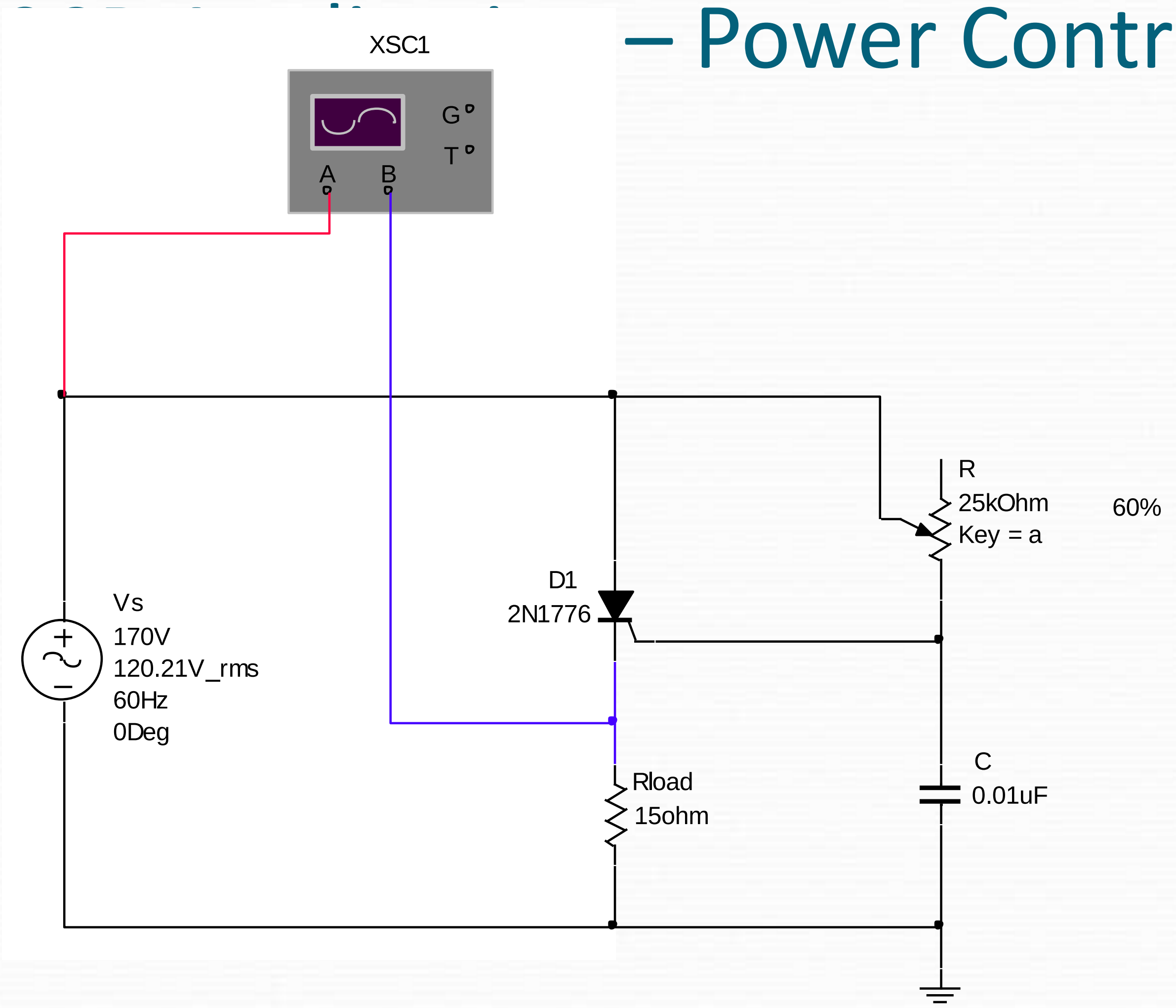


How do you turn it OFF?

- Cause the forward current to fall below the value if the “holding” current, I_H

- Reverse bias the device

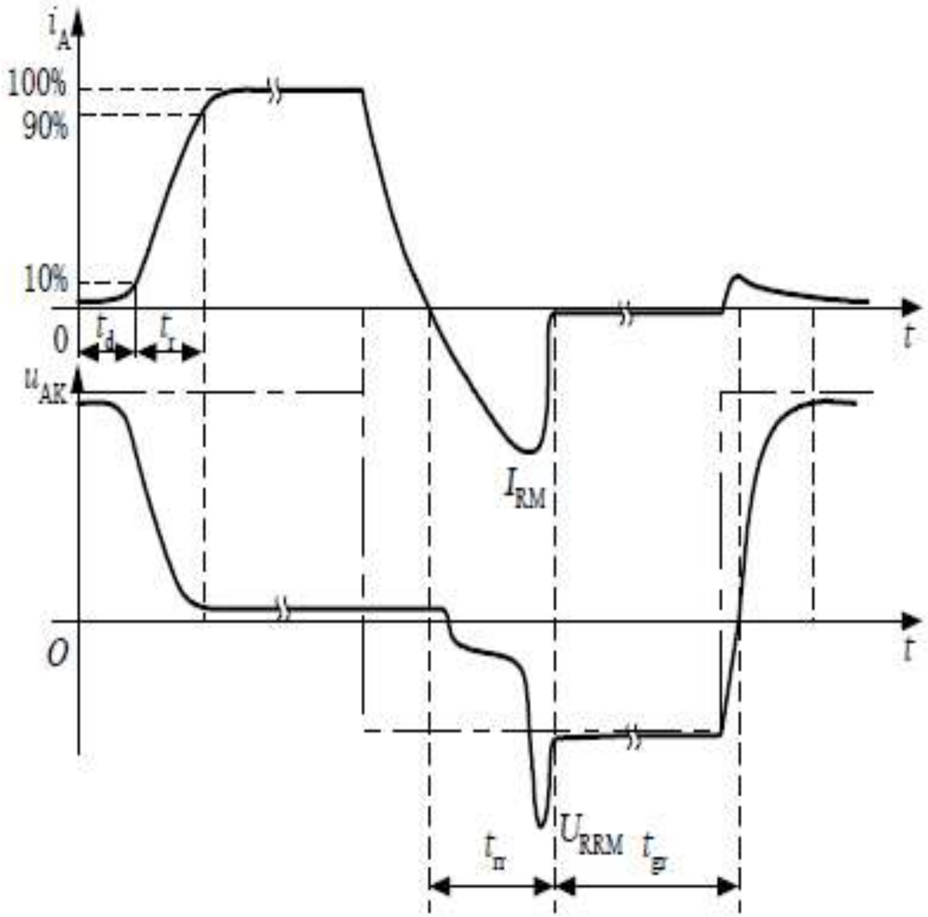
– Power Control



When the voltage across the capacitor reaches the "trigger-point" voltage of the device, the SCR turns ON, current flows in the Load for the remainder of the positive half-cycle.

Current flow stops when the applied voltage goes negative.

SWITCHING CHARACTERISTICS OF SCR



Turn-on transient

- Delay time t_d
- Rise time t_r
- Turn-on time t_{gt}

Turn-off transient

- Reverse recovery time t_{rr}
- Forward recovery time t_{gr}
- Turn-off time t_q

SCR OPERATING MODES

FORWARD BLOCKING MODE: Anode is positive w.r.t cathode, but the anode voltage is less than the break over voltage (VBO) .

only leakage current flows, so thyristor is not conducting .

FORWARD CONDUCTING MODE: When anode voltage becomes greater than VBO, thyristor switches from forward blocking to forward conduction state, a large forward current flows.

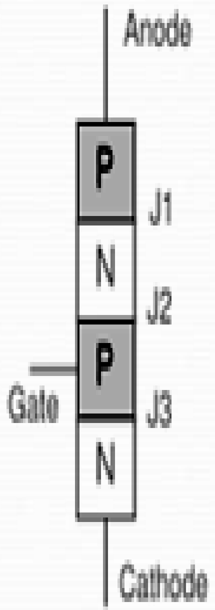
If the IG=IG1, thyristor can be turned ON even when anode voltage is less than VBO.

- The current must be more than the latching current (IL).
- If the current reduced less than the holding current (IH), thyristor switches back to forward blocking state.

REVERSE BLOCKING MODE: When cathode is more positive than anode , small reverse leakage current flows. However if cathode voltage is increased to reverse breakdown voltage , Avalanche breakdown occurs and large current flows.

Thyristor- Operation Principle

- Thyristor has three p-n junctions (J1, J2, J3 from the anode).
- When anode is at a positive potential (VAK) w.r.t cathode with no voltage applied at the gate, junctions J1 & J3 are forward biased, while junction J2 is reverse biased.
  - As J2 is reverse biased, no conduction takes place, so thyristor is in forward blocking state (OFF state).
  - Now if *VAK* (forward voltage) is increased w.r.t cathode, forward leakage current will flow through the device.
  - When this forward voltage reaches a value of breakdown voltage (*V*BO) of the thyristor, forward leakage current will reach saturation and reverse biased junction (J2) will have avalanche breakdown and thyristor starts conducting (ON state), known as forward conducting state .
- If Cathode is made more positive w.r.t anode, Junction J1 & J3 will be reverse biased and junction J2 will be forward biased.
- A small reverse leakage current flows, this state is known as reverse blocking state.
- As cathode is made more and more positive, stage is reached when both junctions A & C will be breakdown, this voltage is referd as reverse breakdown voltage (OFF state), and device is in reverse blocking state



TRIGGERING METHODS

- THYRISTOR TURNING ON IS ALSO KNOWN AS **TRIGGERING**.
- WITH ANODE POSITIVE WITH RESPECT TO CATHODE, A THYRISTOR CAN BE TURNED ON BY ANY ONE OF THE FOLLOWING TECHNIQUES :
  - FORWARD VOLTAGE TRIGGERING
  - GATE TRIGGERING
  - DV/DT TRIGGERING
  - TEMPERATURE TRIGGERING
  - LIGHT TRIGGERING

Forward Voltage Triggering

- When breakover voltage (VBO) across a thyristor is exceeded than the rated maximum voltage of the device, thyristor turns ON.
- At the breakover voltage the value of the thyristor anode current is called the latching current (IL) .
- Breakover voltage triggering is not normally used as a triggering method, and most circuit designs attempt to avoid its occurrence.
- When a thyristor is triggered by exceeding VBO, the fall time of the forward voltage is quite low (about 1/20th of the time taken when the thyristor is gate-triggered).
- However, a thyristor switches faster with VBO turn-ON than with gate turn-ON, so permitted di/dt for breakover voltage turn-on is lower.

dv/dt triggering

- With forward voltage across anode & cathode of a thyristor, two outer junctions (A & C) are forward biased but the inner junction (J2) is reverse biased.
- The reversed biased junction J2 behaves like a capacitor because of the space-charge present there.
- As p-n junction has capacitance, so larger the junction area the larger the capacitance.
- If a voltage ramp is applied across the anode-to-cathode, a current will flow in the device to charge the device capacitance according to the relation:

$$i_C = C.\frac{dv}{dt}$$

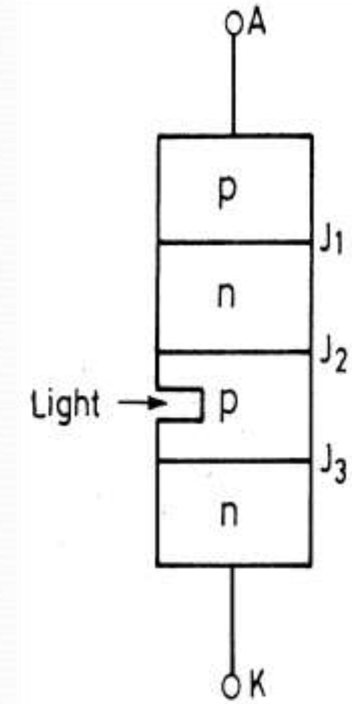
- If the charging current becomes large enough, density of moving current carriers in the device induces switch-on.
- This method of triggering is not desirable because high charging current (Ic) may damage the thyristor.

Temperature Triggering

- During forward blocking, most of the applied voltage appears across reverse biased junction J2.
- This voltage across junction J2 associated with leakage current may raise the temperature of this junction.
- With increase in temperature, leakage current through junction J2 further increases.
- This cumulative process may turn on the SCR at some high temperature.
- High temperature triggering may cause Thermal runaway and is generally avoided.

Light Triggering

- In this method light particles (photons) are made to strike the reverse biased junction, which causes an increase in the number of electron hole pairs and triggering of the thyristor.
- For light-triggered SCRs, a slot (niche) is made in the inner p-layer.
- When it is irradiated, free charge carriers are generated just like when gate signal is applied b/w gate and cathode.
- Pulse light of appropriate wavelength is guided by optical fibers for irradiation.
- If the intensity of this light thrown on the recess exceeds a certain value, forward-biased SCR is turned on. Such a thyristor is known as light-activated SCR (LASCR).
- Light-triggered thyristors is mostly used in high-voltage direct current (HVDC) transmission systems.



Thyristor Gate Control Methods

- An easy method to switch ON a SCR into conduction is to apply a proper positive signal to the gate.
- This signal should be applied when the thyristor is forward biased and should be removed after the device has been switched ON.
- Thyristor turn ON time should be in range of 1-4 micro seconds, while turn-OFF time must be between 8-50 micro seconds.
- Thyristor gate signal can be of three varieties.
  - **D.C Gate signal**
  - **A.c Gate Signal**
  - **Pulse**

Thyristor Gate Control Methods

D.C Gate signal: Application of a d.c gate signal causes the flow of gate current which triggers the SCR.

- Disadvantage is that the gate signal has to be continuously applied, resulting in power loss.
- Gate control circuit is also not isolated from the main power circuit.

A.C Gate Signal: In this method a phase - shifted a.c voltage derived from the mains supplies the gate signal.

- Instant of firing can be controlled by phase angle control of the gate signal.

Pulse: Here the SCR is triggered by the application of a positive pulse of correct magnitude.

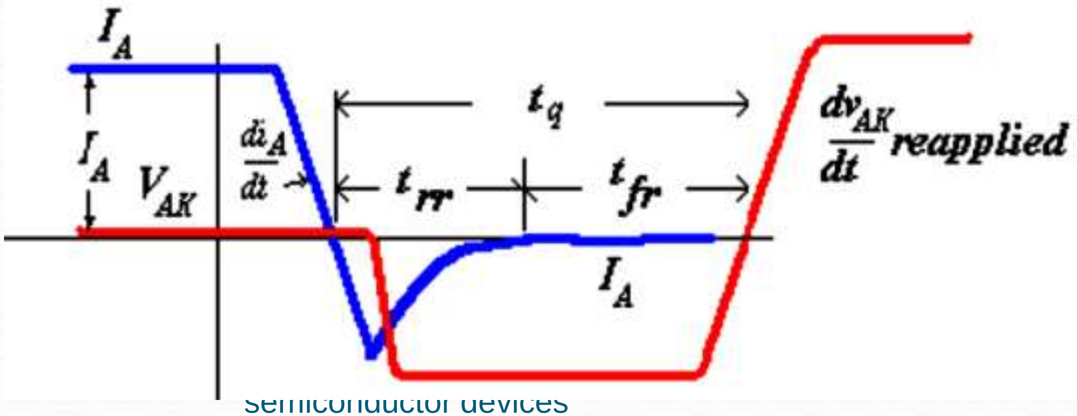
- For Thyristors it is important to switched ON at proper instants in a certain sequence.
- This can be done by train of the high frequency pulses at proper instants through a logic circuit.
- A pulse transformer is used for circuit isolation.
- Here, the gate looses are very low because the drive is discontinuous.

Thyristor Commutation

- Commutation: Process of turning off a conducting thyristor
  - Current Commutation
  - Voltage Commutation
- A thyristor can be turned ON by applying a positive voltage of about a volt or a current of a few tens of milliamps at the gate-cathode terminals.
- But SCR cannot be turned OFF via the gate terminal.
- It will turn-off only after the anode current is negated either naturally or using forced commutation techniques.
- These methods of turn-off do not refer to those cases where the anode current is gradually reduced below Holding Current level manually or through a slow process.
- Once the SCR is turned ON, it remains ON even after removal of the gate signal, as long as a minimum current, the Holding Current (IH), is maintained in the main or rectifier circuit.

Thyristor Turn-off Mechanism

- In all practical cases, a negative current flows through the device.
- This current returns to zero only after the reverse recovery time (*trr*) , when the SCR is said to have regained its reverse blocking capability.
- The device can block a forward voltage only after a further *tfr*, the forward recovery time has elapsed.
- Consequently, the SCR must continue to be reverse-biased for a minimum of *tfr + trr = tq*, the rated turn-off time of the device.
- The external circuit must therefore reverse bias the SCR for a time *toff > tq*.
- Subsequently, the reapplied forward biasing voltage must rise at a dv/dt < dv/dt (reapplied) rated. This dv/dt is less than the static counterpart.



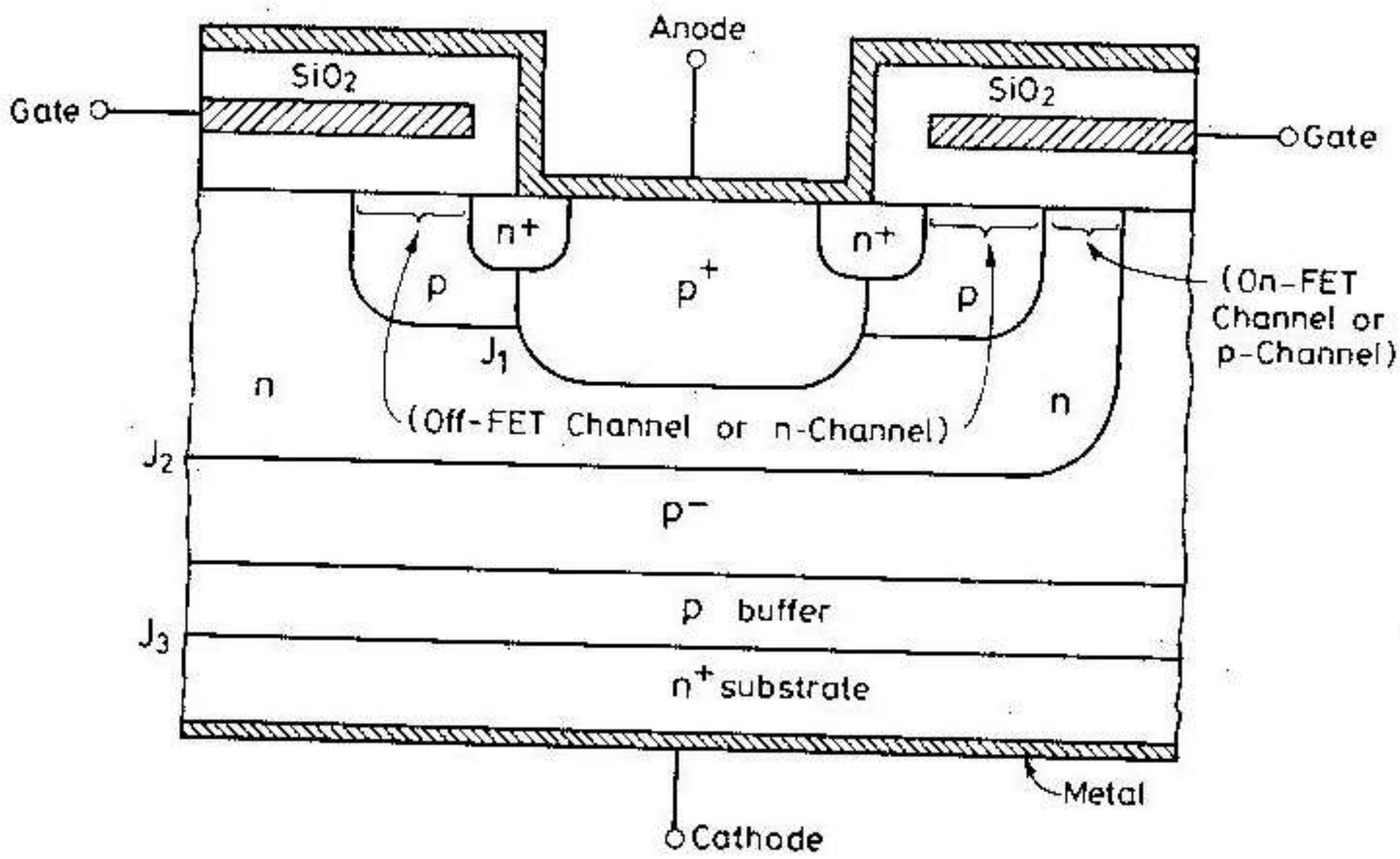
Thyristor Commutation Classification

- Commutation can be classified as
  - Natural commutation
  - Forced commutation

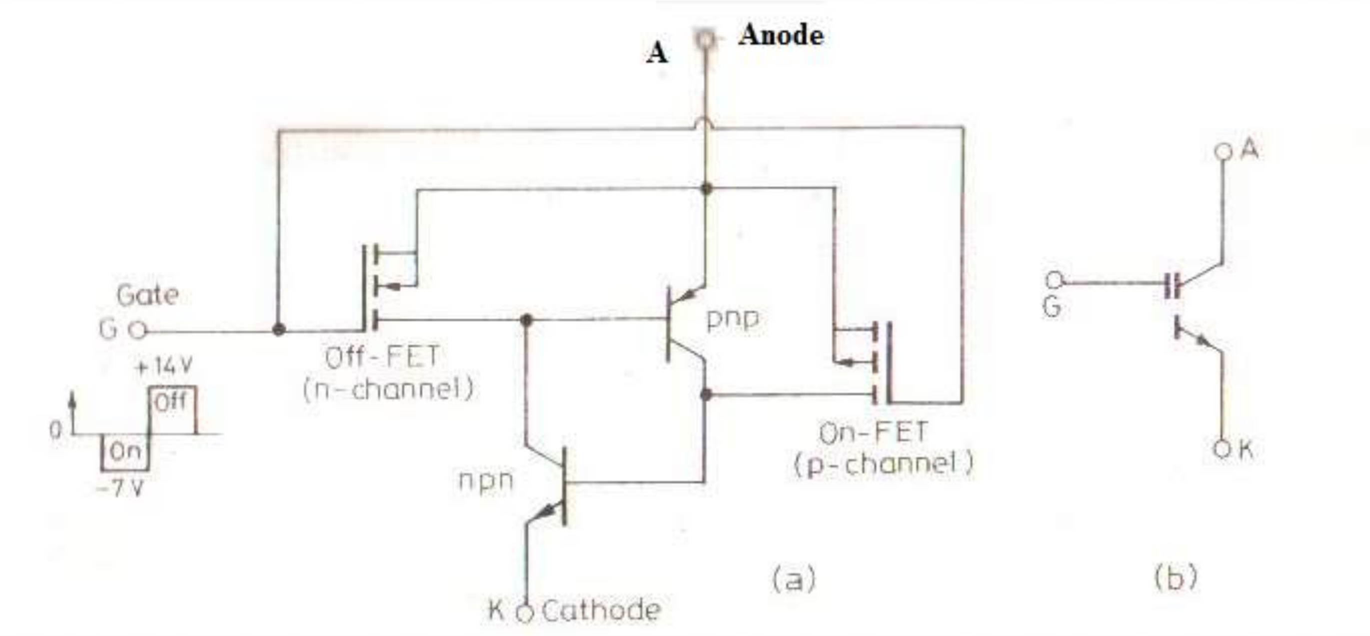
MOS CONTROLLED THYRISTOR (MCT)

- IT IS BASICALLY A THYRISTOR WITH TWO MOSFETS BUILT INTO THE GATE STRUCTURE
- ONE MOSFET IS USED TO TURN ON THE MCT AND THE OTHER FOR TURNING OFF OF MCT.
- IT IS A HIGH FREQUENCY,HIGH POWER,LOW CONDUCTION DROP SWITCHING DEVICE.
- IN A MCT, THE ANODE IS THE REFERENCE W.R.TO WHICH ALL THE GATE SIGNALS ARE APPLIED. IN A SCR,CATHODE IS THE REFERENCE SIGNAL TO THE GATE SIGNAL.

BASIC STRUCTURE OF MCT



EQUIVALENT CIRCUIT OF MCT

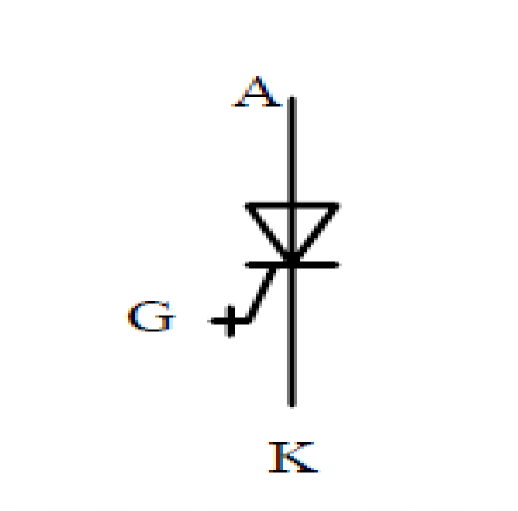


MERITS OF MCT

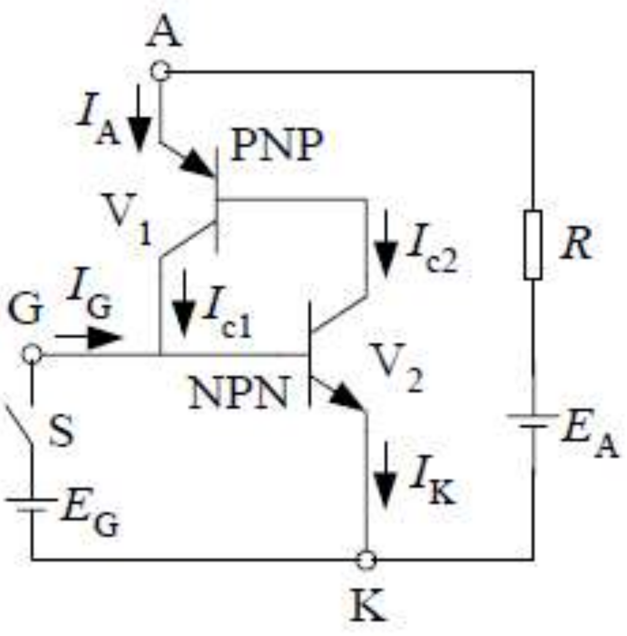
- LOW FORWARD CONDUCTION DROP
- FAST TURN AND TURN OFF TIMES
- LOW SWITCHING LOSSES
- HIGH GATE INPUT IMPEDANCE

- LOW REVERSE VOLTAGE BLOCKING CAPABILITY IS THE MAIN **DISADVANTAGE** OF MCT

GATE TURN OFF THYRISTORS (GTO)



PRINCIPLE OF OPERATION



The basic operation of GTO is the same as that of the conventional thyristor.

The principal differences lie in the modifications in the structure to achieve gate turn-off capability.

- Large α_2
- $\alpha_1+\alpha_2$ is just a little larger than the critical value 1.
- Short distance from gate to cathode makes it possible to drive current out of gate.

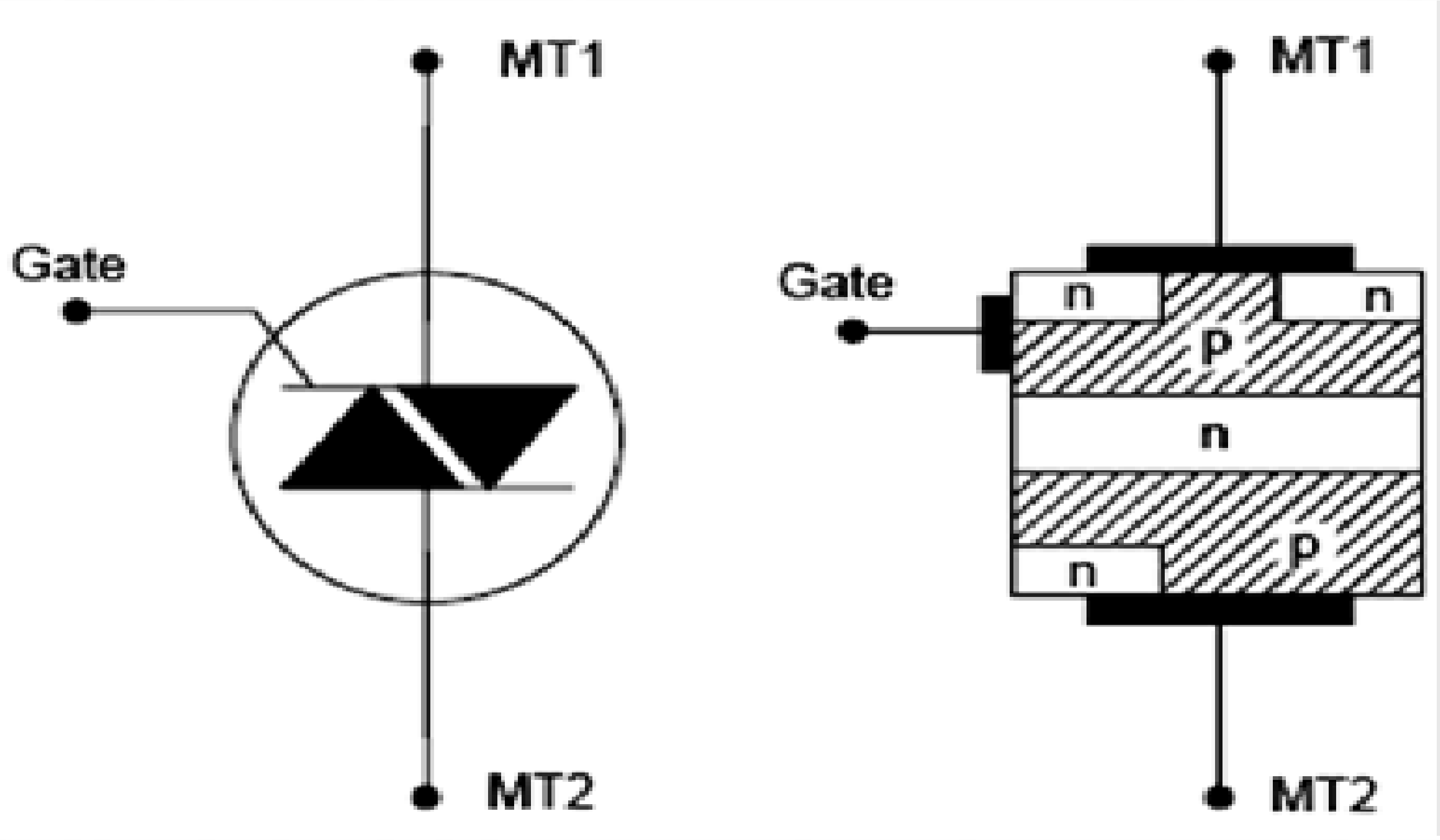
TRIAC
(TRIODE FOR ALTERNATING CURRENT)

- TRIAC is five layer device that is able to pass current bidirectionally and therefore behaves as an a.c. power control device.
- The main connections are simply named main terminal 1 (MT1) and main terminal 2 (MT2).
- The gate designation still applies, and is still used as it was with the SCR.

TRIAC (CONTD….)

- it not only carries current in either direction, but the gate trigger pulse can be either polarity regardless of the polarity of the main applied voltage.
- The gate can inject either free electrons or holes into the body of the triac to trigger conduction either way.
  - So triac is referred to as a "four-quadrant" device.
- Triac is used in an ac environment, so it will always turn off when the applied voltage reaches zero at the end of the current half-cycle.
- If a turn-on pulse is applied at some controllable point after the start of each half cycle, we can directly control what percentage of that half-cycle gets applied to the load, which is typically connected in series with MT2.
- USED for light dimmer controls and motor speed controls.

TRIAC SYMBOL AND BASIC STRUCTURE



TRIAC OPERATION

- TRIAC can be considered as two thyristors connected in antiparallel .The single gate terminal is common to both thyristors.
- The main terminals MT1 and MT2 are connected to both p and n regions of the device and the current path through the layers of the device depends upon the polarity of the applied voltage between the main terminals.
- Device polarity is usually described with reference to MT1, where the term MT2+ denotes that terminal MT2 is positive with respect to terminal MT1.

UNIT II
AC - DC CONVERTERS
PHASE CONTROLLED RECTIFIERS

- RECTIFIERS CONVERT AC TO DC
- CLASSIFIED AS
  - UNCONTROLLED - DIODES ARED USED
  - CONTROLLED - THYRISTORS ARE USED

CLASSIFICATION OF RECTIFIERS

- BASED ON INPUT SUPPLY
  - SINGLE PHASE
  - THREE PHASE
- BASED ON QUADRANT OPERATION
  - 1 QUADRANT
  - 2 QUADRANT
  - 4 QUADRANT
- BASED ON NO. OF PULSES
  - ONE PULSE
  - TWO PULSES
  - THREE PULSES
  - SIX PULSES

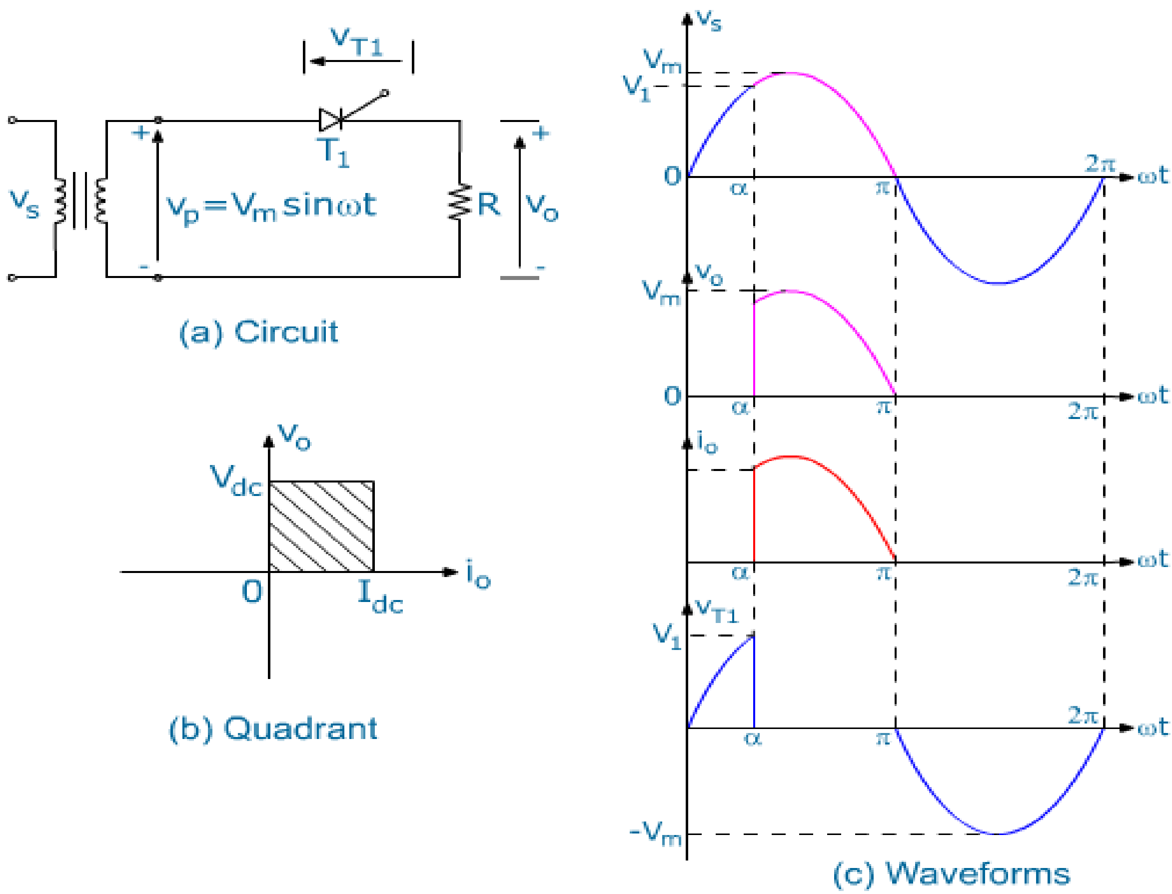
APPLICATIONS OF RECTIFIERS

- DC MOTOR SPEED CONTROL
- DC SUPPLY FOR INVERTERS
- ELECTROCHEMICAL PROCESSES
- DC TRACTION
- HVDC TRANSMISSION

RECTIFIERS

- SINGLE PHASE HALF WAVE RECTIFIER WITH R,RL,RLE LOAD
- SINGLE PHASE FULL WAVE RECTIFIER WITH R ,RL, RLE LOAD
- THREE PHASE HALF WAVE RECTIFIER WITH R,RL LOAD
- THREE PHASE FULL WAVE RECTIFIER WITH R,RL LOAD

SINGLE PHASE HWR WITH R LOAD



FIRING ANGLE α

- ANGLE BETWEEN THE ZERO CROSSING OF THE INPUT VOLTAGE AND THE INSTANT THYRISTOR IS FIRED.

AVERAGE OUTPUT VOLTAGE OF SINGLE PHASE HWR WITH R LOAD

The average output voltage $\mathbf{V_{dc}}$ is given by

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d(\omega t)$$

$$V_{dc} = \frac{V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$V_{dc} = \frac{V_m}{2\pi}\left(1+\cos\alpha\right)$$

The output voltage $\mathbf{V_{dc}}$ can be varied from $\mathbf{V_m}/\pi$ to zero as the firing angle α varies from zero to π.

RMS OUTPUT VOLTAGE OF SINGLE PHASE HWR WITH R LOAD

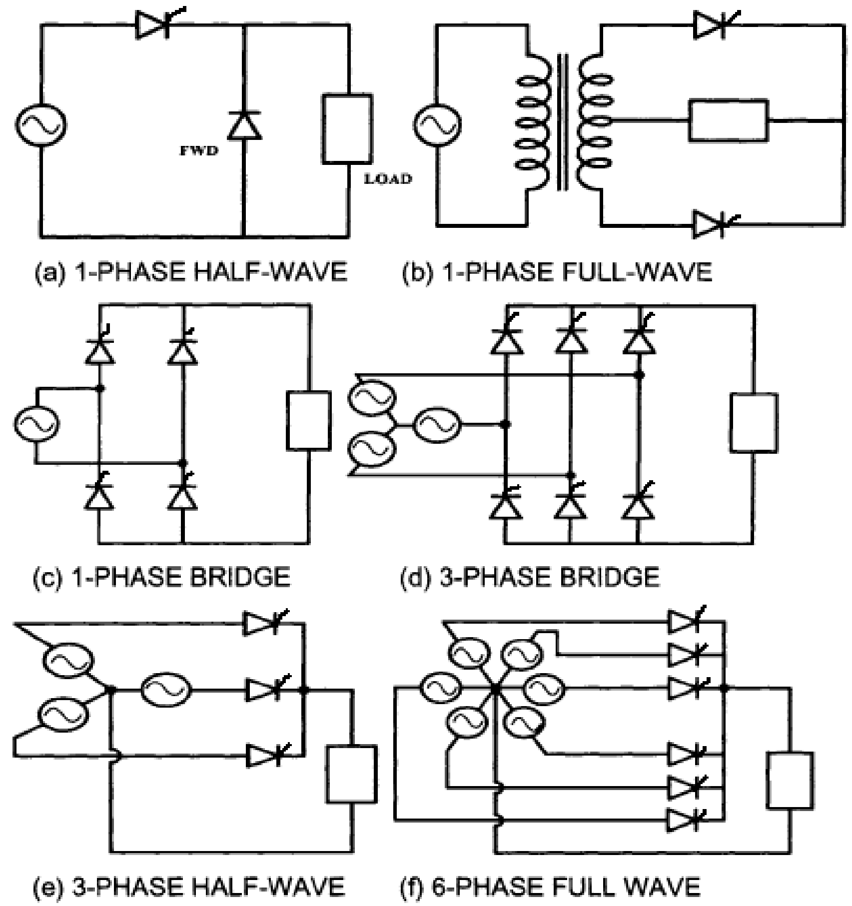
The rms output voltage is given by

$$V_{rms} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \, d(\omega t)\right]^{1/2}$$

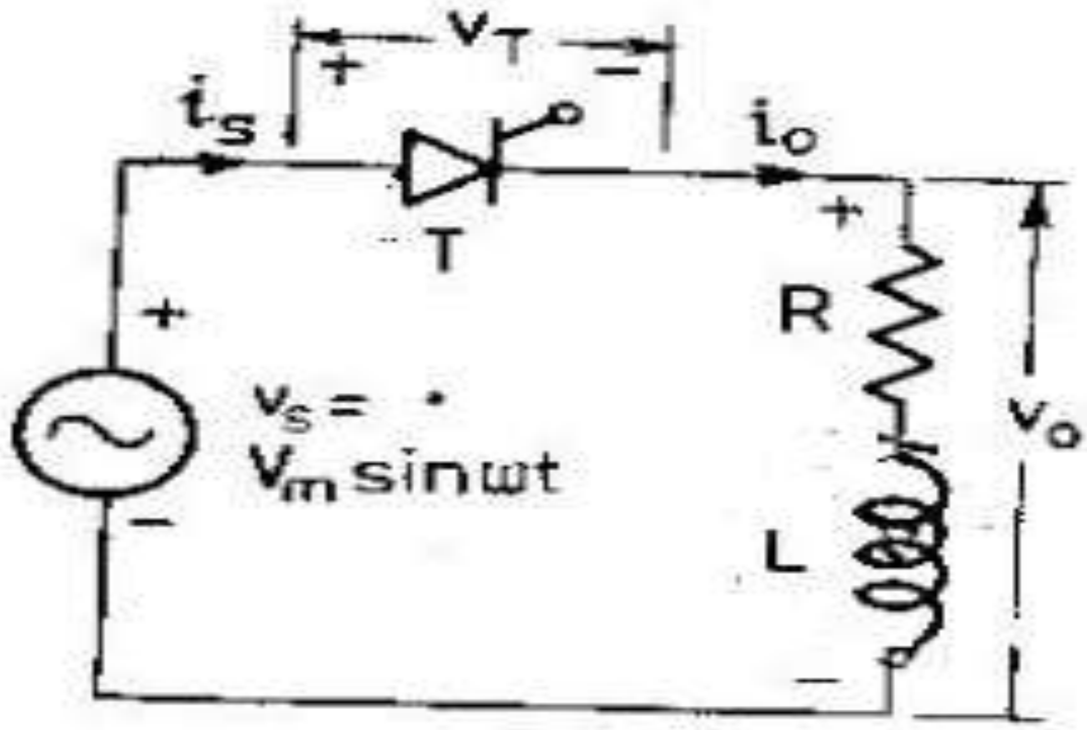
$$V_{rms} = \left[\frac{V_m^2}{4\pi}\int_{\alpha}^{\pi} (1 - \cos 2\omega t) \, d(\omega t)\right]^{1/2}$$

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

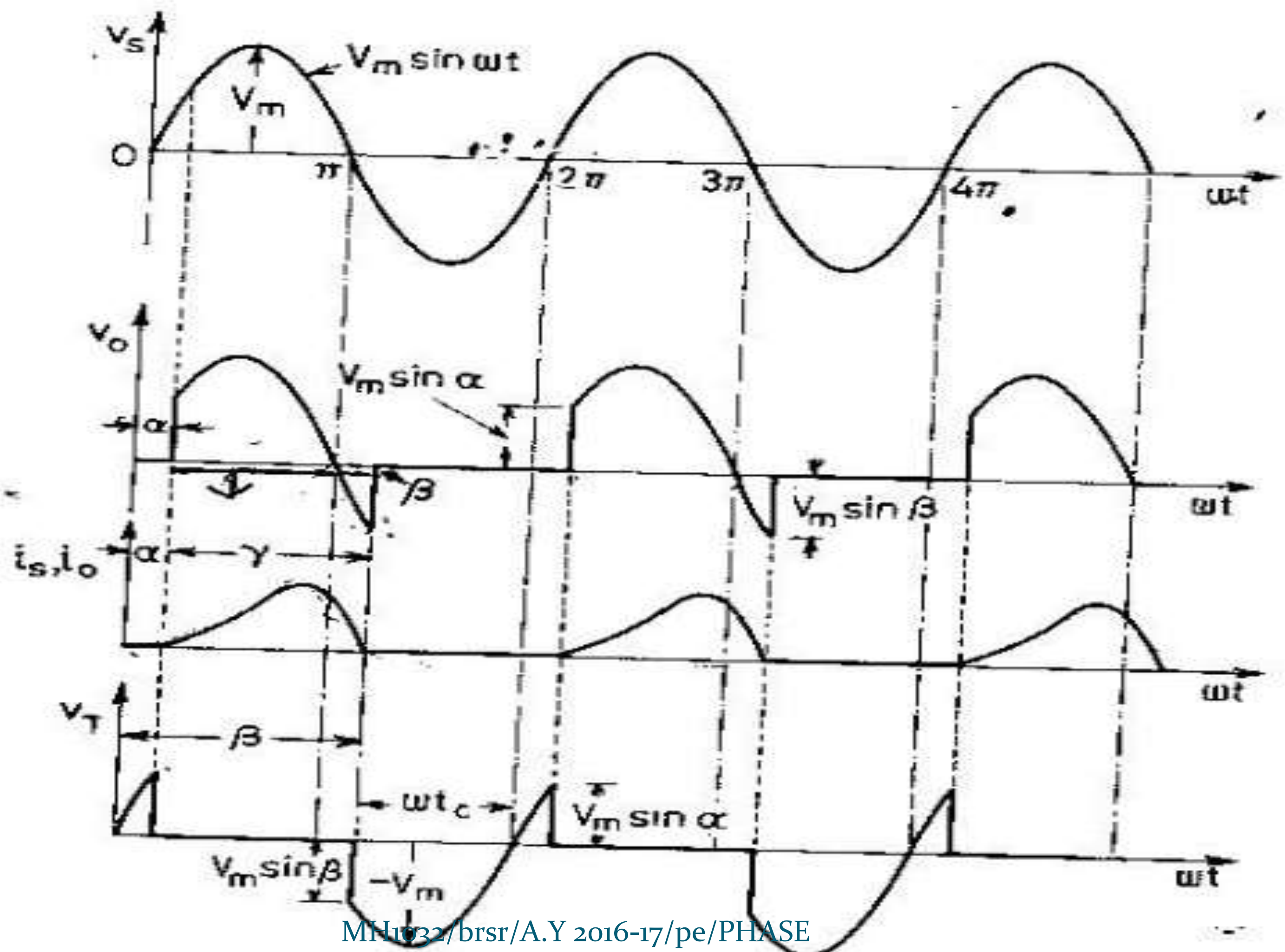
PRINCIPAL TOPOLOGIES OF PHASE CONTROLLED RECTIFIERS



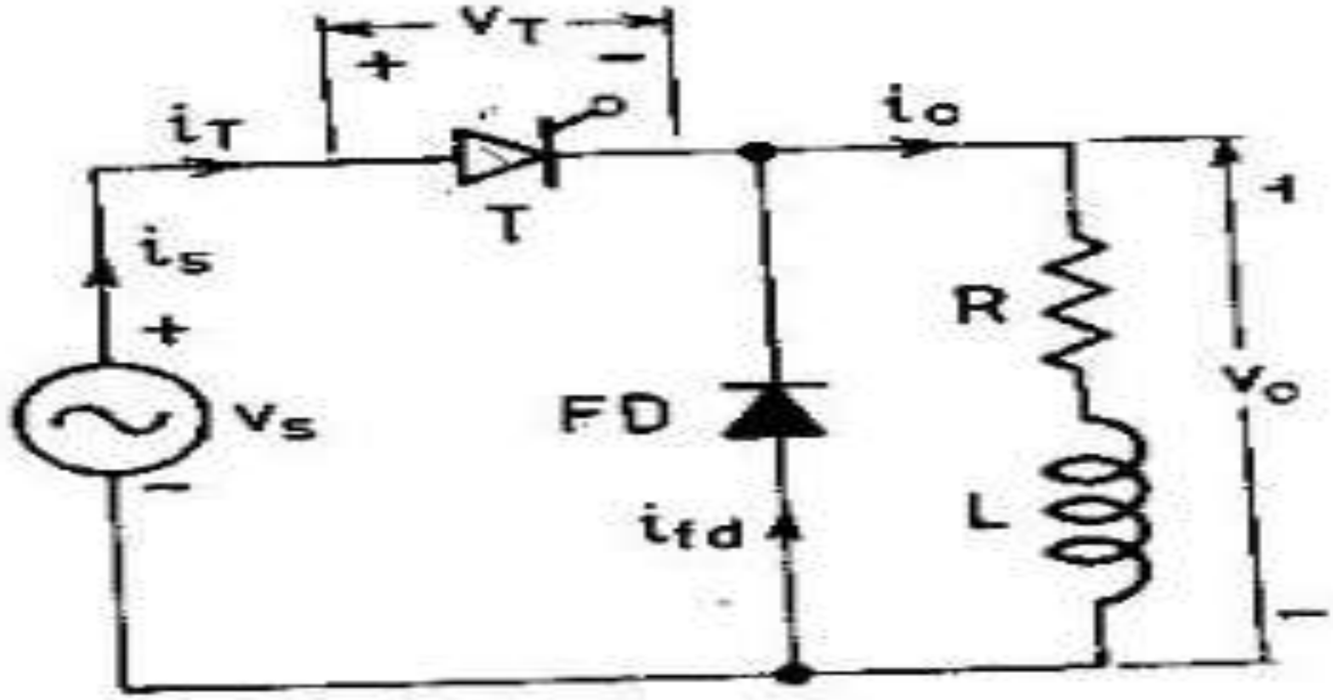
SINGLE PHASE HWR WITH RL LOAD



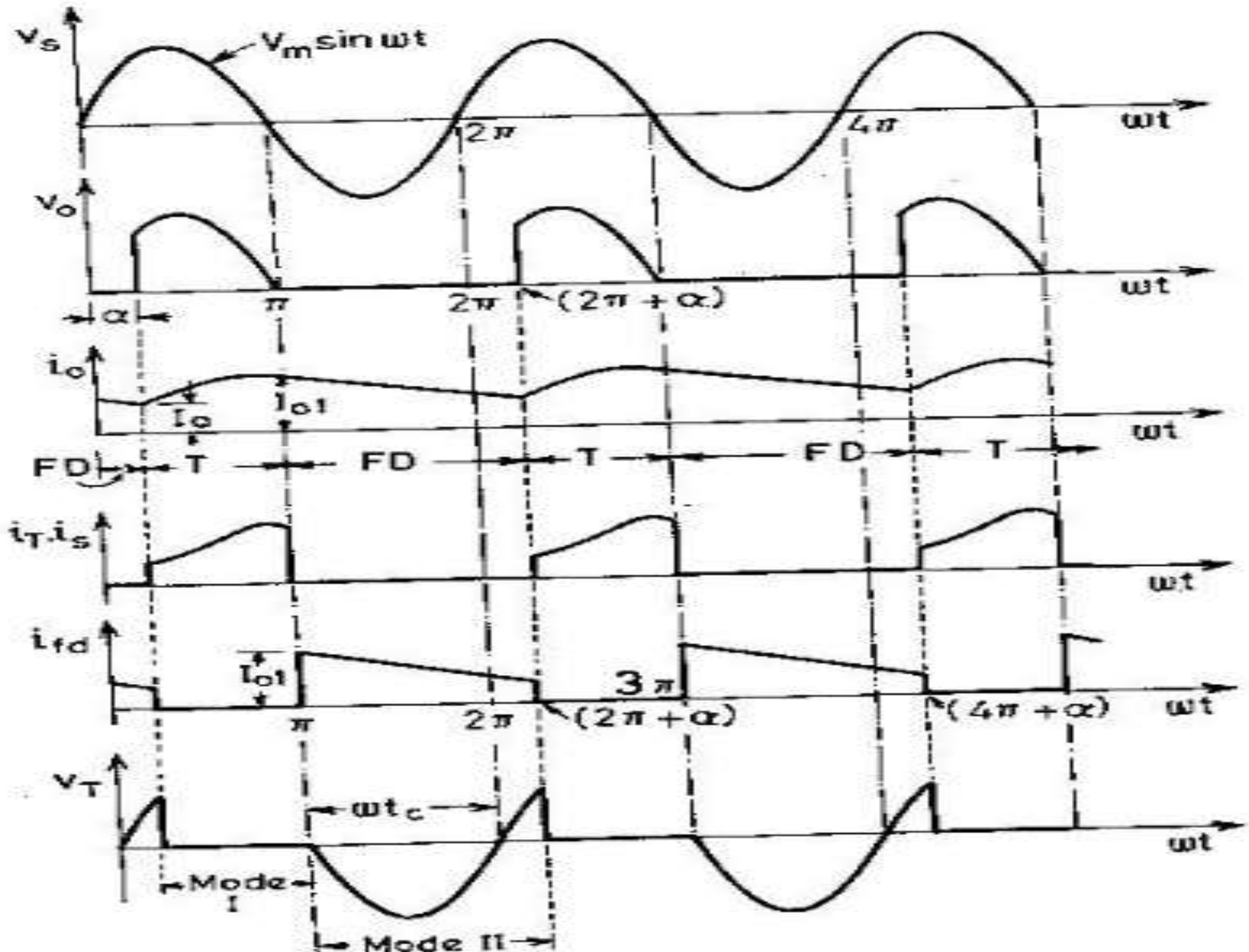
WAVEFORMS OF HWR SINGLE PHASE WITH RL LOAD



SINGLE PHASE HWR WITH RL LOAD AND FD



WAVEFORMS OF SINGLE PHASE HWR WITH RL LOAD AND FD



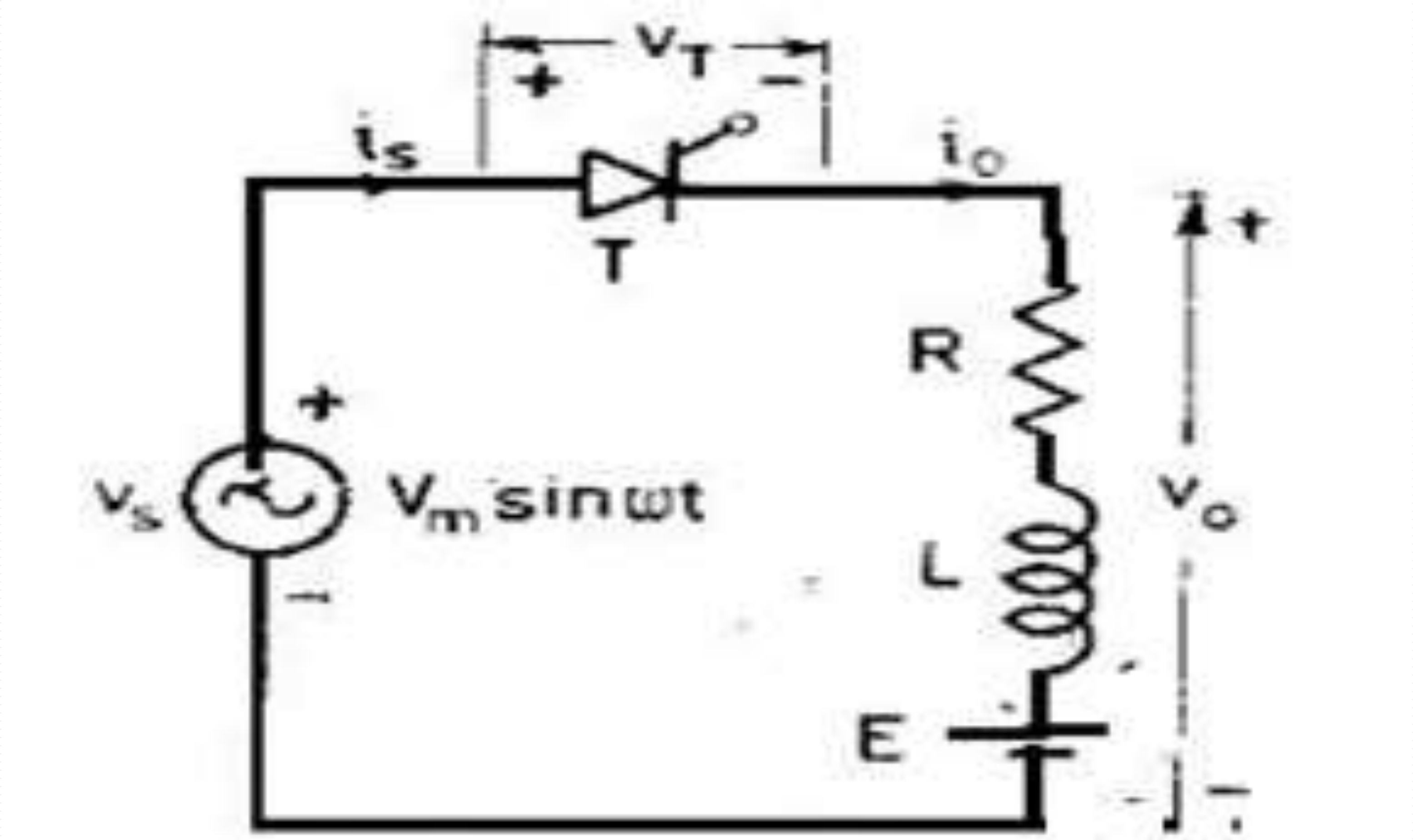
ADVANTAGES OF USING FREEWHEELING DIODE

- INPUT POWER FACTOR IS IMPROVED
- LOAD CURRENT WAVEFORM IS IMPROVED AND LOAD PERFORMANCE IS BETTER.

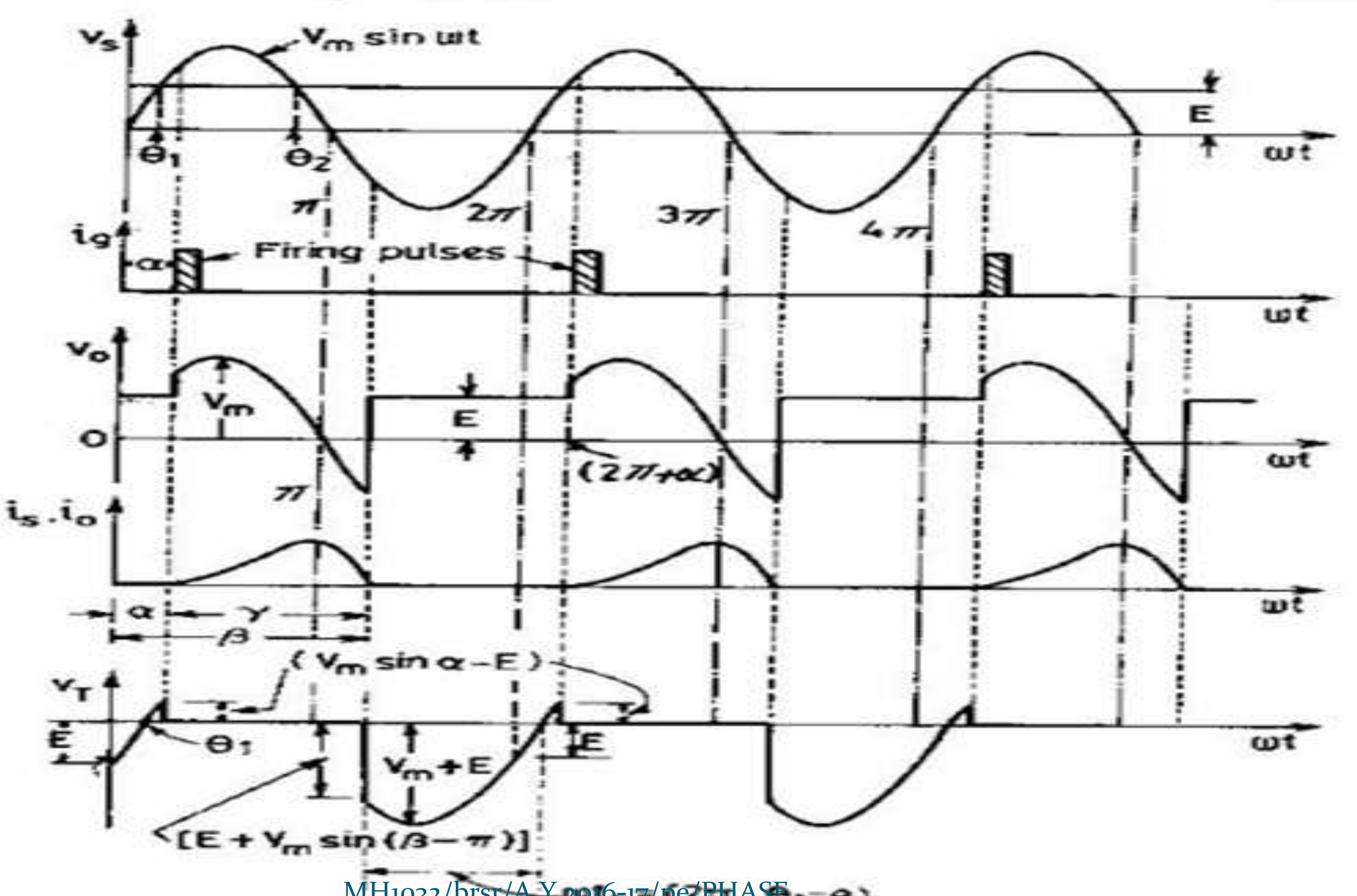
MAIN FUNCTIONS OF **FWD**

- IT PREVENTS THE REVERSAL OF LOAD VOLTAGE EXCEPT FOR A SMALL VOLTAGE DROP
- IT TRANSFERS THE LOAD CURRENT AWAY FROM THE MAIN RECTIFIER THEREBY ALLOWING ALL THE THYRISTORS TO REGAIN THEIR BLOCKING STATES

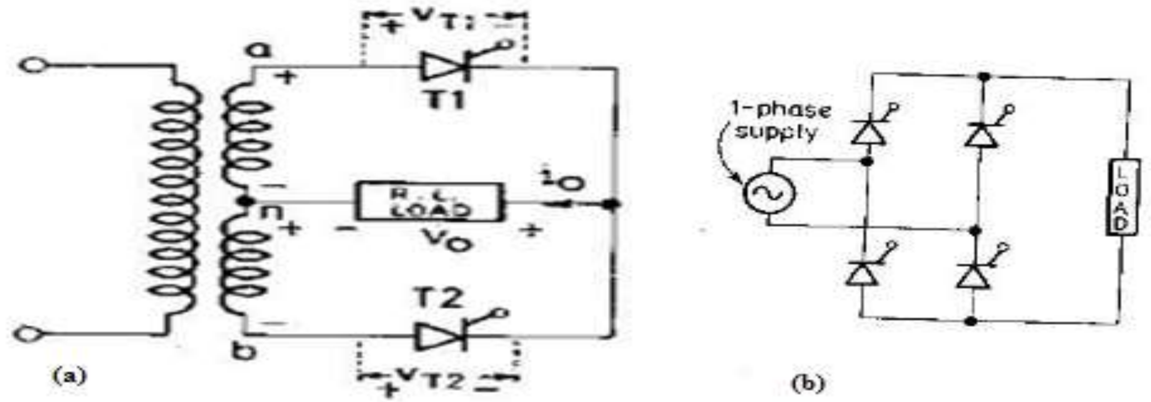
SINGLE PHASE HWR WITH RLE LOAD



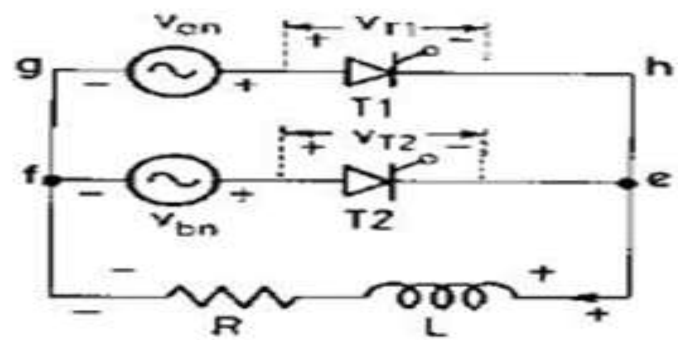
WAVEFORMS OF SINGLE PHASE HWR WITH RLE LOAD



SINGLE PHASE FULL WAVE CONVERTER WITH RL LOAD AND ITS EQUIVALENT CIRCUIT

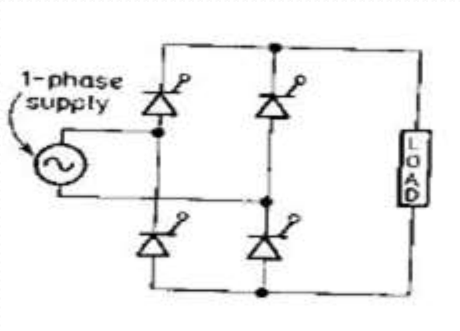


(a)FULL WAVE MID-POINT CONVERTER (b)FULL WAVE BRIDGE CONVERTER

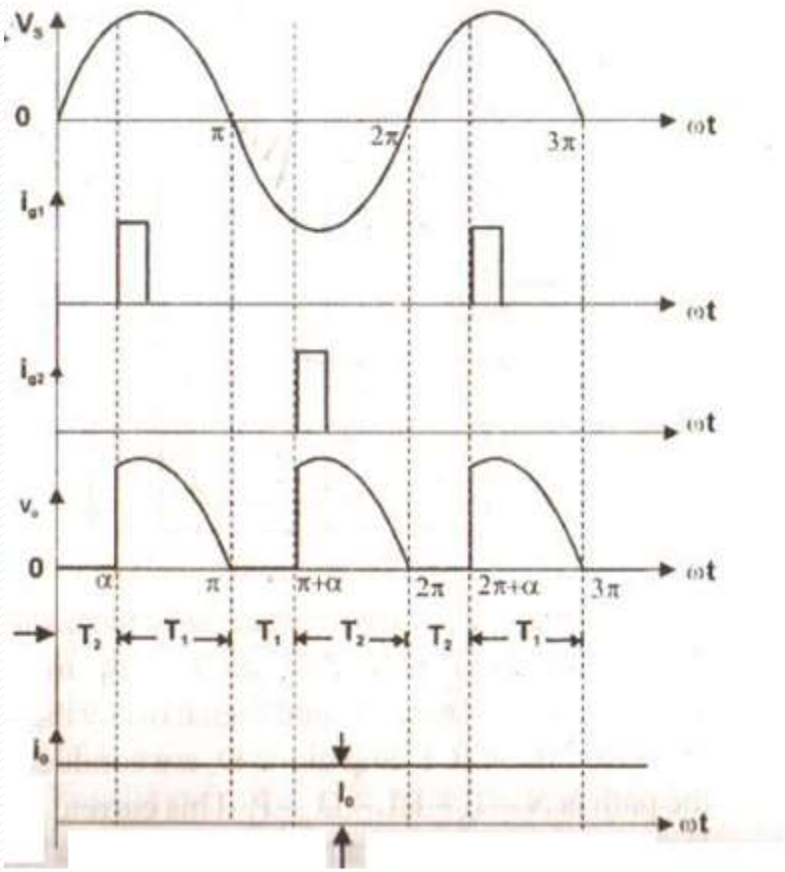


EQUIVALENT CIRCUIT OF FULL WAVE MID-POINT CONVERTER

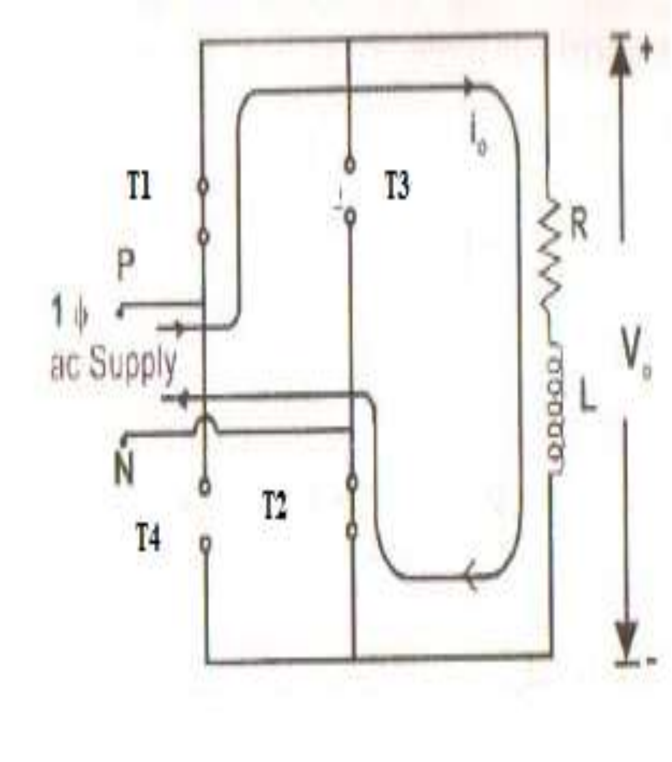
FULL WAVE RECTIFIER

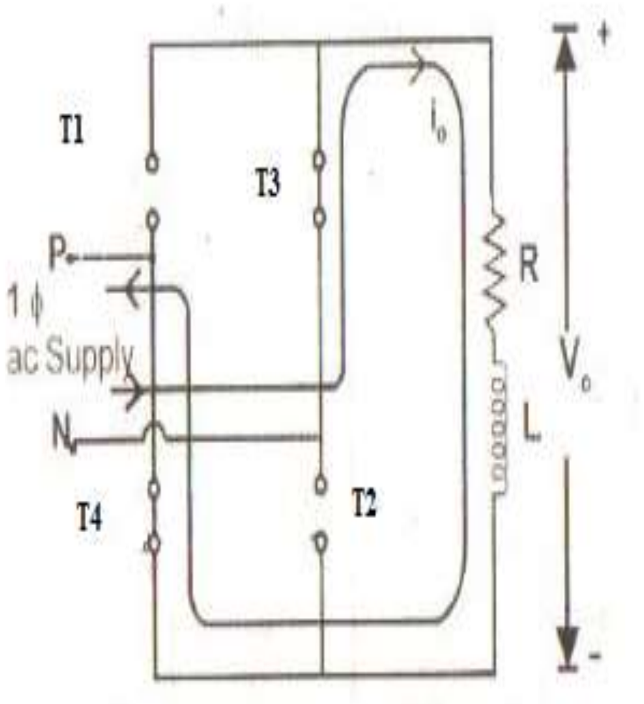


FULL WAVE RECTIFIER WITH R LOAD

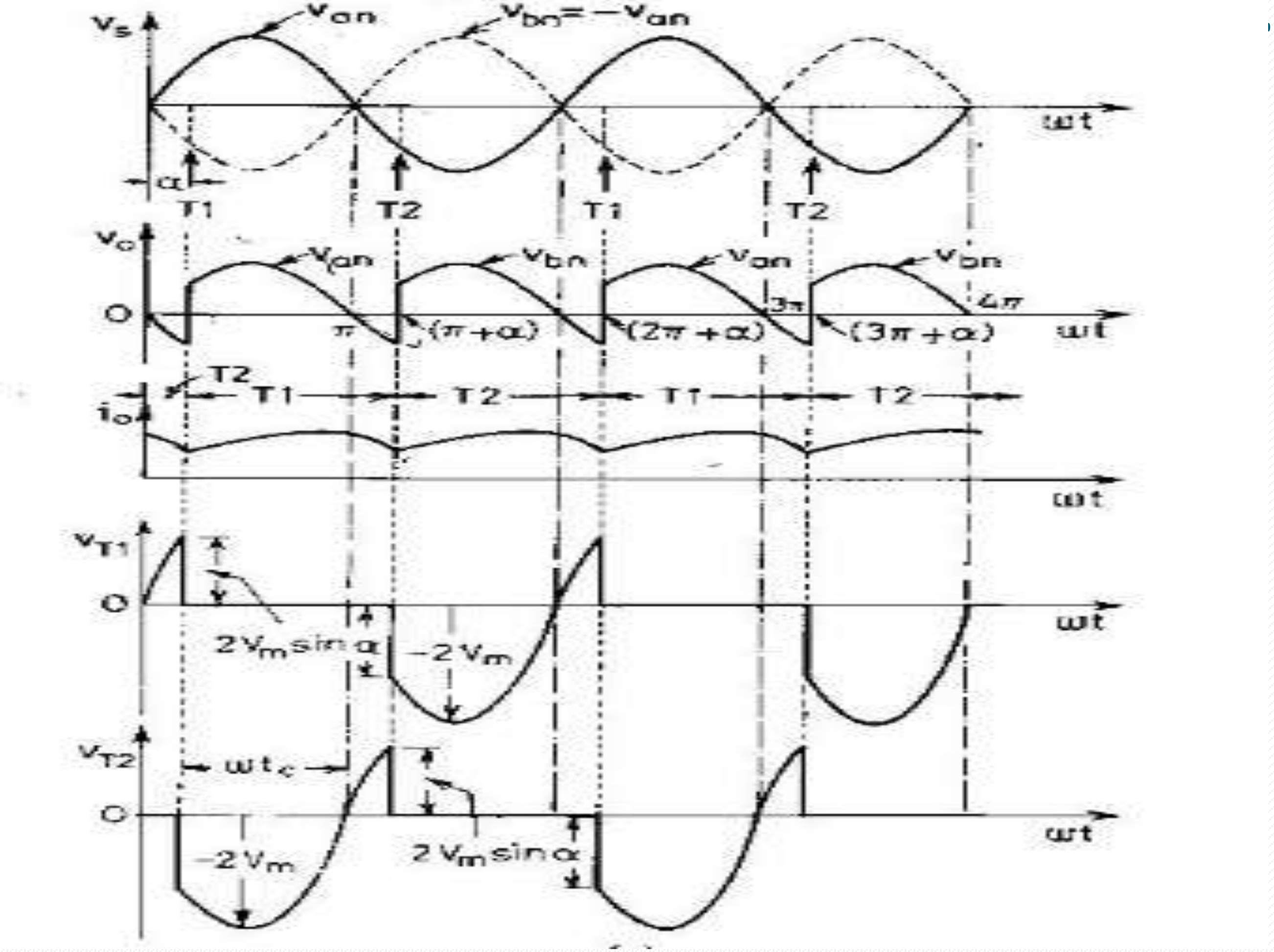


OPERATION OF FWR WITH RL LOAD





WAVEFORMS OF FULL WAVE MID-POINT CONVERTER WITH RL LOAD



SINGLE PHASE FULL WAVE CONTROLLED BRIDGE RECTIFIER WITH R LOAD

SINGLE PHASE FULL WAVE CONTROLLED BRIDGE RECTIFIER WITH R LOAD

(i) Average output voltage (V_{dc})

$$V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)$$

(ii) Average load Current (I_{dc})

$$I_{dc} = \frac{V_m}{\pi R}(1+\cos\alpha)$$

(iii) Rms load Voltage (V_{rms})

$$V_{rms} = [\frac{1}{\pi}\int_{\alpha}^{\pi} V_m^{\,2}\sin^2 \omega t.d\omega t]^{\frac{1}{2}}$$

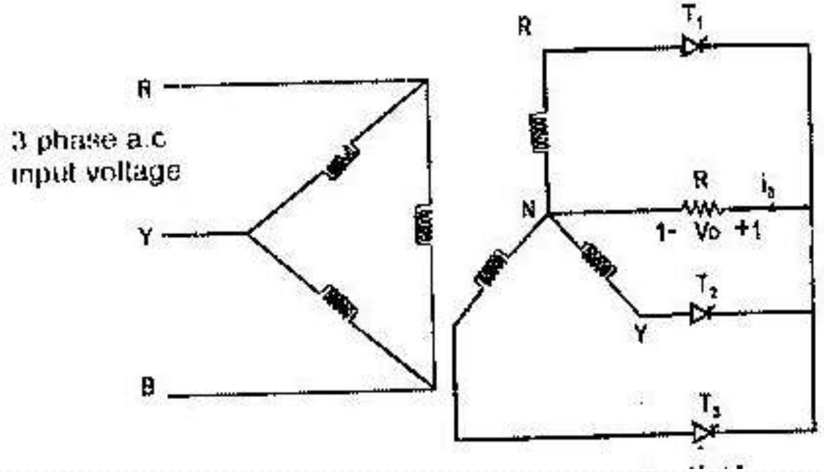
$$V_{rms} = V_m[\frac{\pi-\alpha}{2\pi}+\frac{\sin 2\alpha}{4\pi}]^{\frac{1}{2}}$$

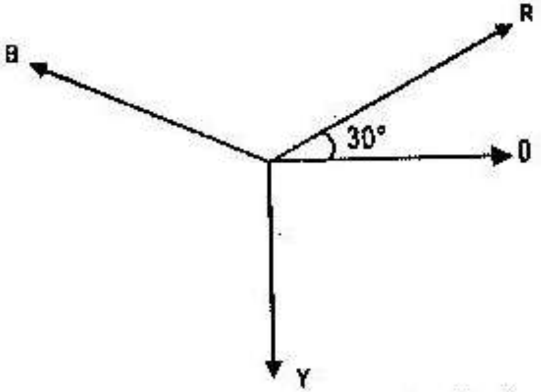
(iv) $$I_{rms} = \frac{V_{rms}}{R}$$

THREE PHASE CONTROLLED RECTIFIERS

- ADVANTAGES
  - REDUCED RIPPLE CONTENT IN THE OUTPUT VOLTAGE
  - CAN BE USED FOR HIGH POWER APPLICATIONS
- TYPES
  - THREE PULSE CONVERTERS
  - SIX PULSE CONVERTERS
  - TWELVE PULSE CONVERTERS (HIGHER THE NO.OF PULSES, SMOOTHER IS THE OUTPUT VOLTAGE)

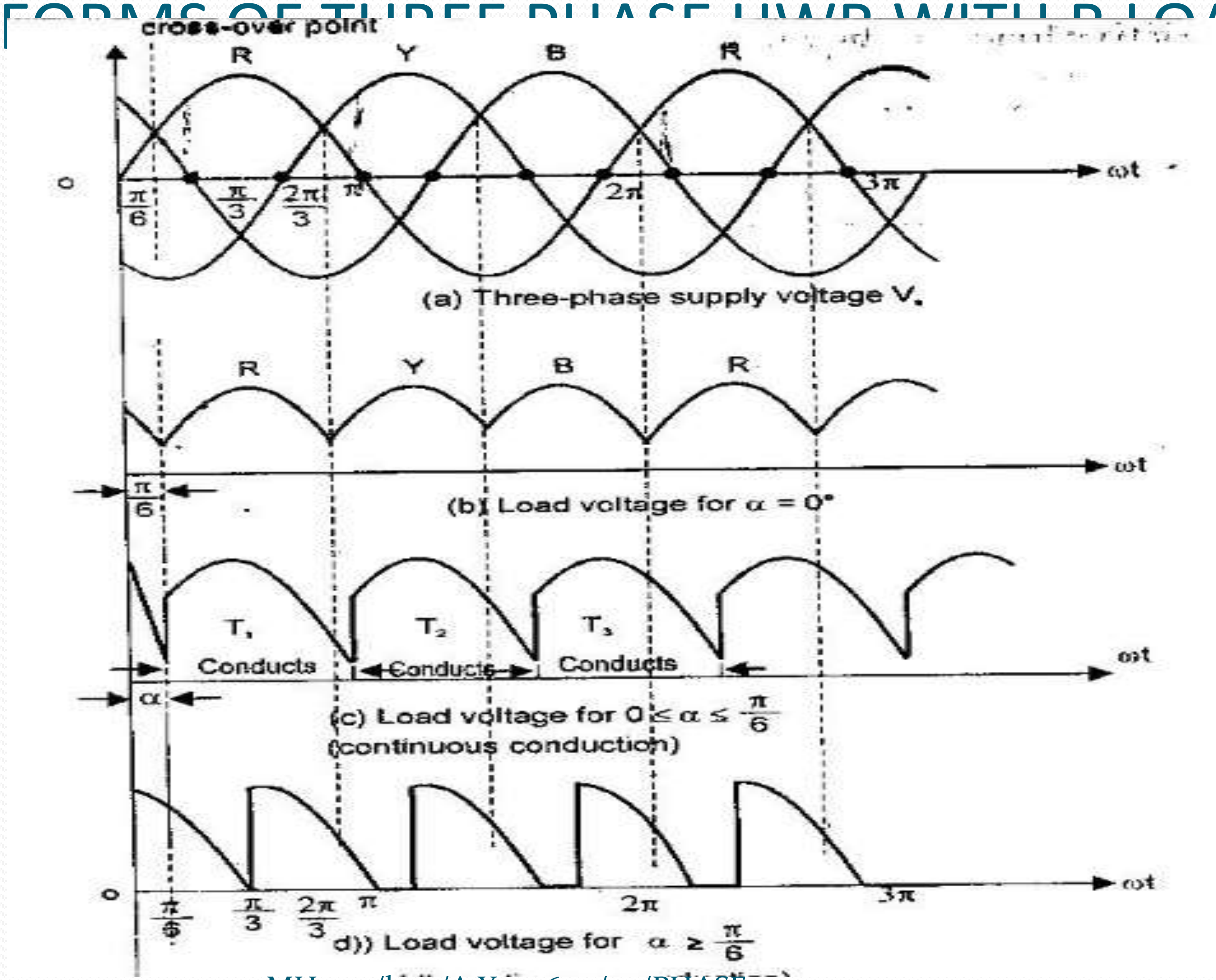
THREE PHASE HALF WAVE RECTIFIER WITH R LOAD



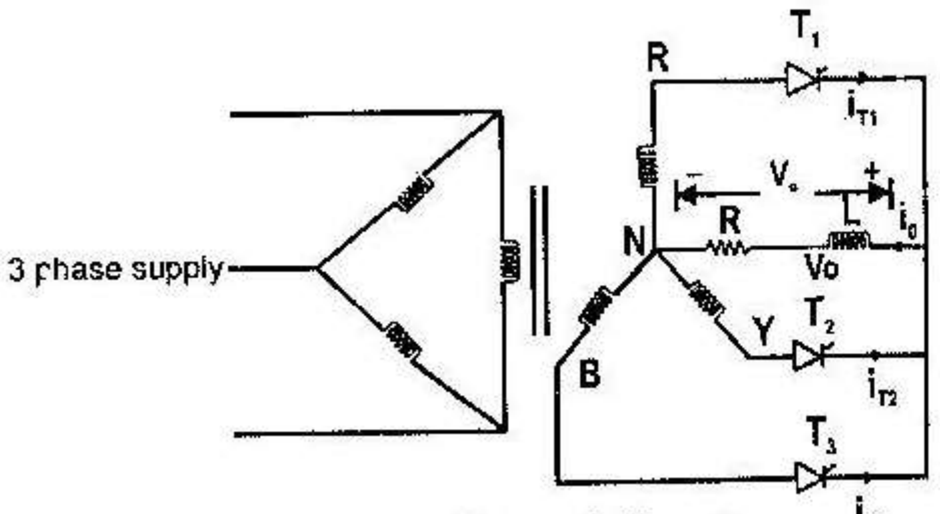


Vector diagram for 3 phase voltage

WAVEFORMS OF THREE PHASE HWR WITH R LOAD

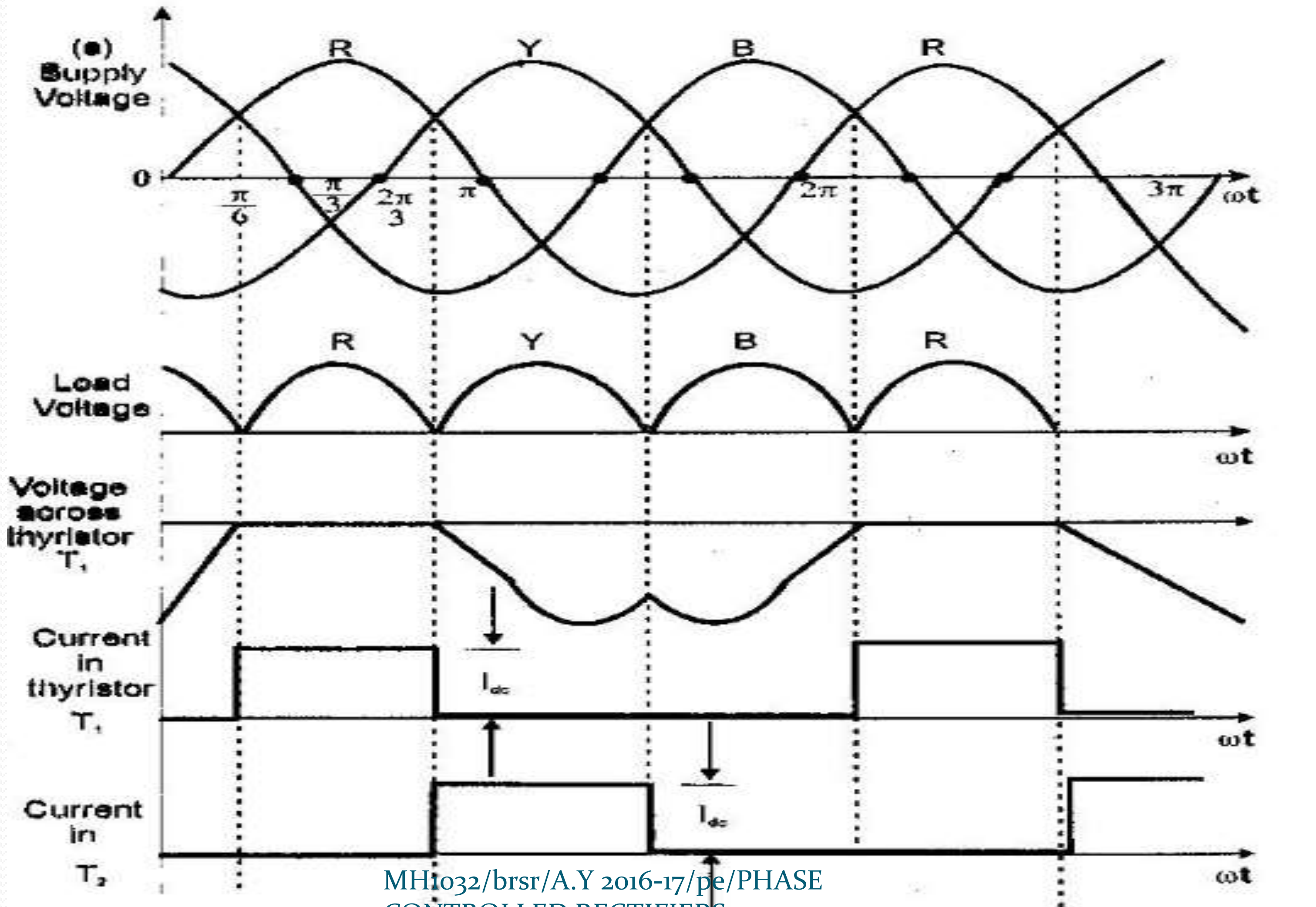


THREE PHASE HWR WITH RL LOAD

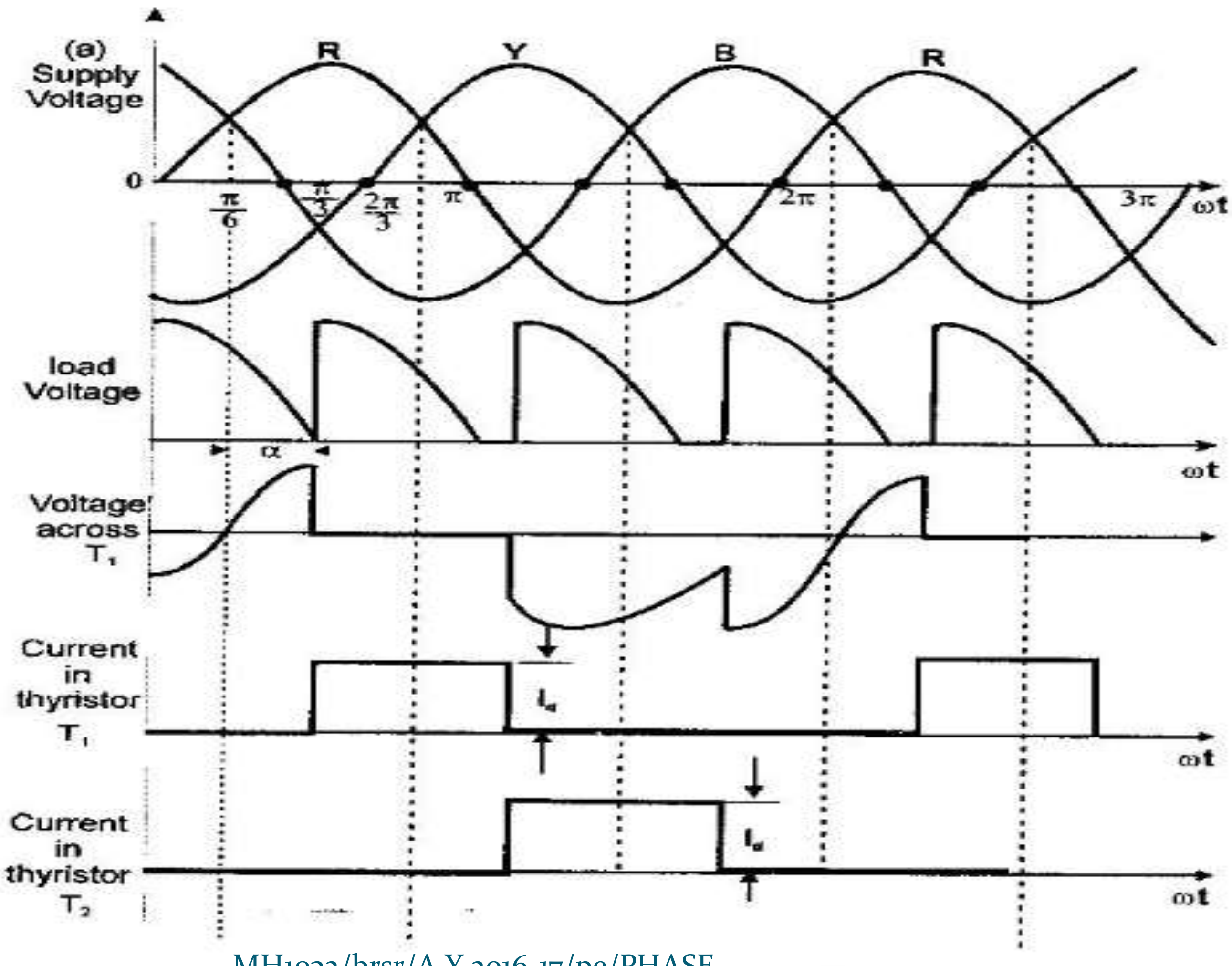


3 phase half wave
controlled rectifier with RL load

WAVEFORMS OF THREE PHASE HWR WITH RL LOAD ($\alpha=0^0$)

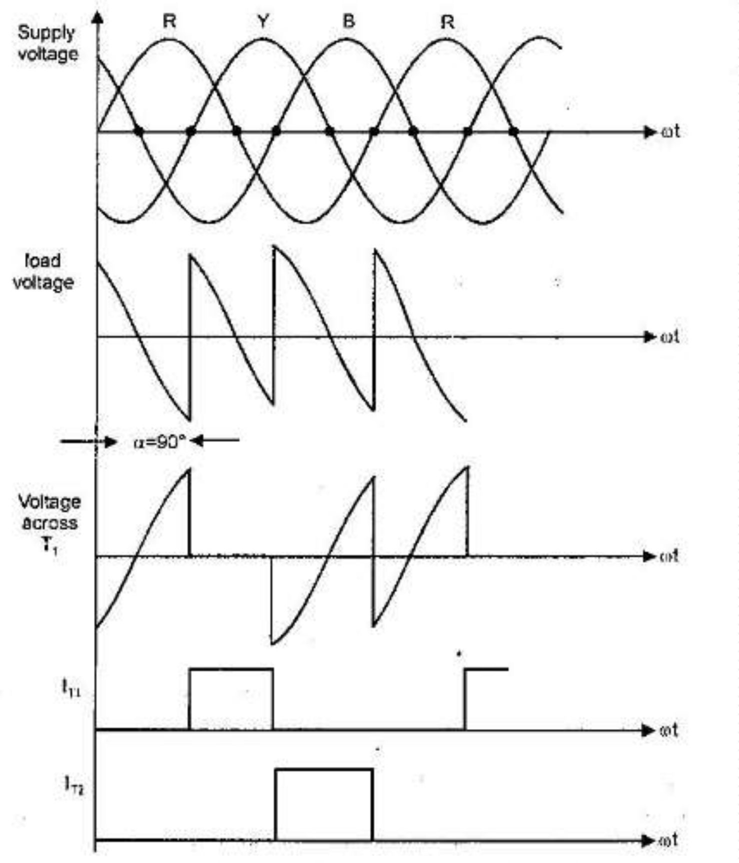


WAVEFORMS OF THREE PHASE HWR WITH RL LOAD (α=45^0)



Voltage and current waveforms for α=45°

WAVEFORMS OF THREE PHASE HWR WITH RL LOAD ($\alpha=90^0$)



Voltage and current waveforms for α=90°

THREE PHASE HALF WAVE CONTROLLED RECTIFIER WITH R LOAD

THREE PHASE HALF WAVE CONTROLLED RECTIFIER WITH R LOAD

(i) Average output voltage (V_{dc})

$$V_{dc} = \frac{3\sqrt{3}}{2\pi} V_m \cos\alpha$$

(ii) Average load Current (I_{dc})

$$I_{dc} = \frac{3\sqrt{3}}{2\pi R} V_m \cos\alpha$$

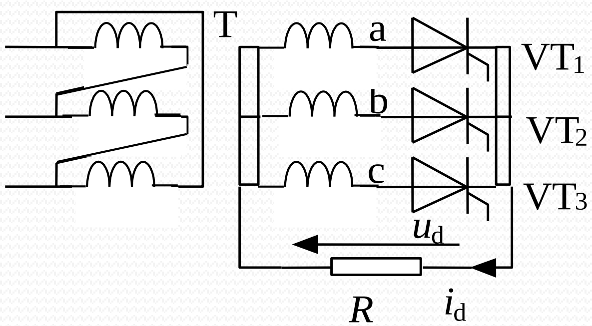
(iii) Rms load Voltage (V_{rms})

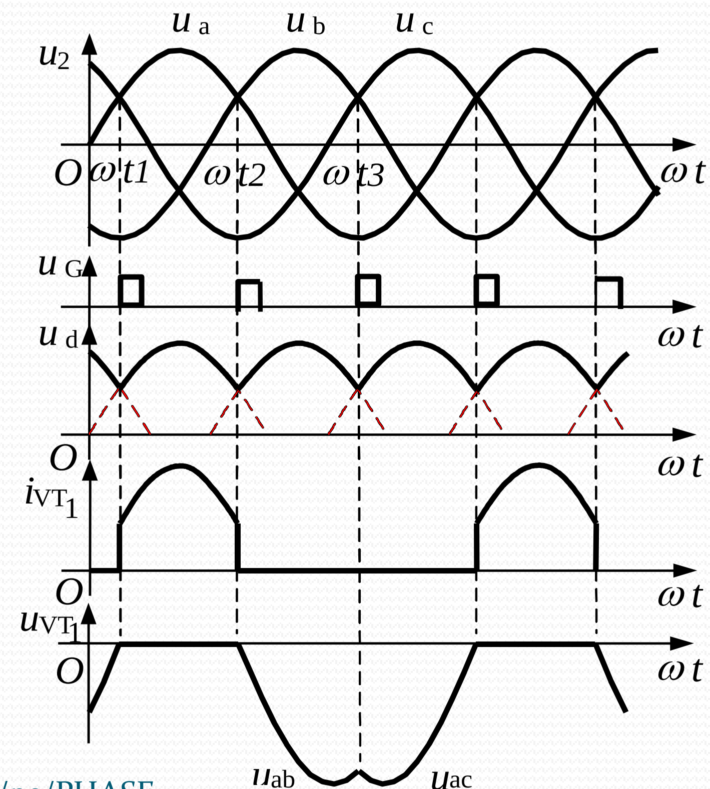
$$V_{rms} = [\frac{1}{2} + \frac{3\sqrt{3}}{8\pi} \cos 2\alpha]^{\frac{1}{2}}$$

THREE- PHASE HALF WAVE CONTROLLED RECTIFIER

Three- phase half- wave controlled rectifier

Resistive load, α= 0º

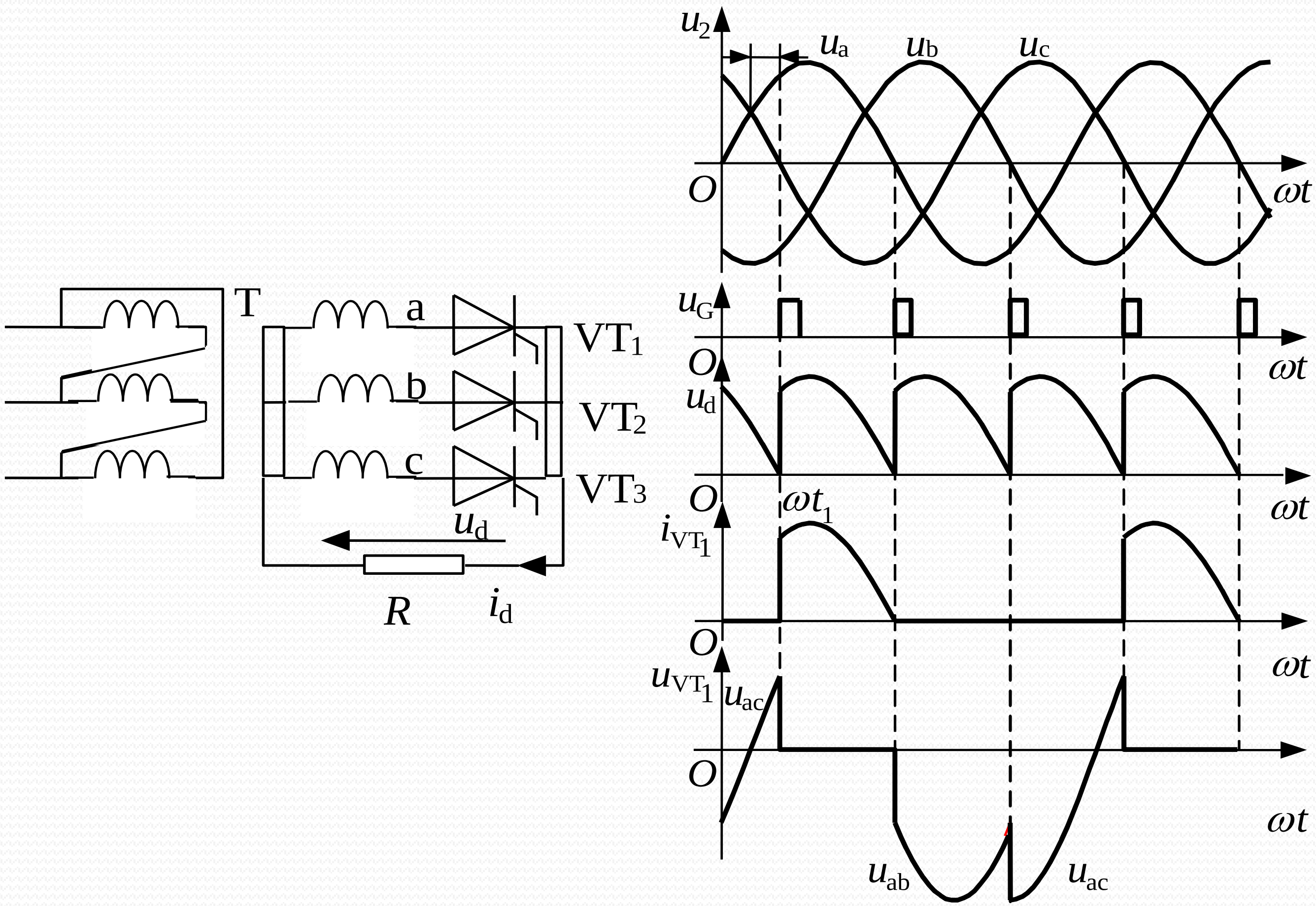




Common-cathode connection

Natural commutation point

Resistive load, α= 30º



UNIT III
DC - DC CONVERTERS
DC Choppers

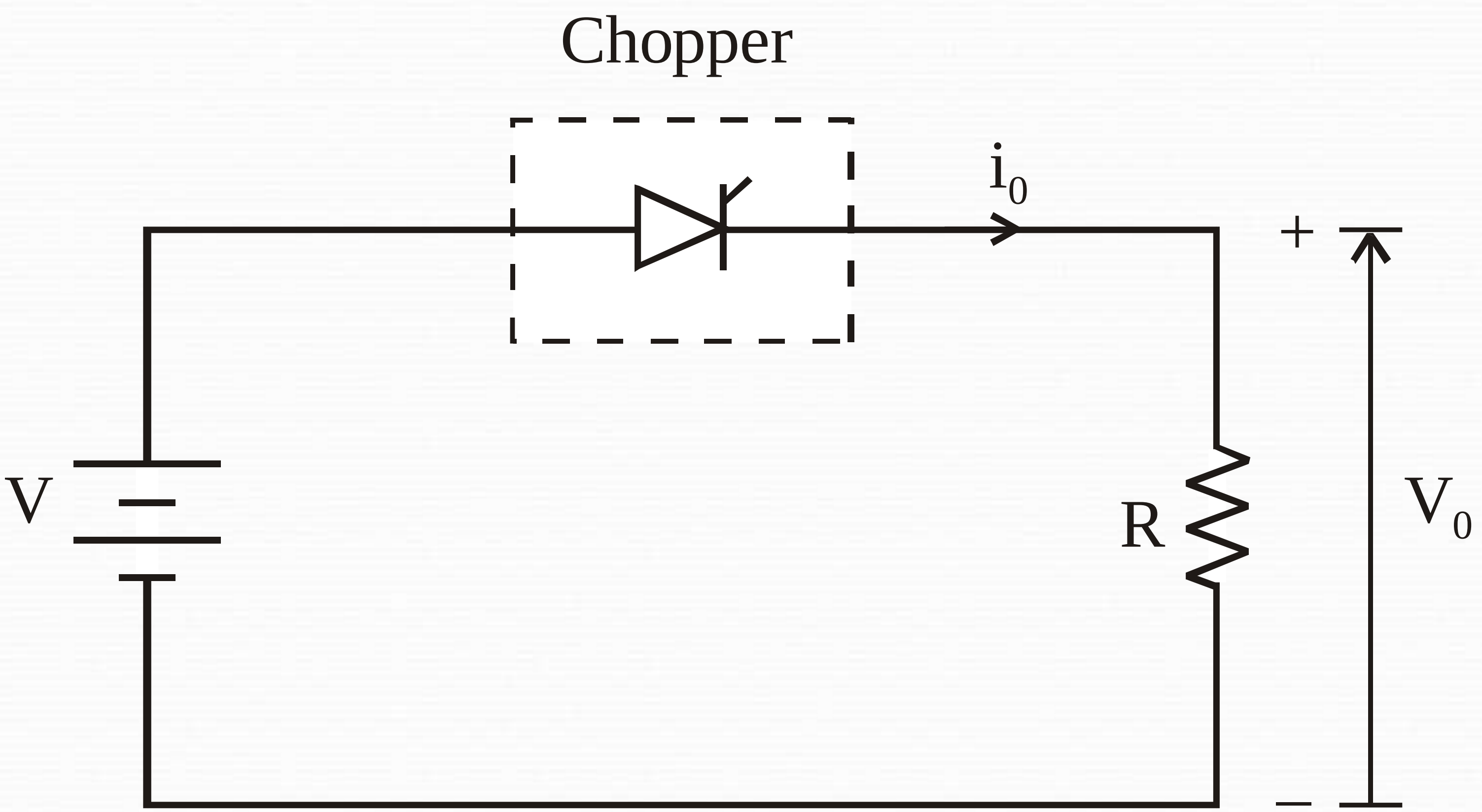
Introduction

- Chopper is a static device.
- A variable dc voltage is obtained from a constant dc voltage source.
- Also known as dc-to-dc converter.
- Widely used for motor control.
- Also used in regenerative braking.
- Thyristor converter offers greater efficiency, faster response, lower maintenance, smaller size and smooth control.

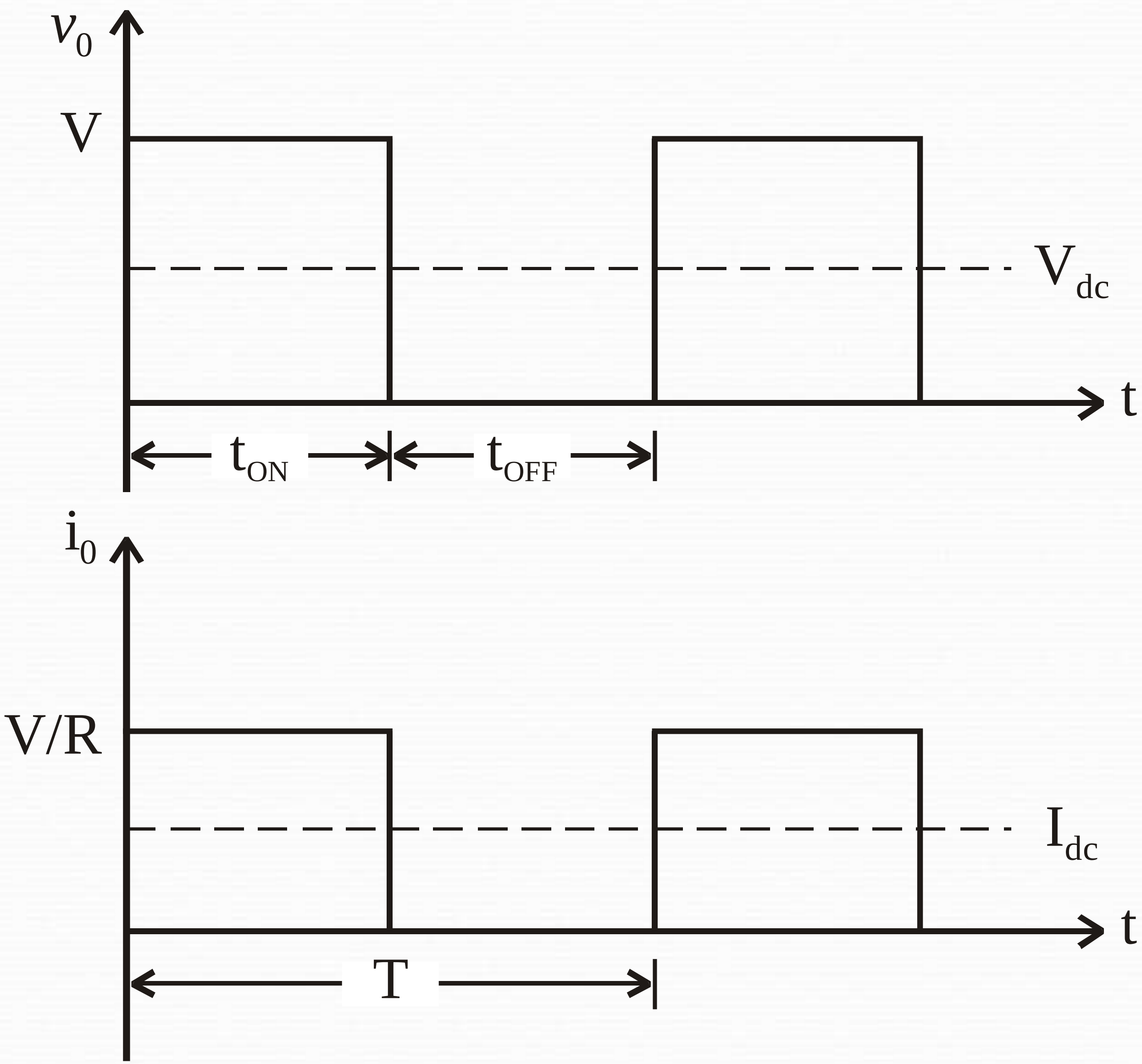
Choppers are of Two Types

- Step-down choppers.
- Step-up choppers.
  - In step down chopper output voltage is less than input voltage.
  - In step up chopper output voltage is more than input voltage.

Principle Of
Step-down Chopper



- A step-down chopper with resistive load.
- The thyristor in the circuit acts as a switch.
- When thyristor is ON, supply voltage appears across the load
- When thyristor is OFF, the voltage across the load will be zero.



v_0
V
V_{dc}
t
t_{ON}
t_{OFF}
i_0
V/R
I_{dc}
t
T

$$V_{dc} = \text{Average value of output or load voltage.}$$

$$I_{dc} = \text{Average value of output or load current.}$$

$$t_{ON} = \text{Time interval for which SCR conducts.}$$

$$t_{OFF} = \text{Time interval for which SCR is OFF.}$$

$$T = t_{ON} + t_{OFF} = \text{Period of switching or chopping period.}$$

$$f = \frac{1}{T} = \text{ Freq. of chopper switching or chopping freq.}$$

Average Output Voltage

$$V_{dc} = V\left(\frac{t_{ON}}{t_{ON} + t_{OFF}}\right)$$

$$V_{dc} = V\left(\frac{t_{ON}}{T}\right) = V.d$$

$$but\ \left(\frac{t_{ON}}{t}\right) = d = \text{duty cycle}$$

Average Output Current

$$I_{dc} = \frac{V_{dc}}{R}$$

$$I_{dc} = \frac{V}{R}\left(\frac{t_{ON}}{T}\right) = \frac{V}{R}d$$

RMS value of output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} v_o^2 dt}$$

But during t_{ON}, $v_o = V$

Therefore RMS output voltage

$$V_O = \sqrt{\frac{1}{T}\int_0^{t_{ON}} V^2 dt}$$

$$V_O = \sqrt{\frac{V^2}{T} t_{ON}} = \sqrt{\frac{t_{ON}}{T}}.V$$

$$V_O = \sqrt{d}.V$$

Output power $P_O = V_O I_O$

But $I_O = \frac{V_O}{R}$

$\therefore$ Output power

$$P_O = \frac{V_O^2}{R}$$

$$P_O = \frac{dV^2}{R}$$

Effective input resistance of chopper

$$R_i = \frac{V}{I_{dc}}$$

$$R_i = \frac{R}{d}$$

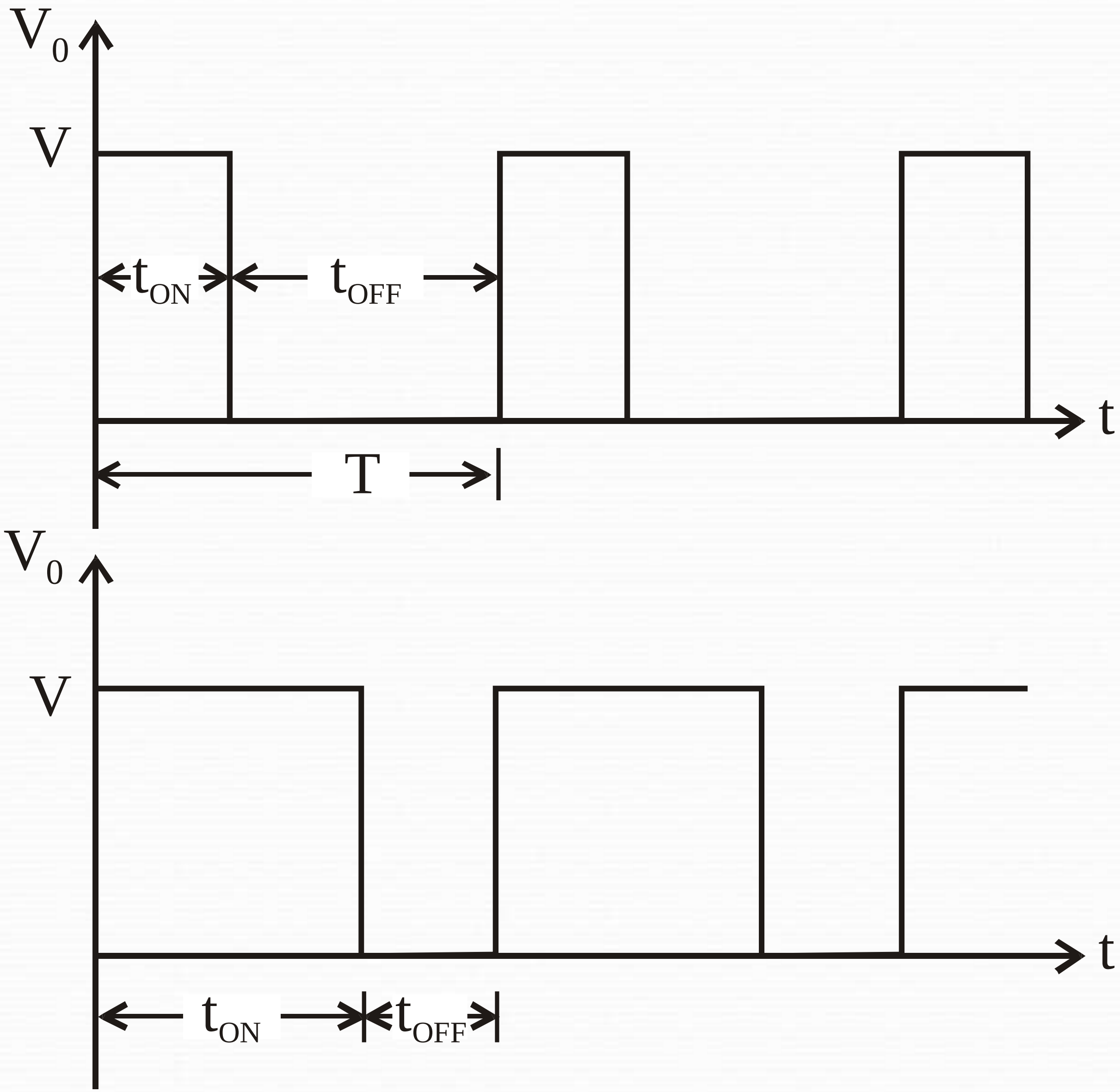
The output voltage can be varied by varying the duty cycle.

Methods Of Control

- The output dc voltage can be varied by the following methods.
  - Pulse width modulation control or constant frequency operation.
  - Variable frequency control.

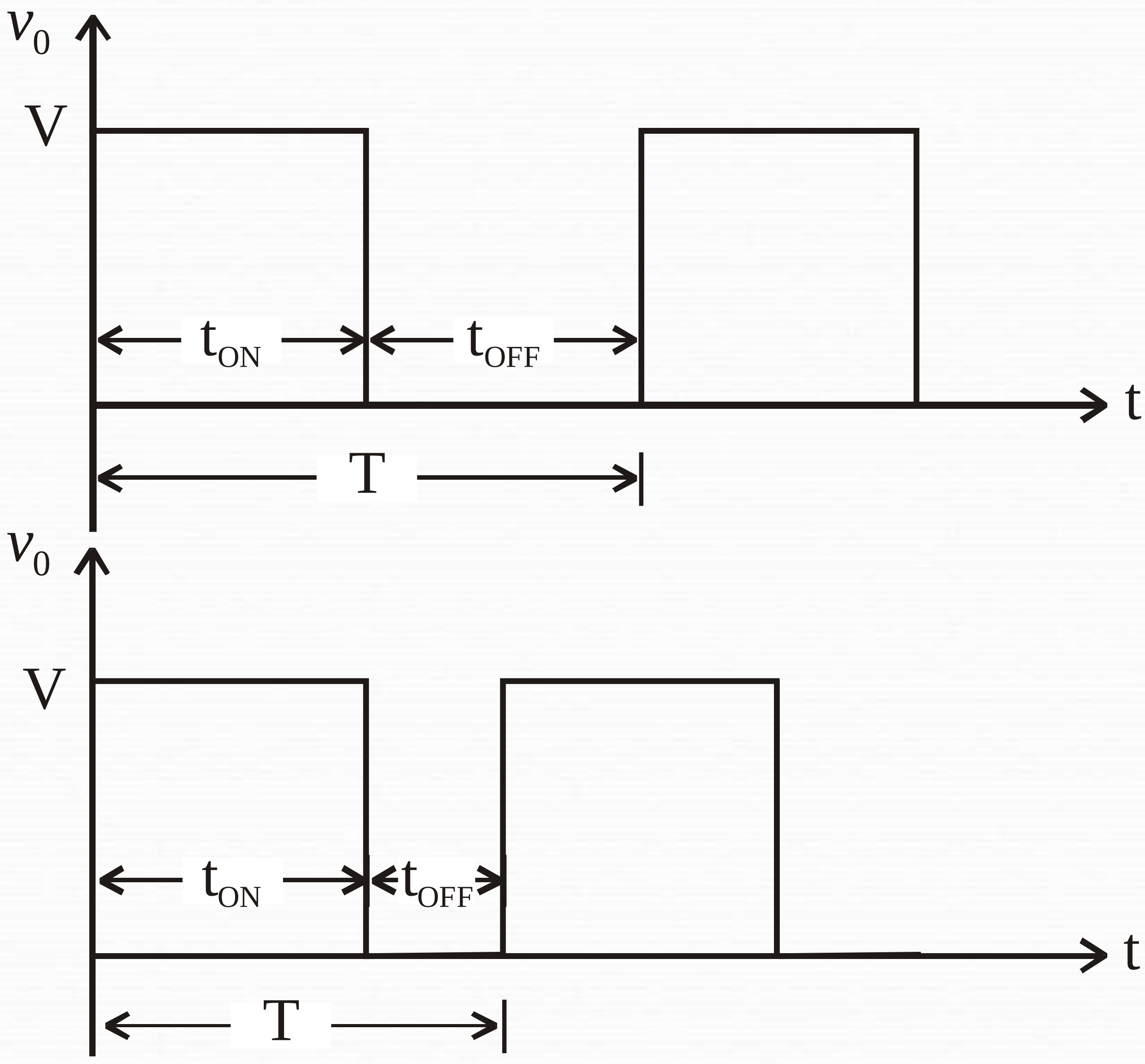
Pulse Width Modulation

- t_{ON} is varied keeping chopping frequency 'f' & chopping period 'T' constant.
- Output voltage is varied by varying the ON time t_{ON}


V0
V
tON
tOFF
t
T
V0
V
t
tON
tOFF

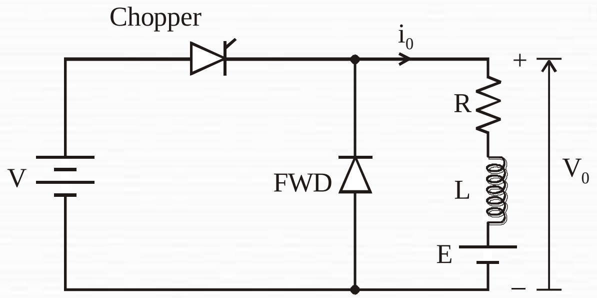
Variable Frequency Control

- Chopping frequency '*f*' is varied keeping either t_{ON} or t_{OFF} constant.
- To obtain full output voltage range, frequency has to be varied over a wide range.
- This method produces harmonics in the output and for large t_{OFF} load current may become discontinuous



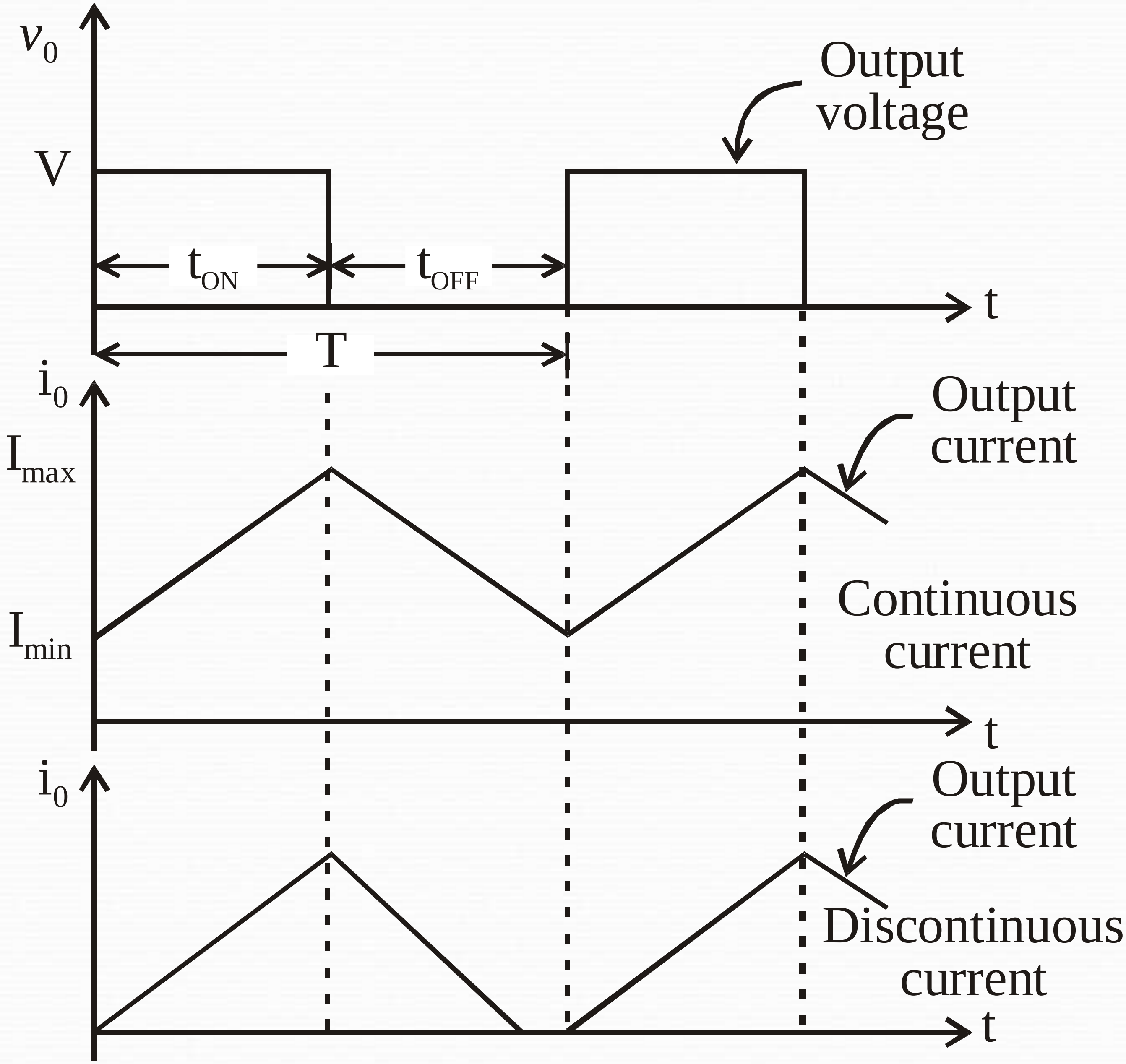
v_0
V
t_{ON}
t_{OFF}
t
T
v_0
V
t_{ON}
t_{OFF}
t
T

Step-down Chopper
With R-L Load



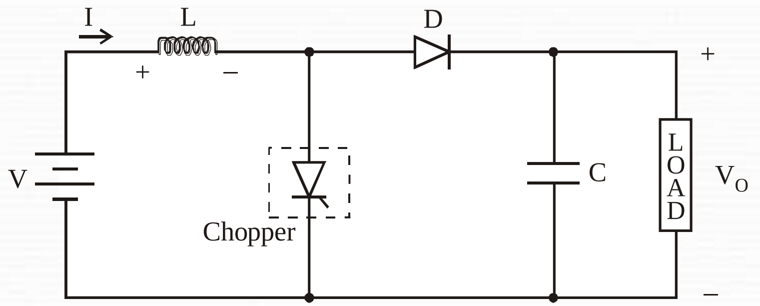
- When chopper is ON, supply is connected across load.
- Current flows from supply to load.
- When chopper is OFF, load current continues to flow in the same direction through FWD due to energy stored in inductor '*L*'.

- Load current can be continuous or discontinuous depending on the values of *'L'* and duty cycle *'d'*
- For a continuous current operation, load current varies between two limits I_{max} and I_{min}
- When current becomes equal to I_{max} the chopper is turned-off and it is turned-on when current reduces to I_{min}.



v_0
V
Output
voltage
t_{ON}
t_{OFF}
t
T
i_0
I_{max}
I_{min}
Output
current
Continuous
current
t
i_0
Output
current
Discontinuous
current
t

Principle Of Step-up Chopper



- Step-up chopper is used to obtain a load voltage higher than the input voltage *V*.
- The values of *L* and *C* are chosen depending upon the requirement of output voltage and current.
- When the chopper is *ON*, the inductor *L* is connected across the supply.
- The inductor current '*I*' rises and the inductor stores energy during the *ON* time of the chopper, t_{ON}.

- When the chopper is off, the inductor current *I* is forced to flow through the diode *D* and load for a period, t_{OFF}.
- The current tends to decrease resulting in reversing the polarity of induced EMF in *L*.
- Therefore voltage across load is given by

$$V_O = V + L\frac{dI}{dt} \quad i.e., \quad V_O > V$$

- A large capacitor 'C' connected across the load, will provide a continuous output voltage .
- Diode *D* prevents any current flow from capacitor to the source.
- Step up choppers are used for regenerative braking of dc motors.

Expression For Output Voltage

Assume the average inductor current to be

I during ON and OFF time of Chopper.

When Chopper is ON

Voltage across inductor $L = V$

Therefore energy stored in inductor

$$= V.I.t_{ON}$$

Where $t_{ON} = ON$ period of chopper.

When Chopper is OFF

(energy is supplied by inductor to load)

Voltage across $L = V_O - V$

Energy supplied by inductor $L = \left(V_O - V\right) It_{OFF}$

where $t_{OFF} = OFF$ period of Chopper.

Neglecting losses, energy stored in inductor

L = energy supplied by inductor L

$$\therefore \quad VIt_{ON} = \left(V_O - V\right) It_{OFF}$$

$$V_O = \frac{V\left[t_{ON} + t_{OFF}\right]}{t_{OFF}}$$

$$V_O = V\left(\frac{T}{T - t_{ON}}\right)$$

Where

T = Chopping period or period of switching.

$$T = t_{ON} + t_{OFF}$$

$$V_O = V\left(\frac{1}{1-\frac{t_{ON}}{T}}\right)$$

$$\therefore \qquad V_O = V\left(\frac{1}{1-d}\right)$$

Where $d = \frac{t_{ON}}{T} =$ duty cyle

For variation of duty cycle $'d'$ in the range of $0 < d < 1$ the output voltage V_O will vary in the range $V < V_O < \infty$

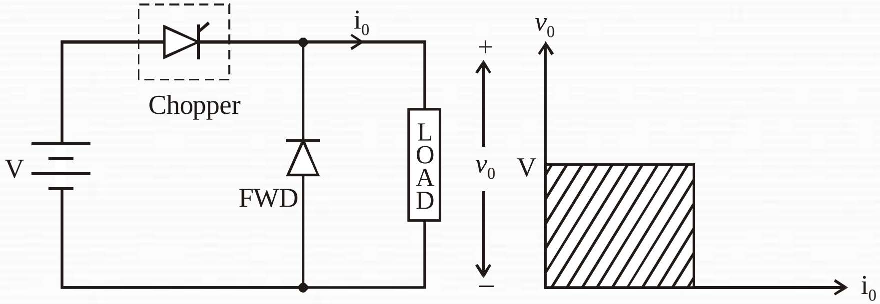
Performance Parameters

- The thyristor requires a certain minimum time to turn *ON* and turn *OFF*.
- Duty cycle *d* can be varied only between a min. & max. value, limiting the min. and max. value of the output voltage.
- Ripple in the load current depends inversely on the chopping frequency, *f*.
- To reduce the load ripple current, frequency should be as high as possible.

Classification Of Choppers

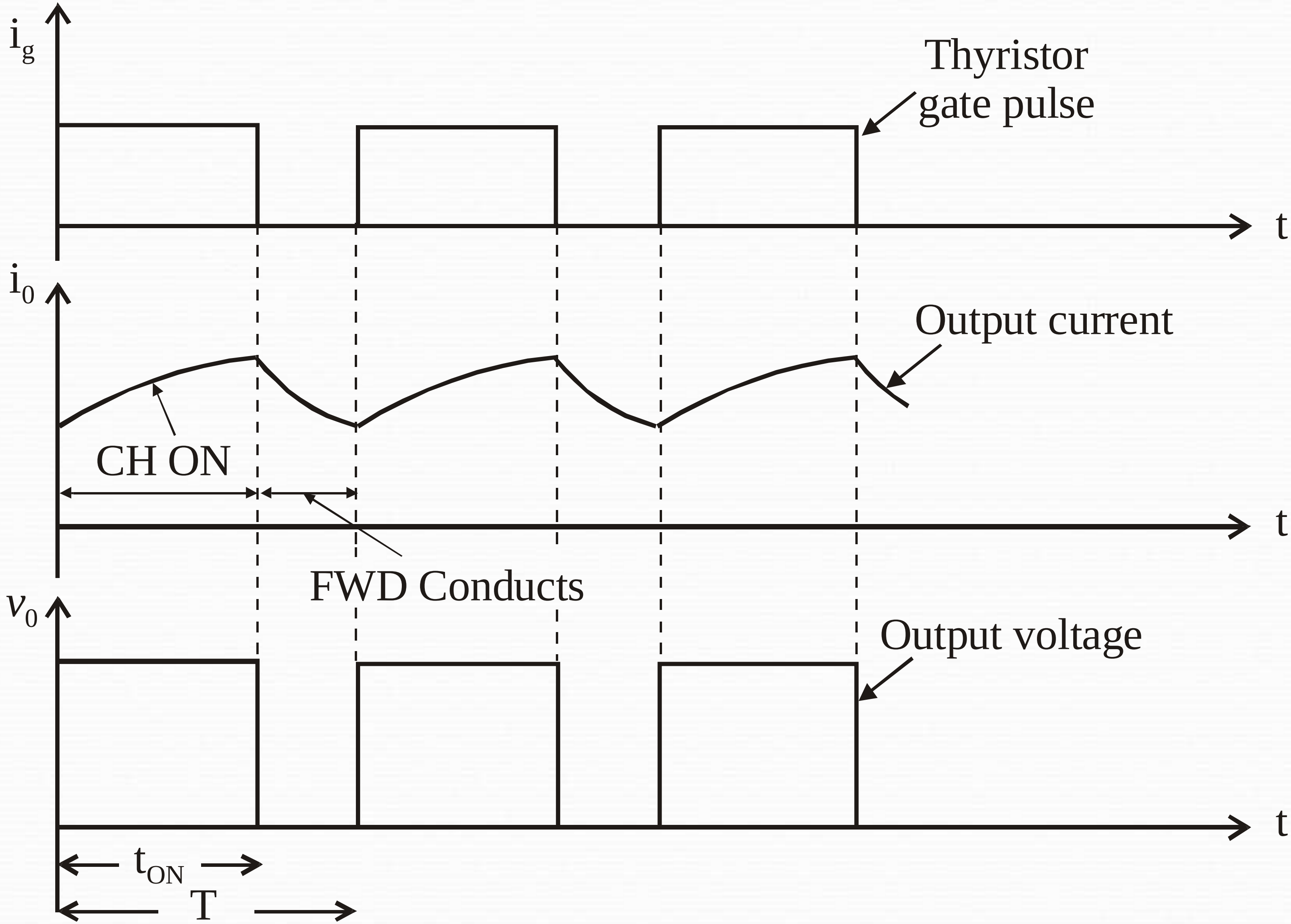
- Choppers are classified as
  - Class A Chopper
  - Class B Chopper
  - Class C Chopper
  - Class D Chopper
  - Class E Chopper

Class A Chopper



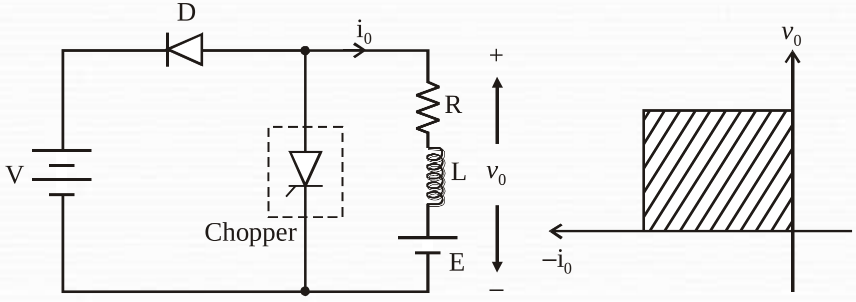
- When chopper is *ON*, supply voltage *V* is connected across the load.
- When chopper is OFF, $v_O = 0$ and the load current continues to flow in the same direction through the FWD.
- The average values of output voltage and current are always positive.
- *Class A Chopper* is a first quadrant chopper .

- *Class A Chopper* is a step-down chopper in which power always flows form source to load.
- It is used to control the speed of dc motor.
- The output current equations obtained in step down chopper with *R-L* load can be used to study the performance of *Class A Chopper.*



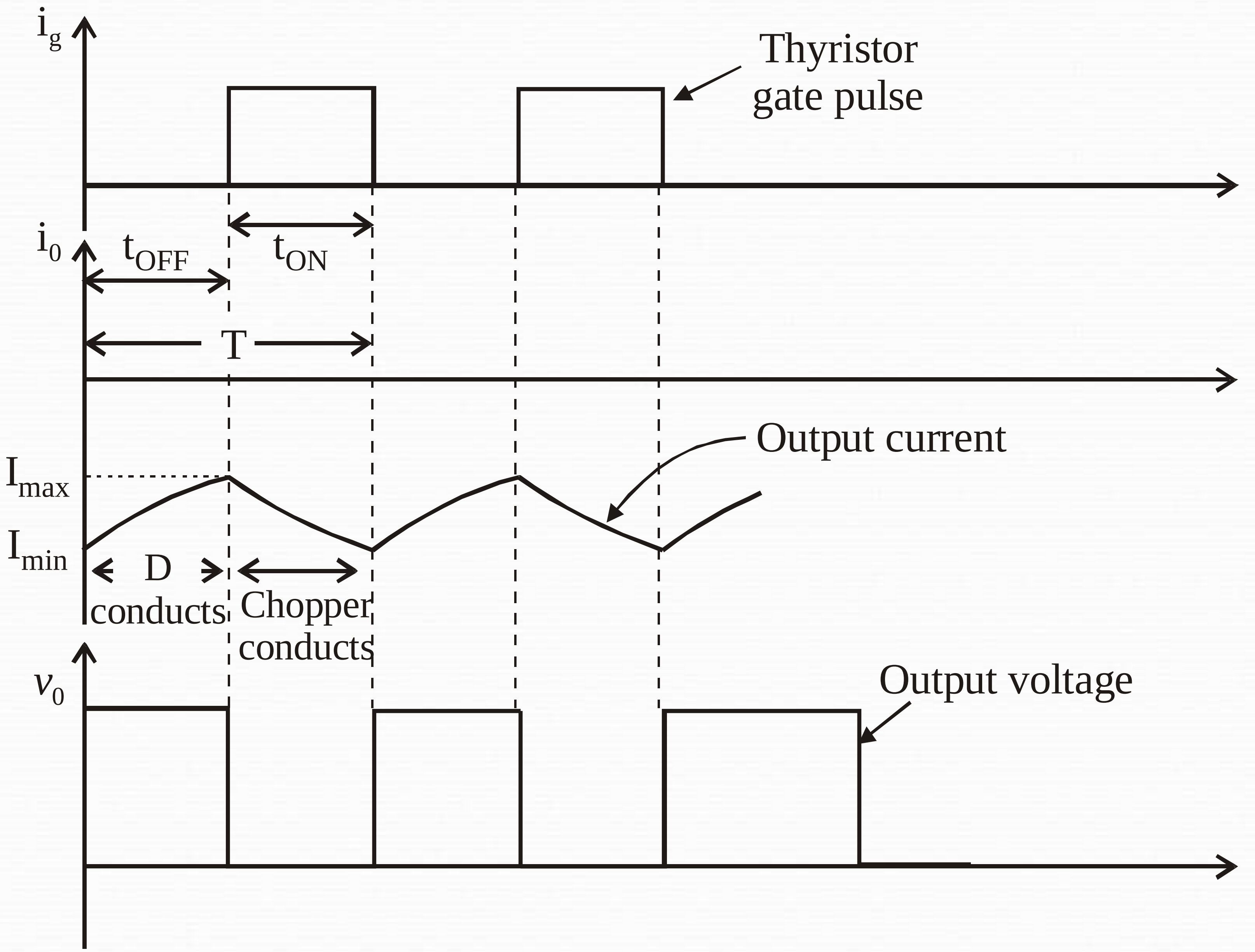
i_g
Thyristor gate pulse
t
i_0
Output current
CH ON
t
FWD Conducts
v_0
Output voltage
t
t_ON
T

Class B Chopper



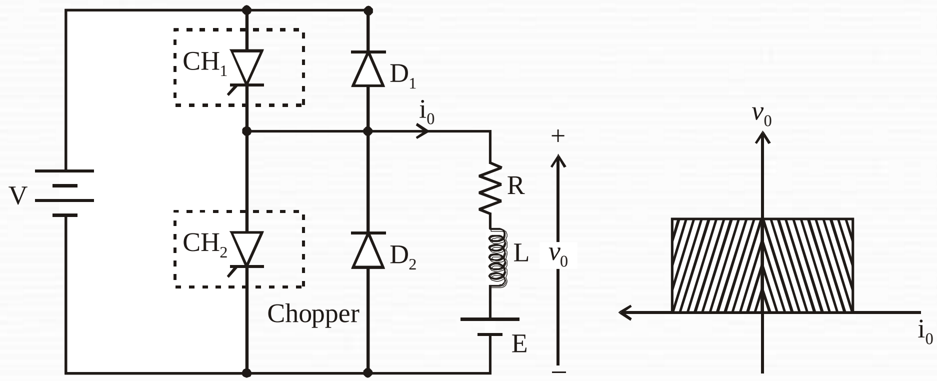
- When chopper is ON, *E* drives a current through *L* and R in a direction opposite to that shown in figure.
- During the ON period of the chopper, the inductance *L* stores energy.
- When Chopper is OFF, diode *D* conducts, and part of the energy stored in inductor *L* is returned to the supply.

- Average output voltage is positive.
- Average output current is negative.
- Therefore *Class B Chopper* operates in second quadrant.
- In this chopper, power flows from load to source.
- *Class B Chopper* is used for regenerative braking of dc motor.
- *Class B Chopper* is a step-up chopper.



i_g
Thyristor gate pulse
t
i_0
t_{OFF}
t_{ON}
T
t
Output current
I_{max}
I_{min}
D conducts
Chopper conducts
v_0
Output voltage
t

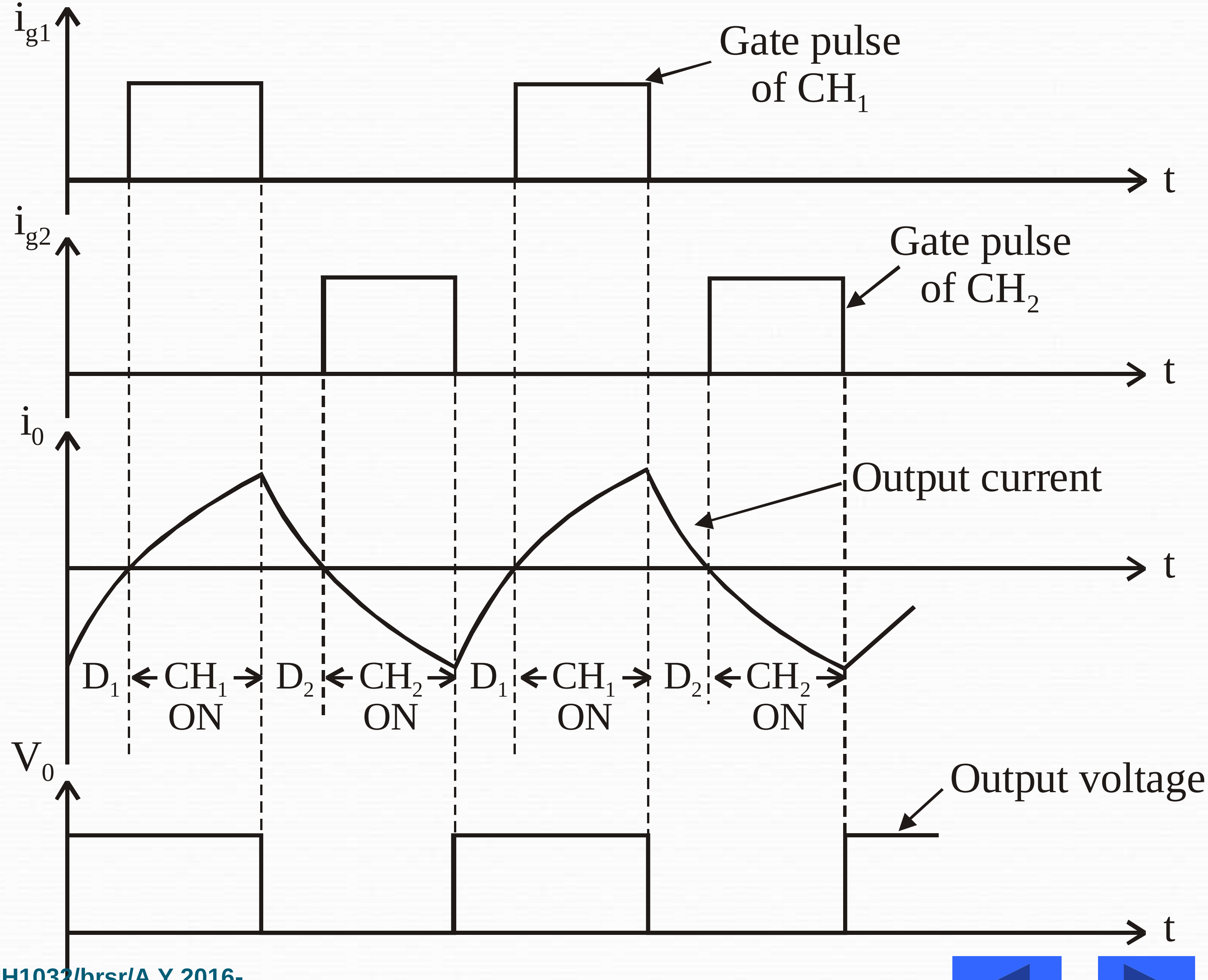
Class C Chopper



- *Class C Chopper* is a combination of *Class A* and *Class B Choppers*.
- For first quadrant operation, CH_1 is ON or D_2 conducts.
- For second quadrant operation, CH_2 is ON or D_1 conducts.
- When CH_1 is ON, the load current is positive.
- The output voltage is equal to '*V*' & the load receives power from the source.
- When CH_1 is turned OFF, energy stored in inductance *L* forces current to flow through the diode D_2 and the output voltage is zero.

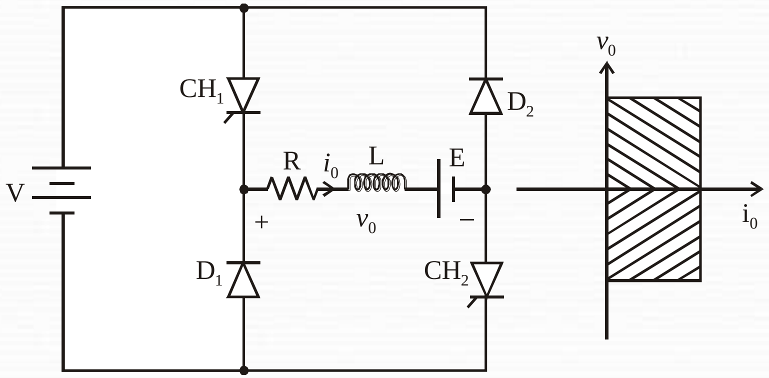
- Current continues to flow in positive direction.
- When CH_2 is triggered, the voltage E forces current to flow in opposite direction through L and CH_2 .
- The output voltage is zero.
- On turning OFF CH_2 , the energy stored in the inductance drives current through diode D_1 and the supply
- Output voltage is V, the input current becomes negative and power flows from load to source.

- Average output voltage is positive
- Average output current can take both positive and negative values.
- Choppers CH_1 & CH_2 should not be turned ON simultaneously as it would result in short circuiting the supply.
- *Class C Chopper* can be used both for dc motor control and regenerative braking of dc motor.
- *Class C Chopper* can be used as a step-up or step-down chopper.



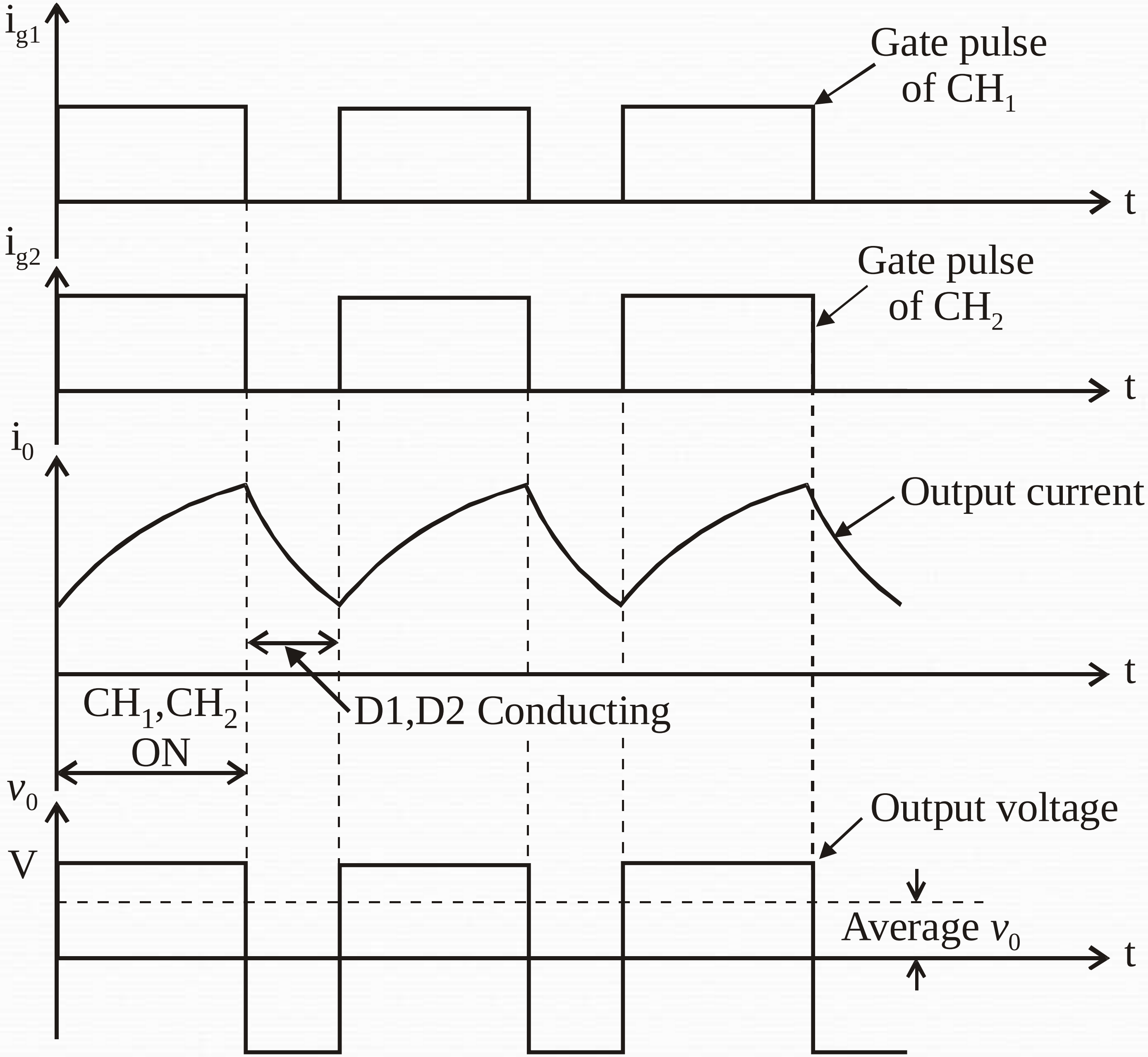
i_{g1}
Gate pulse of CH_1
t
i_{g2}
Gate pulse of CH_2
t
i_0
Output current
t
D_1
CH_1 ON
D_2
CH_2 ON
D_1
CH_1 ON
D_2
CH_2 ON
V_0
Output voltage
t

Class D Chopper

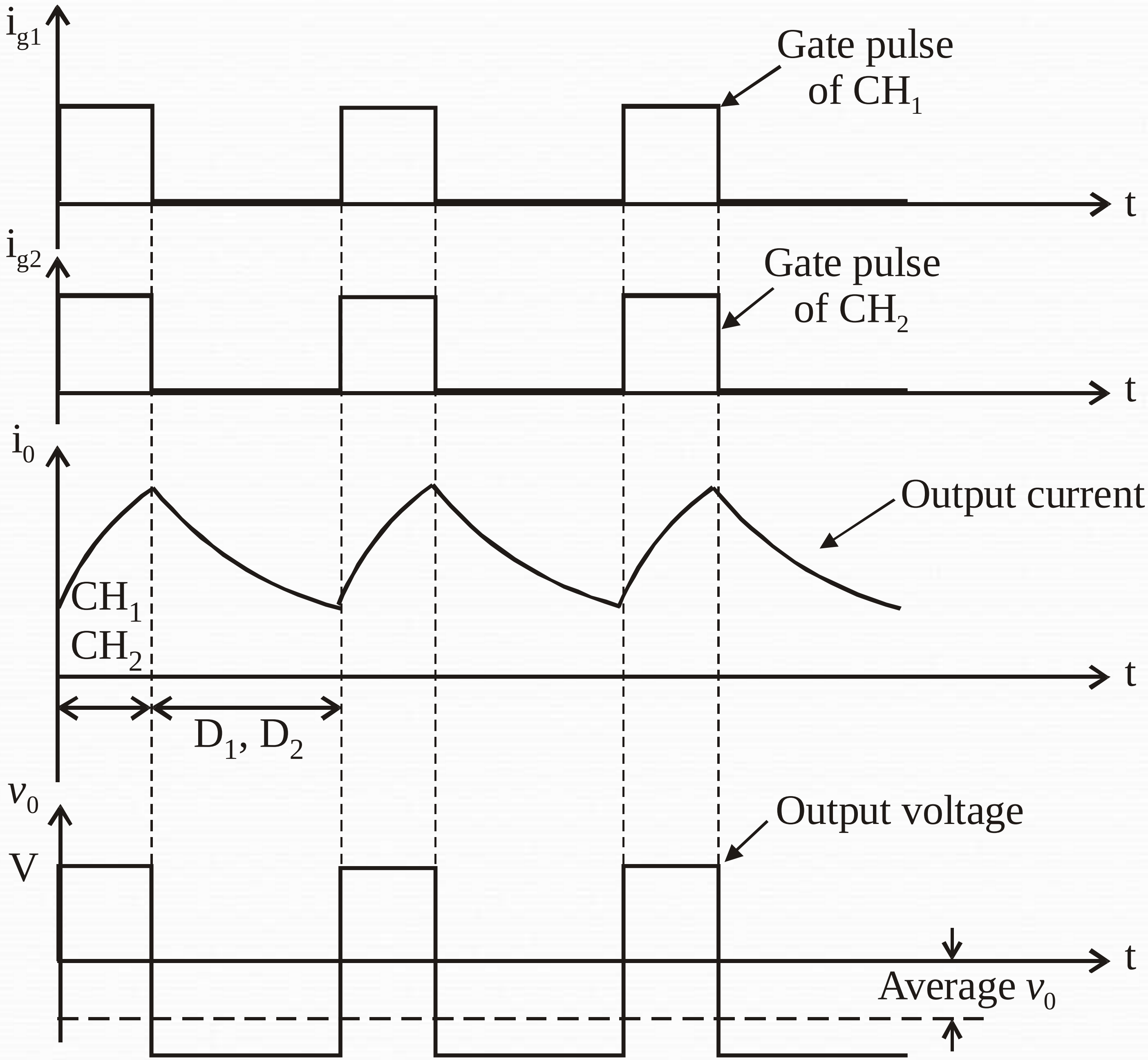


- Class D is a two quadrant chopper.
- When both CH_1 and CH_2 are triggered simultaneously, the output voltage $v_O = V$ and output current flows through the load.
- When CH_1 and CH_2 are turned OFF, the load current continues to flow in the same direction through load, D_1 and D_2 , due to the energy stored in the inductor L.
- Output voltage $v_O = - V$.

- Average load voltage is positive if chopper ON time is more than the OFF time
- Average output voltage becomes negative if $t_{ON} < t_{OFF}$.
- Hence the direction of load current is always positive but load voltage can be positive or negative.

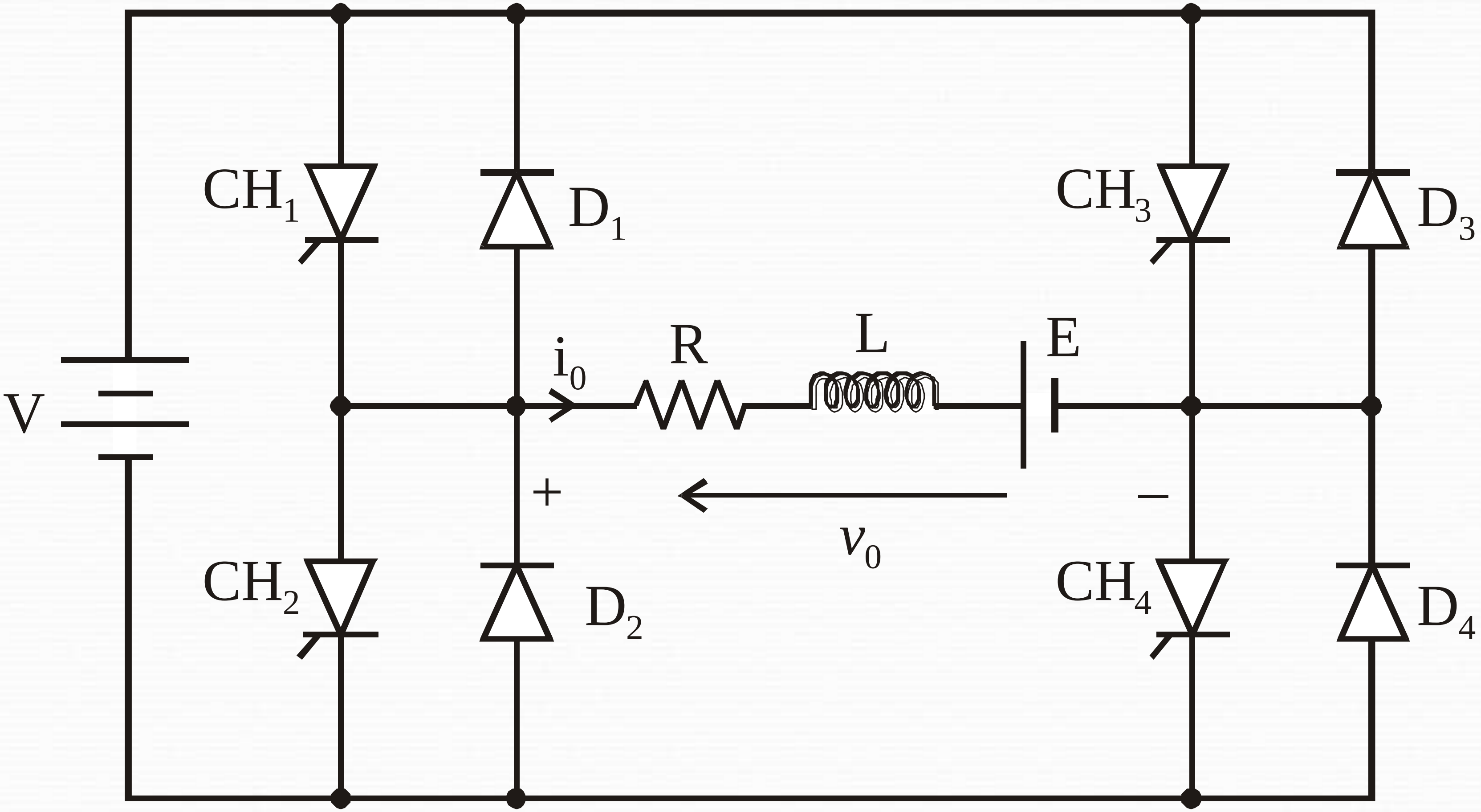


i_{g1}
Gate pulse of CH_1
t
i_{g2}
Gate pulse of CH_2
t
i_0
Output current
t
CH_1,CH_2 ON
D1,D2 Conducting
v_0
V
Output voltage
Average v_0
t

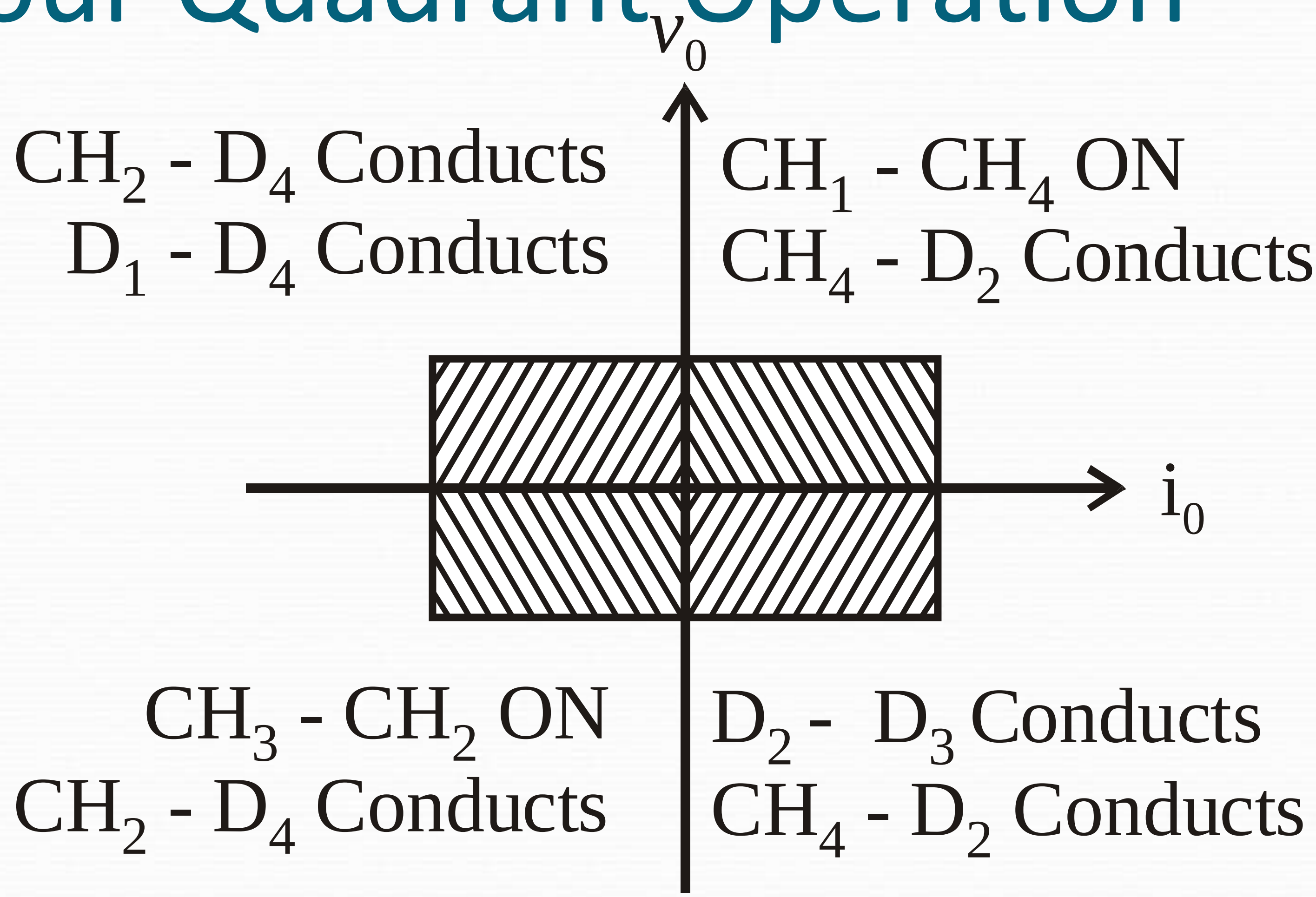


i_{g1}
Gate pulse of CH_1
t
i_{g2}
Gate pulse of CH_2
t
i_0
Output current
CH_1
CH_2
t
D_1, D_2
v_0
V
Output voltage
t
Average v_0

Class E Chopper



Four Quadrant Operation



- Class E is a four quadrant chopper
- When CH_1 and CH_4 are triggered, output current i_O flows in positive direction through CH_1 and CH_4, and with output voltage $v_O = V$.
- This gives the first quadrant operation.
- When both CH_1 and CH_4 are OFF, the energy stored in the inductor L drives i_O through D_2 and D_3 in the same direction, but output voltage $v_O = -V$.

- Therefore the chopper operates in the fourth quadrant.
- When CH_2 and CH_3 are triggered, the load current i_O flows in opposite direction & output voltage $v_O = -V$.
- Since both i_O and v_O are negative, the chopper operates in third quadrant.

- When both CH_2 and CH_3 are OFF, the load current i_O continues to flow in the same direction D_1 and D_4 and the output voltage $v_O = V$.
- Therefore the chopper operates in second quadrant as v_O is positive but i_O is negative.

Effect Of Source & Load Inductance

- The source inductance should be as small as possible to limit the transient voltage.
- Also source inductance may cause commutation problem for the chopper.
- Usually an input filter is used to overcome the problem of source inductance.

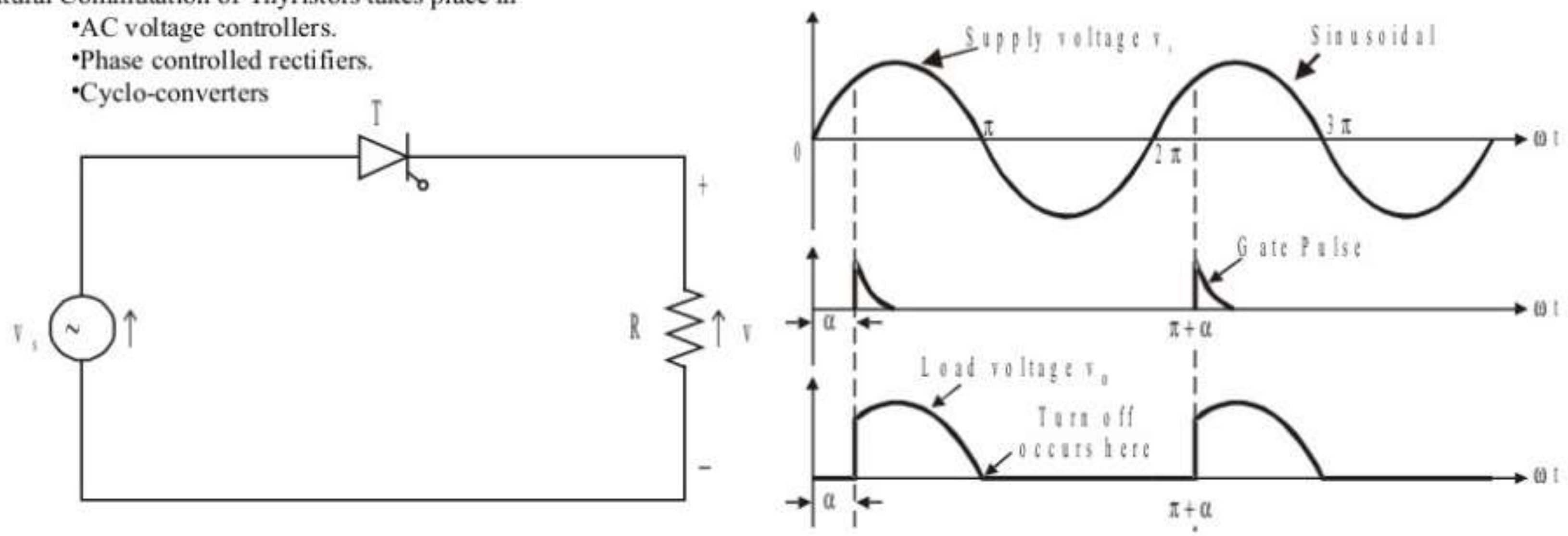
- The load ripple current is inversely proportional to load inductance and chopping frequency.
- Peak load current depends on load inductance.
- To limit the load ripple current, a smoothing inductor is connected in series with the load.

Types of Commutation

- Natural
- Forced

Natural commutation

- Occurs in AC circuits
- Natural Commutation of Thyristors takes place in
  - AC voltage controllers.
  - Phase controlled rectifiers.
  - Cyclo-converters



Forced commutation

- Applied to
  - dc circuits
  - Choppers
  - Inverters.
- Commutation achieved by reverse biasing the SCR or by reducing the SCR current below holding current value.
- Commutating elements such as inductance and capacitance are used for commutation purpose.

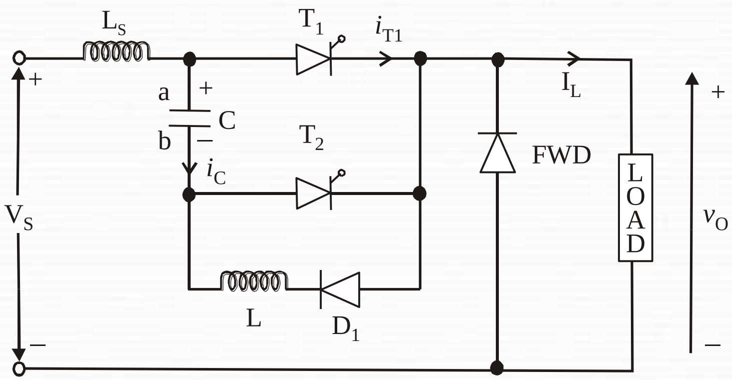
Methods of Forced Commutation

- Self commutation.
- Resonant pulse commutation.
- Complementary commutation.
- Impulse commutation.
- External pulse commutation.
- Line Commutation.

Voltage Commutated chopper

(Impulse Commutated Chopper)

- Impulse commutated choppers are widely used in high power circuits where load fluctuation is not large.
- This chopper is also known as
  - Parallel capacitor turn-off chopper
  - Voltage commutated chopper
  - Classical chopper.

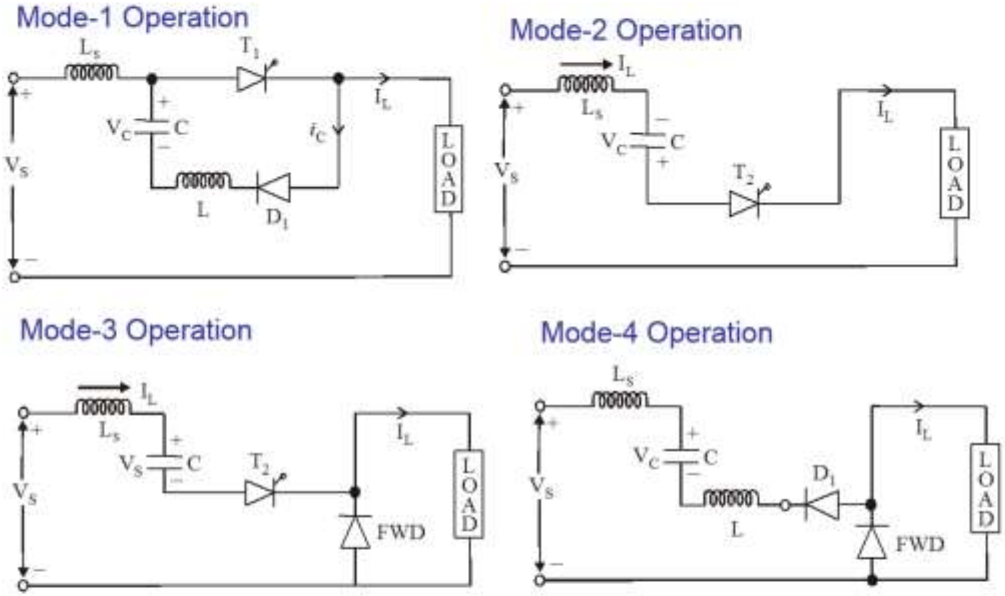


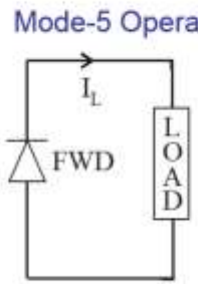
L_S
T_1
i_T1
I_L
+
a
+
C
b
–
T_2
i_C
FWD
L
O
A
D
V_S
v_O
–
L
D_1
–

- To start the circuit, capacitor *'C'* is initially charged with polarity (with plate 'a' positive) by triggering the thyristor T_2.
- Capacitor *'C'* gets charged through V_S, C, T_2 and load.
- As the charging current decays to zero thyristor T_2 will be turned-off.
- With capacitor charged with plate 'a' positive the circuit is ready for operation.
- Assume that the load current remains constant during the commutation process.

- For convenience the chopper operation is divided into five modes.
  - Mode-1
  - Mode-2
  - Mode-3
  - Mode-4
  - Mode-5

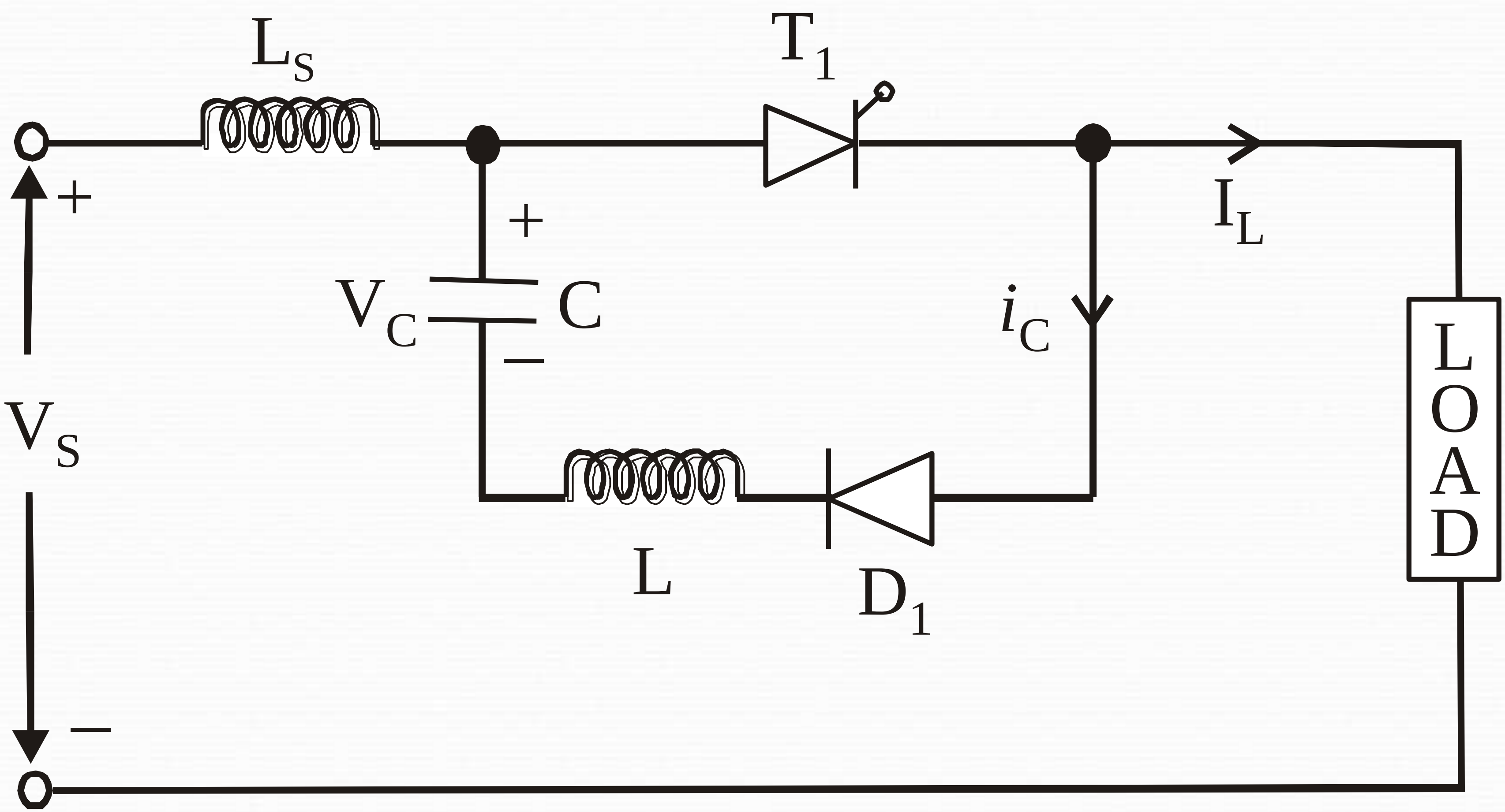
Modes of Operation





- Both thyristors are off and the load current flows through the FWD.
- This mode will end once thyristor T_1 is fired.

Mode-1 Operation



- Thyristor T_1 is fired at $t = 0$.
- The supply voltage comes across the load.
- Load current I_L flows through T_1 and load.
- At the same time capacitor discharges through T_1, D_1, L_1, & 'C' and the capacitor reverses its voltage.
- This reverse voltage on capacitor is held constant by diode D_1.

Capacitor Discharge Current

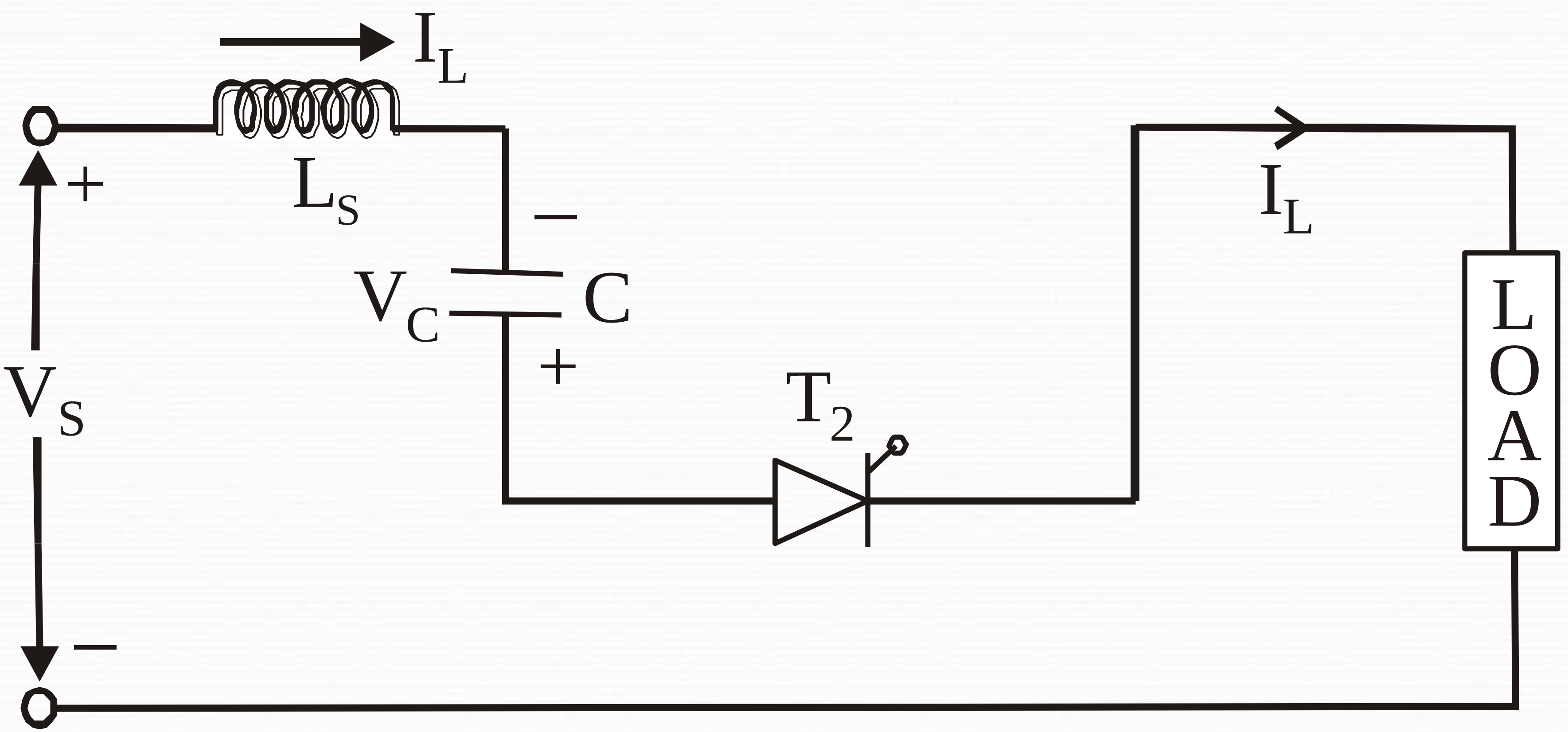
$$i_C(t) = V\sqrt{\frac{C}{L}}\sin\omega t$$

Where $$\omega = \frac{1}{\sqrt{LC}}$$

& Capacitor Voltage

$$V_C(t) = V\cos\omega t$$

Mode-2 Operation



- Thyristor T_2 is now fired to commutate thyristor T_1.
- When T_2 is ON capacitor voltage reverse biases T_1 and turns if off.
- The capacitor discharges through the load from $-V$ to 0.
- Discharge time is known as circuit turn-off time.

Circuit turn-off time is given by

$$t_C = \frac{V_C \times C}{I_L}$$

Where I_L is load current.

t_C depends on load current, it must be designed for the worst case condition which occur at the maximum value of load current and minimum value of capacitor voltage.

- Capacitor recharges back to the supply voltage (with plate 'a' positive).
- This time is called the recharging time and is given by

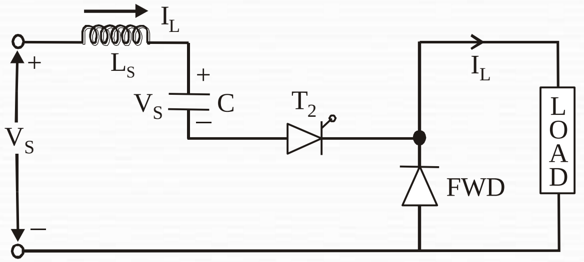
$$t_d = \frac{V_S \times C}{I_L}$$

- The total time required for the capacitor to discharge and recharge is called the commutation time and it is given by

$$t_r = t_C + t_d$$

- At the end of Mode-2 capacitor has recharged to V_S and the free wheeling diode starts conducting.

Mode-3 Operation



- *FWD* starts conducting and the load current decays.
- The energy stored in source inductance L_S is transferred to capacitor.
- Hence capacitor charges to a voltage higher than supply voltage, T_2 naturally turns off.

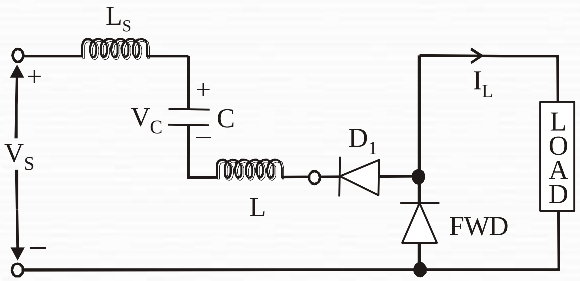
The instantaneous capacitor voltage is

$$V_C(t) = V_S + I_L \sqrt{\frac{L_S}{C}} \sin \omega_S t$$

Where

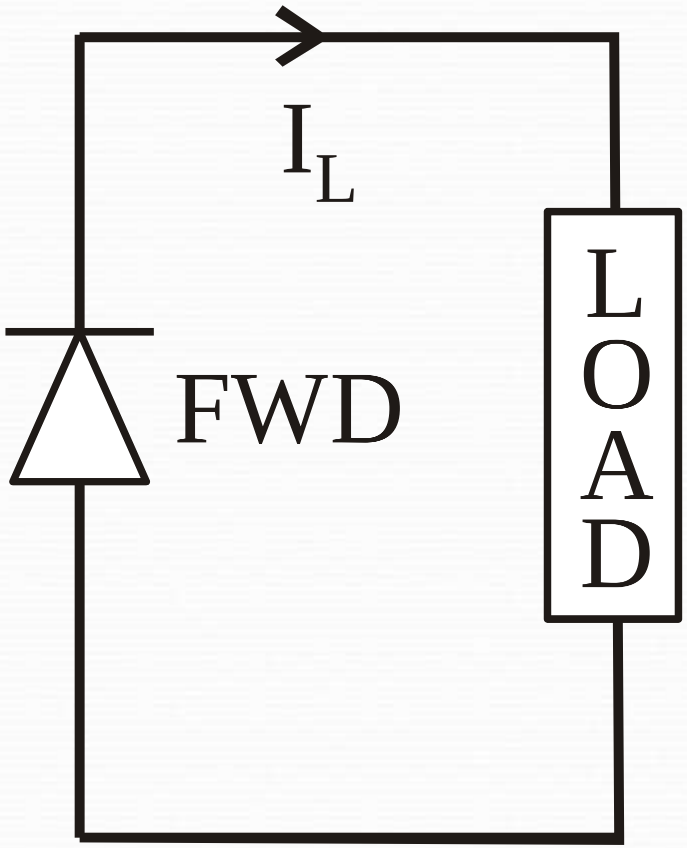
$$\omega_S = \frac{1}{\sqrt{L_S C}}$$

Mode-4 Operation

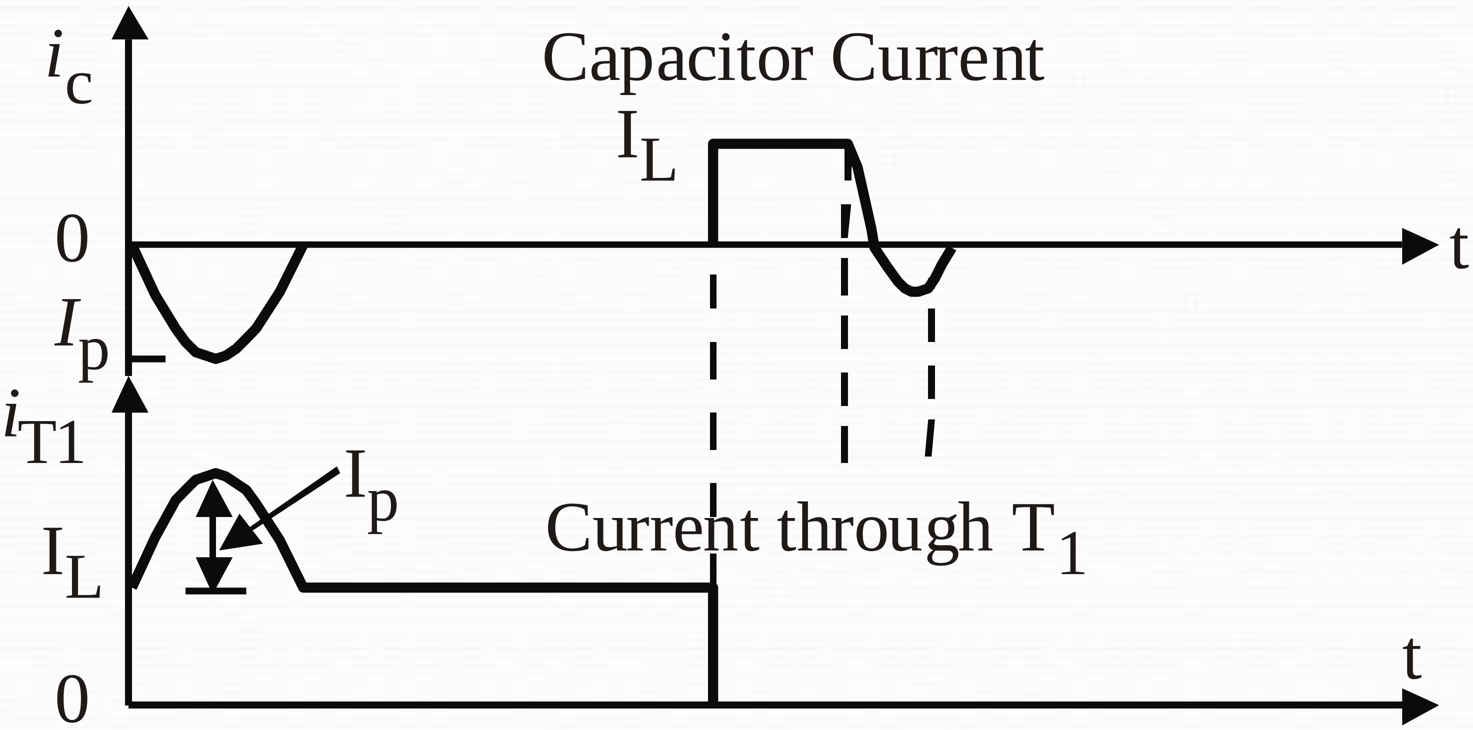


- Capacitor has been overcharged i.e. its voltage is above supply voltage.
- Capacitor starts discharging in reverse direction.
- Hence capacitor current becomes negative.
- The capacitor discharges through L_S, V_S, *FWD*, D_1 *and* *L*.
- When this current reduces to zero D_1 will stop conducting and the capacitor voltage will be same as the supply voltage

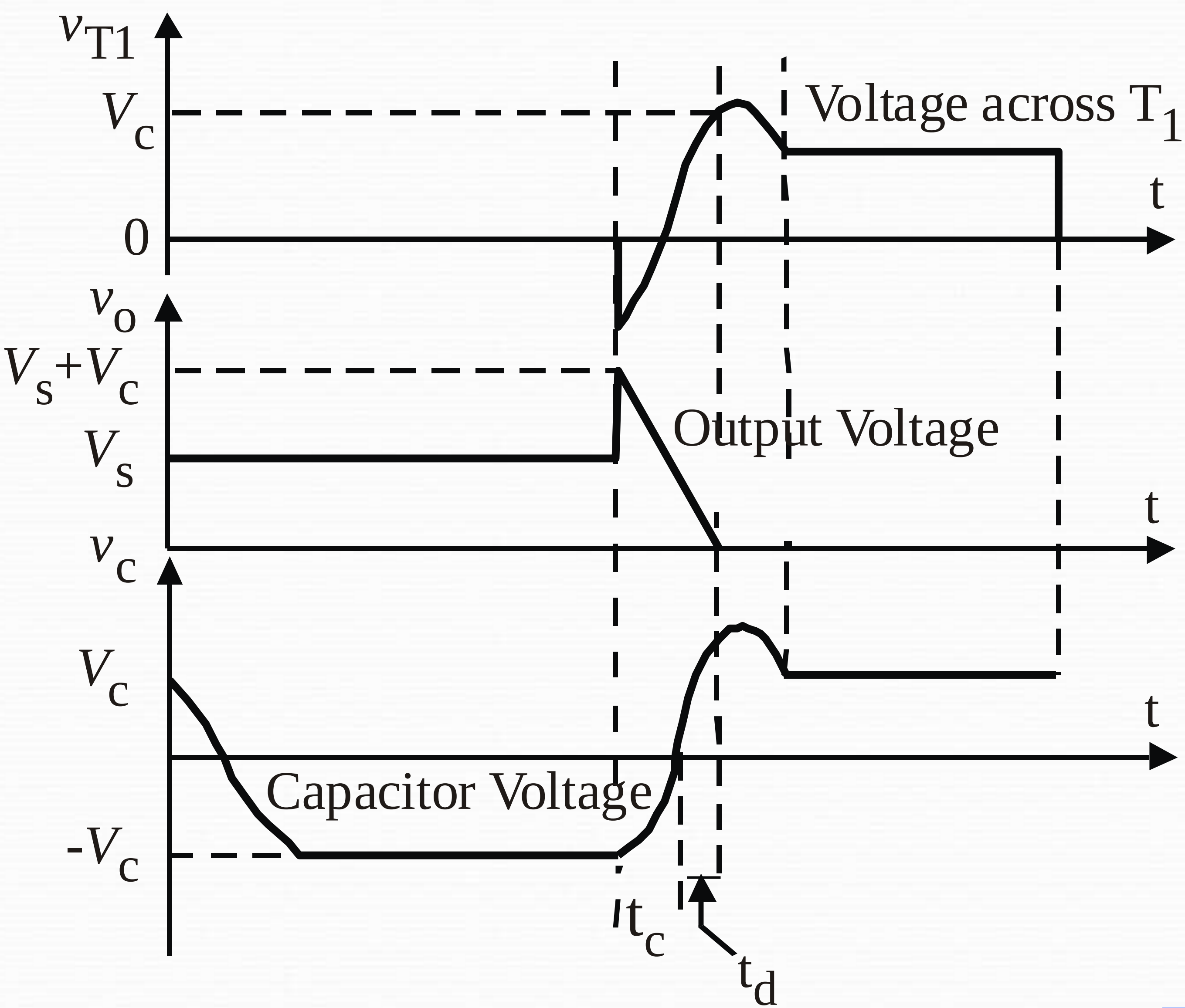
Mode-5 Operation



- Both thyristors are off and the load current flows through the FWD.
- This mode will end once thyristor T_1 is fired.



i_c
Capacitor Current
I_L
0
t
I_p
i_{T1}
I_p
I_L
Current through T_1
t
0


v_{T1}
V_c
0
Voltage across T_1
t
v_o
V_s+V_c
V_s
Output Voltage
t
v_c
V_c
t
Capacitor Voltage
$-V_c$
t_c
t_d

Disadvantages

- A starting circuit is required and the starting circuit should be such that it triggers thyristor T_2 first.
- Load voltage jumps to almost twice the supply voltage when the commutation is initiated.
- The discharging and charging time of commutation capacitor are dependent on the load current and this limits high frequency operation, especially at low load current.

- Chopper cannot be tested without connecting load.
- Thyristor T_1 has to carry load current as well as resonant current resulting in increasing its peak current rating.

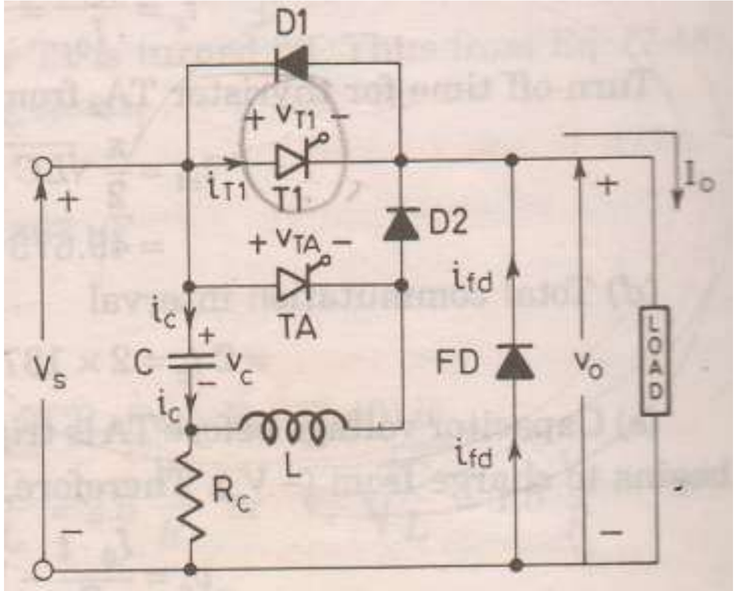
What is meant by Current Commutation?

- Chopper is used to change the dc level of voltage, it is dc/dc converter.
- In current commutated chopper , as the name suggests, chopper is commutated by current pulse.
- In this process, a current pulse is made to flow in the reverse direction through the conducting thyristor and when the net thyristor current becomes zero, it is turned off.

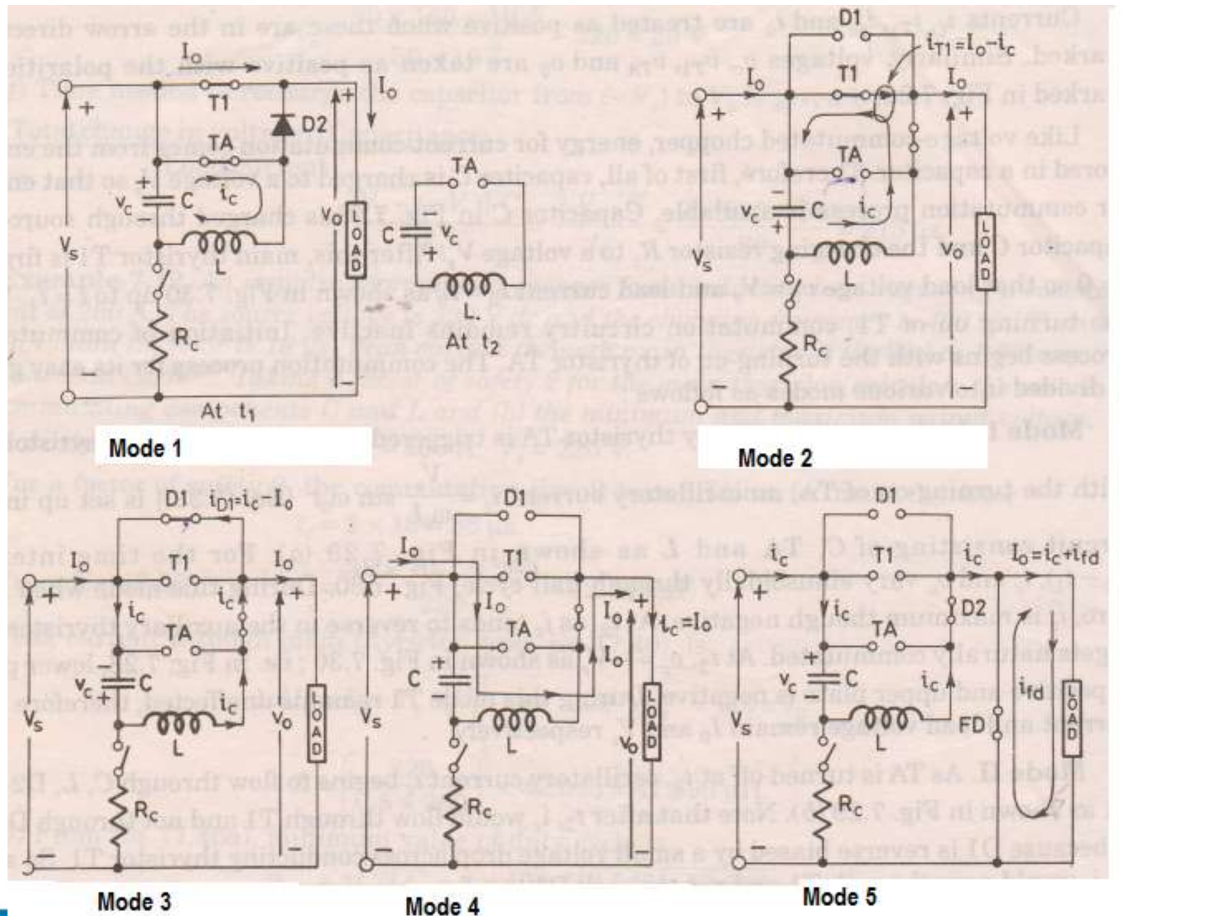
Assumptions

- Some assumption are:
  - Load current is constant.
  - SCR and Diodes are ideal switches.
  - R_C is so large such that it can be treated as open circuit during the commutation interval.
- The energy for commutation comes from energy stored in capacitor.
- Capacitor is charges to E_{dc} , so that energy for commutation is available.

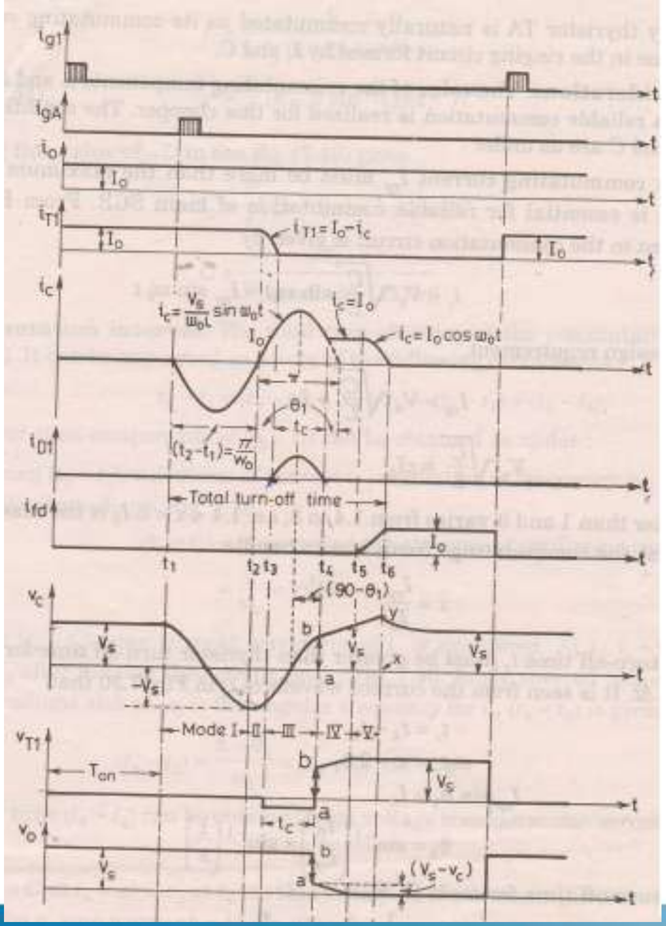
Current commutated Chopper



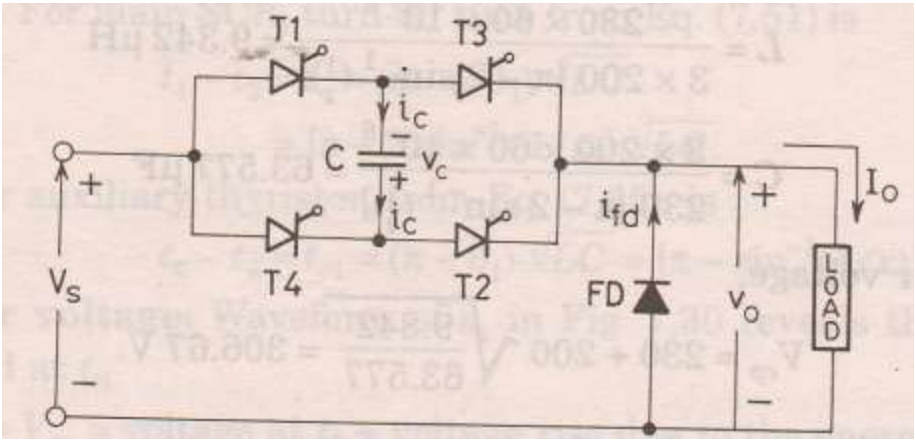
Modes of Operation



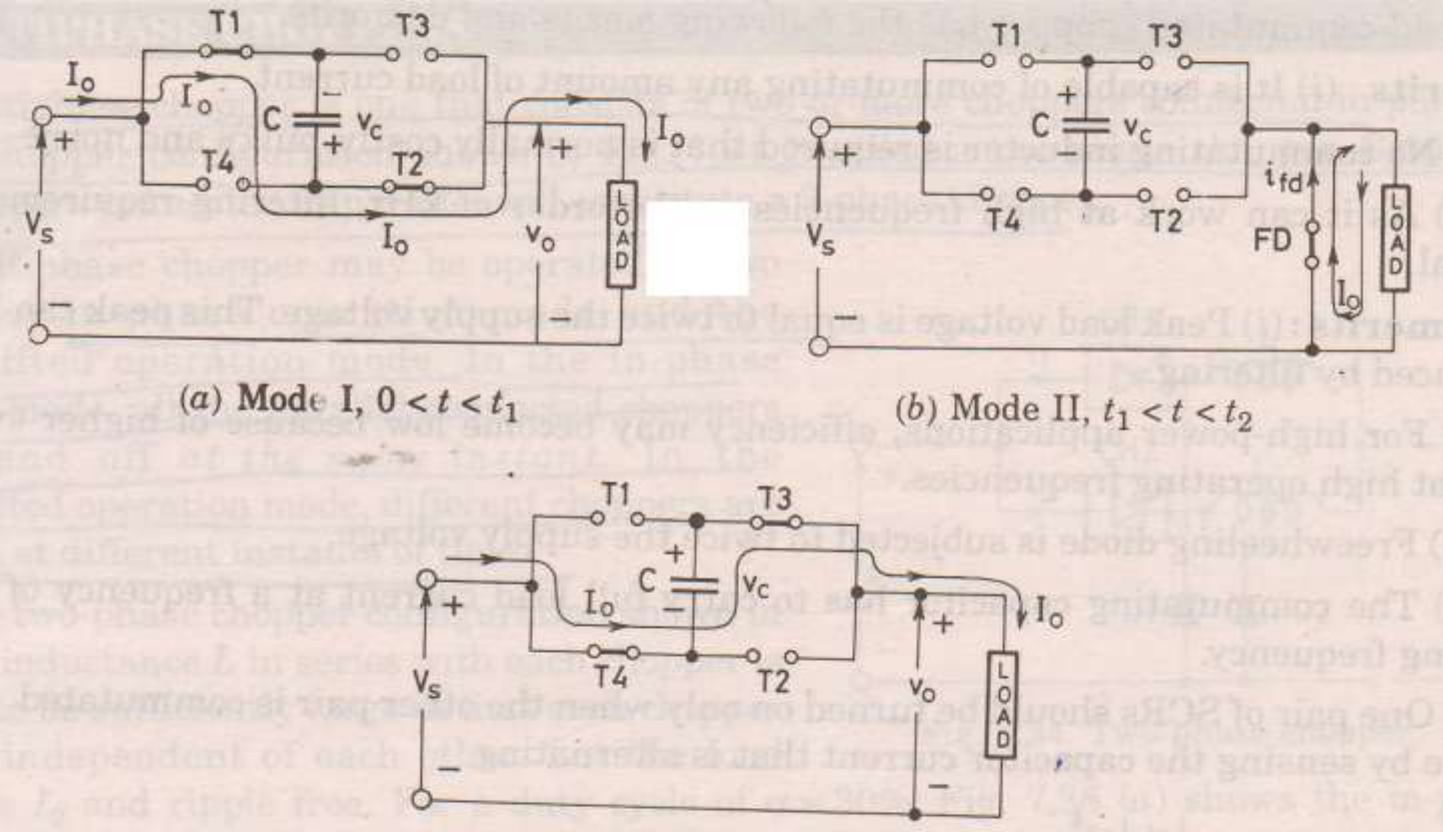
Voltage and Current waveforms of CCC



Load Commutated Chopper



Modes of Operation of Load Commutated Chopper



(a) Mode I, $0 < t < t_1$

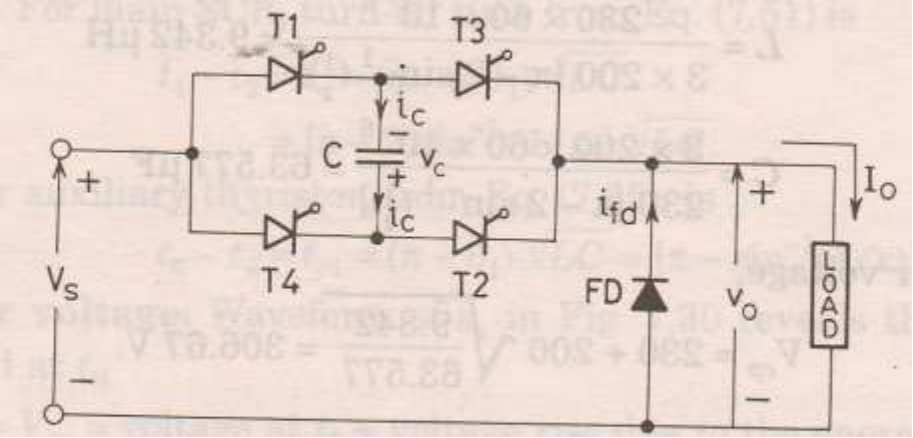
(b) Mode II, $t_1 < t < t_2$

(c) Mode III, $t_2 < t < t_3$

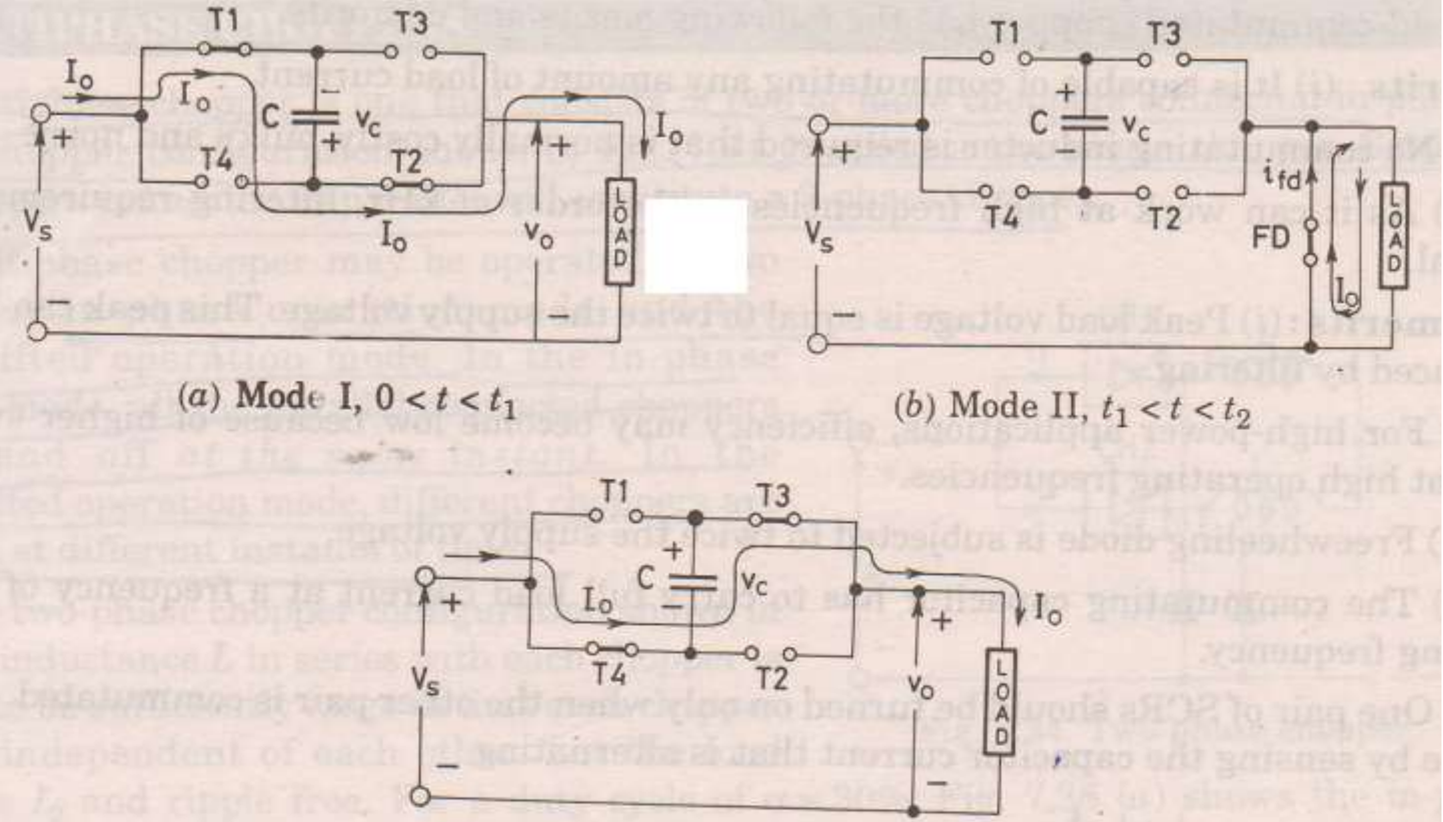
Advantages of Current commutated Chopper

- The capacitor always remains charged with the correct polarity.
- Commutation is reliable as load current is less than the peak commutation current I_{CP}.
- The auxiliary thyristor T2 is naturally commutated as its current passes through zero value.

Load Commutated Chopper



Modes of Operation of Load Commutated Chopper



(a) Mode I, $0 < t < t_1$

(b) Mode II, $t_1 < t < t_2$

(c) Mode III, $t_2 < t < t_3$

MULTIPHASE CHOPPERS

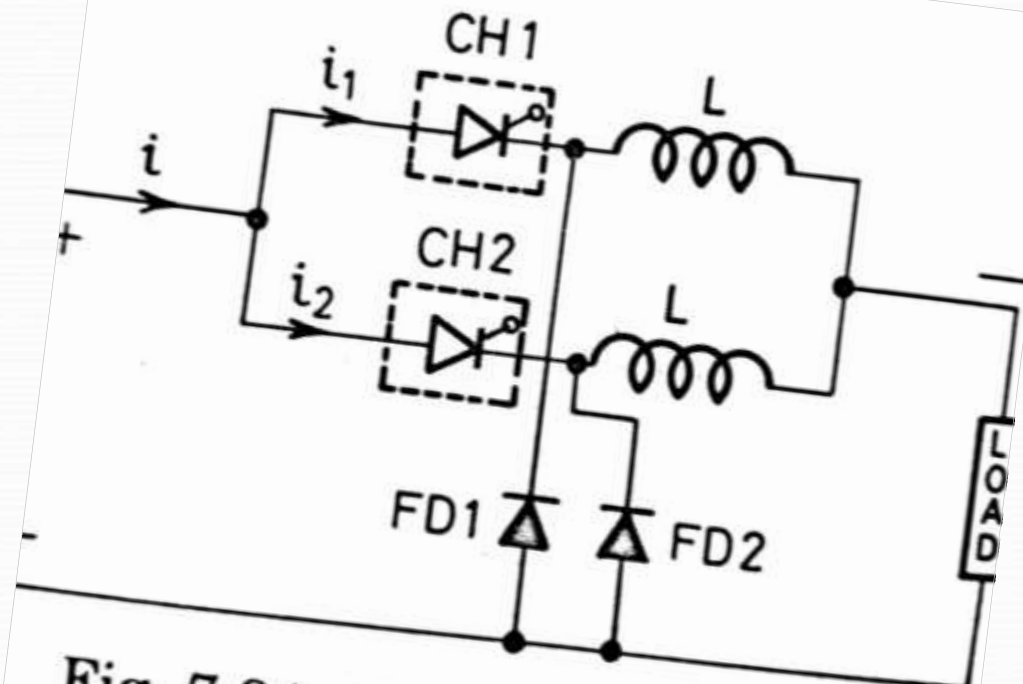


Fig. 7.34. Two-phase chopper.

The multiphase chopper [illegible] more choppers connected in parallel. Inductance L is assumed to be sufficiently large such that each chopper operates independent of each other.

Modes of operation

- **In-phase operation**
- **Phase shifted operation**

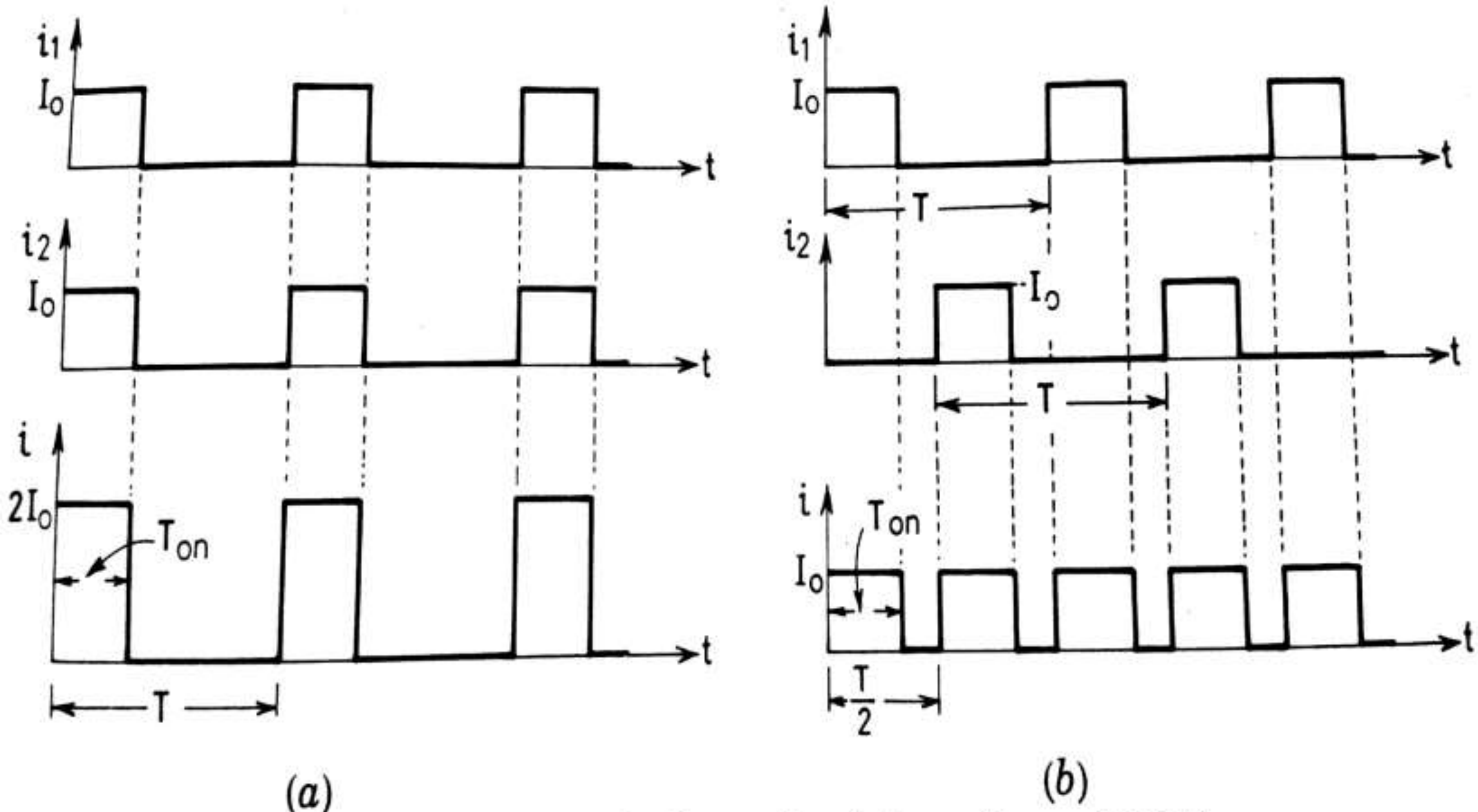


Fig. 7.35. Input current waveforms for duty cycle $\alpha = 0.30$ for (a) in-phase operation and (b) phase-shifted operation.

*Load current Io is ripple free

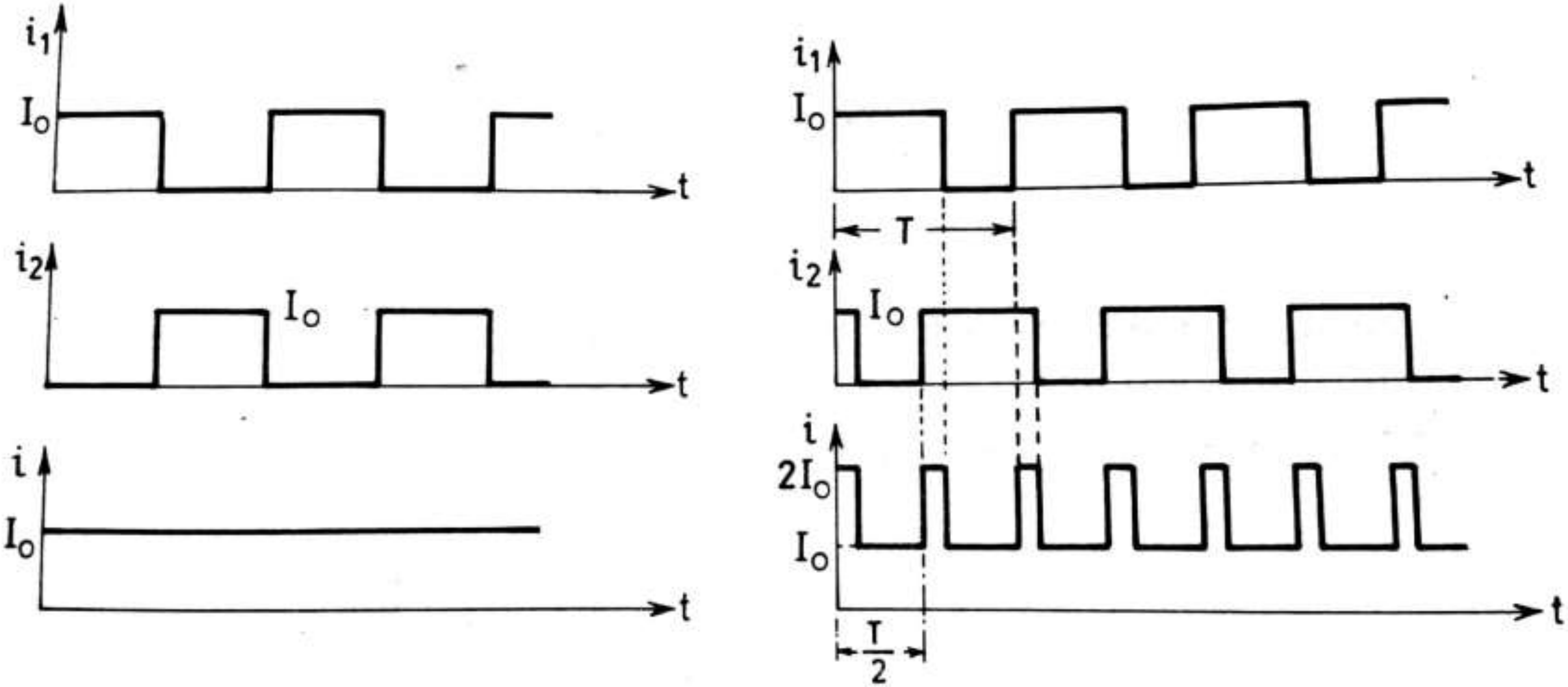
→**For a duty cycle of 30 %**

In phase operation

- All the parallel connected choppers are on and off at the same instant.
- Input current $i = i_1 + i_2$ is doubled.
- Operation is equivalent to a single chopper operation.
- Frequency of harmonics in the input current = 1/T (Switching frequency of each chopper).

Phase shifted operation

- Different choppers are ON and OFF at different instansts of time.
- For α=30 % chopper 1 is ON for 0.3T from t=0,chopper 2 is made ON such that i_1+i_2 is periodic in nature.
- Frequency of 'i' is doubled and its ripple current amplitude [Imax –Imin] is halved.
- Frequency of harmonics in the input current is 2 x 1/T.
- Size of filter is reduced as a result, making phase-shifted operation of multiphase choppers the most preferred.



(c) (d)

Fig. 7.35. Current waveform for phase-shifted operation for (c) $\alpha = 0.50$ and (d) $\alpha = 0.60$.

→For α=50%

i for phase shifted operation is continuous and without any ripples.

→For α=60%

I is continuous with a pedestal of 0.5 Io

*Multiphase choppers are used where large load current is required.

Advantage:

Input current has reduced ripple amplitude and increased ripple frequency. As a consequence the size of the filter is reduced.

Disadvantage:

- Extra commutation circuits
- Additional external inductors
- Complexity in the control logic

UNIT IV
DC - AC CONVERTERS
INVERTERS

Introduction

- A device which converts dc power to an ac power of desired output and frequency is called as Inverter
- Output voltage can be fixed or variable at a fixed or variable frequency
- For low and medium Power ,transistorised inverters are used and for high power outputs, SCRs are used
- Low power inverters are usually single phase and high power inverters are of three phase

Applications of Inverters

- Variable speed ac motor drives
- UPS(Uninterrupted Power Supplies)
- Induction heating,Standby Power supplies
- HVDC transmission lines
- Aircraft power supplies

Introduction-contd….

DC power input to the inverter can be obtained from

- DC Power source
- Fuel cell
- Photovoltaic array
- Rotating Alternator through Rectifiers
- Magneto HydroDynamic generator(MHD)

Introduction-contd….

- AC output voltage waveforms from the Inverter should be sinusoidal but practically, the waveforms are non sinusoidal and contain harmonics
- The harmonics can be minimized by using high speed switching methods for the semiconductor devices used.
- For low and medium power applications, square wave or quasi square wave voltages are obtained as inverter output and for high power applications,low distorted sinusoidal waveforms can be obtained.

Types of inverters

- Based on Commutation
  - Line commutated inverter
  - Load commutated inverter
  - Self commutated inverter
  - Forced commutated inverter
- Based on method of connections
  - Series Inverter
  - Parallel Inverter
  - Bridge Inverter
    - Single Phase
      - Half bridge
      - Full bridge
    - Three Phase
- Based on Number of Phases of load
  - Single phase
  - Three phase
- Broad classification
  - Voltage Source Inverter (VSI) or Voltage Fed inverter (VFI)
  - Current Source Inverter (CSI) or Current Fed inverter (VFI)

Basic Series Inverter

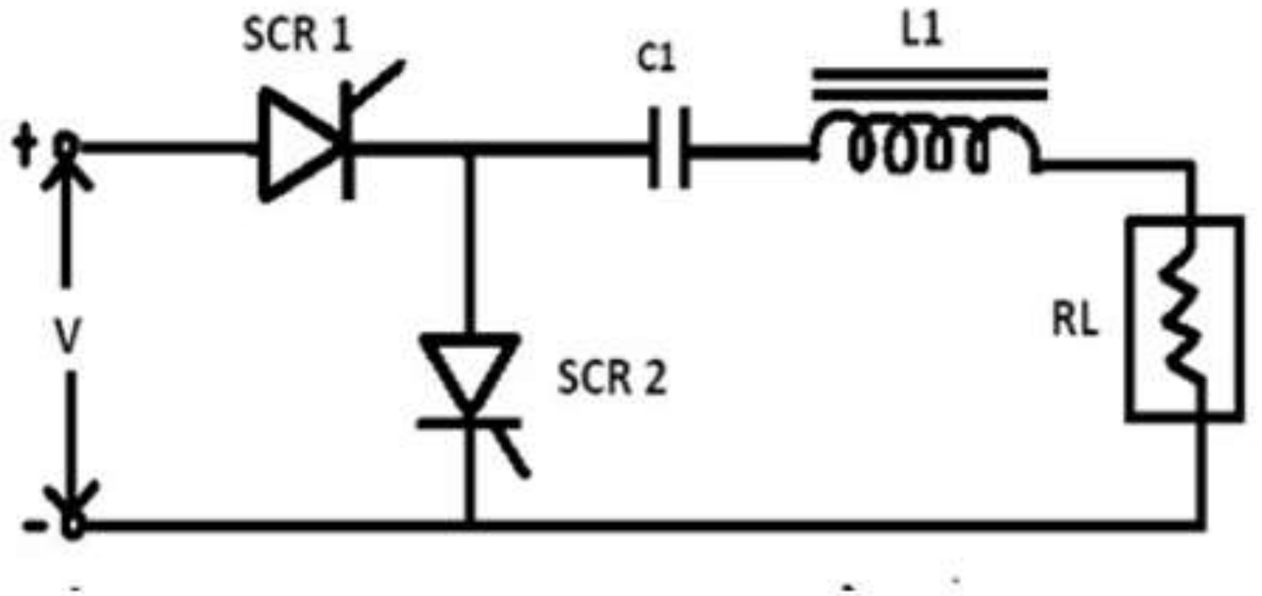


Fig. (a)Basic series configuration

Mode 1 Operation

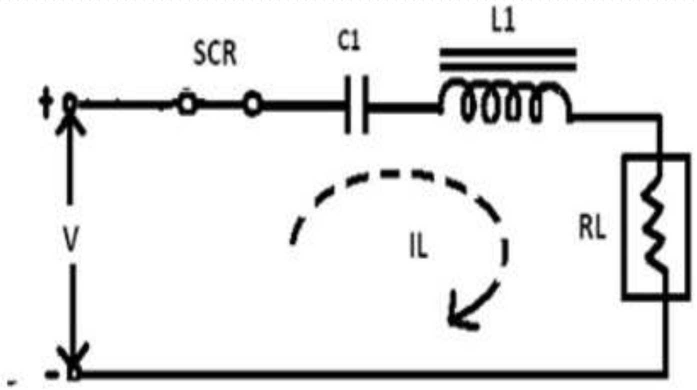


Fig (b) Mode I (t0 to t1)

- The capacitor C1 start charging in the opposite direction as shown in fig B.The load current eventually comes to zero at instant t1 and SCR1 comes out of conduction due to natural commutation.
- The voltage on the capacitor C1 at instant t1 is greater than V with its left plate positive w.r.t. its right plate.
- As there is no discharge path for the capacitor, this voltage will be held constant up to instant t2 where SCR2 is triggered.

Mode 2 Operation

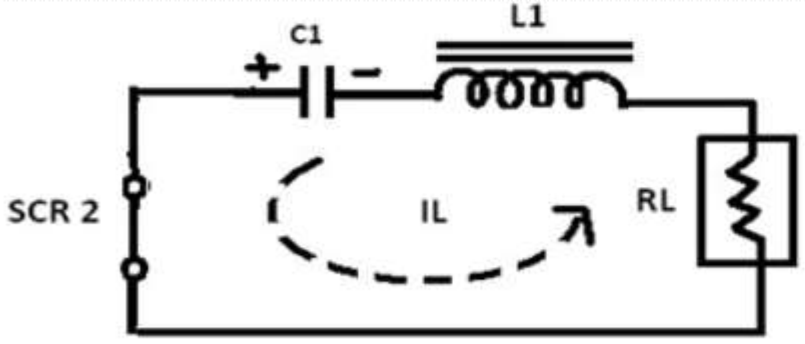


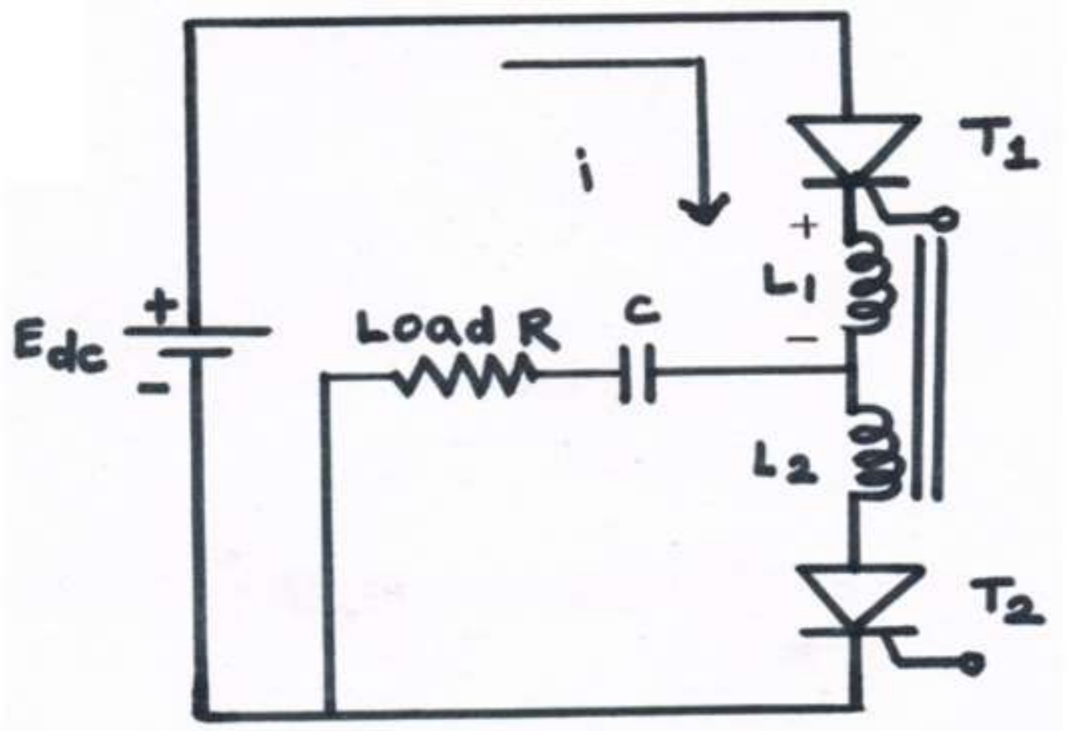
Fig (c) Mode 2 (t1 to t2)

- At instant t2, SCR2 is turned on and the load voltage and current both becomes negative.
- The capacitor now discharges resonantly through SCR2, R, L1, as shown in fig (c)
- At instant t3 the discharge current goes to zero and SCR2 turned off again due to natural commutation. The voltage on C1 is equal to vc.
- **Off time :** During the **time interval between t1 and t2** both the SCRs are in the off state. Load voltage as well as load current are zero. Therefore this interval is known as **off time** of the circuit.

DISADVANTAGES

- Limitation on the maximum operating frequency
- Distortion in the output wave form
- High rating of commutating components
- The peak amplitude and duration of output current depends on the load parameters resulting in poor regulation for the inverter.
- The power flow from the dc source is intermittent. Therefore, the dc supply must have a large peak current rating and the input current contains high percentage of harmonics.

MODIFIED SERIES INVERTER



MODES OF OPERATION

The operation can be divided into two modes.

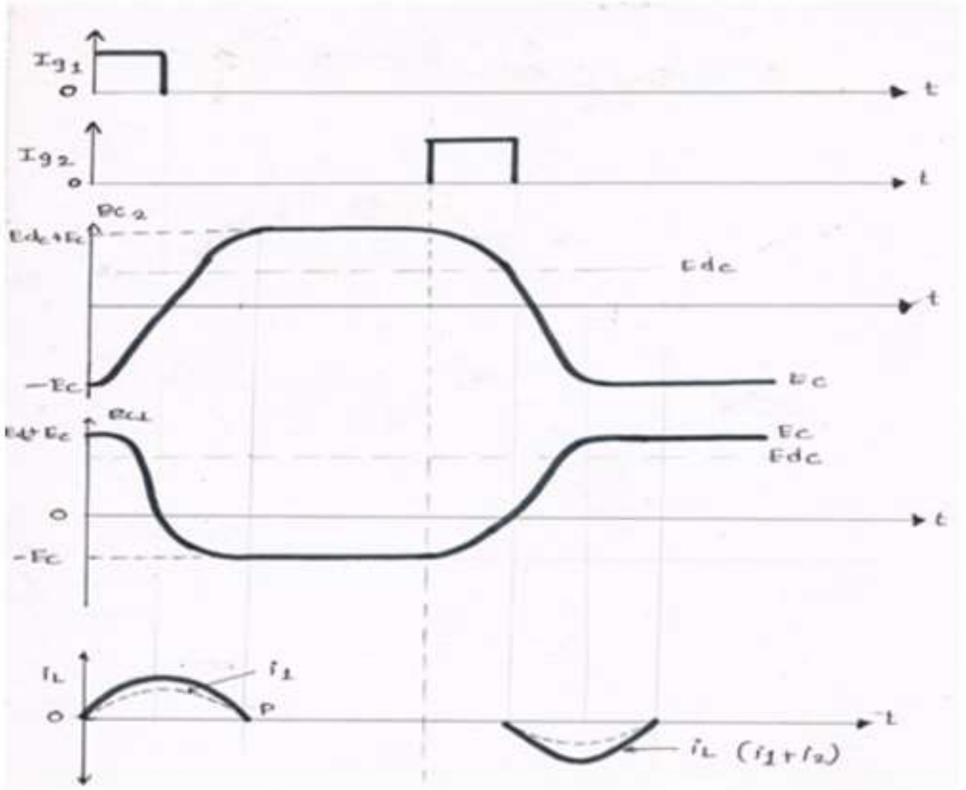
Mode 1:

At the instant **when SCR T_2 is triggered**, the voltage across the capacitor will be slightly less than ($E_c + E_{dc}$)and the load voltage and current will be closed to zero. Hence the voltage across the capacitor minus the load voltage will appear across L_2.Since L_1 is closely coupled to L_2, the same voltage will appear across L_1.

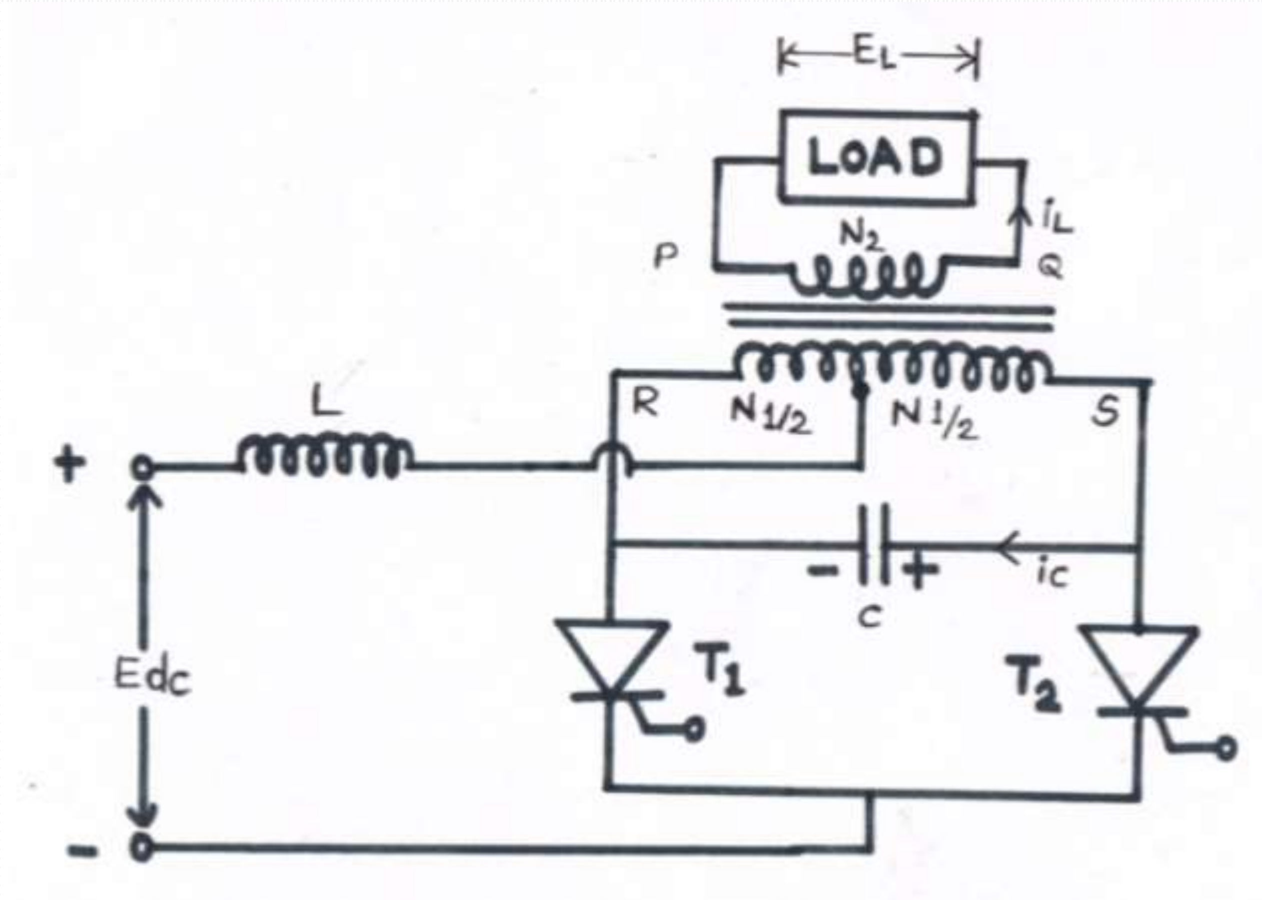
Mode 2:

The voltage across L_1 will tend to increase the cathode potential of SCR T_1 more than its anode potential and therefore, **SCR T_1 will be reverse biased and turn-off** . Thus, even if SCR T_2 is turned on before SCR T_1 is switched off, it will not result into short circuiting of the d.c. source. A similar operation will take place if SCR T_1 is triggered before SCR T_2 is turned off.

WAVEFORMS OF MODIFIED SERIES INVERTER



PARALLEL INVERTER



MODES OF OPERATION

Basic Parallel Inverter

- A parallel inverter is used to produce a square-wave from a d.c. supply.
- In this inverter, the commutating capacitor comes in parallel with the load during the operation of the inverter. Hence it is called as '**parallel inverter**'.

Operation

Mode 1:

- This mode begins when T_1 is fired and current flows through the inductance L and the thyristor T_1.
- When SCR is turned on, a d.c. voltage E_{dc} appears across half the transformer primary, which means the total primary voltage is $2E_{dc}$, hence the capacitor is charged to $2E_{dc}$.

MODES OF OPERATION-MODE 2 & mode 3

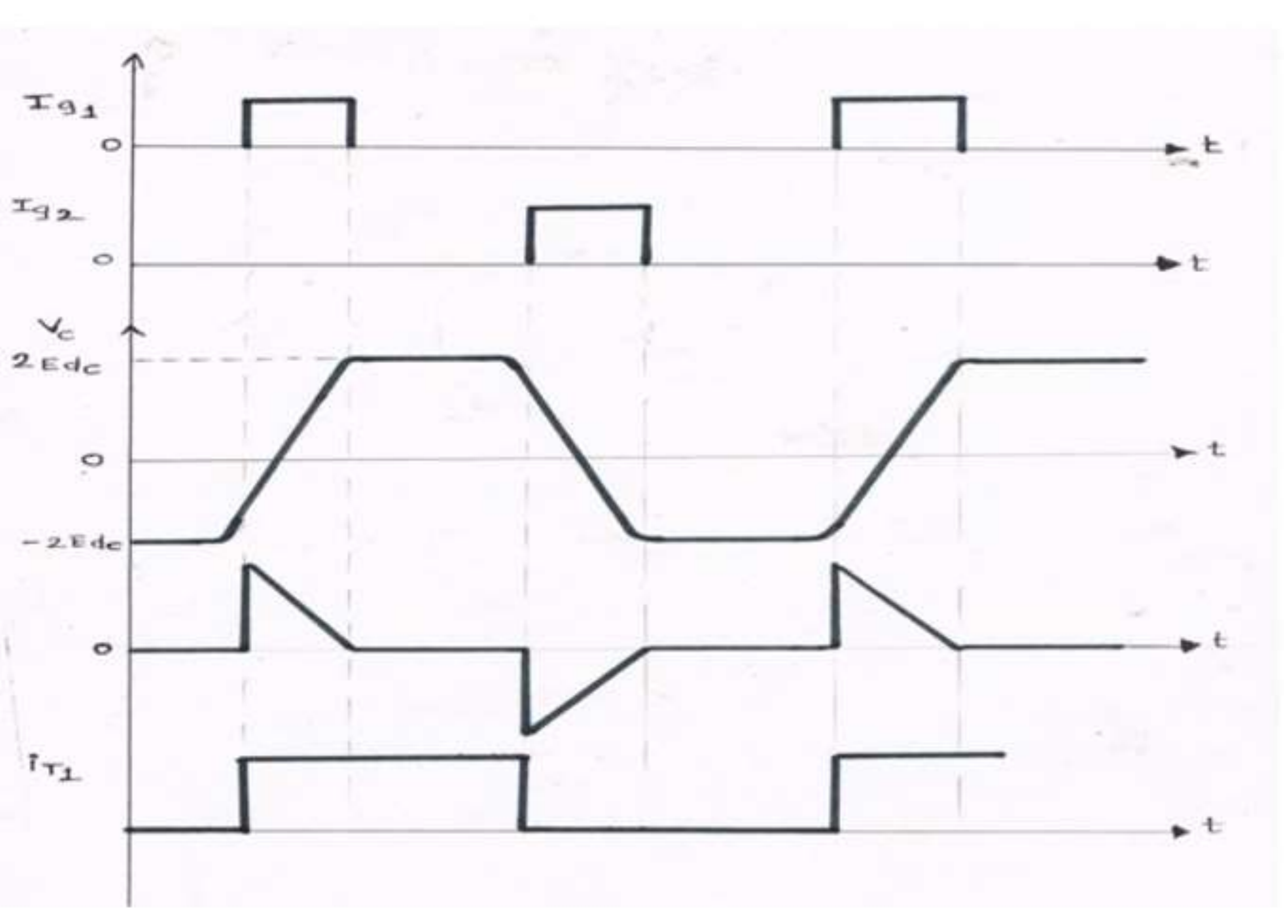
- This mode begins when thyristor T_2 is fired. When T_2 is turned on, the commutating capacitor applies voltage -2 E_{dc} to appear across T_1, it will be turn off.
- SCR T_2 will now be conducting and the voltage of 2 E_{dc} will appear across the transformer primary and commutating capacitor, but with reverse polarity.

Mode 3:

•During mode 3, this SCR is again turned on. Commutating capacitor applies a voltage -2 E_{dc} to appear across T_2.

•when this reverse voltage is applied for sufficient time across T_2, it will be turned off. If trigger pulses are applied periodically to alternate thyristors, an approximately rectangular voltage waveform will be obtained at transformer output terminals.

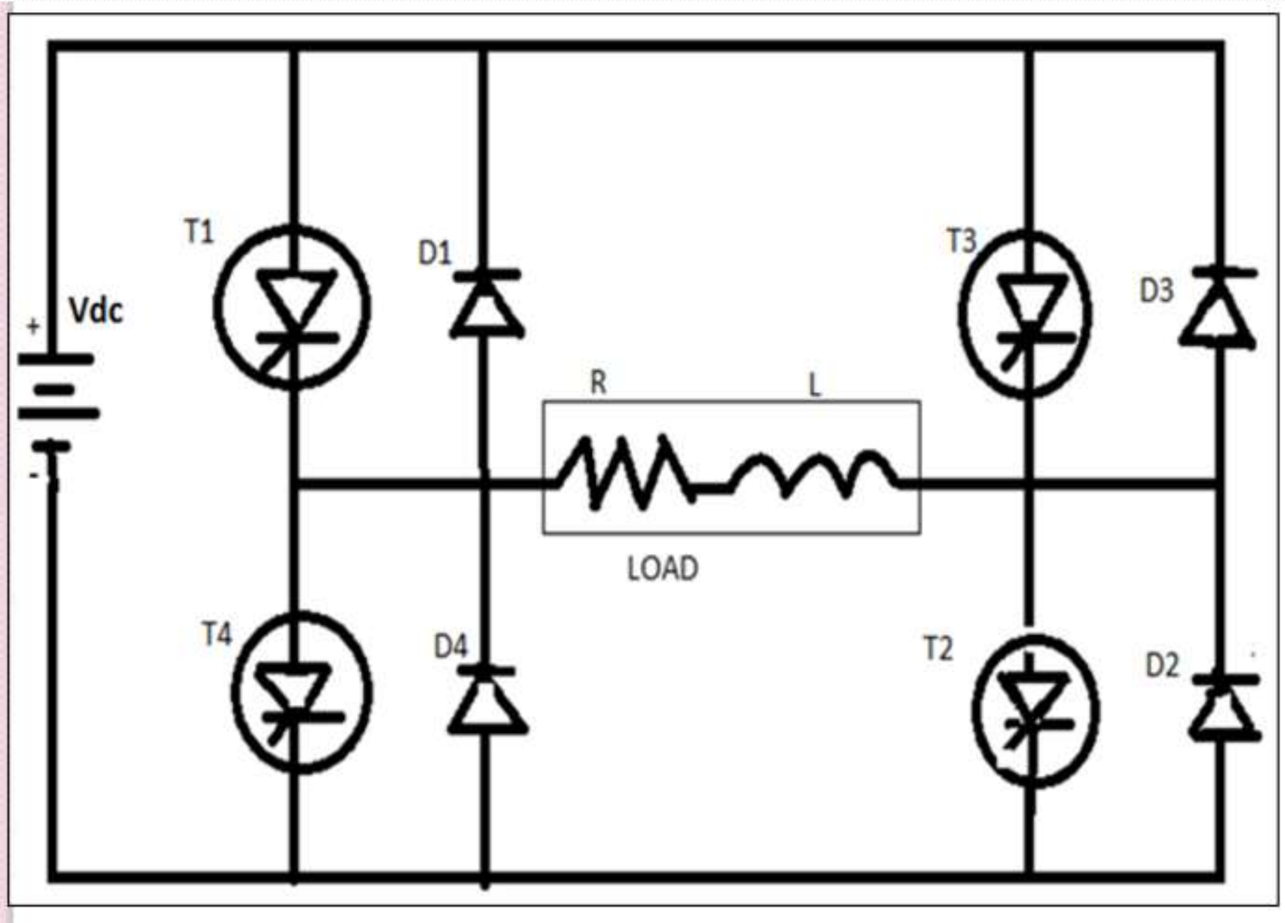
WAVEFORMS OF PARALLEL INVERTER



SINGLE PHASE INVERTER

A serious drawback of the half bridge inverter is that, it requires a 3-wire dc supply. This is overcomed by the commonly full bridge inverter.

FULL BRIDGE SERIES INVERTER



CONSTRUCTION

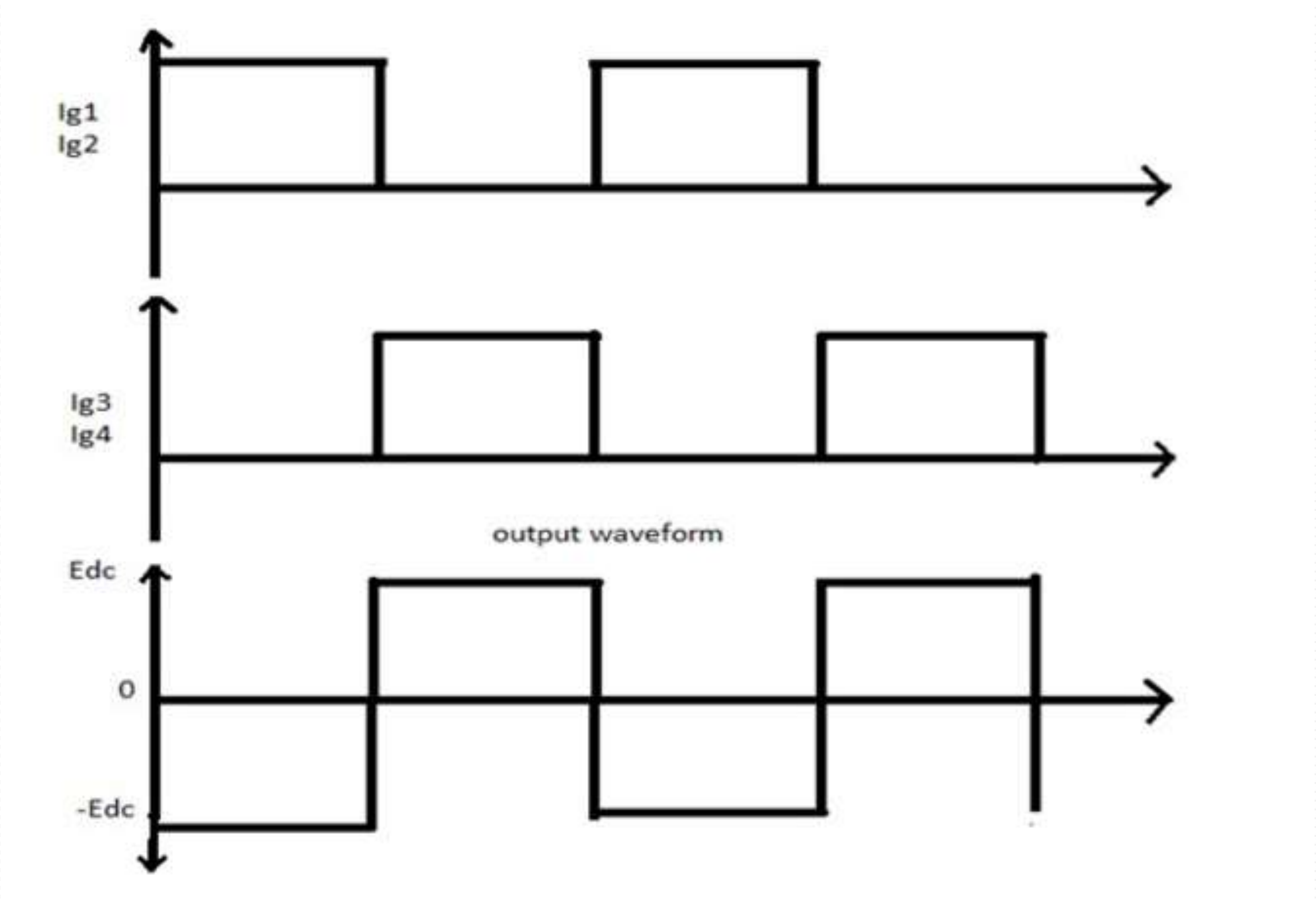
It has consist of four thyristor and four freewheeling diode.

Two thyristor T1 and T2 must be gated simultaneously at frequency F=1/T and thyristor T3and T4 must be gated 180 out of phase frequency can be controlled by varying the periodic time T.

OPERATION

- When we apply positive load voltage Edc then thyristor T1 and T2 conduct.
- When we apply negative voltage –edc then thyristor T3and T4 is conduct.
- Diode D1to D4 serve to feed the load reactive power back to the dc supply.
- In place of SCRT1, hear two thyristor T1 and T2 conduct similarly in place of SCR2 thyristor T3 and T4 conduct and in place of D1 and diodeD1, D2 conduct, where as instead of D2, hear D3and D4 conduct
- The load voltage wave form is fairly rectangular and is not affected by the nature of the load.

WAVEFORM



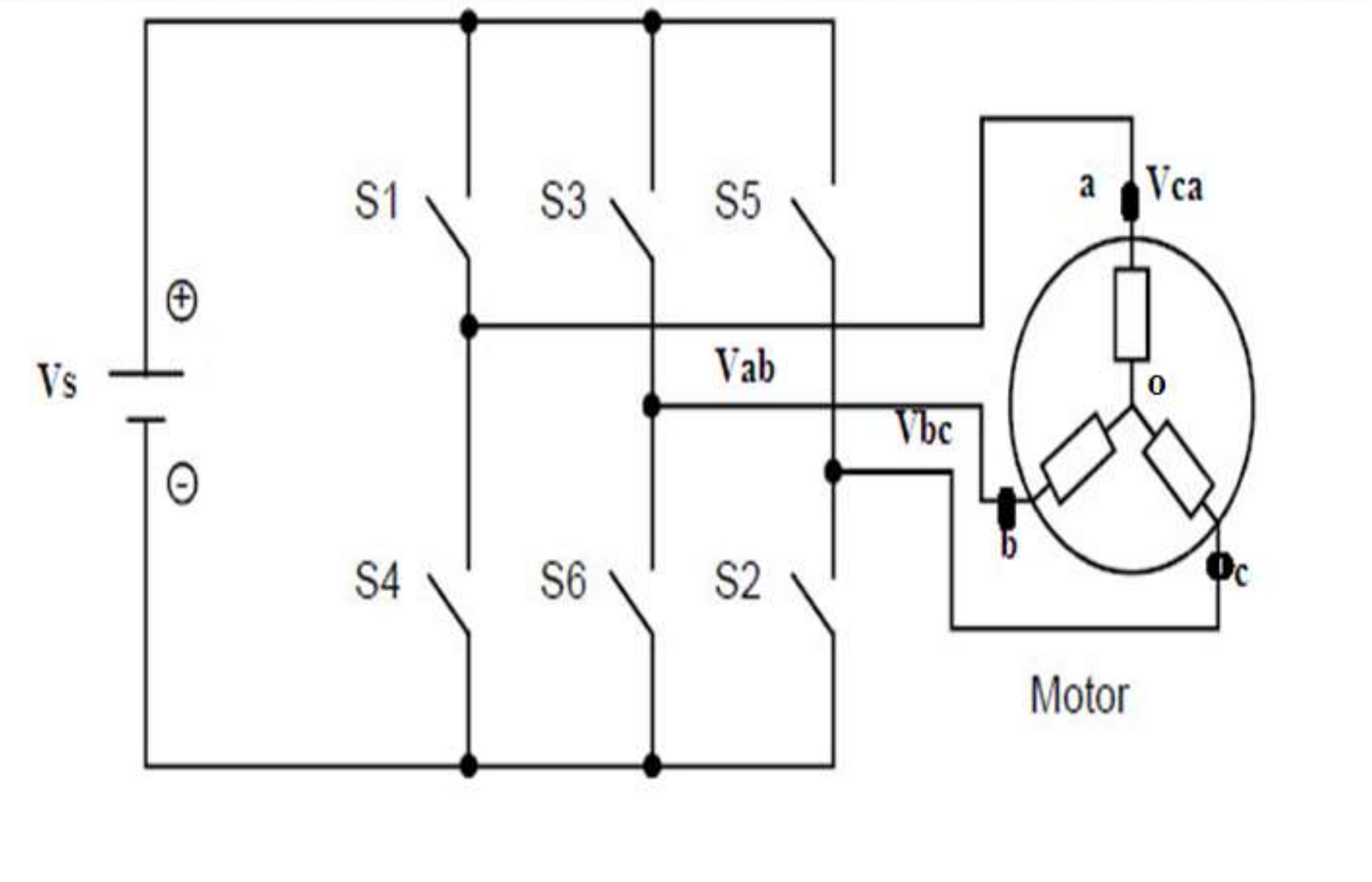
FULL BRIDGE CONVERTER

- ***Advantage :***
- No need of an output transformer.
- Efficiency is high.
- The current rating of power device is equal to the load current.

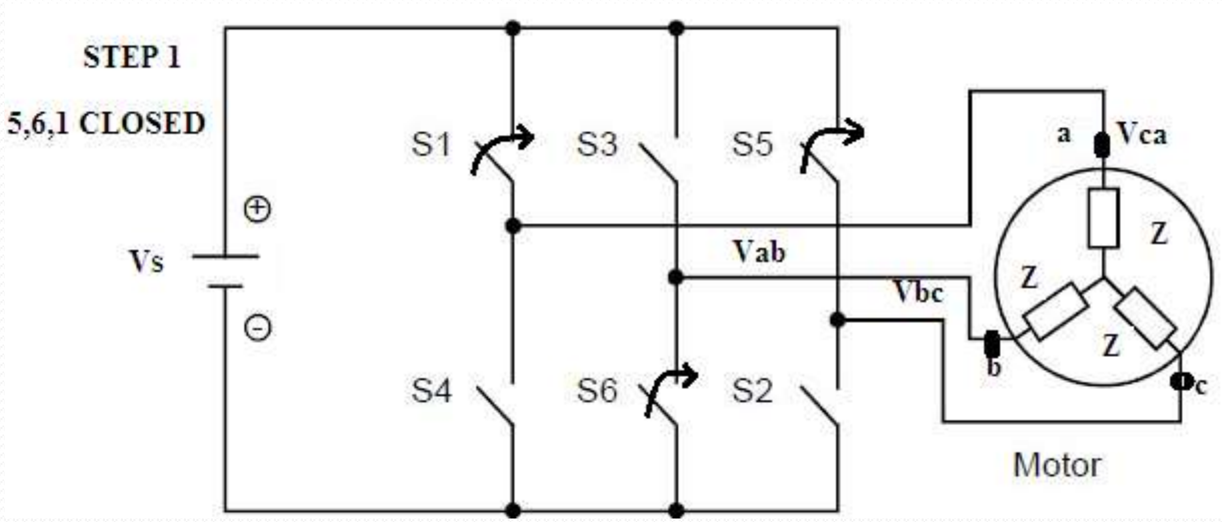
- ***Disadvantage :***
- Number of four transistors are required
- Costs is high

- ***Application :***
- Used in commutation circuit for bridge inverter

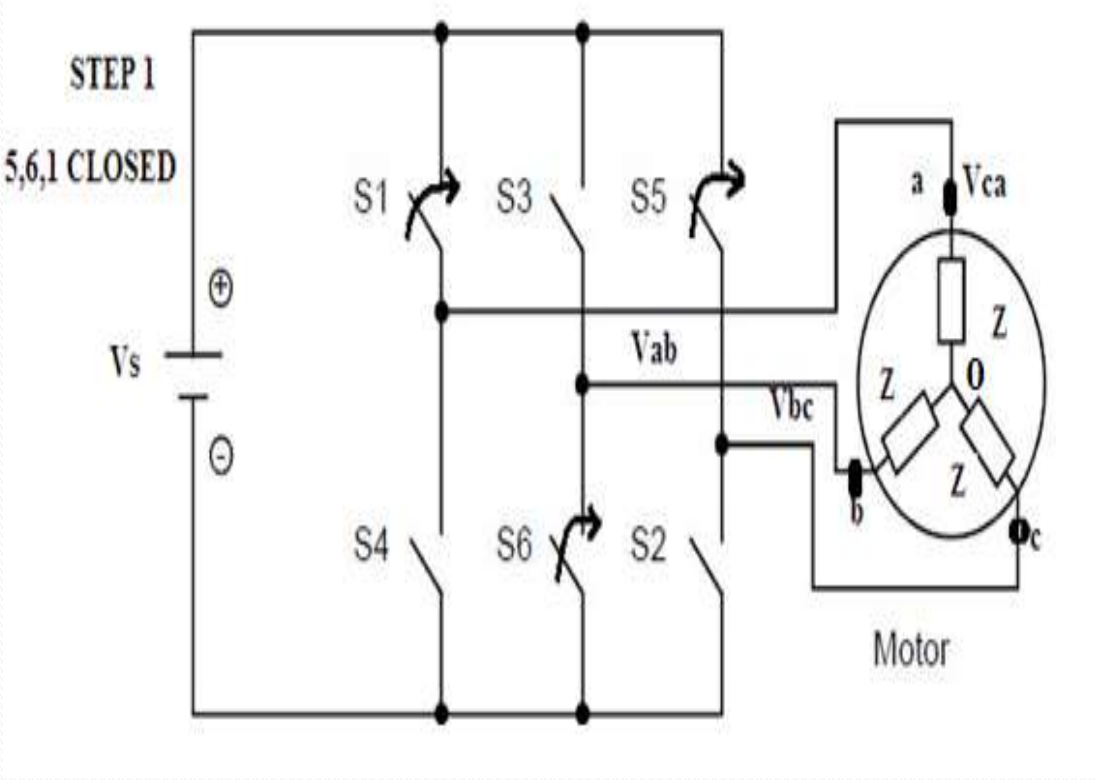
THREE PHASE BRIDGE INVERTER- Voltage Source Inverter (VSI)

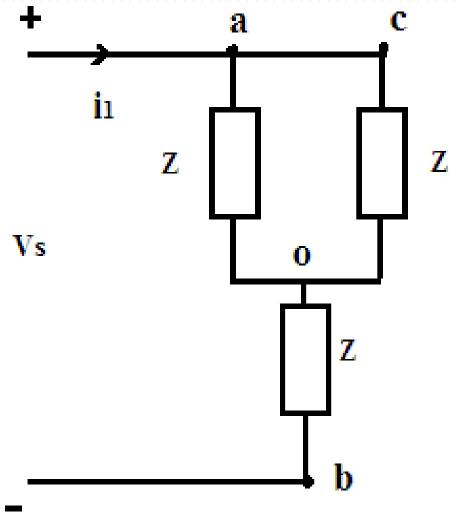


Voltage Source Inverter (VSI)-180 Degree mode



VSI 180 degree operation
Step 1





$$i_1 = \frac{V_s}{\frac{Z}{2}+Z} = \frac{2}{3}\frac{V_s}{Z}$$

$$V_{ao} = i_1 * \frac{Z}{2} = \frac{2}{3}\frac{V_s}{Z} * \frac{Z}{2}$$

$$\Rightarrow V_{ao} = \frac{V_s}{3}$$

$$V_{bo} = i_1 * Z = \frac{2}{3}\frac{V_s}{Z} * Z$$

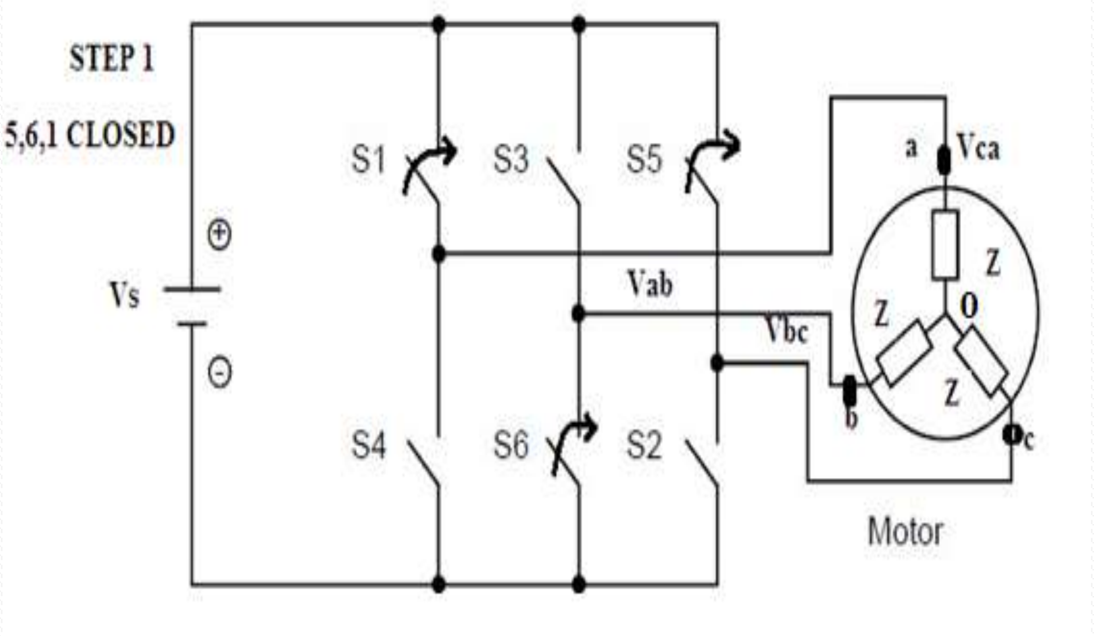
$$\Rightarrow V_{bo} = \frac{2}{3}V_s$$

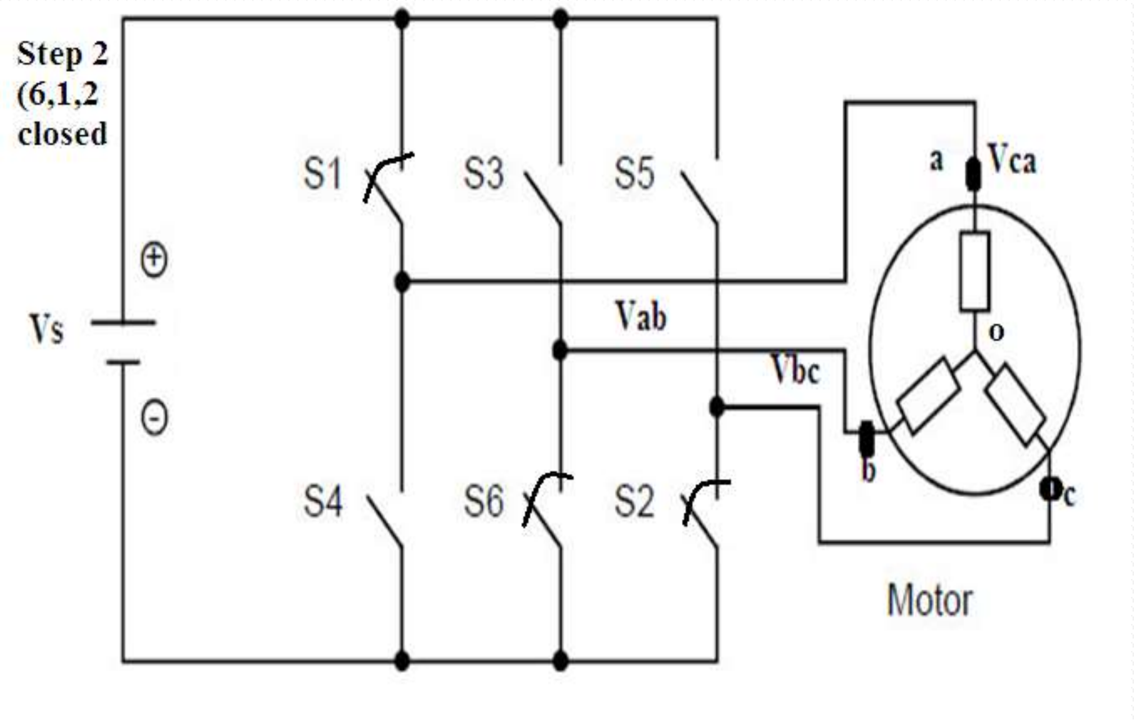
$$\Rightarrow V_{co} = V_{ao}$$

Sequence of steps

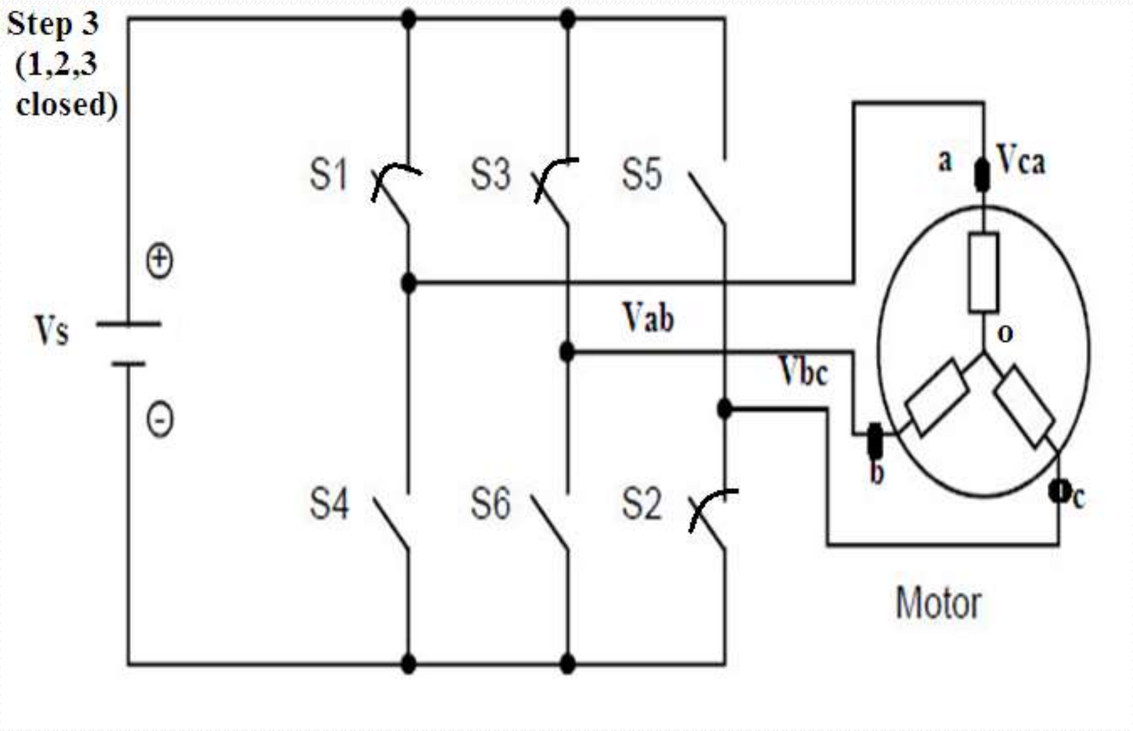
- Step I - 5,6,1
- Step II - 6,1,2
- Step III - 1,2,3
- Step IV - 2,3,4
- Step V - 3,4,5
- Step VI - 5,6,1

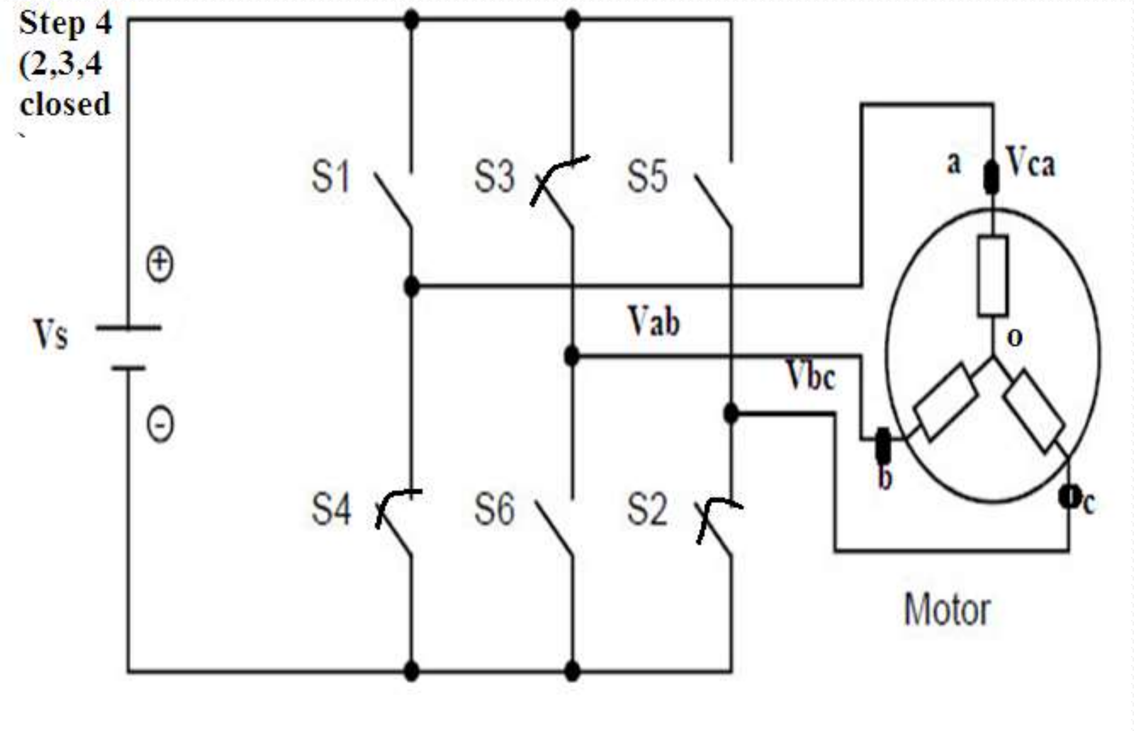
Steps 1 & 2


STEP 1
5,6,1 CLOSED
S1
S3
S5
S4
S6
S2
Vs
a
Vca
Vab
Vbc
Z
Z
Z
O
b
c
Motor

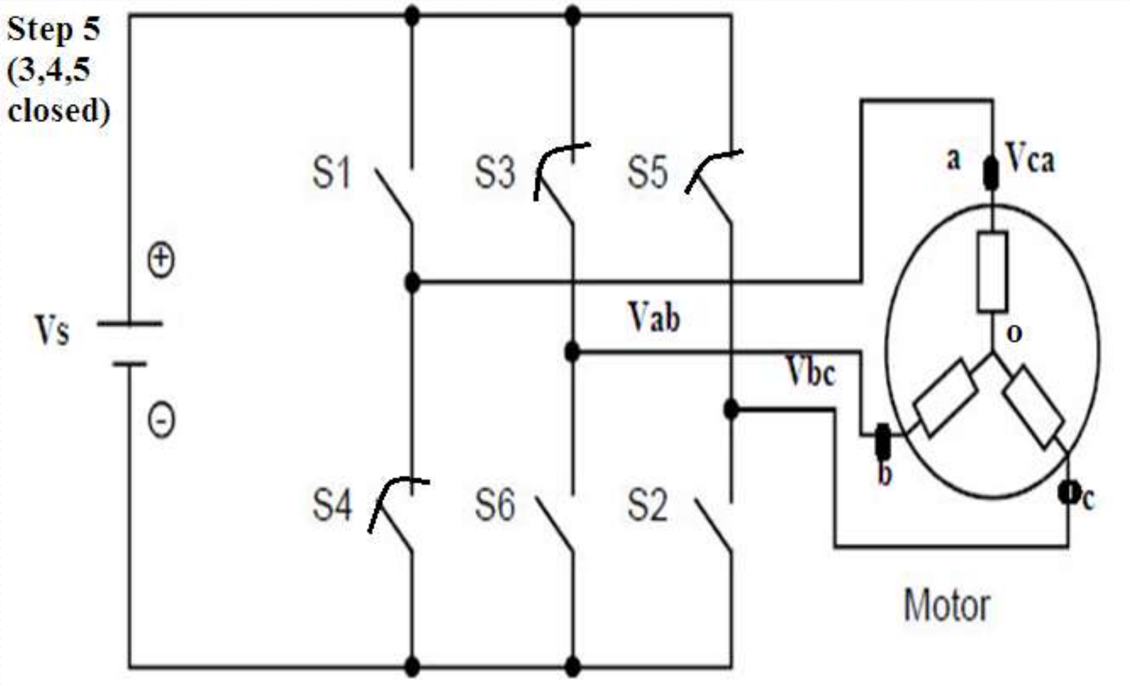

Step 2
(6,1,2
closed
S1
S3
S5
S4
S6
S2
Vs
a
Vca
Vab
Vbc
o
b
c
Motor

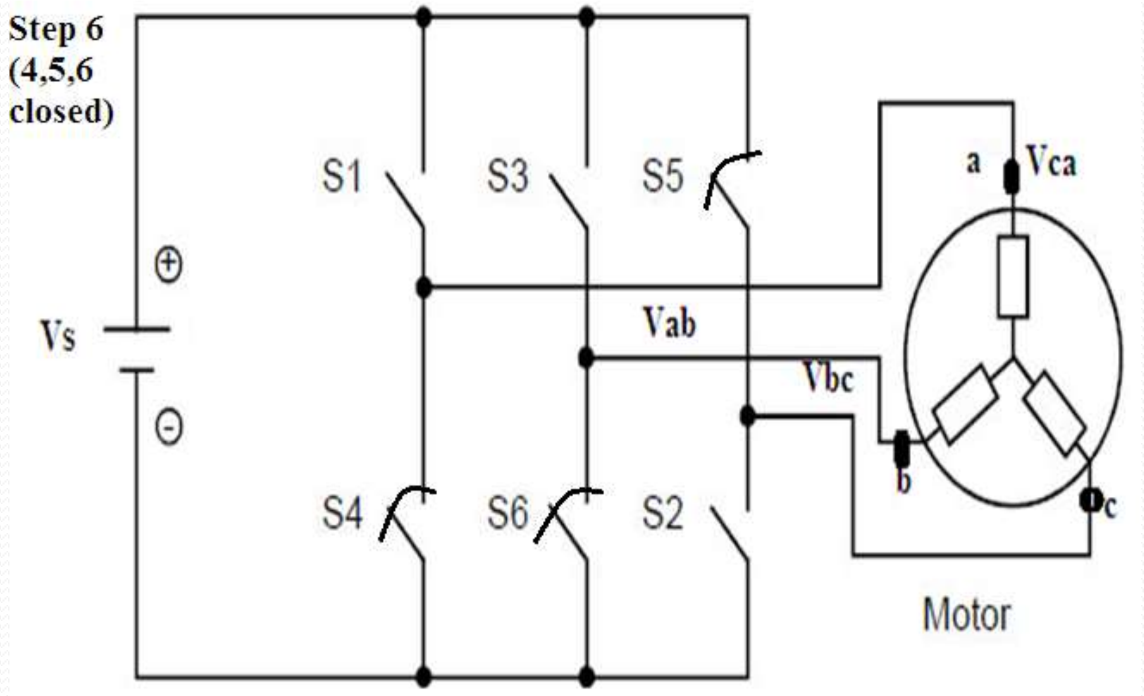
Steps 3 & 4


Step 3
(1,2,3
closed)
S1
S3
S5
a
Vca
Vab
o
Vbc
Vs
b
c
S4
S6
S2
Motor


Step 4
(2,3,4
closed
S1
S3
S5
a
Vca
Vab
o
Vbc
Vs
b
c
S4
S6
S2
Motor

Steps 5 & 6


Step 5
(3,4,5
closed)
S1
S3
S5
S4
S6
S2
Vs
a
Vca
o
Vab
Vbc
b
c
Motor


Step 6
(4,5,6
closed)
S1
S3
S5
S4
S6
S2
Vs
a
Vca
Vab
Vbc
b
c
Motor

Phase and Line Voltages for 180 degree mode VSI

Degree/ Voltage	Phase Voltage Vao	Phase Voltage Vbo	Phase Voltage Vco	Line Voltage Vab	Line Voltage Vbc	Line Voltage Vca
0-60	Vs/3	-2Vs/3	Vs/3	Vs	-Vs	0
60-120	2Vs/3	-Vs/3	-Vs/3	Vs	0	-Vs
120-180	Vs/3	Vs/3	-2Vs/3	0	Vs	-Vs
180-240	-Vs/3	2Vs/3	-Vs/3	-Vs	Vs	0
240-300	-2vs/3	Vs/3	Vs/3	-Vs	0	Vs
300-360	-Vs/3	-Vs/3	2Vs/3	0	-Vs	Vs

180° mode of conduction

In this mode of conduction, every device is in conduction state for 180° where they are switched ON at 60° intervals. The terminals A, B and C are the output terminals of the bridge that are connected to the three-phase delta or star connection of the load.

The load voltages are gives as follows;

$V_{AN} = V/3,$

$V_{BN} = -2V/3,$

$V_{CN} = V/3$

The line voltages are given as follows;

$V_{AB} = V_{AN} - V_{BN} = V,$

$V_{BC} = V_{BN} - V_{CN} = -V,$

$V_{CA} = V_{CN} - V_{AN} = 0$

120° mode of conduction

In this mode of conduction, each electronic device is in a conduction state for 120°. It is most suitable for a delta connection in a load because it results in a six-step type of waveform across any of its phases. Therefore, at any instant only two devices are conducting because each device conducts at only 120°.

The terminal A on the load is connected to the positive end while the terminal B is connected to the negative end of the source. The terminal C on the load is in a condition called floating state. Furthermore, the phase voltages are equal to the load voltages as shown below.

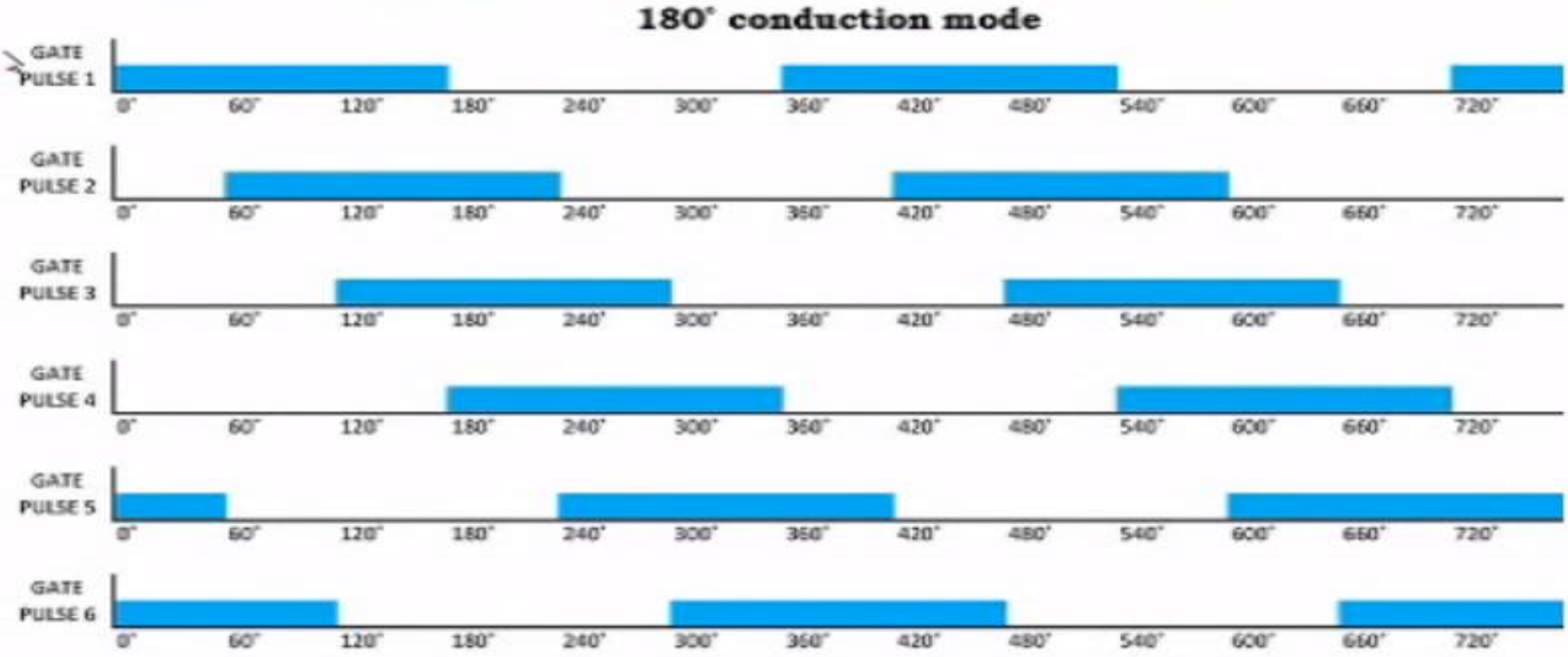
Phase voltages = Line voltages

$V_{AB} = V$

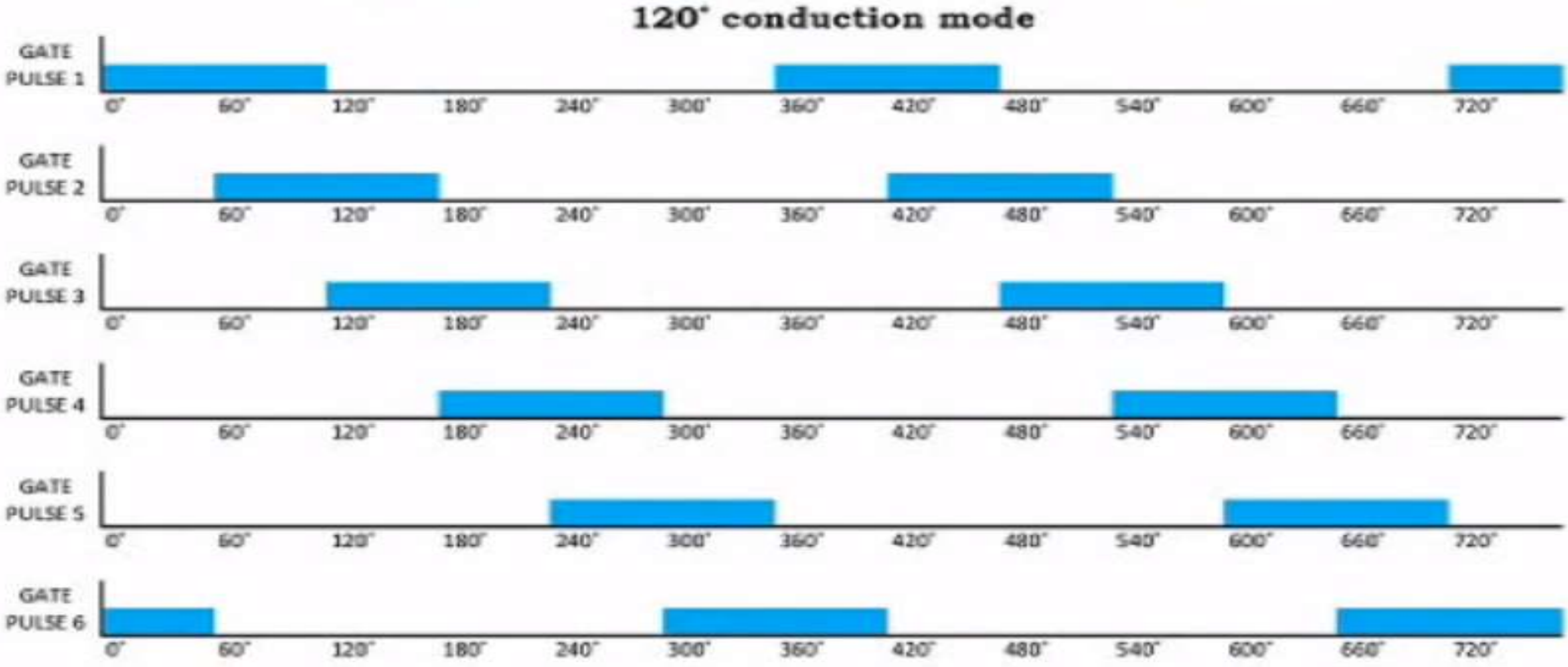
$V_{BC} = -V/2$

$V_{CA} = -V/2$

Six Step Voltage Source Inverter

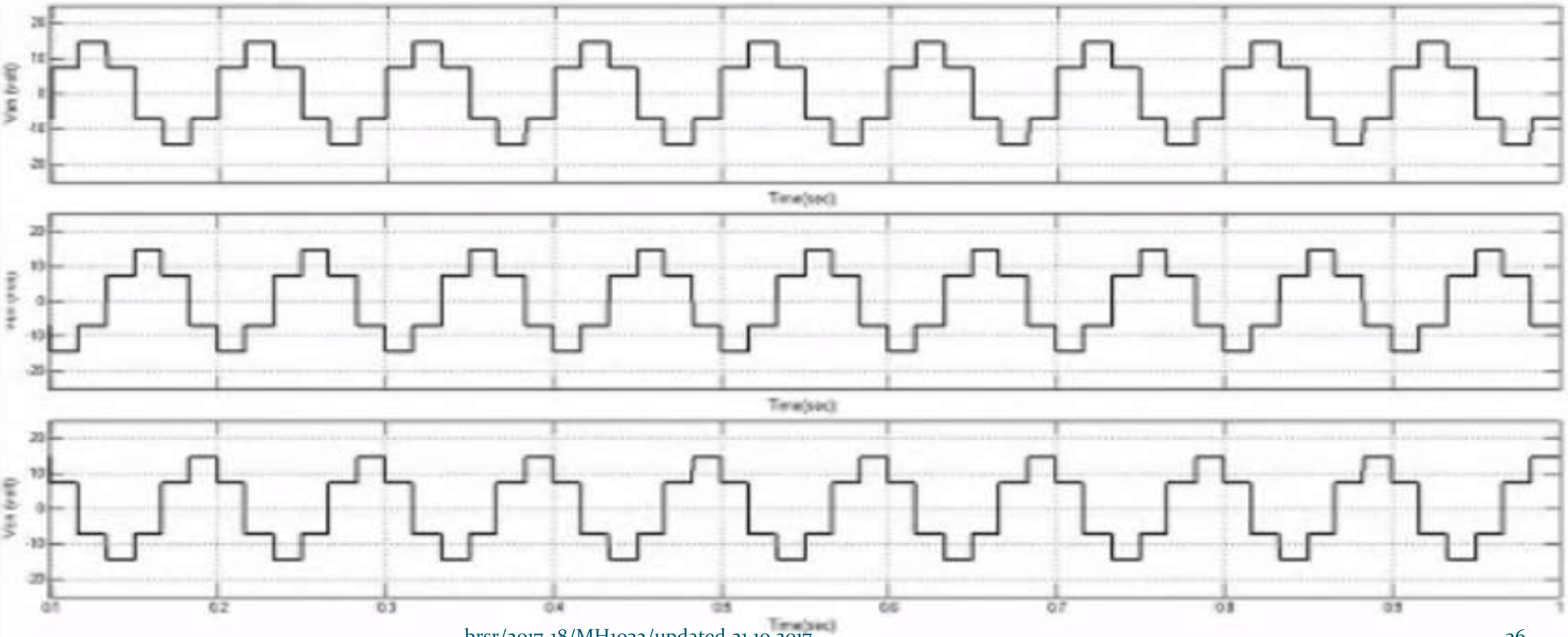


Six Step Voltage Source Inverter



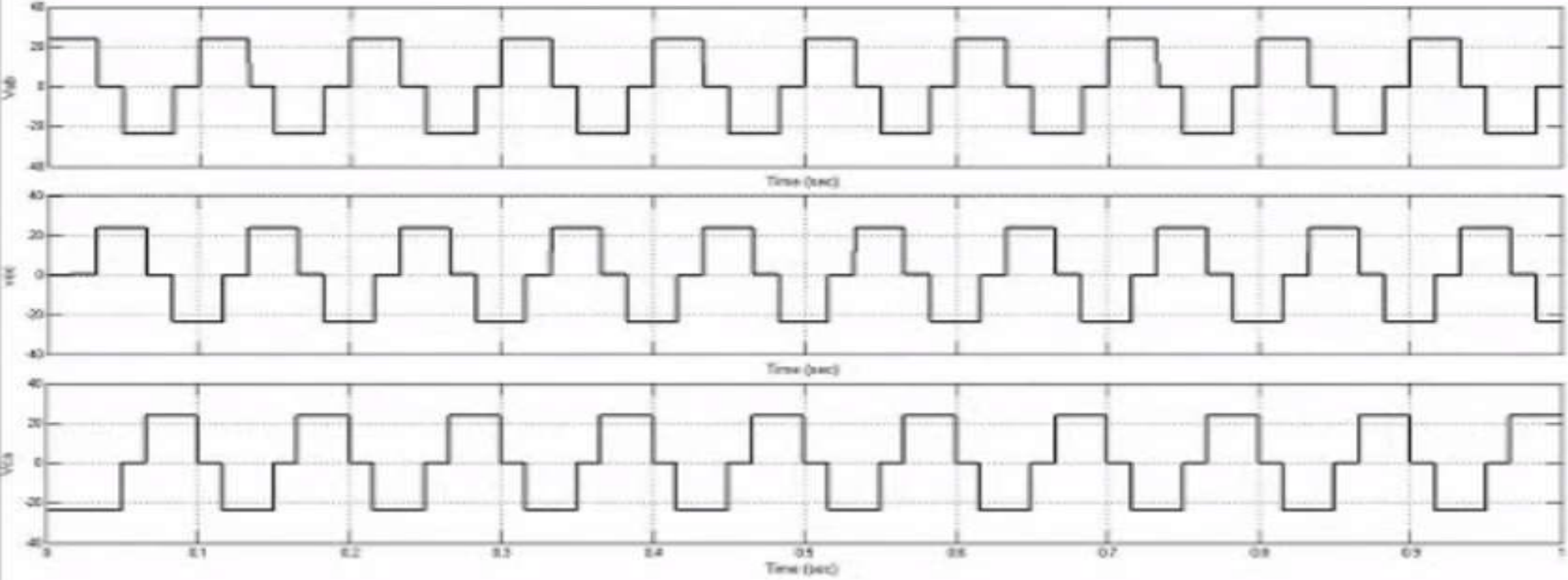
Six Step Voltage Source Inverter

180° conduction mode : Phase voltage



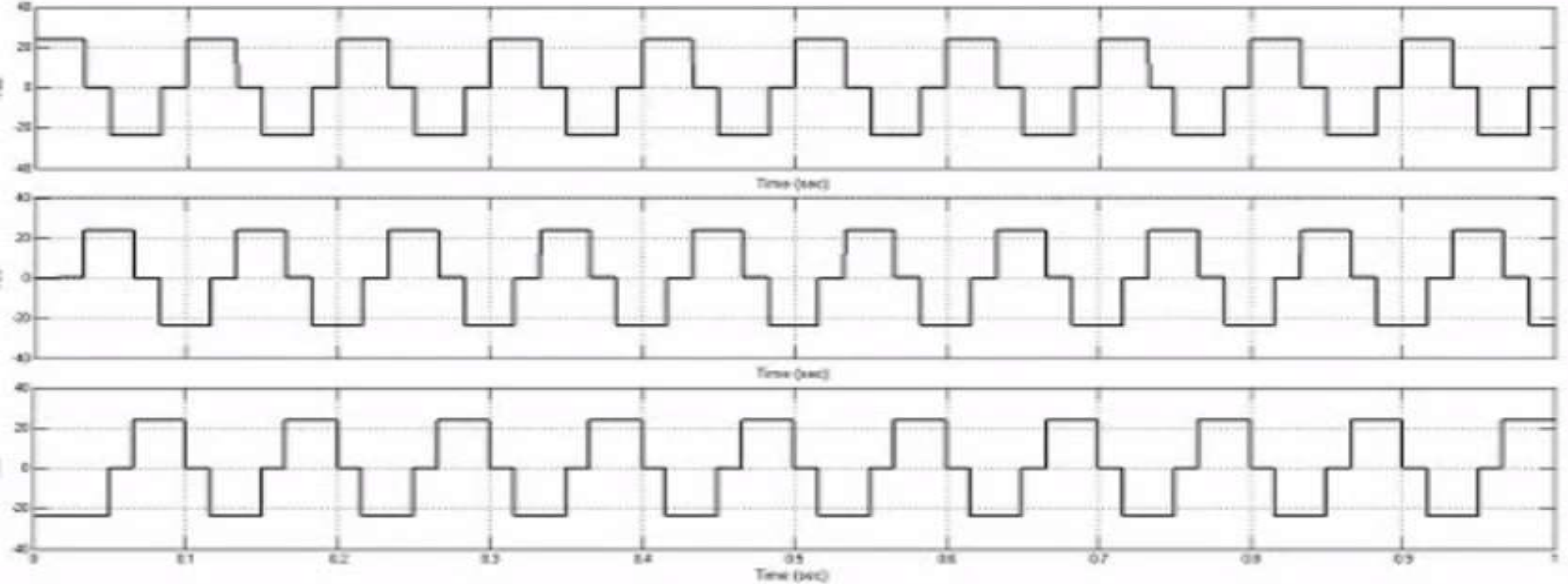
Six Step Voltage Source Inverter

180˚ conduction mode : Line voltage



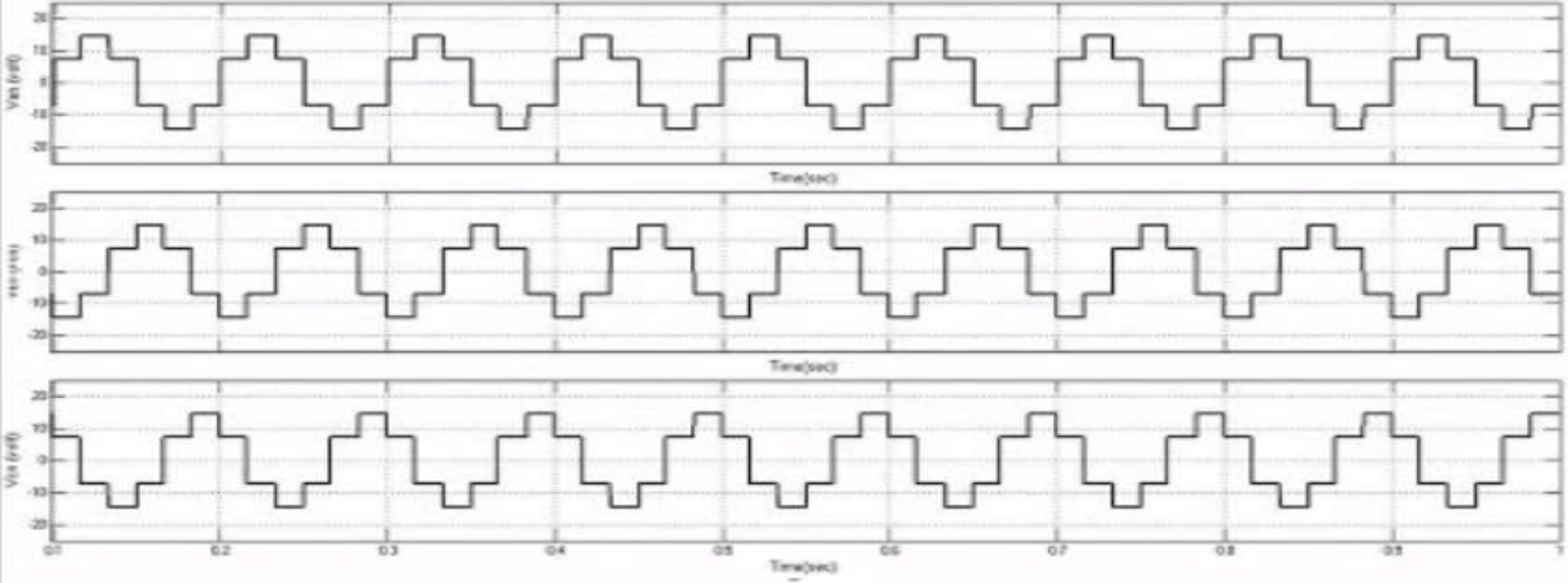
Six Step Voltage Source Inverter

120° conduction mode : Phase voltage



Six Step Voltage Source Inverter

120° conduction mode : Line voltage



McMurray Inverter

Circuit

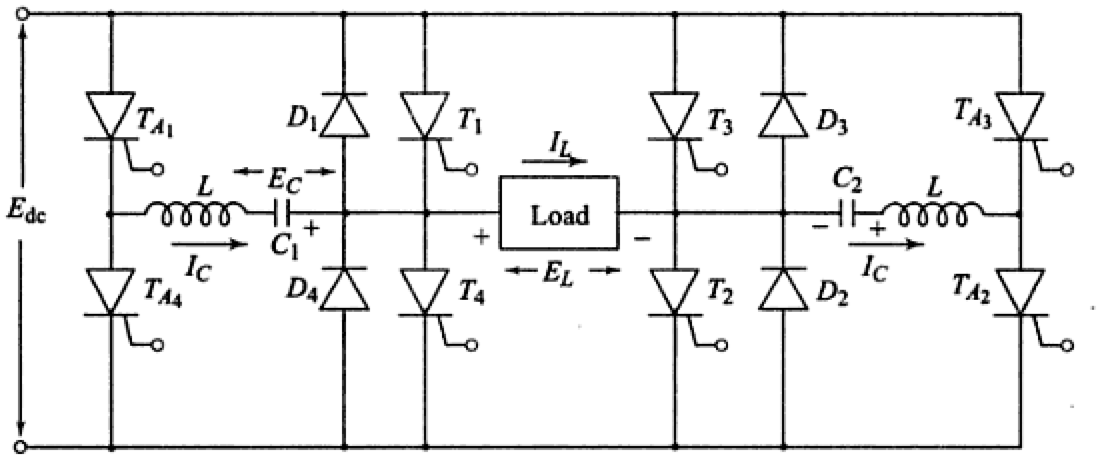
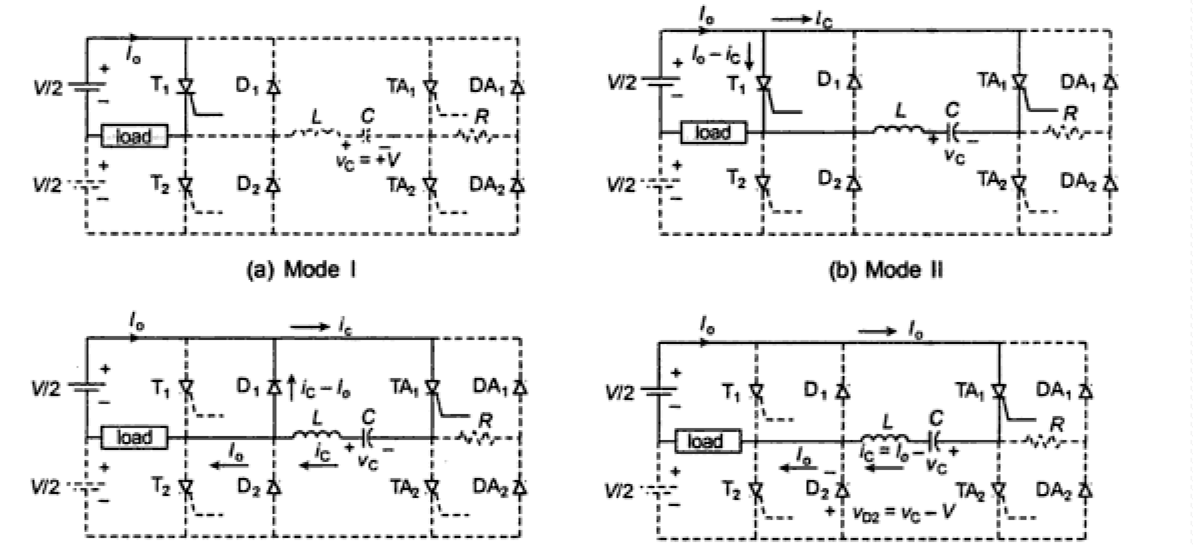


Fig. 9.44 *Single-phase McMurray inverter*

Modes



(a) Mode I

(b) Mode II

(c) Mode III

(d) Mode IV

Modes

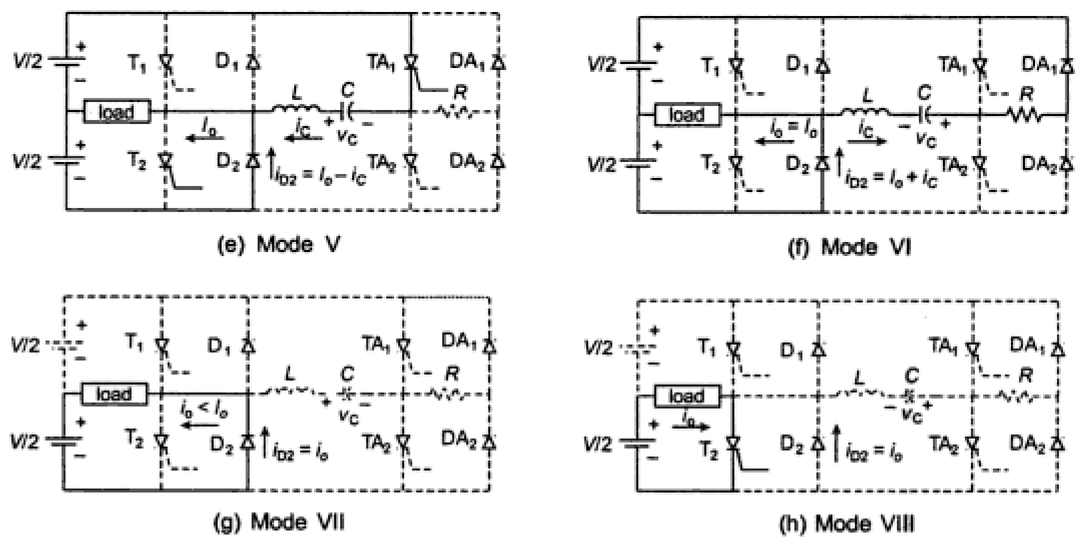
Mode I $(t < 0)$ In this mode main thyristor T_1 conducts and a constant positive load current (I_o) flows. The load voltage is positive and the capacitor is charged up to $+V$ (left plate positive), as shown in Fig. 8.27a. The auxiliary thyristor TA_1 is forward biased by the capacitor voltage.

Mode II $(0 < t < t_1)$ TA_1 is triggered at $t = 0$ to commutate T_1. This results in flow of resonating current i_C through L, C, T_1 and TA_1, as shown in Fig. 8.27b. This current increases while the net current through T_1 $(i_{T1} = I_o - i_C)$ reduces. At $t = t_1$, i_C becomes equal to I_o while i_{T1} reduces to zero. Then T_1 turns-off.

Mode III $(t_1 < t < t_2)$ As the resonating current i_C becomes higher than the load current (I_o), the surplus current $(i_C - I_o)$ flows through the diode D_1, as shown in Fig. 8.27c. The resonating current reaches the peak value and the falls to I_o at t_2, as shown in Fig. 8.28. The current through D_1, (i_{D1}), also becomes zero at t_2 which commutates D_1. During this interval, the capacitor voltage reduces. It becomes negative (right plate positive) after i_C reaches its peak value.

Mode IV $(t_2 < t < t_3)$ When D_1 turns off at the end of mode-III, the capacitor is charged in reverse direction (right plate positive) by the constant load current I_o. During this interval, the voltage across diode D_2, v_{D2}, is equal to $v_c - V$. (This may be verified by applying KVL to the path formed by the voltage source, TA_1, C, L and D_2.) At t_3, the capacitor charges to a voltage slightly higher than V. This results in forward biasing of D_2, and D_2 turns on.

Modes


V/2
T₁
D₁
TA₁
DA₁
load
L
C
R
T₂
D₂
TA₂
DA₂
(e) Mode V
(f) Mode VI
(g) Mode VII
(h) Mode VIII

Modes

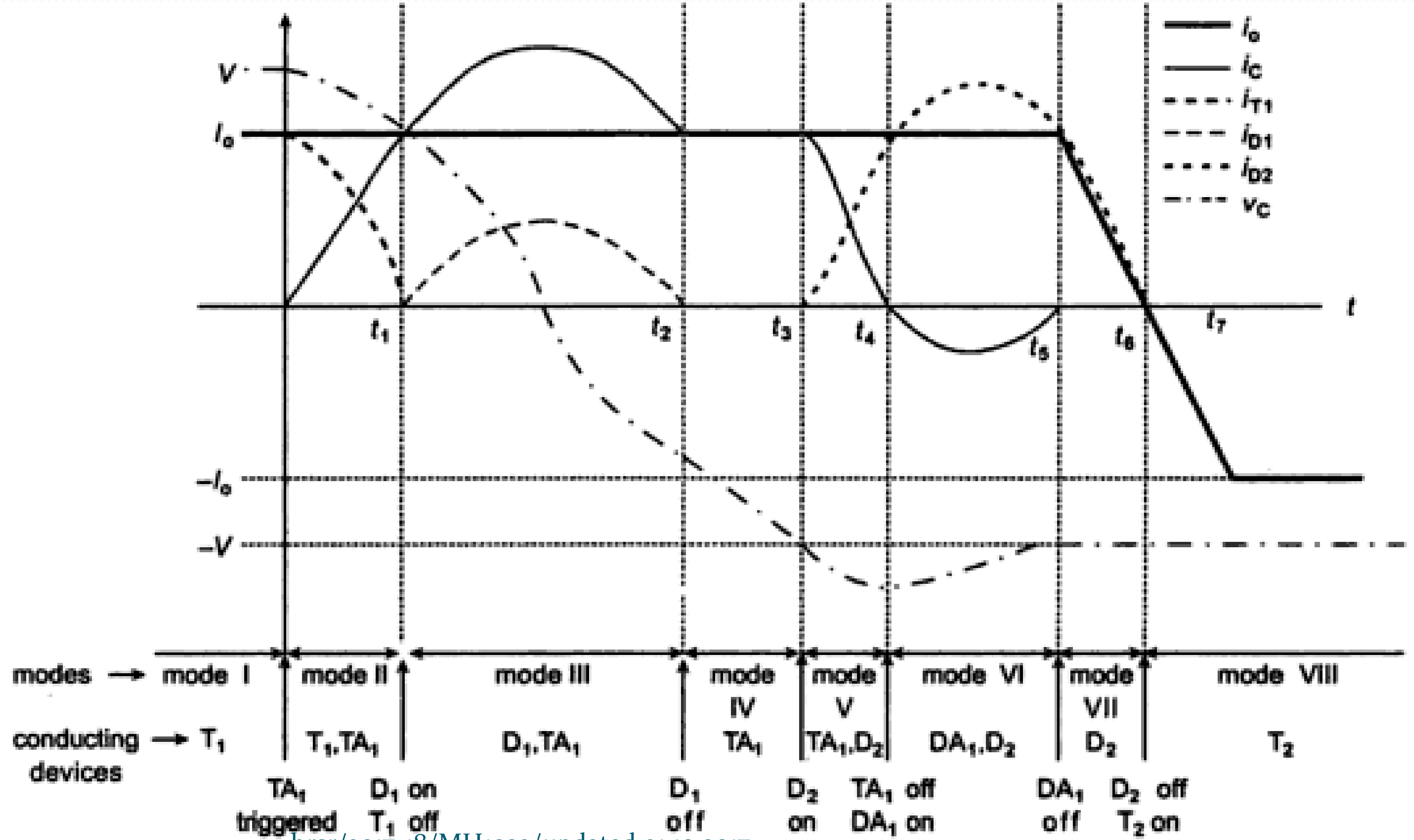
Mode V ($t_3 < t < t_4$) When D_2 turns on, I_o is shared by i_{D2} and i_C, as shown in Fig. 8.27e. As i_C decreases, i_{D2} increases, which is equal to $(I_o - i_C)$. At t_4, $i_C = i_{TA1} = 0$ and TA_1 turns off. After t_3, trigger signal is given to T_2. However, it will turn on only when D_2 turns off.

Mode VI ($t_4 < t < t_5$) As i_C tries to reverse at t_4, DA_1 turns on. At this instant, the capacitor voltage is more than the source voltage. Now the capacitor discharges through V, D_2, L, DA_1 and the damping resistance R. At t_5, the capacitor current falls to zero and DA_1 is commutated. Moreover, the capacitor is charged up to $-V$ (right plate positive).

Mode VII ($t_5 < t < t_6$) During this interval, i_o flows through D_2 and the lower source, as shown in Fig. 8.27g. The load current reduces under the influence of the negative source voltage. At t_6, i_o becomes zero and D_2 turns off.

Mode VIII ($t > t_6$) When D_2 turns off, T_2, which is already recieving the gate signal, turns on. It conducts and the negative load current (Fig. 8.27h), rises to become equal to I_o at $t = t_7$. At this instant, the capacitor voltage forward biases the auxiliary thyristor TA_2. To initiate the turn-off process of T_2, TA_2 will be triggered.

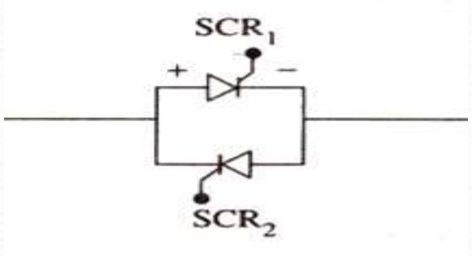
Timing Diagram

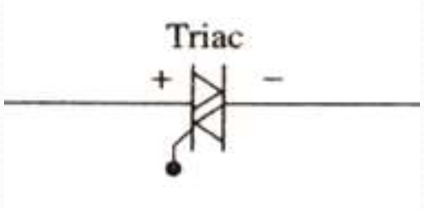


UNIT V
AC - AC CONVERTERS
AC VOLTAGE CONTROLLERS

Introduction

- AC voltage controllers are thyristor based devices which convert fixed alternating voltage directly to variable alternating voltage without change in frequency.
- Using these controllers, rms value of the voltage across the load is steplessly varied from a maximum value to zero.
- The simplest way to control AC voltage to the load is by using AC switch (bidirectional).
- The bi-directional conducting property can be achieved by simply connecting two unidirectional thyristors in inverse parallel to each other.



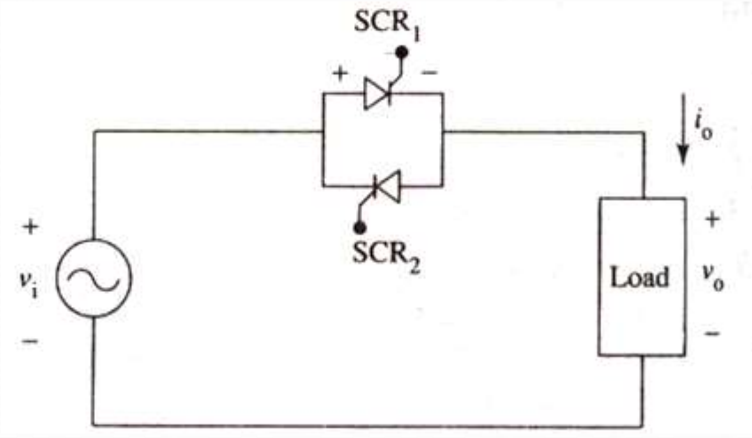


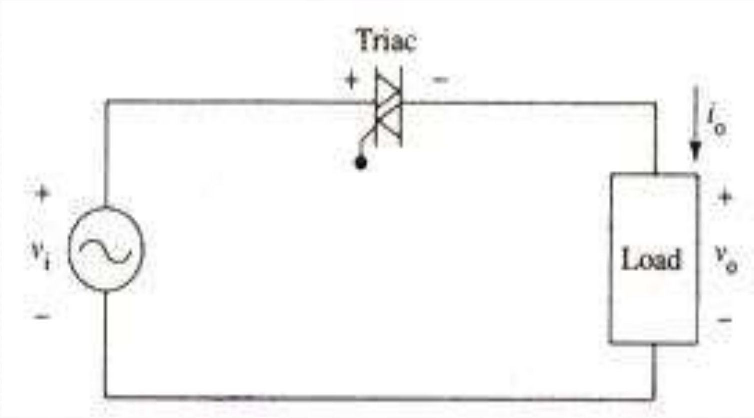
- AC voltage controllers are naturally commutated.

AC Power Control

Control of AC voltage controllers is of two kinds.

1. **On-Off Control (Integral Cycle Control)**
2. **Phase Control**





Single Phase AC voltage Controller

1- On-Off Control (Integral Cycle Control)

- **The load power can be controlled by connecting the source to the load for few complete cycles then disconnecting the source from the load for another number of cycles, and repeating the switching cycle.**

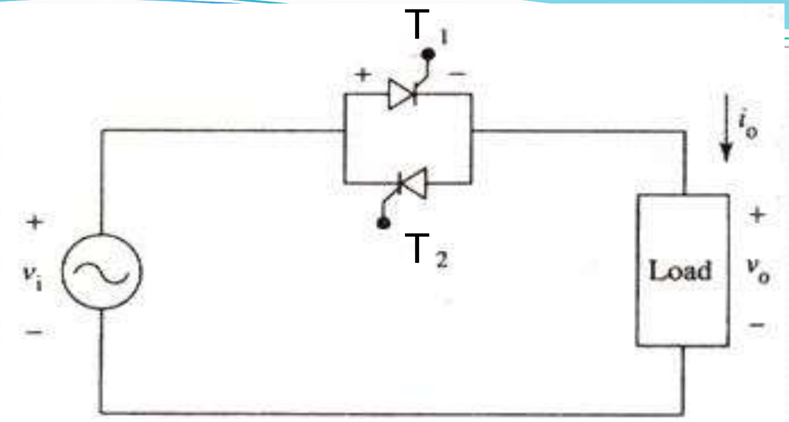
- **Suitable for systems with large time constants.**

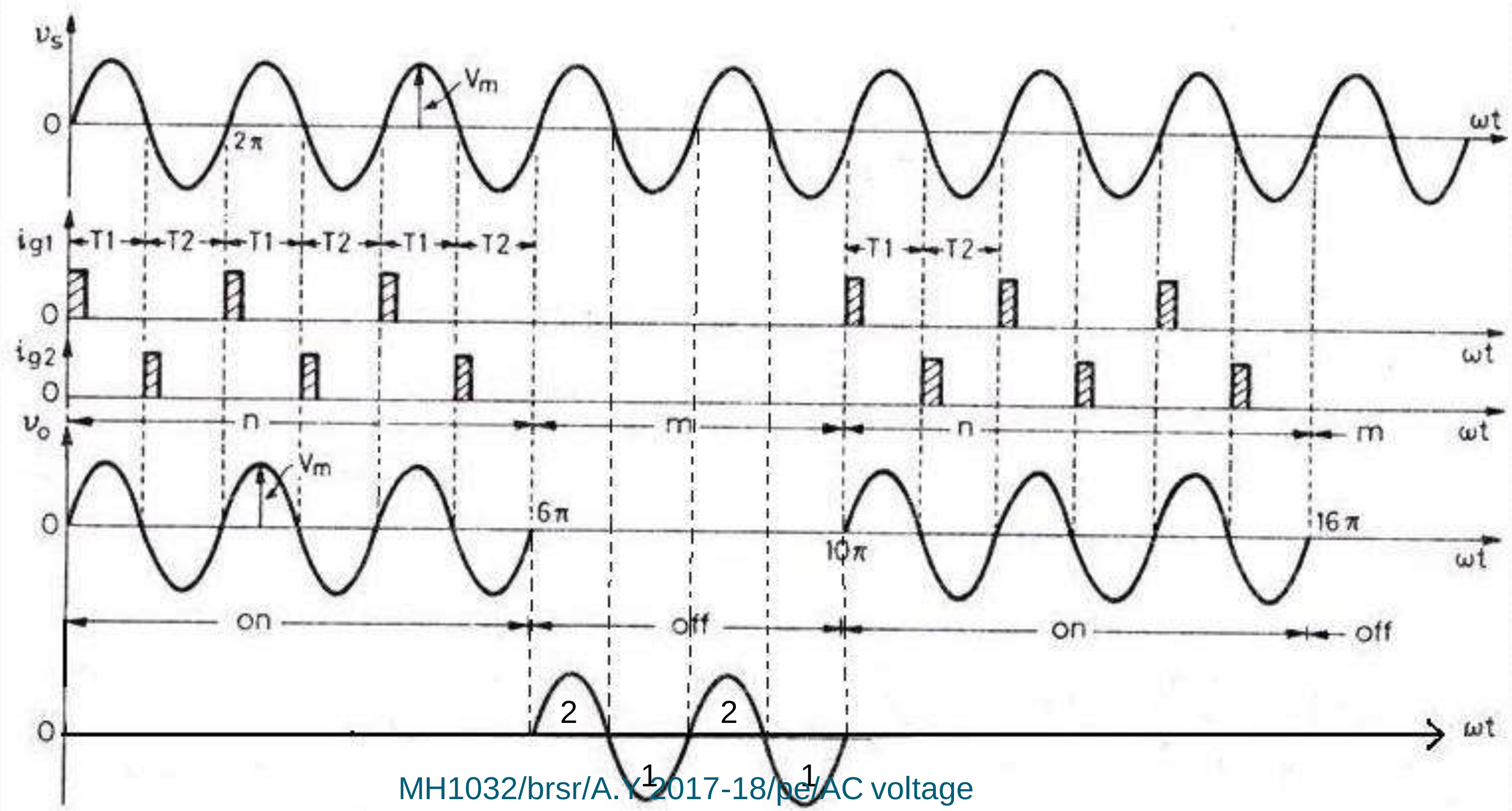
- **Average power to the load can be varied from 0% through 100%**

- **Integral cycle control finds applications in heating loads and for motor speed control.**

  (In industry, there are several applications in which mechanical time constant or thermal time constant is of the order of several seconds. For example, mechanical time constant for many of the speed-control drives, or thermal time constants for most of the heating loads is usually quite high. For such applications, almost no variation in speed or temperature will be noticed if control is achieved connecting the load to source for some on cycles and then disconnecting the load for some off cycles.)

For resistive load





Voltage across thyristors

RMS value of output voltage is:

$$Vo = Vi\sqrt{K}$$

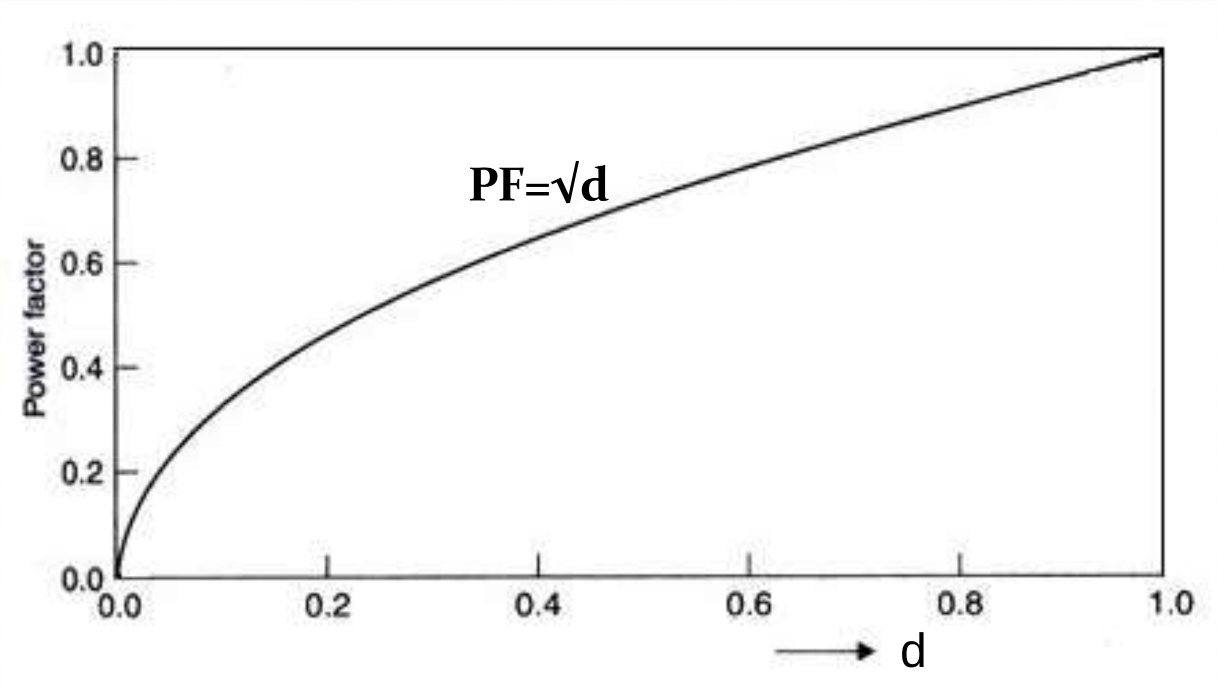
where $$K = \frac{Ton}{Ton + Toff}$$

Ratio of on time to total cycle time controls average load power as well as rms output voltage.

Power factor is:

$$PF=\sqrt{(T_{ON}/T)} = \sqrt{d}$$

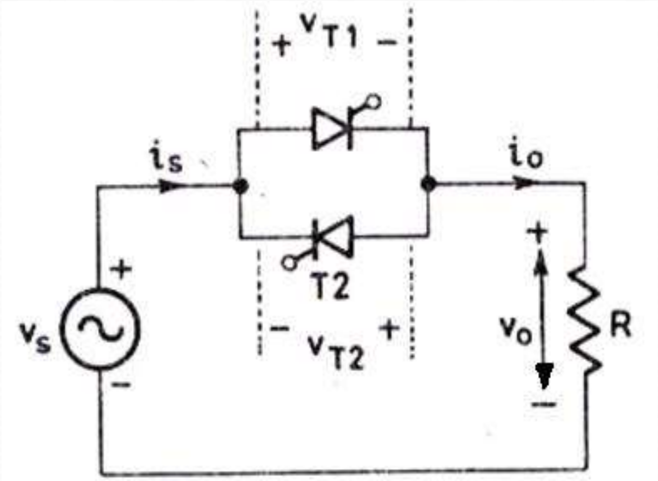
Source current is always in time phase with source voltage. This does not mean that integral cycle control circuit operates at unity power factor- for part of time, the source current is not present at all and therefore is not in phase with source voltage.

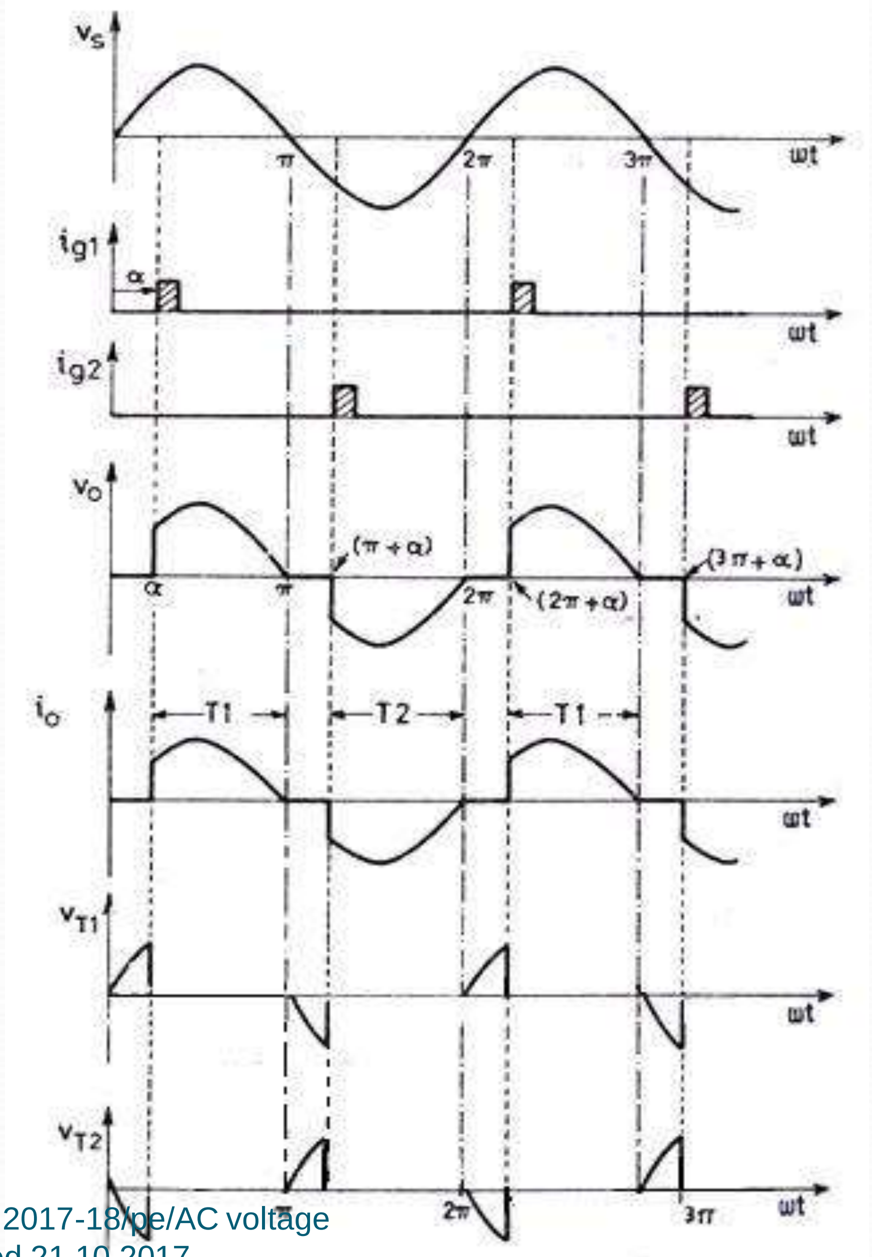


2- AC Phase Control

- Phase control is kind in which thyristors are fired once every cycle and the instant of firing can be delayed from the zero crossing. By this, only a part of the voltage waveform appears across the load, providing voltage control. The load current appears in pulses, the zero crossing of which can be used for turn-off of the thyristors.
- Suitable for loads with short time constants.
- Firing instants of thyristors are 180° apart, each occuring in its respective half cycle.
- By controlling this instant of firing, the effective voltage occuring across the load can be varied.
- As the two thyristors have firing pulses delayed by 180° , the AC current pulses are periodic and symmetrical and there is no DC current component. The load voltage also does not have any DC component.

Single-phase AC voltage controller with resistive load





Load power can be varied by changing α over the full range from zero to 180°

RMS value of output voltage is:

$$V_{o(RMS)} = V_i \left\{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right\}^{1/2}$$

RMS value of output current is:

$$I_{o(RMS)} = \frac{V_i}{R} \left\{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right\}^{1/2}$$

Output power is:

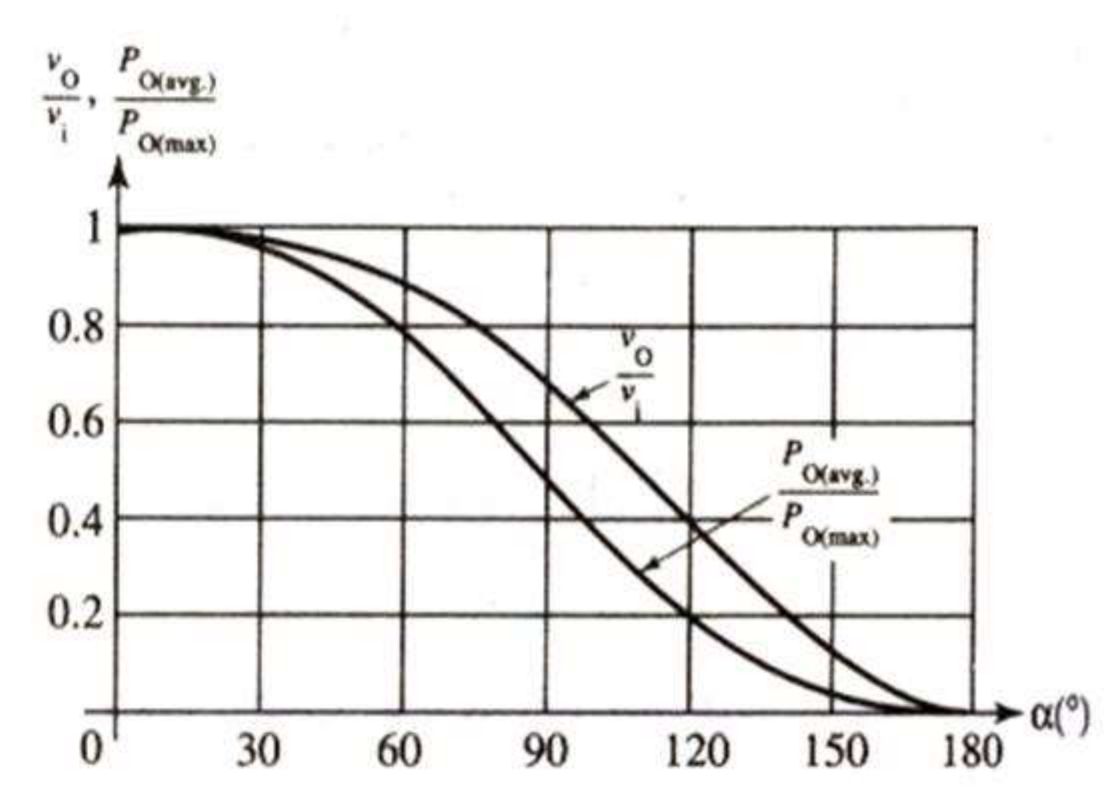
$P_{o(avg.)} = I^2_{o(RMS)}(R)$ Or $V^2_{o(RMS)}/R$

Power factor is given by:

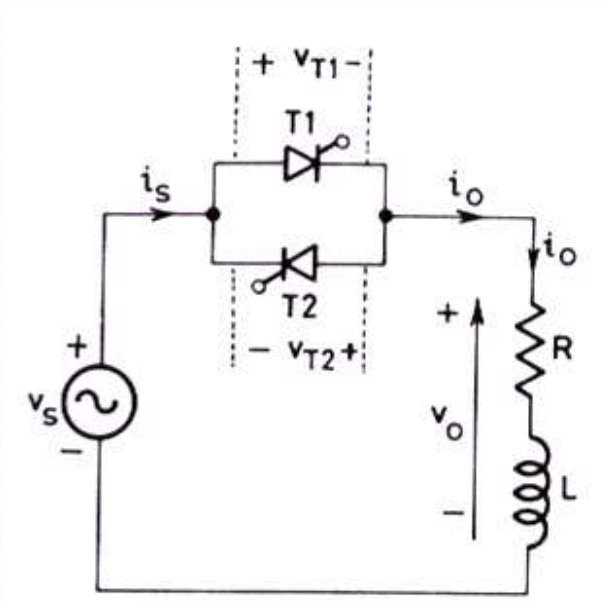
$$PF = \left\{1 - \frac{\alpha}{\pi} + \frac{\sin 2\alpha}{2\pi}\right\}^{1/2}$$

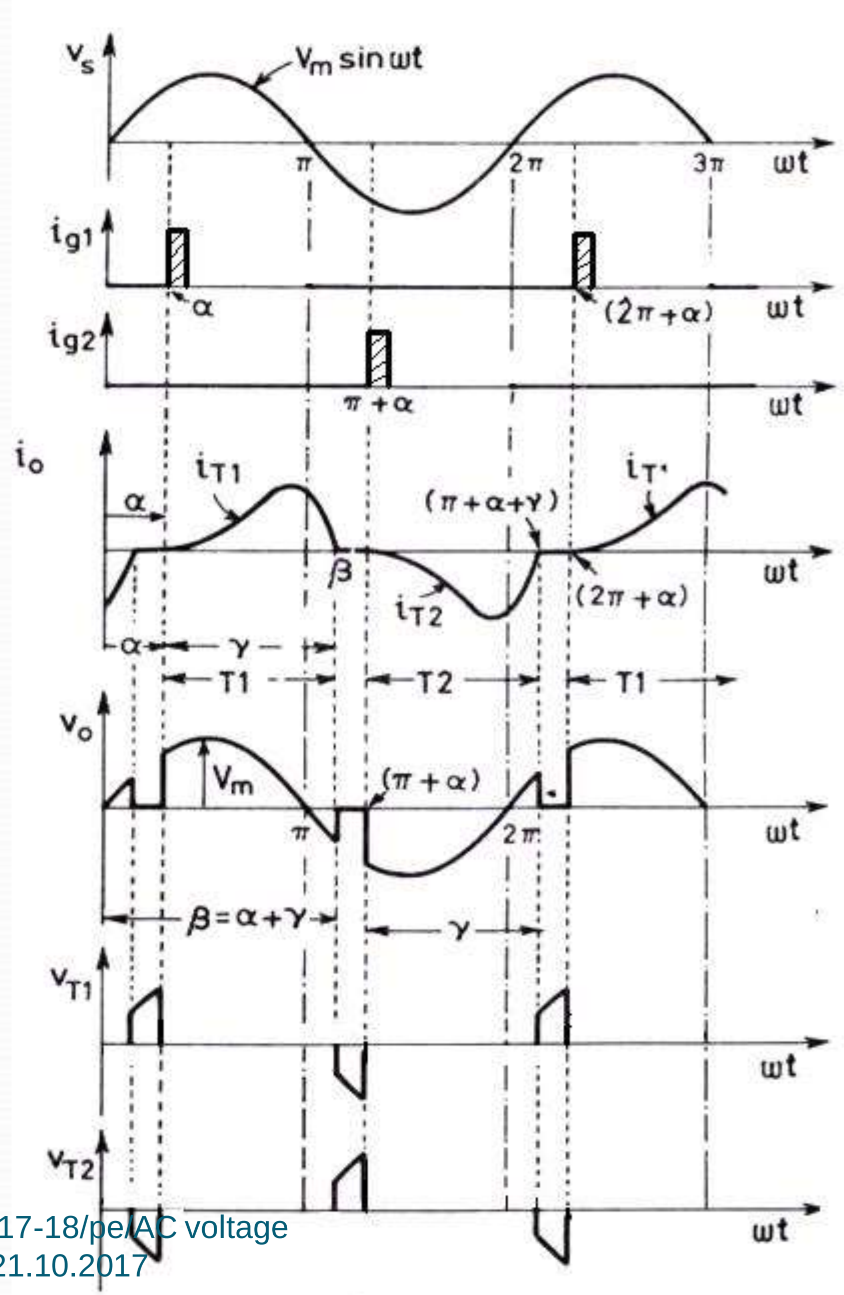
Power factor is unity when firing angle (α) is zero; it becomes progressively smaller as α increases, becoming approximately zero for α=180°

Variation of output voltage and power With delay angle for resistive load



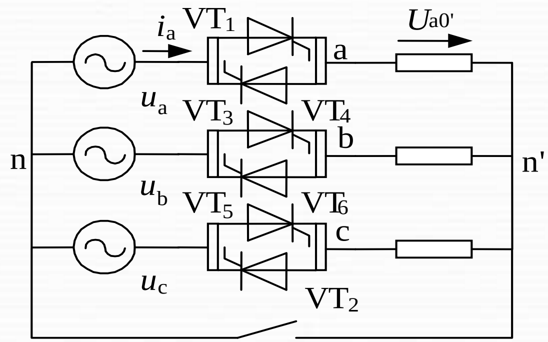
Single-phase AC voltage controller with inductive (RL) load



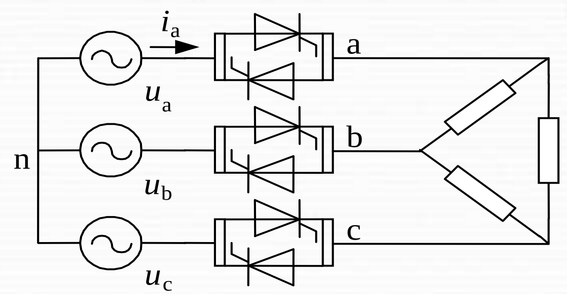


Classification of three- phase circuits

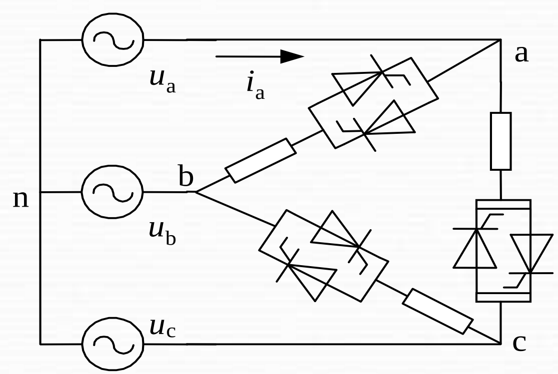
THREE-PHASE AC VOLTAGE CONTROLLER



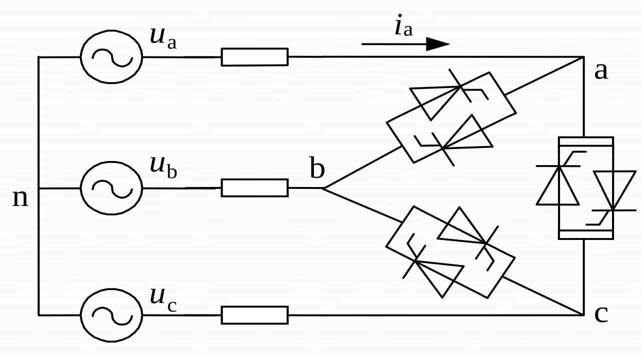
Y connection



Line- controlled Δ connection

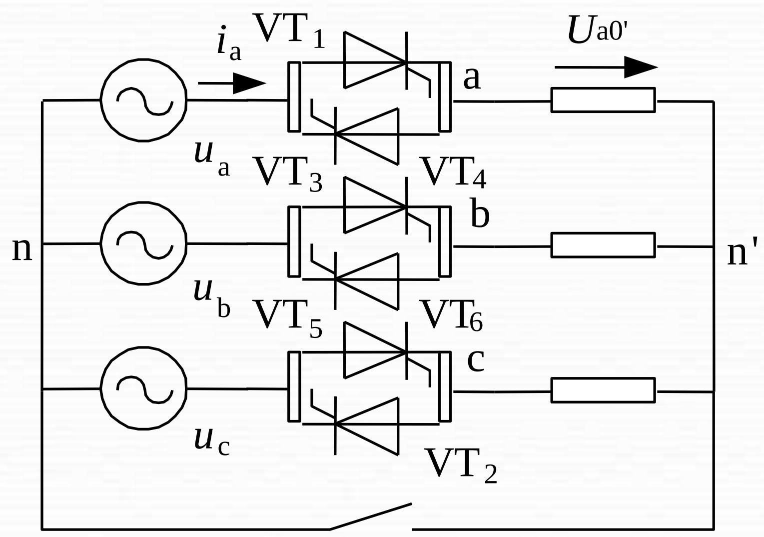


Branch-controlled Δ connection



Neutral-point controlled Δconnection

3- phase 3- wire Y connection AC voltage controller



For a time instant, there are 2 possible conduction states:

–Each phase has a thyristor conducting. Load voltages are the same as the source voltages.

–There are only 2 thyristors conducting, each from a phase. The load voltages of the two conducting phases are half of the corresponding line to line voltage, while the load voltage of the other phase is 0.

CYCLOCONVERTERS

Cycloconverters

- Cycloconverters directly convert ac signals of one frequency (usually line frequency) to ac signals of variable frequency. These variable frequency ac signals can then be used to directly control the speed of ac motors.
- Thyristor-based cycloconverters are typically used in low speed, high power (multi-MW) applications for driving induction and wound field synchronous motors

Introduction

- **Cycloconverter is a frequency changer that converts AC power at one input frequency to AC output power at a different frequency.**

- **Variable frequency output can be obtained by AC→ DC → AC using phase-controlled converters (rectifier followed by inverter).**
- **This is two stage frequency conversion.**

Introduction

- **Single-stage frequency conversion is called cycloconversion.**
- **Cycloconversion can be anyone of following:**

  1- conversion of variable frequency to fixed one (aircraft or shipboard power supplies or wind generators)

  2- conversion of fixed frequency to a variable one (AC motor speed control)

- **Cycloconverters can be step-up or step-down**
- **For efficient operation, cycloconverters are usually operated in frequency**

  range of zero to less than one-third the source frequency.

Applications

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

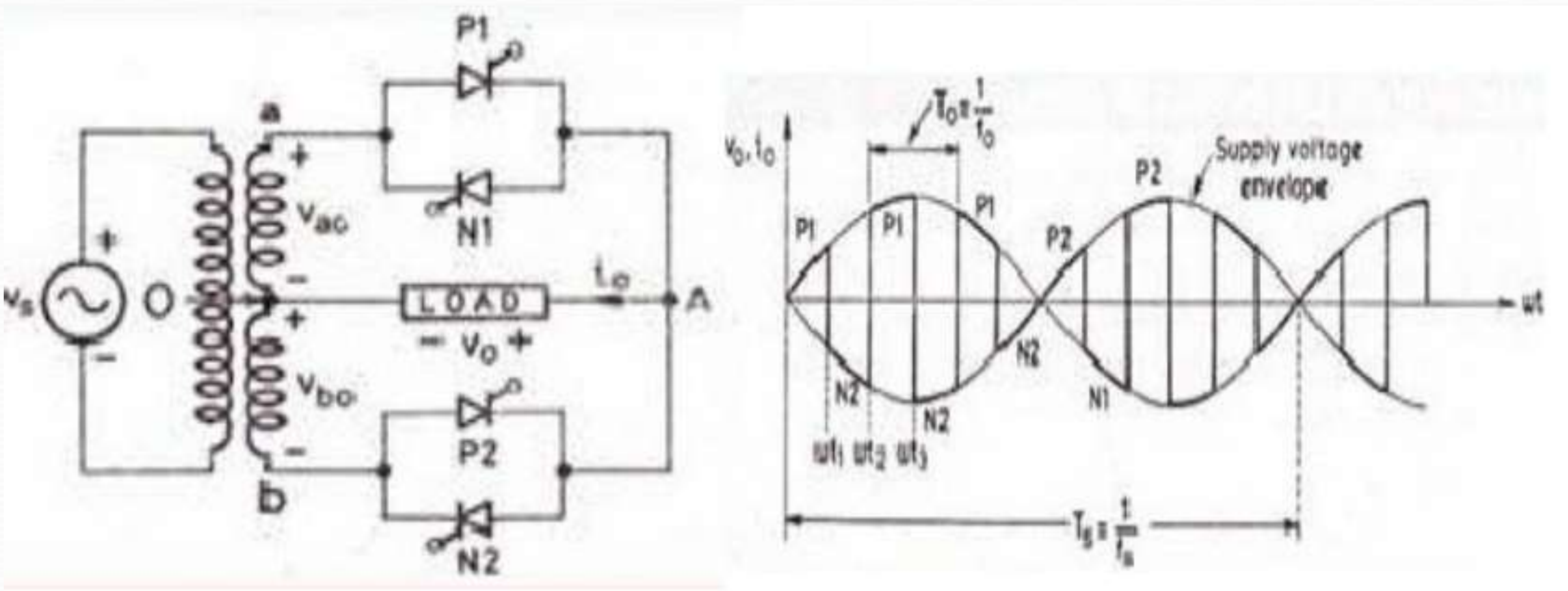
Types of Cycloconverters

- Step up cycloconverter (Fo>Fs)
- Step down cycloconverter(Fo<Fs)
- Single phase to single phase
  - Mid-point cycloconverter
  - Bridge type cycloconverter
- Three phase cycloconverter

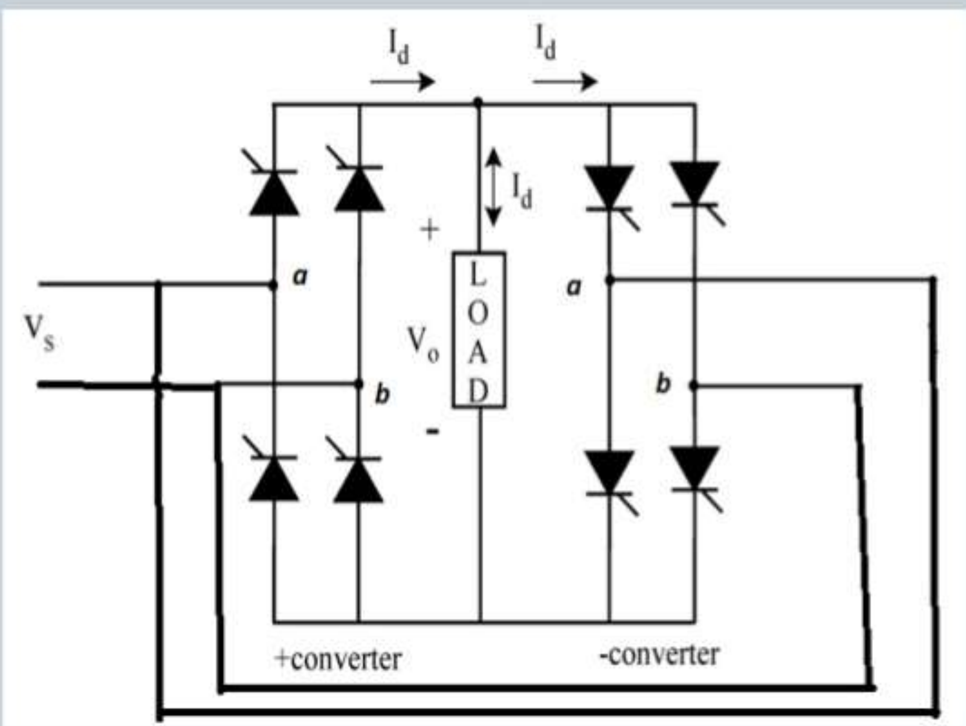
- Step up Cycloconverter:-
  - LOW Frequency to HIGH Frequency
- Step down Cycloconverter:-
  - HIGH Frequency to LOW Frequency

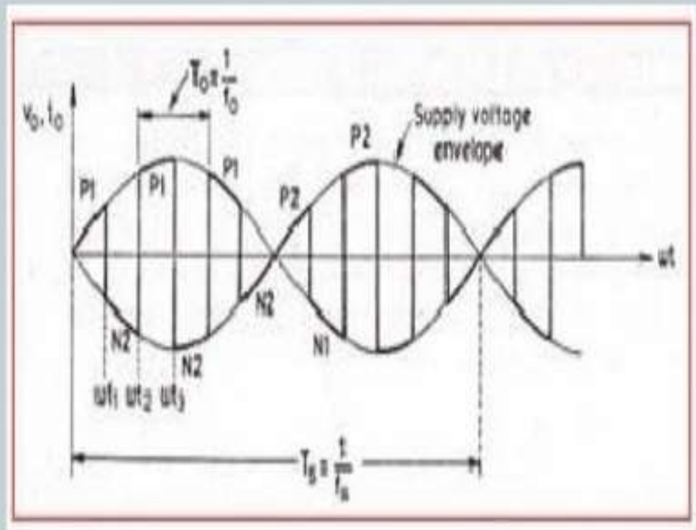
- LOW TO HIGH FREQUENCY CONVERTER
  - MID-POINT CYCLOCONVERTER
  - BRIDGE TYPE CYCLOCONVERTER

Midpoint Cycloconverter



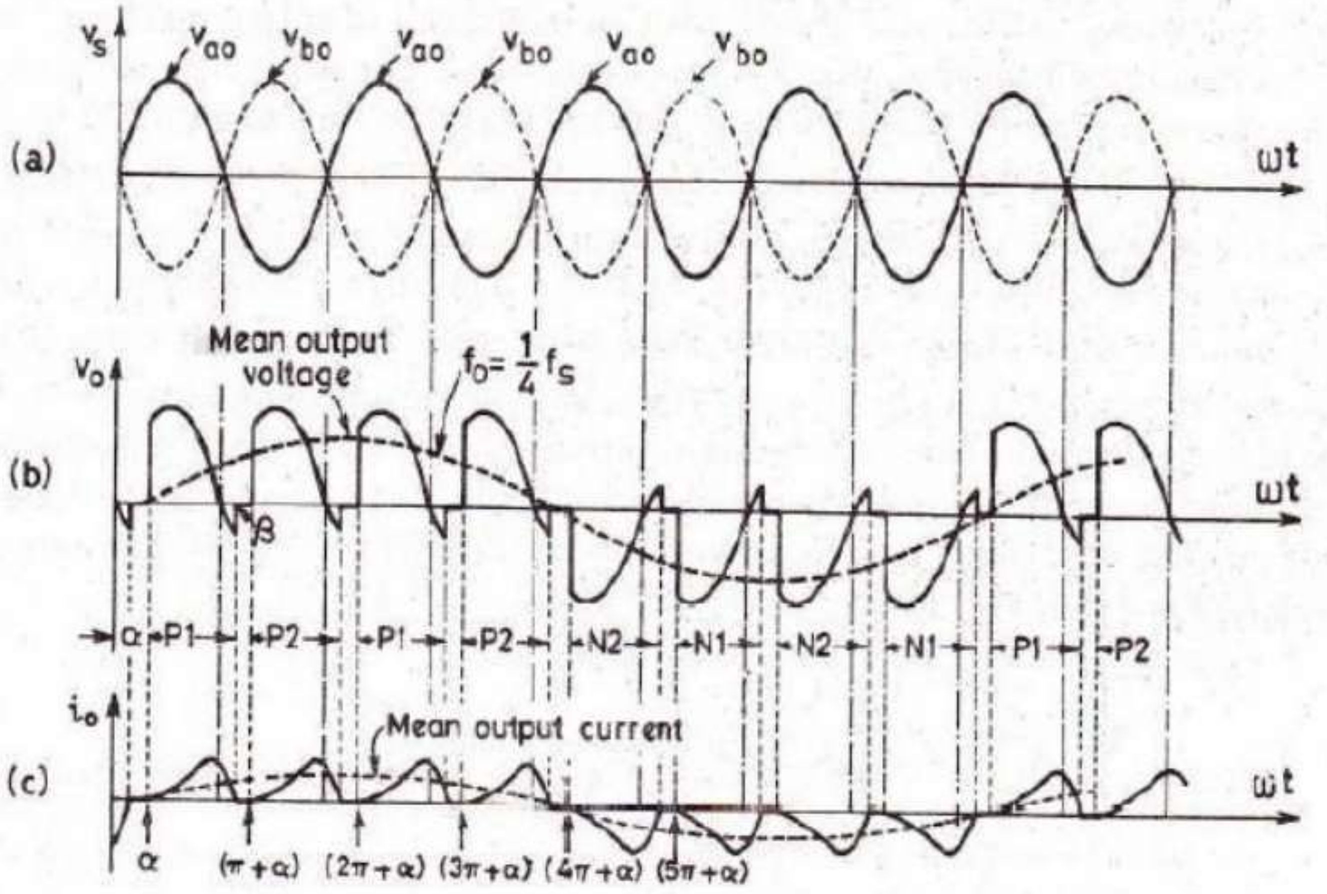
Bridge type Cycloconverter





HIGH TO LOW FREQUENCY CONVERTER

- MID POINT CYCLOCONVERTER
- BRIDGE TYPE CYCLOCONVERTER



v_s
v_{ao}
v_{bo}
(a)
ωt
Mean output voltage
v_o
$f_o = \frac{1}{4} f_s$
(b)
β
α
P1
P2
N2
N1
i_o
Mean output current
(c)
(π+α)
(2π+α)
(3π+α)
(4π+α)
(5π+α)

Three phase cycloconverter

- THREE PHASE TO SINGLE PHASE
- THREE PHASE TO THREE PHASE

Three-Phase to Single-Phase (3f-1f) Cycloconverter

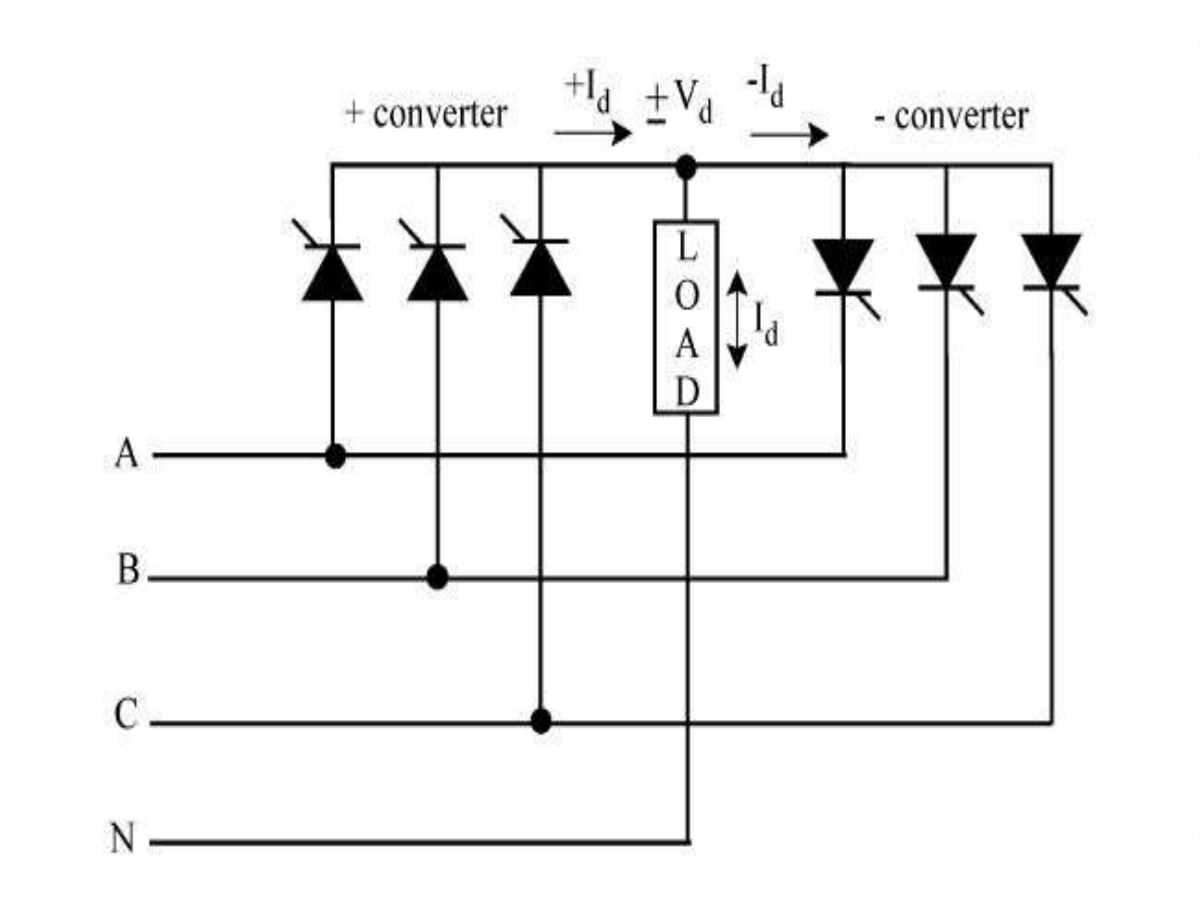
There are two kinds of three-phase to single-phase (3f-1f) cyclo-converters

- 3f-1f half-wave cyclo-converter
- 3f-1f bridge cyclo-converter

Three-Phase to Single-Phase (3f-1f) Cycloconverter

- The 3f-1f cyclo converter applies rectified voltage to the load. Both positive and negative converters can generate voltages at either polarity, but the positive converter can only supply positive current and the negative converter can only supply negative current. Thus, the cyclo converter can operate in four quadrants: (+v, +i) and (-v, -i) rectification modes and (+v, -i) and (-v, +i) inversion modes.
- The modulation of the output voltage and the fundamental output voltage are Note that a is sinusoidally modulated over the cycle to generate harmonically optimum output voltage

3f-1f half-wave cyclo-converter



3f-1f half-wave cvclo-converter waveforms

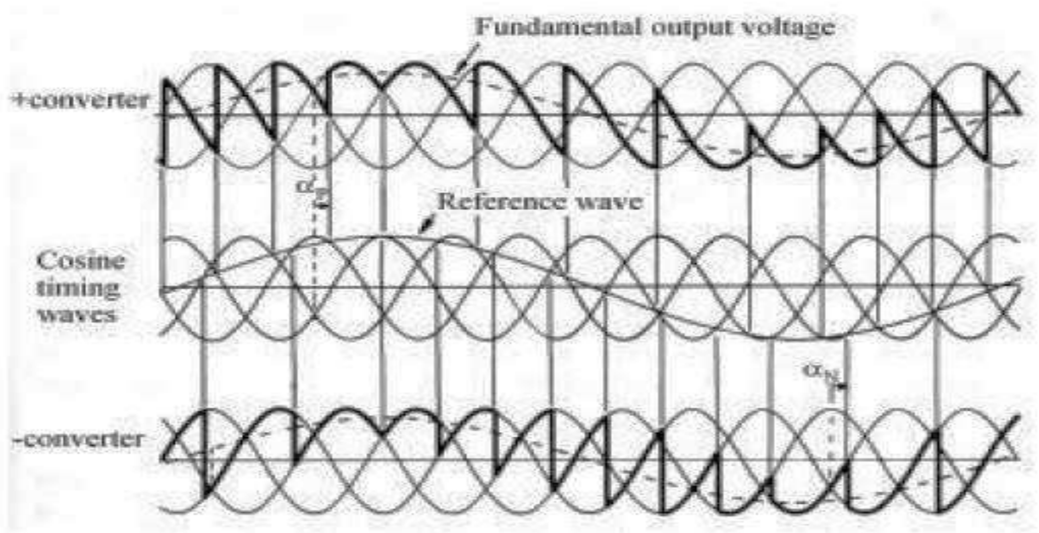


Fig. 6 3ϕ-1ϕ half-wave cycloconverter waveforms
a) + converter output voltage
b) cosine timing waves
c) – converter output voltage

Three-Phase to Single-Phase (3f-1f) Cycloconverter

- The load always requires the fundamental voltage to be continuous. Therefore, during the current polarity reversal, the average voltage supplied by both of the converters should be equal.
- Otherwise , switching from one converter to the other one would cause an undesirable voltage jump.
- To prevent this problem, the converters are forced to produce the same average voltage at all times

Three-Phase to Single-Phase (3f-1f) Cyclo-converter

The output phase voltage v_o can be written as:

$$v_0 = \sqrt{2}V_0 \sin \omega_0 t$$

where V_o is the rms output voltage and ω_o is the output angular frequency. :