Course Outcomes (CO)

CO 1:

Able to describe the characteristics of power semiconductor devices and identify suitable switch choices for a given application.

CO 2:

Able to design and analyze single phase controlled rectifiers and its control circuit according to the specifications.

CO 3:

Able to design and analyze three phase controlled rectifiers and dual converters.

CO 4:

Able to design and analyze single phase and three phase inverters with reduced harmonics for practical applications

CO 5:

Acquire knowledge in voltage control in inveters especially about AC voltage controllers.

CO 6:

Able to analyze basic chopper circuits

EET306
POWER ELECTRONICS

Department of
Electrical And Electronics Engineering

Vision

Endeavour to Ensure Excellence

Mission

Mould technically competent and morally strong Engineers
Achieve dynamic leadership through quality Education
Cater the needs of industry and community through Emulation
Empower the students to serve the nation with
Dedication

SYLLABUS

Module 1 - 11 hrs

Introduction to Power Electronics-Scope and applications-power electronics vs signal electronics (1 hr)

Structure and principle of operation ofpower devices- Power diode, Power MOSFET & IGBT – switching characteristics - comparison. Basic principles of wideband gap devices-SiC, GaN (4 hrs)

SCR- Structure, Static characteristics & Switching (turn-on & turn-off) characteristics - di/dt& dv/dt protection – Turn-on methods of SCR - Two transistor analogy (5 hr)

Gate triggering circuits – Requirements of isolation and synchronization in gate drive circuits- Opto and pulse transformer based isolation (1hr)

Module 2 - 9 hrs

Controlled Rectifiers (Single Phase) – Half-wave controlled rectifier with R load– Fully controlled and half controlled bridge rectifier with R, RL and RLE loads (continuous & discontinuous conduction) – Output voltage equation- related simple problems(5 hrs)

Controlled Rectifiers (3-Phase) - 3-phase half-wave controlled rectifier with R load – Fully controlled & half-controlled bridge converter with RLE load (continuous conduction, ripple free) – Output voltage equation-Waveforms for various triggering angles (detailed mathematical analysis not required) (4 hrs)

Module 3 - 9 hrs

AC voltage controllers (ACVC) – 1-phase full-wave ACVC with R, & RL loads – Waveforms – RMS output voltage, Input power factor with R load (2 hrs)

Inverters – Voltage Source Inverters– 1-phase half-bridge & full bridge inverter with R and RL loads – THD in output voltage – 3-phase bridge inverter with R load – 120° and 180° conduction modes– Current Source Inverters-1-phase capacitor commutated CSI.(5 hrs)

Voltage control in 1-phase inverters – Pulse width modulation – Single pulse width, Multiple pulse width and Sine-triangle PWM (unipolar & bipolar modulation) – Modulation Index - Frequency modulation ratio.(2 hrs)

Module 4 - 8 hrs

DC-DC converters – Step down and Step up choppers – Single-quadrant, Two-quadrant and Four quadrant chopper – Pulse width modulation & current limit control in dc-dc converters. (4 hrs)

Switching regulators – Buck, Boost & Buck-boost –Operation with continuous conduction mode – Waveforms – Design of Power circuits (switch selection, filter inductance and capacitance) (4 hrs)

Module 5 - 11 hrs

Electric Drive: Introduction to electric drives – Block diagram – advantages of electric drives- types of load – classification of load torque (2 hrs)

DC Drives: Single phase semi converter and single phase fully controlled converter drives. Dual Converters for Speed control of DC motor-1-phase and 3-phase configurations; Simultaneous and Non-simultaneous operation. Chopper controlled DC drives- Single quadrant chopper drives- Regenerative braking control- Two quadrant chopper drives- Four quadrant chopper drives(6 hrs)

AC Drives: Three phase induction motor speed control. Stator voltage control – stator frequency control - Stator voltage and frequency control (v/f) (3 hrs)

(It is expected to emphasize the ease of independent control of field flux and armature flux in SEDC motor and relate the same with Induction motor)

REFERENCES

1. P.S. Bimbhra, Power Electronics, Khanna Publishers, New Delhi
2. Mohan N., T. M. Undeland and W. P. Robbins., Power Electronics, Converters, Applications & Design, Wiley-India
3. Muhammad H. Rashid, *Power Electronics Circuits, Devices and Applications, Pearson Education*
4. Singh M. D. and K. B. Khanchandani, *Power Electronics, Tata McGraw Hill*, *New Delhi, 2008.*
5. L. Umanand, Power Electronics – Essentials & Applications, Wiley-India
6. Krein P. T., Elements of Power Electronics, Oxford University Press, 1998.
7. Joseph Vithayathil, Power Electronics: Principles and Applications, McGraw-Hill College; International edition,1995
8. www.nptel.ac.in
9. G.K.Dubey,Fundamentals of Electric Drives, Narosa publishers, second edition, 2010.

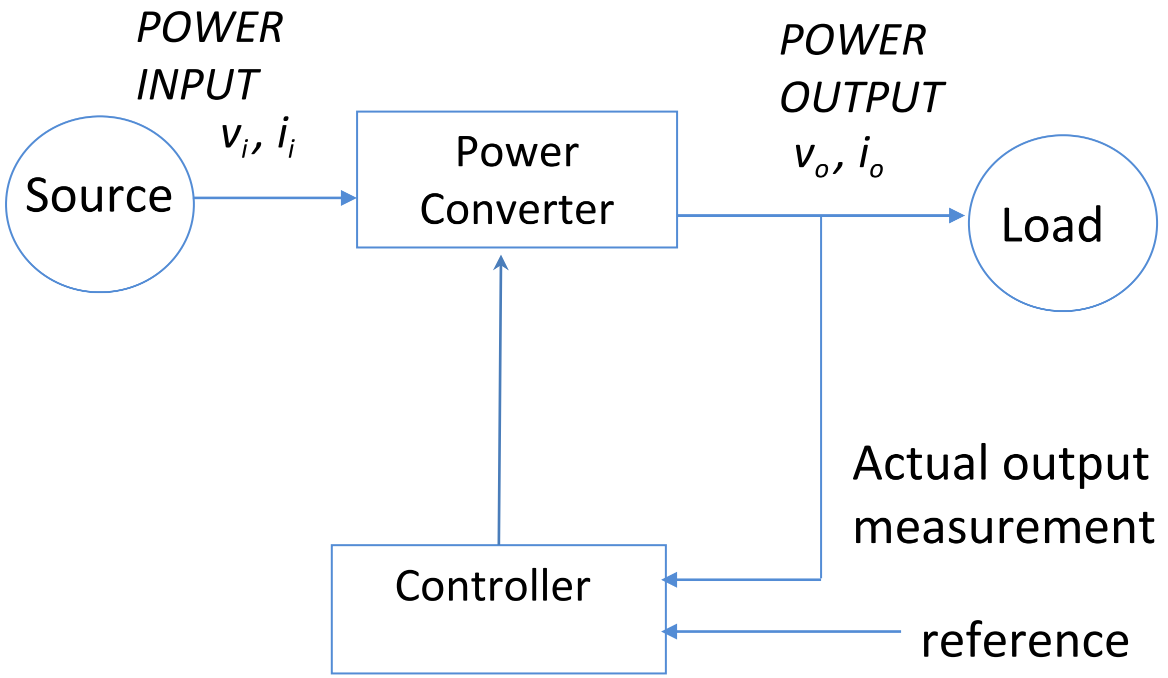
MODULE 1

Introduction

Power Electronics

Power Electronics deals with the use of electronics for the control of large power. The function of Power Electronics is to process and control the electrical energy by supplying voltage and current in a form that is optimally suited to the load.

Basic block diagram of a Power Electronic System



Power Semiconductor Devices

- Uncontrolled turn on and turn off devices

  eg., diodes
- Controlled turn on and uncontrolled turn off devices

  eg., SCR
- Controlled turn on and turn off devices

  eg., BJT, MOSFET, GTO, IGBT

Types of Power Converters

CONVERSION FROM/TO	NAME	FUNCTION	SYMBOL
DC to DC	Chopper	Constant to variable DC or variable to constant DC	
DC to AC	Inverter	DC to AC of desired voltage and frequency	
AC to DC	Rectifier	AC to unipolar (DC) current	
AC to AC	Cycloconverter, AC-PAC, Matrix converter	AC of desired frequency and/or magnitude from generally line AC	

Power Electronics Systems Applications

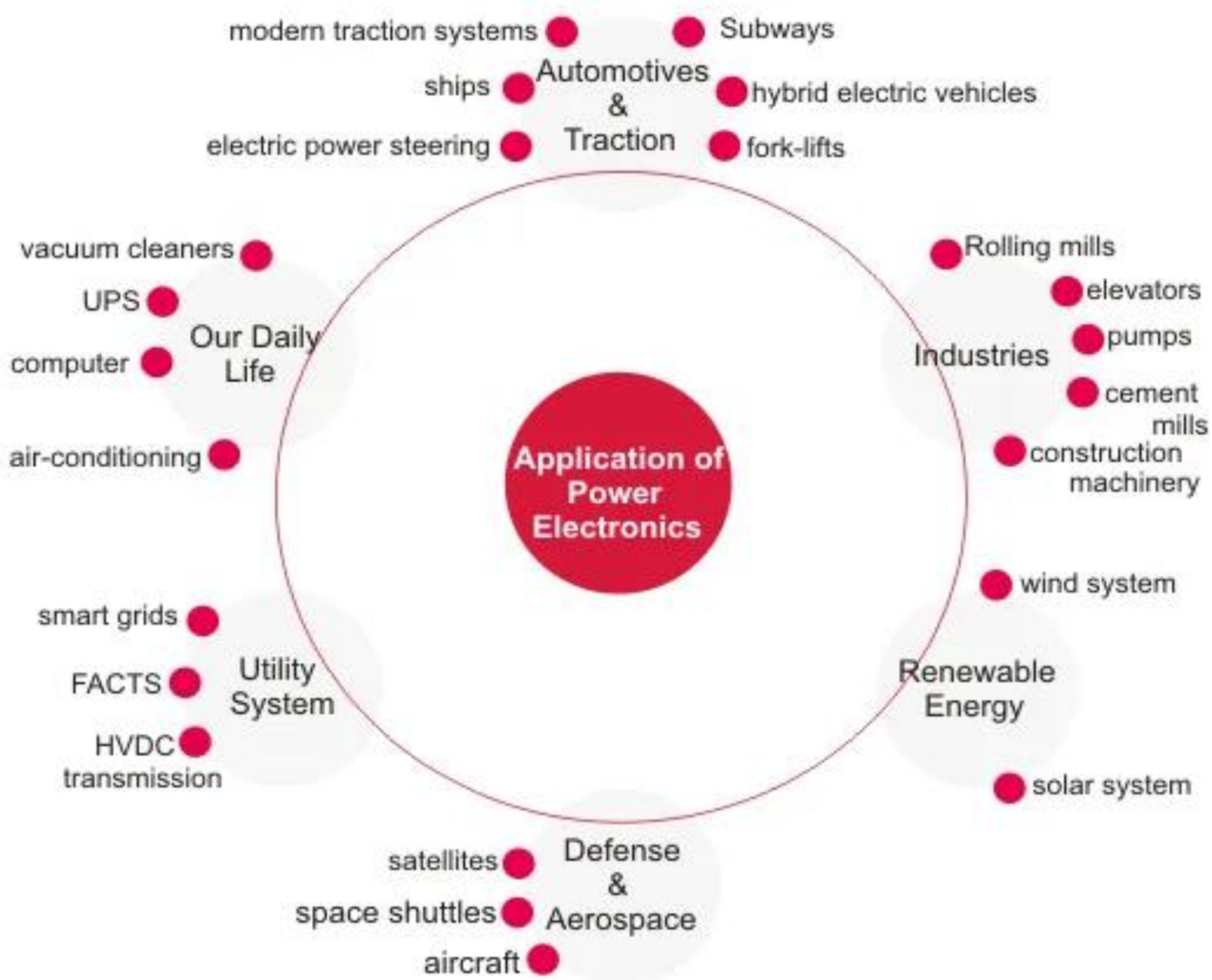
- To convert electrical energy from one form to another, i.e. from the source to load with:
  - highest efficiency,
  - highest availability
  - highest reliability
  - lowest cost,
  - smallest size
  - least weight.

- **Static applications**
  - involves non-rotating or moving mechanical components.
  - Examples:
    - DC Power supply, Un-interruptible power supply, Power generation and transmission (HVDC), Electroplating, Welding, Heating, Cooling, Electronic ballast

- **Drive applications**
  - intimately contains moving or rotating components such as motors.
  - Examples:
    - Electric trains, Electric vehicles, Air-conditioning System, Pumps, Compressor, Conveyer Belt (Factory automation).

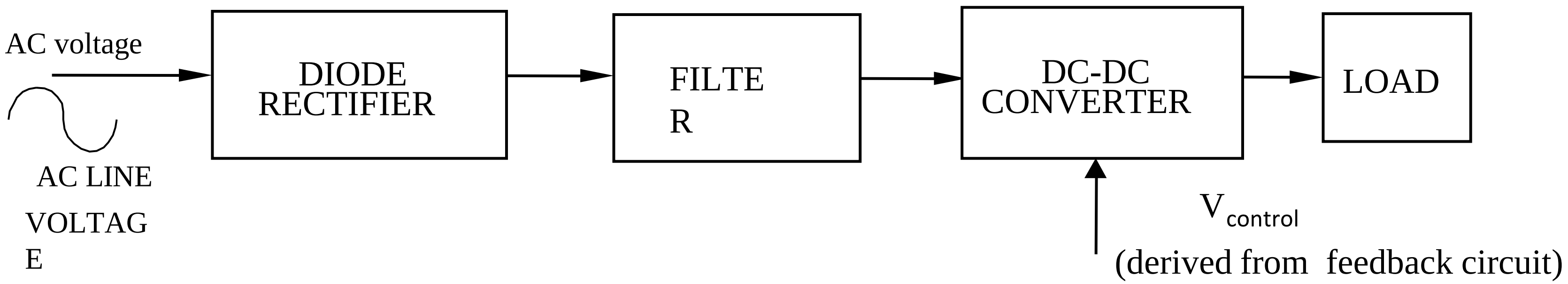
Power Electronics Systems Applications

Power Electronics Systems Applications

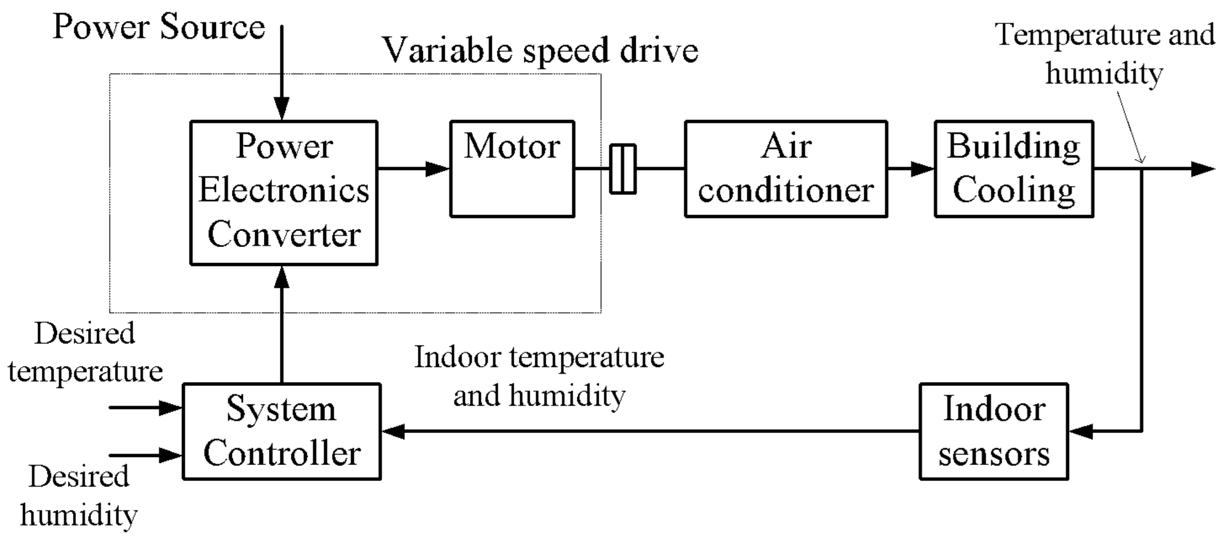


Application examples

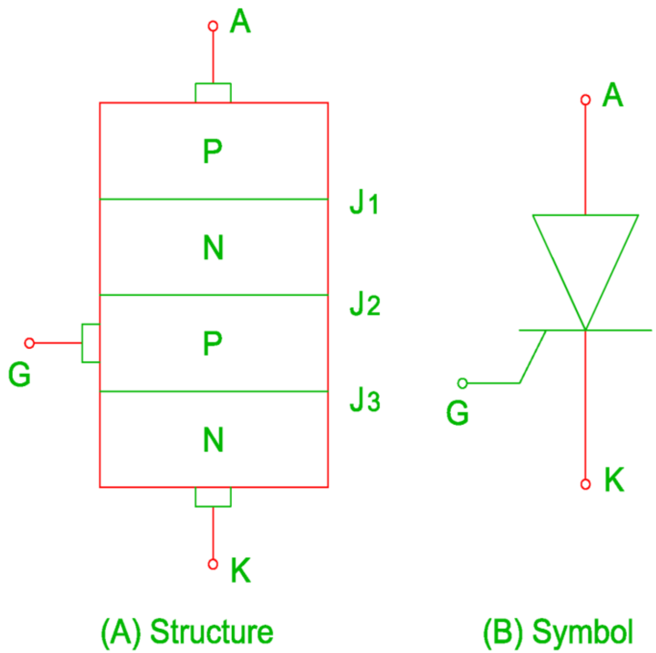
Static Application: DC Power Supply

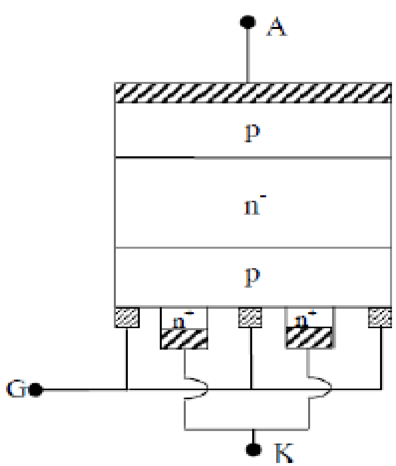


Drive Application: Air-Conditioning System



SILICON CONTROLLED RECTIFIER (SCR)



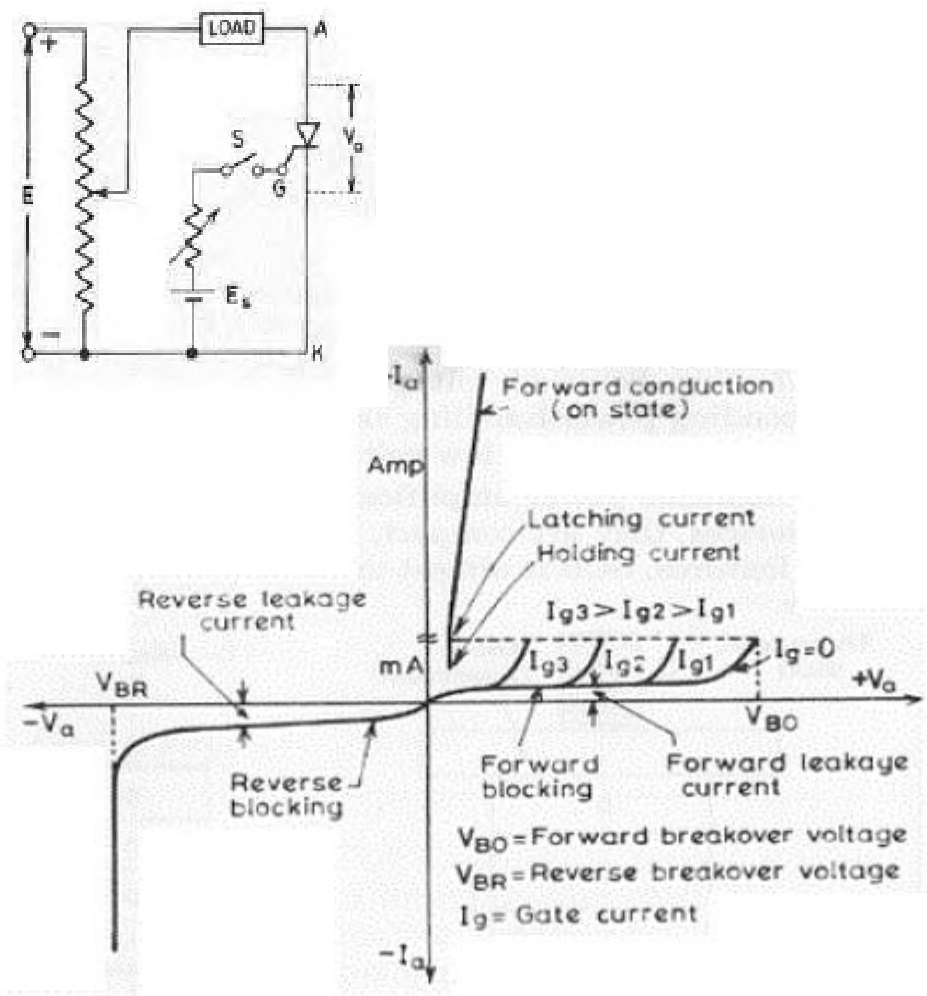


- The thyristor is a four layer, three terminal semiconducting device, with each layer consisting of alternately N-type or P-type material, for example P-N-P-N.

- The main terminals, labelled anode and cathode, are across the full four layers and the control terminal, called the gate, is attached to P-type material near to the cathode.

- The thyristor has three P-N junctions serially named j_1, j_2, j_3 from the anode.

Static VI characteristics of SCR



V_{BO}=Forward breakover voltage

V_{BR}=Reverse breakover voltage

I_g =Gate current

V_a =Anode voltage across the thyristor terminal A, K.

I_a =Anode current

SCR have 3 modes of operation:

1. Reverse blocking mode
2. Forward blocking mode (off state)
3. Forward conduction mode (on state)

1. Reverse Blocking Mode

When cathode of the thyristor is made positive with respect to anode with switch open thyristor is reverse biased. Junctions J_1 and J_2 are reverse biased where junction J_2 is forward biased. The device behaves as if two diodes are connected in series with reverse voltage applied across them.

A small leakage current of the order of few mA only flows. As the thyristor is reverse biased and in blocking mode. It is called as acting in reverse blocking mode of operation.

Now if the reverse voltage is increased, at a critical breakdown level called reverse breakdown voltage V_{BR},an avalanche occurs at J_1 and J_3 and the reverse current increases rapidly. As a large current associated with V_{BR} and hence more losses to the SCR.

This results in Thyristor damage as junction temperature may exceed its maximum temperature rise.

2. Forward Blocking Mode

When anode is positive with respect to cathode, with gate circuit open, thyristor is said to be forward biased.

Thus junction J_1 and J_3 are forward biased and J_2 is reverse biased. As the forward voltage is increases junction J_2 will have an avalanche breakdown at a voltage called forward breakover voltageV_{BO}. When forward voltage is less then V_{BO}thyristor offers high impedance. Thus a thyristor acts as an open switch in forward blocking mode.

3. Forward Conduction Mode

Here thyristor conducts current from anode to cathode with a very small voltage drop across it. So a thyristor can be brought from forward blocking mode to forward conducting mode:

1. By exceeding the forward breakover voltage.
2. By applying a gate pulse between gate and cathode.

During forward conduction mode of operation thyristor is in on state and behave like a close switch. Voltage drop is of the order of 1 to 2mV. This small voltage drop is due to ohmic drop across the four layers of the device.

- Once the SCR is conducting a forward current, reverse biased junction J_2 no longer exist.
- No gate current is required for the device to remains in on state.
- Therefore if the gate current is removed, the conduction of current from anode to cathode is unaffected.
- However if the gate current reduced to zero before rising the anode current attains a value, called latching current the device will turnoff again.
- *The latching current maybe defined as the minimum value of anode current which it must attain during turn on process to maintain conduction when gate signal is removed.*

- Once the thyristor is conducting, gate losses control.
- The thyristor can be turned off only if the forward current falls below a low level current called holding current
- *The holding current may be defined as the minimum value of anode current below which it must fall for turning off the thyristor*
- The latching current is higher than holding current
- The latching current is associated with the turn on process and holding current with turn off process
- Usually latching current is 2 to 3 times the holding current
- In industrial applications, holding current (typically 10mA) is almost taken as zero

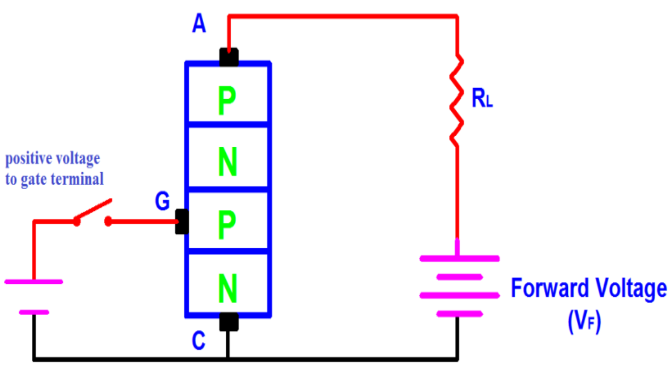
Switching (turn-on & turn-off) characteristics of SCR

Also known as dynamic or transient characteristics

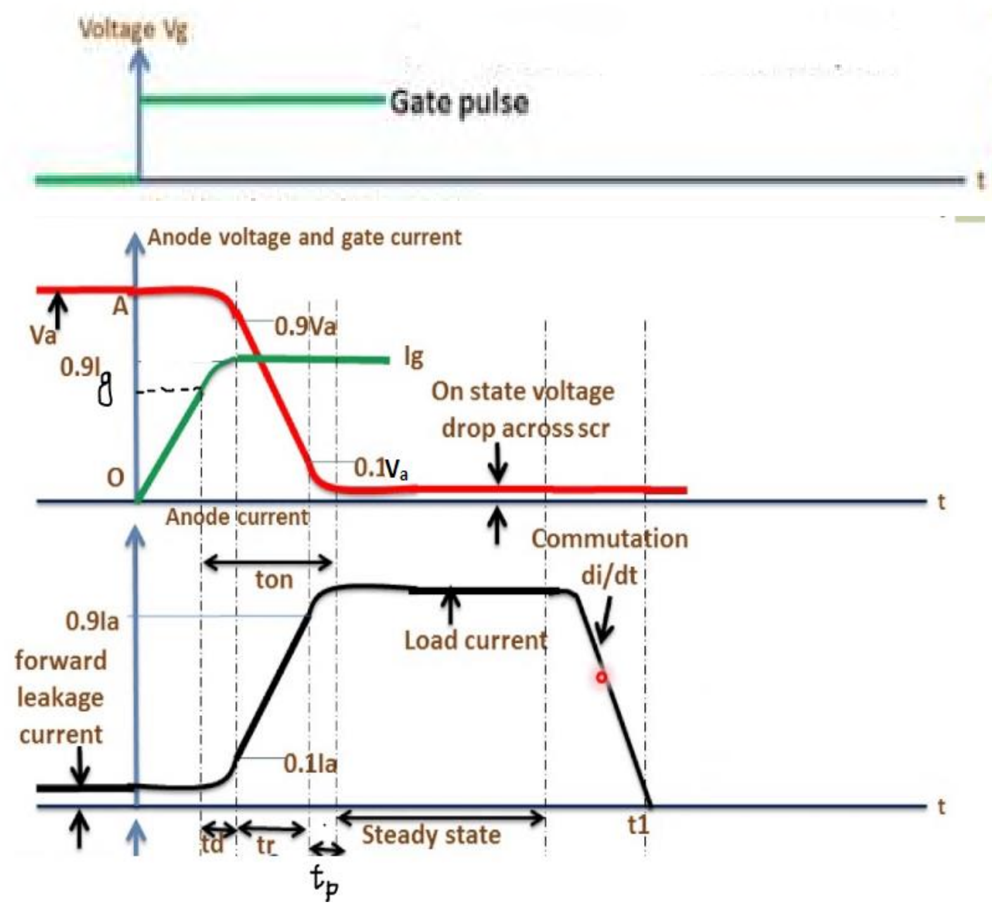
1. Turn on characteristics
2. Turn off characteristics

Switching (turn-on & turn-off) characteristics

- Turn on characteristics



Gate Triggering of SCR



1. Delay time (t_d)
2. Rise time (t_r)
3. Spread time (t_p)

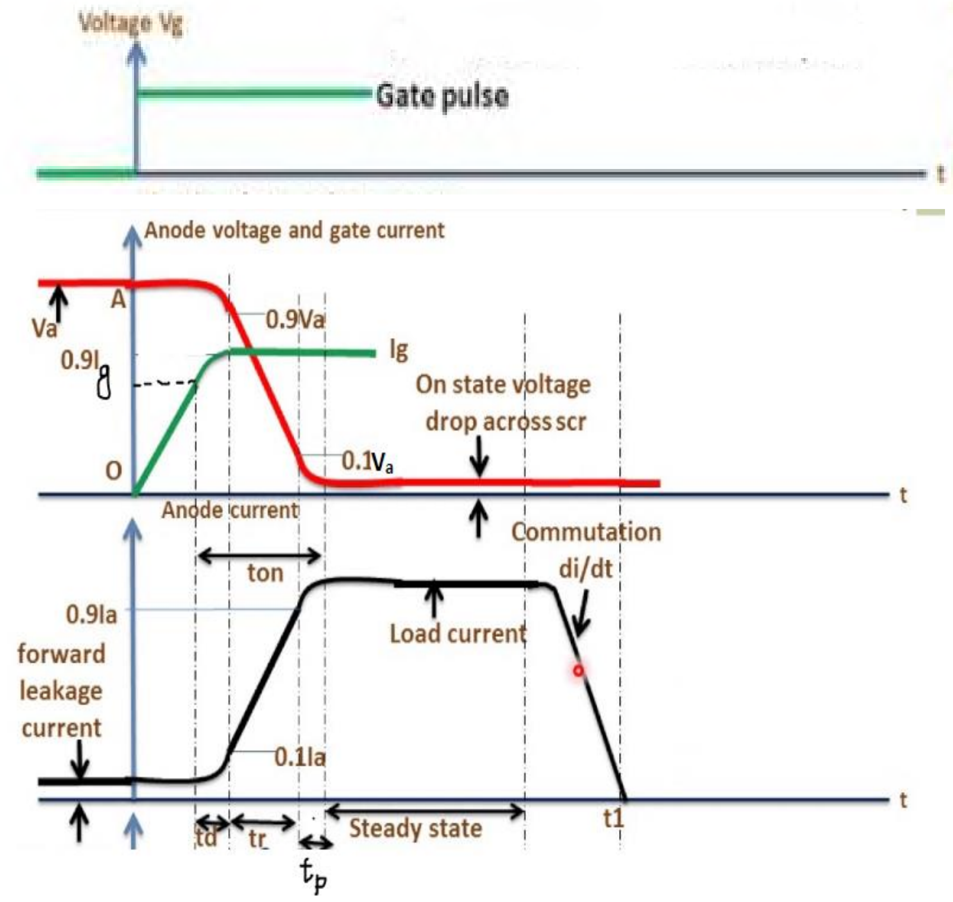
Turn on characteristics of SCR

1. Delay time (t_d)

Measured from the instant at which gate current reaches 0.9Ig to the instant at which anode current reaches $0.1I_a$, where I_g and I_a are the final values of gate and anode currents.

It can also be defined as the time during which anode voltage falls from V_a to $0.9V_a$, where V_a is the initial value of anode voltage.

Another way of defining is the time during which anode current rises from forward leakage current to $0.1I_a$, where I_a is the final value of anode current.



Turn on characteristics of SCR

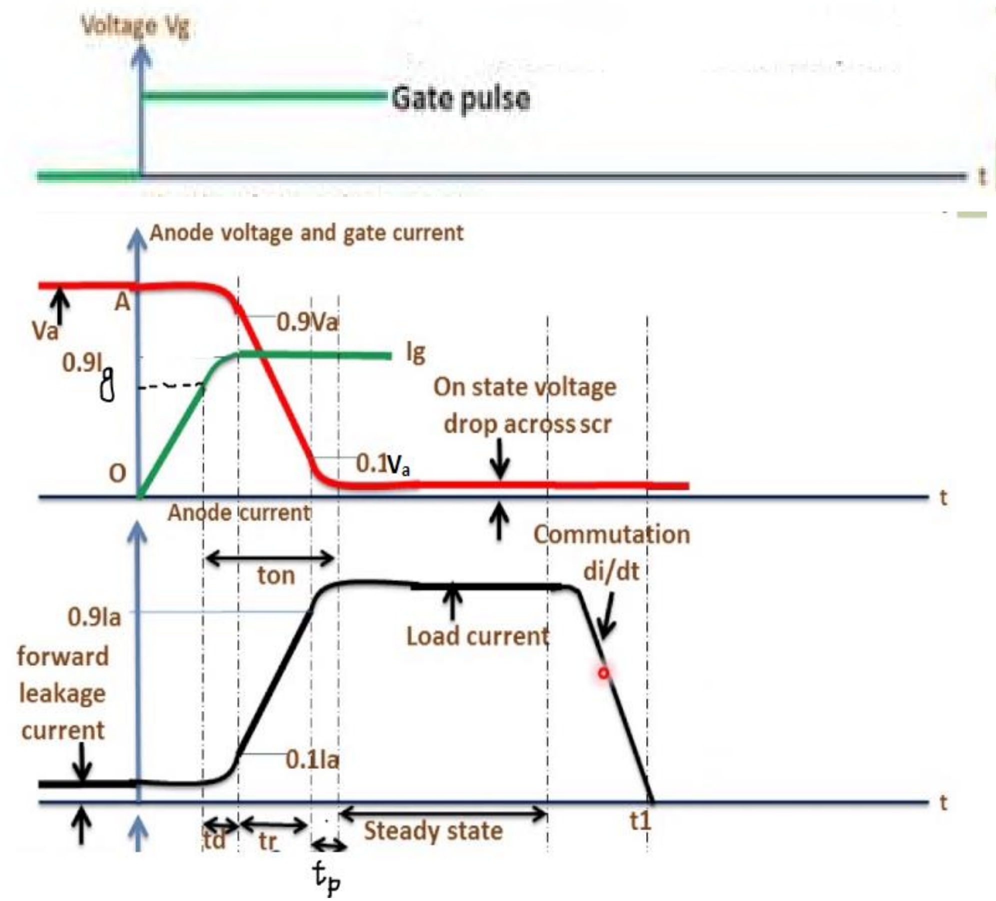
2. Rise time (t_r)

Is the time taken by the anode current to rise from $0.1I_a$ to $0.9I_a$.

Rise time is inversely proportional to the magnitude of gate current and its build up rate

Rise time can be reduced if high and steep current pulses are applied to the gate

The main factor determining the t_r is the nature of anode circuit



Turn on characteristics of SCR

3. Spread time (t_p)

Time taken by the anode current to rise from $0.9I_a$ to I_a .

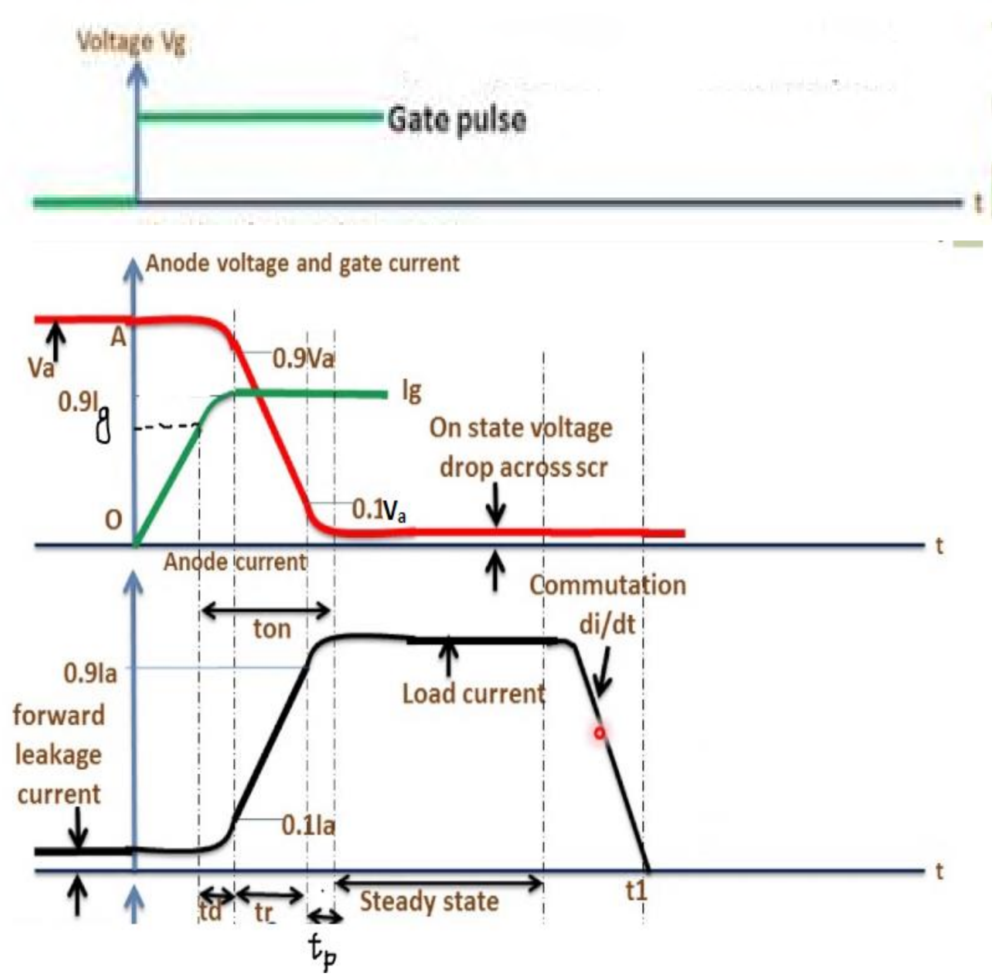
Time for the forward blocking voltage to fall from 0.1 of its initial value of its on state voltage drop (1 to 1.5V).

During this time conduction spreads over entire cross section of the cathode of SCR.

After the spread time anode current attains steady state value and the voltage drop across SCR is equal to the on state voltage drop of the order of 1 to 1.5V.

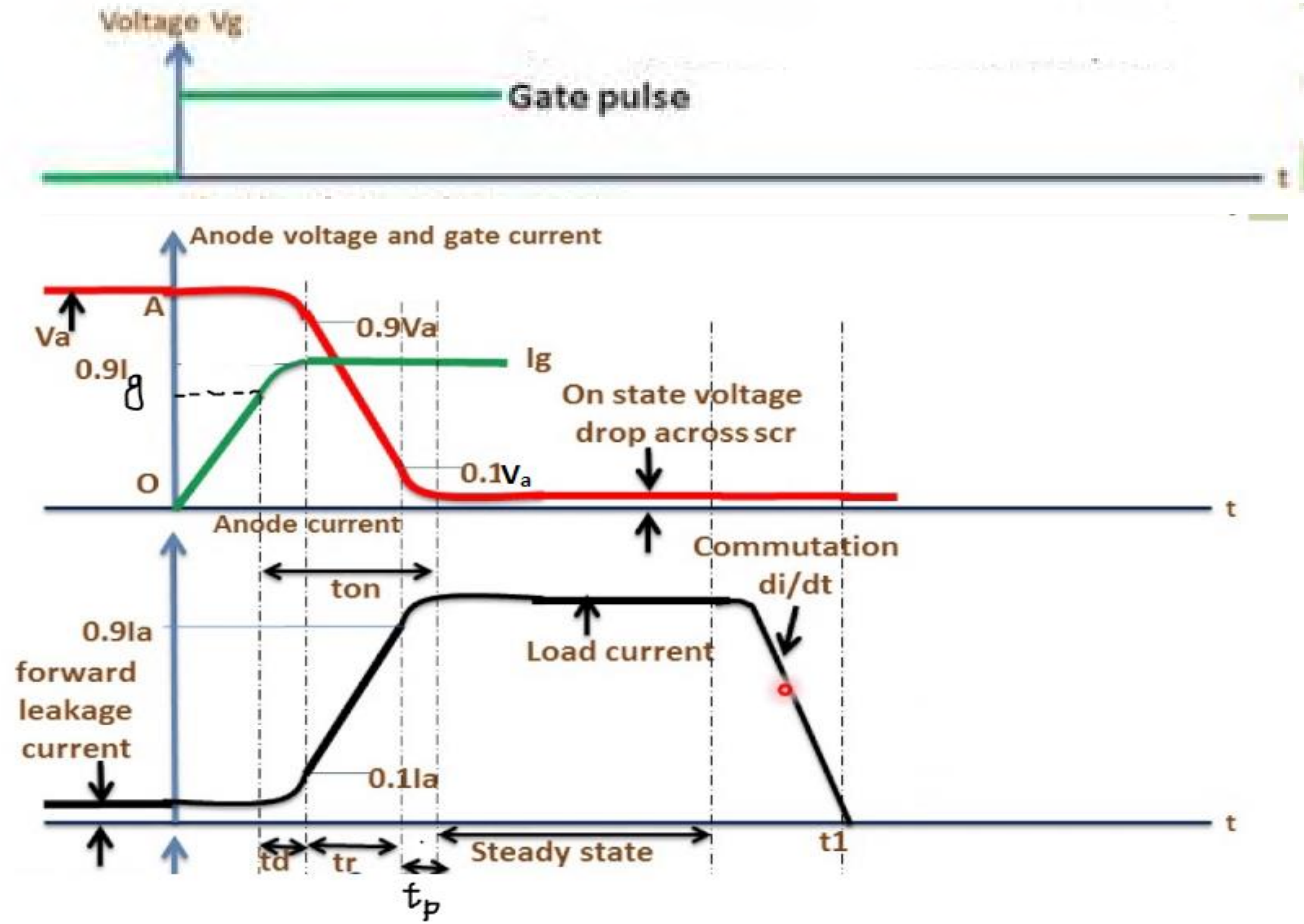
Total turn on time of an SCR is equal to the sum of delay time, rise time and spread time. Manufactures usually specify the rise time which is of the order of 1 to 4μ sec.

Total turn on time depends on the anode circuit parameters and gate signal wave-shapes.



Switching (turn-on & turn-off) characteristics

Turn on characteristics of SCR



Switching (turn-on & turn-off) characteristics of SCR

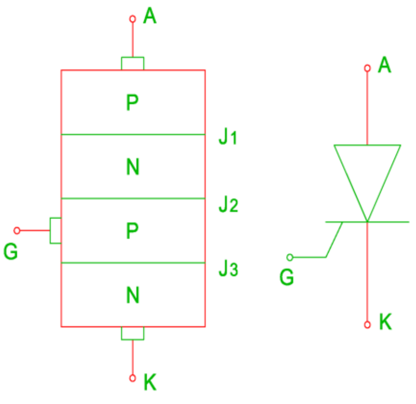
Turn off characteristics of SCR

The turn off time is divided into two interval

1) Reverse recovery time, t_{rr}

2) Gate recovery time, t_{gr}

$$t_q = t_{rr} + t_{gr}$$



(A) Structure (B) Symbol

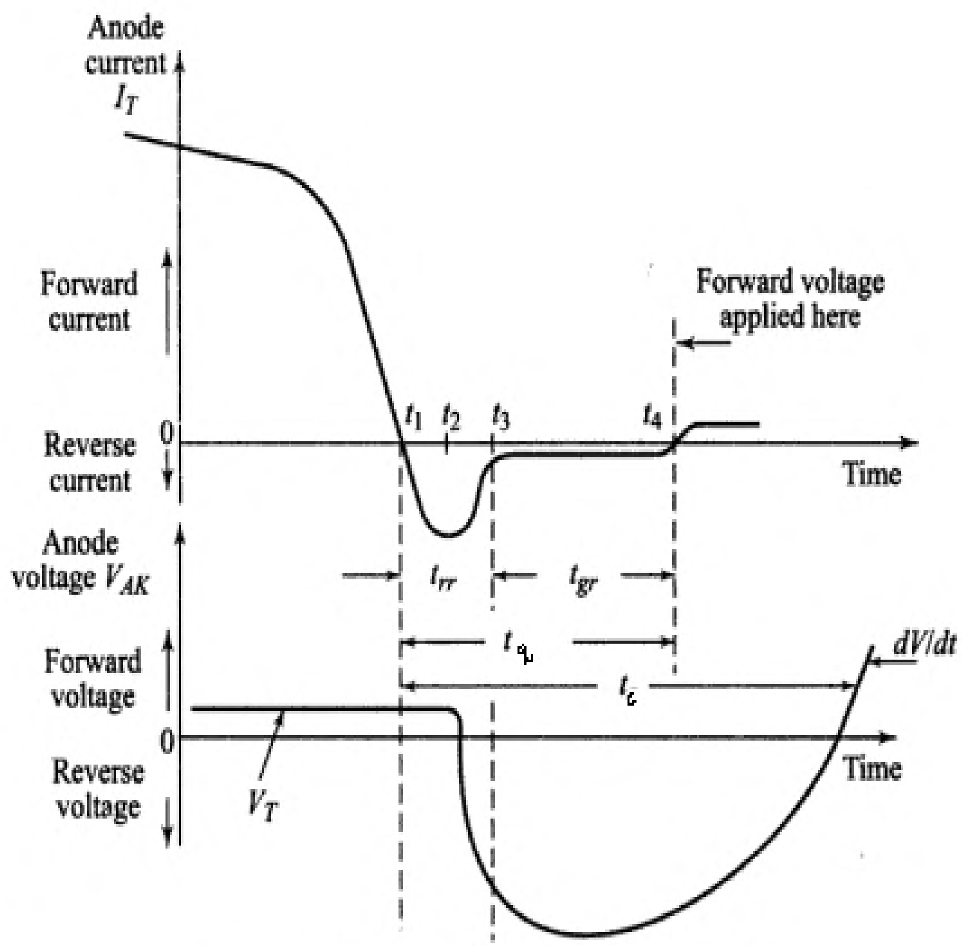


Fig. 2 *Waveforms during SCR turn-off*

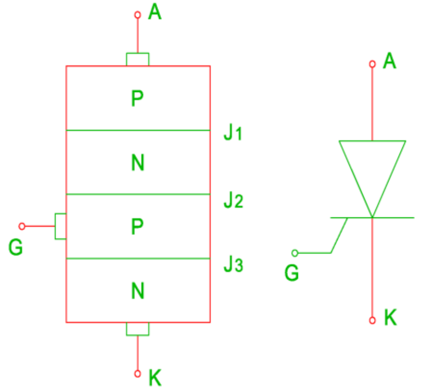
Turn off characteristics of SCR

- Turn off means that SCR has changed from on to off state and is capable of blocking the forward voltage. This dynamic process of SCR from conduction state to forward blocking state is called commutation process or turn off process.
- Once the thyristor is on, gate loses control.
- The SCR can be turned off by reducing the anode current below holding current.
- The turn of time t_q of a thyristor is defined as the time between the instant anode current become zero and the instant SCR regains forward blocking capability.
- During time t_q, all the excess carriers from the four layers of SCR must be removed. This removal of excess carriers consisting of sweeping out of holes from outer p layer and electrons from outer n layer. The carriers around junction J_2 can be removed only by recombination
- The turn off time is divided into two interval

  1) Reverse recovery time, t_{rr}

  2) Gate recovery time, t_{gr}

$$t_q = t_{rr} + t_{gr}$$



(A) Structure (B) Symbol

Turn off characteristics of SCR

Reverse recovery time , t_{rr}

At instant t_1, anode current becomes zero. After t_1, anode current build up in the reverse direction. The reason for the reversal of anode current after t_1 is due to the presence of carriers stored in the four layers. The reverse recovery current removes excess carriers from the end junction J_1 and J_3 between the instant t_1 and t_3.

In other words, reverse recovery current flows due to the sweeping out of holes from top p layer and electrons from bottom n layer.

At instant t_2, when about 60% of the stored charges are removed from the outer two layers carrier density across J_1 and J_3 begins to decrease and with this reverse recovery current also starts decaying

The reverse current decay is fast in the beginning but gradual there after. The fast decay of the recovery current causes a reverse voltage across the device due to the circuit inductance.

This reverse voltage surge may cause damage to the device.

In practice this avoided by using protective RC element across SCR.

At instant t_3, when reverse recovery current has fallen nearly to zero, end junction J_1 and J_3 recover and SCR is able to block the reverse voltage

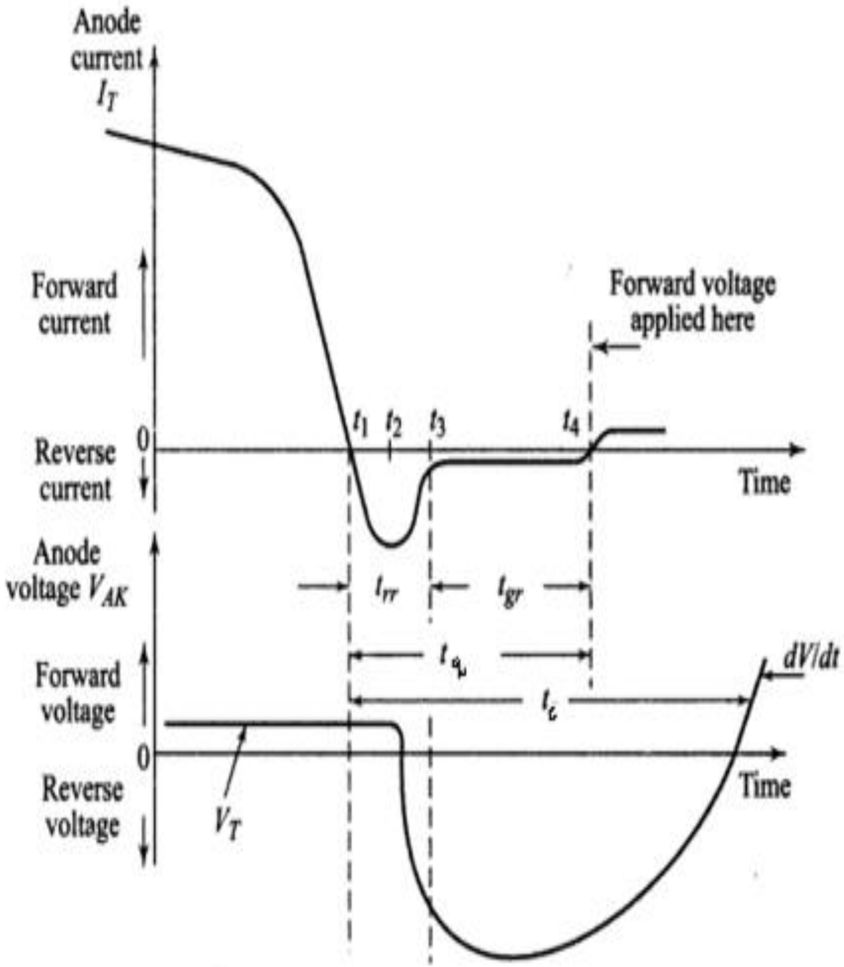


Fig. 2 *Waveforms during SCR turn-off*

Turn off characteristics of SCR

Gate recovery time , t_{gr}

At the end of reverse recovery period (t_1-t_3), the middle junction J_2 still has trapped charges therefore, the thyristor is not able to block the forward voltage at t_3. The trapped charges around J_2 cannot flow to the external circuit. Therefore this charges must decay only by recombination. This recombination is possible if a reverse voltage is maintained across SCR. The rate of recombination of charges is independent of the external circuit parameter. The time for recombination of charges between t_3 and t_4 is called gate recovery time t_{gr}

At instant t_4, junction J_2 recovers and the forward voltage can be reapplied between anode and cathode. The turn off time provided to a thyristor by the practical circuit is called circuit turn off time t_c. Is defined as the time between the instant anode current become zero and the instant reverse voltage due to practical circuit reaches zero. t_c must be greater than tq for reliable turn off. Otherwise the device may turn on at undesired instant, process called commutation failure

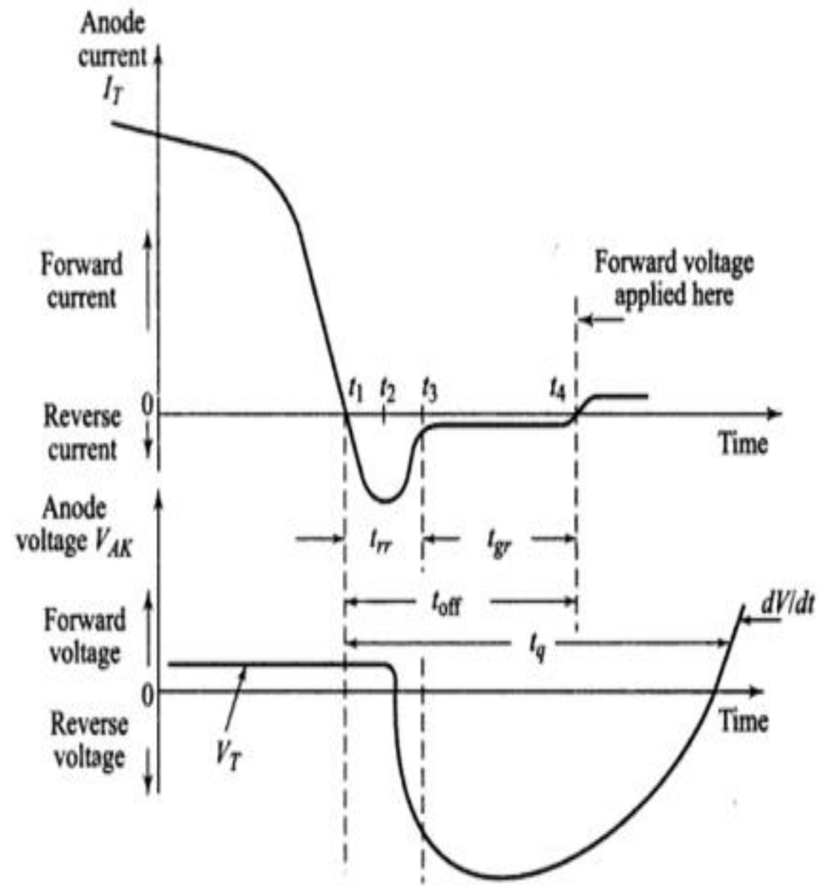
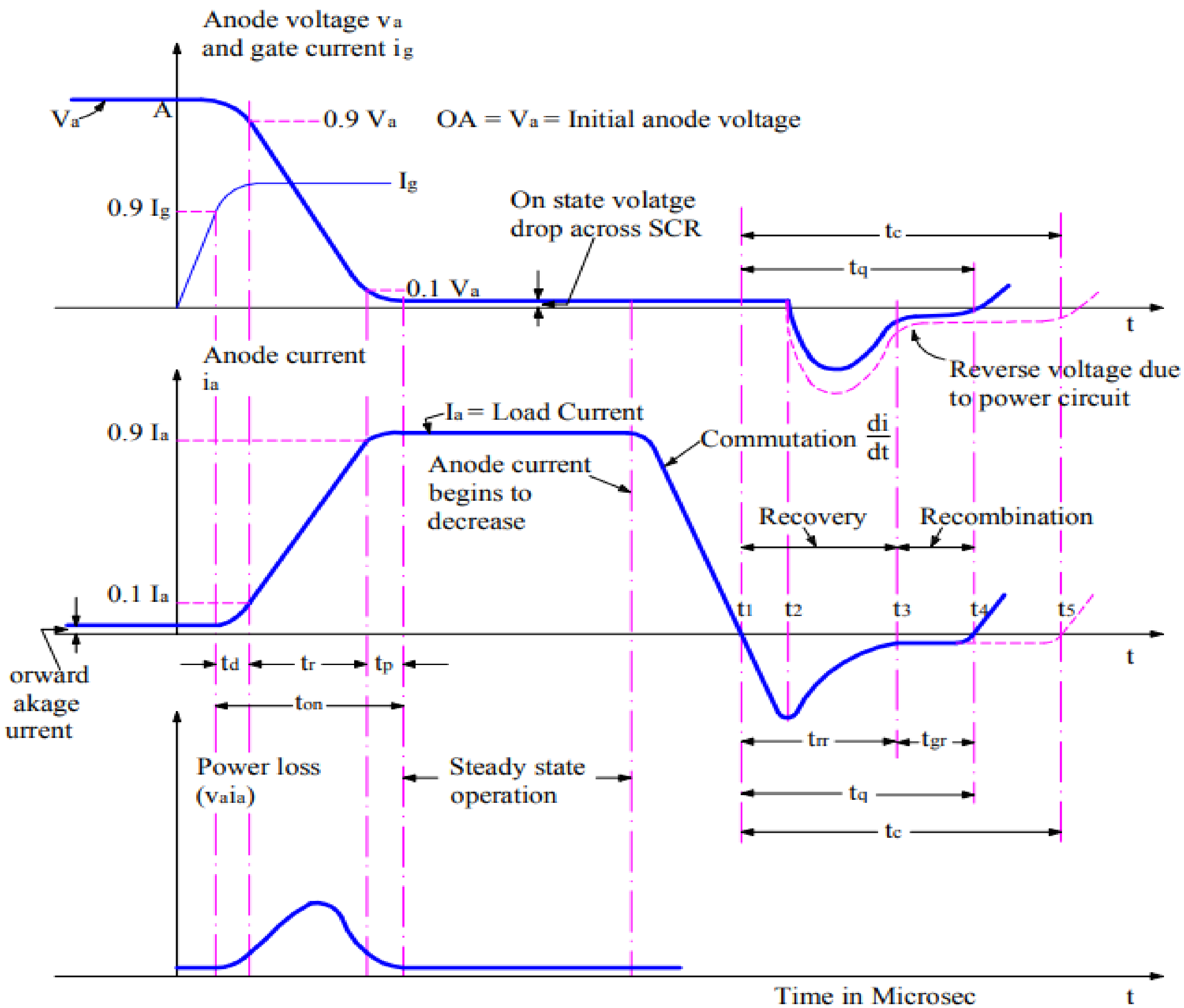


Fig. 2 *Waveforms during SCR turn-off*

Switching characteristics of SCR



Thyristor protection

- Reliable operation of a thyristor demands that its specified ratings are not exceeded
- In practice, a thyristor may be subjected to over voltages or over-currents
- During SCR turn on, di/dt may be prohibitively large.
- There may be false triggering of SCR by high value of dv/dt.
- A thyristor must be protected against all such abnormal conditions for satisfactory and reliable operation of SCR circuit and the equipment.

1) di/dt protection

2) dv/dt protection

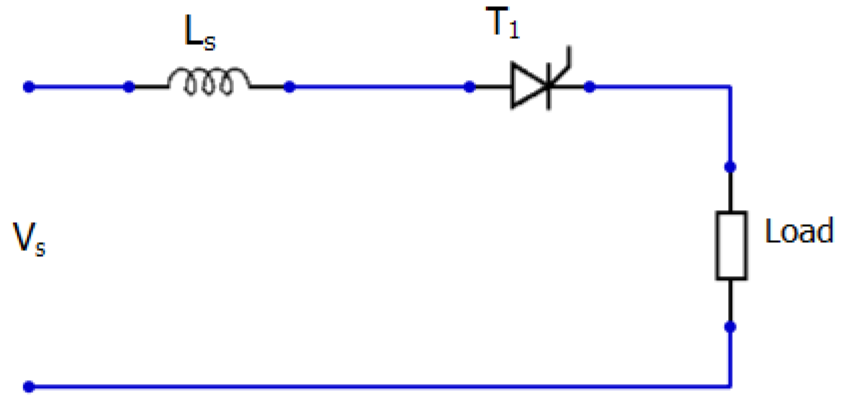
di/dt protection

- When a thyristor is forward biased and is turned on by a gate pulse, conduction of anode current begins in the immediate neighbourhood of the gate cathode junction
- There after the current spread across the whole area of the junction
- The thyristor design permit the spread of conduction to the whole junction area as rapidly as possible
- However if the rate of rise of anode current i.e., di/dt is large as compared to the spread velocity of carriers, local hot spot will be formed near the gate junction
- This localized heating may destroy the thyristor
- Therefore the rate of rise of anode current at the time of turn on must be kept below the specified limiting value.
- The value of di/dt can be maintained below acceptable limit by using a small inductor called, di/dt inductor in series with the anode circuit
- Typical di/dt limit values of SCR are 20–500A/μsec
- Local hot spot heating can also be avoided by ensuring that the conduction spreads to the whole area as early as possible
- This can be achieved by applying a gate current nearer to the maximum specified gate current

di/dt protection

$di/dt = V_s / L_s$

where L_s–series inductance including stray inductance



dv/dt protection

- If rate of rise of suddenly applied voltage across thyristor is high, the device may get turned on
- Such phenomena of turning on a thyristor is called dv/dt turn on and this must be avoided as it leads to false operation of the thyristor circuit
- For controllable operation of the thyristor, the rate of rise of anode to cathode voltage dVa/dt must be kept below the specified limit
- Typical value of dv/dt are20–500V/μsec
- False turn on of a thyristor by large dv/dt can be prevented by using a snubber circuit in parallel with the device

dv/dt protection

Snubber circuit

- Consist of a series combination of resistance R_s and capacitance C_s in parallel with the thyristor
- C_s in parallel with the device is sufficient to prevent unwanted dv/dt triggering of the SCR
- When switch, S is closed, a sudden voltage appear across the circuit
- Capacitor C_s behaves like a short circuit, therefore voltage across SCR is zero
- With the passage of time voltage across C_s builds up at a slow rate such that dv/dt across C_s and therefore across SCR is less than the specified maximum dv/dt rating of the device
- When the SCR is turned on capacitor discharges through the SCR and sends a current equal to V_s/(resistance of the path formed by C_s and SCR)
- As this resistance is quite low, the turn di/dt will tend to be excessive and as a result SCR may be destroyed
- In order to limit the magnitude of discharge current a resistance R_s is inserted in series with C_s
- The value of snubber circuit constant $\tau = R_s C_s$ can be determined from $\frac{dv}{dt} = \frac{V_s}{R_s C_s}$ for a known value of dv/dt

dv/dt protection

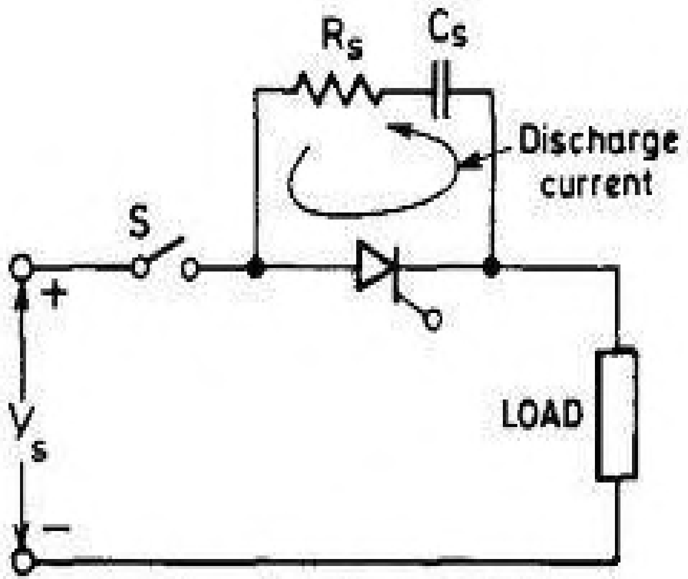
Snubber circuit

- The value of Rs is found from

$$R_s = \frac{V_s}{I_{TD}}$$

- The discharging current

$$I_{TD} = \frac{V_s}{R_1 + R_2}$$



Snubber circuit across SCR.

Series and Parallel operation of SCR

- For some industrial applications, the demand for voltage and current ratings is so high that a single SCR cannot fulfill such requirements
- In such cases *SCRs are connected in series in order to meet the H.V demand and in parallel to meet the high current demand*
- For series or parallel connected SCR it should be ensure that each SCR rating is fully utilized and the system operation is satisfactory
- String efficiency is a term that is used for measuring the degree of utilization of SCRs in a string

$$\text{string efficiency} = \frac{\text{actual voltage/current rating of the whole string}}{[\text{individual volatge/current rating of oneSCR}]\,[\text{Number of SCR in a string}]}$$

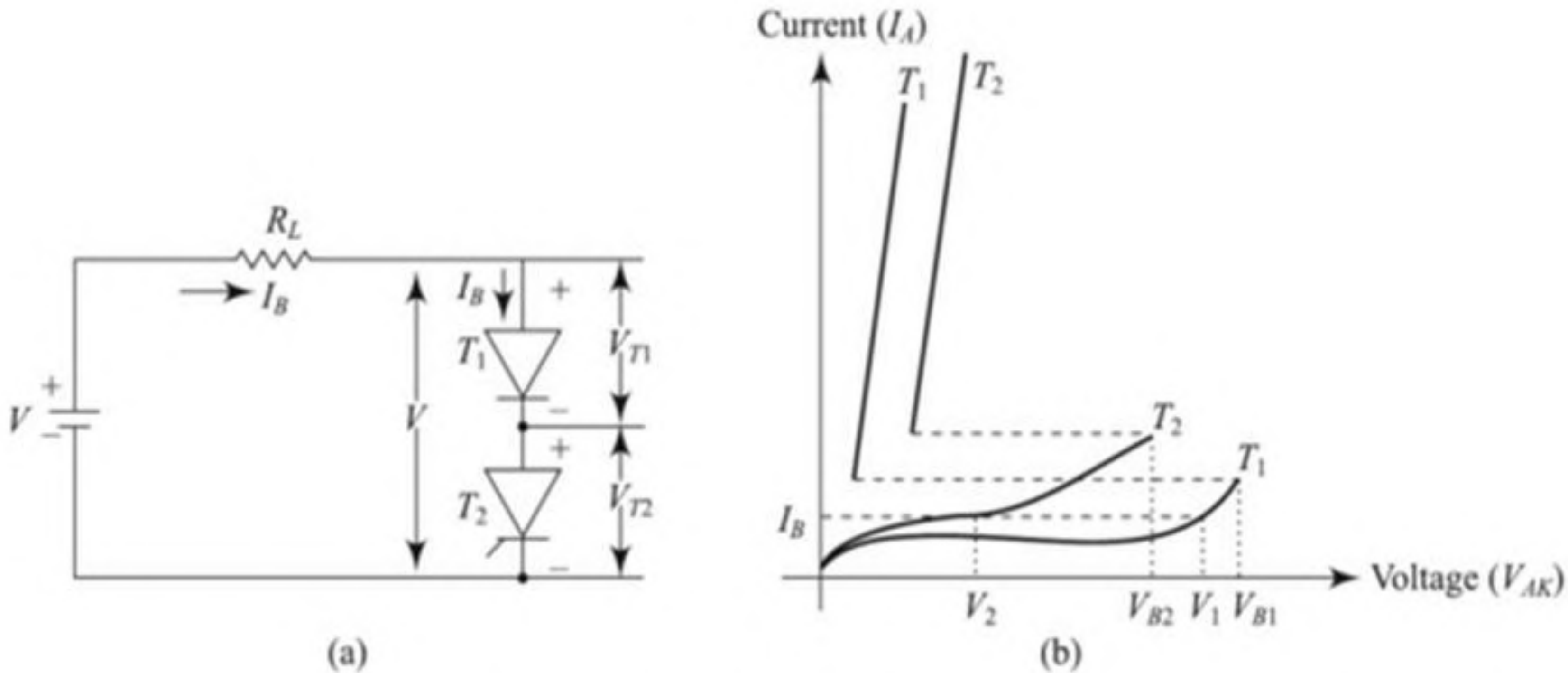
In practice this ratio is less than one

Series and Parallel operation of SCR

- For obtaining highest possible string efficiency, the SCRs connected in series/parallel string must have identical V-I characteristics
- As SCRs of same ratings and specifications do not have identical characteristics, unequal voltage/current sharing is bound to occur for all SCRs in a string
- As a consequence string efficiency can never be equal to one
- However unequal voltage/current sharing by the SCRs in a string can be minimized to a great extend by using external equalizing circuits
- Even this equalizing circuits, the efficiency is less than unity
- For a given system if one extra unit is added to the series/parallel string, the voltage/current shared by each device would become lower than its normal rating
- The use of voltage/current shared by each device would become lower than its normal rating
- The use of this extra unit will certainly improve the reliability of the string though at an increased cost
- A measure of the reliability of the string is given by a factor called DRF–de rating factor

DRF=1- string efficiency

Series operation



(a) Series connection of thyristors T_1 and T_2 (b) V-I characteristics of thyristors T_1 and T_2

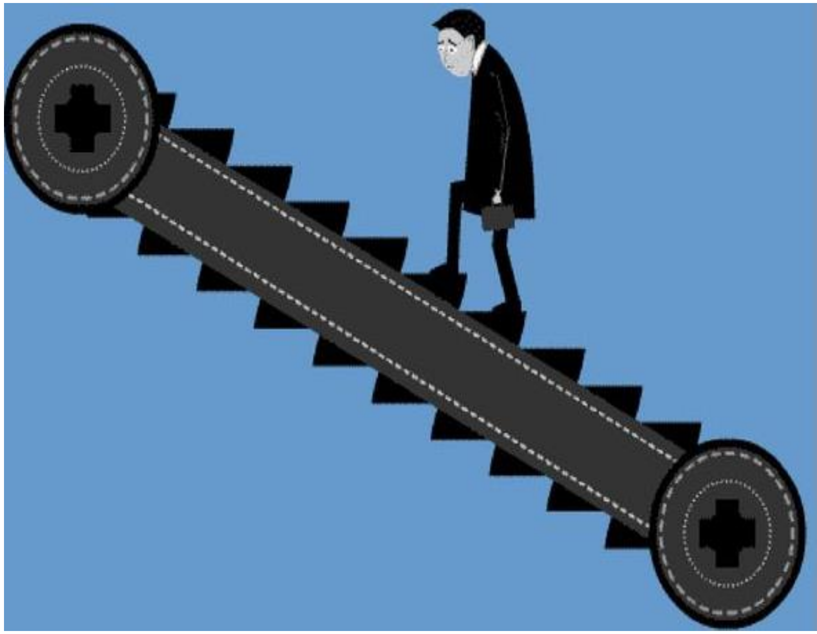
Module 5 - 11 hrs

Electric Drive: Introduction to electric drives – Block diagram – advantages of electric drives- types of load – classification of load torque (2 hrs)

DC Drives: Single phase semi converter and single phase fully controlled converter drives. Dual Converters for Speed control of DC motor-1-phase and 3-phase configurations; Simultaneous and Non-simultaneous operation. Chopper controlled DC drives- Single quadrant chopper drives- Regenerative braking control- Two quadrant chopper drives- Four quadrant chopper drives(6 hrs)

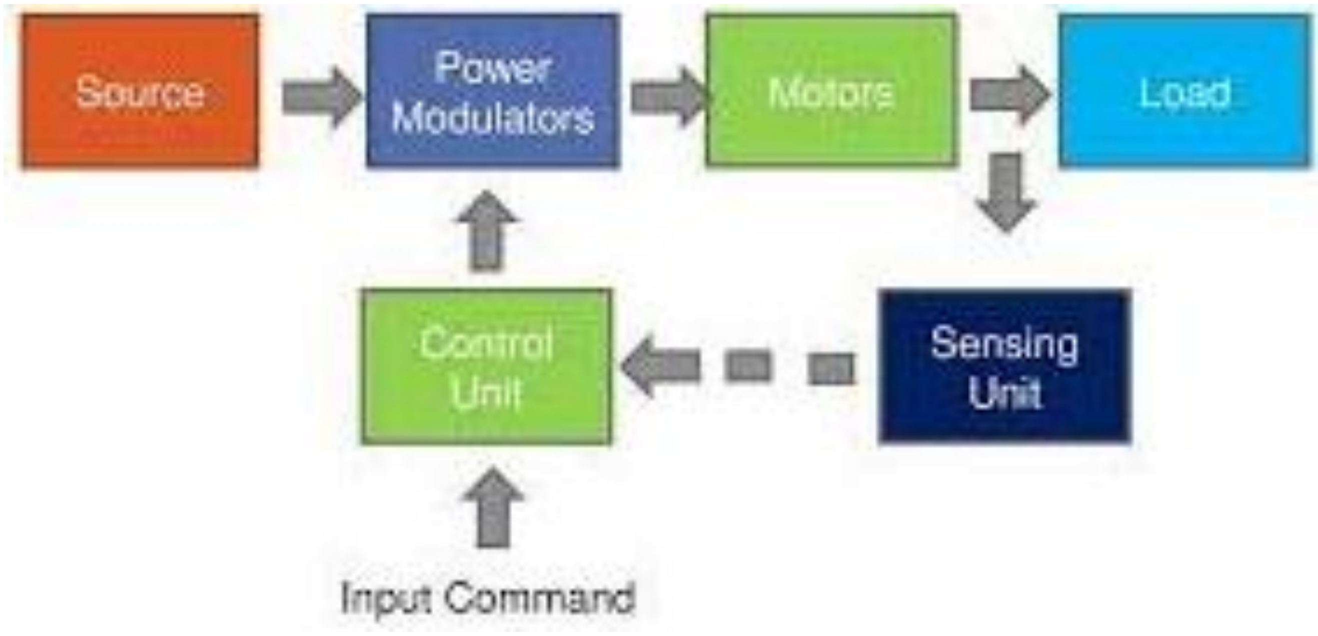
AC Drives: Three phase induction motor speed control. Stator voltage control – stator frequency control - Stator voltage and frequency control (v/f) (3 hrs)

Motion Control- DRIVE



ELECTRICAL DRIVES

- Systems employed for motion control are called *DRIVES*
- Employ any of prime movers such as diesel or petrol engine, gas, hydraulic motors & electric motors
- Drives supplying electric motors are known as electrical drives
- Block diagram of an electrical drive:



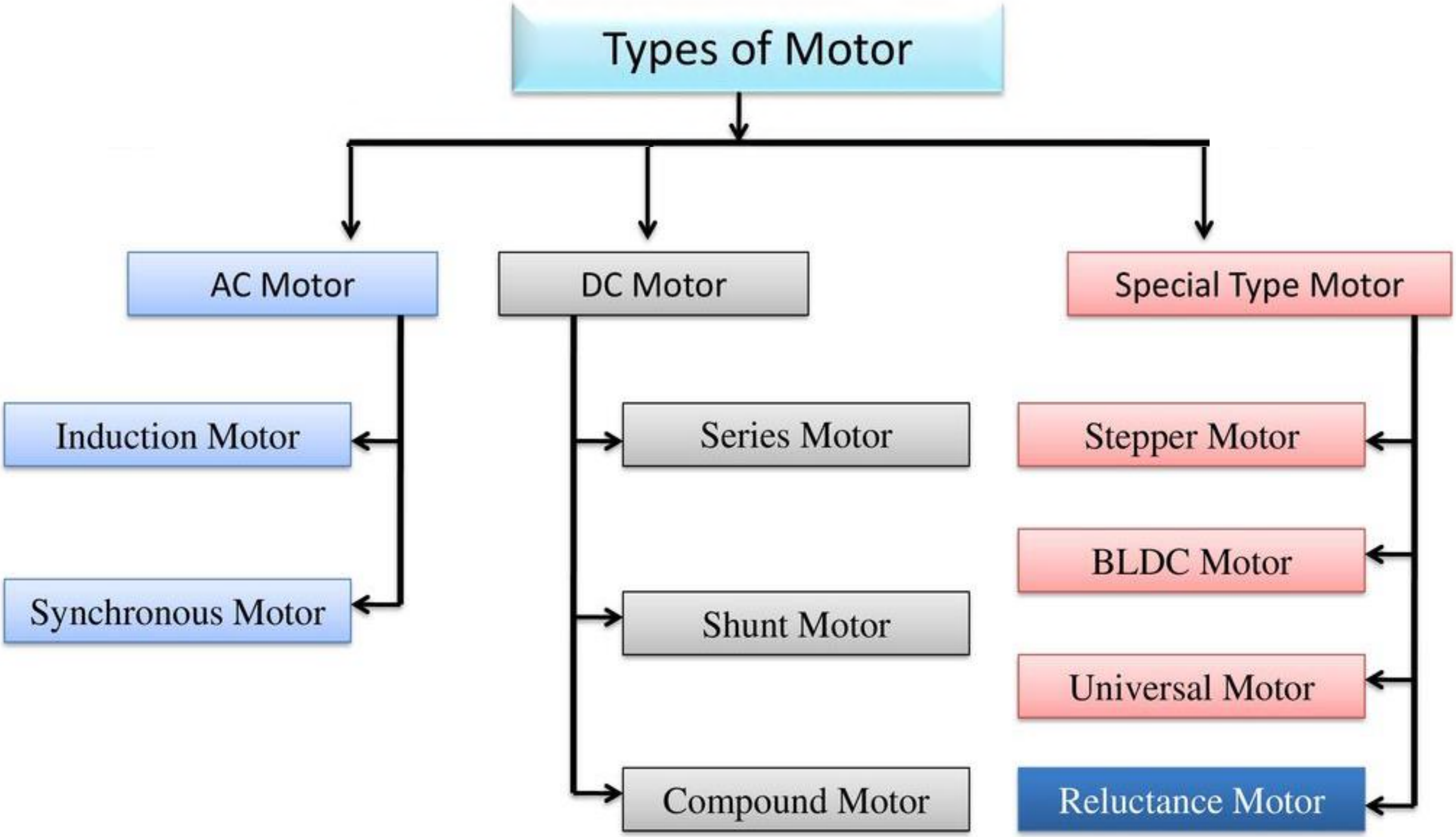
Advantages of ELECTRICAL DRIVES

- They have flexible control characteristics – automatic fault detection systems
- They are available in wide range of torque, speed & power
- Electric Motors have high efficiency, low no load losses, short time overloading capability, longer life, lower noise, low maintenance requirements, cleaner operation.
- Do not pollute the environment
- Can operate in all 4 quadrants of speed torque plane.
- No need refuel or warm up the motor. Motor can be started instantly & can immediately be fully loaded.
- They are powered by electrical energy which has a number of advantages over other forms of energy.

What is Motor……?

Electrical Energy

(Rotational Force) Mechanical Energy


Types of Motor
AC Motor
DC Motor
Special Type Motor
Induction Motor
Synchronous Motor
Series Motor
Shunt Motor
Compound Motor
Stepper Motor
BLDC Motor
Universal Motor
Reluctance Motor

Type of Loads

- Load torque can be of two types
- (1) Active load torque:- Active torques continues to act in the same direction irrespective of the direction of the drive. e.g. gravitational force or deformation in elastic bodies.
- (2) Passive load torque:- the sense of the load torque changes with the change in the direction of motion of drive. e. g. torques due to friction, due to shear and deformation of inelastic bodies.

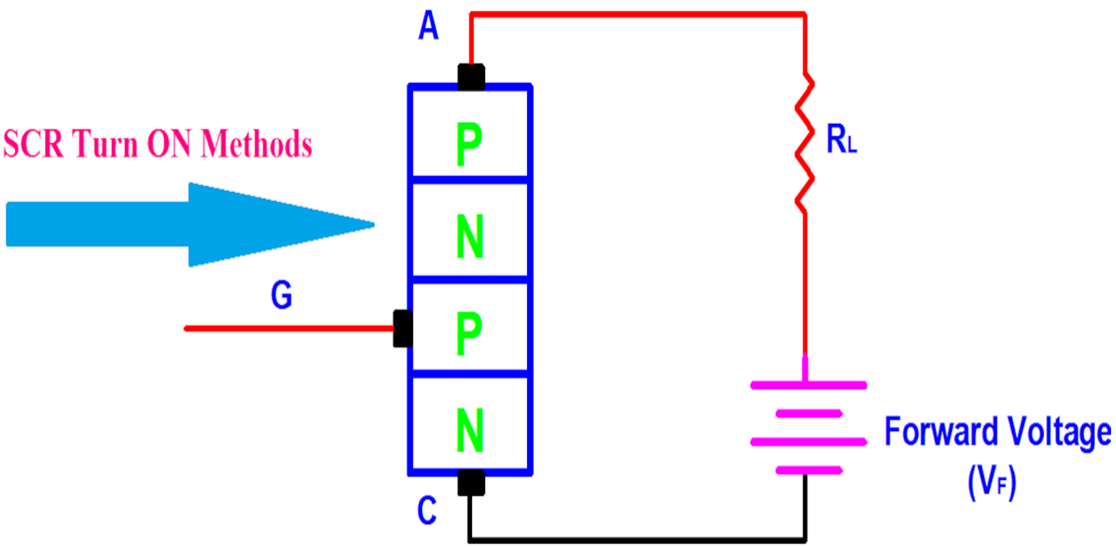
REFERENCES

1. P.S. Bimbhra, Power Electronics, Khanna Publishers, New Delhi
2. Mohan N., T. M. Undeland and W. P. Robbins., Power Electronics, Converters, Applications & Design, Wiley-India
3. Muhammad H. Rashid, *Power Electronics Circuits, Devices and Applications, Pearson Education*
4. Singh M. D. and K. B. Khanchandani, *Power Electronics, Tata McGraw Hill*, *New Delhi, 2008.*
5. L. Umanand, Power Electronics – Essentials & Applications, Wiley-India
6. Krein P. T., Elements of Power Electronics, Oxford University Press, 1998.
7. Joseph Vithayathil, Power Electronics: Principles and Applications, McGraw-Hill College; International edition,1995
8. www.nptel.ac.in
9. G.K.Dubey,Fundamentals of Electric Drives, Narosa publishers, second edition, 2010.

Turn on methods of SCR

An SCR can be switched from off-state to on-state in several ways:

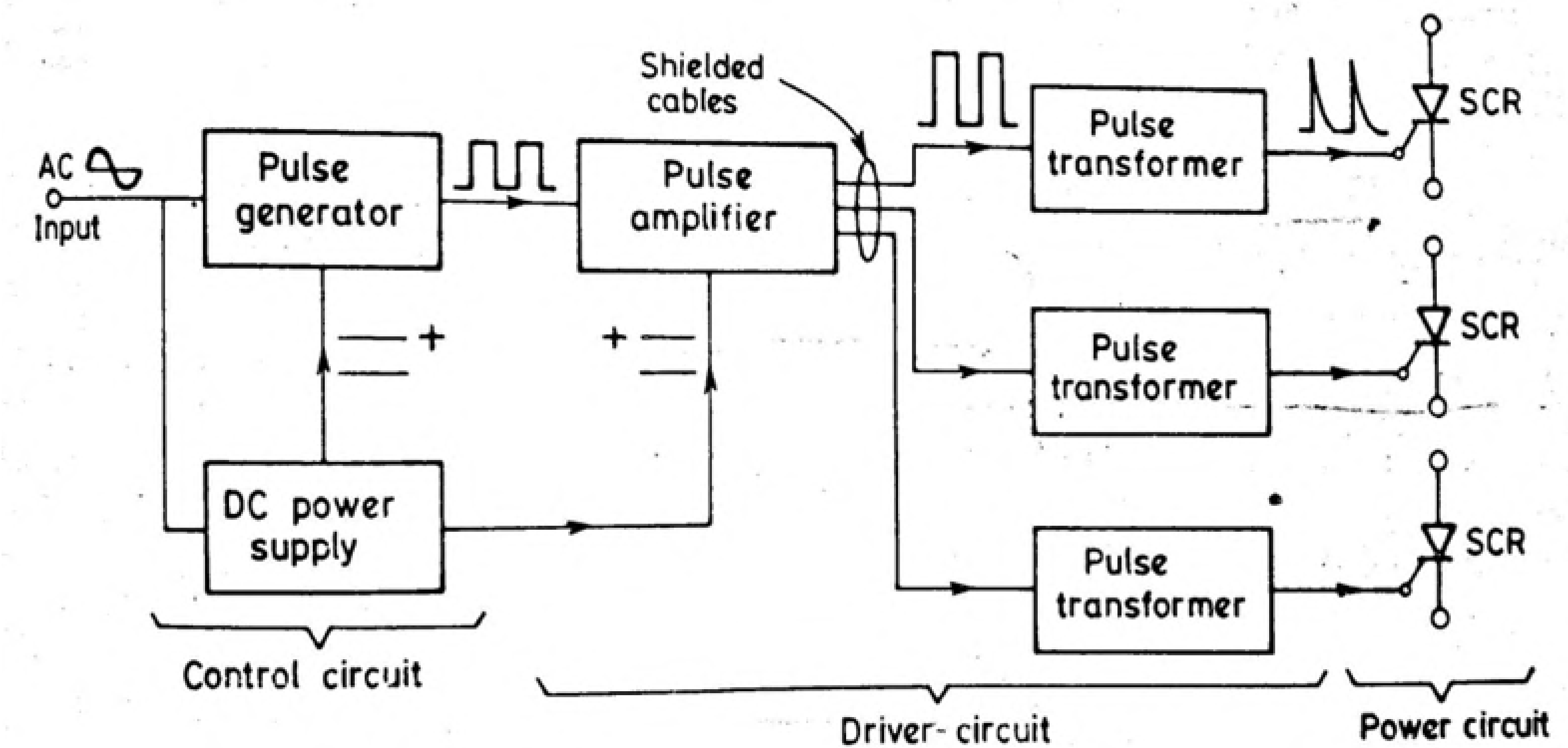
1. Forward voltage triggering
2. dv/dt triggering
3. Temperature triggering
4. Light triggering
5. Gate triggering



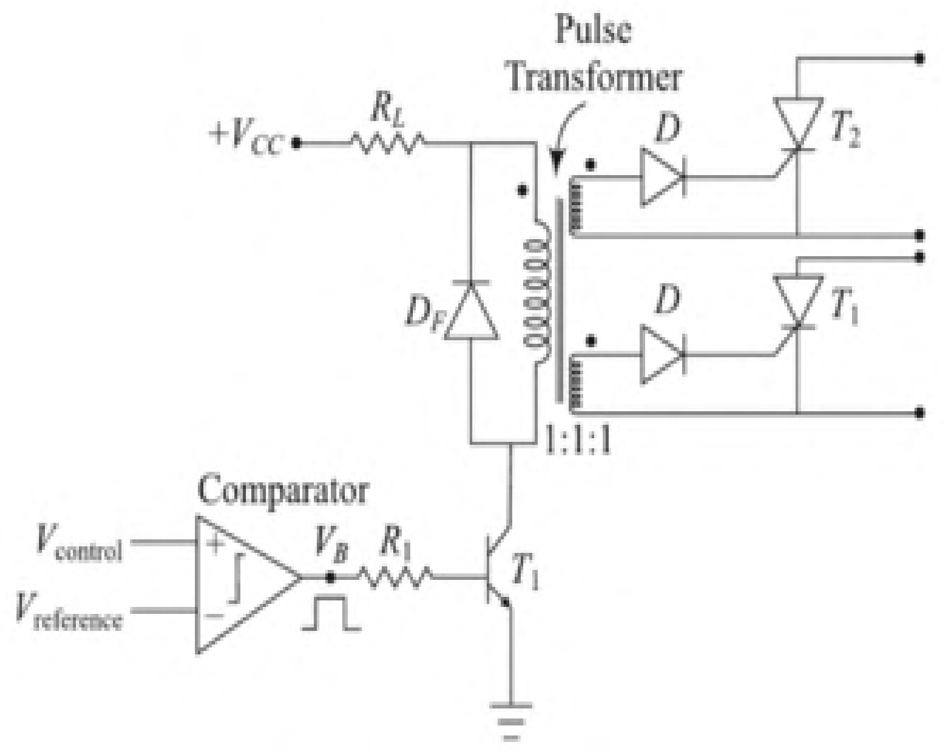
Gate triggering

- Most common method, efficient and reliable
- Gate control circuit is also called firing or triggering circuit
- Gate circuits are usually low power electronics circuits
- A firing circuit should fulfill the following two functions
  - If power circuit has more than one SCR, the firing circuit should produce gating pulses for each SCR at the desired instant for proper operation of the power circuit
  - The control signal generated by a firing circuit may not be able to turn on an SCR. It is therefore common to feed the voltage pulse to a driver circuit and then to a gate cathode circuit

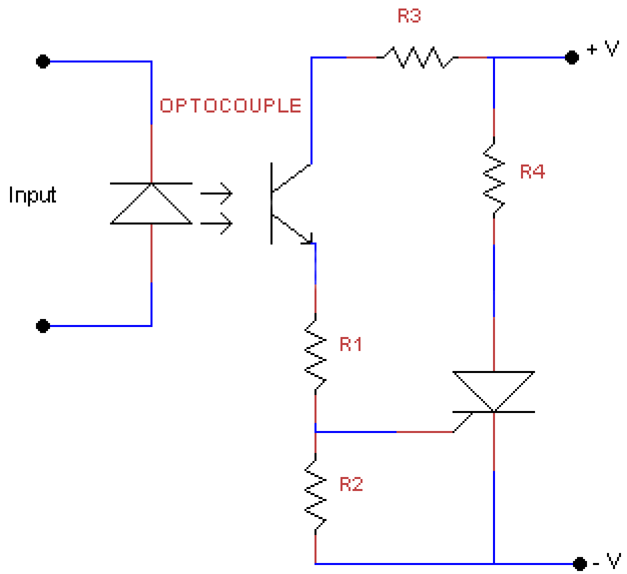
Gate triggering Circuits



Pulse transformer in firing circuit



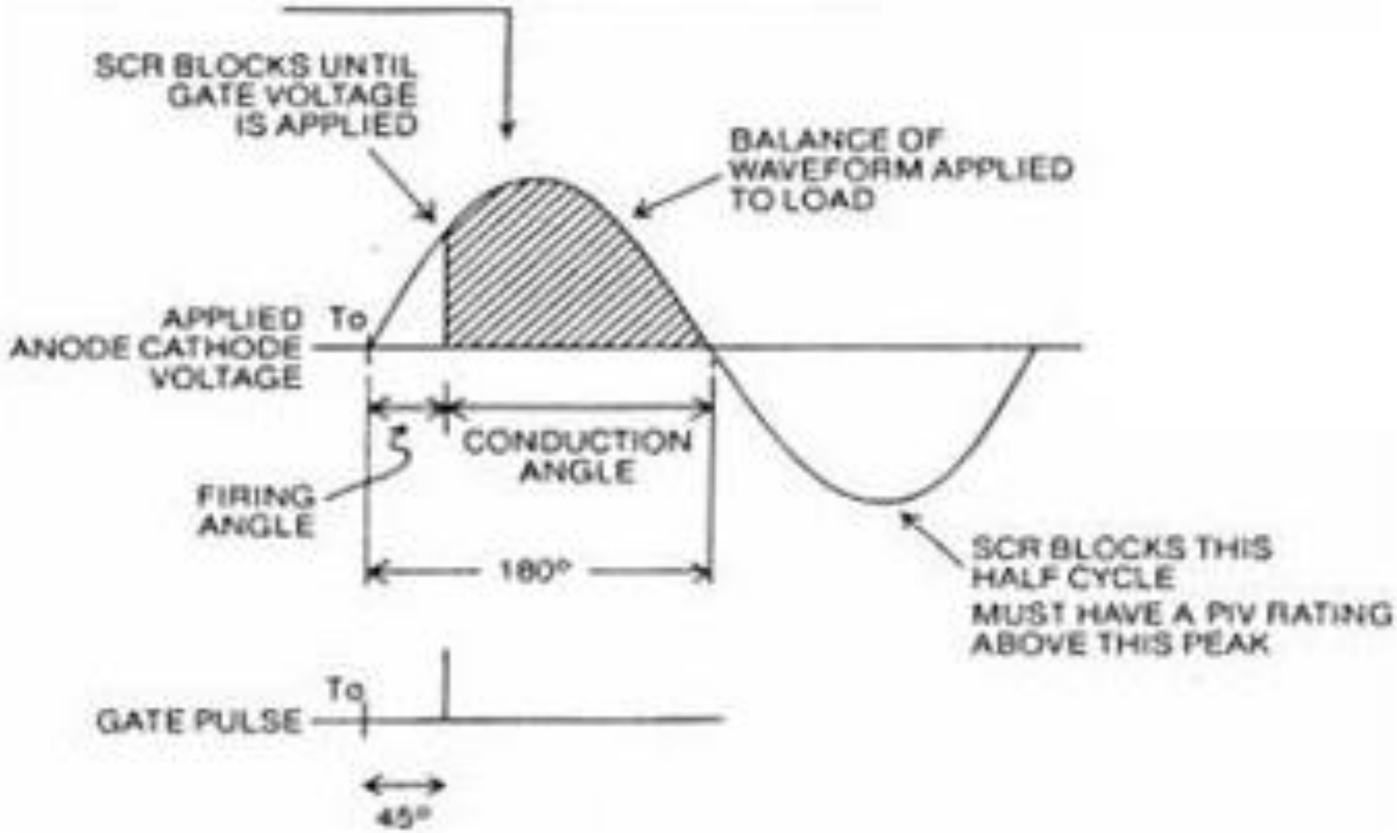
Opto coupler in firing circuit



An **Optocoupler**, is an electronic components that interconnects two separate electrical circuits by means of a light sensitive optical interface.

The basic design of an optocoupler, also known as an **Opto-isolator**, consists of an LED that produces infra-red light and a semiconductor photo-sensitive device that is used to detect the emitted infra-red beam. Both the LED and photo-sensitive device are enclosed in a light-tight body or package with metal legs for the electrical connections

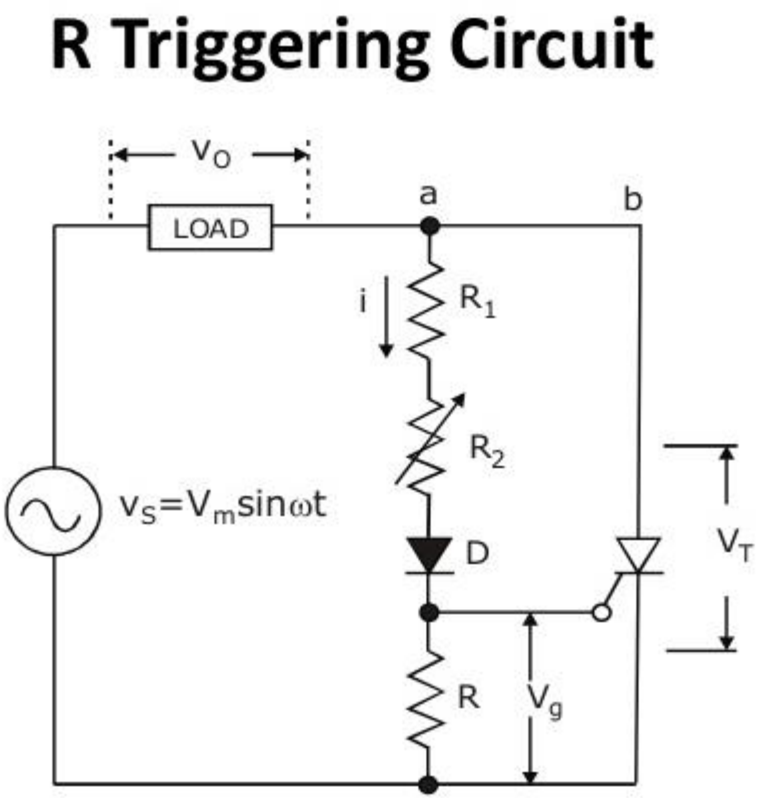
Firing angle (α)



Gate triggering Circuits

- Resistance triggering circuit (R Triggering Circuit)
- Resistance Capacitance triggering circuit (RC Triggering Circuit)
- UJT triggering circuit (Unijunction Transistor Triggering Circuit)

R triggering circuit (Resistance triggering)



Simple and most economical

Limited range of firing angle control (0 to 90^0)

R_2-variable resistance

R–stabilizing resistance

In case R_2=0, gate current may flow from source, through load, R_1, D and gate to cathode, then the current is limited by R_1

$$I_{gm} \le \frac{V_m}{R_1} \Rightarrow R_1 \ge \frac{V_m}{I_{gm}}$$

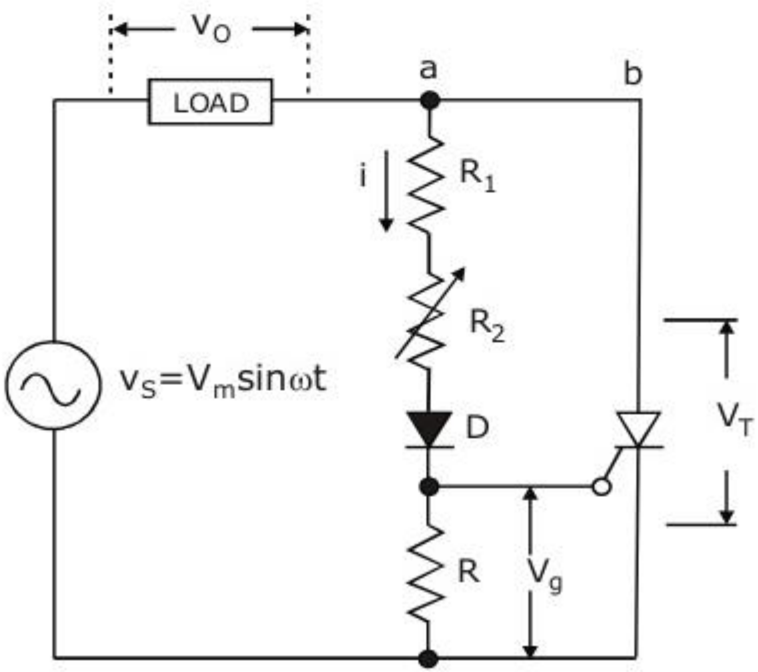
R is chosen such that max. voltage across it doesn't exceed max. forward gate voltage V_{gm}

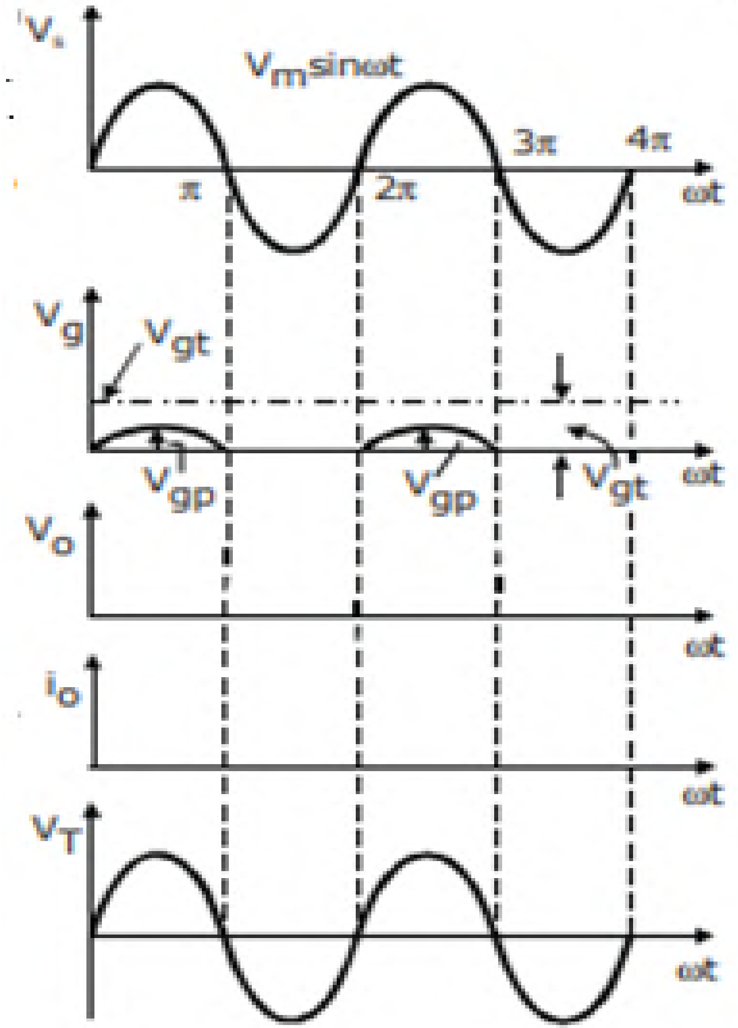
Therefore,

$$\frac{V_m}{R+R_1} R \le V_{gm} \Rightarrow R \le \frac{V_{gm} R_1}{V_m - V_{gm}}, \quad (R_2 = 0)$$

$V_{gp} < V_{gt}$

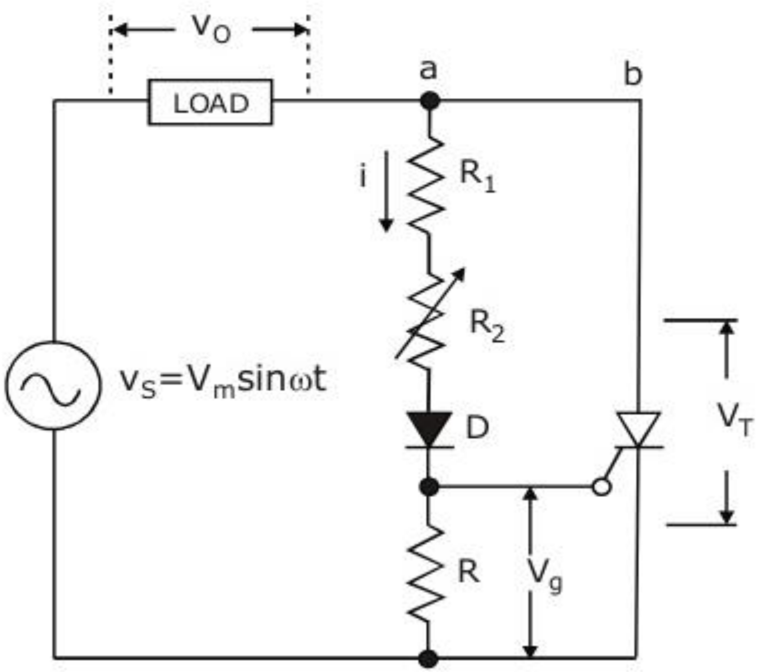
R Triggering Circuit

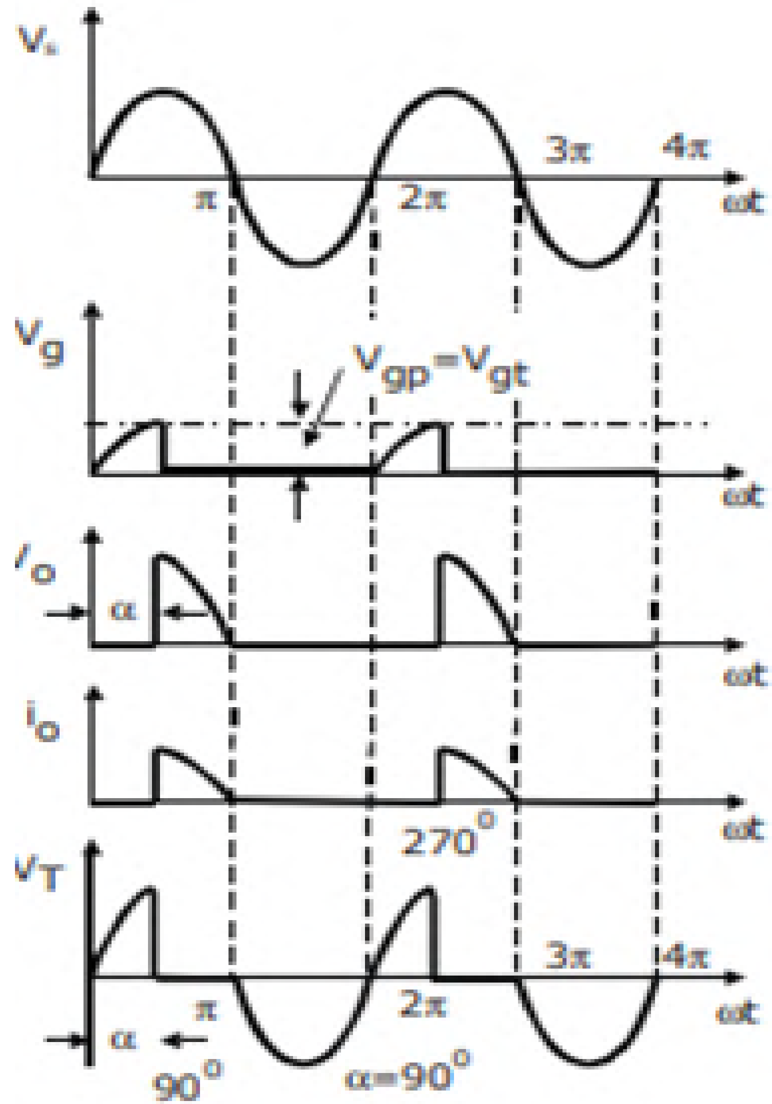




$V_{gp} = V_{gt}$

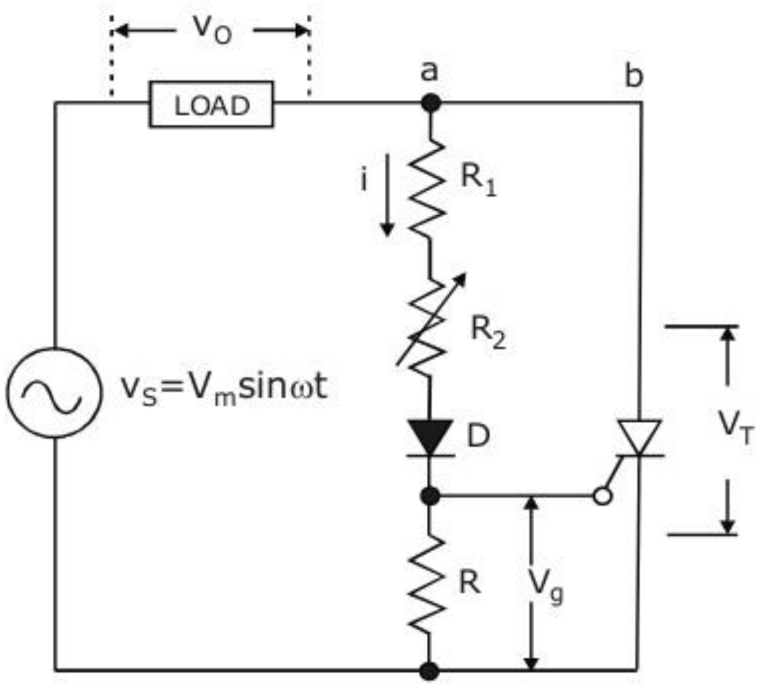
R Triggering Circuit

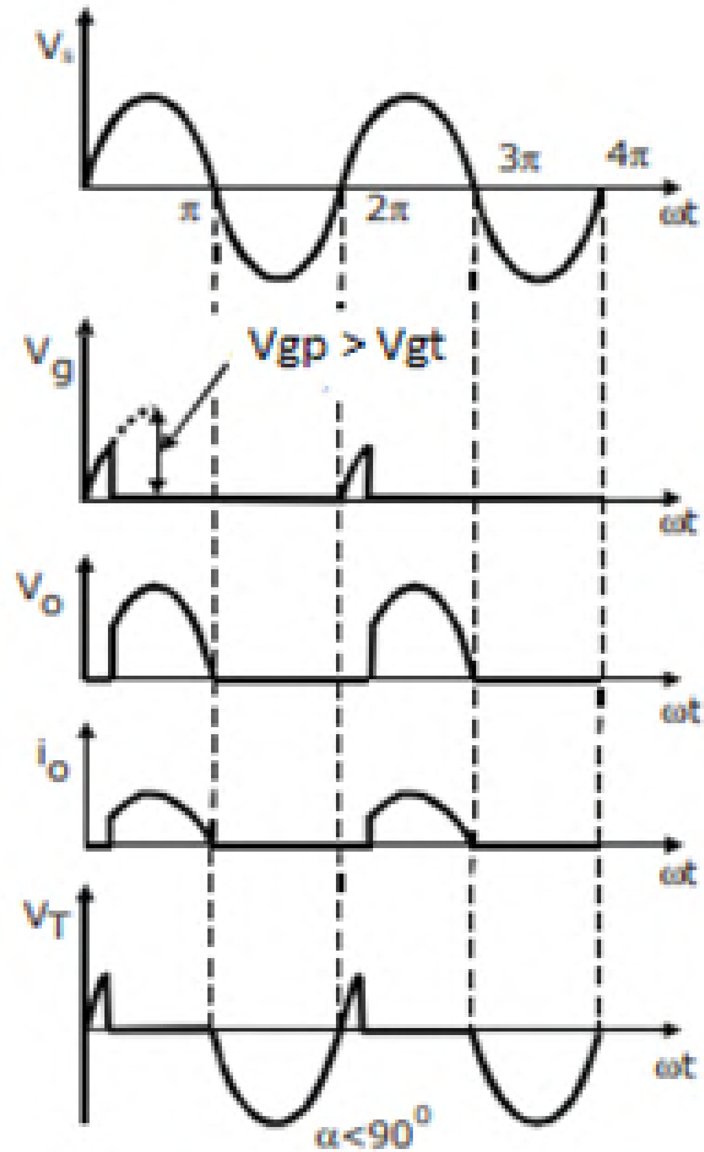




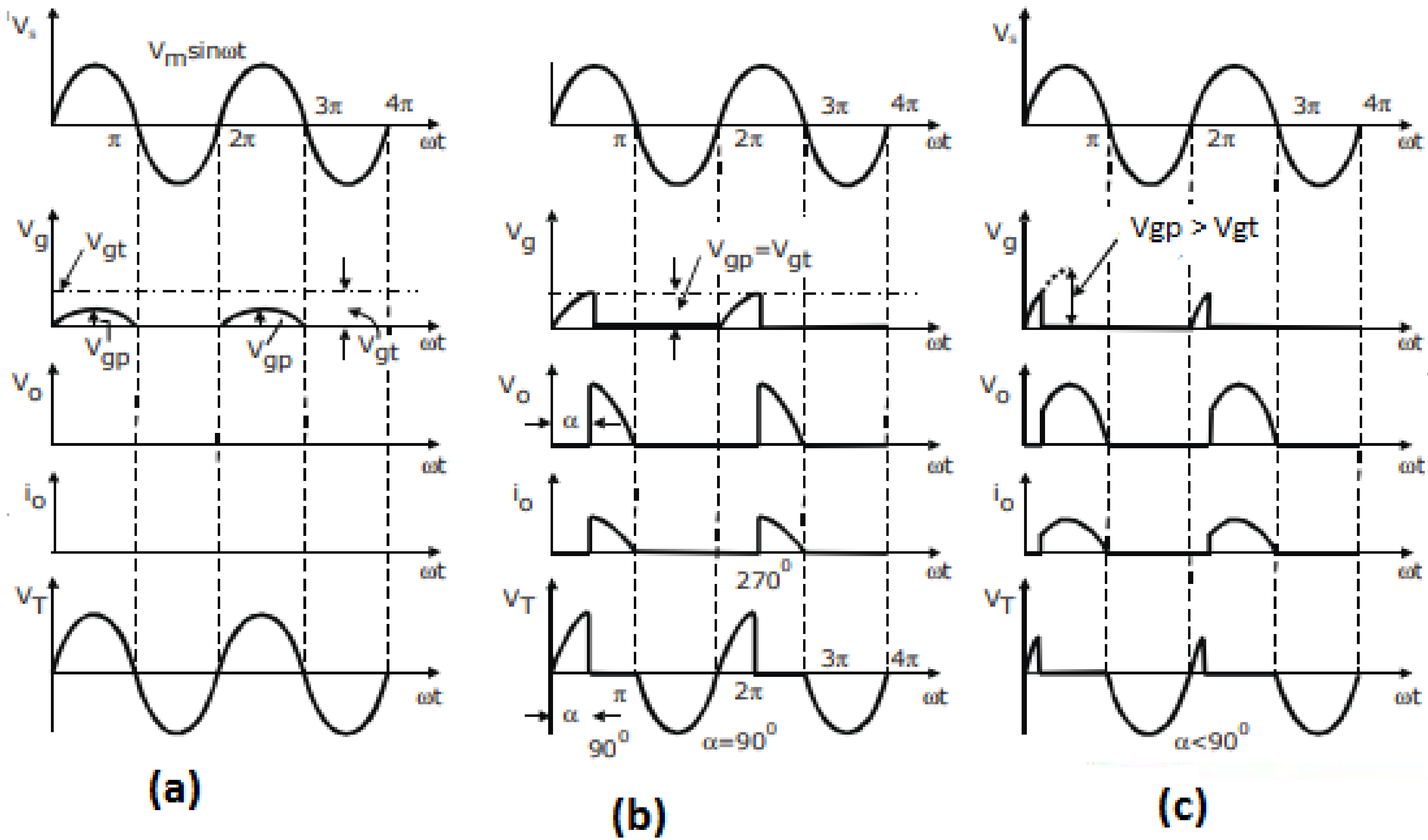
$V_{gp} > V_{gt}$

R Triggering Circuit





$$\alpha = \sin^{-1}\left[\frac{V_{gt}(R_1 + R_2 + R)}{V_m.R}\right]$$



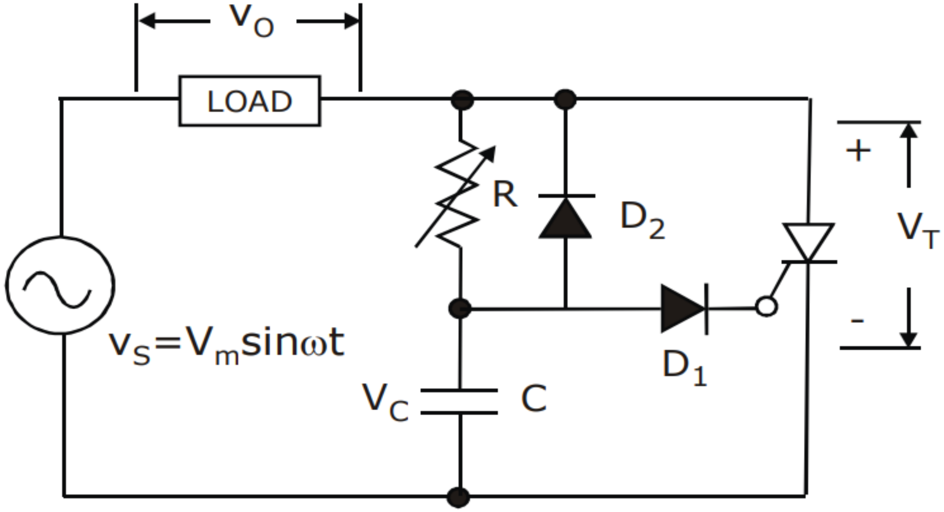
RC triggering circuit

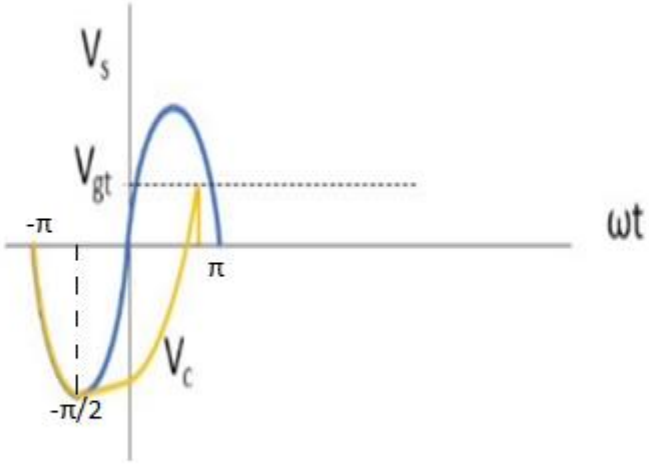
- Resistance – capacitance firing circuit
- Two circuit configurations

    1) RC half wave triggering circuit

    2) RC full wave triggering circuit

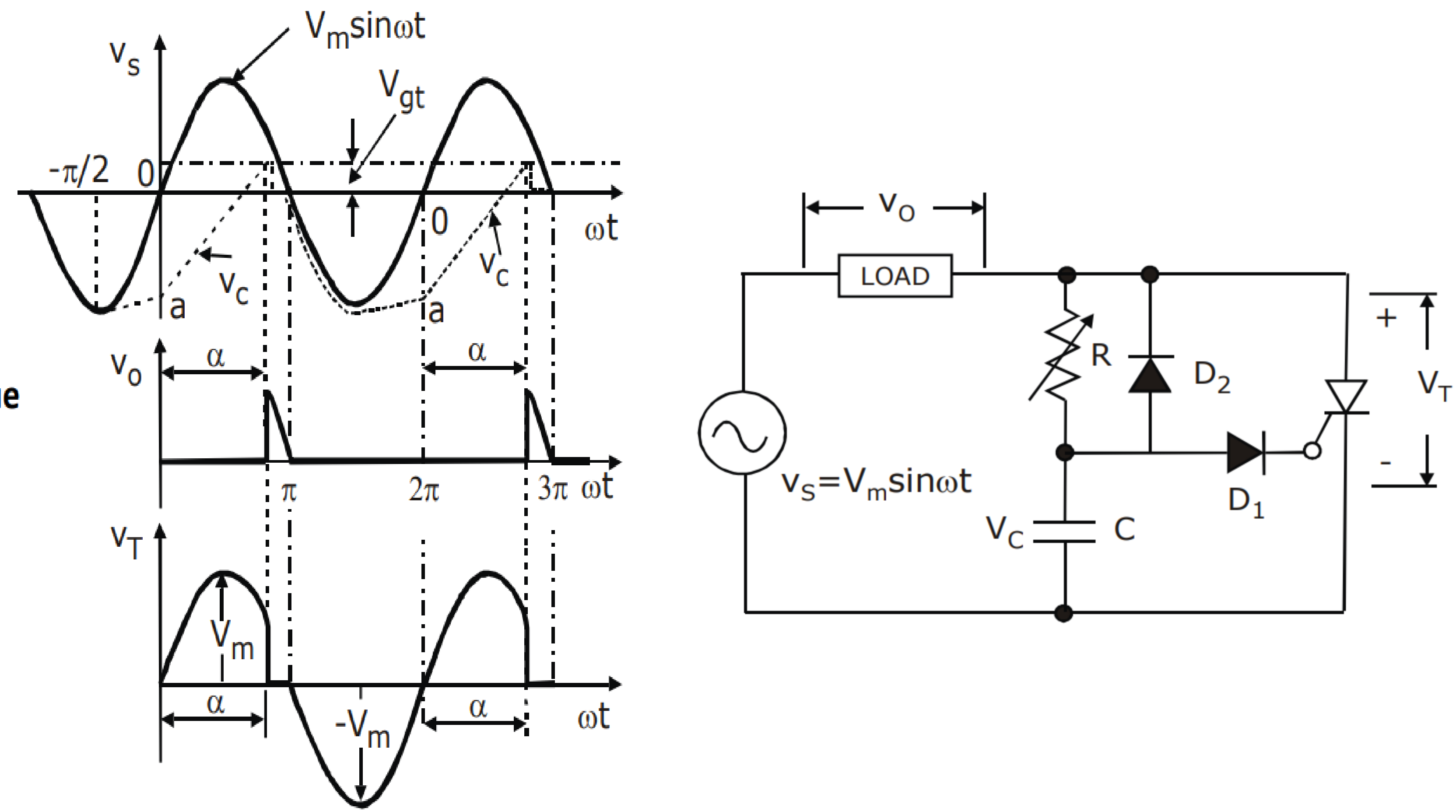
RC half wave triggering circuit



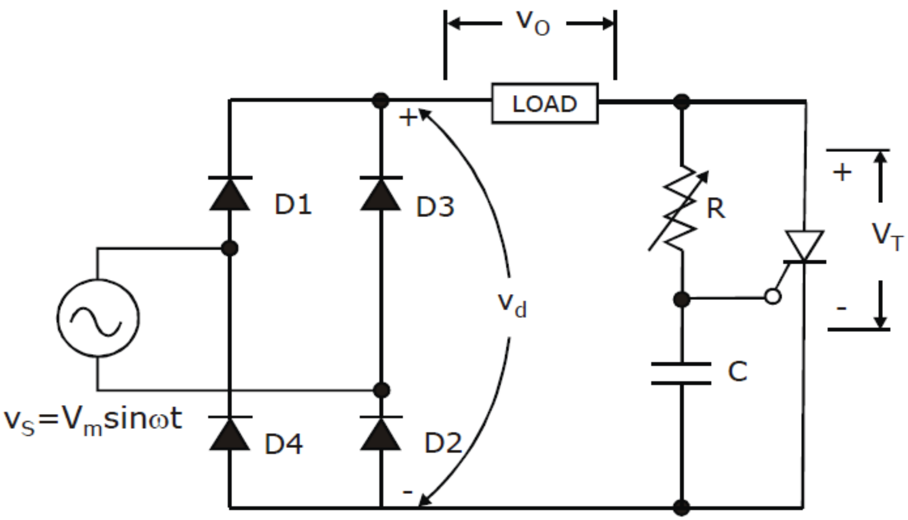


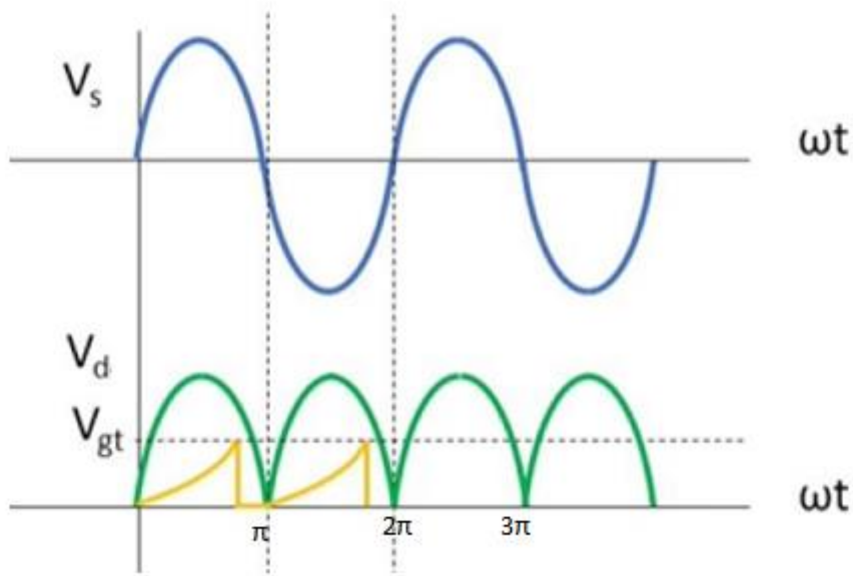
RC half wave triggering circuit

High Value of R



RC full wave triggering circuit

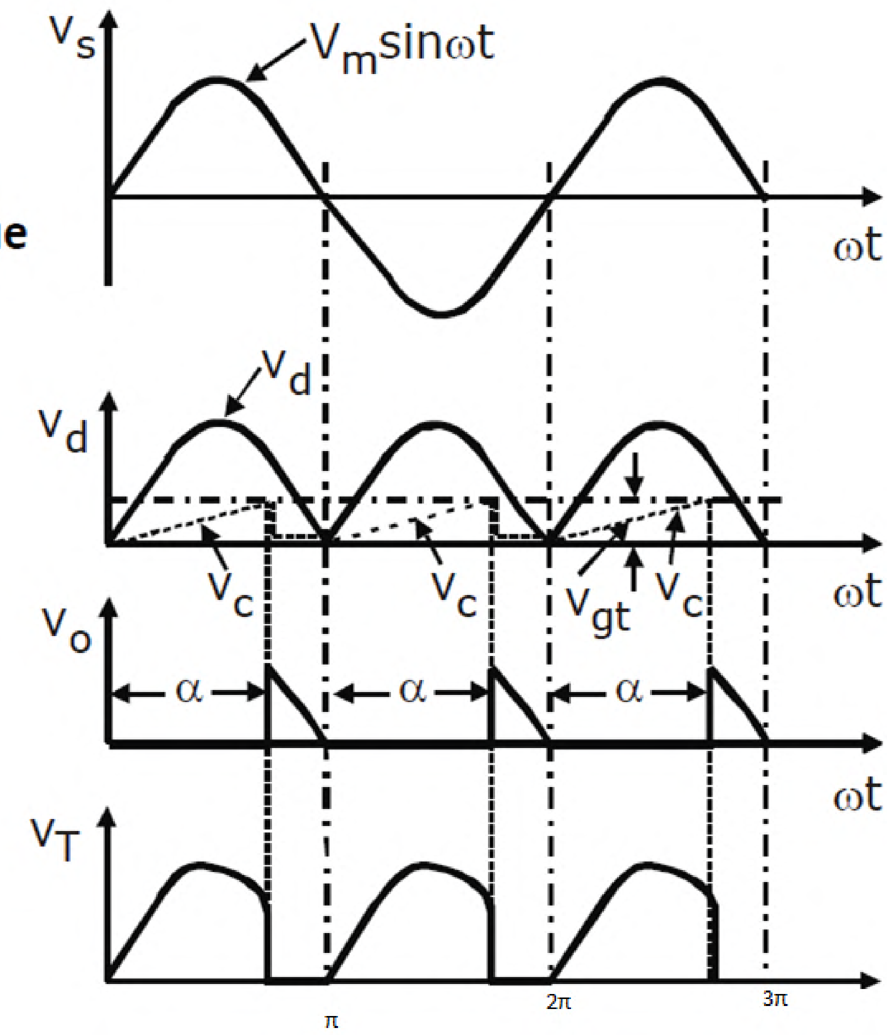




- The above trigger circuit gives full wave o/p
- Diodes form a *full-wave bridge*
- Initial voltage from which the C begins to charge is almost zero
- Again SCR triggers at $V_c = V_{gt}$
- At the triggering instant V_c resets to zero by the clamping action of SCR gate

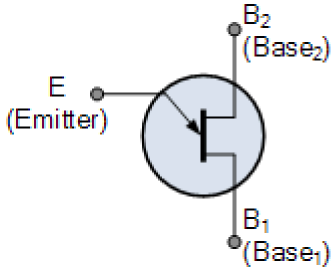
RC full wave triggering circuit

High Value of R

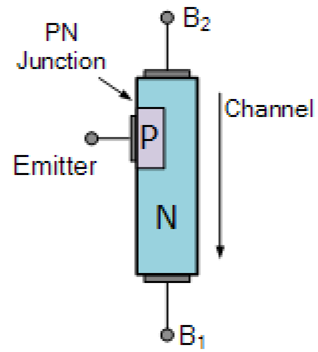


UJT triggering circuit

- Unijunction Transistor (UJT)

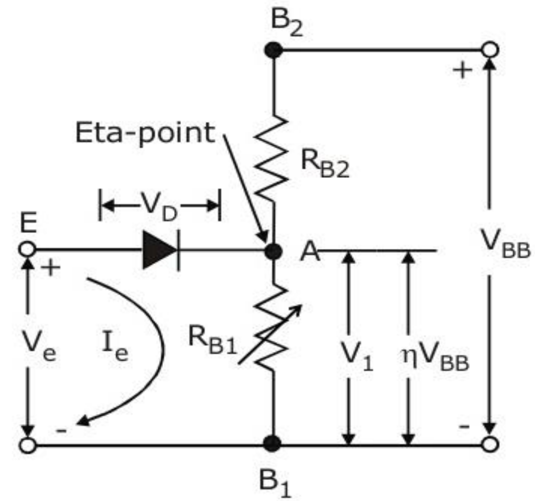


Circuit symbol



Structure of UJT

Equivalent Circuit



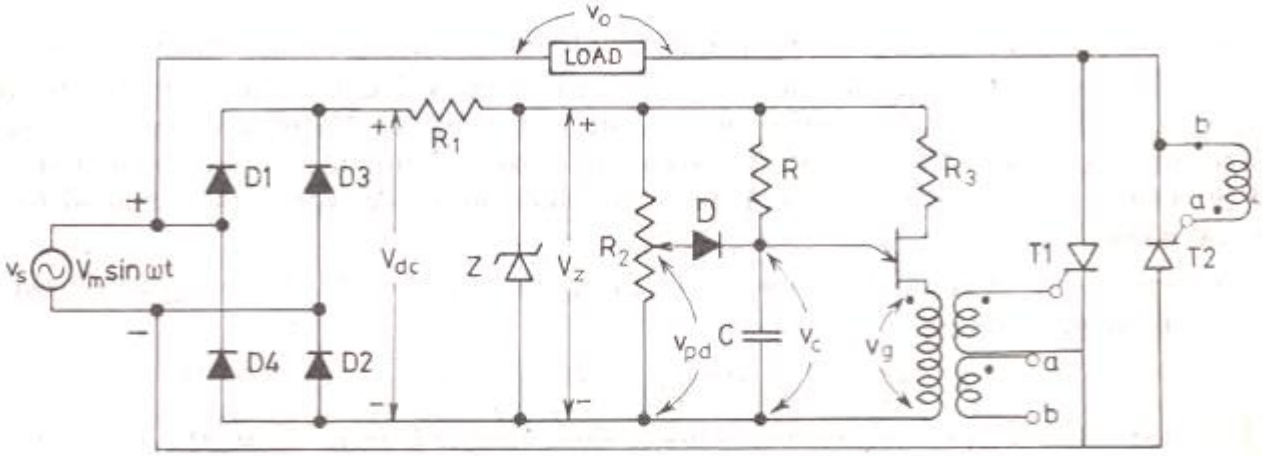
Equivalent Circuit of UJT

$$V_{AB1} = \frac{V_{BB}}{R_{B1} + R_{B2}} \cdot R_{B1} = \frac{R_{B1}}{R_{B1} + R_{B2}} \cdot V_{BB} = \eta\, V_{BB}$$

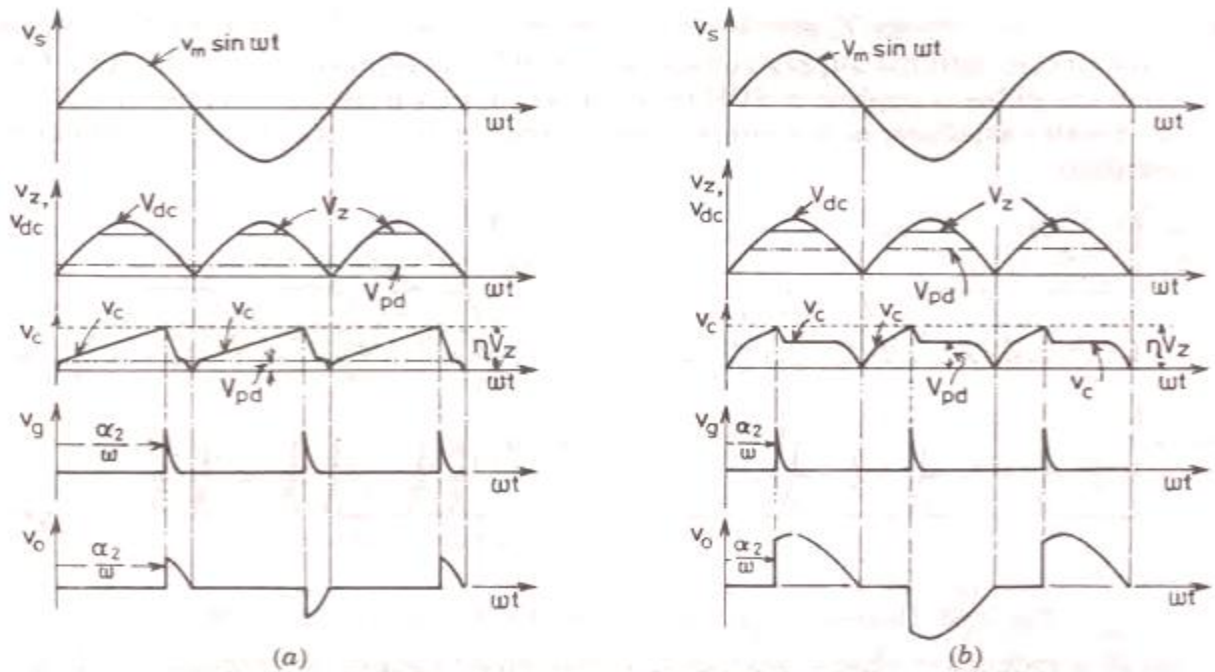
where $\eta = \frac{R_{B1}}{R_{B1} + R_{B2}}$ is called the *intrinsic stand-off ratio*. Typical values of η are 0.51 to 0.82.

Interbase resistance $R_{BB} = R_{B1} + R_{B2}$ is of the order of 5–10 kΩ.

Ramp and pedestal triggering

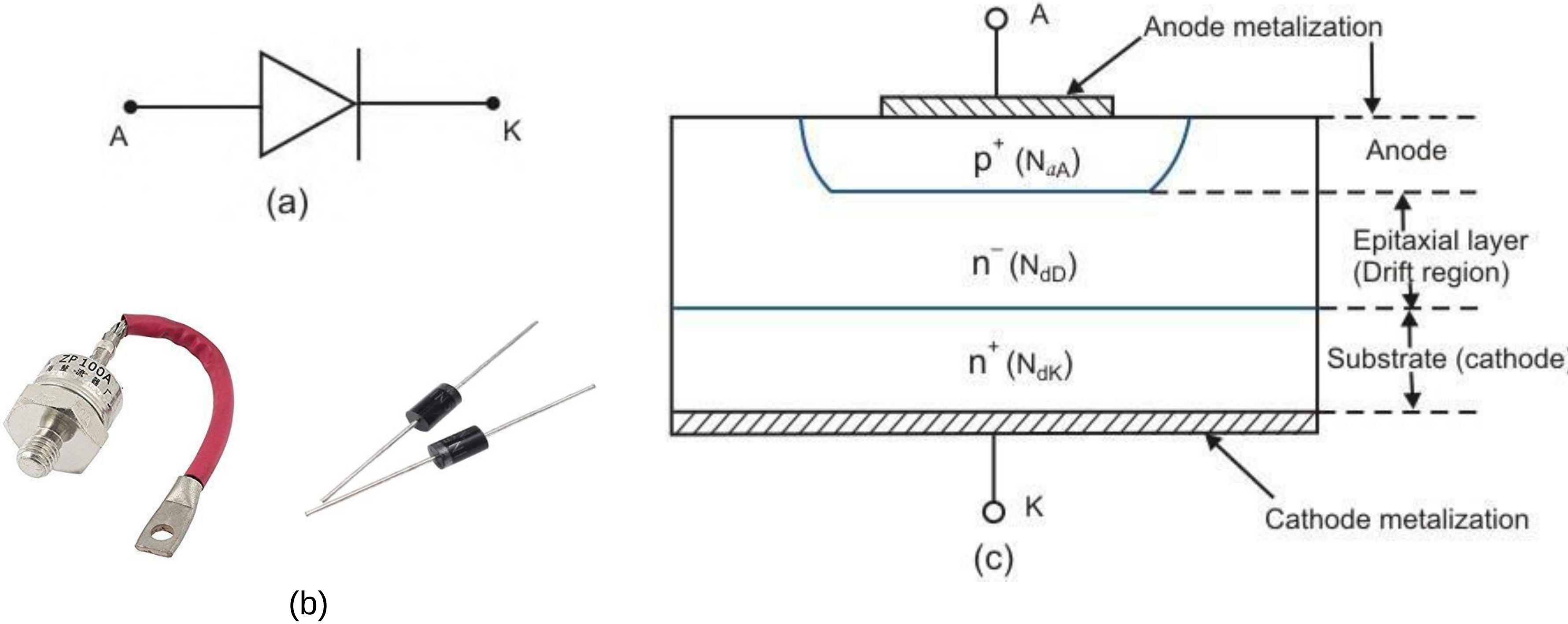


Ramp and pedestal trigger circuit for ac load.



Waveforms for ramp-and-pedestal circuit

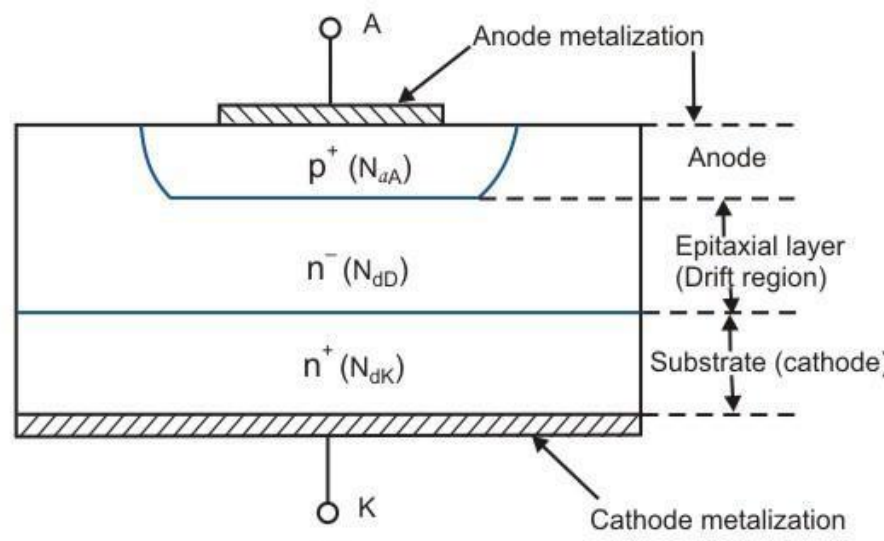
Power semiconductor diode – structure



Circuit symbol, photograph and cross sectional view of power diode

Power semiconductor diode – structure

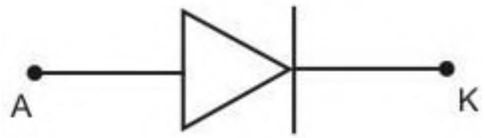
- Heavily doped n+ substrate.
- On this substrate, a lightly doped n- layer is epitaxially grown.
- Heavily doped p+ layer is diffused into n- layer to form the anode of the power diode.
- n- layer is the basic structural feature not found in signal diodes.
- The function of n- layer is to absorb the depletion layer of the reverse biased p+ n-junction J_1.



(c)

Power semiconductor diode – structure

- The drawback of n- layer is to add significant ohmic resistance to the diode when it is conducting a forward current
- This leads to large power dissipation in the diode
- So proper cooling arrangements in large diode ratings are essential
- Circuit symbol of a power diode is same as that of a signal diode



(a)

Power semiconductor diode - Chara.

- Power diode is a two terminal, p-n semiconductor device
- The two terminals of diode are called, anode and cathode
- The two important characteristics of diode are

  1) Diode V-I characteristics

  2) Diode reverse recovery characteristics

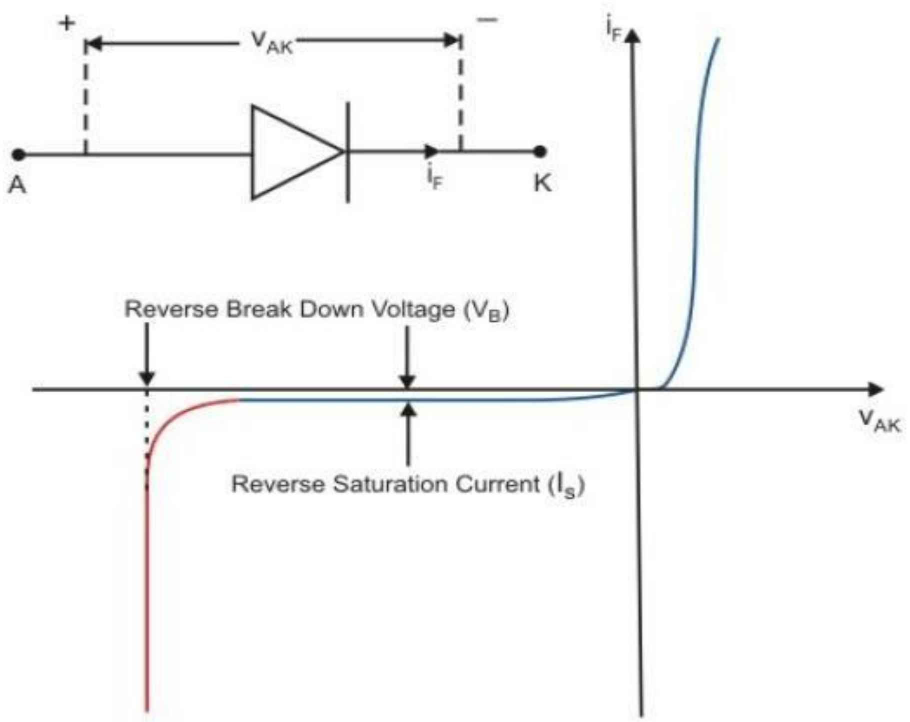
Power semiconductor diode - Chara.

Diode V-I characteristics

- When anode is positive with respect to cathode, diode is said to be forward biased
- With increase of the source voltage V_s from zero value, initially diode current is zero
- *Cut in voltage is also known as, threshold voltage or turn on voltage*
- Beyond cut in voltage, the diode current rises rapidly and the diode is said to conduct

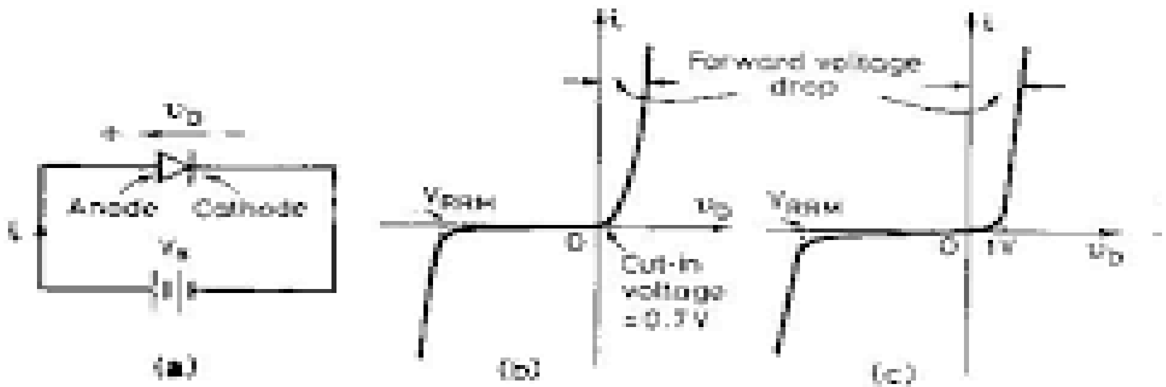
Power semiconductor diode - Chara.

- For silicon diode, the cut in voltage is around 0.7V
- When diode conducts, there is a forward voltage drop of the order of 0.8 to 1V



Power semiconductor diode - Chara.

- When cathode is positive w.r.t anode, the diode is said to be reverse biased
- In the reverse biased condition a small reverse current called leakage current of the order of microamperes or mill amperes flows
- A large reverse breakdown voltage, associated with high reverse current leads to excessive power loss that may destroy the diode



(a) Forward biased Power Diode

(b) V-I Charateristics of Signal Diode

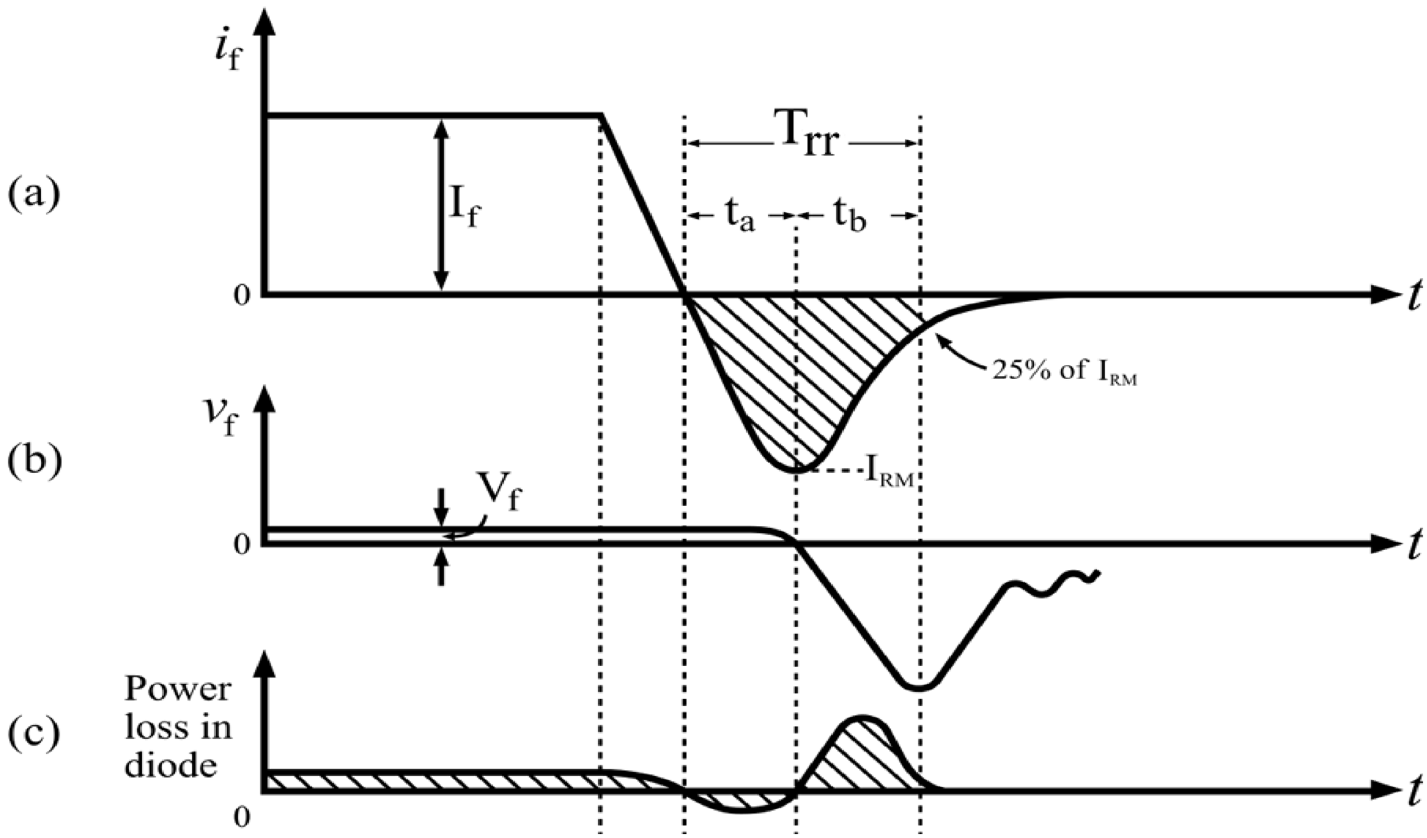
(c) V-I Characteristics of Power Diode

Power semiconductor diode - Chara.

Diode reverse recovery characteristics

- After the forward diode current decays to zero, the diode continues to conduct in the reverse direction because of the presence of stored charges in the depletion region and the semiconductor layers
- The reverse current flows for a time called reverse recovery time t_{rr}
- The diode regain its blocking capability until reverse recovery current decays to zero
- Is defined as *the time between the instant forward diode current becomes zero and the instant reverse recovery current decays to 25% of its reverse peak value* I_{RM}

Power semiconductor diode - Chara.



Reverse recovery characteristics

Power semiconductor diode - Chara.

- The reverse recovery time is composed of two segments time ta and tb, i.e. $t_{rr}=t_a+t_b$
- Time ta is the time between zero crossing of forward current and peak reverse current I_{RM}
- During t_a, charge stored in depletion layer is removed
- t_b is measured from the instant of reverse peak value I_{RM} to the instant when $0.25I_{RM}$ is reached
- During tb charge from the semiconductor layer is removed
- The shaded area represent the stored charge, or reverse recovery charge Q_R which must be removed during the reverse recovery time t_{rr}

Power semiconductor diode - Chara.

- The ratio t_b/t_a is called the softness factor or S - factor
- Its usual value is unity and this indicate low oscillatory reverse recovery process
- A diode with S-factor unity is called soft-recovery diode
- A diode with S factor <1 is called snappy recovery diode or fast recovery diode
- The peak inverse current can be expressed as

$$I_{RM} = t_a \frac{di}{dt}$$

$$Q_R = \frac{1}{2} I_{RM} t_{rr} \qquad I_{RM} = \frac{2Q_R}{t_{rr}}$$

Power semiconductor diode - Chara.

- If $t_{rr}=t_a$

$$I_{RM} = t_{rr}\frac{di}{dt} \qquad t_{rr}\frac{di}{dt} = \frac{2Q_R}{t_{rr}}$$

$$t_{rr} = \left[\frac{2Q_R}{\left({di}/{dt}\right)}\right]^{1/2}$$

- With $t_a=t_{rr}$, we get

$$I_{RM} = t_{rr}\frac{di}{dt} = \left[\frac{2Q_R}{\left({di}/{dt}\right)}\right]^{1/2} \cdot \frac{di}{dt}$$

$$= \left[2Q_R\left(\frac{di}{dt}\right)\right]^{1/2}$$

Power semiconductor diode- Types

General purpose diode

- High reverse recovery time, order of 25 micro sec
- Current rating from 1A to several thousands of ampere
- Voltage rating – 5V to 5kV
- Application – battery charging, electric traction, electroplating, welding, UPS etc..

Fast-recovery diode

- Low reverse recovery time of about 5 micro sec
- Application– chopper, commutation circuit, SMPS, induction heating etc...
- Current rating from 1A to several thousands of ampere
- Voltage rating – 50V to 3kV

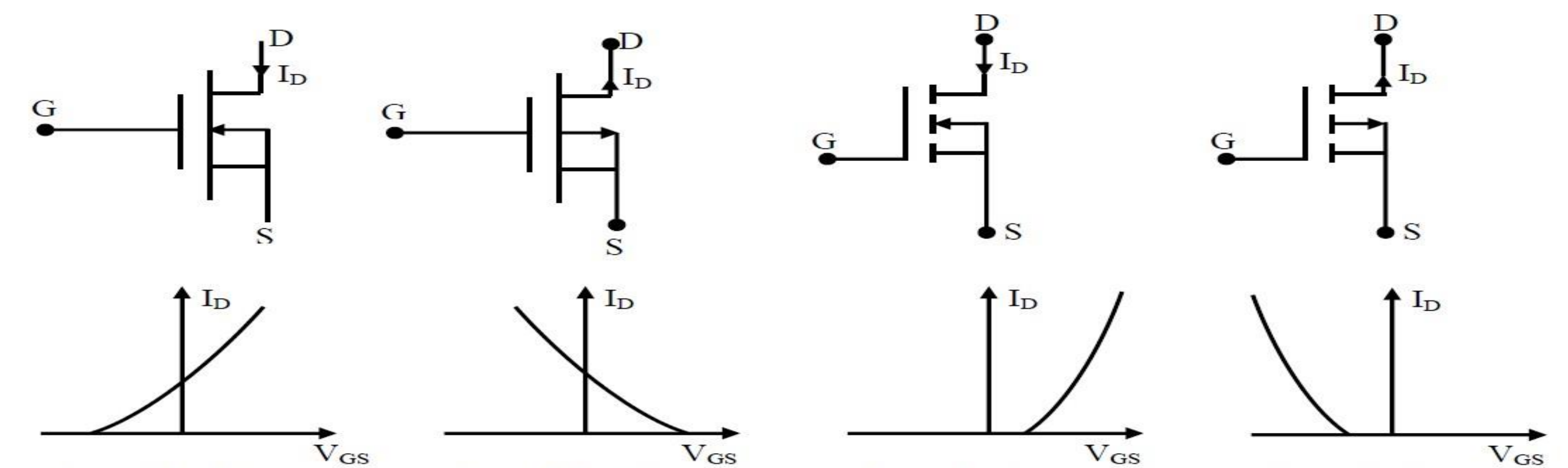
Power semiconductor diode- Types

Schottky diode

- Use metal-to-semiconductor junction for rectification
- The metal is usually aluminum
- Low cut in voltage
- Higher reverse leakage current
- Higher operating frequency
- Reverse Voltage rating – 100V
- Forward current rating – 1A to 300A
- Applications– high frequencyinstrumentation, switching power supplies

Power MOSFET

- Metal Oxide Semiconductor Field Effect Transistor
- Recent device developed by combining the areas of field effect concept and MOS technology
- Three terminal called drain (D), source (S) and gate (G)



n-channel depletion type MOSFET

p-channel depletion type MOSFET

n-channel enhancement type MOSFET

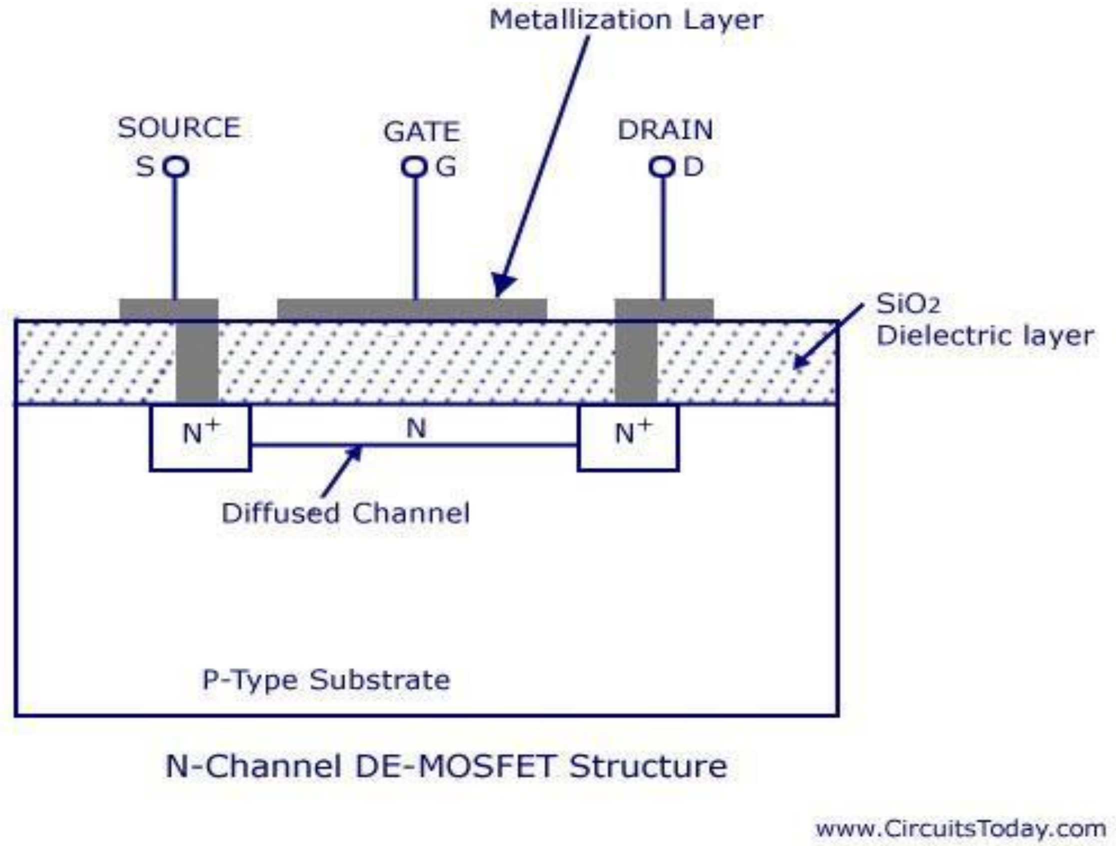
p-channel enhancement type MOSFET

Power MOSFET

- Arrow indicates the direction of electron flow
- MOSFET is a voltage controlled device
- Its operation depends on the flow of majority carriers only, hence it is a uni-polar device
- Power MOSFET are now finding increasing applications in low power high frequency converters
- Power MOSFETs are of two type – n channel enhancement MOSFET and p channel enhancement MOSFET
- n channel enhancement MOSFET is more common because of higher mobility of electrons

Power MOSFET

- Structure of n channel MOSFET of low power rating is shown below



Power MOSFET

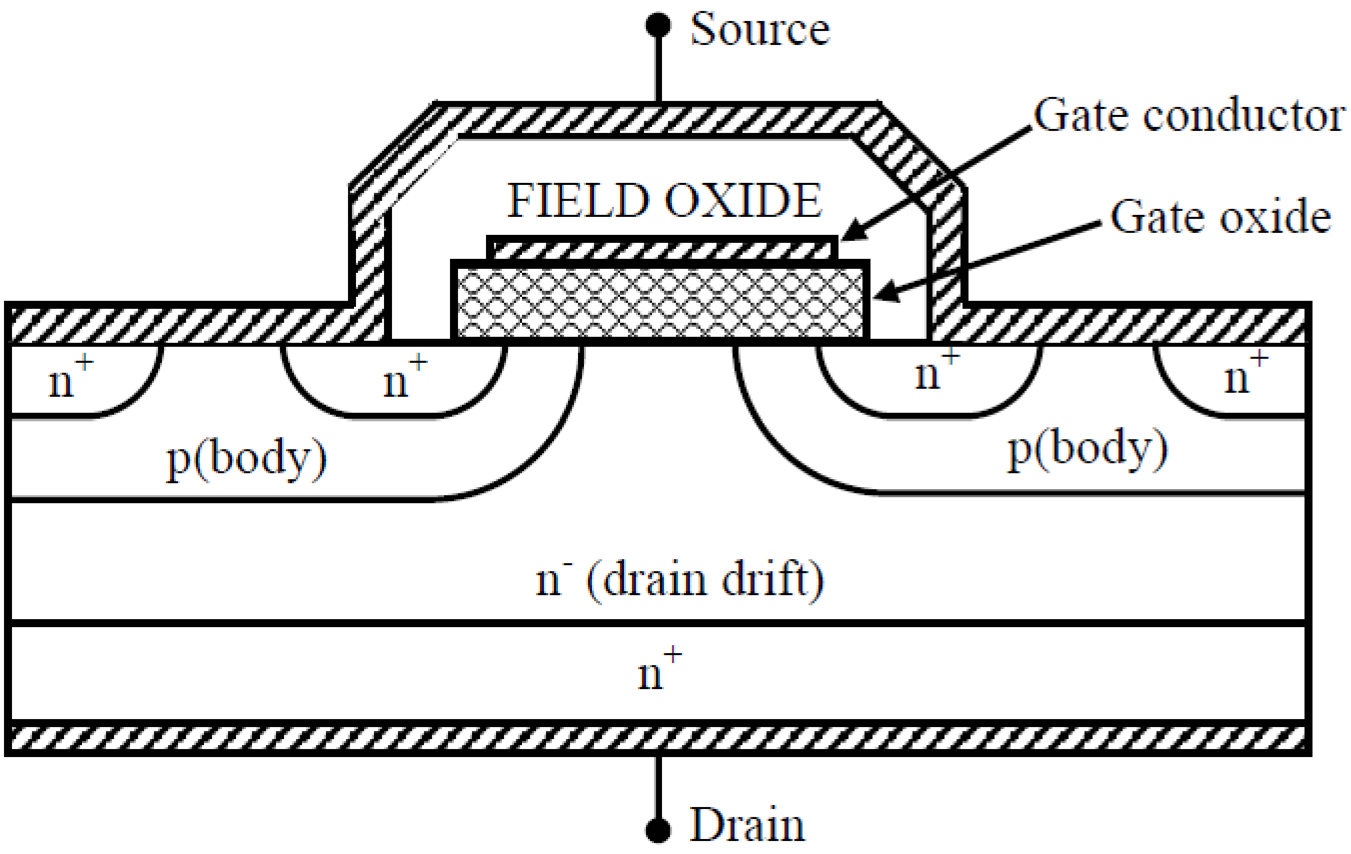
- On p substrate or body two heavily doped n+ region are diffused
- An insulating layer of silicon dioxide is grown on the surface
- This insulating layer is etched in order to embed metallic source and drain terminals
- n+ region makes in contact with drain an source terminals
- When gate circuit is open, junction between n+ region below drain and p substrate is reverse biased by input voltage V_{DD}
- Therefore no current flows from drain to source and load

Power MOSFET

- When gate is made +ve w.r.t source an electric field is established
- Eventually induced –ve charges in the p substrate below SiO2 layer
- Causing p layer below gate to become induced n layer
- These –ve charges called electrons, from n channel between two n+ region and current can flow from drain to source as shown by the arrow
- If V_{GS} is made more +ve, induced n channel become more deep and therefore more current flows from D to S
- This shows that drain current I_D is enhanced by the gradual increase of the gate voltage, hence the name enhancement MOSFET

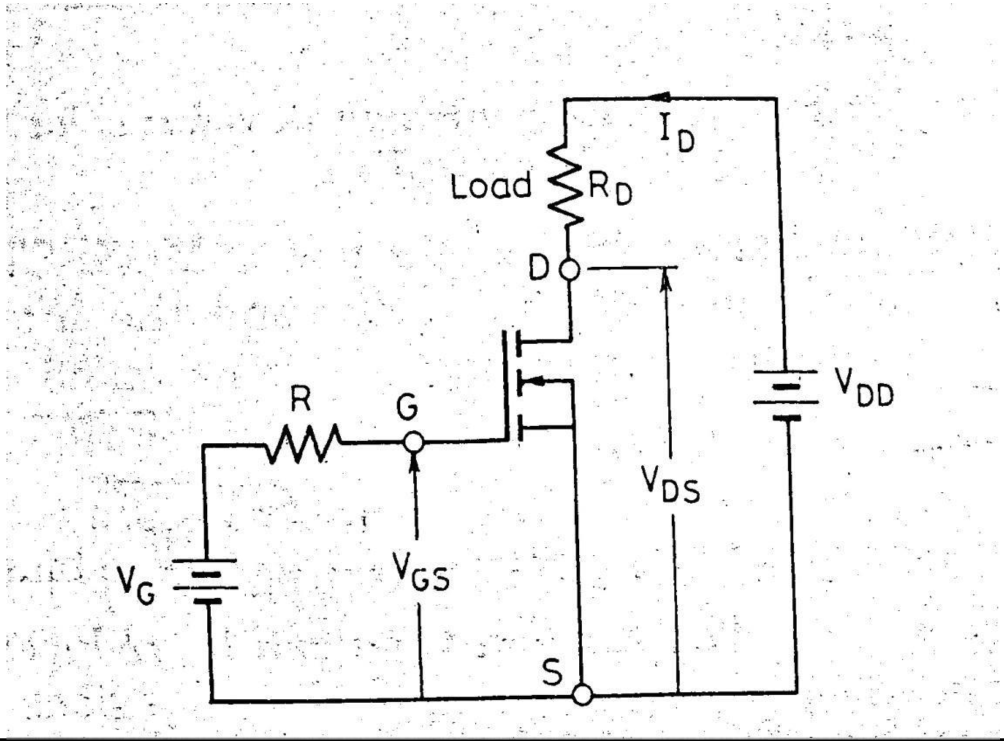
Power MOSFET

Basic structure of a n channel diffused MOS power MOSFET



Power MOSFET – Characteristics

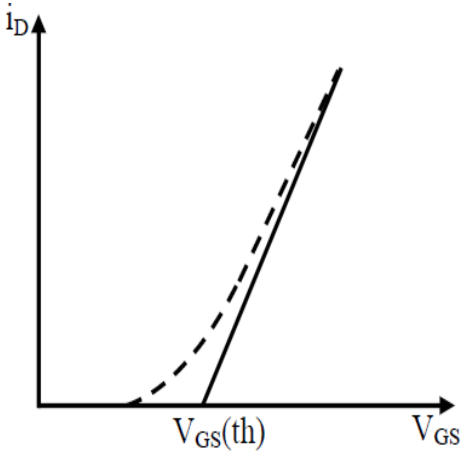
- The basic circuit diagram for n channel PMOSFET is shown below
- The source is taken as common terminal, between input and output of a MOSFET



Power MOSFET – Characteristics

Transfer characteristics

- Variation of drain current I_D as a function of gate source voltage V_{GS}
- Threshold voltage – V_{GST}
- Minimum +ve voltage between gate and source to induce n channel
- For voltage below V_{GST} – device is in off state
- Magnitude of V_{GST} is of the order of 2 to 3V

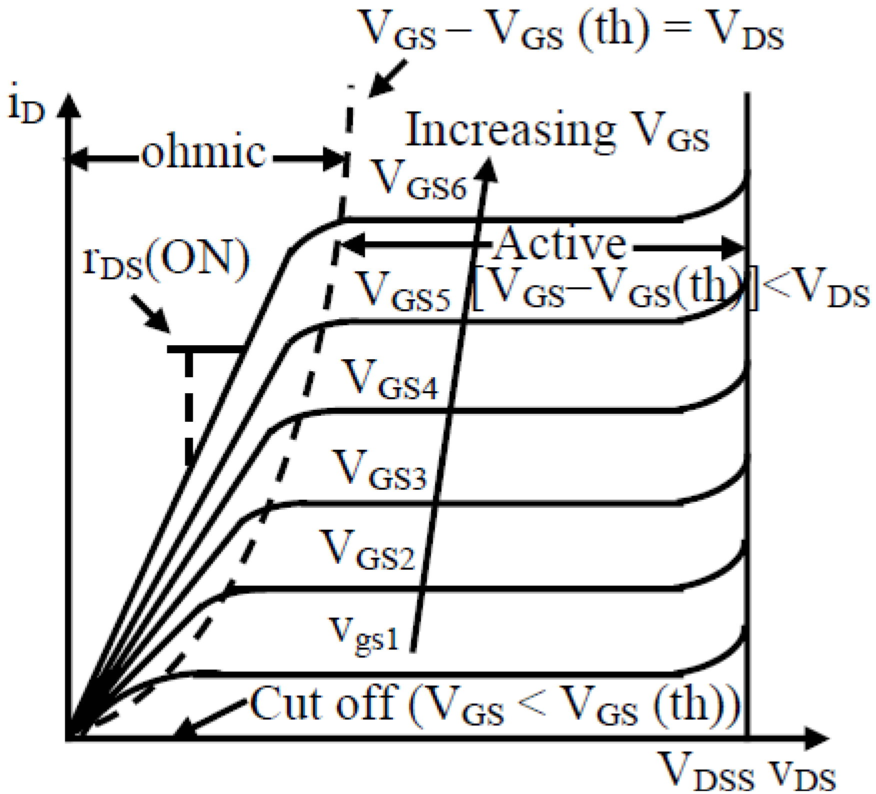


Power MOSFET – Characteristics

Output characteristics

- Variation of drain current I_D as a function of drain source voltage V_{DS} with V_{GS} as a parameter
- For low values of V_{DS}, the graph between I_D - V_{DS} is almost linear
- This indicates a constant value of on resistance $R_{DS} = V_{DS}/I_D$
- For given V_{GS} if V_{DS} is increased output characteristics is relatively flat, indicating drain current constant

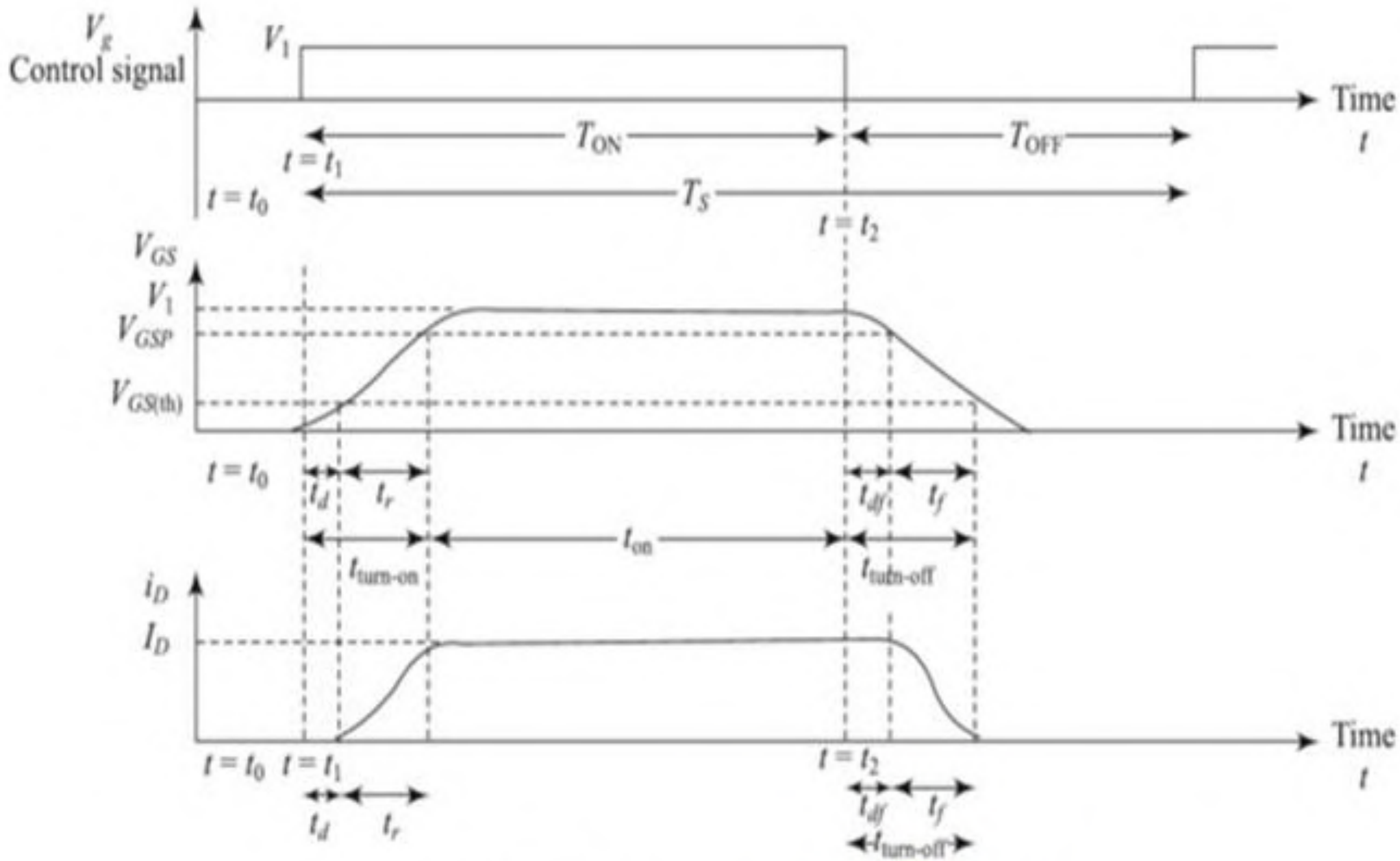
Power MOSFET – Characteristics



Output characteristics

Power MOSFET – Characteristics

Switching characteristics



The switching waveforms of a Power MOSFET

Power MOSFET – Characteristics

Switching characteristics

- At turn on, there is an initial delay t_{dn} during which input capacitances charges to gate threshold voltage VGST
- Here t_{dn} is called – turn on delay time
- There is further delay called tr – rise time
- Gate voltage rises to V_{GSP}
- A voltage sufficient to drive the MOSFET into on state
- During tr, rain current rises from zero to full on current I_D
- Thus total turn on time ton = tdn + tr

Power MOSFET – Characteristics

- As MOSFET is a majority carrier device, turn off process is initiated soon after removal of gate voltage at time t1
- Turn off delay time, tdf, is the time during which input capacitance discharges from overdrive gate voltage V1 to V_{GSP}
- The fall time tf, is the time during which input capacitances discharges form V_{GSP} to threshold voltage
- During tf, drain current falls from I_D to zero
- When $V_{GS} \leq V_{GST}$, PMOSFET turn off is complete

Power MOSFET – Applications

- High frequency switching application
- SMPS and inverter
- Available with 500 V, 140 A ratings

PMOSFET- Gate Drive

- MOSFET, being a voltage controlled device, does not require a continuous gate current to keep it in the ON state.
- However, it is required to charge and discharge the gate-source and the gate-drain capacitors in each switching operation.
- The switching times of a MOSFET essentially depends on the charging and discharging rate of these capacitors.
- Therefore, if fast charging and discharging of a MOSFET is desired at fast switching frequency the gate drive power requirement may become significant.

PMOSFET- Gate Drive

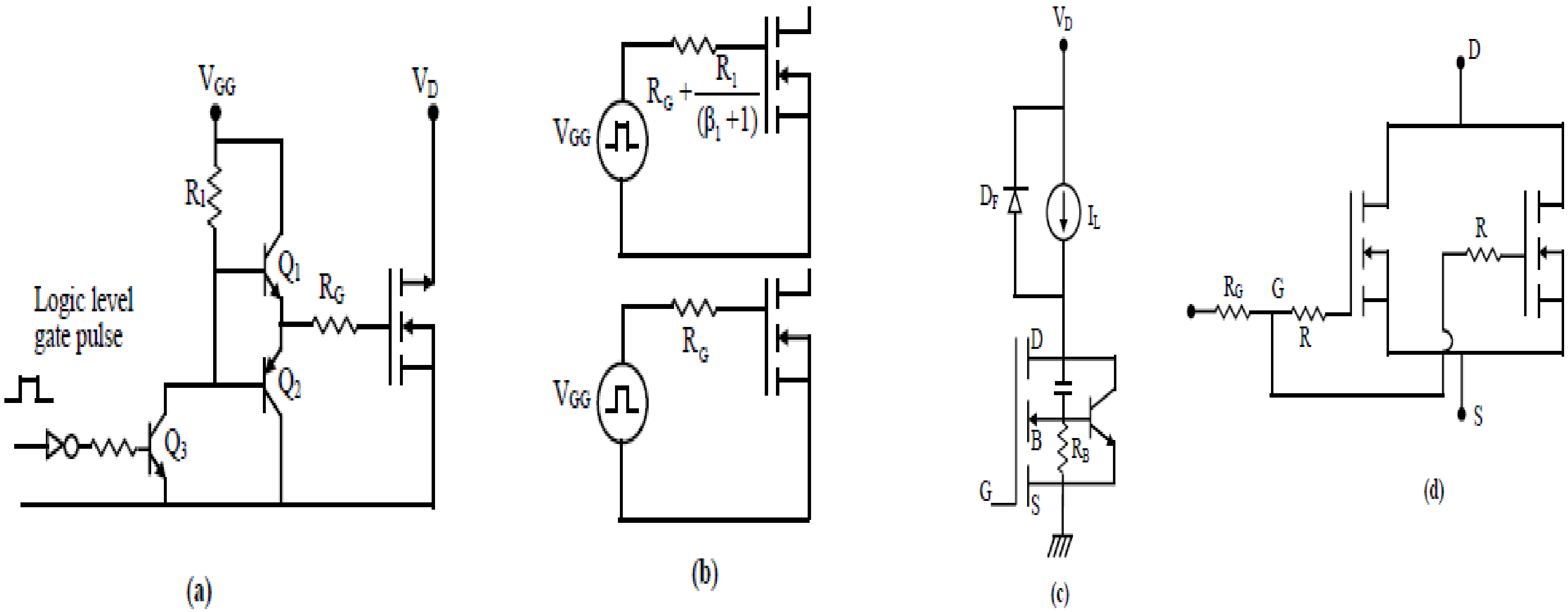


Fig. 6.10: MOSFET gate drive circuit.
(a) Gate drive circuit; (b) Equivalent circuit during turn on and off;
(b) Effect of parasitic BJT; (d) Parallel connection of MOSFET's.

PMOSFET- Gate Drive

- To turn the MOSFET on the logic level input to the inverting buffer is set to high state so that transistor Q_3 turns off and Q_1 turns on.
- The top circuit of Fig (b) shows the equivalent circuit during turn on.
- To turn off the MOSFET the logic level input is set to low state. Q_3 and Q_2 turns on whole Q_1 turns off.
- The corresponding equivalent circuit is given by the bottom circuit of Fig (b)
- The switching time of the MOSFET can be adjusted by choosing a proper value of R_G.
- Reducing R_G will incase the switching speed of the MOSFET.

PMOSFET- Gate Drive

- However, caution should be exercised while increasing the switching speed of the MOSFET in order not to turn on the parasitic BJT in the MOSFET structure inadvertently.
- Since MOSFET on state resistance has positive temperature coefficient they can be paralleled without taking any special precaution for equal current sharing.
- To parallel two MOSFETs the drain and source terminals are connected together as shown in Fig(d).
- However, small resistances (R) are connected to individual gates before joining them together.
- This is because the gate inputs are highly capacitive with almost no losses. Some stray inductance of wiring may however be present.
- This stray inductance and the MOSFET capacitance can give rise to unwanted high frequency oscillation of the gate voltage that can result in puncture of the gate qxide layer due to voltage increase during oscillations.
- This is avoided by the damping resistance R.

IGBT

- Developed by combining the best qualities of both BJT and MOSFET
- Thus an IGBT posses high input impedance like MOSFET and has low on state power loss as in BJT
- Free from secondary breakdown problem
- Also known as

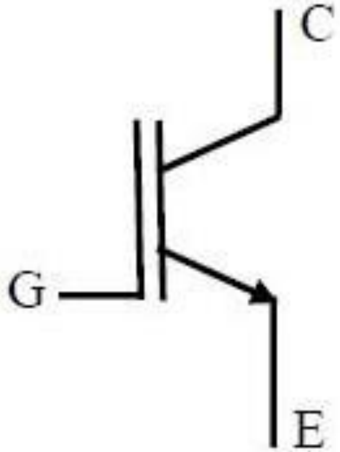
  Metal Oxide Insulated Gate Transistor (MOSIGT)

  Conductively Modulated Field Effect Transistor (COMFET)

  Gain Modulated FET (GEMFET)

  Insulted Gate Transistor (IGT)

IGBT



(a)

(b)

Circuit symbol of an IGBT.
(a) Circuit symbol.
(b) Photograph.

IGBT

Basic structure of an IGBT

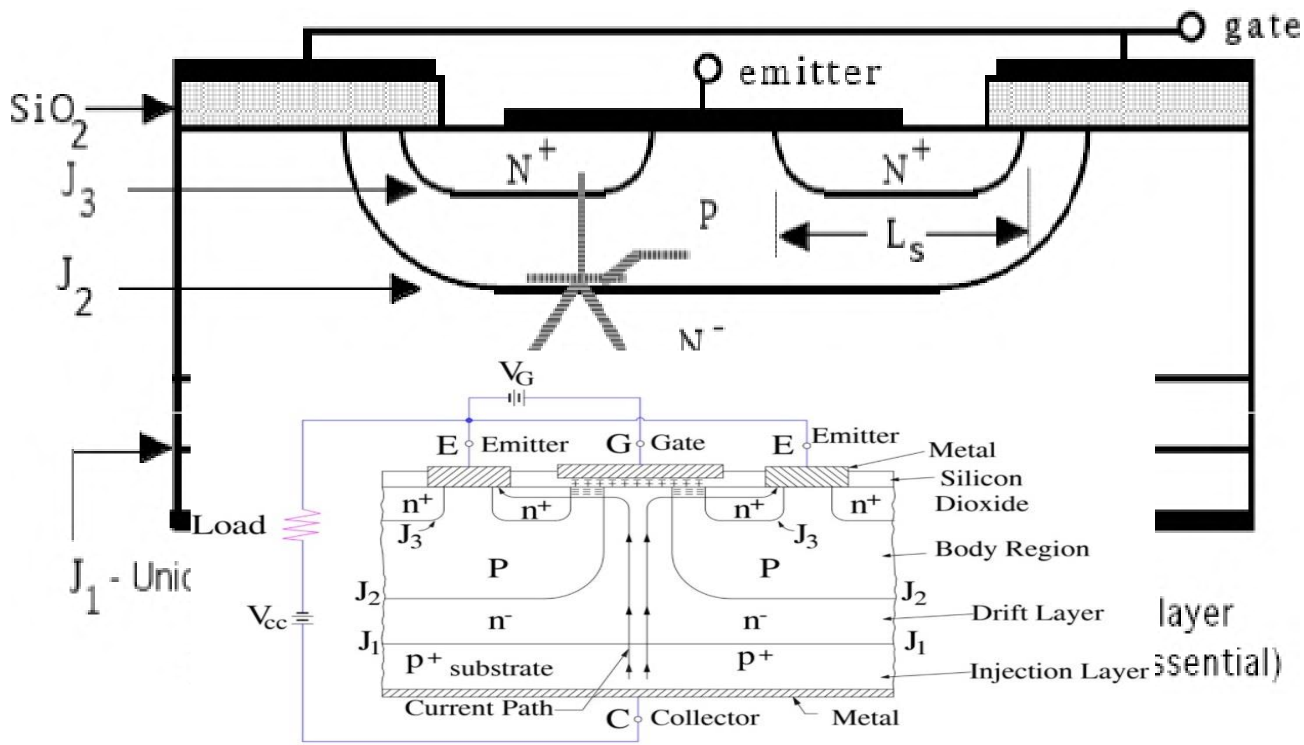


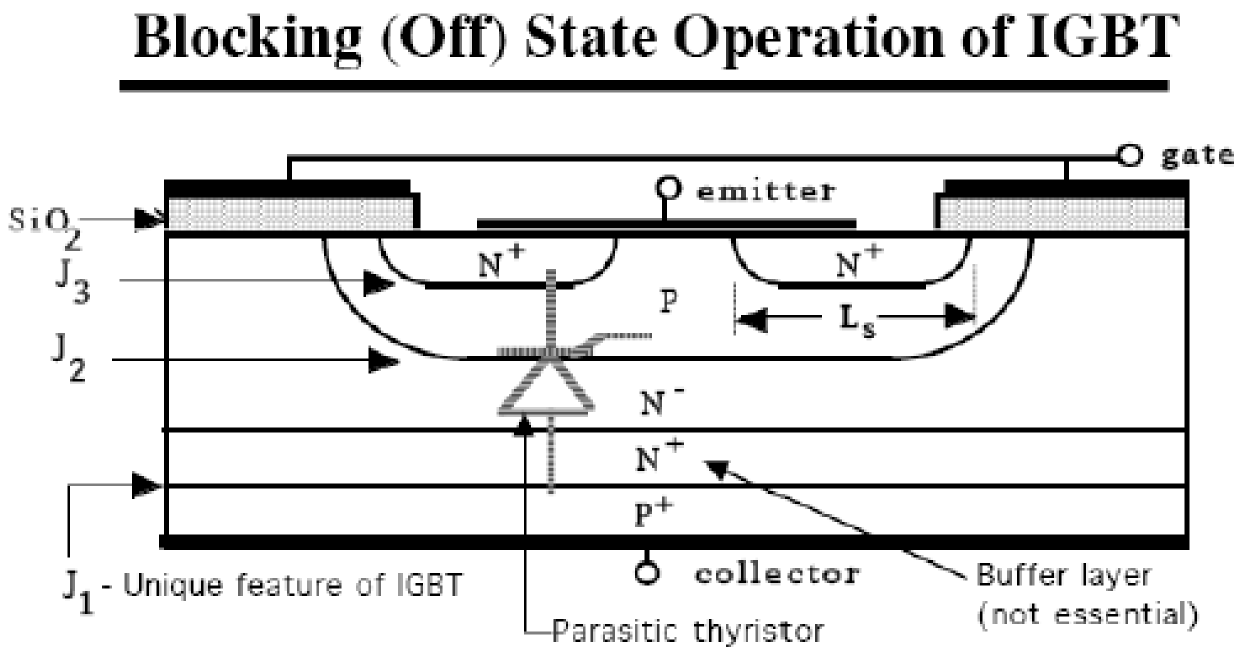
Fig-1

IGBT

- Body region and emitter is shorted to minimize possible turn on of the thyristor.
- n+ buffer layer is between P+ and n- drift layer, is not essential for the operation of the IGBT.
- (IGBT with buffer layer is called punch- through type, PT-IGBT‟s and without buffer layer is called non-punch through type, NPT- IGBT‟s)
- Buffer layer improves the operation of IGBT.

IGBT - Device operation

Blocking state operation



- Blocking state operation - $V_{GE} < V_{GE(th)}$

IGBT - Device operation

- Applied Collector emitter voltage is dropped across junction J2 and only very small leakage current flows.
- Depletion region of the J2 junction extends principally into the n- drift region (since P type body region is more doped than n- drift region)
- Thickness of drift region is large enough to accommodate depletion layer so that depletion layer boundary does not touch P+ layer. So it can block reverse voltage (magnitude same as forward voltage)
- This type of IGBT is known as symmetrical IGBT or non-punch through IGBT.

IGBT - Device operation

- This reverse voltage blocking capability is useful in some ac circuit applications.
- If thickness of drift region is reduced , depletion layer may touch P+ .To avoid that we keep a buffer layer, n+ layer.
- This type of structureis called anti symmetricor punch through IGBT .
- Shorter drift region means lower on-state losses.
- Presence of buffer layer reverse voltage capability quite low.

IGBT - Device operation

On state operation

- Gate – emitter voltage increases to more than threshold value , an inversion layer is formed beneath the gate of IGBT.
- This inversion layer shorts the n- drift region to the n+ source region exactly as in the MOSFET.
- An electron current flows through this inversion layer which in turn causes substantial hole injection from the P+ drain contact layer in to n- drift region as shown in figure.
- The injected holes move across the drift region by both drift and diffusion, taking a variety of path, and reach the p type body region that surrounds the n+ source region.

IGBT - Device operation

- As soon as the holes are in the p type body region, their space charge attracts electrons from the emitter metallization that contacts the body region, and the excess holes are quickly recombined.

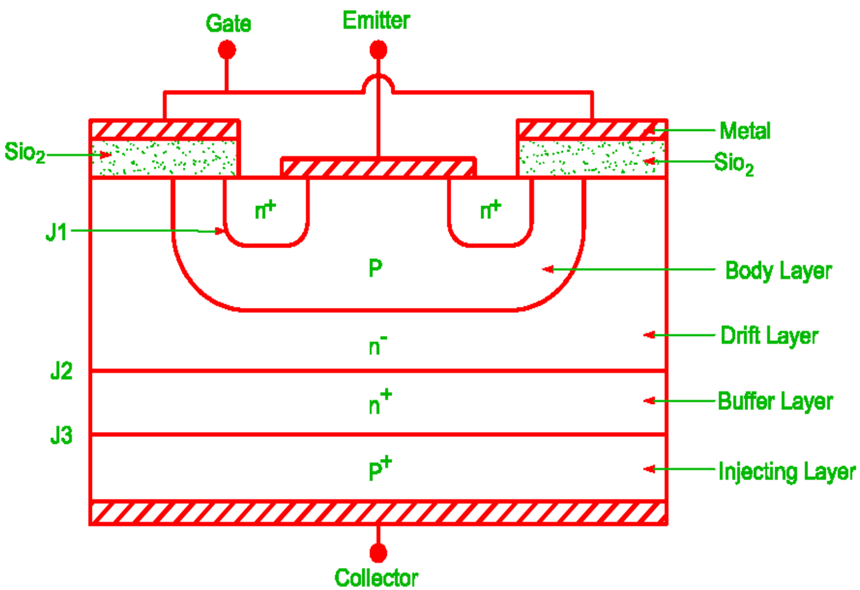
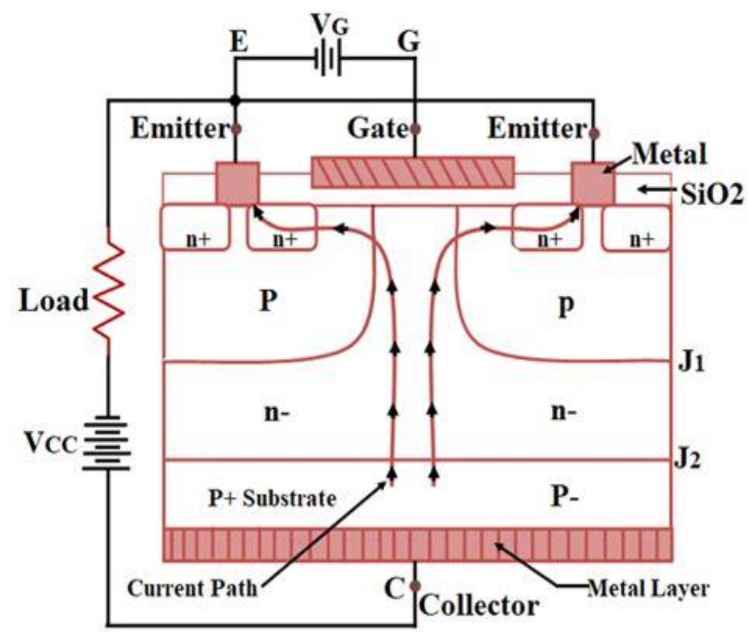


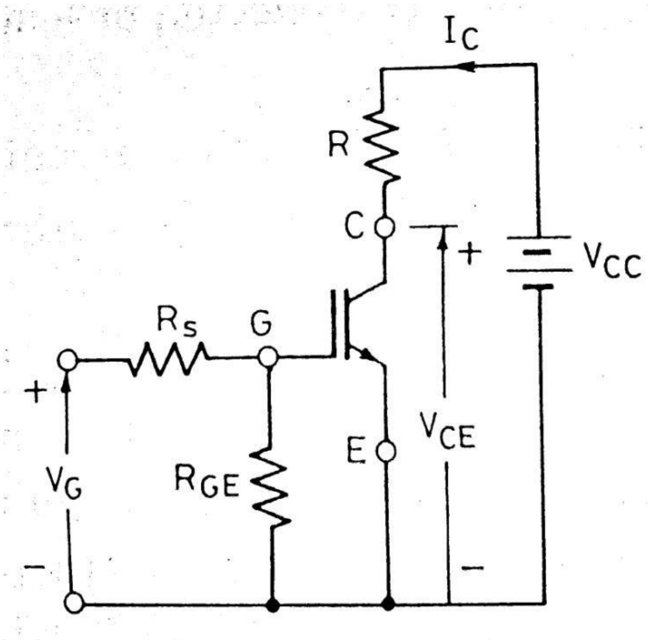
FIG A : STRUCTURE OF AN IGBT

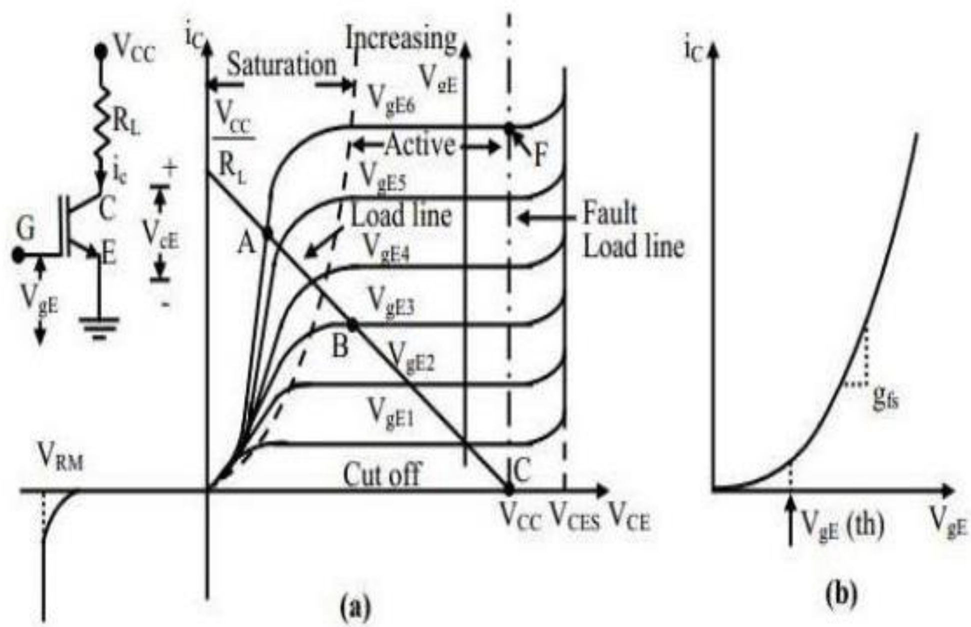


IGBT – Characteristics

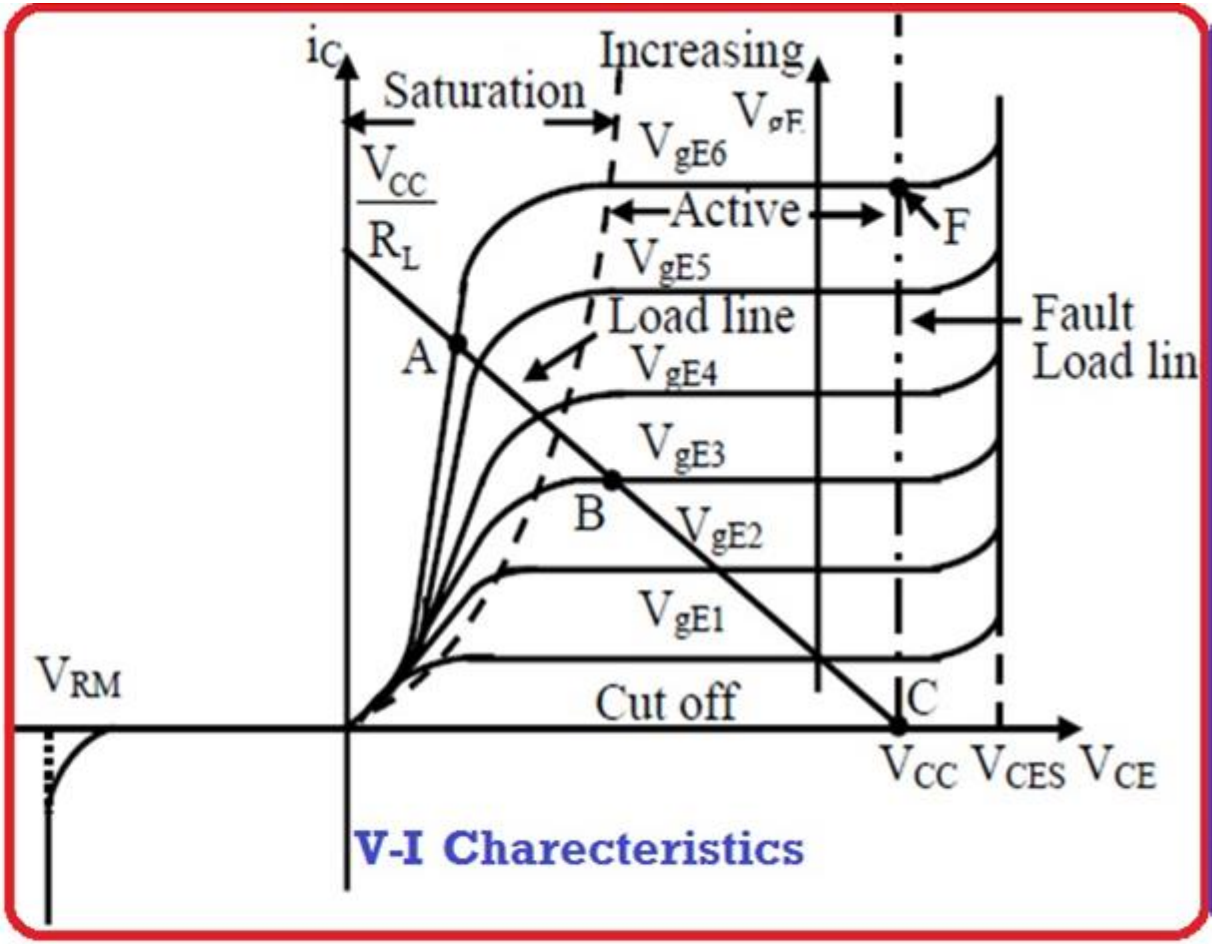
V-I characteristics

- Output characteristics is the plot of I_c versus V_{CE}
- Transfer characteristics – plot of I_c versus V_{GE}



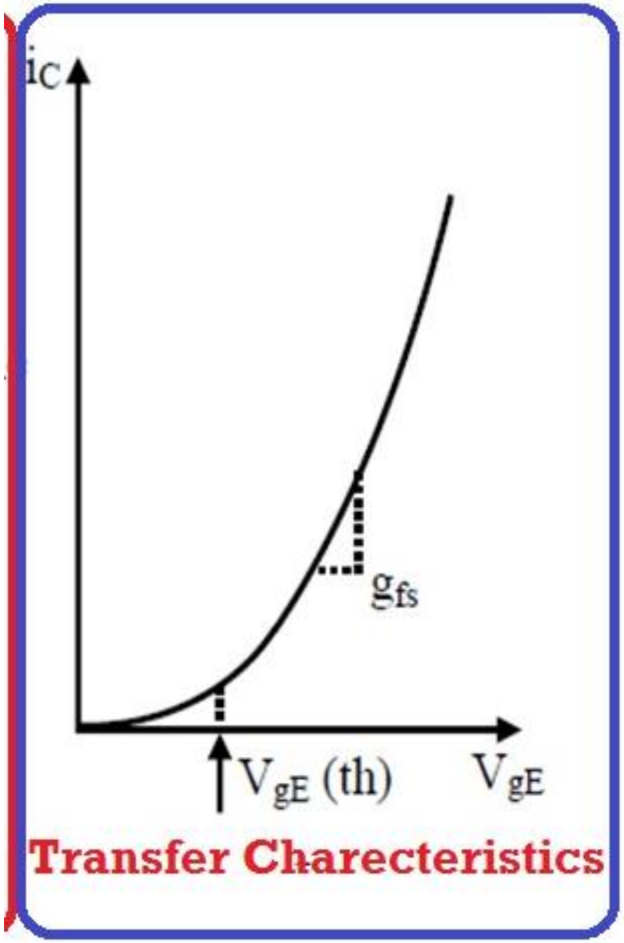


IGBT – Characteristics



V-I Charecteristics

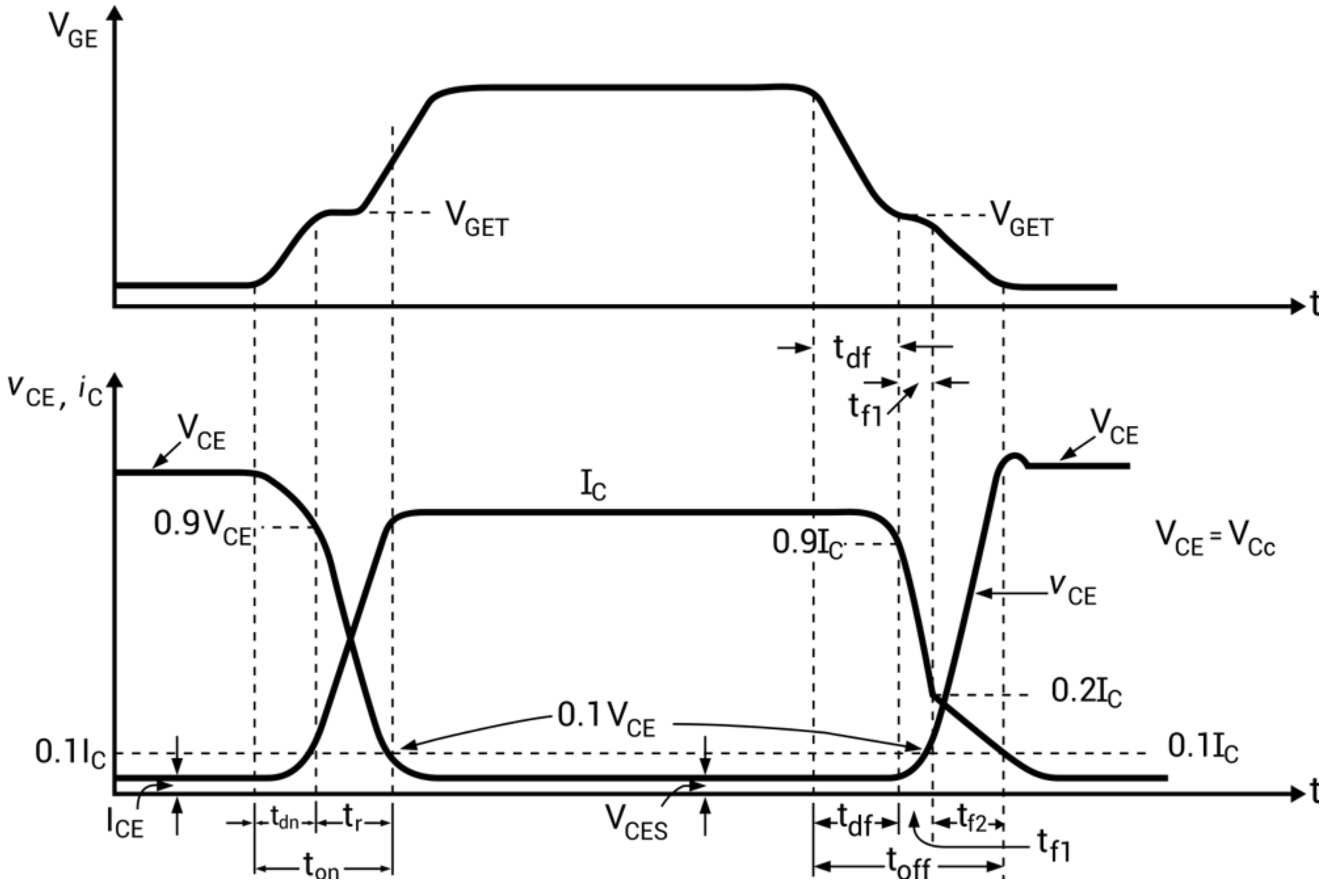
IGBT – Characteristics



IGBT – Characteristics

Switching characteristics

Turn on and turn off characteristics are shown



IGBT – Characteristics

Turn on characteristics

- Turn on time is composed of two time called, delay time t_{dn} and rise time t_r
- Delay time – time for the collector emitter voltage to fall from V_{CE} to 0.9 V_{CE}
- Also defined as the time for collector current to rise from its initial leakage current I_{CE} to 0.1 I_C
- Rise time – time during which collector emitter voltage falls from 0.9 V_{CE} to 0.1 V_{CE}
- It is also defined as the time during which collector current rises from $0.1I_c$ to its final value I_c

IGBT – Characteristics

Turn off characteristics

- It consist of three intervals
- Delay time t_{df}, initial fall time t_{f1}, final fall time t_{f2}
- Delay time – time during which gate voltage fall from V_{GE} to threshold voltage V_{GET}, the collector current from Ic to $0.9I_c$
- First fall time – time during which collector current falls from 90 to 20% of its initial value Ic or collector emitter voltage rises from V_{CES} to 0.1 V_{CE}
- Final fall time – time during which collector current falls from 20 to 10% of Ic or collector emitter voltage rises from 0.1 V_{CE} to V_{CE}

Comparison of IGBT with MOSFET

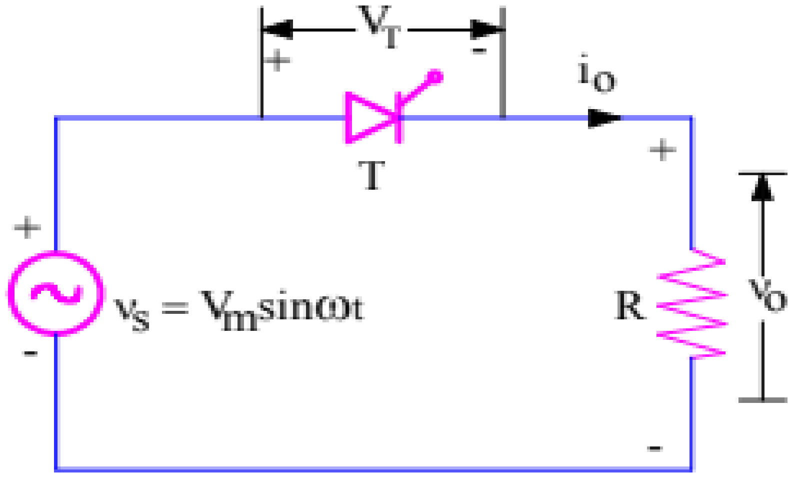
IGBT	MOSFET
Three terminal called, gate, emitter and collector	Three terminal called, gate, source and drain
High input impedance	High input impedance
Voltage controlled device	Voltage controlled device
Can designed for higher voltage rating than PMOSFET	On state voltage drop and losses rises rapidly than IGBT with rise in temperature

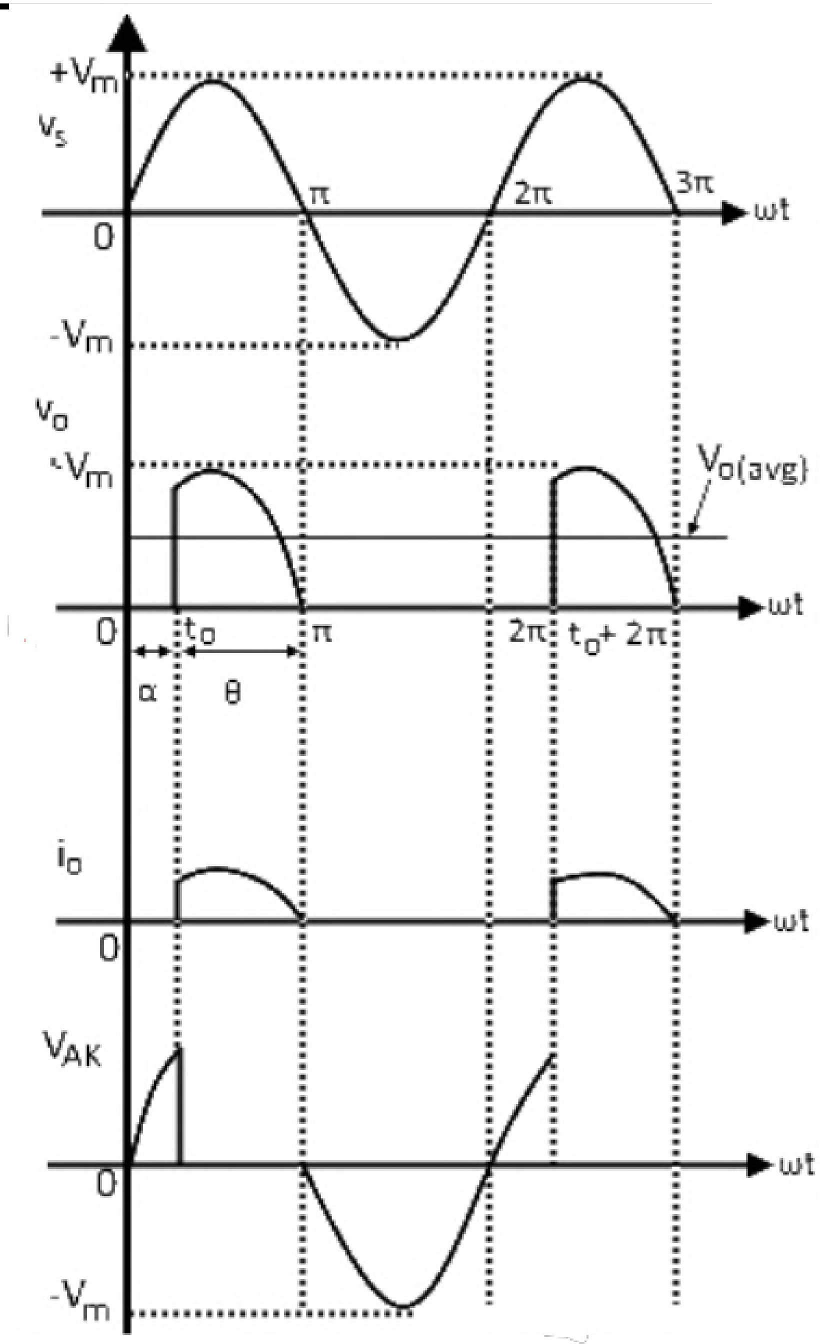
Module 2 - 9 hrs

Controlled Rectifiers (Single Phase) – Half-wave controlled rectifier with R load– Fully controlled and half controlled bridge rectifier with R, RL and RLE loads (continuous & discontinuous conduction) – Output voltage equation- related simple problems(5 hrs)

Controlled Rectifiers (3-Phase) - 3-phase half-wave controlled rectifier with R load – Fully controlled & half-controlled bridge converter with RLE load (continuous conduction, ripple free) – Output voltage equation-Waveforms for various triggering angles (detailed mathematical analysis not required) (4 hrs)

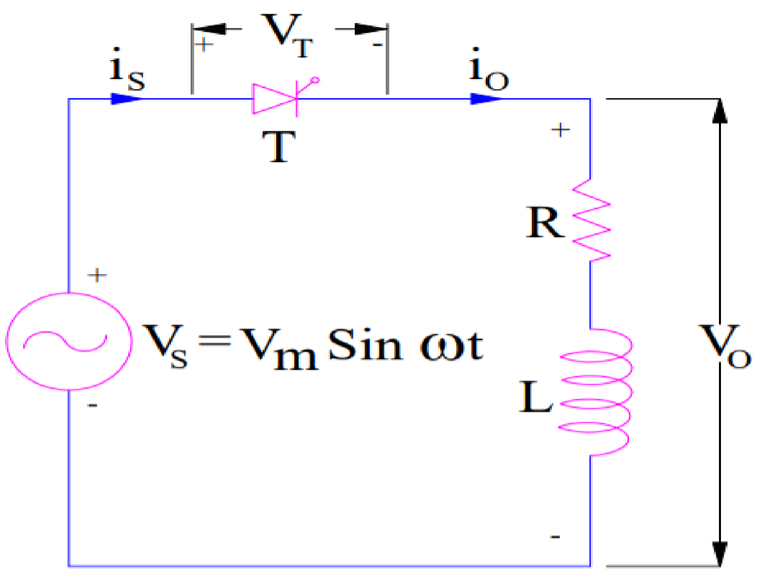
• ***SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER WITH R LOAD***

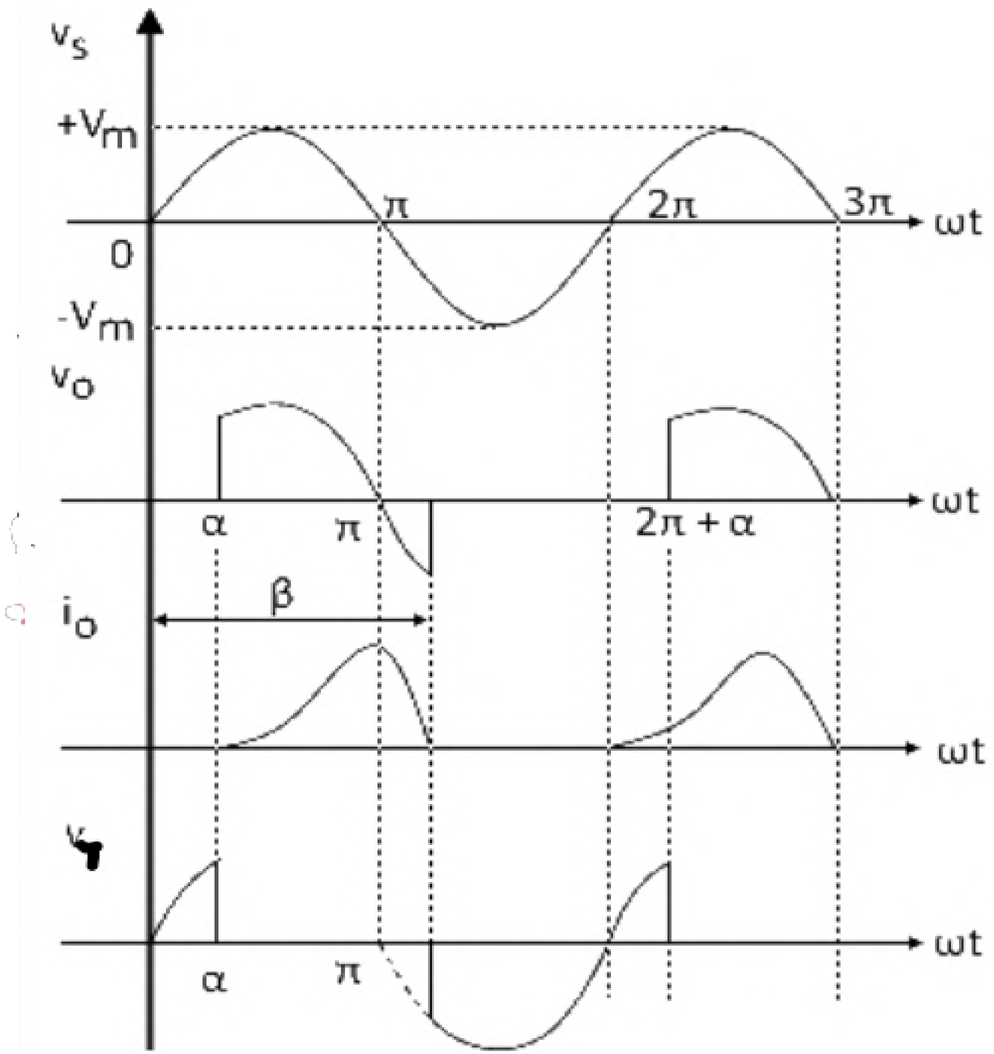




- T1 Forward blocking State- ON at α
- At π, SCR current become 0, natural commutation

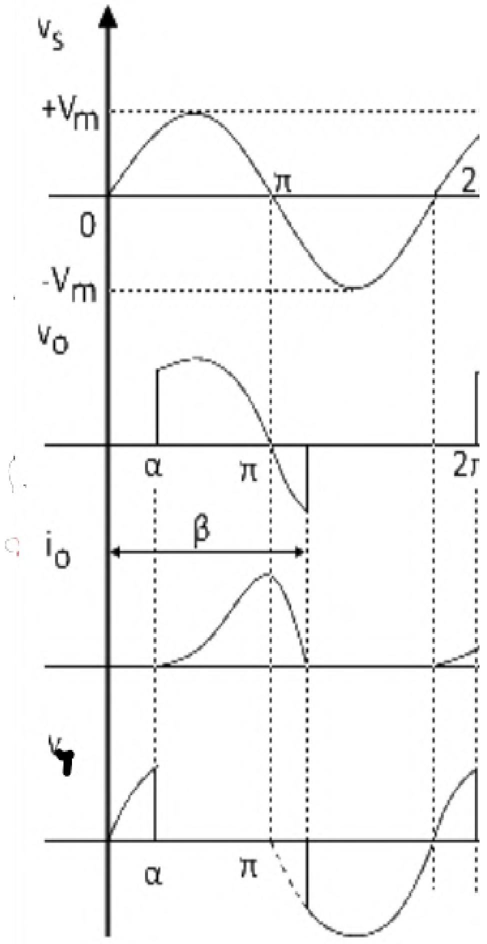
SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER WITH RL LOAD

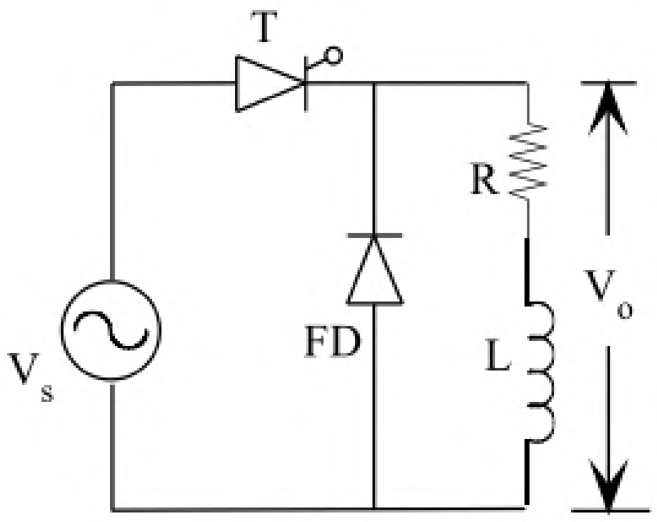


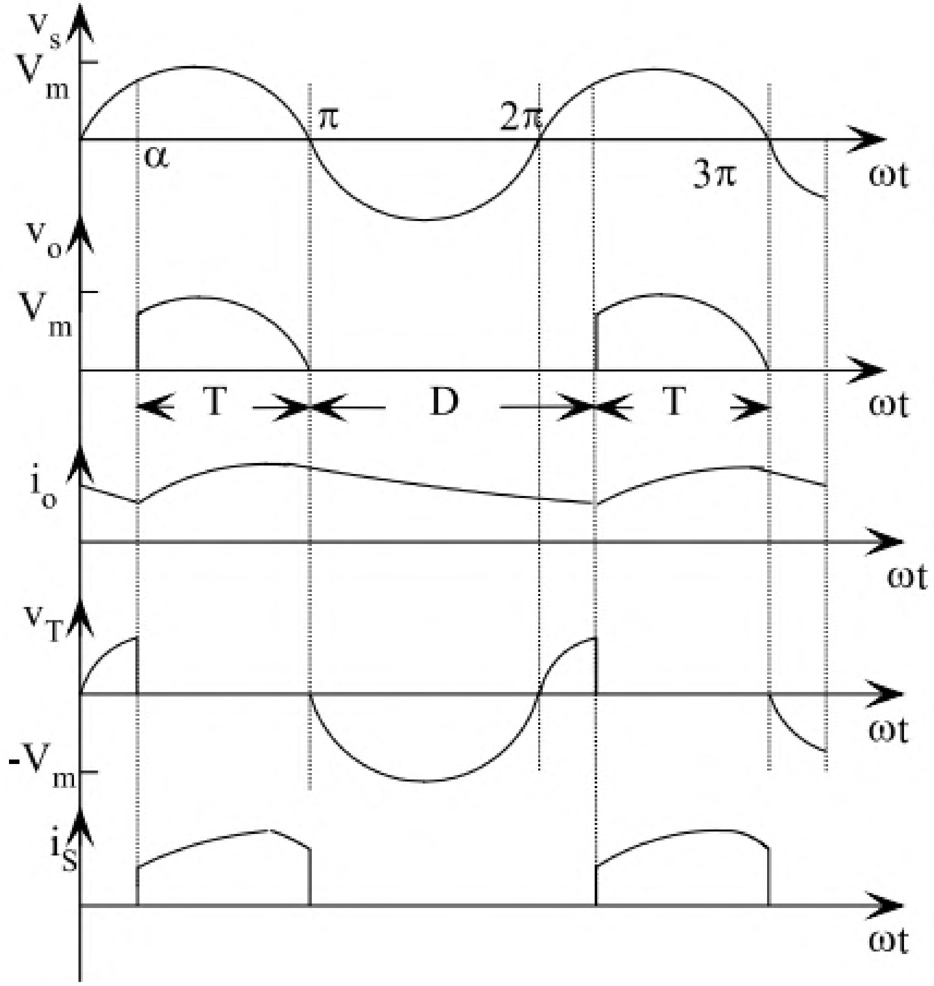


- L filter
- On at α
- π, iL doesnot fall to 0, continues to flow until β.
- + cycle- energy stored in L
- - cycle – Energy returned to source partly & dissipated to R

SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER WITH RL LOAD & FREEWHEELING DIODE





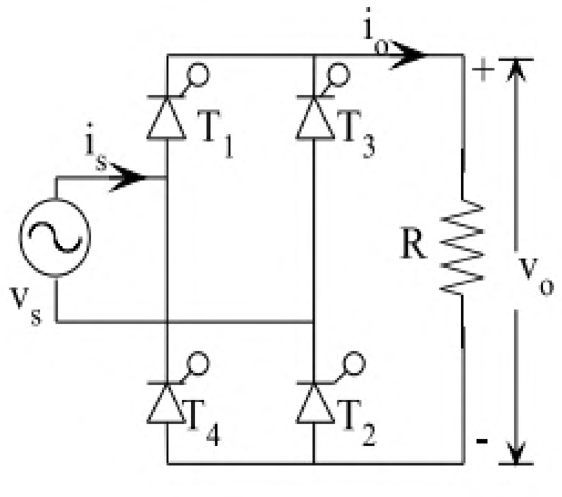


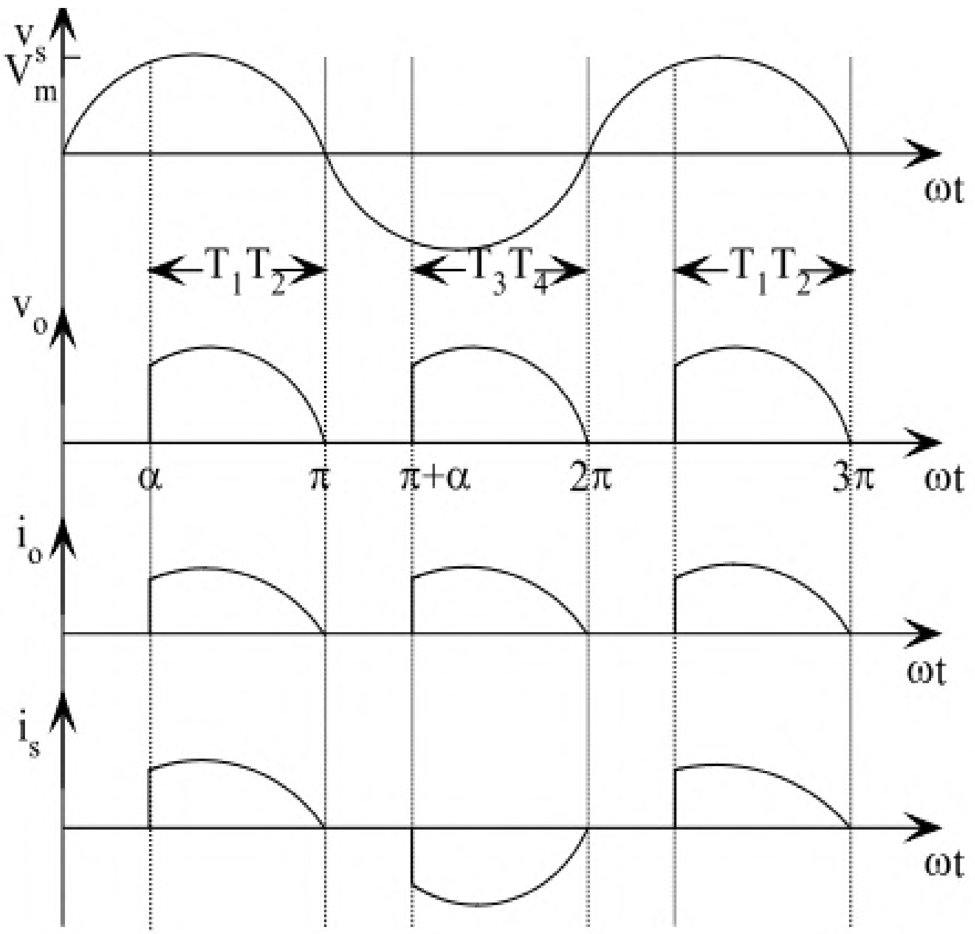
- On at α
- + cycle- energy stored in L
- - cycle – free wheeling diode is forward biased, SCR commutated at π
- Load current free wheels through diode
- Ripple current is reduced
- Load voltage & current are positive

1-PHASE FULLY CONTROLLED BRIDGE RECTIFIER (FULL CONVERTER)

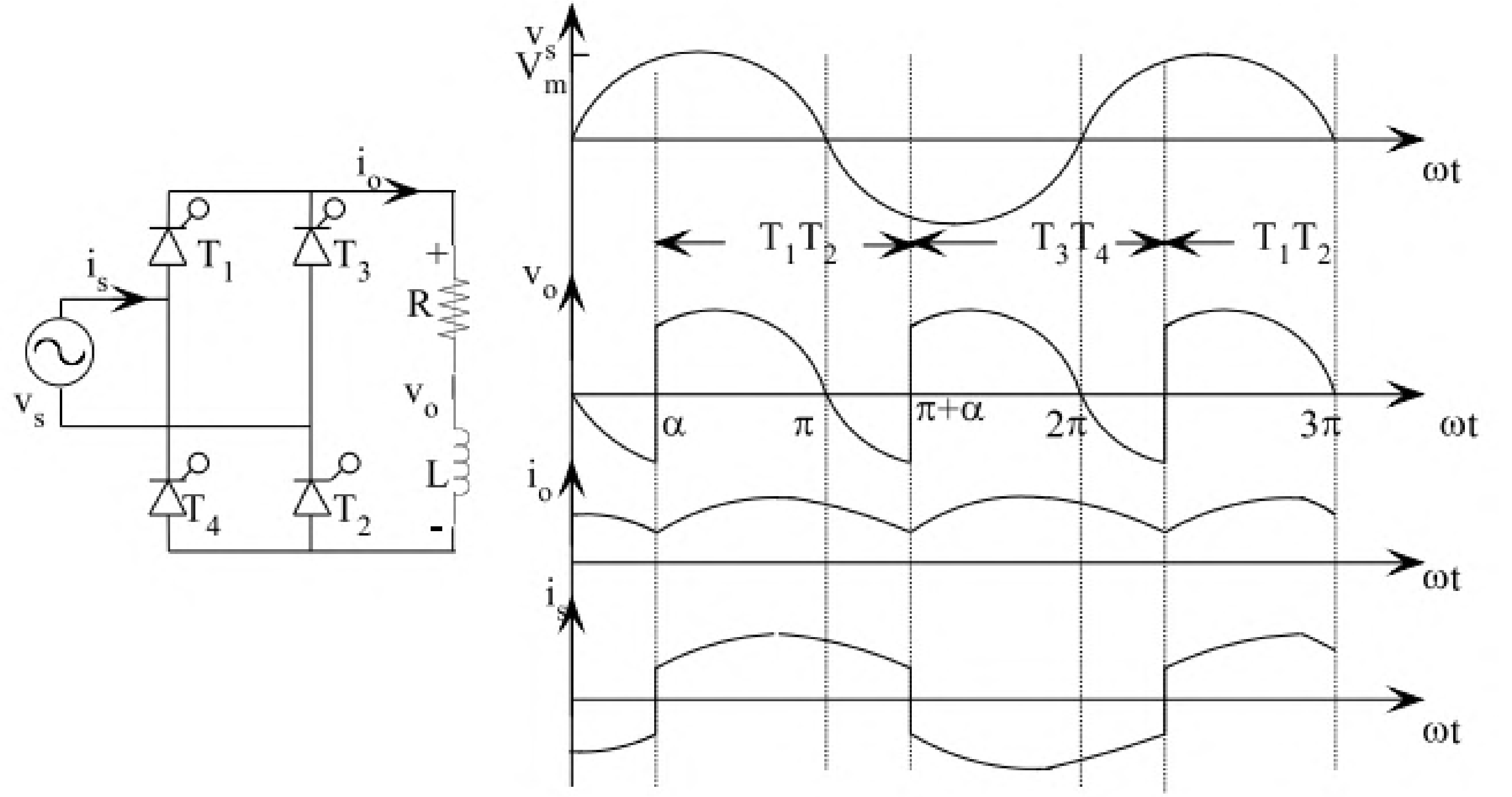
SINGLE PHASE FULLY CONTROLLED RECTIFIER WITH R-LOAD

(Discontinuous Conduction mode)

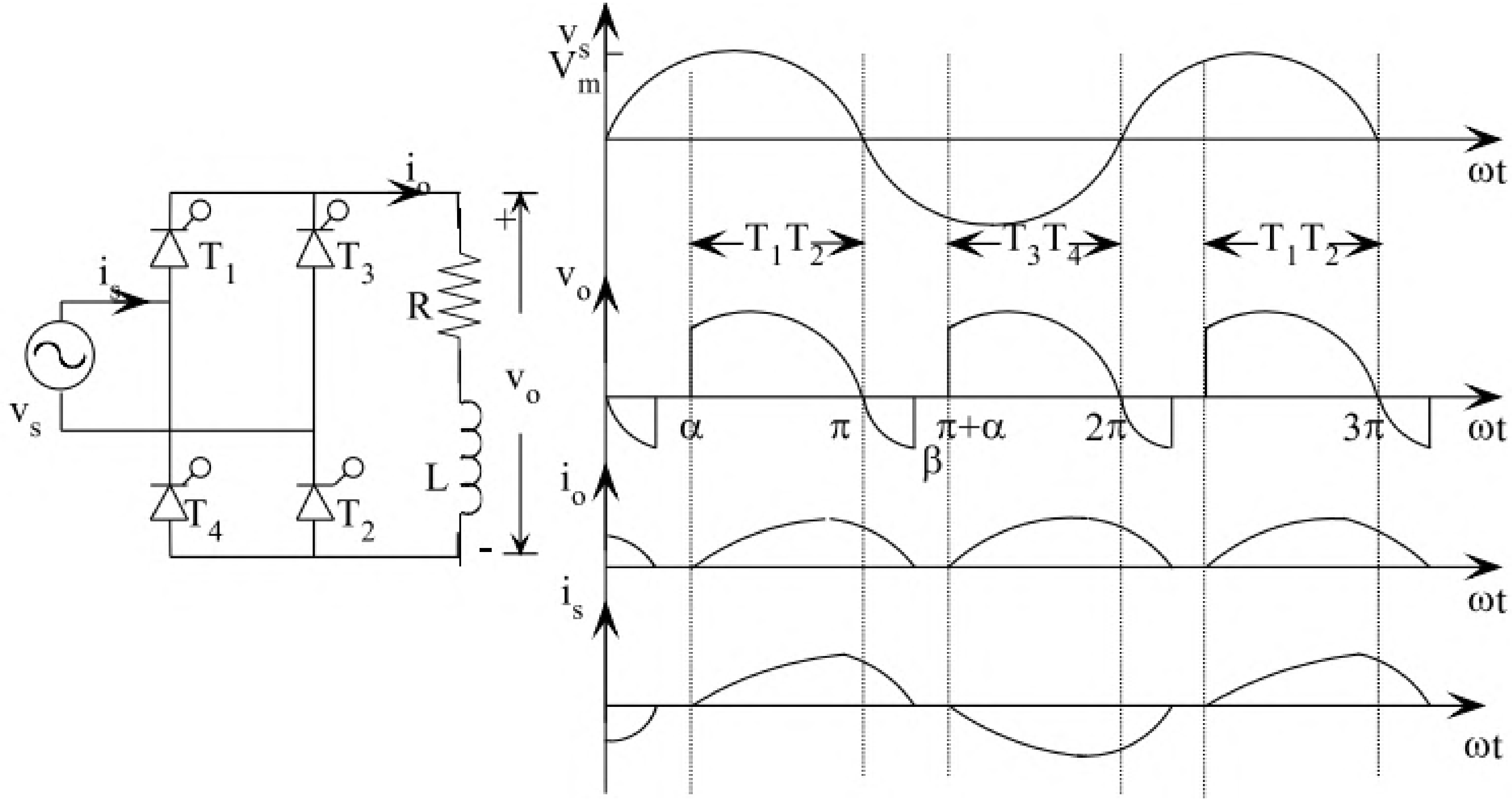




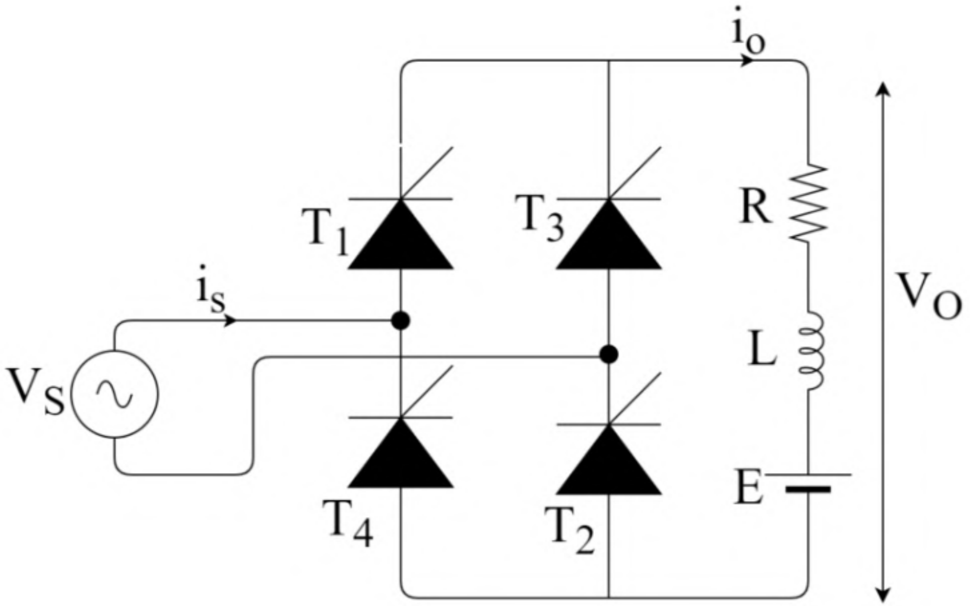
FULL CONVERTER WITH RL-LOAD (Continuous conduction) (Load current is continuous)

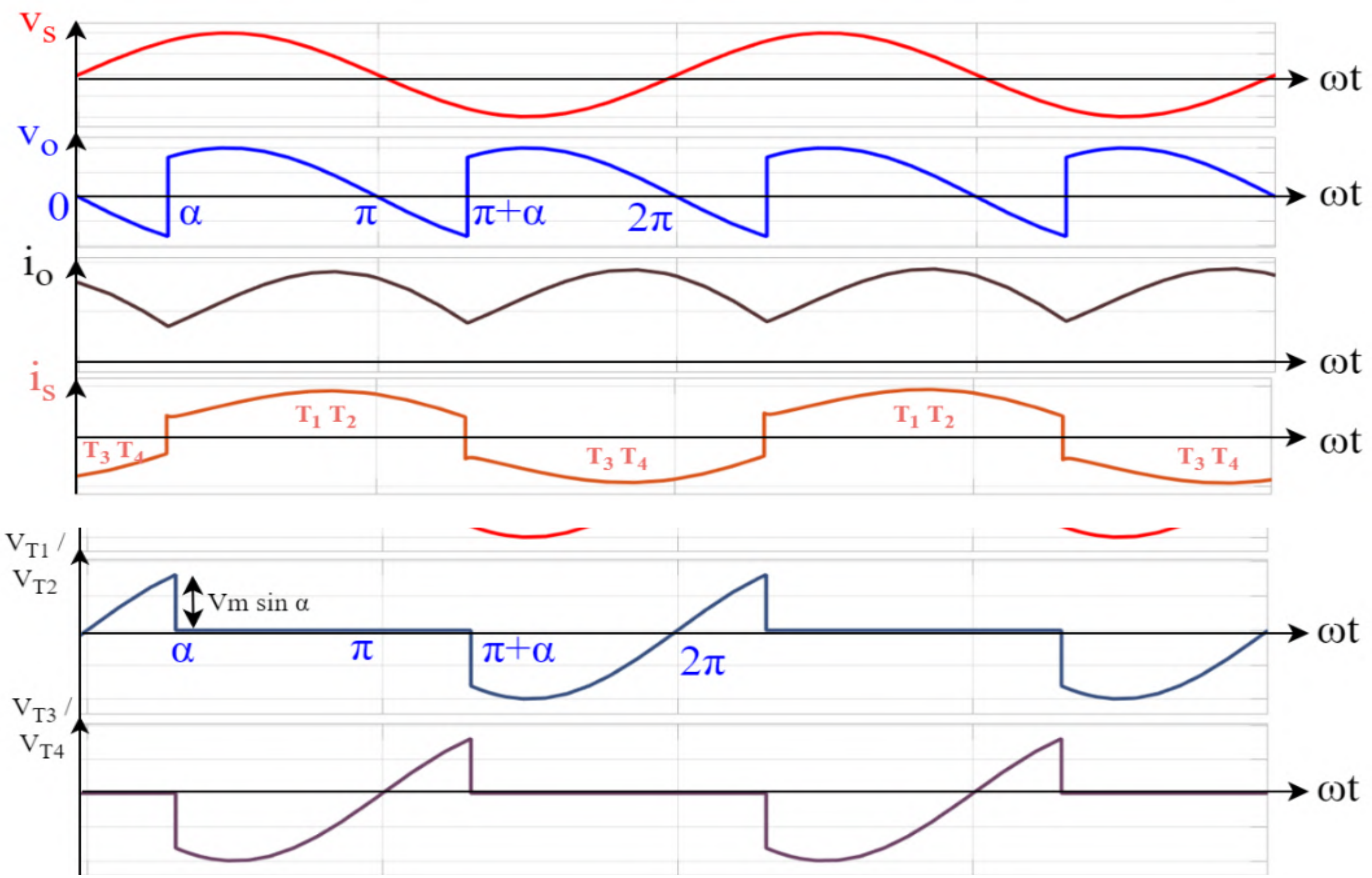


SINGLE PHASE FULL CONVERTER WITH RL-LOAD
(Discontinuous conduction)

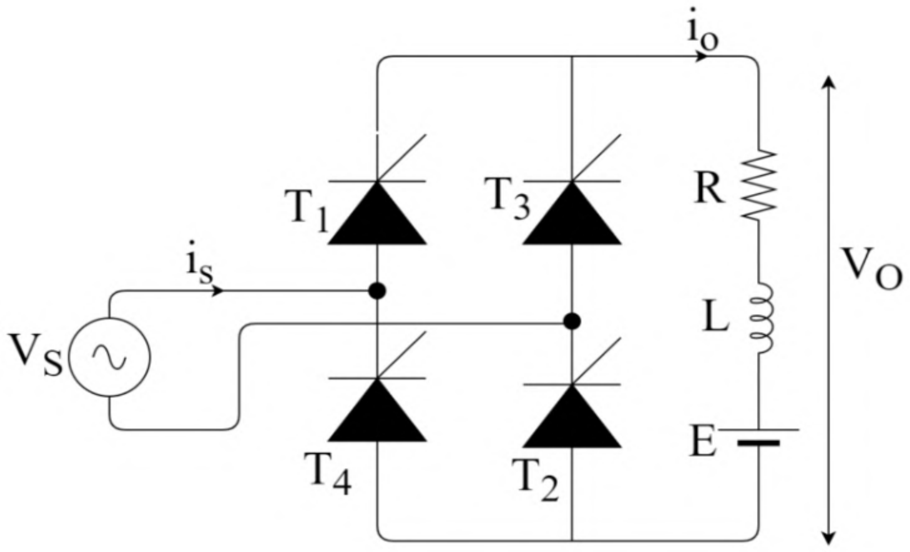


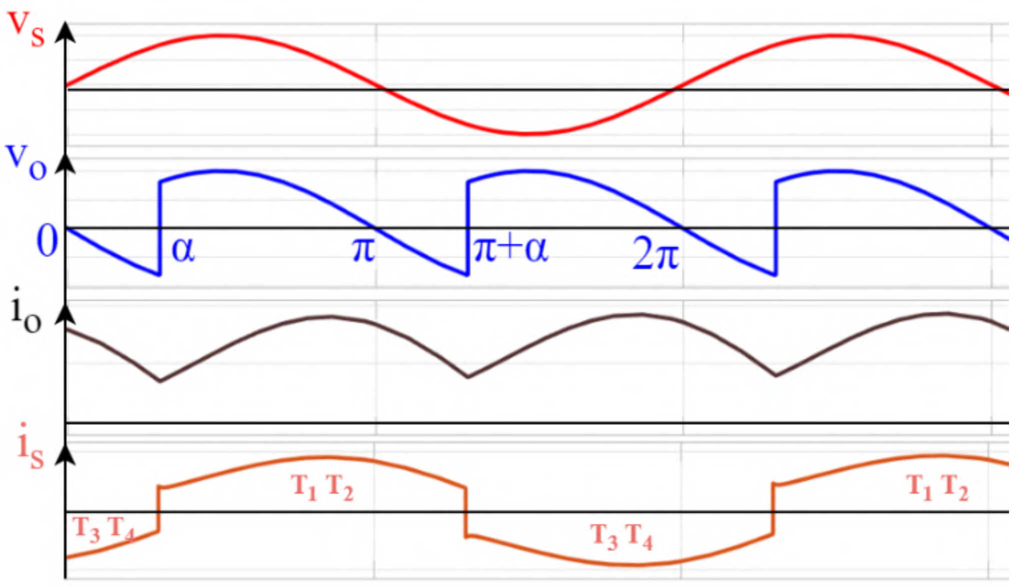
FULL CONVERTER WITH RLE-LOAD (Continuous conduction)

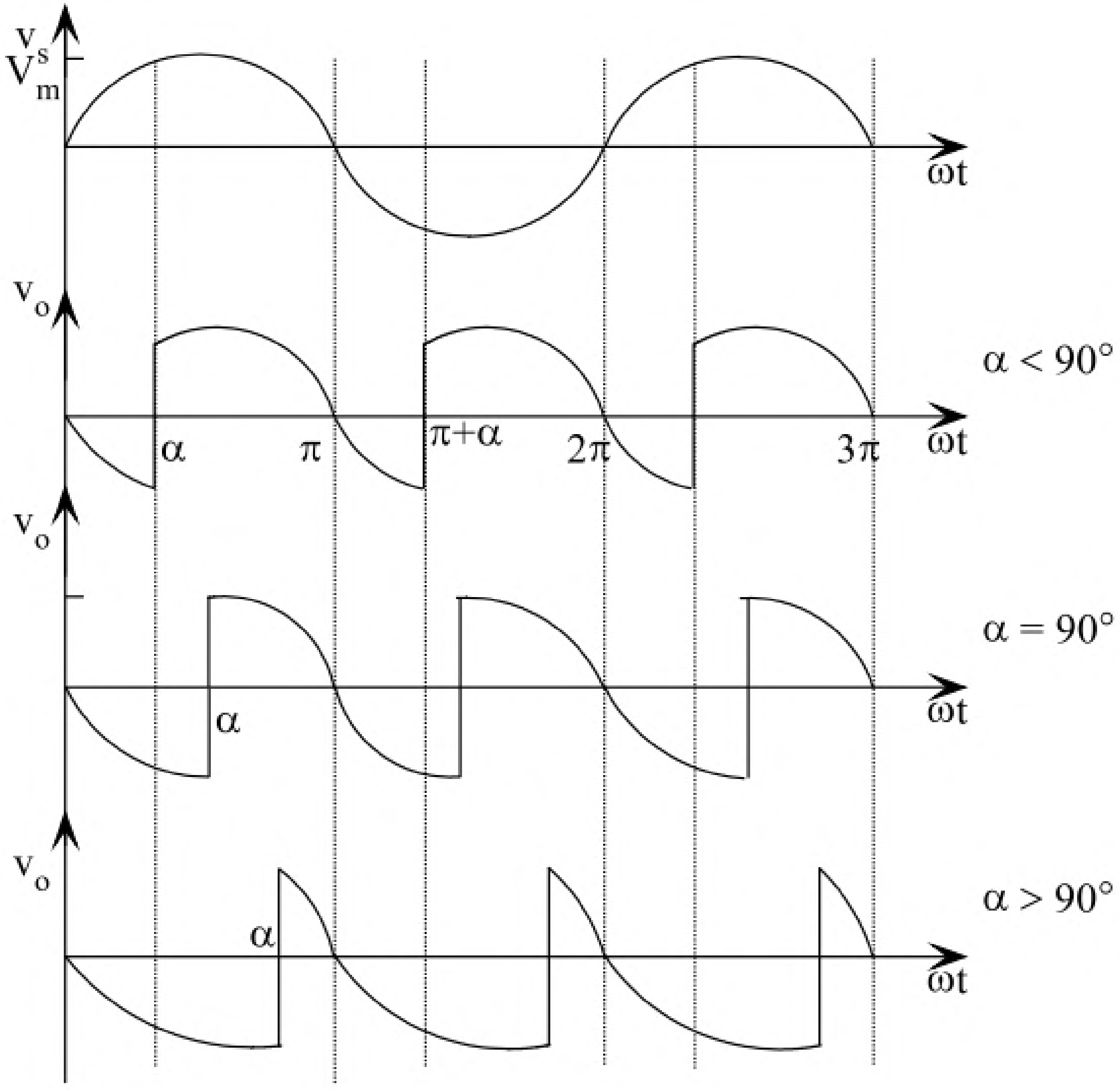




FULL CONVERTER WITH RLE-LOAD (Continuous conduction)

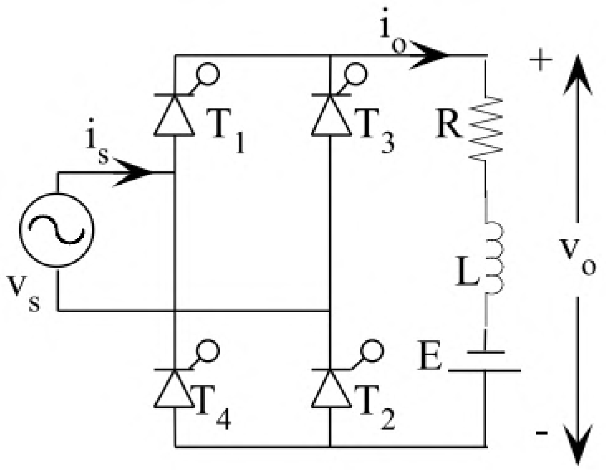


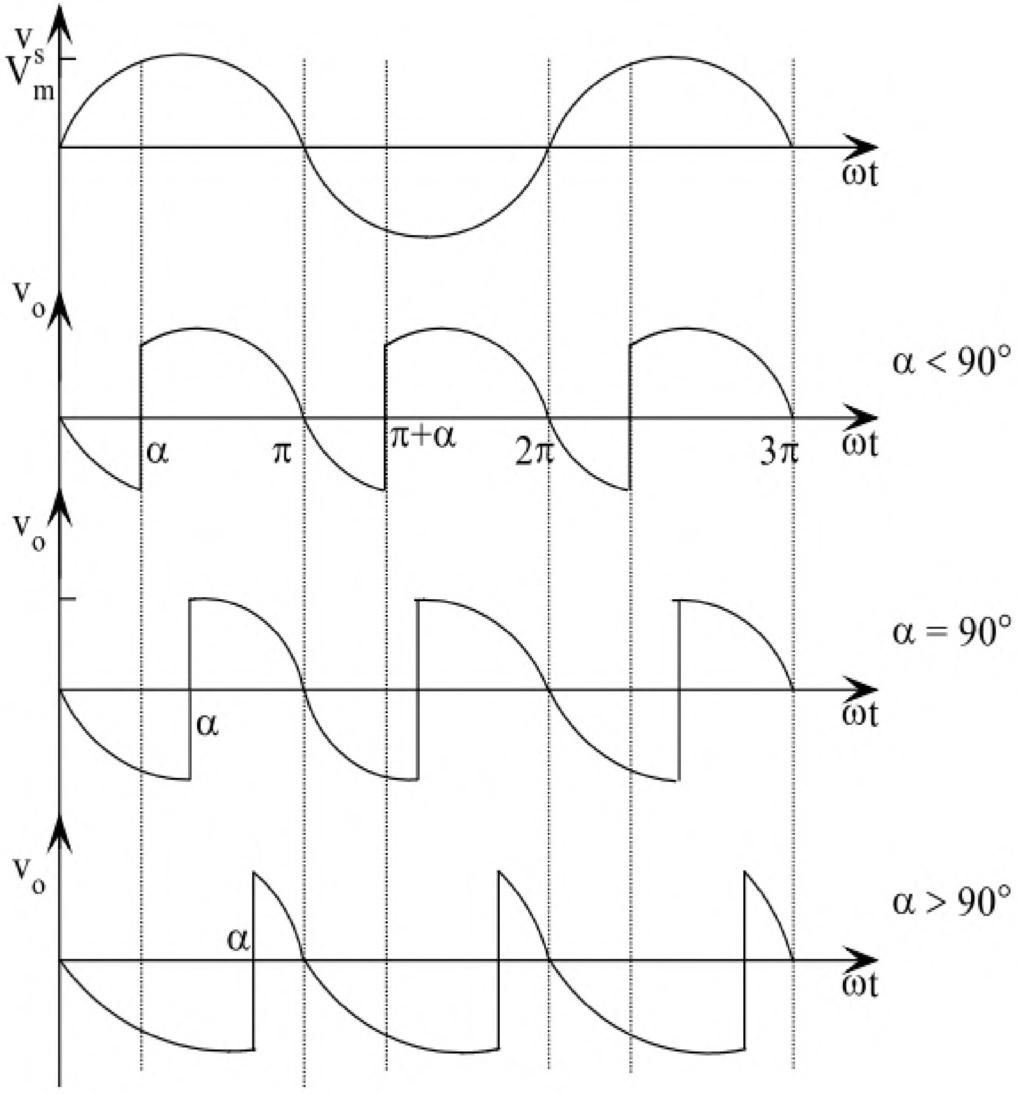




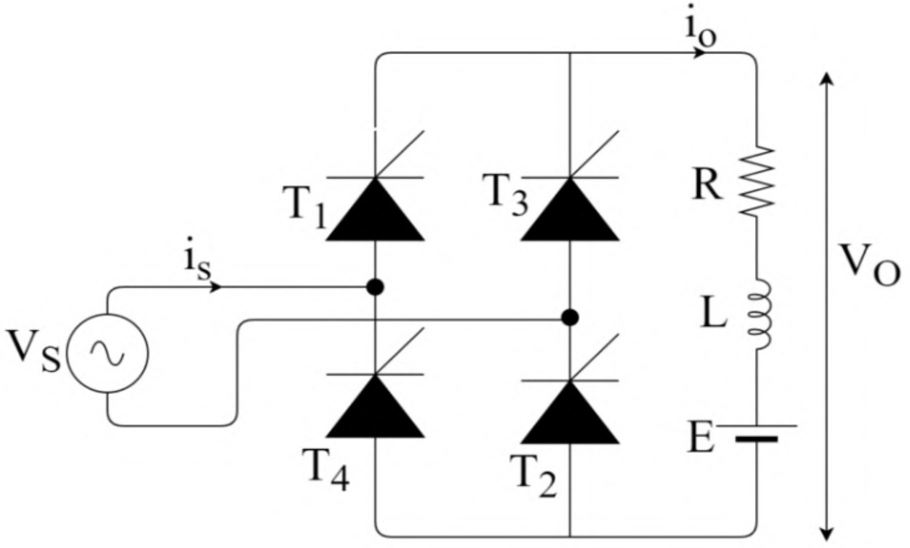
FULL CONVERTER WITH RLE-LOAD (Continuous conduction)

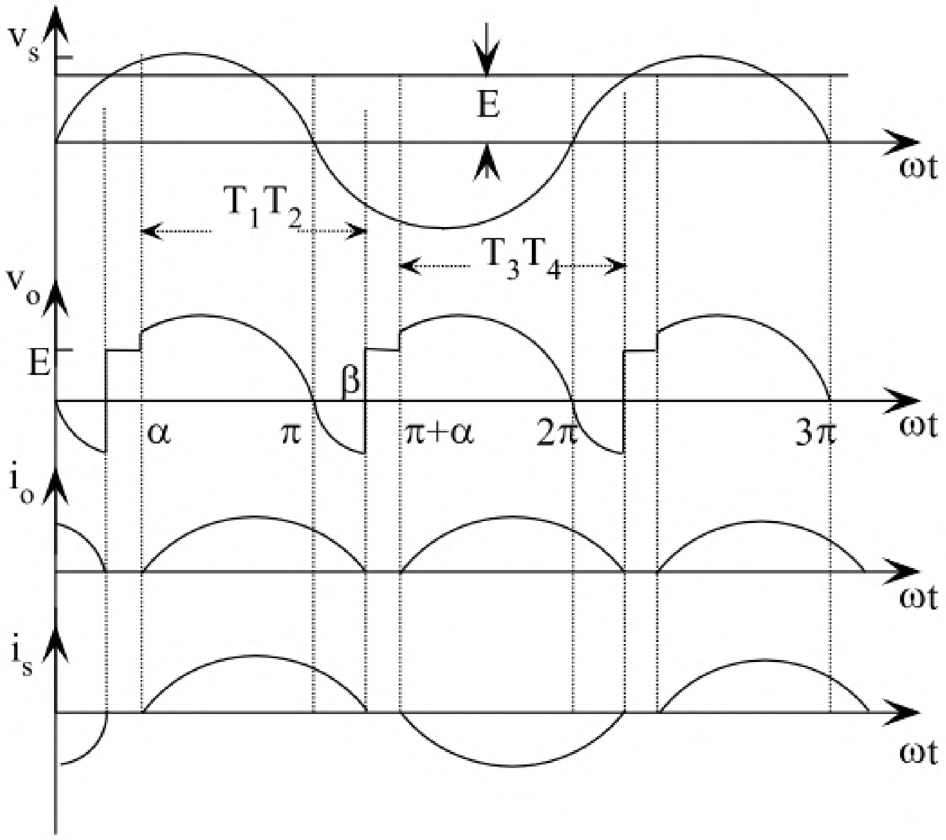
- α> 90, output voltage is negative,
- If E is reversed, E feed power back to ac source
- Inverter operation
- Back emf of a dc motor during its regenerative braking
- Converter : Vo > E
- Inverter: E > Vo





FULL CONVERTER WITH RLE-LOAD (Discontinuous conduction)





SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER WITH R LOAD

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

RMS value of output voltage, $V_{rms}=\sqrt{\frac{1}{2\pi}\times\int_{\alpha}^{\pi}V_m^{\ 2}\sin^2\omega t d(\omega t)}=\frac{V_m}{2}\sqrt{\frac{1}{\pi}(\pi-\alpha+\frac{\sin 2\alpha}{2})}$

SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER WITH RL LOAD

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

SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER WITH RL LOAD & FREEWHEELING DIODE

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

SINGLE PHASE FULL CONVERTER WITH RL-LOAD (Discontinuous conduction)

Average output voltage, $V_{dc}=\frac{1}{\pi}\int_{\alpha}^{\beta}V_m\sin\omega t d(\omega t)=\frac{V_m}{\pi}(\cos\alpha-\cos\beta)$

FULL CONVERTER WITH RL-LOAD (Continuous conduction)

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

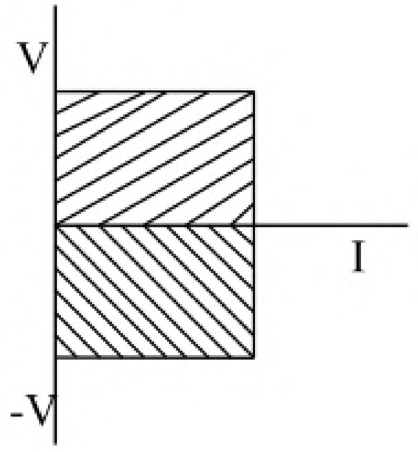
FULL CONVERTER WITH RLE-LOAD (Continuous conduction)

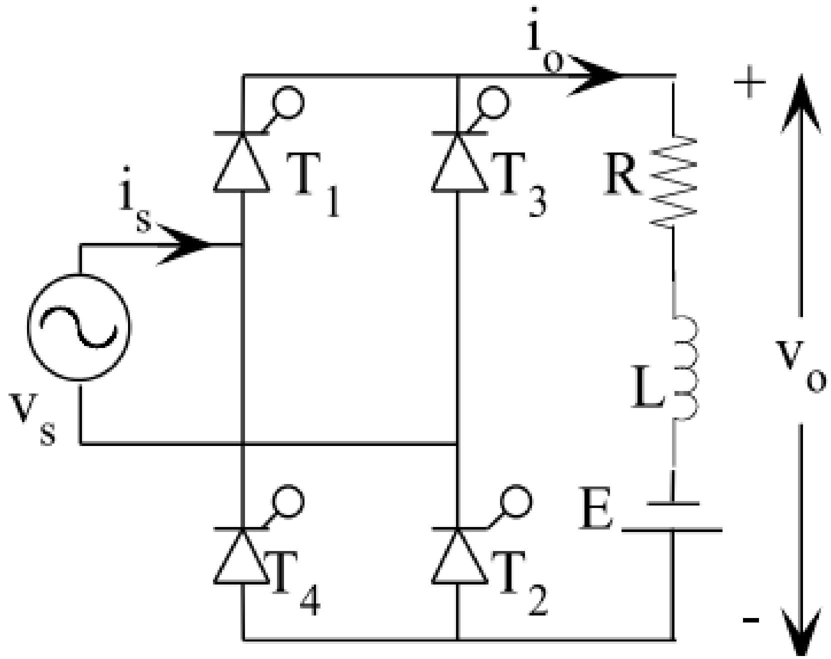
Average output voltage, $V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin\omega t\, d(\omega t) = \frac{2V_m}{\pi}\cos\alpha$

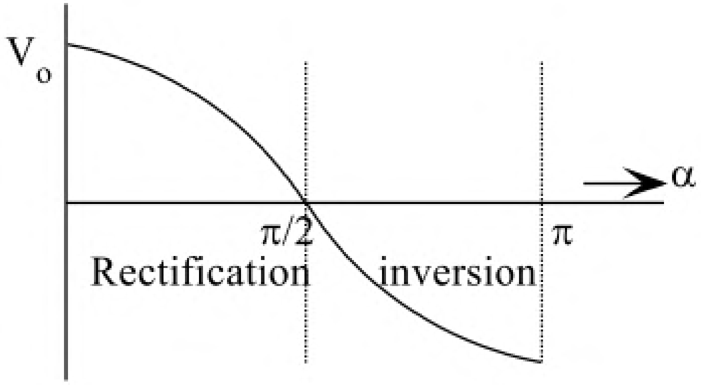
For α > 90°, average output voltage is negative, but the load current continues to flow in the same direction, so output power is negative. Power flows from load to source. It is possible only for active load, i.e., when the load has an emf source (RLE). Operation of the converter lies in I and IV quadrants.

(For regenerative braking of dc motor, α is made greater than 90° and at the same time armature terminals are interchanged so that the current flows from the dc machine, acting as a generator, to the ac source. A mechanical arrangement is used for reversal of the connections.)

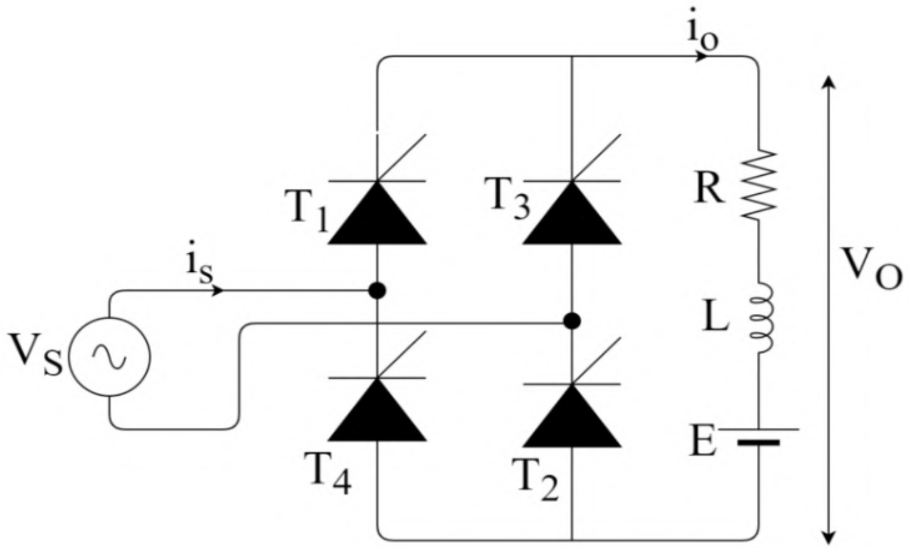
Connection of converter and DC motor during inversion (α > 90°) is shown below.

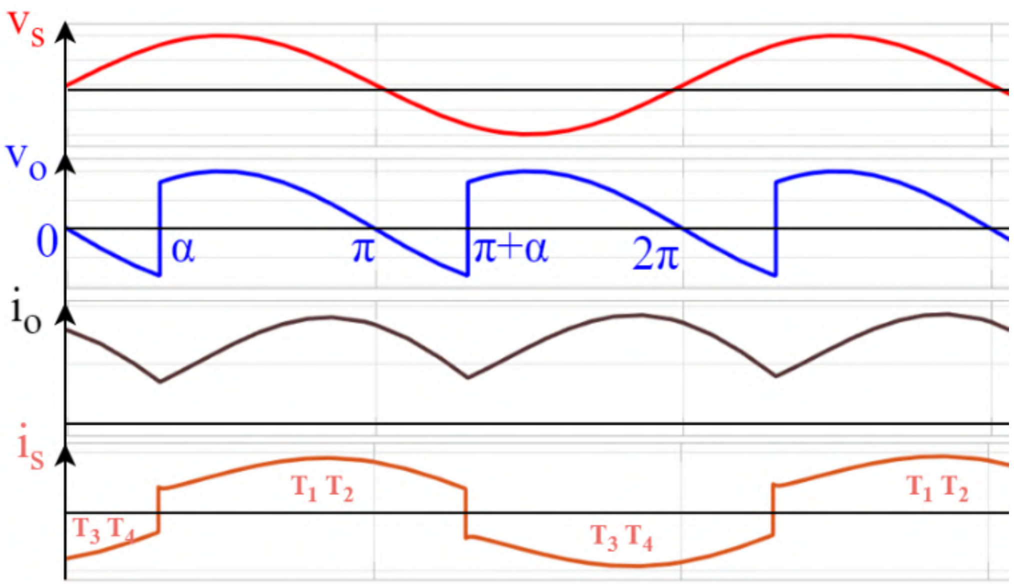


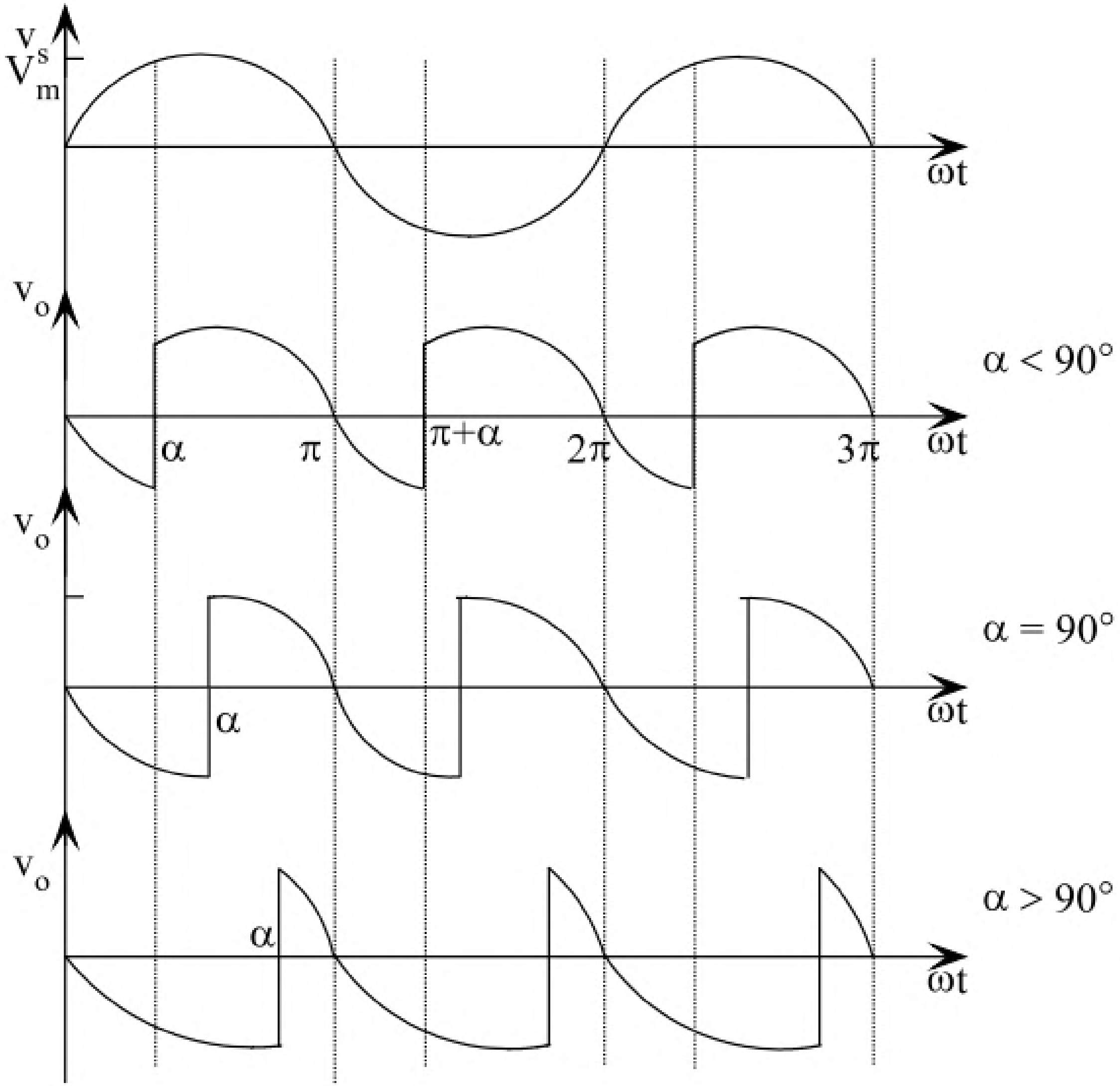




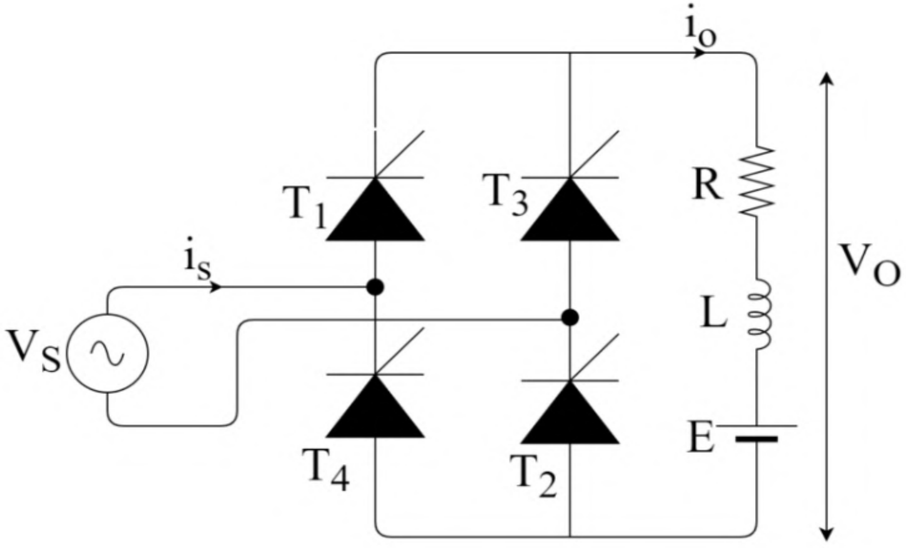
FULL CONVERTER WITH RLE-LOAD (Continuous conduction)

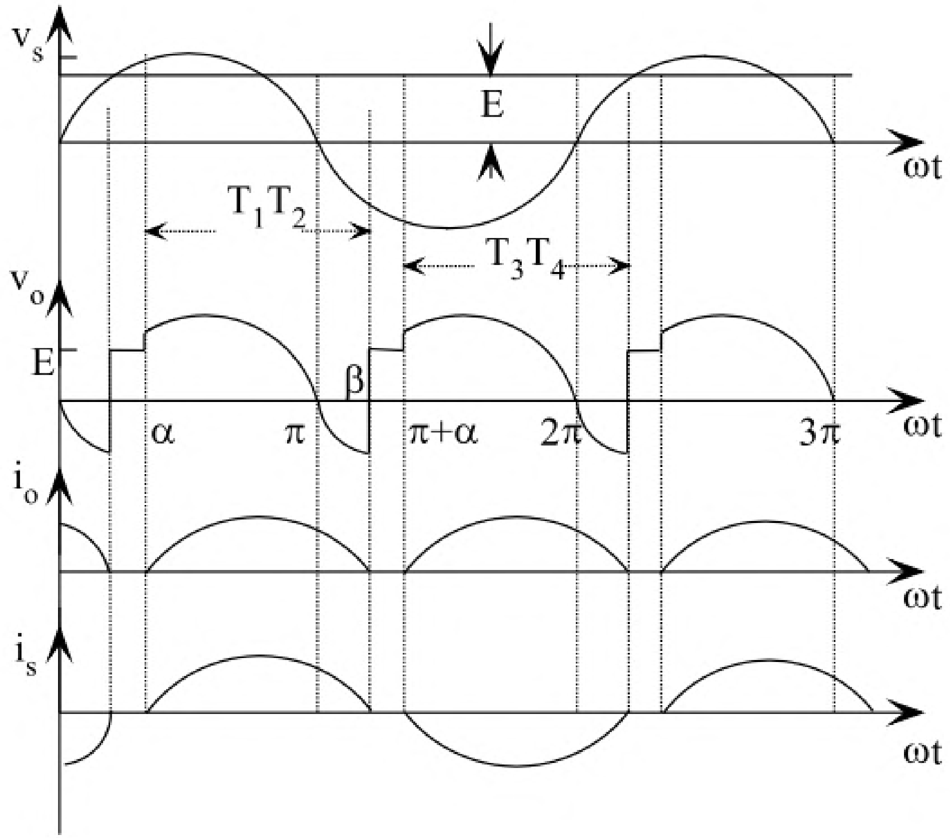






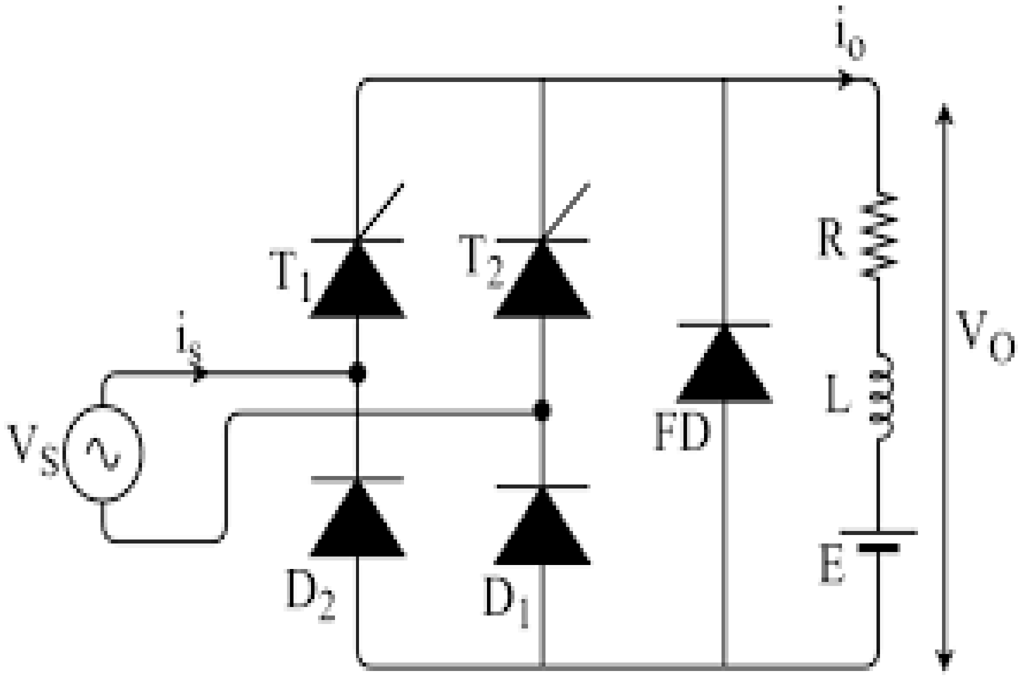
FULL CONVERTER WITH RLE-LOAD (Discontinuous conduction)



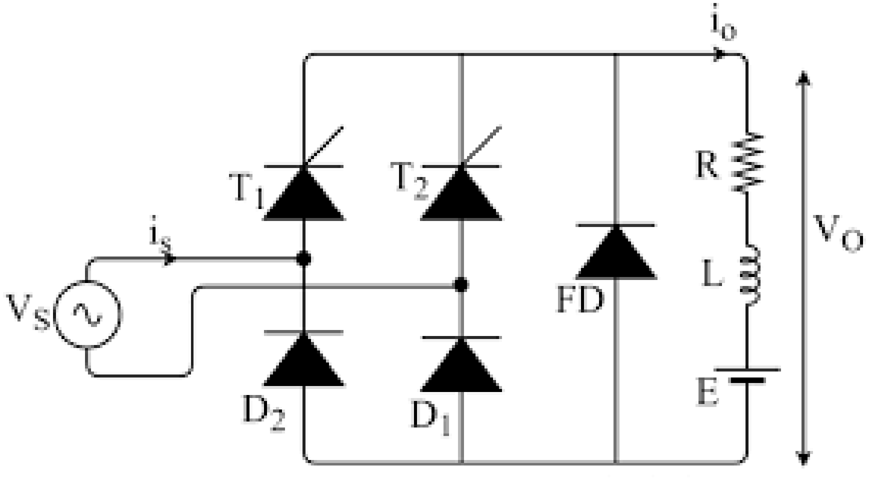


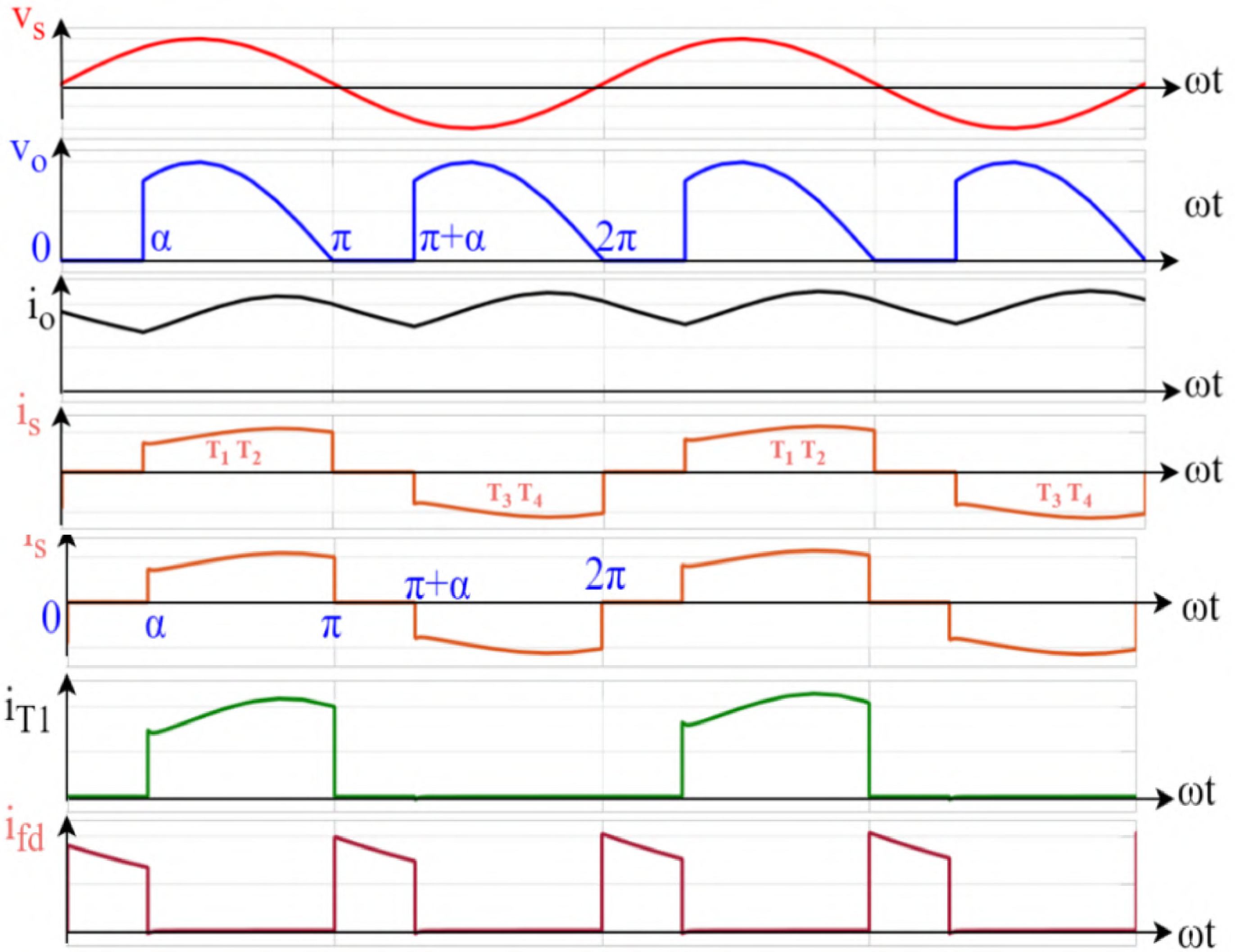
1-PHASE HALF CONTROLLED BRIDGE RECTIFIER OR SEMICONVERTER

- Continuous conduction
- 3 Diode- Two thyristors are replaced by two diodes & F.D internally.
- Half controlled bridge rectifier operates only in one quadrant 1st - forward motoring
- Assumption : Load current is continuous and ripple free io=Io
- T1 triggered α, Vsinα > E, io – T1- RLE-D1
- At π, FD is FB & conducts
- -ve Half: T2 conduct Vs>E at π+ α, T2-D2



1-PHASE HALF CONTROLLED BRIDGE RECTIFIER OR SEMICONVERTER

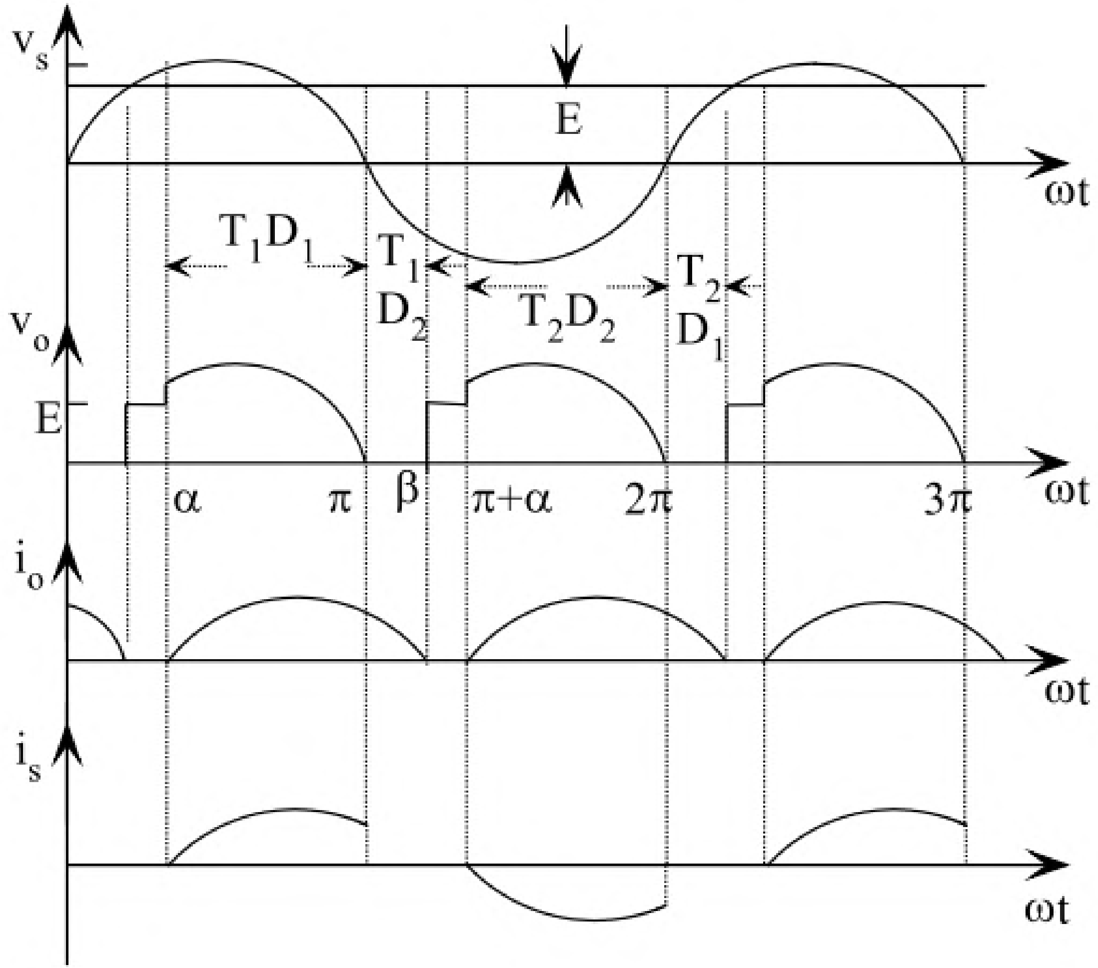




- T1 triggered α, Vsinα > E, io – T1- RLE-D1
- At π, FD is FB & conducts
- -ve Half: T2 conduct Vs>E at π+ α, T2-D2

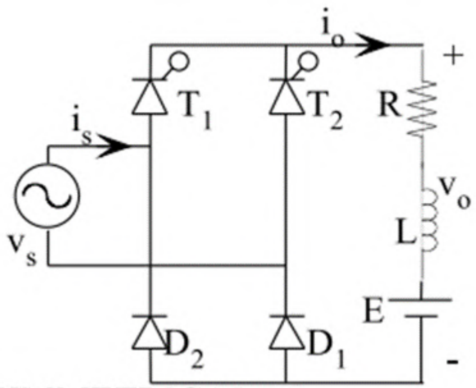
1-PHASE HALF CONTROLLED BRIDGE RECTIFIER OR SEMICONVERTER

- Discontinous Mode

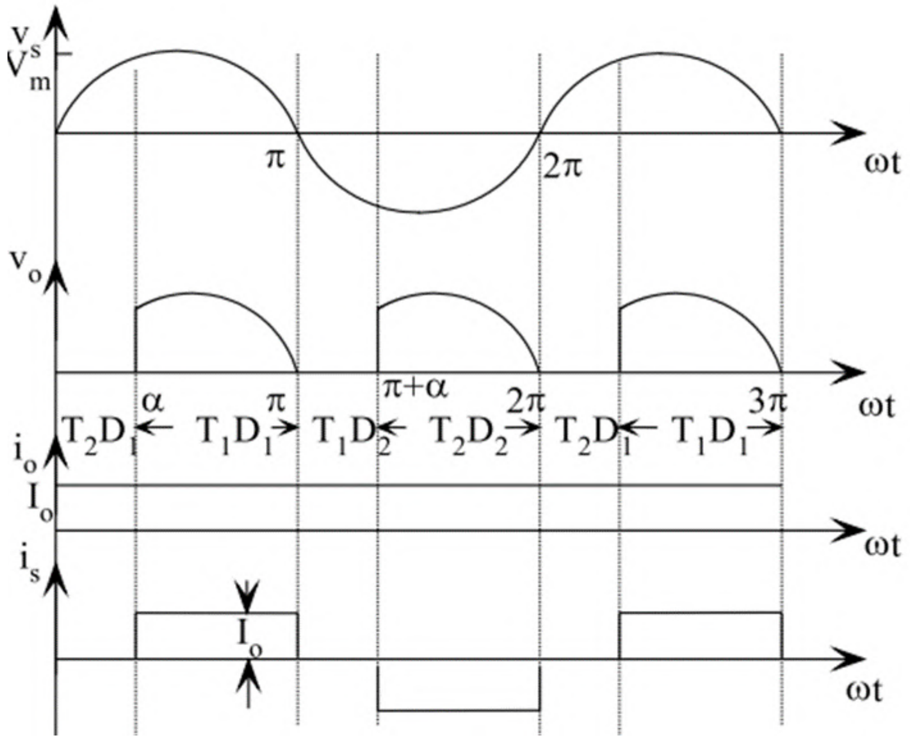


SYMMETRICAL CONFIGURATION

- Each leg- 1 T & 1 D
- At ωt=α, T1 is turned on, both T1 and D1 will conductor. Load current flows through T1, load, D1 and source.
- After ωt=π, D2 is forward biased and it starts conducting. D1 is reverse biased.
- Load is disconnected from source and its current io flows through D2 and T1, which is known as freewheeling action.
- At ωt=π+α, T2 is turned on, which commutates T1 and load current flows through T2 , load, D2 and source

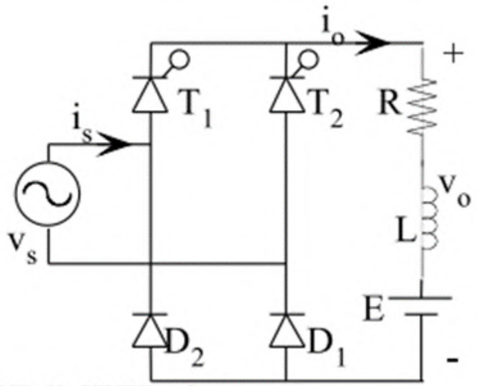


SYMMETRICAL CONFIGURATION

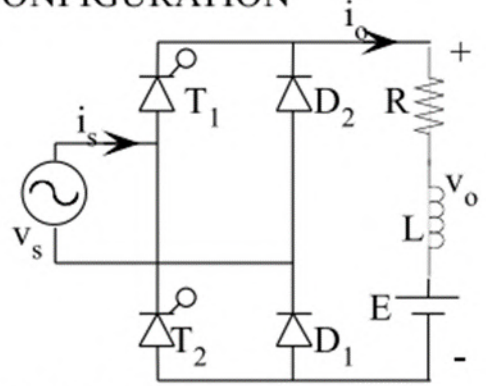


ASYMMETRICAL CONFIGURATION

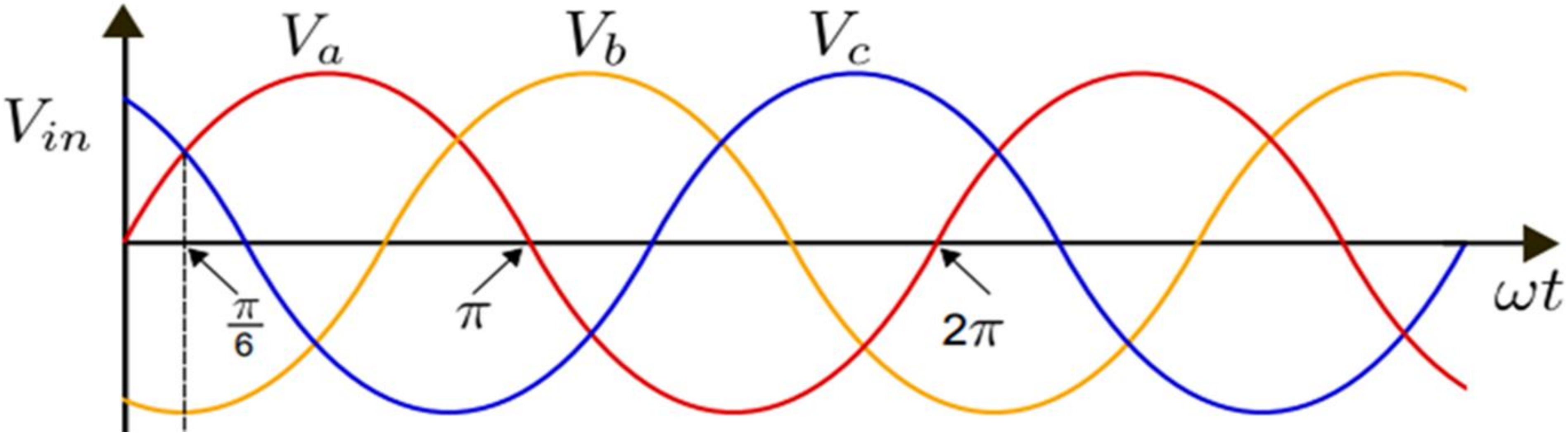
- 2 Cathodes of T1 & T2 connected together
- Two seperate triggering circuit is needed



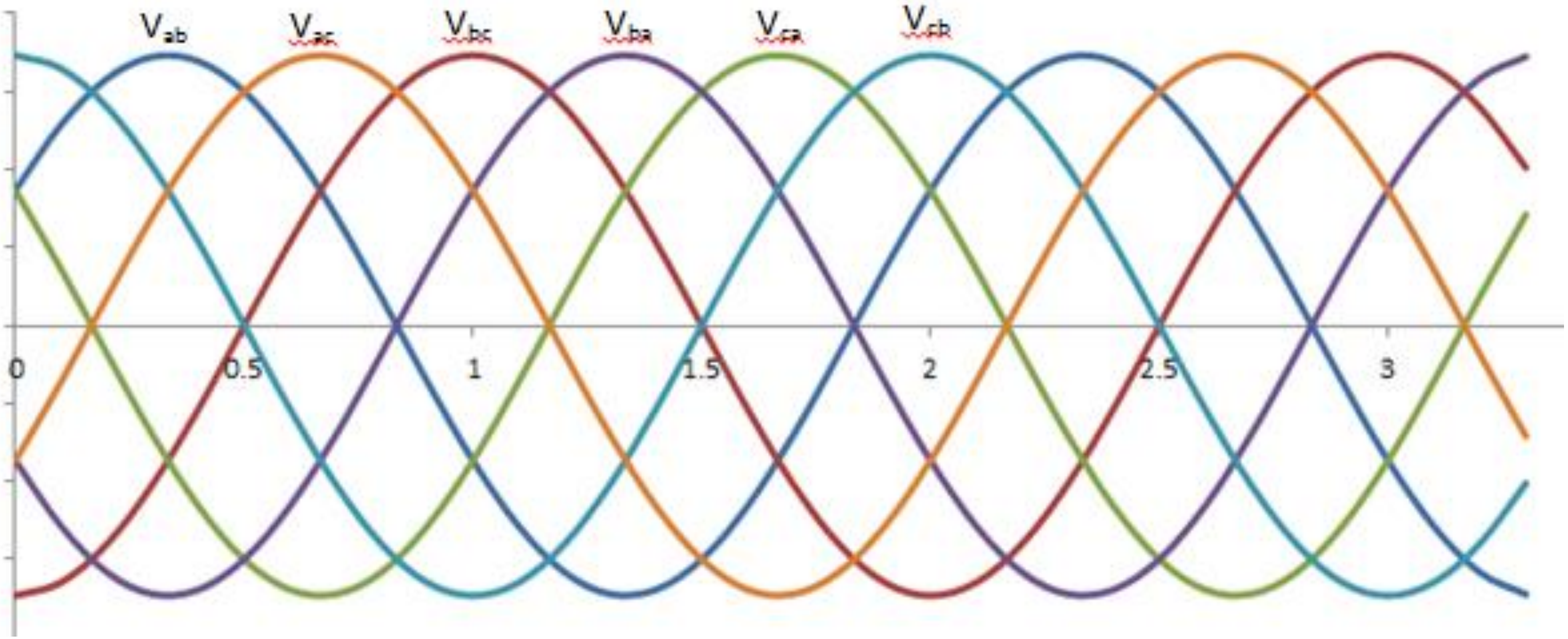
SYMMETRICAL CONFIGURATION



ASYMMETRICAL CONFIGURATION



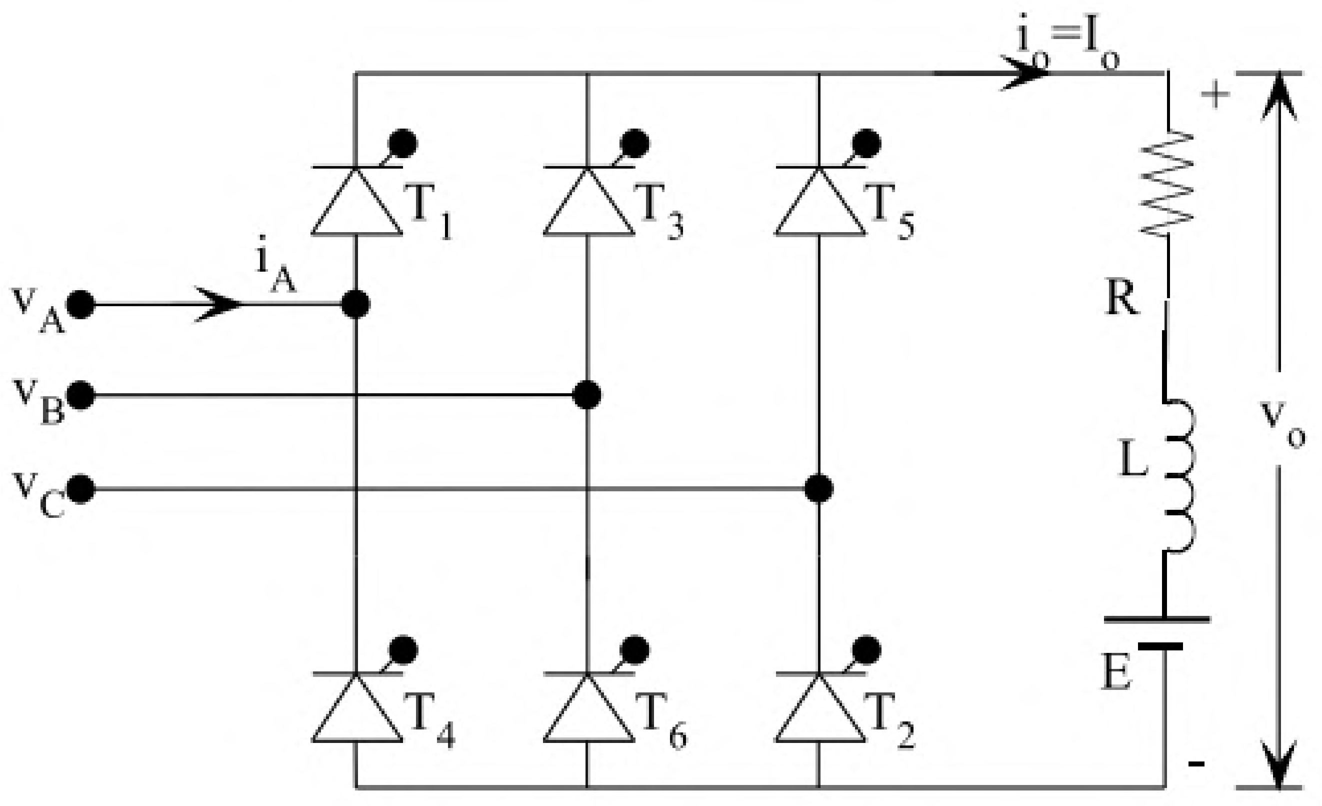
Phase Voltage

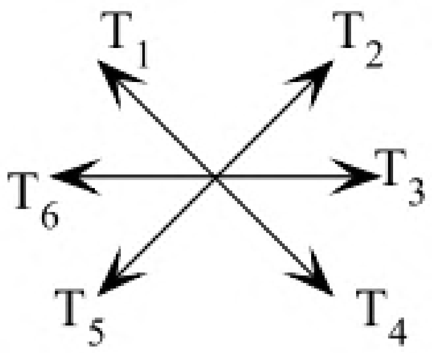


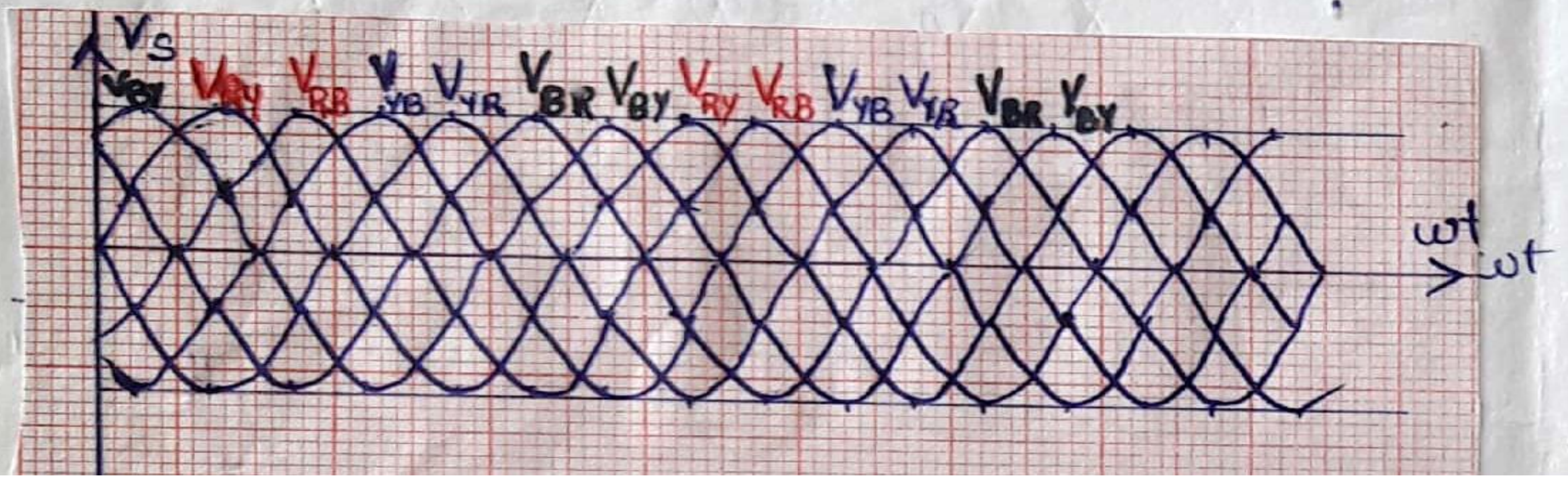
Line Voltage

THREE PHASE FULLY CONTROLLED BRIDGE CONVERTER WITH RLE LOAD

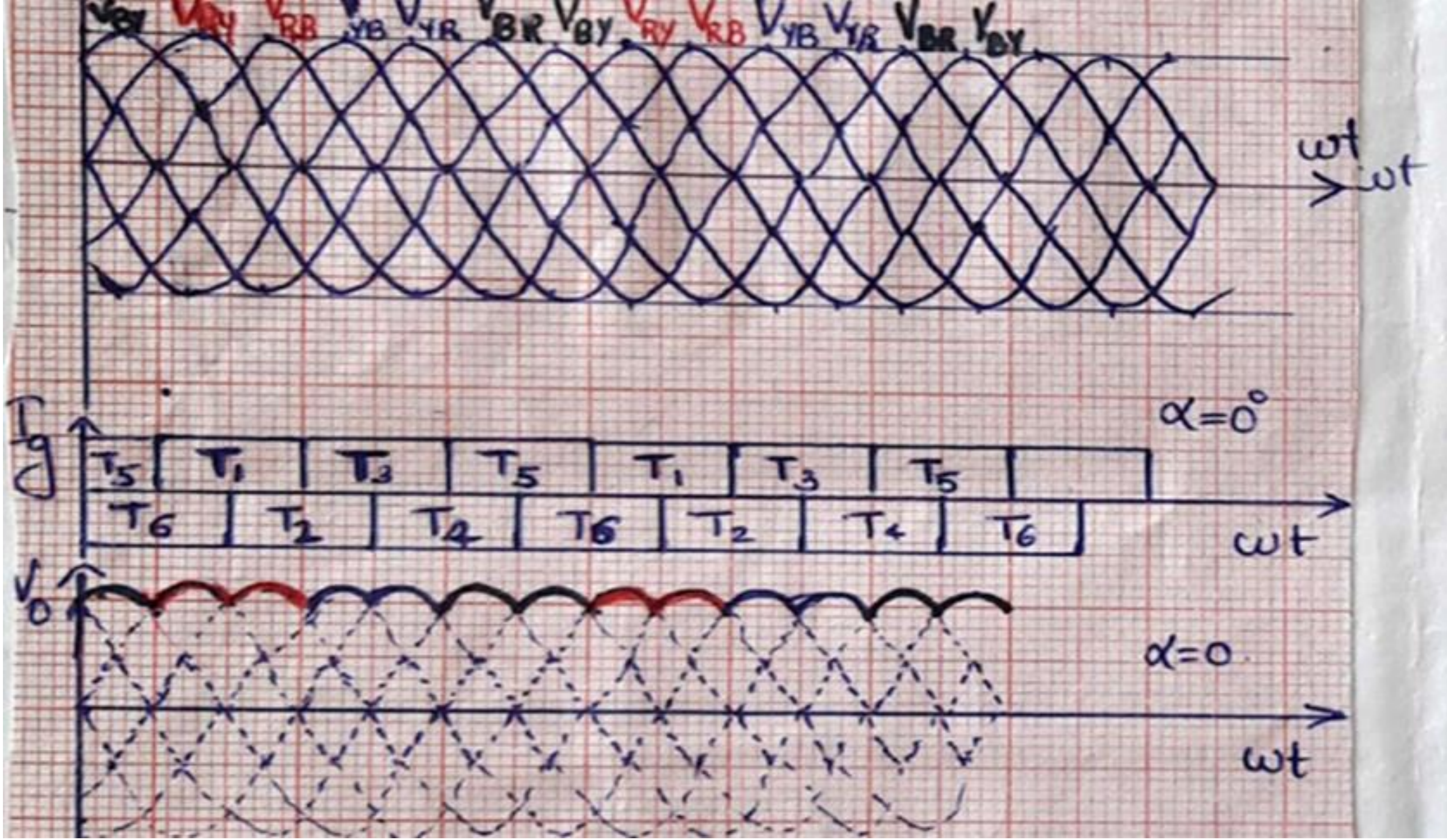
- Assumption Load current is assumed to be continuous and ripple free (io=Io)



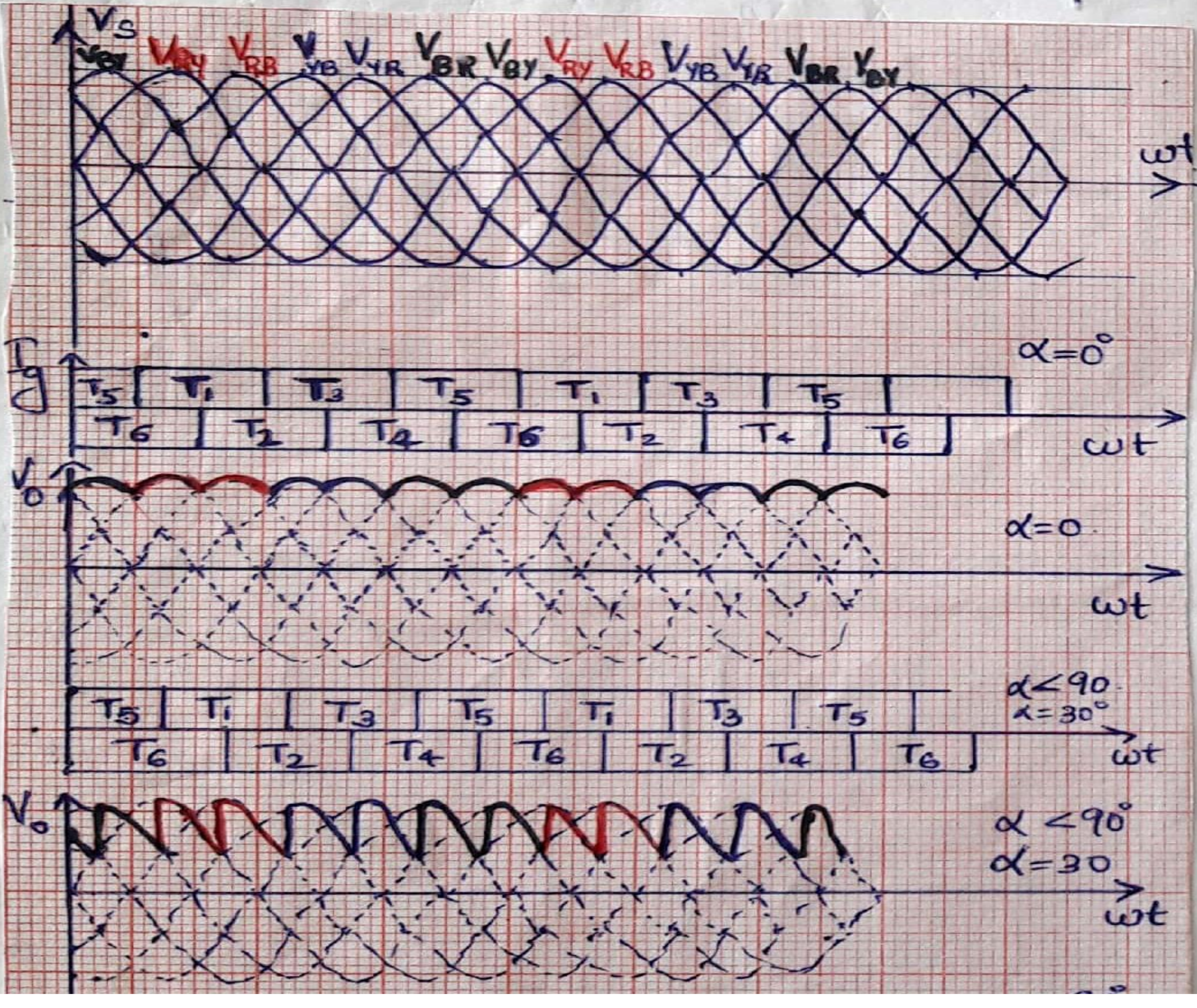




Vs
VBY
VRY
VRB
VYB
VYR
VBR
VBY
VRY
VRB
VYB
VYR
VBR
VBY
ωt
ωt



V_BY V_RY V_RB V_YB V_YR V_BR V_BY V_RY V_RB V_YB V_YR V_BR V_BY
ωt
ωt
Ig
α=0°
T5 T1 T3 T5 T1 T3 T5
T6 T2 T4 T6 T2 T4 T6
ωt
V0
α=0
ωt



Vs
VBY VRY VRB VYB VYR VBR VBY VRY VRB VYB VYR VBR VBY
ωt
Tg
α=0°
T5 T1 T3 T5 T1 T3 T5
T6 T2 T4 T6 T2 T4 T6
ωt
V0
α=0
ωt
α<90
α=30°
T5 T1 T3 T5 T1 T3 T5
T6 T2 T4 T6 T2 T4 T6
ωt
V0
α<90°
α=30
ωt

THREE PHASE SEMI CONVERTER:

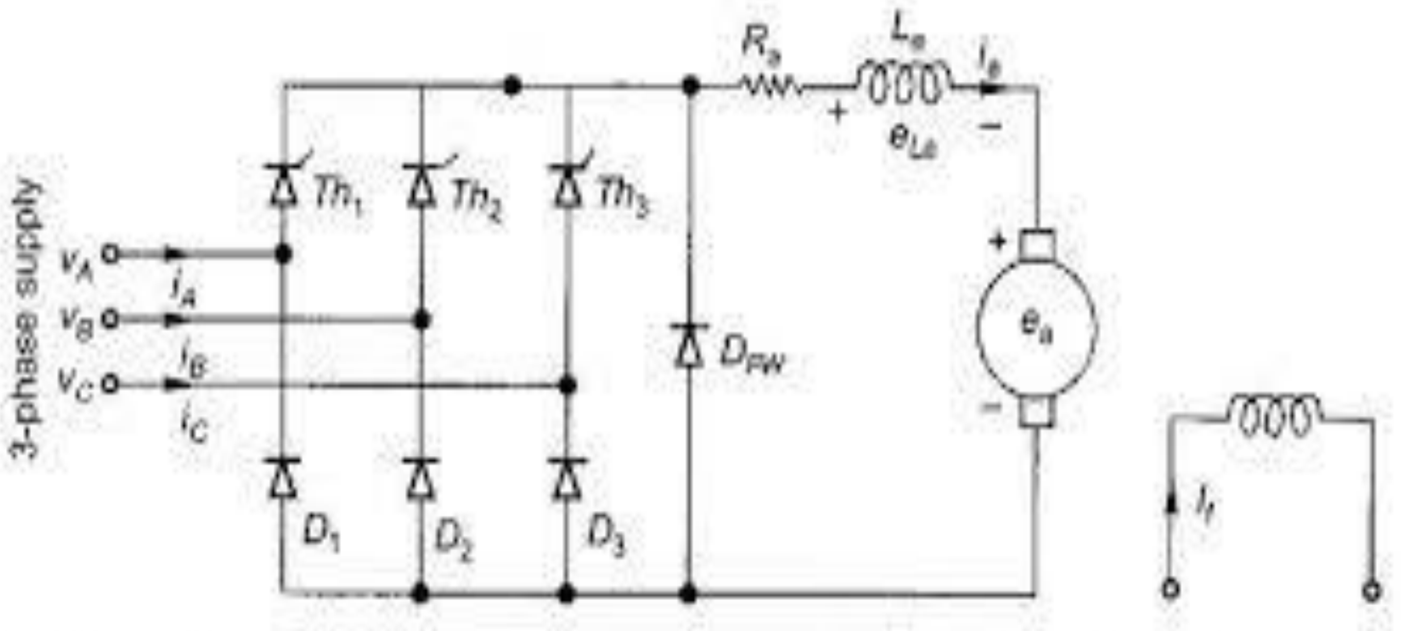
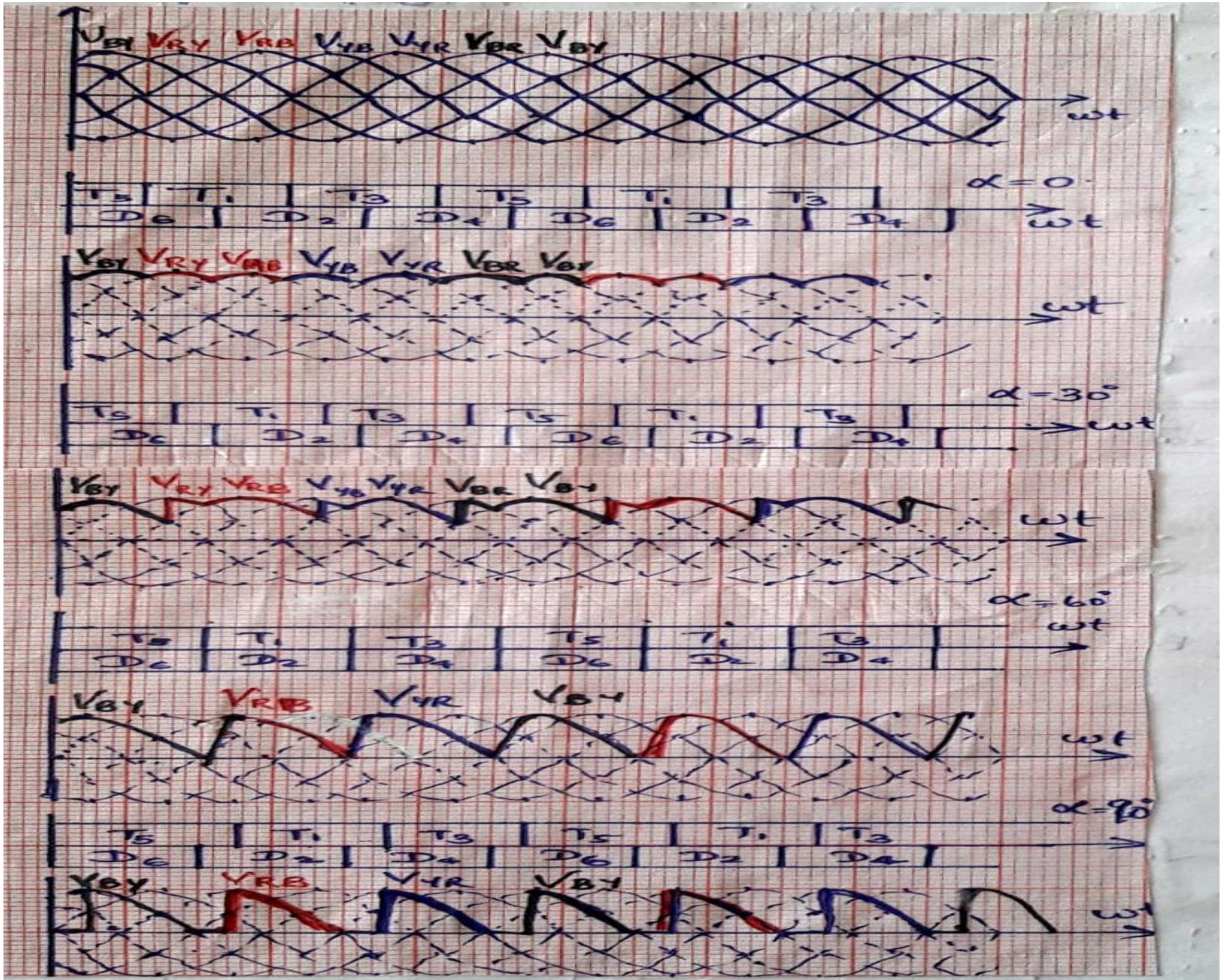


Fig. 11.25 *Three-phase semi-converter feeding separately excited dc motor*

- Low Displacement factor compared to full converter
- Complexity of circuit is reduced



VBY VRY VRB VYB VYR VBR VBY
ωt
α=0°
T5 T1 T3 T5 T1 T3
D6 D2 D4 D6 D2 D4
α=30°
α=60°
VRB
VYR
α=90°

Analysis.

$$V_o = \frac{2}{2\pi/3} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} V_m \sin\omega t \, d\omega t$$

$$= \frac{3V_m}{\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sin\omega t \, d\omega t$$

$$= \frac{3V_m}{\pi} \left[-\cos\omega t\right]_{\pi/3+\alpha}^{\frac{2\pi}{3}+\alpha}$$

$$= \frac{3V_m}{\pi} \left[\cos\left(\frac{\pi}{3}+\alpha\right) - \cos\left(\frac{2\pi}{3}+\alpha\right)\right]$$

$$= \frac{3V_m}{\pi} \left[\cos\frac{\pi}{3}\cos\alpha - \sin\frac{\pi}{3}\sin\alpha - \cos\frac{2\pi}{3}\cos\alpha + \sin\frac{2\pi}{3}\sin\alpha\right]$$

$$= \frac{3V_m}{\pi} \left[\frac{\cos\alpha}{2} - \frac{\sqrt{3}}{2}\sin\alpha + \frac{1}{2}\cos\alpha + \frac{\sqrt{3}}{2}\sin\alpha\right]$$

$$= \frac{3V_{ml}}{\pi} \cos\alpha.$$

Average output voltage

For $\alpha \le \frac{\pi}{3}$ average output voltage

$$V_{av} = V_o = \frac{1}{2\pi/3}\left[\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} V_m \sin\omega t \, d\omega t + \int_{\frac{2\pi}{3}}^{\frac{3\pi}{3}+\alpha} V_m \sin\left(\omega t - \frac{\pi}{3}\right) d\omega t\right]$$

$$V_{avg} = \frac{3V_m}{2\pi}\left[\left[-\cos\omega t\right]_{\pi/3+\alpha}^{\frac{2\pi}{3}} + \left[-\cos\left(\omega t - \frac{\pi}{3}\right)\right]_{\frac{2\pi}{3}}^{\frac{3\pi}{3}+\alpha}\right]$$

$$V_{avg} = \frac{3V_m}{2\pi}\left[\cos\left(\frac{\pi}{3}+\alpha\right) - \cos\frac{2\pi}{3} + \cos\left(\frac{2\pi}{3}-\frac{\pi}{3}\right) - \cos\left(\frac{2\pi}{3}+\alpha-\frac{\pi}{3}\right)\right]$$

$$= \frac{3V_m}{2\pi}\left[\cos\frac{\pi}{3}\cos\alpha - \sin\frac{\pi}{3}\sin\alpha - \cos\frac{2\pi}{3} + \cos\frac{\pi}{3} - \cos\frac{2\pi}{3}\cos\alpha + \sin\frac{2\pi}{3}\sin\alpha\right]$$

$$= \frac{3V_m}{2\pi}\left[\frac{\cos\alpha}{2} - \frac{\sqrt{3}}{2}\sin\alpha + \frac{1}{2} + \frac{1}{2} + \frac{\cos\alpha}{2} + \frac{\sqrt{3}}{2}\sin\alpha\right]$$

$$= \frac{3V_m}{2\pi}\left[\cos\alpha + 1\right]$$

$$V_{avg} = \frac{3V_m}{2\pi}\left[1+\cos\alpha\right]$$

For $\alpha \ge \frac{\pi}{3}$

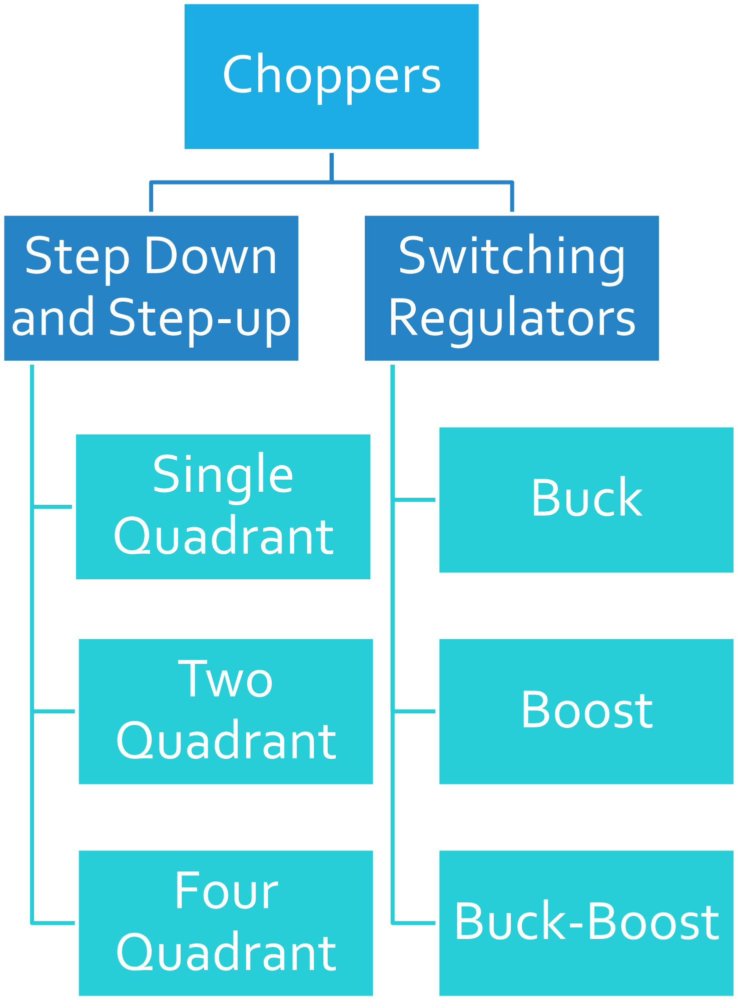
$$V_{avg} = \frac{3V_m}{2\pi}\left[1+\cos\alpha\right]$$

Module 4

DC-DC converters

Step down and Step up choppers – Single-quadrant, Two-quadrant and Four quadrant chopper – Pulse width modulation & current limit control in dc-dc converters. (4 hrs)

Switching regulators – Buck, Boost & Buck-boost –Operation with continuous conduction mode – Waveforms – Design of Power circuits (switch selection, filter inductance and capacitance) (4 hrs)


Choppers
Step Down and Step-up
Switching Regulators
Single Quadrant
Two Quadrant
Four Quadrant
Buck
Boost
Buck-Boost

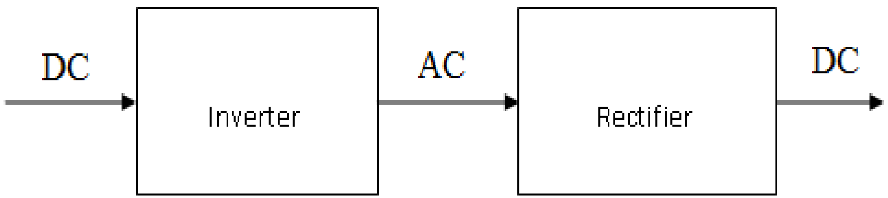
DC-DC converter (Chopper)

- Many industrial applications require power from dc voltage source
- E.g.: subway cars, trolley buses, battery operated vehicles, battery charging etc…
- The ***conversion of fixed dc voltage to an adjustable dc output voltage*** through the use of semiconductor devices can be carried out by the use of two types of dc to dc converter : AC link chopper & DC chopper

DC-DC converter (Chopper)

AC link chopper:

- As the conversion is in two stages, dc to ac and then ac to dc, ac link chopper is costly, bulky and less efficient

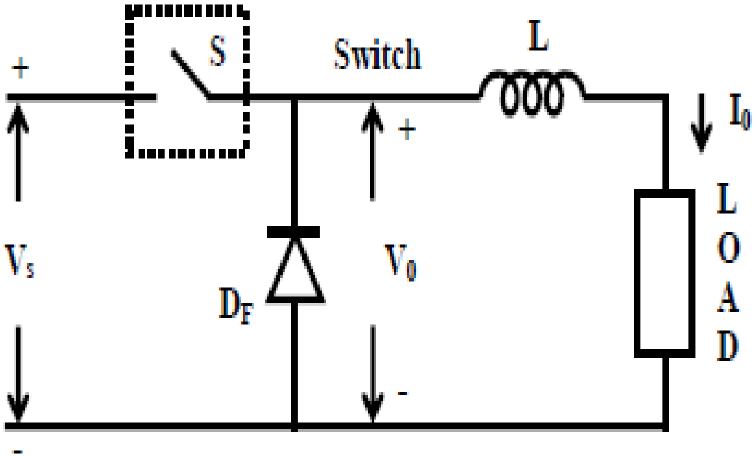


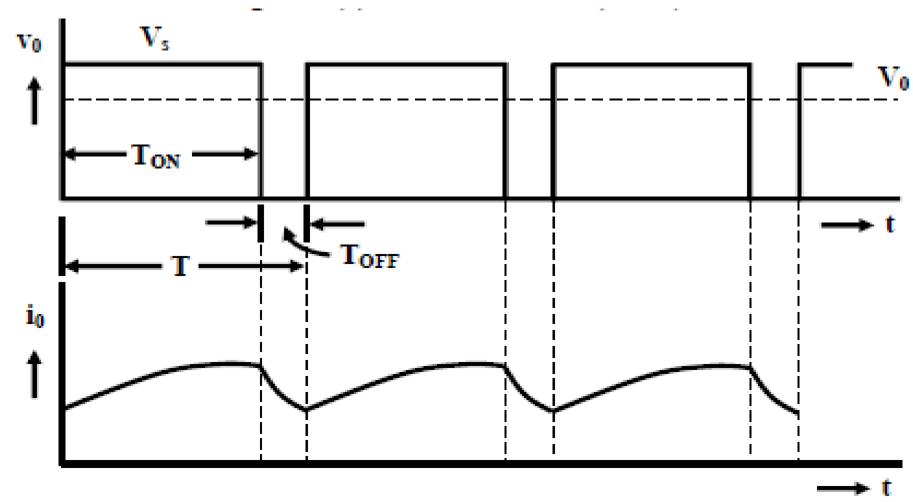
DC-DC converter (Chopper)

DC chopper

- *Chopper is a static device that convert fixed dc input voltage to a variable dc output voltage*
- Dc equivalent of an ac transformer
- Efficient

Step-down chopper





Step-down chopper

$$V_o = \frac{T_{on}}{T_{on} + T_{off}} V_s = \frac{T_{on}}{T} V = \alpha V_s$$

- T on = on-time; T off = off-time
- T=Ton+Toff = Chopping period
- Duty cycle

$$\alpha = \frac{T_{on}}{T}$$

- Thus load voltage can be controlled by varying duty cycle

$$V_o = f \cdot T_{on} \cdot V_s$$

- Where f is the chopping frequency
- *Average output voltage is always less than the input voltage hence called as step down chopper*

Switching regulators

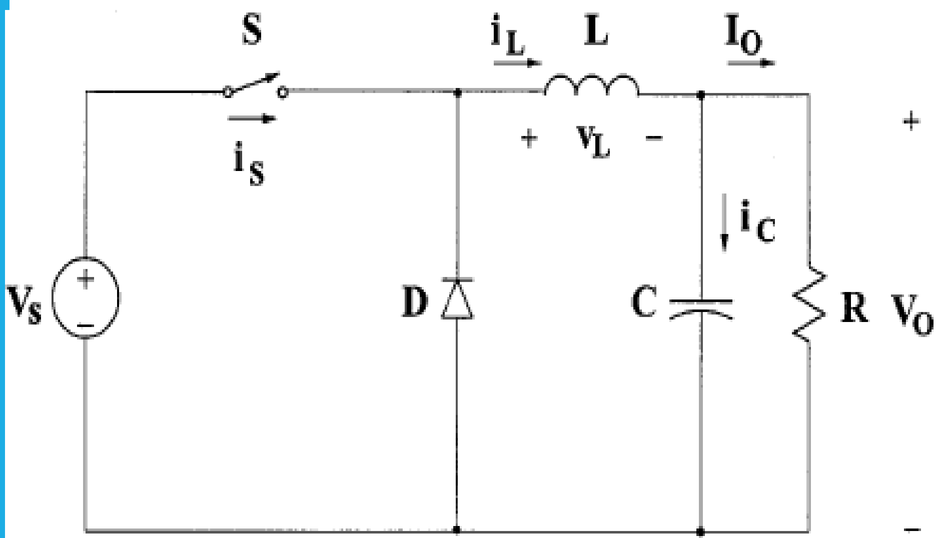
- DC converters can be used as switching mode regulators to convert a dc voltage.
- The regulation is normally achieved by PWM at a fixed frequency and the switching device is normally BJT, MOSFET or IGBT
- The ripple content is normally reduced by an LC filter
- There are four basic topologies of switching regulators Buck regulator

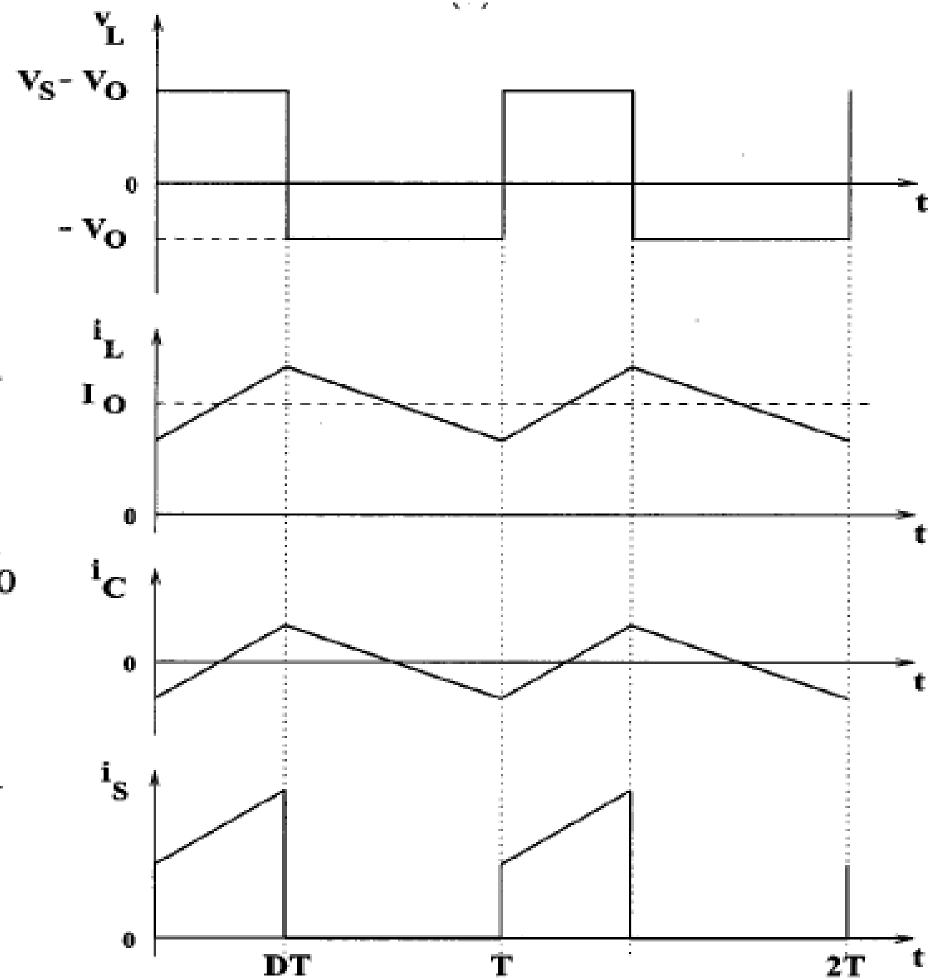
  Boost regulator

  Buck-boost regulator

  Buck regulator

Buck regulator





Buck regulator

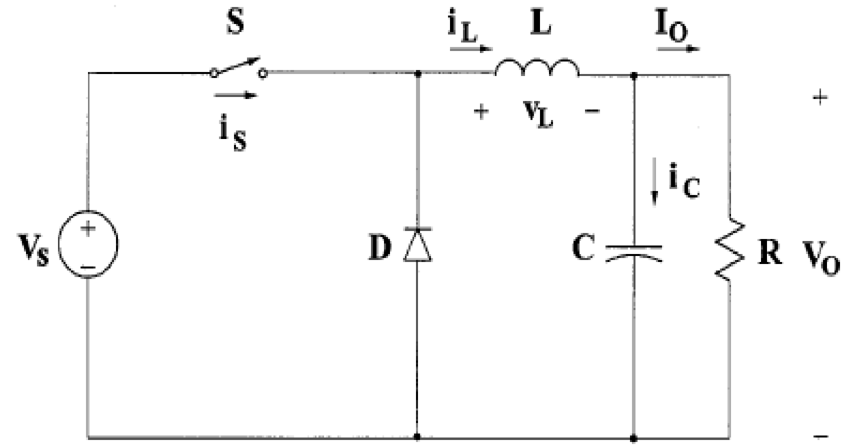
- V_o is less than V_s : buck converter
- One switch, high efficiency > 90 %
- 2 modes

Mode I

- Begins when switch is turned on
- The input current rises, which flows through filter inductor L, filter capacitor C and the load resistor R

Mode II

- Begins when switch is turned off
- Freewheeling diode conduct due to energy stored in the inductor and the inductor current continues to flows through L, C, load and diode



Buck regulator

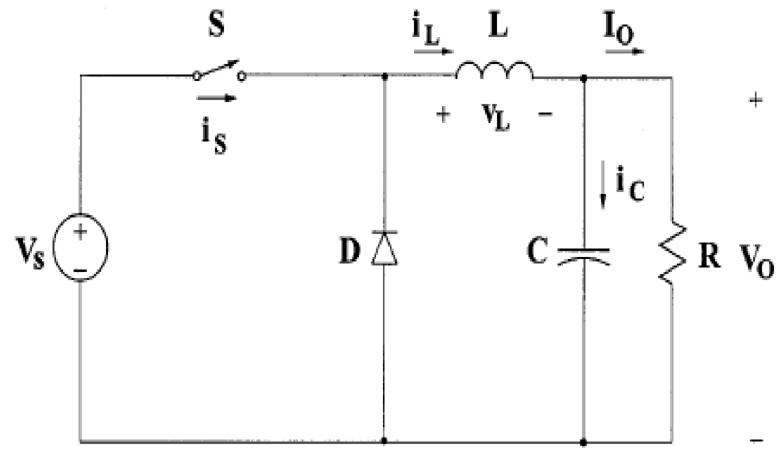
- Depending on the switching frequency, filter inductance and capacitance the inductor current could be discontinues
- The voltage across the inductor L is in general

$$e_L = L\frac{di}{dt}$$

- Assuming that inductor current rises linearly from I1 to I2 in time t1

$$V_s - V_a = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1}$$

$$t_1 = \frac{\Delta I\, L}{V_s - V_a}$$



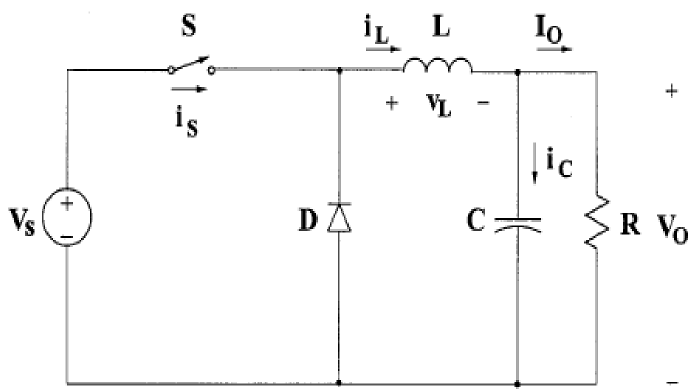
Buck regulator

- And the inductor current falls linearly from I2 to I1 in time t2,

$$-V_a = -L\frac{\Delta I}{t_2} \qquad t_2 = \frac{\Delta I\, L}{V_a}$$

- Where ΔI= I2-I1 is the peak to peak ripple current of the inductor
- Equating the value of ΔI

$$\Delta I = \frac{(V_s - V_a)t_1}{L} = \frac{V_a t_2}{L}$$



Buck regulator

- Assuming a lossless circuit, Vs.Is = Vo.Io =D.Vs.Io and the average input current Is=k.Io
- The switching period T can be expressed as

$$T = \frac{1}{f} = t_1 + t_2 = \frac{\Delta I\, L}{V_s - V_a} + \frac{\Delta I\, L}{V_a} = \frac{\Delta I\, L V_s}{V_a(V_s - V_a)}$$

- Which gives the peak to peak ripple current as

$$\Delta I = \frac{V_a(V_s - V_a)}{f L V_s} = \frac{V_s k(1-k)}{f L}$$

- Using Kirchhoff's current law, we can write the inductor current as

$$i_L = i_c + i_o$$

- If we assume that the load ripple current Δio is very small and negligible, ΔiL=Δic

Buck regulator

- The average capacitor current, which flows into for ton/2+toff/2=T/2 is

$$I_c = \frac{\Delta I}{4}$$

- The capacitor voltage is expressed as

$$v_c = \frac{1}{C}\int i_c dt + v_c(t=0)$$

- And the peak to peak ripple voltage of the capacitor is

$$\Delta V_c = v_c - v_c(t=0) = \frac{1}{C}\int_0^{T/2} \frac{\Delta I}{4} dt = \frac{\Delta I . T}{8C} = \frac{\Delta I}{8fC}$$

- Substituting the value of ΔI

$$\Delta V_c = \frac{V_a(V_s - V_a)}{8LCf^2 V_s} = \frac{V_s k(1-k)}{8LCf^2}$$

Buck regulator

- Condition for continues inductor current and capacitor voltage
  - If IL is the average inductor current, inductor current ripple current ΔI=2IL

$$\frac{V_s k(1-k)}{fL} = 2I_L = 2I_a = \frac{2kV_s}{R}$$

  - Which gives the critical value of the inductor Lc as

$$L_c = L = \frac{R\,(1-k)}{2f}$$

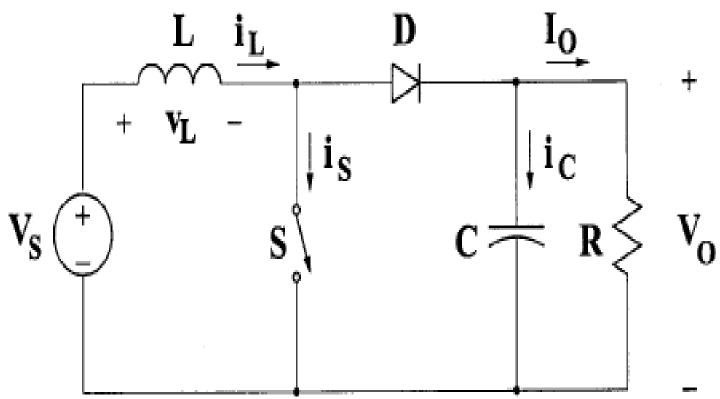
  - If Vc is the average capacitor voltage, capacitor ripple voltage Δ Vc=2Vo

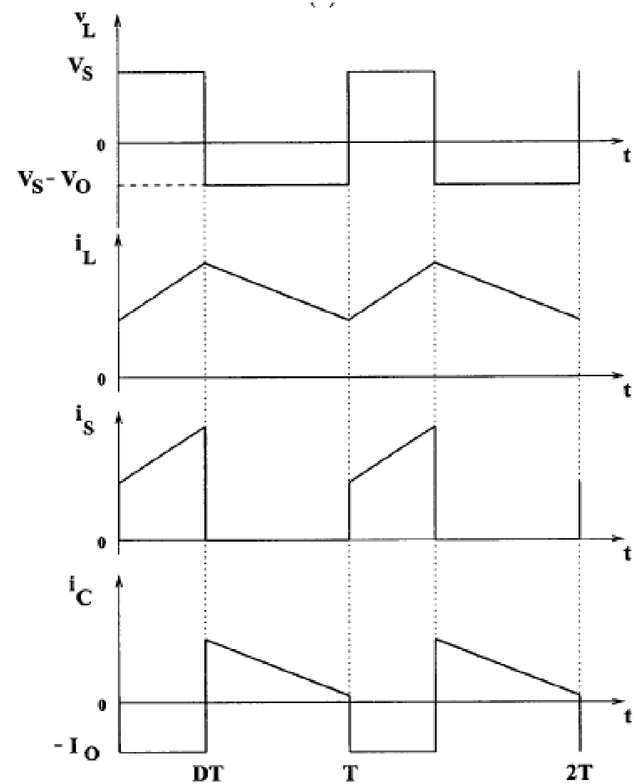
$$\frac{V_s k(1-k)}{8LCf^2} = 2V_a = 2kV_s$$

  - Which gives the critical value of the capacitor Cc

$$C_c = C = \frac{(1-k)}{16Lf^2}$$

Boost regulator





Module 5 - 11 hrs

Electric Drive: Introduction to electric drives – Block diagram – advantages of electric drives- types of load – classification of load torque (2 hrs)

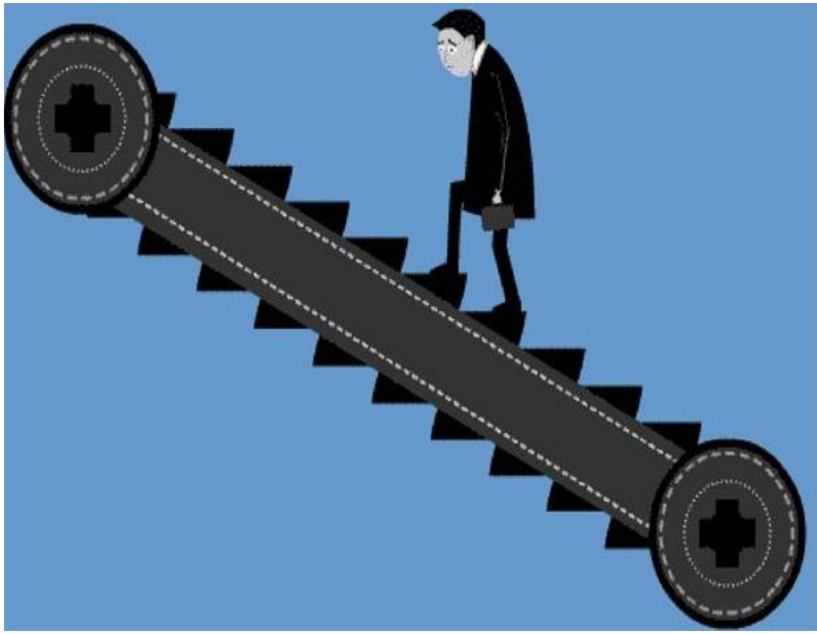
DC Drives: Single phase semi converter and single phase fully controlled converter drives. Dual Converters for Speed control of DC motor-1-phase and 3-phase configurations; Simultaneous and Non-simultaneous operation. Chopper controlled DC drives- Single quadrant chopper drives- Regenerative braking control- Two quadrant chopper drives- Four quadrant chopper drives(6 hrs)

AC Drives: Three phase induction motor speed control. Stator voltage control – stator frequency control - Stator voltage and frequency control (v/f) (3 hrs)

Reference Textbook:

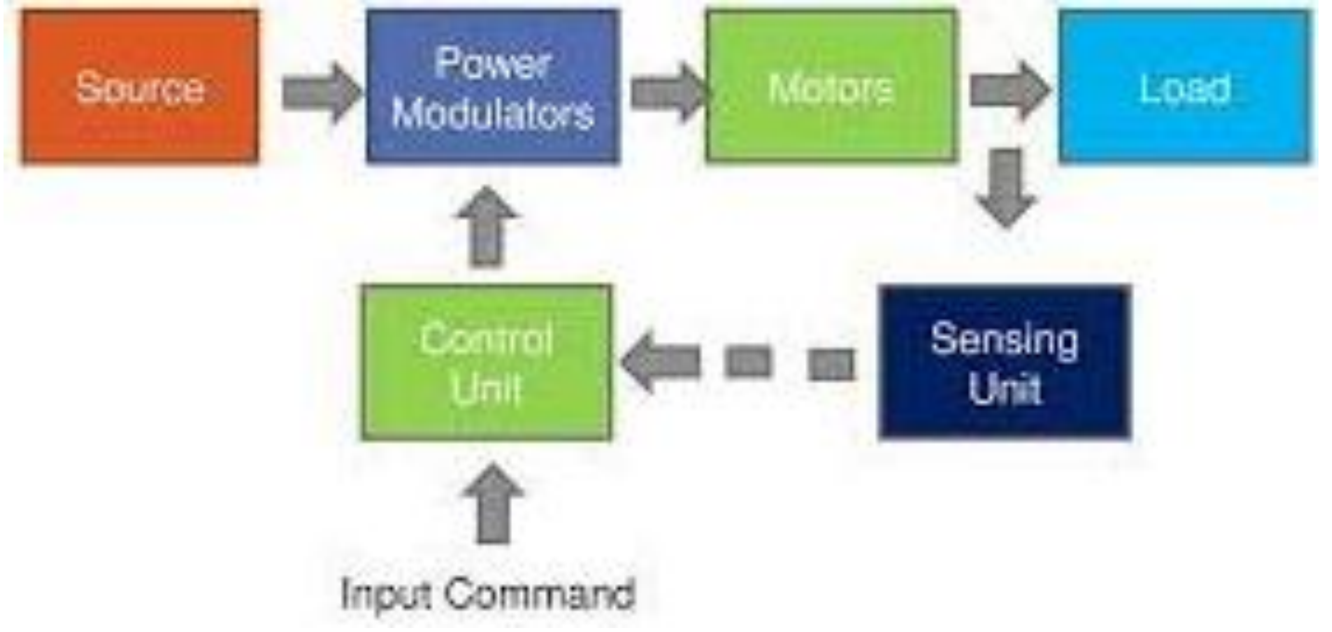
- ***Fundamentals of Electrical Drives – Gopal K Dubey***

Motion Control- DRIVE



ELECTRICAL DRIVES

- Systems employed for motion control are called *DRIVES*
- Employ any of prime movers such as diesel or petrol engine, gas, hydraulic motors & electric motors
- Drives supplying electric motors are known as electrical drives
- Block diagram of an electrical drive:



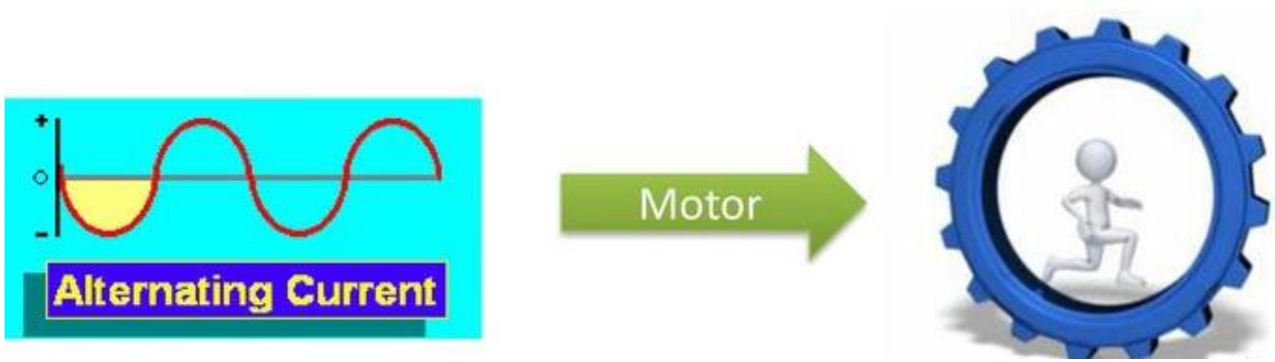
Advantages of ELECTRICAL DRIVES

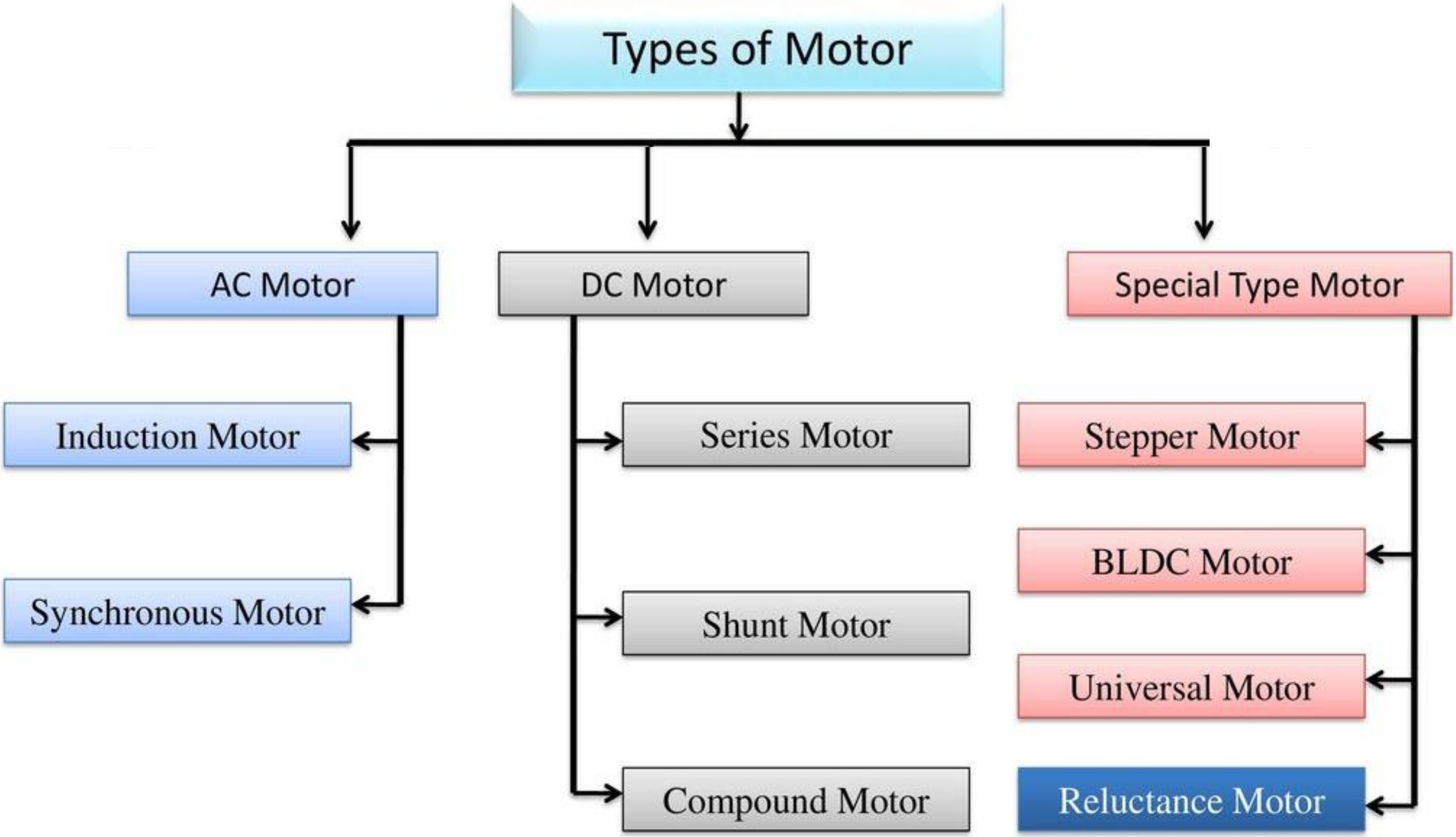
- They have flexible control characteristics – automatic fault detection systems
- They are available in wide range of torque, speed & power
- Electric Motors have high efficiency, low no load losses, short time overloading capability, longer life, lower noise, low maintenance requirements, cleaner operation.
- Adaptable to any operating conditions explosive or radioactive etc
- Do not pollute the environment
- Can operate in all 4 quadrants of speed torque plane.
- No need refuel or warm up the motor. Motor can be started instantly & can immediately be fully loaded.
- They are powered by electrical energy which has a number of advantages over other forms of energy.

What is Motor......?

Electrical Energy

(Rotational Force) Mechanical Energy





Types of Motor
AC Motor
DC Motor
Special Type Motor
Induction Motor
Synchronous Motor
Series Motor
Shunt Motor
Compound Motor
Stepper Motor
BLDC Motor
Universal Motor
Reluctance Motor

Type of Loads

- Load torque can be of two types
- (1) Active load torque:- Active torques continues to act in the same direction irrespective of the direction of the drive. e.g. gravitational force or deformation in elastic bodies.
- (2) Passive load torque:- the sense of the load torque changes with the change in the direction of motion of drive. e. g. torques due to friction, due to shear and deformation of inelastic bodies.


THANK YOU

MODULE 5
CLASSIFICATION OF ELECTRIC DRIVES

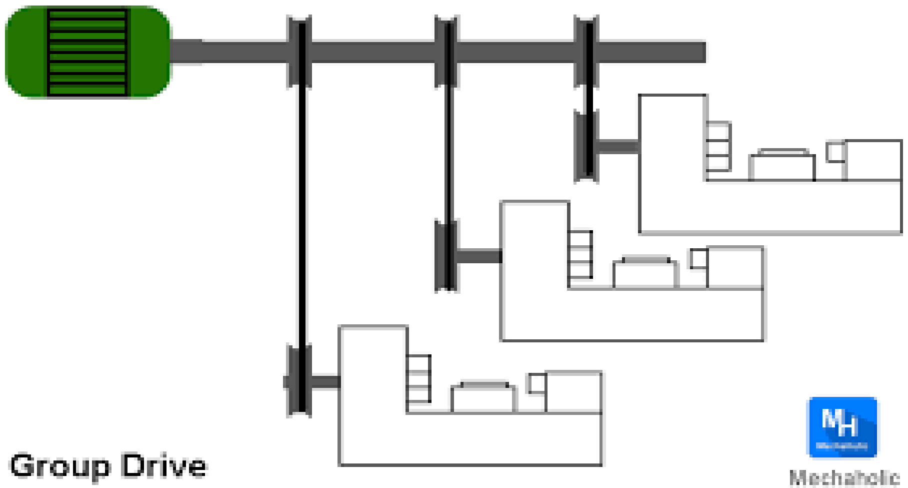
Generally classified into 3 categories:

- Group drive
- Individual Drive
- Multimotor Drive

CLASSIFICATION OF ELECTRIC DRIVES(Cont'd)

Group Drive :

- If several group of mechanisms or machines are organized on one shaft and driven or actuated by one motor, the system is called a group drive or shaft drive.



Group Drive

Advantage :

Most Economical

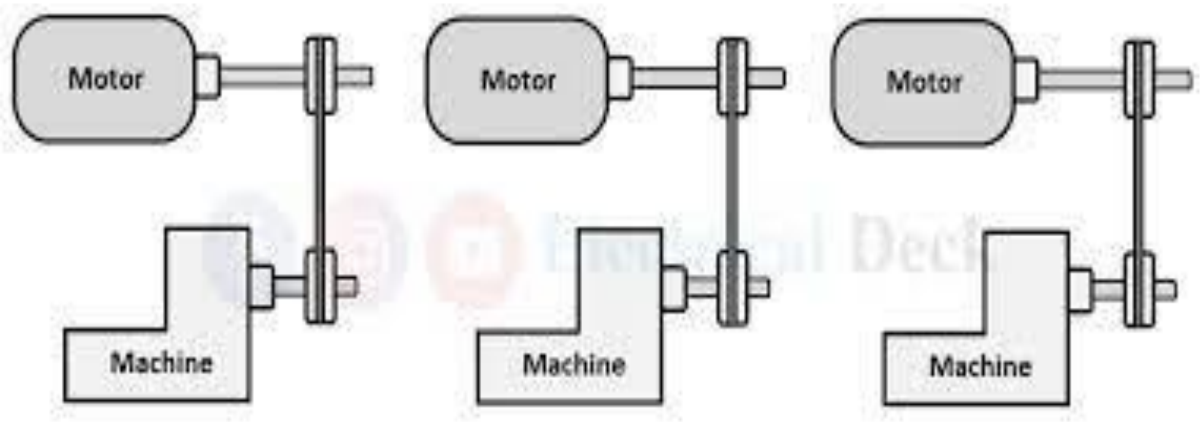
Disadvantage :

- Any Fault that occurs in the driving motor renders all the driving equipment idle.
- Efficiency low because of losses occurring in the energy transmitting mechanisms (Power loss).
- Not safe to operate. Also Noise level at the working spot is high.

CLASSIFICATION OF ELECTRIC DRIVES(Cont'd)

Individual Drive:

- If a single motor is used to drive or actuate a given mechanism and it does all the jobs connected with this load , the drive is called individual drive.
- All the operations connected with operating a lathe may be performed by a single motor.
- Each motor is driven by its own separated motor with the help of gears , pulleys etc.



Individual Drive

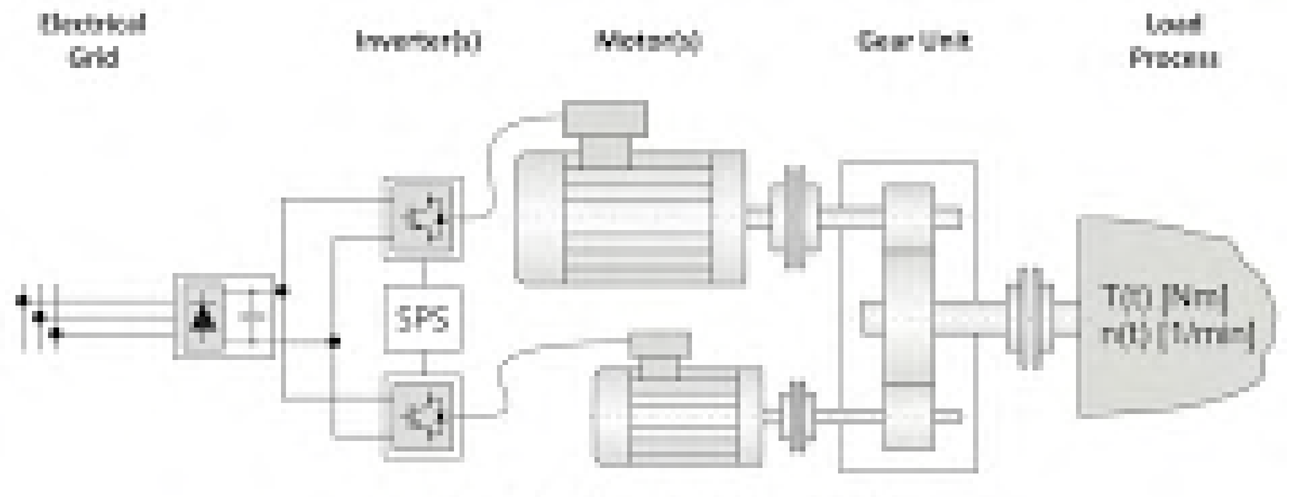
Disadvantage:

- Power loss occurs.

CLASSIFICATION OF ELECTRIC DRIVES(Cont’d)

Multi Motor Drive:

- Each operation of the mechanism is taken care of by a separate drive motor.
- The System contains several individual drives each of which is used to operate its own mechanism.



Multi-Motor Drive System: MMDS

CLASSIFICATION OF ELECTRIC DRIVES

***Multi Motor Drive*:**

Separate motors are provided for actuating different parts of the driven mechanism.

Advantage :

- Each Machine is driven by a separated motor it can be run and stopped as desired.
- Machines not required can be shut down and also replaced with a minimum of dislocation.
- There is a flexibility in the installation of different machines.
- In the case of motor fault, only its connected machine will stop where as others will continue working undisturbed.
- Absence of belts and line shafts greatly reduces the risk of a accidents to the operating personnel.

Disadvantage:

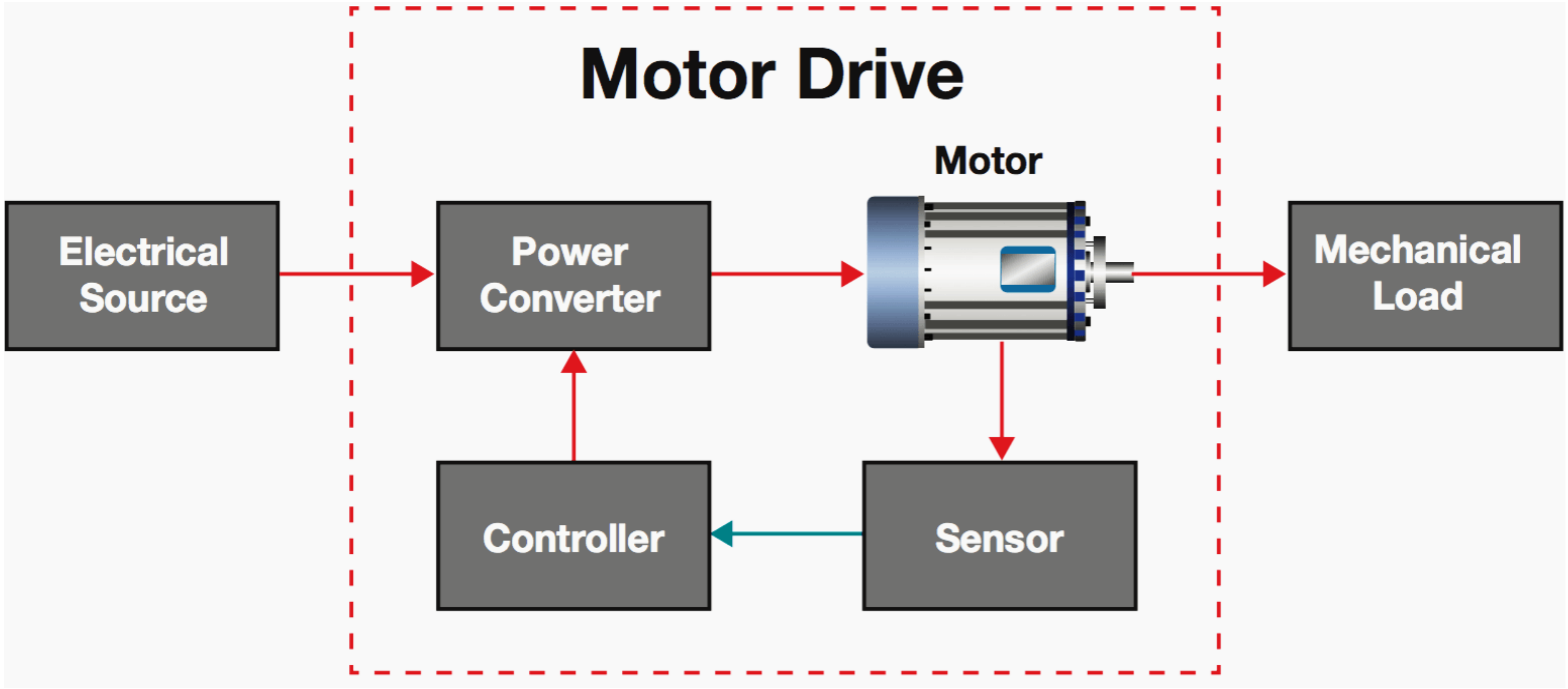
- Initial high cost

Dynamics of Electric Drive

Dynamics of motor-load combination Drive

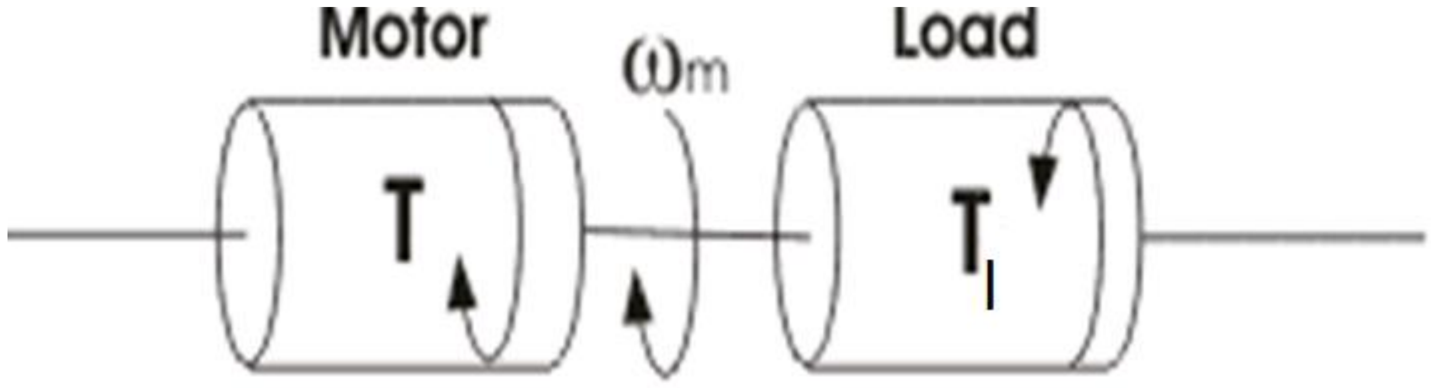
- When an electric motor rotates, it is usually connected to a load which has a rotational or translational motion.

- The speed of the motor may be different from that of the load. To analyze the relation among the drives and loads, the concept of **dynamics of electrical drives** is introduced.



Dynamics of motor-load combination

Drive



Motor Load System

Dynamics of motor-load combination Drive

- We can describe the dynamics of electrical drive easily by the following instant.

  J = Polar moment of inertia of motor load
  ω_m = Instantaneous angular velocity
  T = Instantaneous value of developed motor torque
  T_l = Instantaneous value of load torque referred to motor shaft

Dynamics of motor-load combination Drive

- Now, from the fundamental torque equation –

$$T-T_l=d(J\omega_m)/dt=Jd\,\omega_m/dt+\omega_m\,dJ/dt$$

For drives with constant inertia,

$$dJ/dt=0$$

Therefore

$$T=T_l+Jd\,\omega_m/dt$$

Dynamics of motor-load combination Drive

- So, the above equation states that the motor torque is balanced by load torque and a dynamic torque $J(d\omega_m/dt)$.
- This torque component is termed as dynamic torque as it is only present during the transient operations.
- From this equation, we can determine whether the drive is accelerating or decelerating.

  - *So, the torque, balancing the* ***Dynamics of electrical braking*** *is very helpful.*

CLASSIFICATION OF LOAD TORQUE

Various load torques can be classified into

- Active load torques
- Passive load torques

- Active load torque: Load torques which has the potential to drive the motor under equilibrium conditions are called active load torques.

  Eg: Torque due to force of gravity

  Torque due to tension.

- Passive load torque: Load torques which always oppose the motion and change their sign on the reversal of motion are called passive load torques.

  Eg: Torque due to friction, cutting etc.

COMPONENTS OF LOAD TORQUE

The load torque T_l can be further divided in to following components:

- Friction Torque (T_F)
- Windage Torque (T_W):
- Torque required to do useful mechanical work (T_L).

COMPONENTS OF LOAD TORQUE

Variation of friction torque with speed:

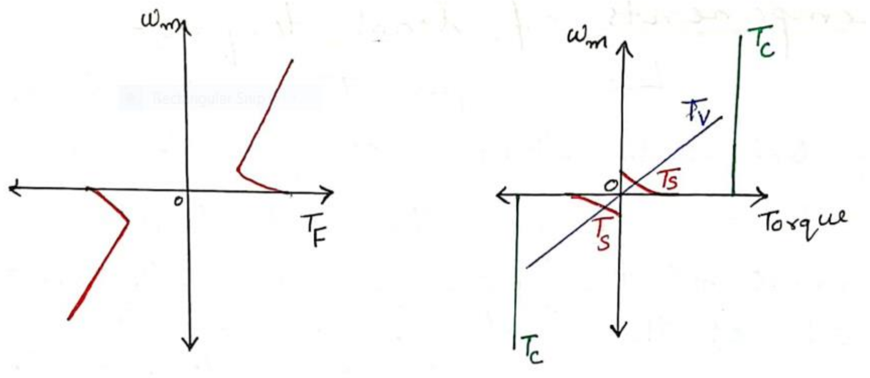


Fig. (a) Fig. (b)

Friction torque can also be resolved into three component:

- Viscous Friction (T_v)
- Coulomb Friction (T_c)
- Static Friction (Stiction, T_s)

COMPONENTS OF LOAD TORQUE

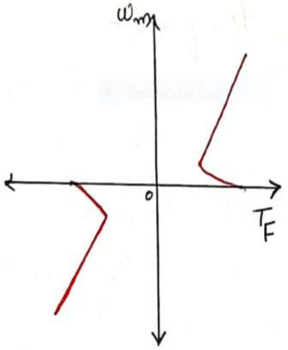


Fig. (a)

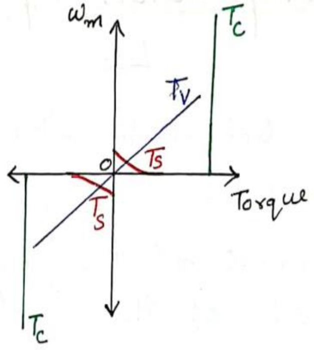


Fig. (b)

- Component T_v varies linearly with speed is called viscous friction and is given by

$$T_v = B\omega_m$$

Where B is viscous friction co-efficient.

- Another component T_C, which is independent of speed, is known as coulomb friction.

- Third component T_s accounts for additional torque present at stand still. Since T_s is present only at stand still it is not taken into account in the dynamic analysis.

COMPONENTS OF LOAD TORQUE

- Windage Torque (T_W):

When motor runs, wind generates a torque opposing the motion. This is known as windage torque. T_W which is proportional to speed squared is given by

$$T_w = C\omega_m^2$$

Where C= constant

- Torque required to do useful mechanical work.

COMPONENTS OF LOAD TORQUE

From this for finite speed

$$T_l = T_F + T_w + T_L$$

$$T_l = T_L + B\omega_m + T_C + C\omega_m^2$$

In many application $T_C + C\omega_m^2$ is very small

Therefore

$$T_l = T_L + B\omega_m$$

Thus the fundamental torque equation

$T = T_l + J d\omega_m / dt$ become

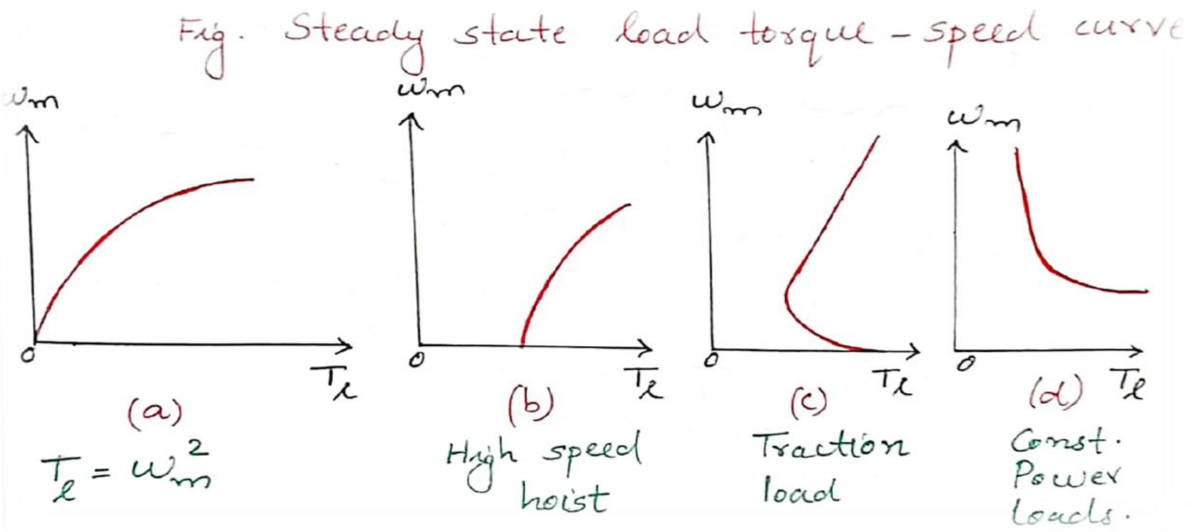
$$T = J d\omega_m / dt + T_L + B\omega_m$$

If there is a torsional elasticity in shaft coupling to the load to the motor an additional component to the load torque, coupling torque, $T_e = K_e \theta_e$

NATURE OF LOAD TORQUE

- Nature of this torque depends upon particular application.

- It may be some function of speed, it may be time invariant or time variant, its nature may also change with the load's mode of operation.



NATURE OF LOAD TORQUE

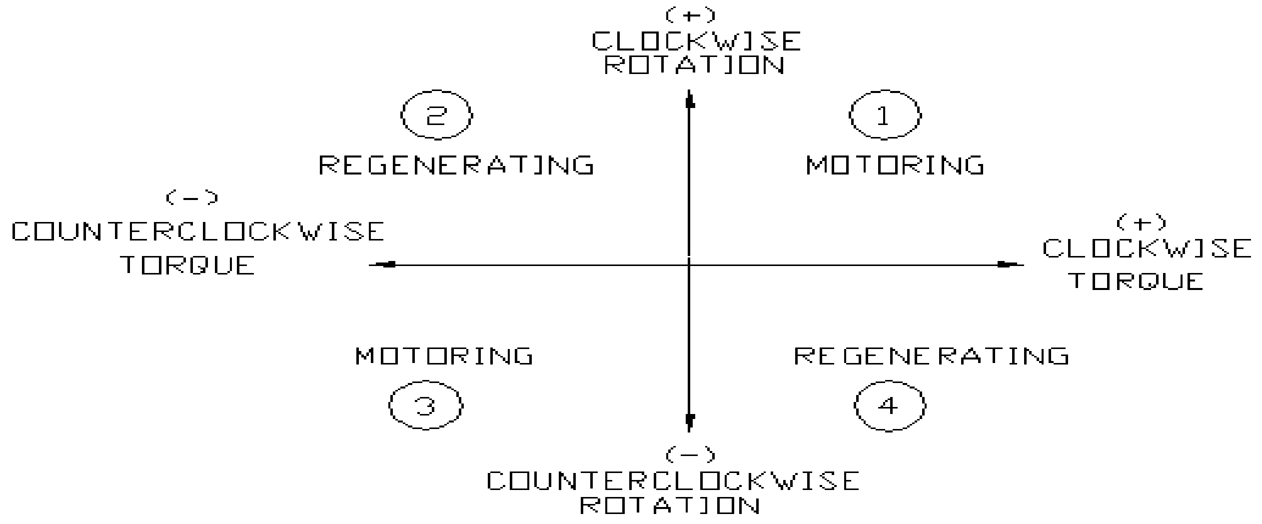
- The nature of load torque depends upon particular application.
- A low speed hoist is an example of load when the torque is constant and independent of speed.
- At low speeds ,windage torque is negligible therefore net torque is mainly due to gravity which is constant and independent of speed.

NATURE OF LOAD TORQUE

- There are drives where coulomb friction dominates over other torque components. conesquently torque is independent of speed.

  Example : Paper mill drive.
- Fans, Compressors, Aeroplanes, Centrifugal pumps, ship propellors, High speed hoists, traction are the example of the case where load torque is a function of speed.

TORQUE-SPEED SIGN CONVENTON



QUADRANT	ROTATION	TORQUE	MOTORING OR REGENERATING
1	(+)	(+)	MOTORING
2	(+)	(-)	REGENERATING
3	(-)	(-)	MOTORING
4	(-)	(+)	REGENERATING

FIGURE D.4 FOUR QUADRANT OPERATION