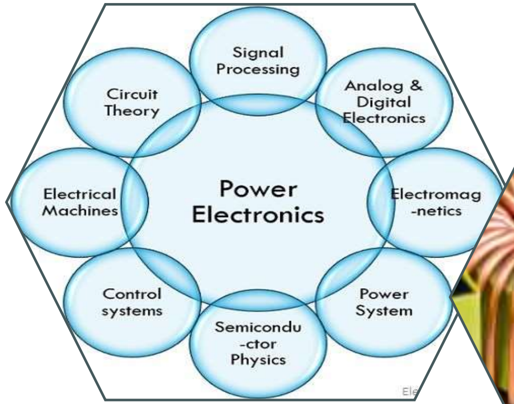


Power Electronics

Prepared by :
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Basic Course Information

Course Title	Power Electronics
Course Code	EEE 319
Credit	03
Marks	150

SYNOPSIS/RATIONALE

The course focuses on the principles and applications of power electronics, which play a critical role in the control and conversion of electrical energy. It provides an in-depth understanding of power semiconductor devices, rectifiers, converters, and inverters, along with their associated control techniques. The course equips students with the ability to analyze, design, and implement power electronic systems for a variety of real-world applications.

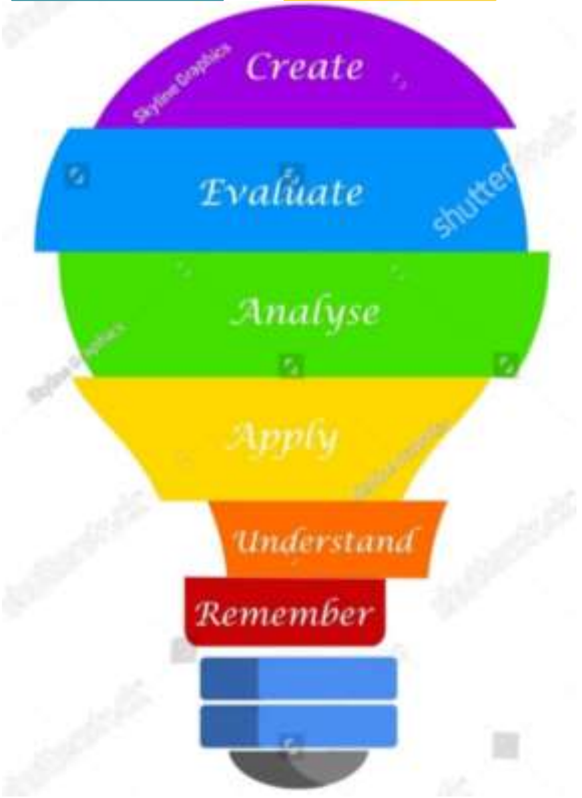
OBJECTIVE

The objectives of the course are:.

- Upon successful completion of this course, students will be able to:
- Comprehend the operational principles of power semiconductor devices such as SCRs, GTOs, IGBTs, and TRIACs.
- Analyze and design rectifiers, DC-DC converters, and inverters for practical applications.
- Implement techniques to protect power electronic devices and ensure system reliability.
- Explore the role of power electronics in sustainable energy solutions, motor drives, and industrial automation.

Course Learning Outcome (CLO)

CLO No.	Course Learning Outcome
CLO1	Explain the static and dynamic characteristics of power semiconductor devices and their applications.
CLO2	Analyze and design performance parameters for rectifiers, DC-DC converters, and inverters.
CLO3	Identify and mitigate issues related to device protection, switching losses, and thermal management.
CLO4	Develop practical solutions for integrating power electronics into renewable energy systems and motor drives.



ASSESSMENT PATTERN

CIE- Continuous Internal Evaluation (90 Marks)

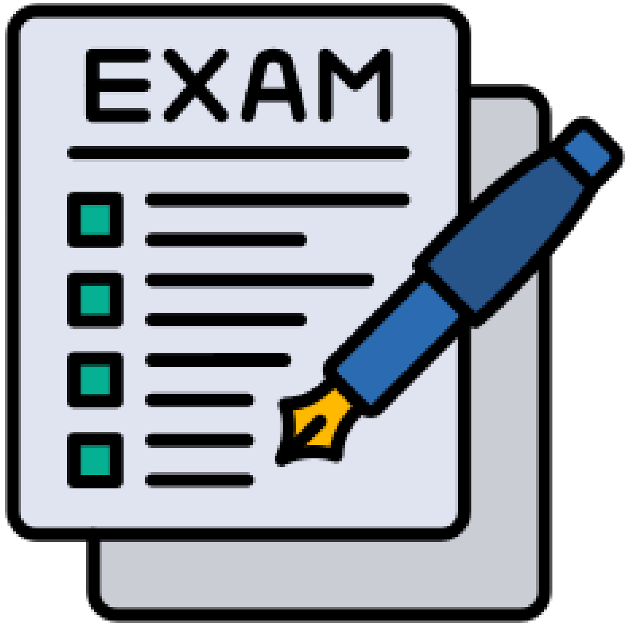
Bloom's Category Marks (out of 90)	Tests Mid-term (45)
Remember	08
Understand	08
Apply	08
Analyze	08
Evaluate	08
Create	05

Class Test	**15**
Presentation	**15**
Attendance	**15**

ASSESSMENT PATTERN

SEE- Semester End Examination (60 Marks)

Bloom's Category	Tests
Remember	**10**
Understand	**10**
Apply	**10**
Analyze	**10**
Evaluate	**10**
Create	**10**



COURSE CONTENT

Module No.	Module Title	Topics
1	Power Semiconductor Devices	Thyristors, SCR, TRIAC, GTO, IGBT, Power MOSFET, and Power BJT; Static and dynamic characteristics; Triggering and commutation techniques; Protection, cooling, and mounting.
2	Rectifiers	Single-phase and three-phase rectifiers (half-wave, full-wave, bridge types); Controlled and uncontrolled rectifiers; Harmonics, power factor improvement, freewheeling diodes.
3	DC-DC Converters	Step-up and step-down choppers; One, two, and four-quadrant operations; Continuous and discontinuous conduction modes; DC motor control and battery charging.
4	Inverters	Single-phase inverters (half-bridge, full-bridge, PWM techniques); Three-phase inverters (120° and 180° modes); Voltage and frequency control techniques; Applications (UPS, SMPS).

Time distributions

Module Title	Course Content	CLOs	Class Duration (Hours)
Power Semiconductor Devices	Thyristors, SCR, TRIAC, GTO, IGBT, Power MOSFET, and Power BJT; Static and dynamic characteristics; Triggering and commutation techniques; Protection, cooling, and mounting.	CLO1: Describe the characteristics and operational principles of power semiconductor devices. (Understanding - C2)	9
Rectifiers	Single-phase and three-phase rectifiers (half-wave, full-wave, bridge types); Controlled and uncontrolled rectifiers; Harmonics, power factor improvement, freewheeling diodes.	CLO2: Apply analysis techniques to design and evaluate rectifiers with various types of loads. (Applying - C3)	8
DC-DC Converters	Step-up and step-down choppers; One, two, and four-quadrant operations; Continuous and discontinuous conduction modes; DC motor control and battery charging.	CLO3: Analyze the performance of DC-DC converters for different operational modes. (Analyzing - C4)	8
Inverters	Single-phase inverters (half-bridge, full-bridge, PWM techniques); Three-phase inverters (120° and 180° modes); Voltage and frequency control techniques; Applications (UPS, SMPS).	CLO4: Design inverter circuits and justify their use in renewable energy and industrial applications. (Creating - C6)	9

Course Schedule

Week No.	Course Content	Teaching-Learning Strategies	Sources	Assessment Strategies	CLOs
1	Introduction to Power Electronics: Overview and applications of power semiconductor devices.	Lecture, Interactive Discussions	Lecture Notes, Reference Textbooks, Videos (Introduction to Power Electronics)	Attendance, Class Participation	CLO1: Describe the characteristics and operational principles of power semiconductor devices. (C2)
2	Thyristors and SCR: Static and dynamic characteristics, triggering mechanisms, and commutation techniques.	Lecture, Problem-Solving Sessions	Lecture Notes, Reference Textbooks, Slides, Video (Thyristor Operation)	Quiz 1	CLO1
3	TRIAC, GTO, IGBT, and MOSFET: Characteristics, operation, and applications.	Lecture, Visual Demonstrations	Lecture Notes, Reference Textbooks, Videos (IGBT Working Principle)	Assignment 1	CLO1
4	Protection and cooling of power semiconductor devices.	Lecture, Case Study Analysis	Lecture Notes, Reference Textbooks, Slides	Group Discussion	CLO1
5	Rectifiers: Single-phase half-wave and full-wave rectifiers, midpoint and bridge configurations.	Lecture, Interactive Problem-Solving	Lecture Notes, Reference Textbooks, Slides, Text (Rectifier Circuit Design)	Quiz 2	CLO2: Apply analysis techniques to design and evaluate rectifiers with various types of loads. (C3)
6	Three-phase rectifiers: Half-wave and full-wave rectifiers, harmonic analysis, and power factor improvement.	Lecture, Problem-Solving Sessions	Lecture Notes, Reference Textbooks, Videos (Three-Phase Rectifiers)	Assignment 2	CLO2
7	Freewheeling diodes and their effects on rectifier performance.	Lecture, Interactive Discussions	Lecture Notes, Reference Textbooks, Slides	Class Participation	CLO2
8	DC-DC Converters: Step-up and step-down choppers, one-quadrant and two-quadrant operations.	Lecture, Case Study Analysis, Practical Demonstrations	Lecture Notes, Reference Textbooks, Videos (DC-DC Converters)	Midterm Review Discussion	CLO3: Analyze the performance of DC-DC converters for different operational modes. (C4)
Midterm Exam	Comprehensive assessment of all content covered in weeks 1-8.	Examination Session	Lecture Notes, Reference Textbooks, Videos (Recap on Power Electronics Basics)	Midterm Exam	CLO1, CLO2, CLO3

Course Schedule

Week No.	Course Content	Teaching-Learning Strategies	Sources	Assessment Strategies	CLOs
9	DC-DC Converters: Four-quadrant operations and continuous/discontinuous conduction modes.	Lecture, Interactive Problem-Solving, Hands-On Examples	Lecture Notes, Reference Textbooks, Text (DC Chopper Design)	Quiz 3	CLO3
10	Applications of DC-DC converters in motor control and battery charging.	Lecture, Practical Examples	Lecture Notes, Reference Textbooks, Videos (DC Motor Control)	Assignment 3	CLO3
11	Inverters: Single-phase inverters (half-bridge, full-bridge, PWM techniques).	Lecture, Interactive Problem-Solving, Practical Demonstrations	Lecture Notes, Reference Textbooks, Videos (Single-Phase Inverters)	Quiz 4	CLO4: Design inverter circuits and justify their use in renewable energy and industrial applications. (C6)
12	Three-phase inverters: 120° and 180° conduction modes, control techniques.	Lecture, Group Discussions, Practical Examples	Lecture Notes, Reference Textbooks, Slides	Assignment 4	CLO4
13	Voltage and frequency control techniques for inverters.	Lecture, Interactive Problem-Solving	Lecture Notes, Reference Textbooks, Text (Inverter Control Techniques)	Class Participation	CLO4
14	Applications of inverters in renewable energy systems and industrial automation.	Lecture, Case Studies, Group Discussions	Lecture Notes, Reference Textbooks, Videos (Renewable Energy Applications)	Group Presentation	CLO4
15	Course Review: Comprehensive analysis of power electronics concepts and practical applications.	Lecture, Open Discussions, Question-and-Answer Sessions	Lecture Notes, Reference Textbooks, Videos (Course Recap)	Mock Test	CLO1, CLO2, CLO3, CLO4
16	Mock Exam Preparation: Practice problems on converters, inverters, and rectifiers.	Problem-Solving Workshops, Hands-On Sessions	Lecture Notes, Reference Textbooks,	Mock Test	CLO1, CLO2, CLO3, CLO4
17	Final Exam: Comprehensive assessment of the entire course.	Examination Session	Lecture Notes, Reference Textbooks,	Final Exam	CLO1, CLO2, CLO3, CLO4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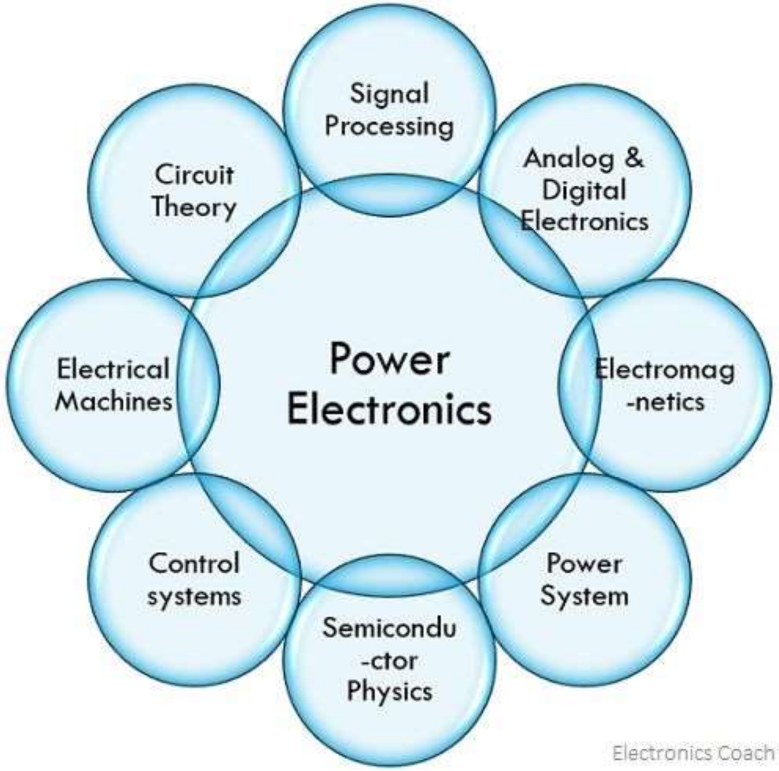
POWER ELECTRONICS

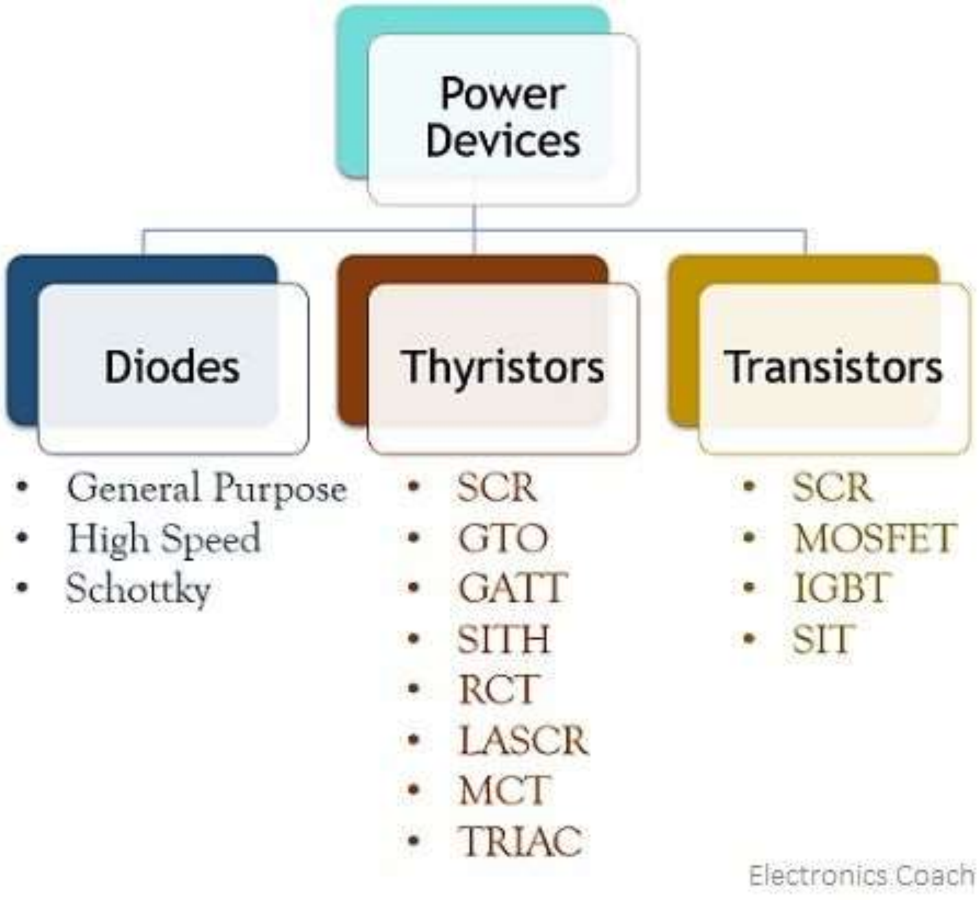
- The control of electric motor drives requires control of electric power. Power electronics have eased the concept of power control. Power electronics signifies the word power electronics and control or we can say the electronic that deal with power equipment for power control.

- Power electronics based on the switching of power semiconductor devices. With the development of power semiconductor technology, the power handling capabilities and switching speed of power devices have been improved tremendously.



Classification

- **The first SCR was developed in late 1957. Power semiconductor devices are broadly categorized into 3 types:**



Power Diode

- A power diode is a semiconductor device that can handle high voltages and currents, and is used to convert alternating current (AC) to direct current (DC). Power diodes are used in many power electronics circuits, and are a key component of modern power electronics

Characteristics of power diodes

- **Operation**

Power diodes act as one-way valves, allowing current to flow in one direction and blocking it in the other.

- **Construction**

Power diodes are made of three layers: a heavily doped P+ layer, a lightly doped n– layer, and a heavily doped n+ layer. The P+ layer acts as the anode, and the n+ layer acts as the cathode.

Types

There are three types of power diodes: general purpose diodes, fast recovery diodes, and Schottky diodes.

Applications

Power diodes are used in many applications, including power supplies, inverters, motor drives, and rectification devices.

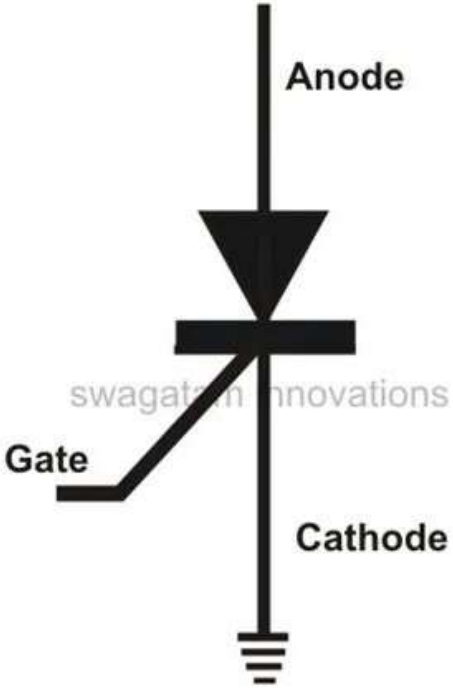
Ratings

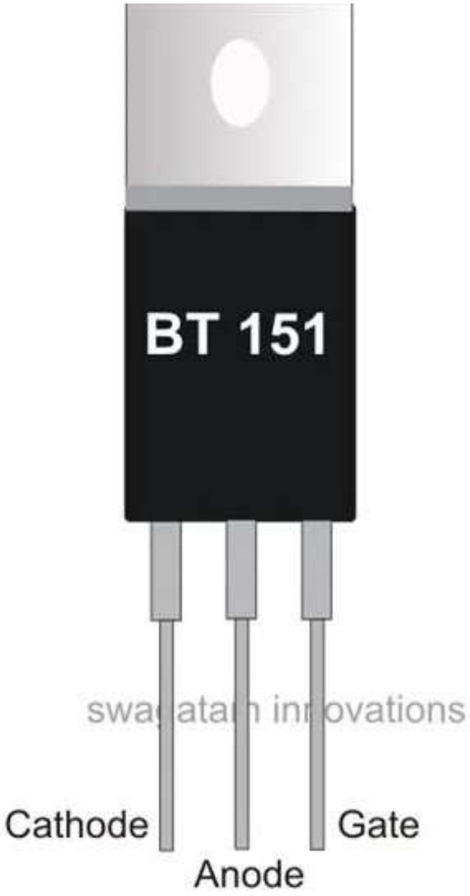
Power diodes can have current ratings from less than 1 A to several thousand amps, and voltage ratings from 50 V to 5 KV.

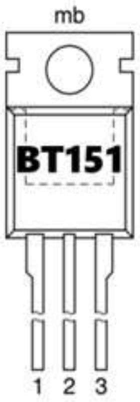
Thyristor

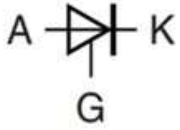
- Thyristor is a four layer three junction pnpn semiconductor switching device.

- It has 3 terminals these are anode, cathode and gate. SCRs are solid state device, so they are compact, possess high reliability and have low loss.









Pin	Symbol	Description
1	K	cathode
2	A	anode
3	G	gate
mb	mb	anode

Silicon controlled rectifier

Silicon controlled rectifier

A semiconductor device that controls the flow of current in one direction. It has three terminals: an anode, a cathode, and a gate. The current flows from the anode to the cathode. SCRs are used in power converters, inverters, lamp dimmers, motor control, and power regulators

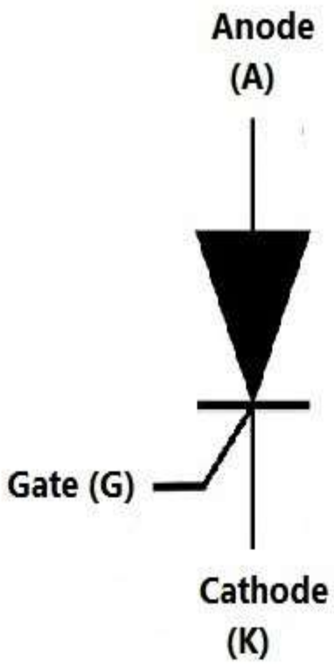
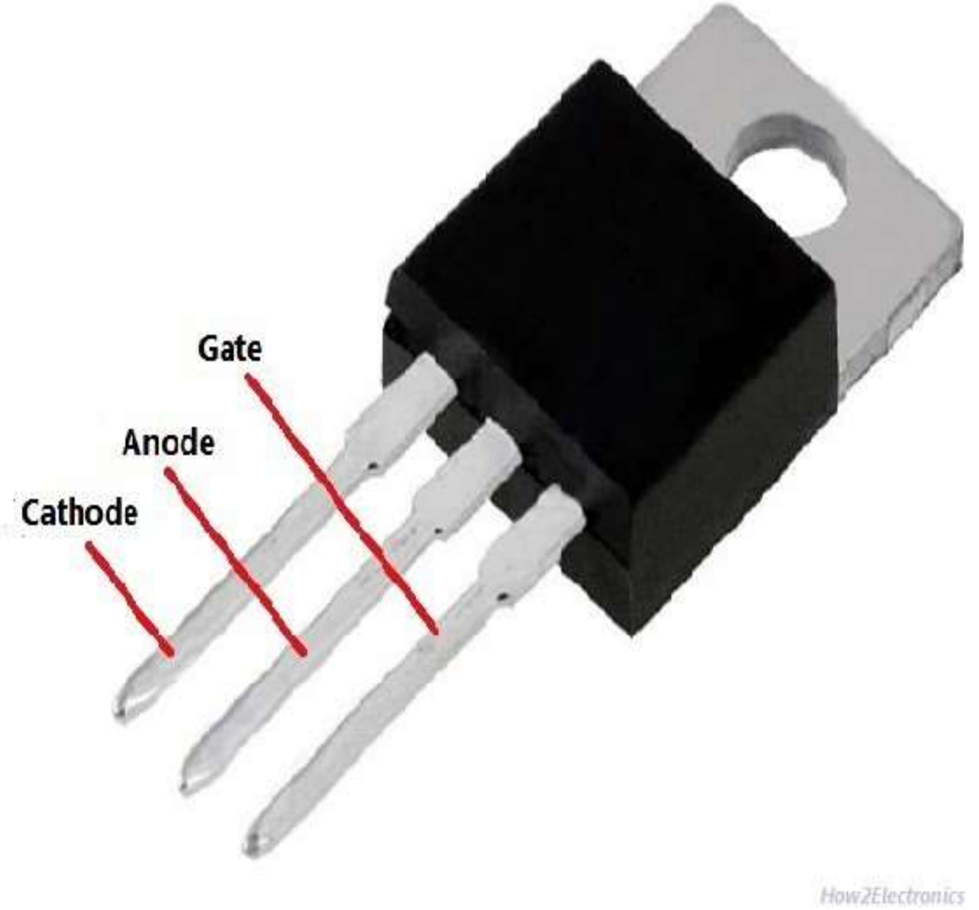
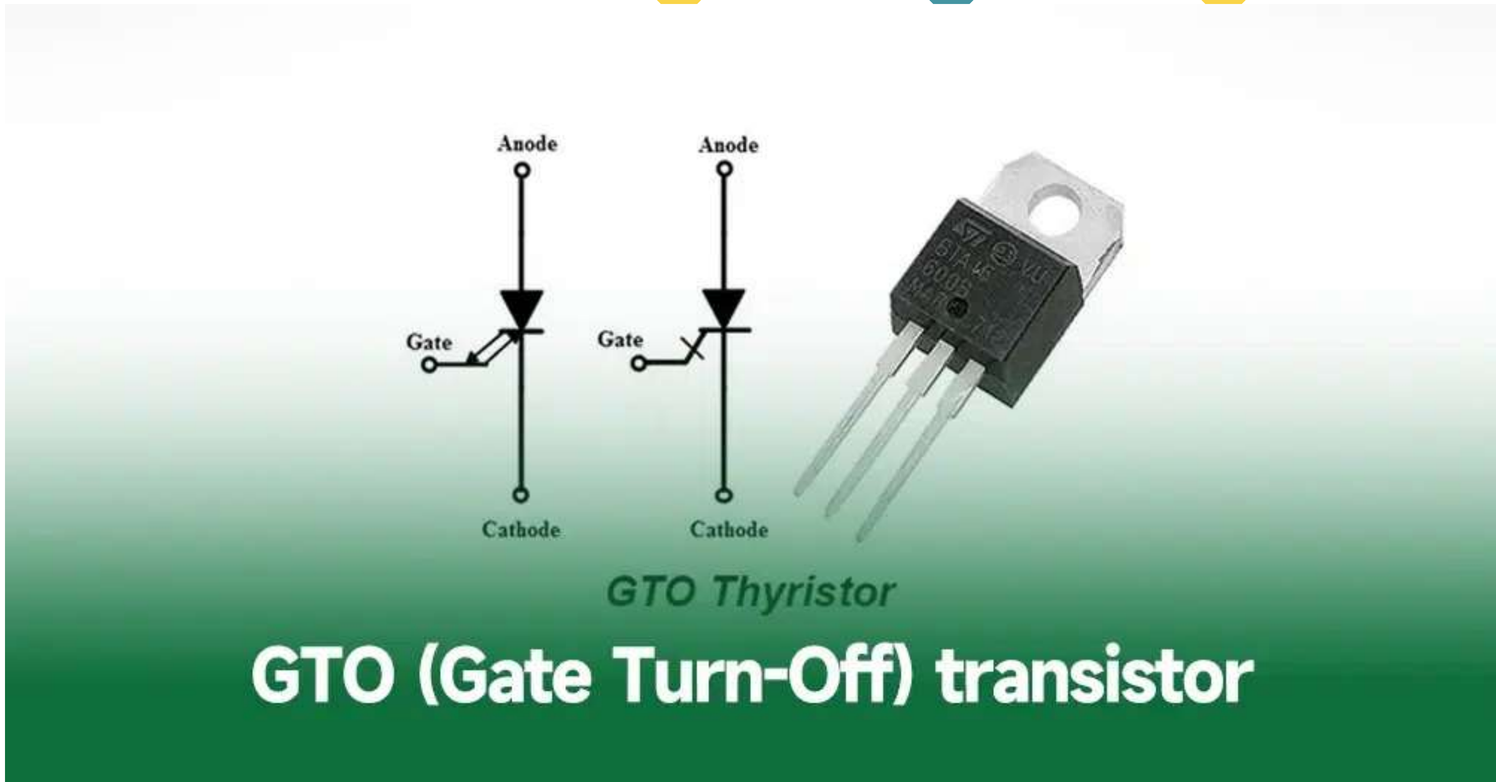


Fig: SCR Symbol



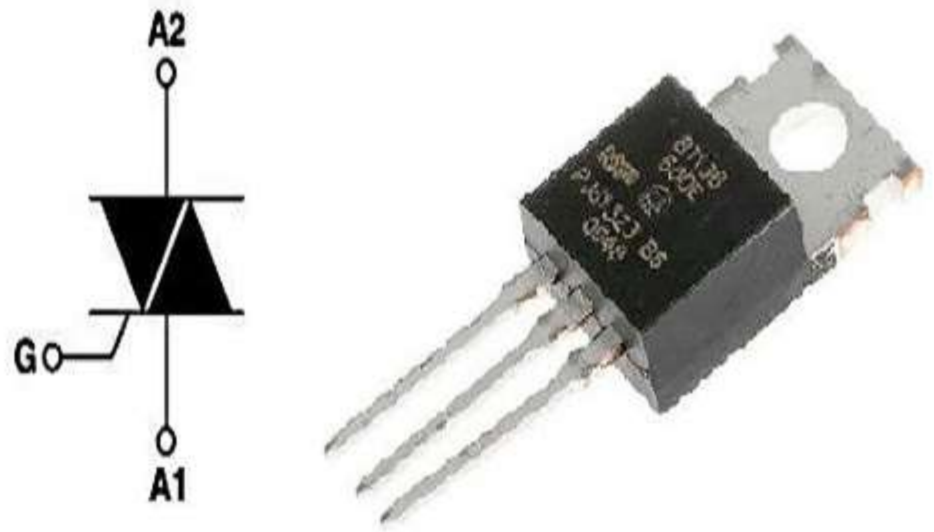
(GTO)

A gate turn-off thyristor (GTO) is a semiconductor device that can be turned on and off with a gate signal, making it a fully controllable switch. GTOs are used in power electronics for switching and controlling electrical power, especially in high-power applications

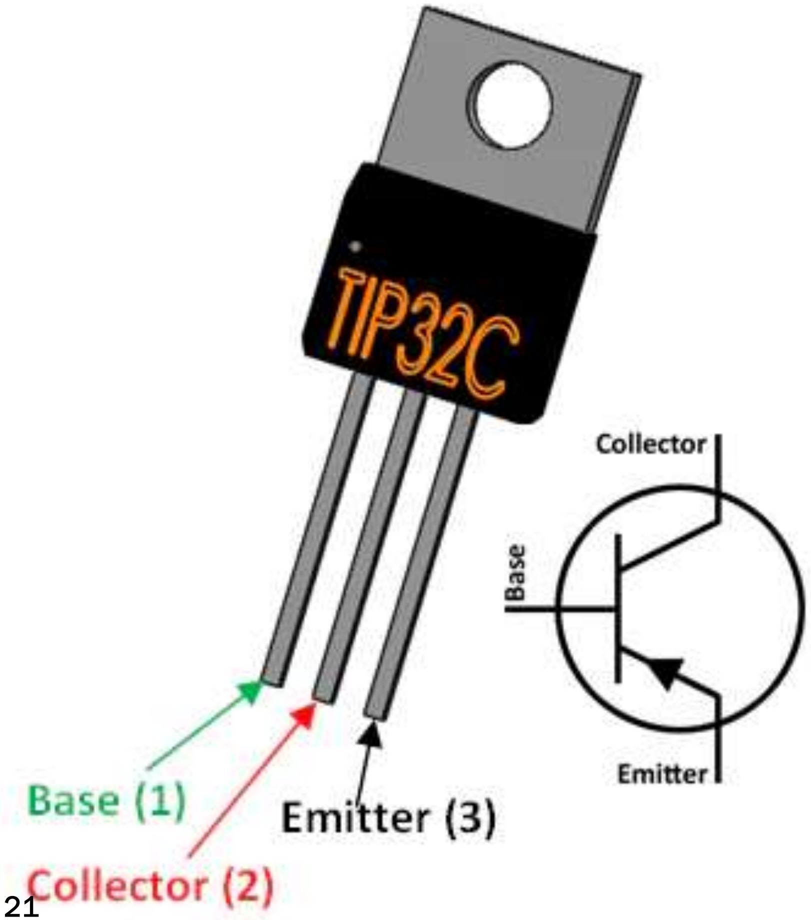


TRIAC

A triac, which stands for "triode for alternating current," is a three-terminal semiconductor device in power electronics that acts as a bidirectional switch, meaning it can conduct electrical current in both directions when triggered by a gate signal, making it ideal for controlling alternating current (AC) power in applications like light dimmers and motor speed controllers; essentially, it functions like two silicon controlled rectifiers (SCRs) connected in reverse parallel with a shared gate terminal

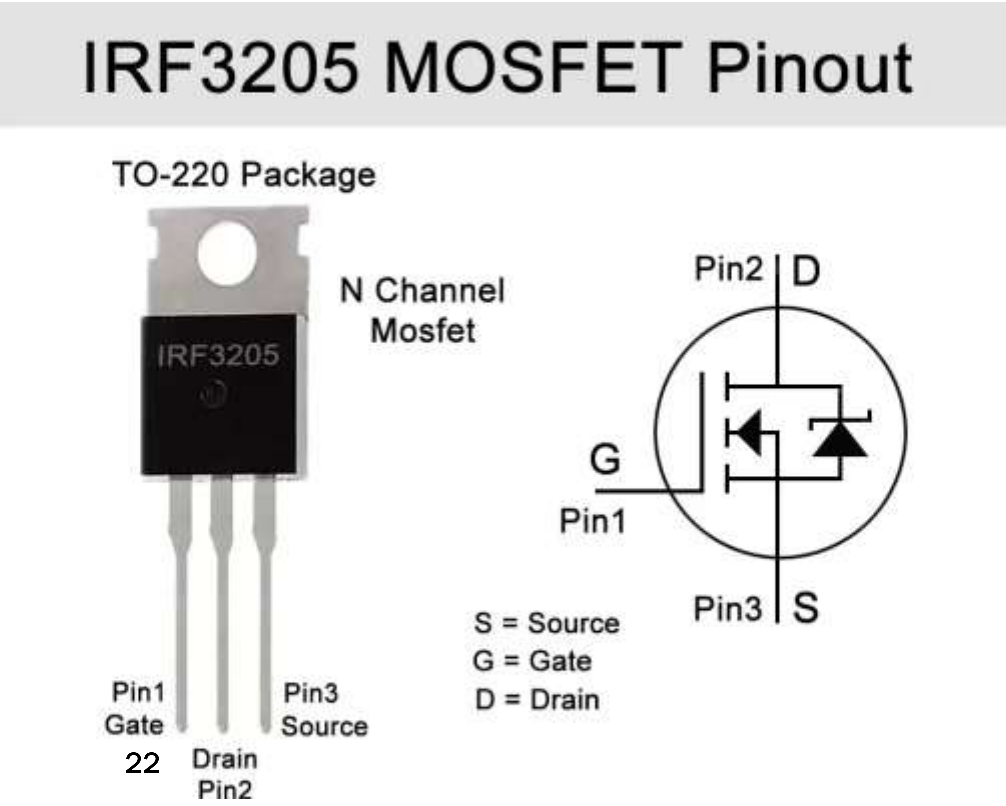


Power Transistor



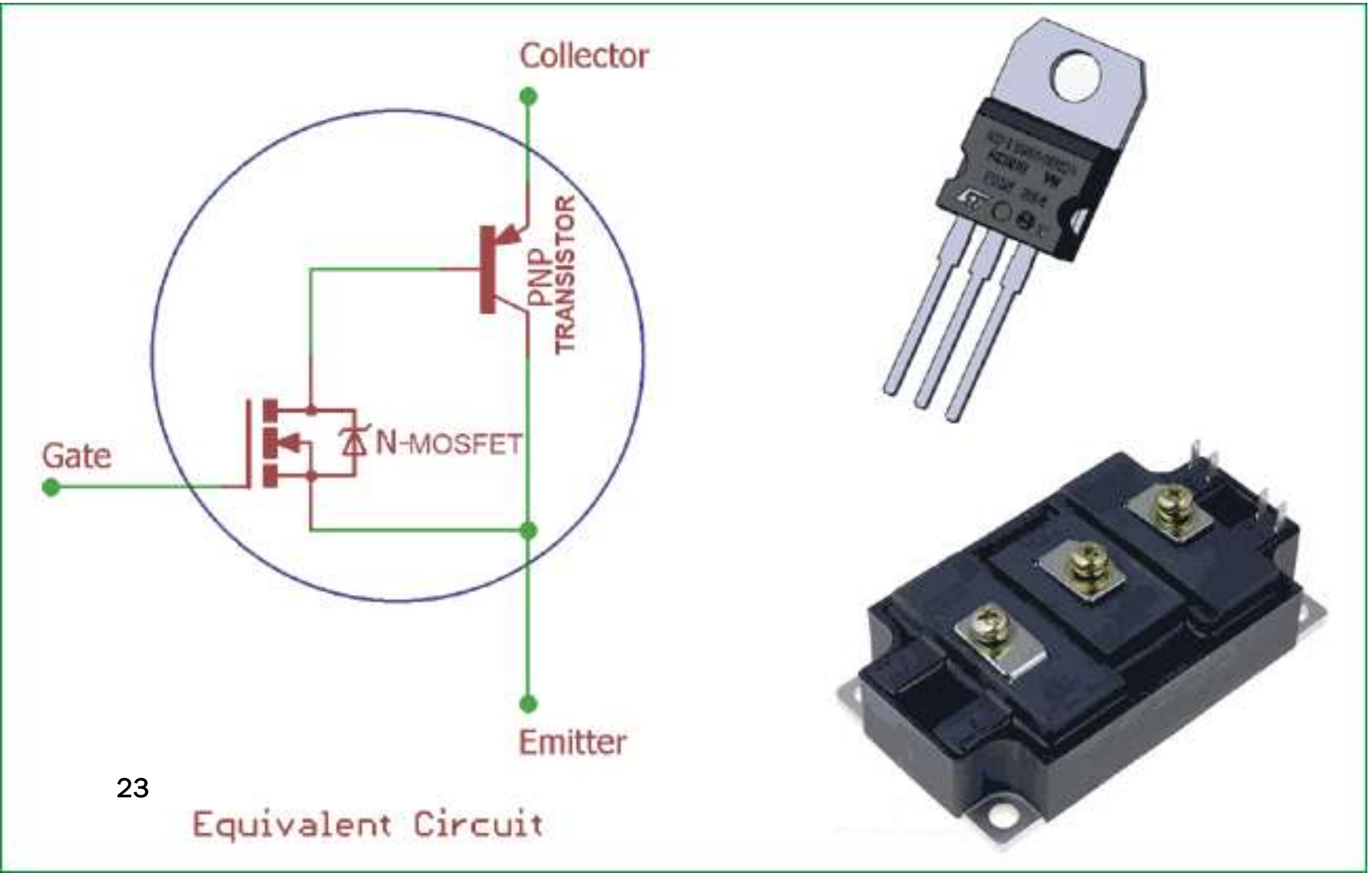
Power transistors are three terminal devices which are composed of semiconductor materials. They feature emitter, base and collector terminals. These devices are particularly designed to control high current – voltage rating.

Power MOSFET



A "Power MOSFET" in power electronics refers to a specialized type of Metal Oxide Semiconductor Field Effect Transistor (MOSFET) designed to handle significant power levels, characterized by its high switching speed, good efficiency at low voltages, and ability to operate at high voltages, making it a widely used component in power converter circuits like DC-DC converters and motor controllers.

IGBT



An IGBT, or Insulated Gate Bipolar Transistor, is a semiconductor device that combines a bipolar power transistor with a MOSFET structure and a control input. IGBTs are used in high-power applications that require high voltage and current capabilities.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SCR

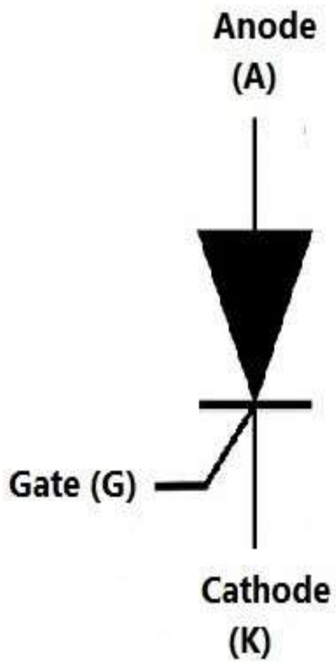
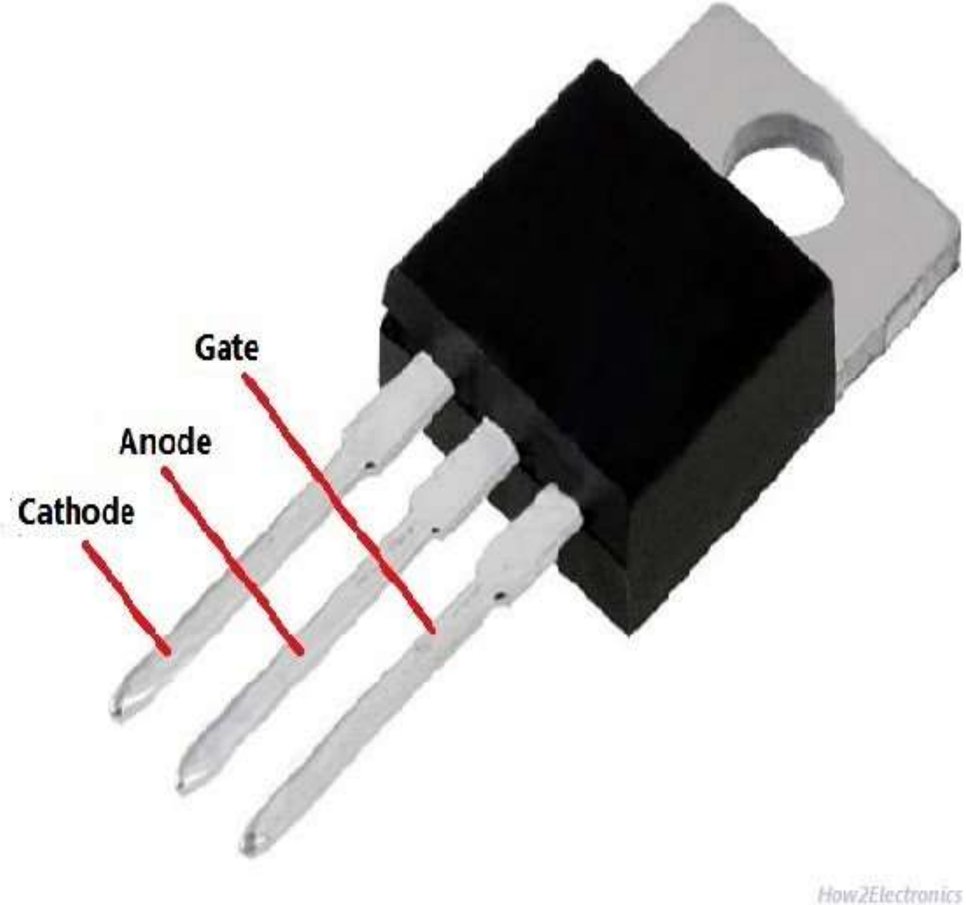
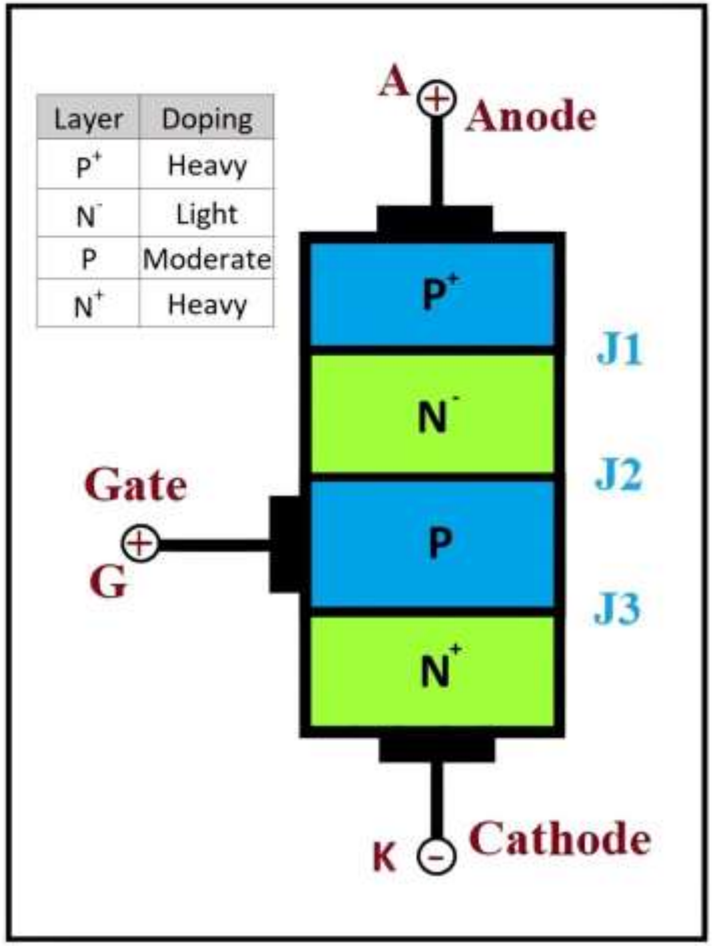


Fig: SCR Symbol



SCR is made up of silicon, it act as a rectifier; it has very low resistance in the forward direction and high resistance in the reverse direction. It is a unidirectional device.

SCR (CONSTRUCTION)



A Silicon Controlled Rectifier (SCR) is a semiconductor device with four layers and three terminals, and is constructed from alternating P-type and N-type semiconductor materials:

SCR (CONSTRUCTION)

Layers

The four layers are made of P and N-type materials, with the outer layers heavily doped and the middle layers lightly doped.

Junctions

The layers are arranged to form three junctions, J1, J2, and J3, which can be alloyed or diffused depending on the construction type.

Terminals

The three terminals are the anode, cathode, and gate. The anode is where current enters the device, and the cathode is where current leaves the device. The gate terminal is attached to the middle P-layer.

Construction types

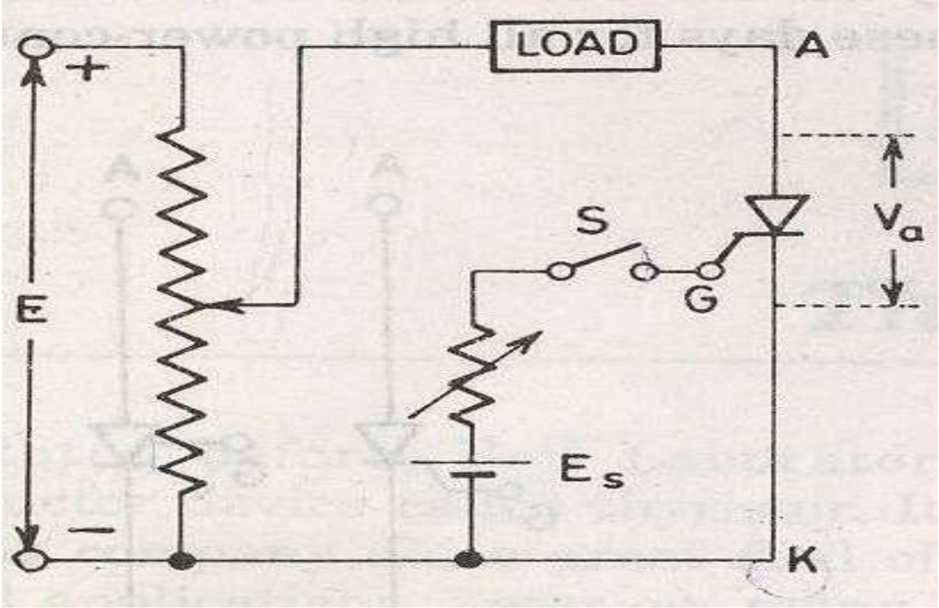
There are three types of SCR construction: planar, mesa, and press pack. Planar construction is used for low power SCRs, while mesa construction is used for high power SCRs.

Bracing

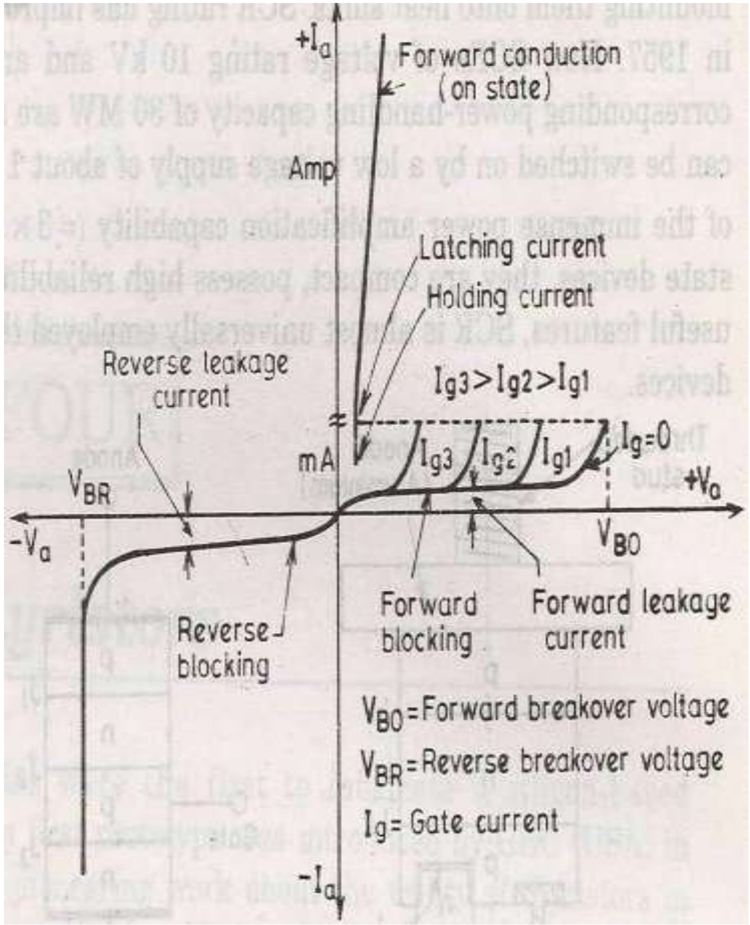
To provide mechanical strength, the SCR is braced with plates made of molybdenum or tungsten. One of the plates is soldered to a copper stud, which is then threaded to connect a heat sink.

Static V-I characteristics of a Thyristor

Anode and cathode are connected to main source voltage through the load. The gate and cathode are fed from source ES.



Static V-I characteristics of a Thyristor



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

A typical SCR V-I characteristic is as shown

Modes of operation

1.<u>Reverse Blocking Mode</u>

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 reversecurrent 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.

SCR have 3 modes of operation:

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

Modes of operation

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.

Different turn ON methods for SCR

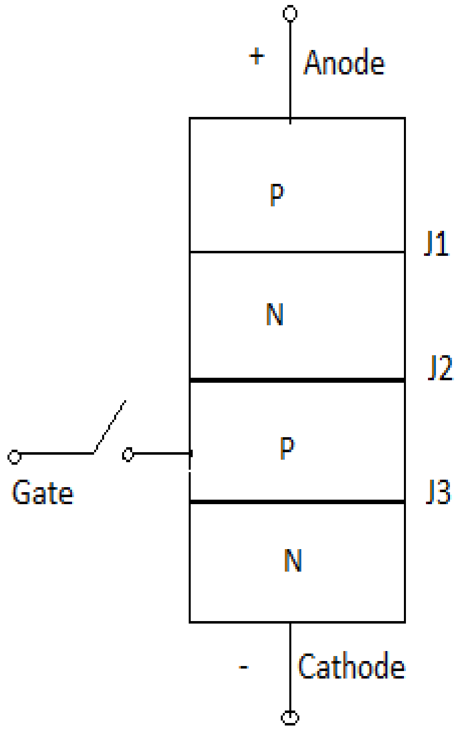
Different turn ON methods for SCR

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

Different turn ON methods for SCR

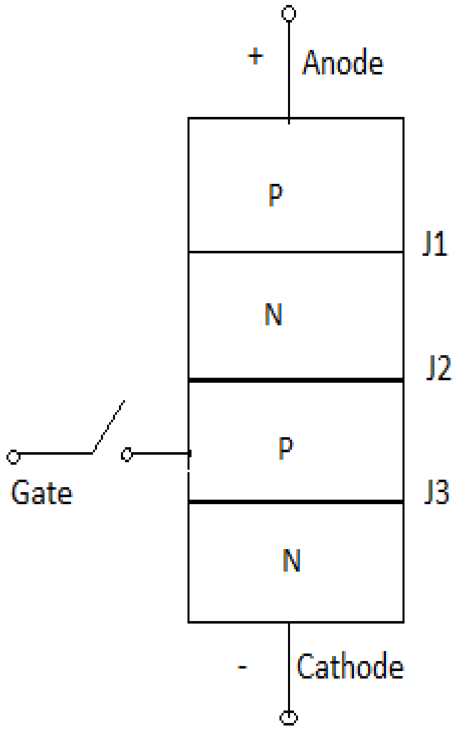
2. Gate triggering

This is the simplest, reliable and efficient method of firing the forward biased SCRs. First SCR is forward biased. Then a positive gate voltage is applied between gate and cathode. In practice the transition from OFF state to ON state by exceeding V_{BO} is never employed as it may destroy the device. The magnitude of V_{BO}, so forward breakover voltage is taken as final voltage rating of the device during the design of SCR application.



Different turn ON methods for SCR

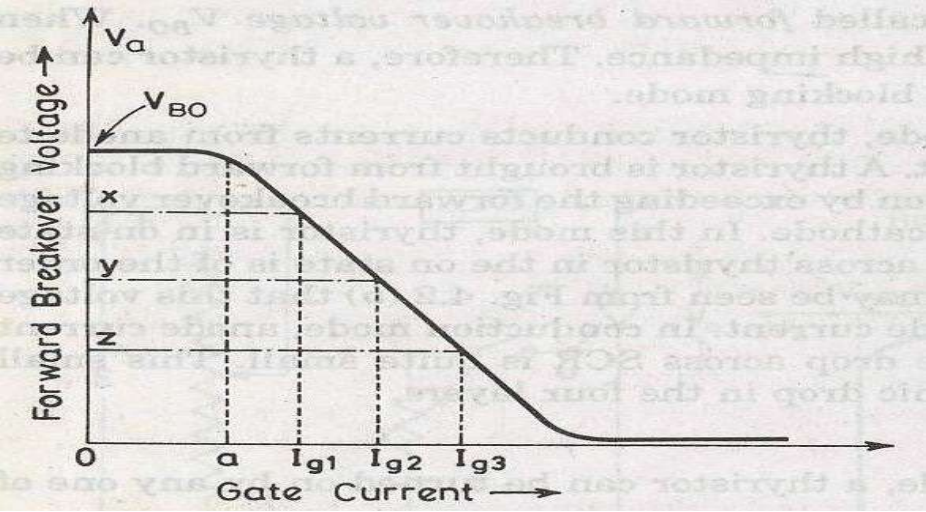
First step is to choose a thyristor with forward breakover voltage (say 800V) higher than the normal working voltage. The benefit is that the thyristor will be in blocking state with normal working voltage applied across the anode and cathode with gate open. When we require the turning ON of a SCR a positive gate voltage between gate and cathode is applied. The point to be noted that cathode n- layer is heavily doped as compared to gate p-layer. So when gate supply is given between gate and cathode gate p-layer is flooded with electron from cathode n-layer. Now the thyristor is forward biased, so some of these electron reach junction J_2 .As a result width of J_2 breaks down or conduction at J_2 occur at a voltage less than V_{BO} .As I_g increases V_{BO} reduces which decreases then turn ON time. Another important point is duration for which the gate current is applied should be more then turn ON time. This means that if the gate current is reduced to zero before the anode current reaches a minimum value known as holding current, SCR can’t turn ON.In this process power loss is less and also low applied voltage is required for triggering.



Different turn ON methods for SCR

3. **<u>dv/dt triggering</u>**

This is a turning ON method but it may lead to destruction of SCR and so it must be avoided. When SCR is forward biased, junction J_1 and J_3 are forward biased and junction J_2 is reversed biased so it behaves as if an insulator is place between two conducting plate. Here J_1 and J_3 acts as a conducting plate and J_2 acts as an insulator. J_2 is known as junction capacitor. So if we increase the rate of change of forward voltage instead of increasing the magnitude of voltage. Junction J_2 breaks and starts conducting. A high value of changing current may damage the SCR. So SCR may be protected from high^{dv}.



Different turn ON methods for SCR

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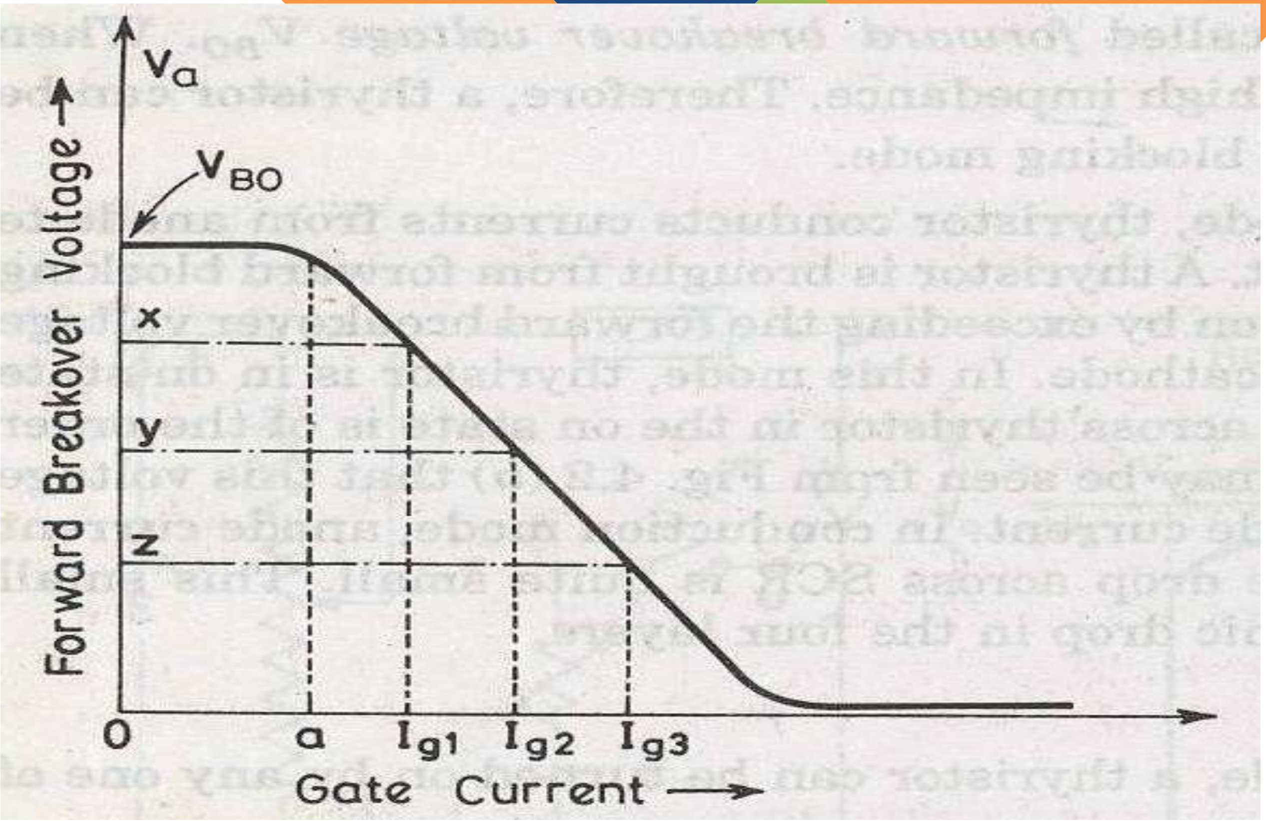

Different turn ON methods for SCR

4. **Temperature triggering**

During forward biased, J_2 is reverse biased so a leakage forward current always associated with SCR. Now as we know the leakage current is temperature dependant, so if we increase the temperature the leakage current will also increase and heat dissipitation of junction

J_2occurs. When this heat reaches a sufficient value J_2 will break and conduction starts.

Disadvantages

This type of triggering causes local hot spot and may cause thermal run away of the device. This triggering cannot be controlled easily. It is very costly as protection is costly.

Different turn ON methods for SCR

5.<u>Light triggering</u>

First a new recess niche is made in the inner p-layer. When this recess is irradiated, then free charge carriers (electron and hole) are generated. Now if the intensity is increased above a certain value then it leads to turn on SCR. Such SCR are known as Light activated SCR (LASCR).

Some definitions:

<u>Latching current</u>

The latching current may be defined as the minimum value of anode current which at must attain during turn ON process to maintain conduction even if gate signal is removed.

<u>Holding current</u>

It is the minimum value of anode current below which if it falls, the SCR will turn OFF.


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Switching characteristics of thyristors

The time variation of voltage across the thyristor and current through it during turn on and turn off process gives the dynamic or switching characteristic of SCR.

Switching characteristic during turn on

Turn on time

It is the time during which it changes from forward blocking state to ON state. Total turn on time is divided into 3 intervals:

1.Delay time
2.Rise time
3.Spread time

Switching characteristics of thyristors

Delay time

If $I_g$and I_a represent the final value of gate current and anode current. Then the delay time can be explained as time during which the gate current attains 0.9 I_g to the instant anode current reaches 0.1 I_g or the anode current rises from forward leakage current to 0.1 I_a.

1.Gate current 0.9 I_g to 0.1 I_a.
2.Anode voltage falls from V_a to 0.9V_a.
3.Anode current rises from forward leakage current to 0.1 I_a.

Switching characteristics of thyristors

Rise time (t_r)

Time during which

1. Anode current rises from 0.1 I_a to 0.9 I_a
2. Forward blocking voltage falls from 0.9V_a to 0.1V_a. V_a is the initial forward blocking voltage.

Spread time (t_p)

1. Time taken by the anode current to rise from 0.9I_a toI_a.
2. Time for the forward voltage to fall from 0.1V_o to on state voltage drop of 1 to 1.5V. During turn on, SCR is considered to be a charge controlled device. A certain amount of charge is injected in the gate region to begin conduction. So higher the magnitude of gate current it requires less time to inject the charges. Thus turn on time is reduced by using large magnitude of gate current.

Switching characteristics of thyristors

<u>How the distribution of charge occurs?</u>

As the gate current begins to flow from gate to cathode with the application of gate signal. Gate current has a non uniform distribution of current density over the cathode surface. Distribution of current density is much higher near the gate. The density decrease as the distance from the gate increases. So anode current flows in a narrow region near gate where gate current densities are highest. From the beginning of rise time the anode current starts spreading itself. The anode current spread at a rate of 0.1mm/sec. The spreading anode current requires some time if the rise time is not sufficient then the anode current cannot spread over the entire region of cathode. Now a large anode current is applied and also a large anode current flowing through the SCR. As a result turn on losses is high. As these losses occur over a small conducting region so local hot spots may form and it may damage the device.

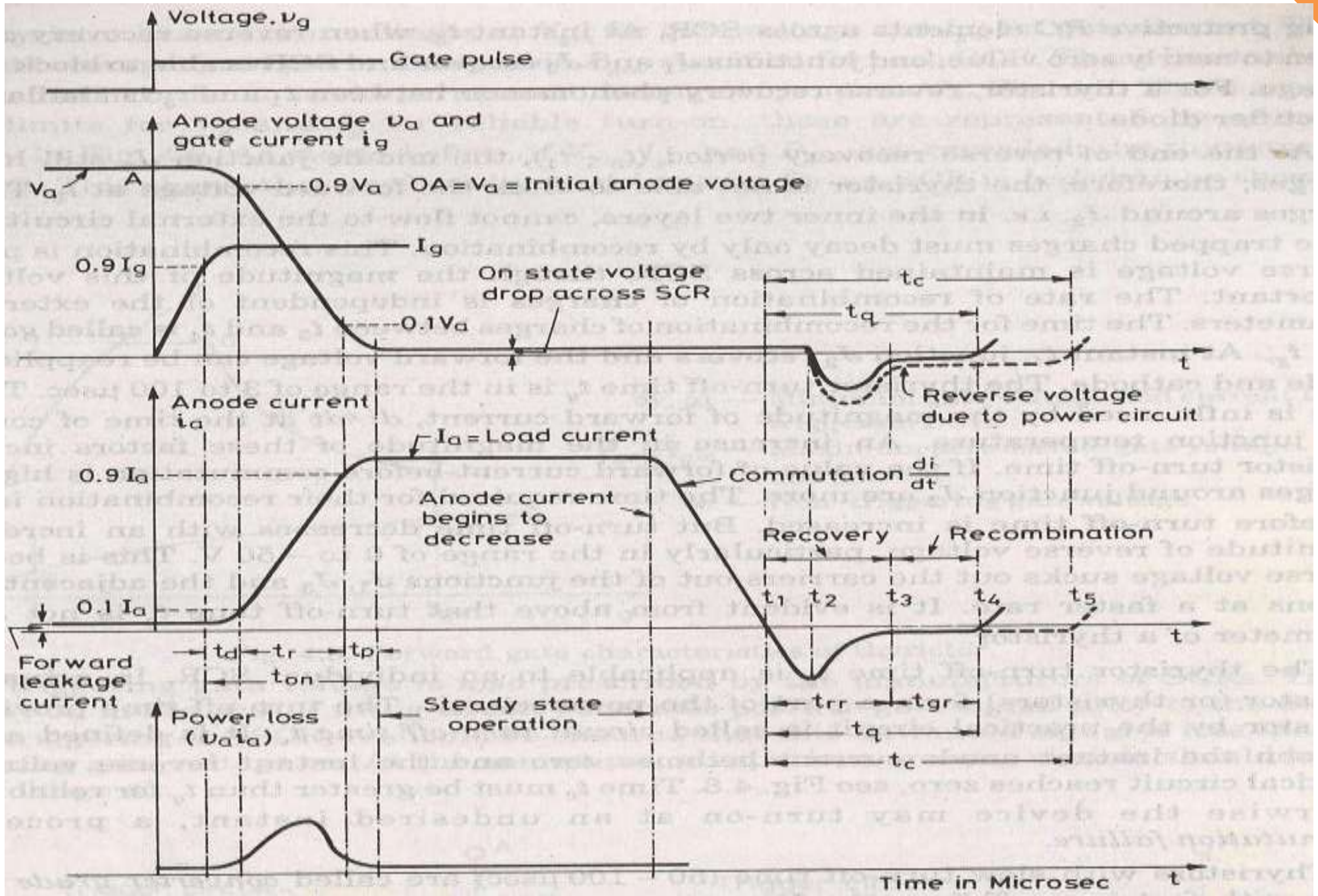
Switching characteristics of thyristors

Switching Characteristics During Turn Off

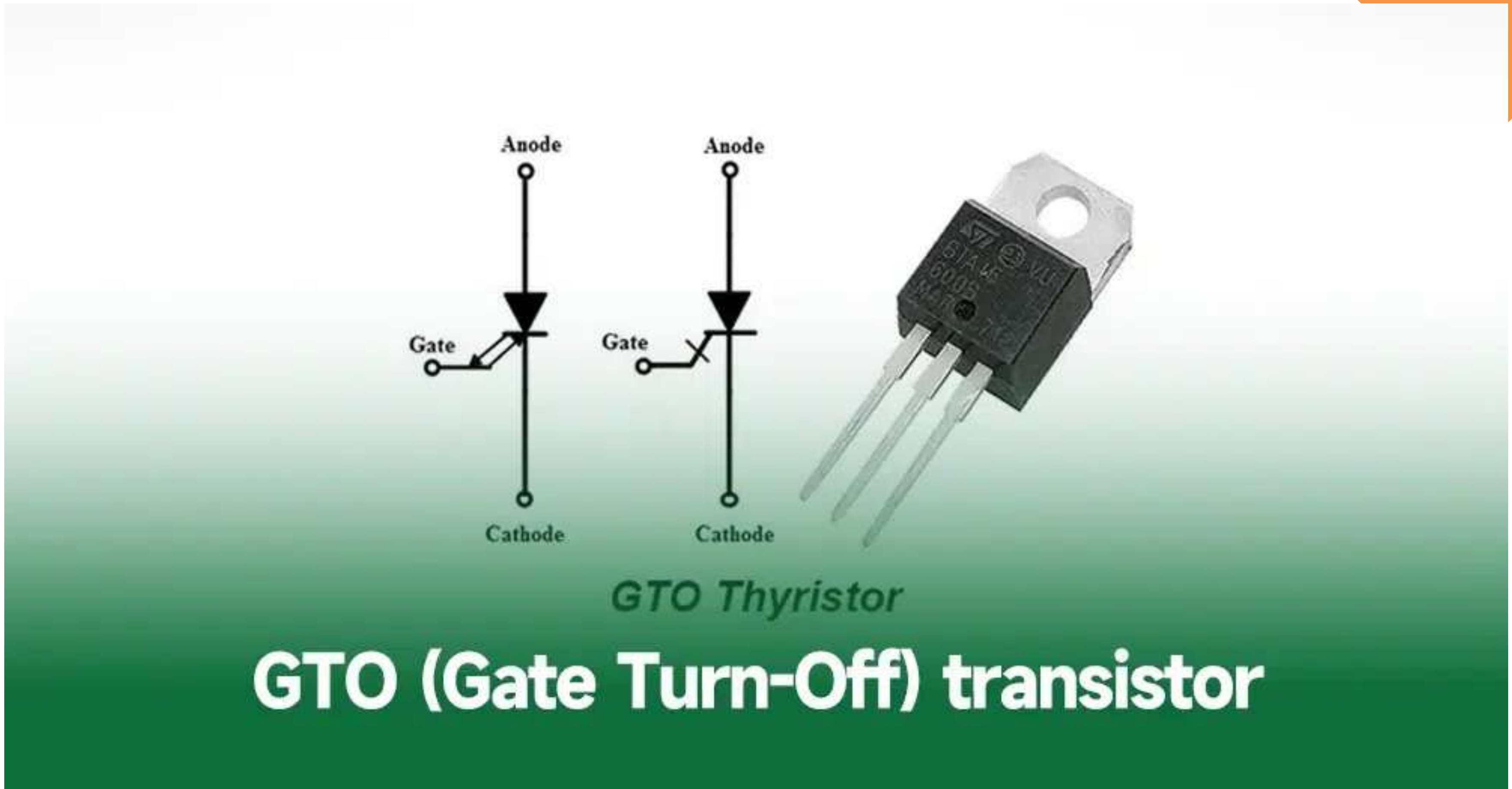
Thyristor turn off means it changed from ON to OFF state. Once thyristor is oON there is no role of gate. As we know thyristor can be made turn OFF by reducing the anode current below the latching current. Here we assume the latching current to be zero ampere. If a forward voltage is applied across the SCR at the moment it reaches zero then SCR will not be able to block this forward voltage. Because the charges trapped in the 4- layer are still favourable for conduction and it may turn on the device. So to avoid such a case, SCR is reverse biased for some time even if the anode current has reached to zero.

So now the turn off time can be different as the instant anode current becomes zero to the instant when SCR regains its forward blocking capability.
$t_q = t_{rr} + t_{qr}$ Where,

Switching characteristics of thyristors



GTO(Gate turn off thyristor)



A gate turn off thyristor is a pnpn device. In which it can be turned ON like an ordinary SCR by a positive gate current. However it can be easily turned off by a negative gate pulse of appropriate magnitude.

GTO(Gate turn off thyristor)

Conventional SCR are turned on by a positive gate signal but once the SCR is turned on gate loses control over it. So to turn it off we require external commutation circuit. These commutation circuits are bulky and costly. So due to these drawbacks GTO comes into existence.

The salient features of GTO are:

1. GTO turned on like conventional SCR and is turned off by a negative gate signal of sufficient magnitude.
2. It is a non latching device.
3. GTO reduces acoustic and electromagnetic noise.

It has high switching frequency and efficiency.

A gate turn off thyristor can turn on like an ordinary thyristor but it is turn off by negative gate pulse of appropriate magnitude.

GTO(Gate turn off thyristor)

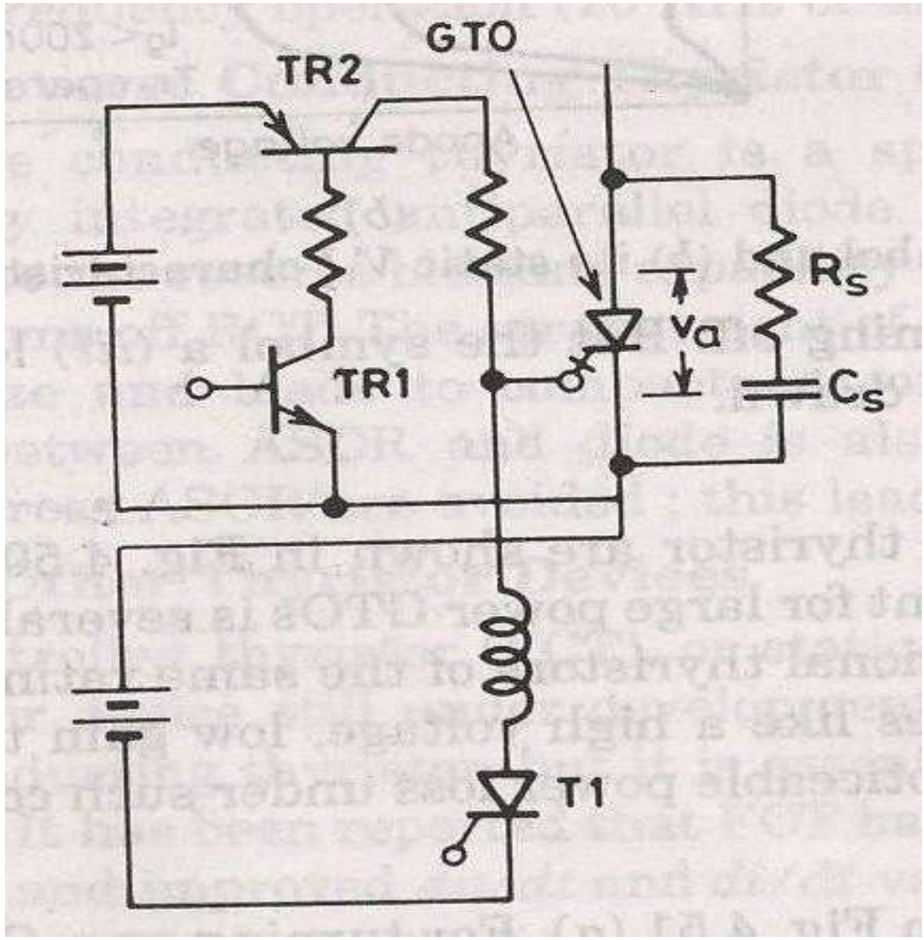
Disadvantage

The negative gate current required to turn off a GTO is quite large that is 20% to 30 % of anode current

Advantage

It is compact and cost less

Switching performance



1.For turning ON a GTO first TR1is turned on.

2.This in turn switches on TR2 so that a positive gate current pulse is applied to turn on the GTO.

3.Thyristor T_1 is used to apply a high peak negative gate current pulse.

Switching performance

Gate turn-on characteristics

1. The gate turn on characteristics is similar to a thyristor. Total turn on time consists of delay time, rise time, spread time.
2. The turn on time can be reduced by increasing its forward gate current.

GATE TURN OFF

Turn off time is different for SCR.Turn off characteristics is divied into 3 pd

1. Storage time
2. Fall time
3. Tail time

Tq=ts+tf+tt

At normal operating condition gto carries a steady state current.The turn off process starts as soon as negative current is applied after t=0.

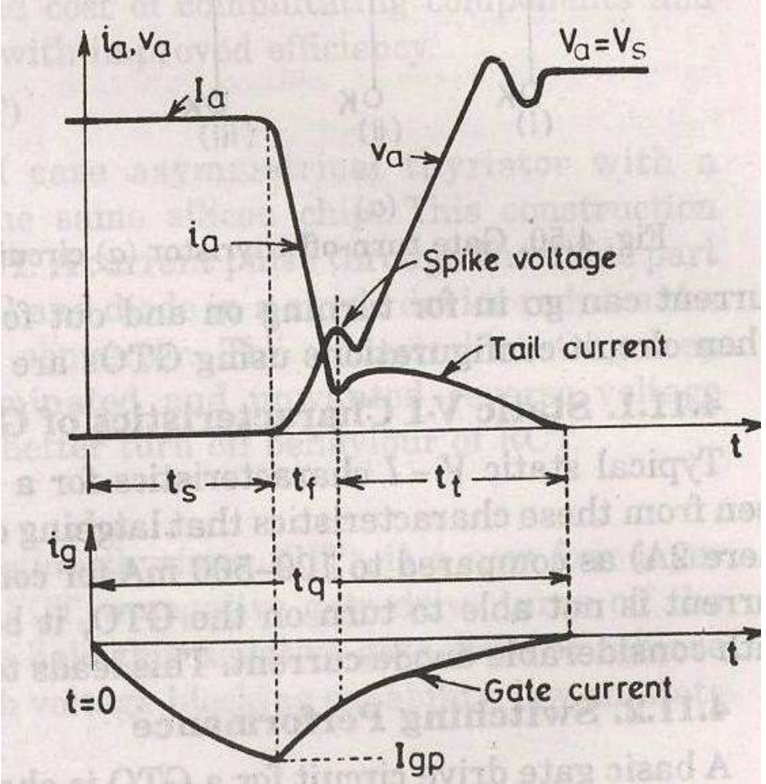
Switching performance

STORAGE TIME

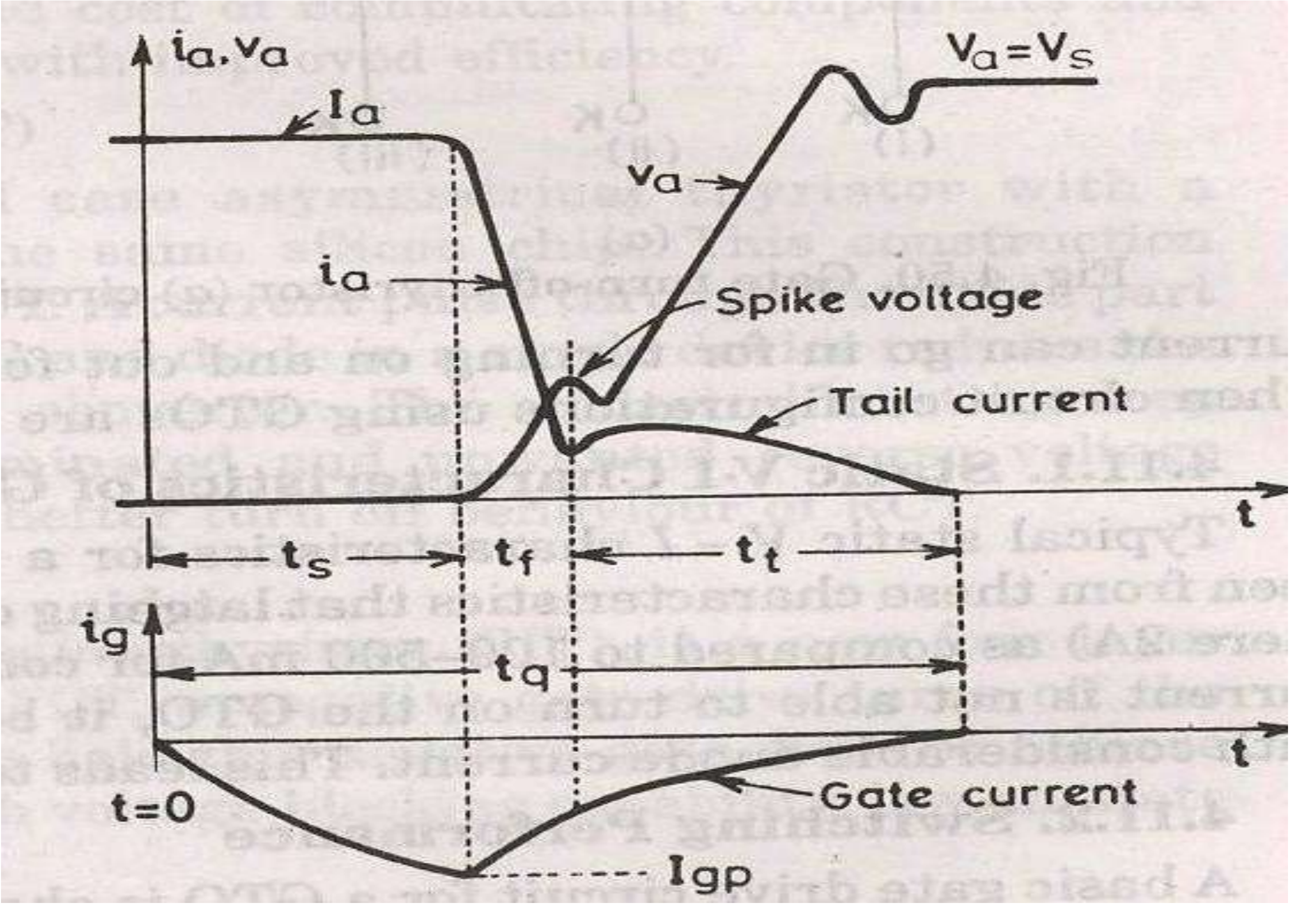
During the storagepd the anode voltage and current remains constant.The gate current rises depending upon the gate circuit impedance and gate applied voltage.The beginning of pd is as soon as negative gate current is applied.The end of storage pd is marked by fall in anode current and rise in voltage,what we have to do is remove the excess carriers.the excess carriers are removed by negative carriers.

FALL TIME

After ts, anode current begins to fall rapidly and anode voltage starts rising.After falling to a certain value,then anode current changes its rate to fall.this time is called fall time.



Switching performance



SPIKE IN VOLTAGE

During the time of storage and fall timethere is achange in voltage due to abrupt current change.

TAIL TIME

During this time ,the anode current and voltage continues towards the turn off values.The transient overshoot is due to the snubber parameter and voltage stabilizes to steady state value.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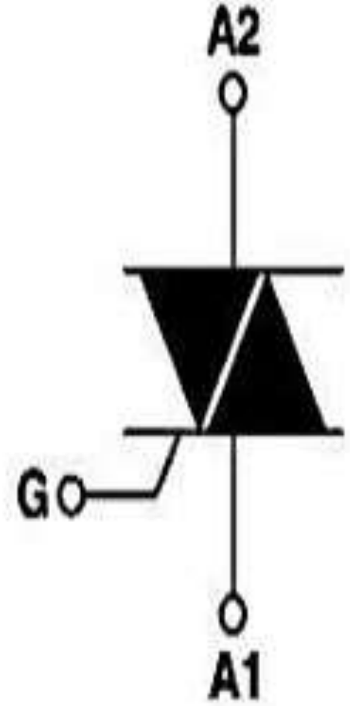
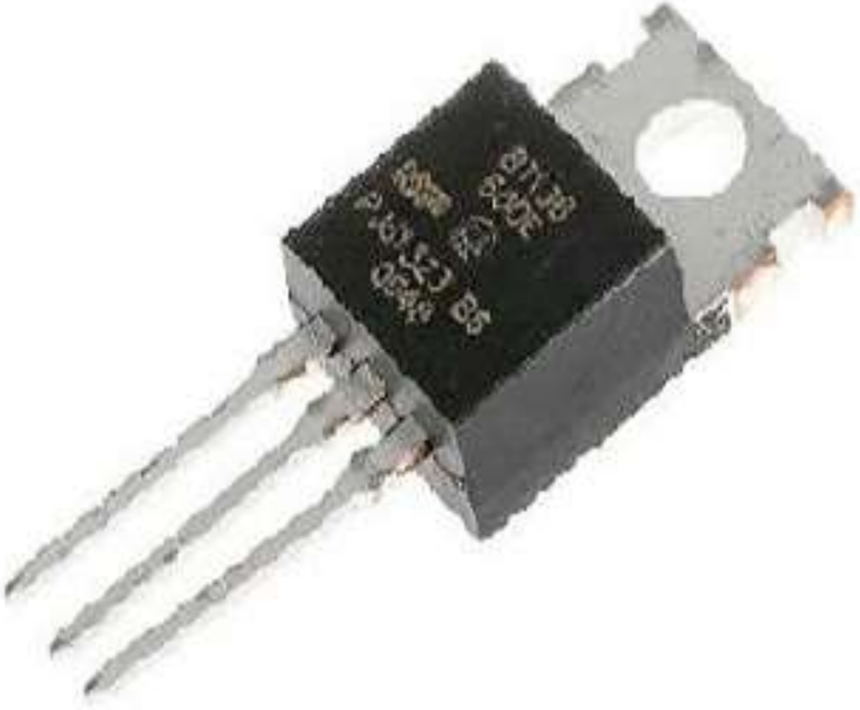
THE TRIAC





As SCR is a unidirectional device,the conduction is from anode to cathode and not from cathode to anode. It conducts in both direction.It is a bidirectional SCR with three terminal.

TRIAC=TRIODE+AC

Here it is considered to be two SCRS connected in anti parallel.As it conducts in both direction so it is named as MT1,MT2 and gate G.

THE TRIAC

SALIENT FEATURES

1.Bi directional triode thyristor

2.TRIAC means triode that works on ac

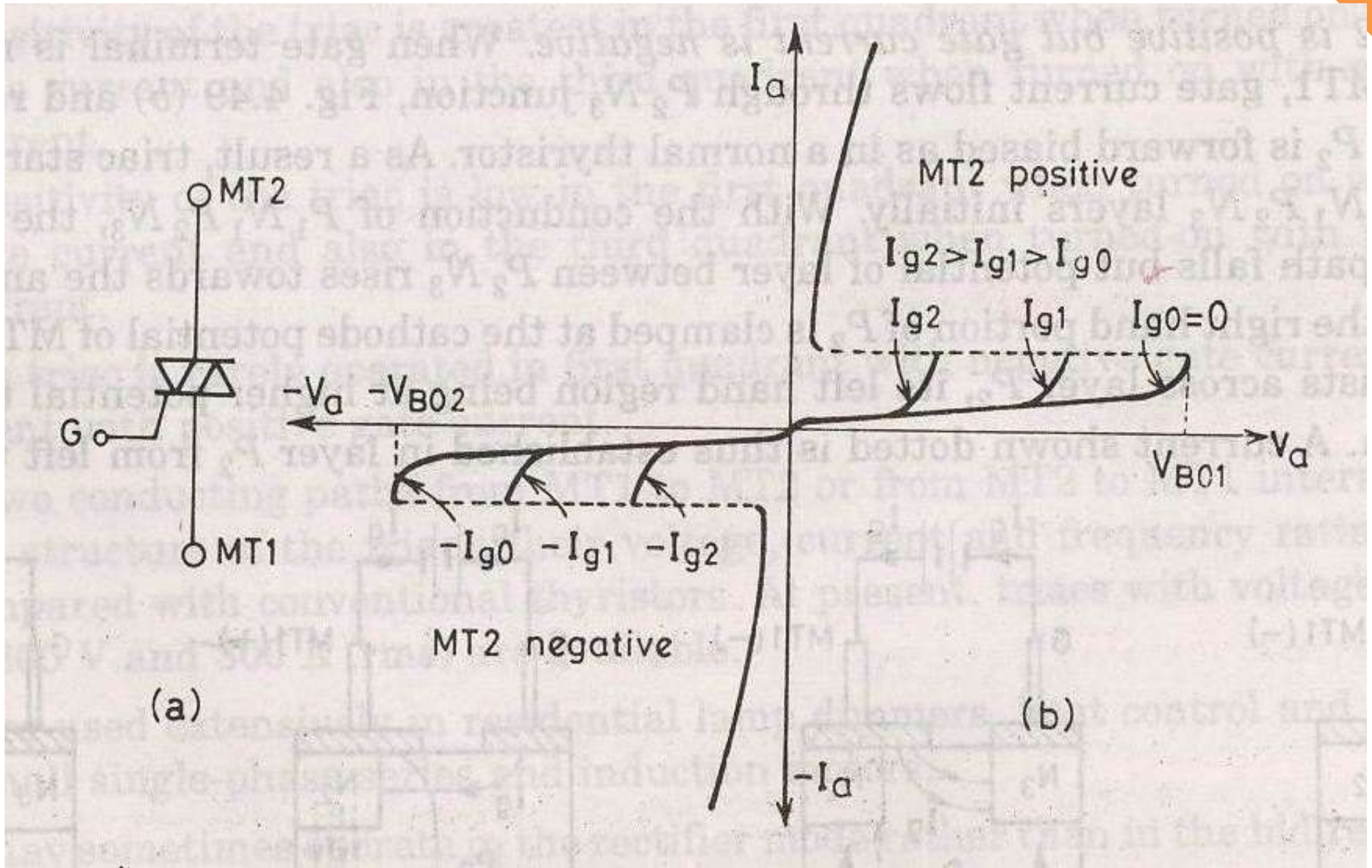
3.It conduct in both direction

4.It is a controlled device

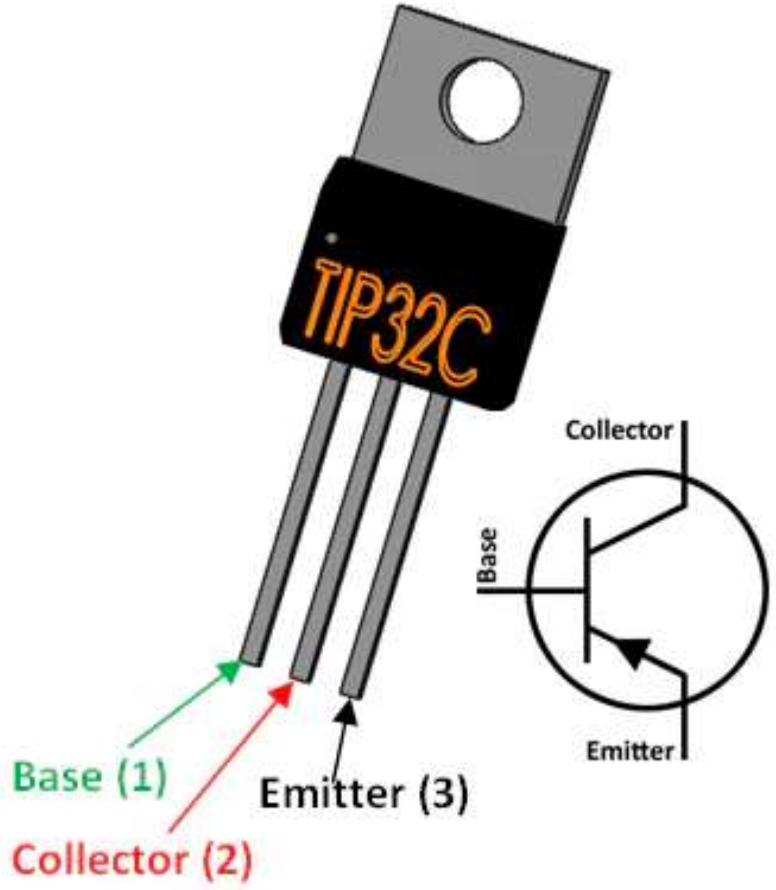
5.Its operation is similar to two devices connected in anti parallel with common gate connection.

6.It has 3 terminals MT1,MT2 and gate G Its use is control of power in ac.

CHARACTERISTIC CURVE



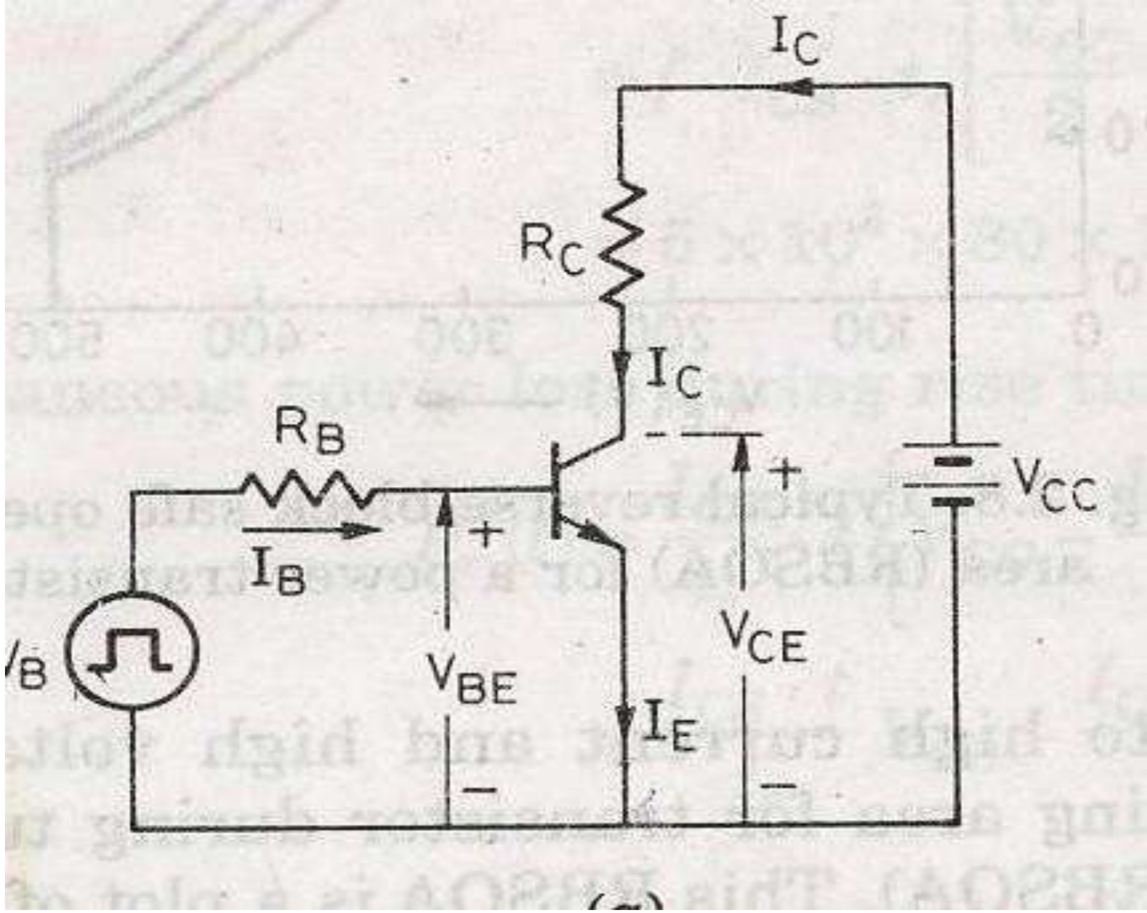
POWER BJT



Power BJT means a large voltage blocking in the OFF state and high current carrying capability in the ON state.

In most power application, base is the input terminal. Emitter is the common terminal. Collector is the output terminal.

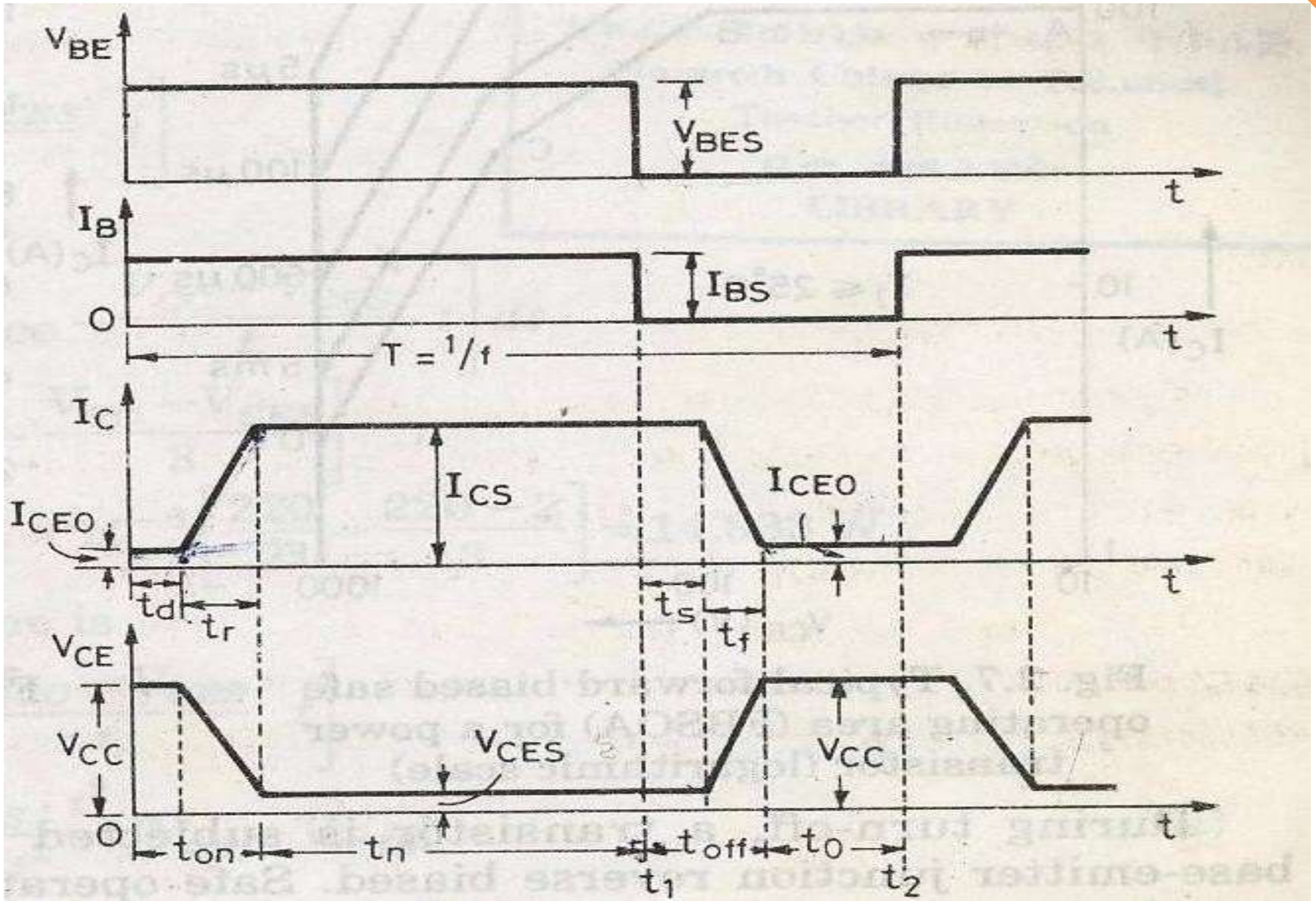
POWER BJT



SIGNAL LEVEL OF BJT

n+ doped emitter layer ,doping of base is more than collector.Depletion layer exists more towards the collector than emitter

POWER BJT



POWER BJT CONSTRUCTION

The maxium collector emitter voltage that can be sustained across the junction, when it is carrying substantial collector current. Vceo=maxium collectorand emitter voltage that can be sustain by the device. Vcbo=collector base breakdown voltage with emitter open

POWER BJT

PRIMARY BREAKDOWN

It is due to convention avalanche breakdown of the C-B junction and its associated large flow of current.The thickness of the depletion region determines the breakdown voltage of the transistor.The base thickness is made as small as possible,in order to have good amplification capability. If the thickness is too small, the breakdown voltage is compromised.So a compromise has to be made between the two.

POWER BJT

PRIMARY BREAKDOWN

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THE DOPING LEVELS-

1.The doping of the emitter layer is quite large.
2. The base doping isB moderate. 3.n- region is lightly doped.

4.n+ region doping level is similar to emitter.

POWER BJT

1.THICKNESS OF DRIFT REGION-

It determines the breakdown length of the transistor.

2.THE BASE THICKNES –

Small base thickness- good amplification capability

Too small base thickness- the breakdown voltage of the transistor has ti be compromised.

For a relatively thick base,the current gain will be relatively small.so it is increase the gain.Monolithicesigns for darlington connected BJT pair have been deveploed.

POWER BJT

SECONDARY BREAKDOWN

Secondary breakdown is due to large power disspation at localized site within the semi conductor.

PHYSICS OF BJT OPERATION-

The transistor is assumed to operate in active region. There is no doped collector drift region. It has importance only in switching operation, in active region of operation.

B-E junction is forward biased and C-B junction is reverse biased. Electrons are injected into base from the emitter. Holes are injected from base into the emitter.

POWER BJT

QUASI SATURATION-

Intially we assume that, the transistor is in active region. Base current is allowed to increase then lets see what happens.first collector rises in response to base current.So there is a increase voltage drop across the collector load.So C-E voltage drops.

Because of increase in collector current, there is a increase in voltage in drift region. This eventually reduces the reverse biased across the C-B junction.so n-p junction get smaller, at some point the junction become forward bised. So now injection of holes from base into collector drift region occurs. Charge neutrality requires the electron to be injected in the drift region of the holes.

POWER BJT

From where these electron came. Since a large no of electron is supplied to the C-B junction via injection from   emitter and subsequent diffusion across the base. As excess carrier build up in the drift region begins to occur quasi saturation region is entered. As the injected carrires increase in the drift region is gradually shotred out and the voltage across the drift region drops. In quasi saturation the drift region is not completely shorted out by high level injection.Hard saturation obtained when excess carrier density reaches the n+ side.

During quasi saturation, the rate of the collector fall.Hard saturation occurs when excess carriers have completely swept across the drift region .


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THYRISTOR PROTECTION

OVER VOLTAGE PROTECTION

Over voltage occurring during the switching operation causes the failure of SCR.

INTERNAL OVERVOLTAGE

It is due to the operating condition of SCR.

During the commutation of SCR ,when the anode current decays to zero anode current reverses due to stored changes. First the reverse current rises to peak value, then reverse current reduces abruptly with large di/dt. During series inductance of SCR large transient large voltage i.e $L\, di/dt$. is generated.

THYRISTOR PROTECTION

EXTERNAL OVER VOLTAGE

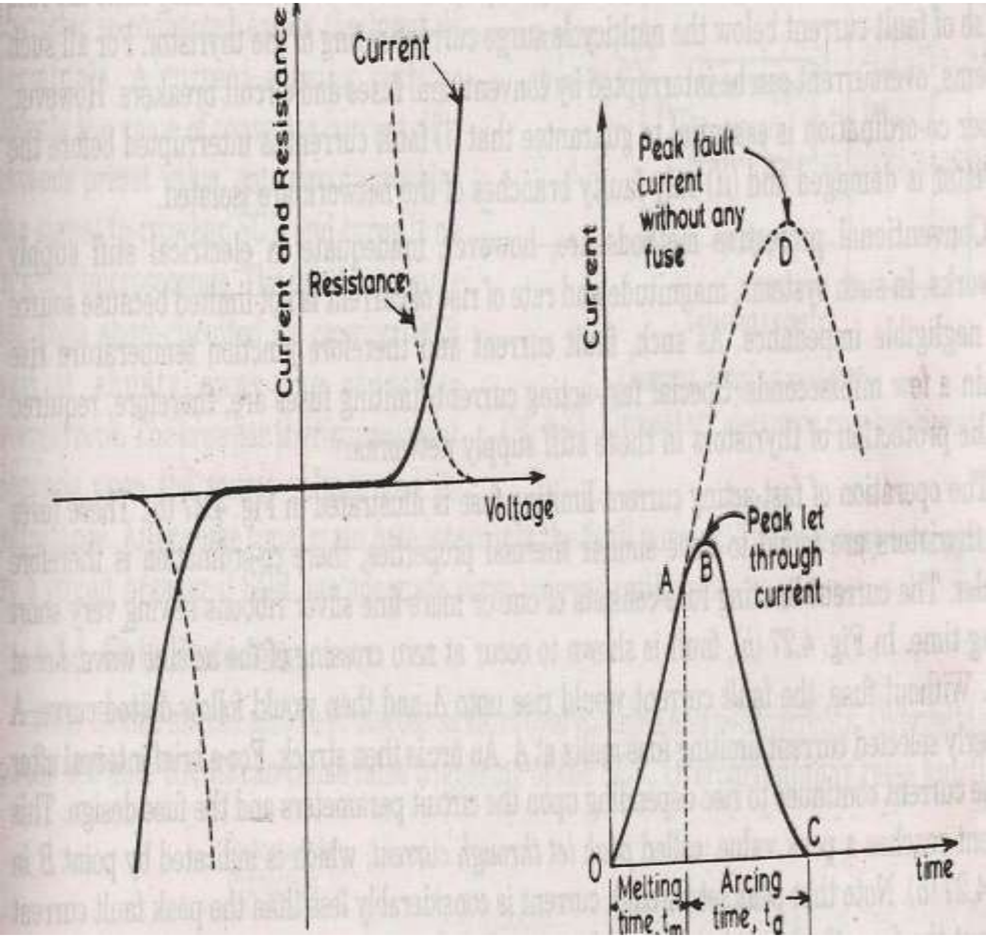
This is due to external supply and load condition. This is because of

1. The interruption of current flow in an inductive circuit.
2. Lightening strokes on the lines feeding the thyristor systems.

This overvoltages cause random turn ON of a SCR. The effect of overvoltage is minimized using

1. RC circuits
2. Non linear resistor called voltage clamping device.

THYRISTOR PROTECTION



Voltage clamping device is a non linear resistor.It is connected between cathode and anode of SCR. The resistance of voltage clamping device decreases with increasing voltages. During normal working condition Voltage clamping (V.C) device has high resistance, drawing only leakage current. When voltage surge appears voltage clamping device offers a low resistance and it create a virtual short circuit across the SCR. Hence voltage across SCR is clamped to a safe value. When surge condition over voltage clamping device returns to high resistance state.

e.g. of voltage clamping device

1.Seleniumthyrector diodes

2. Metal Oxide varistors 3.Avalanche diode supressors

THYRISTOR PROTECTION

OVER CURRENT PROTECTION

Long duration operation of SCR, during over current causes the

1. junction temp. of SCR to rise above the rated value,causing permanent damage to device.

SCR is protected from overcurrent by using

1.Circuit breakers

2.Fast acting fuses

Proper co-ordination is essential because

1..fault current has to be interrupted before SCR gets damaged.

2.only faulty branches of the network has to be replaced.

In stiff supply network,source has negligible impedance.So in such system the magnitude and rate of rise of current is not limited.Fault current hence junction temp rises in a few miliseconds. POINTS TO BE NOTED-

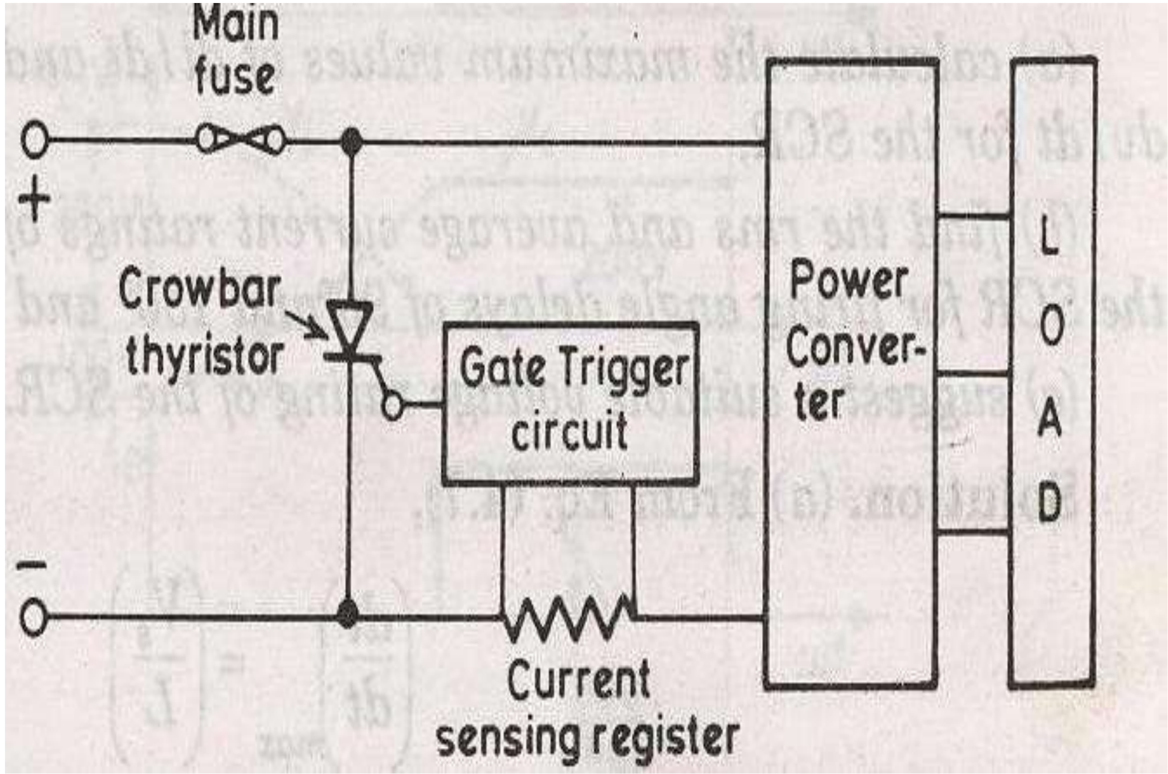
THYRISTOR PROTECTION

Circuit Breaker (C.B)

C.B. has long tripping time. So it is used for protecting the device against continuous overload current or against the surge current for long duration. In order that fuse protects the thyristor realiably the I^2t rating of fuse current must be less than that of SCR.

THYRISTOR PROTECTION

ELECTRONIC CROWBAR PROTECTION



HEAT PROTECTION-

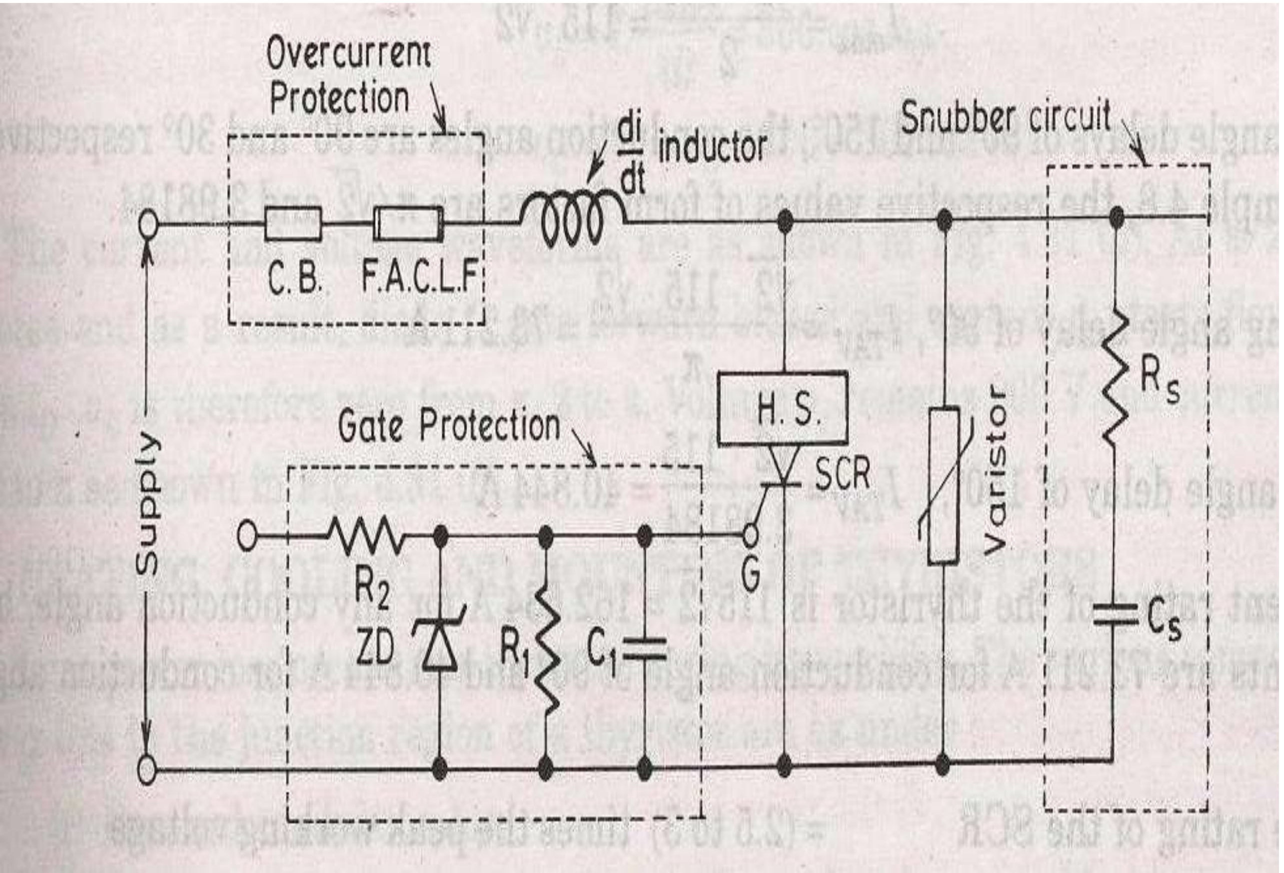
To protect the SCR

1.From the local spots
2.Temp rise

SCRs are mounted over heat sinks.

THYRISTOR PROTECTION

ELECTRONIC CROWBAR PROTECTION



Gate circuit should also be protected from

1.Overvoltages
2.Overcurrents

Overvoltage across the gate circuit causes the false triggering of SCR.Overcurrent raise the junction temperature. Overvoltage protection is by zener the gate circuit

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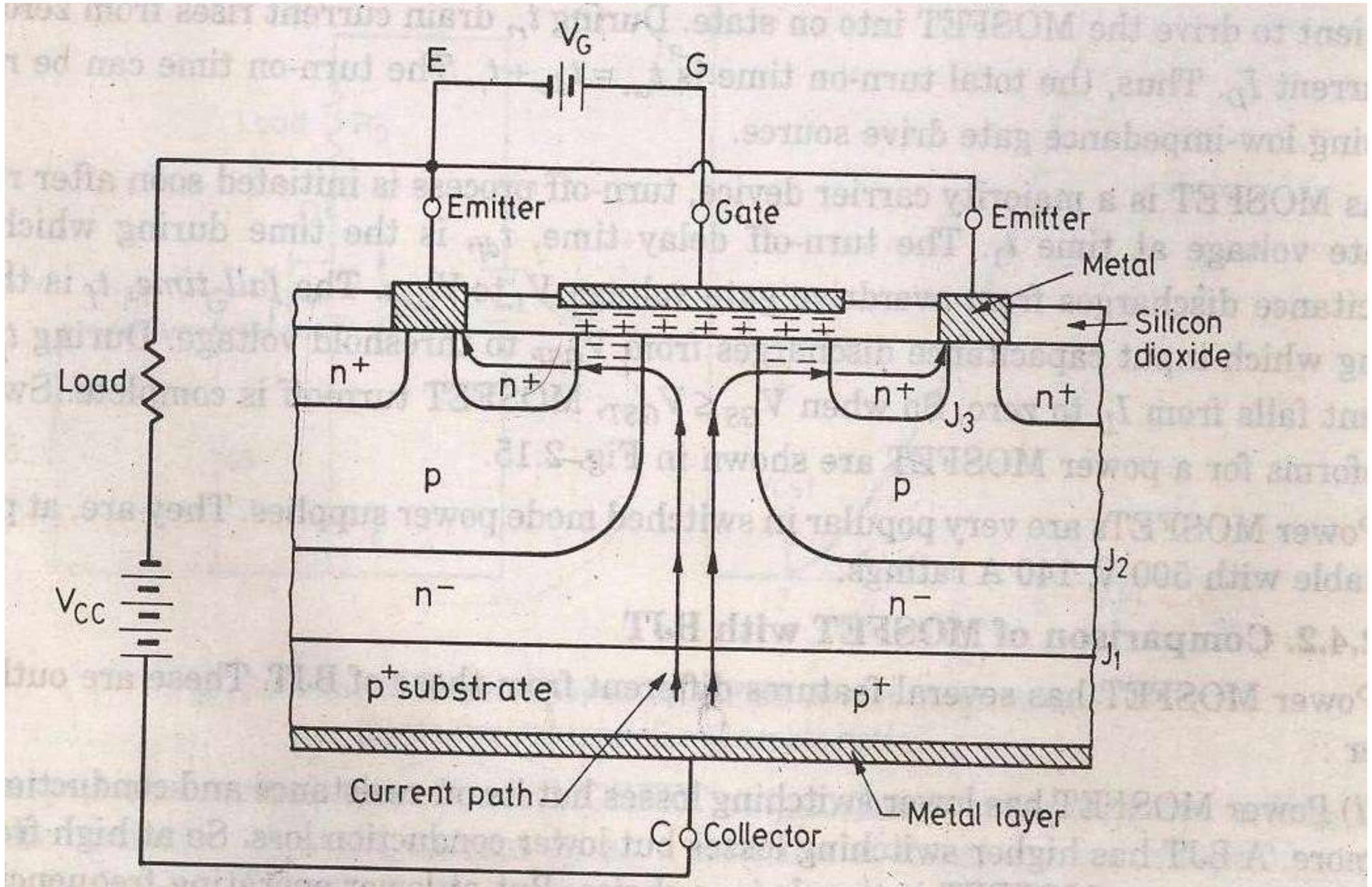
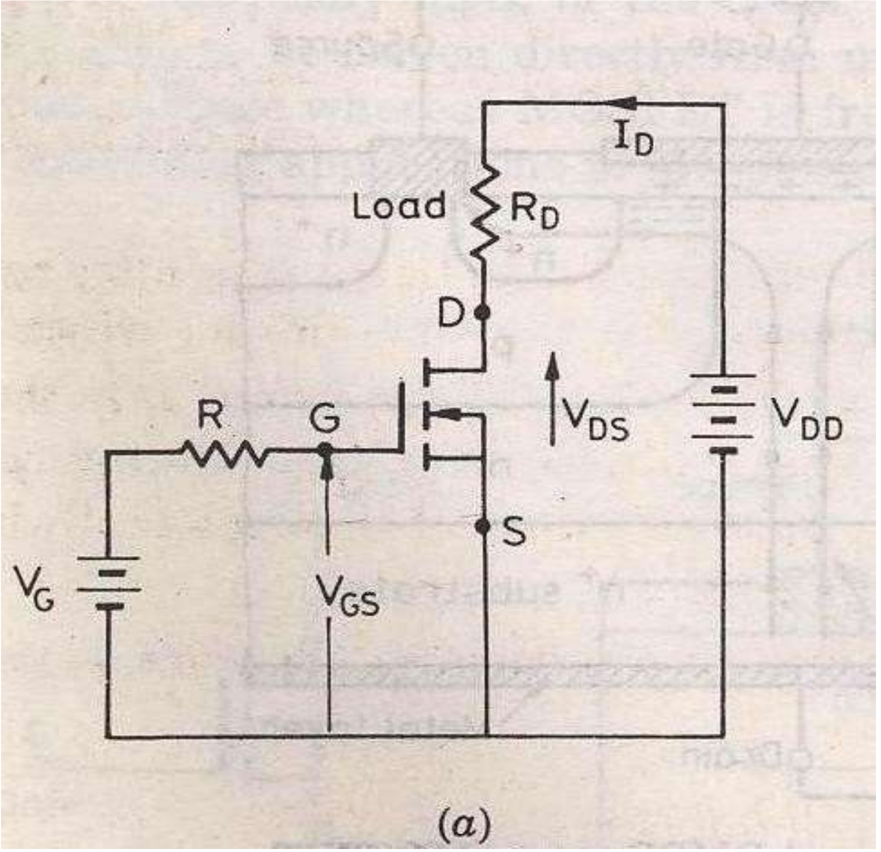
INSULATED GATE BIPOLAR TRANSISTOR(IGBT)-

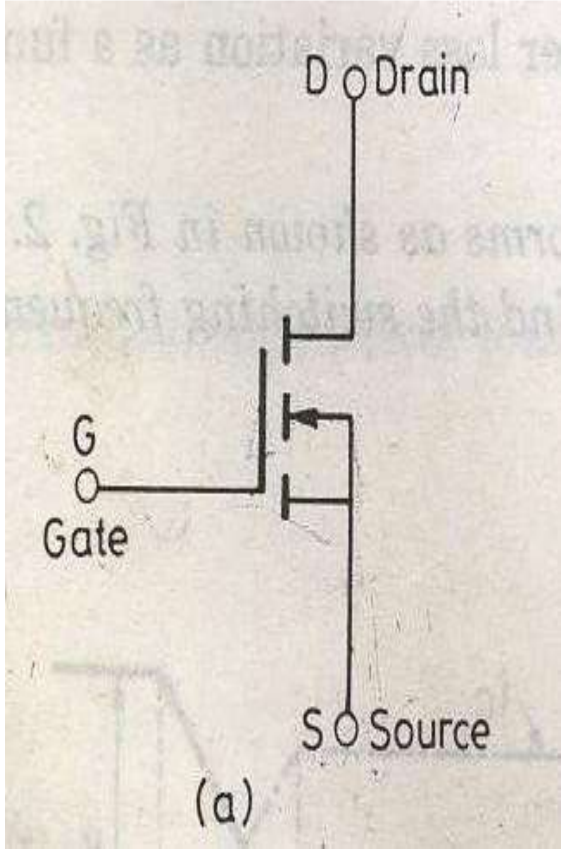


BASIC CONSTRUCTION-

The n+ layer substrate at the drain in the power MOSFET is substituted by p+ layer substrate and called as collector. When gate to emitter voltage is positive,n- channel is formed in the p- region.This n- channel short circuit the n- and n+ layer and an electron movement in n channel cause hole injection from p+subtrate layer to n- layer.

POWER MOSFET





A power MOSFET has three terminal device. Arrow indicates the direction of current flow. MOSFET is a voltage controlled device. The operation of MOSFET depends on flow of majority carriers only.

POWER MOSFET

Switching Characteristics:-

The switching characteristic is influenced by

1.Internal capacitance of the device.

2.Internal impedance of the gate drive circuit. Total **turn on time** is divided into

3.Turn on delay time

4.Rise time

Turn on time is affected by impedance of gate drive source. During turn on delay time gate to source voltage attends its threshold value V_{GST}.

After t_{dn} and during rise time gate to source voltage rise to V_{Gsp}, a voltage which is sufficient to drive the MOSFET to ON state.

The turn off process is initiated by removing the gate to source voltage. Turn off time is composed of turn off delay time to fall time.

POWER MOSFET

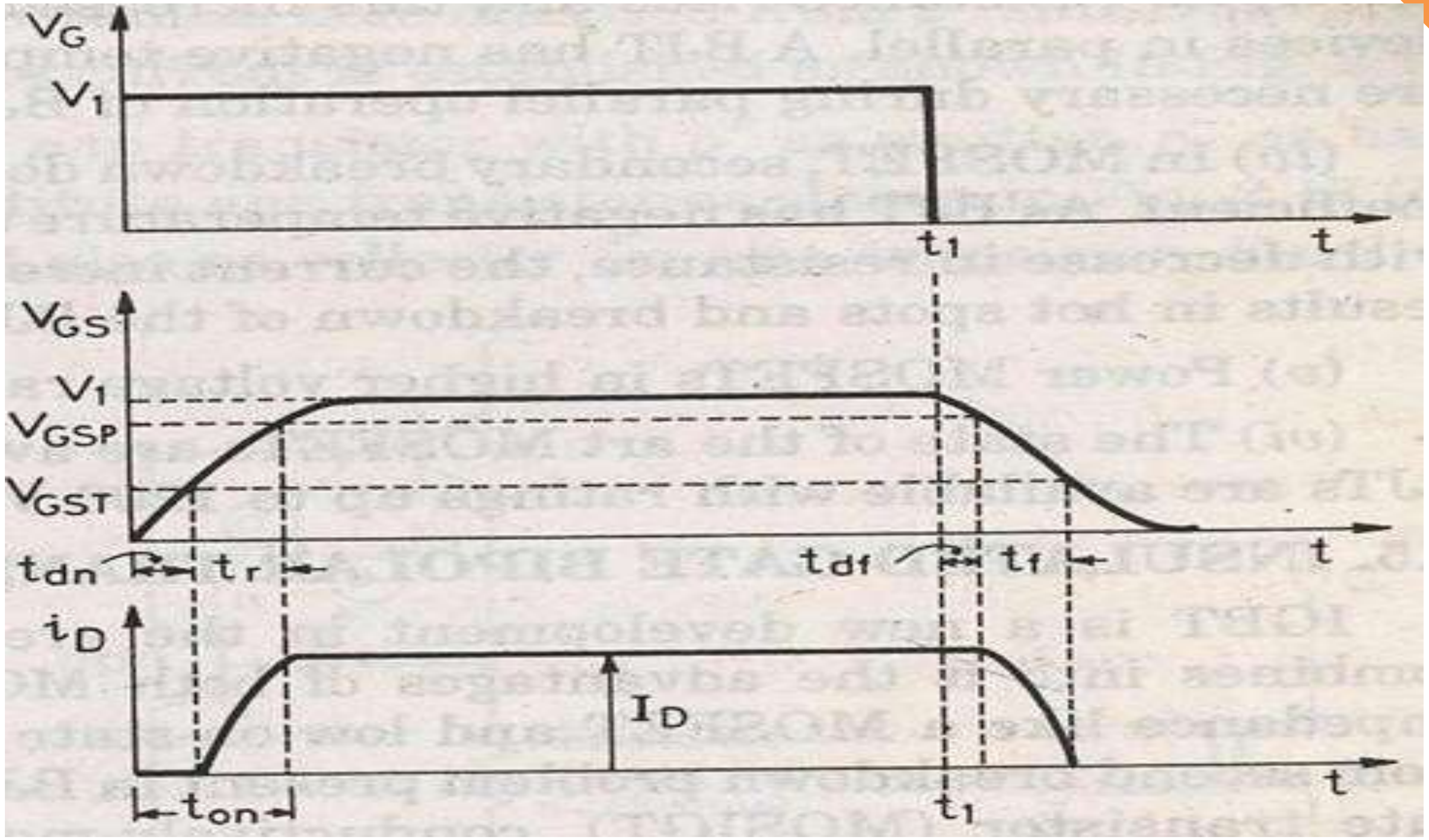
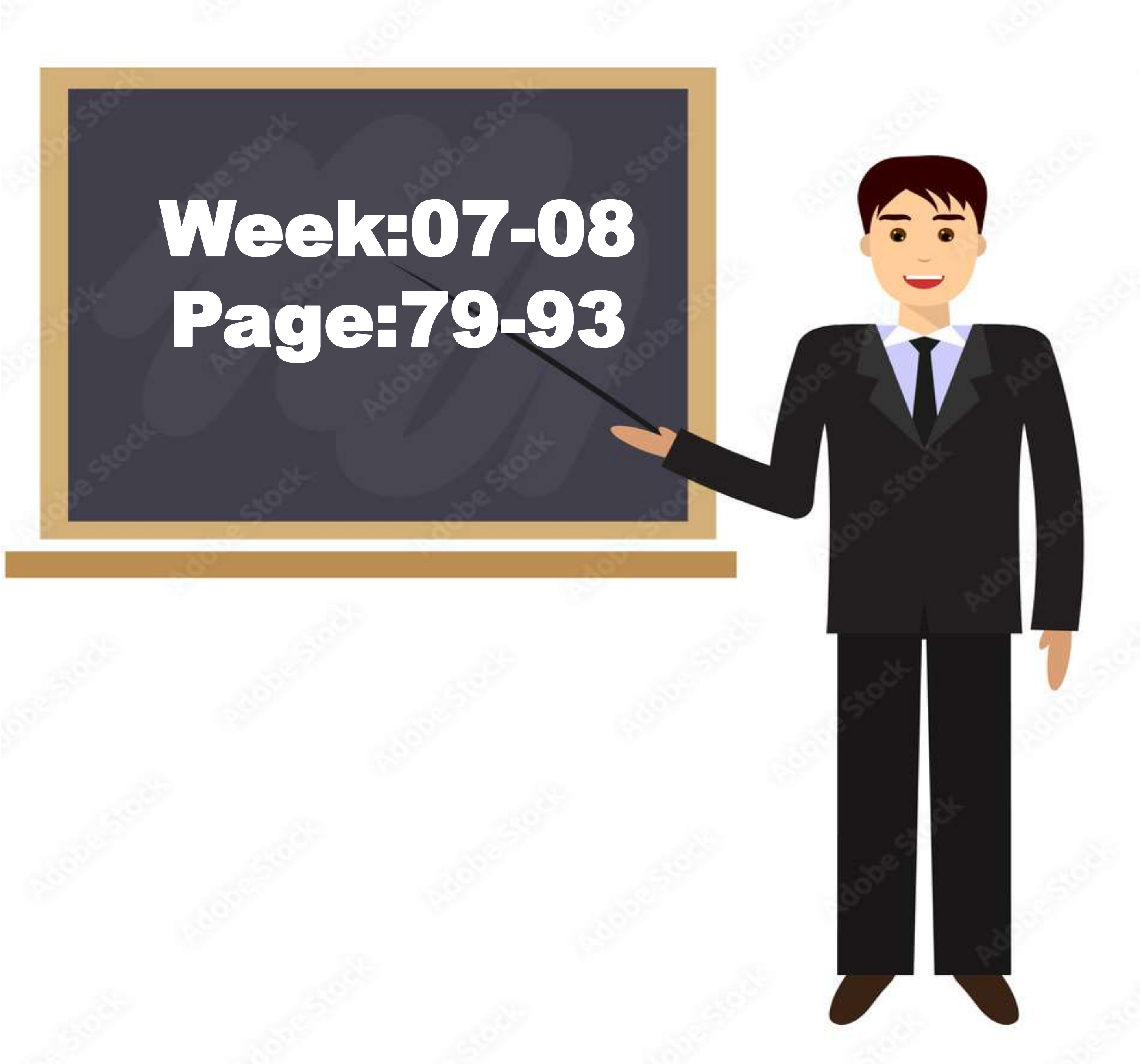


Fig. Switching waveform of power MOSFET

Turn off delay time

To turn off the MOSFET the input capacitance has to be discharged . During t_{df} the input capacitance discharge from $V_1$to V_{Gsp}. During t_f , fall time ,the input capacitance discharges from V_{Gsp} to V_{GST} . During t_f drain current falls from I_D to zero.

So when $V_{Gs} \leq V_{GST}$, MOFSET turn off is complete.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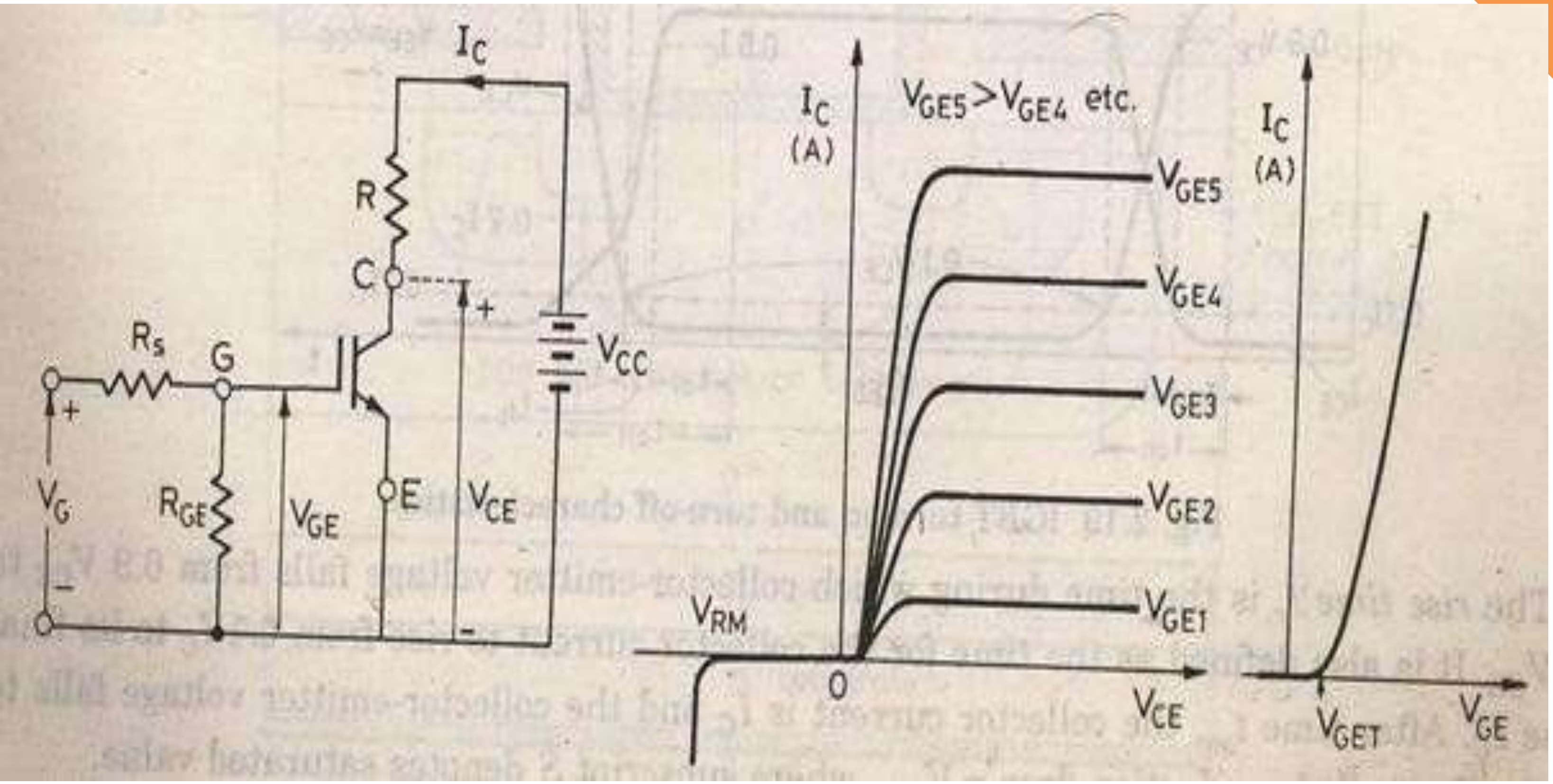
Insulated Gate Bipolar Transistor (IGBT)

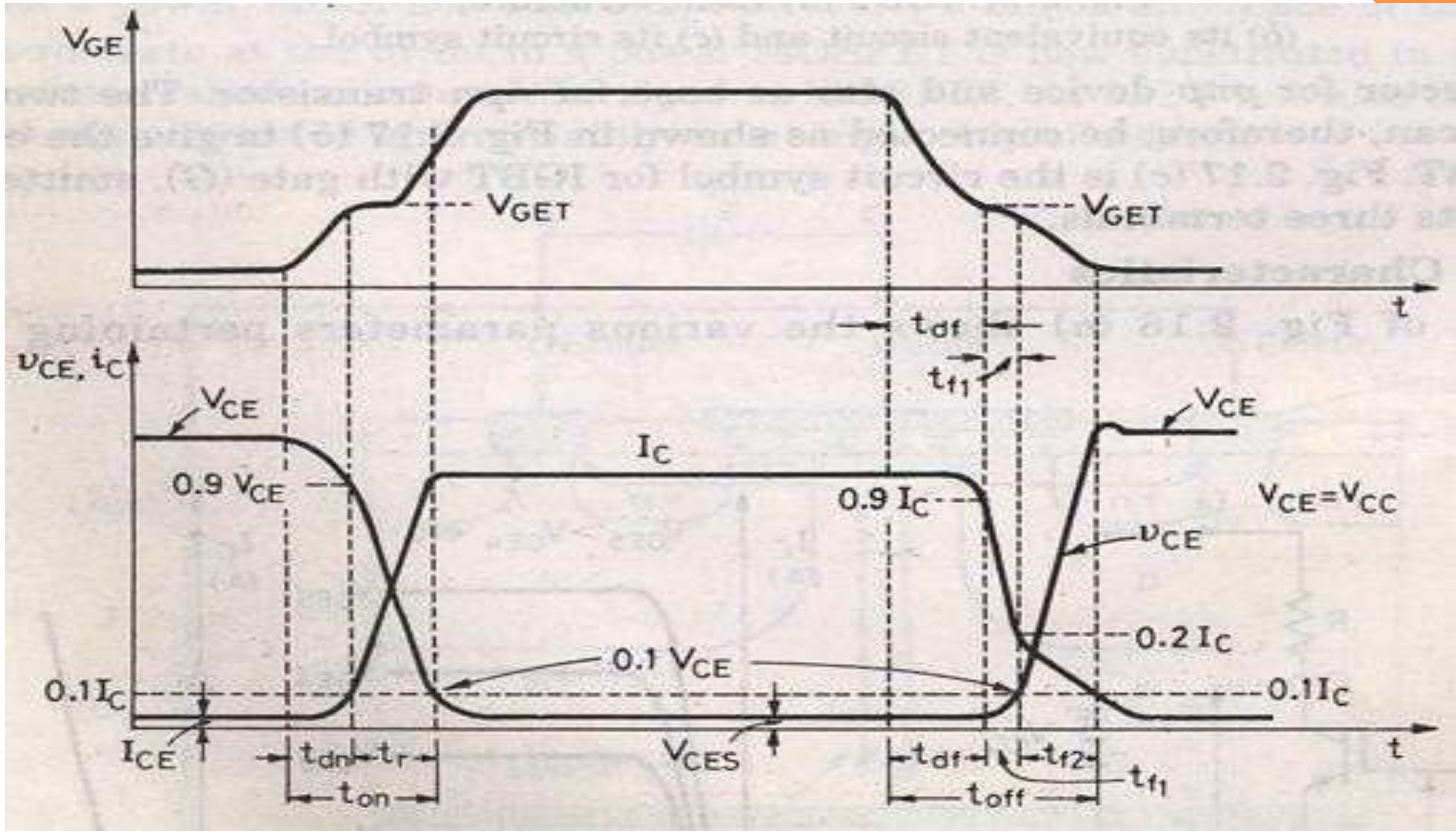


IGBT has high input impedance like MOFFSET and low on state power lose as in BJT.

<u>IGBT Characteristics</u>

Here the controlling parameter is gate emitter voltage As IGBT is a voltage controlled device. When V_{GE} is less than V_{GET} that is gate emitter threshold voltage IGBT is in off state.

Insulated Gate Bipolar Transistor (IGBT)



<u>Switching characteristics:</u> Figure shows the turn ON and turn OFF characteristics of IGBT

Insulated Gate Bipolar Transistor (IGBT)

<u>Turn on time</u>

Time between the instants forward blocking state to forward on -state .

Turn on time = Delay time + Rise time

Delay time = Time for collector emitter voltage fall from V_{CE} to 0.9V_{CE}

V_{CE}=Initial collector emitter voltage

t_{dn}=collector current to rise from initial leakage current to 0.1Ic Ic= Final value of collector current

<u>Rise time</u>

Collector emitter voltage to fall from 0.9V_{CE} to 0.1V_{CE} .

1.Ic to Ic

After t_{on} the device is on state the device carries a steady current of Ic and the collector emitter voltage falls to a small value called conduction drop V_{CES}

Insulated Gate Bipolar Transistor (IGBT)

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<u>Turn off time</u>

1)Delay time t_{d_f}
2)Initial fall time t_{f_1}
3)Final fall time t_{f_2}

$t_{Off} = t_{d_f} + t_{f_1} + t_{f_2}$

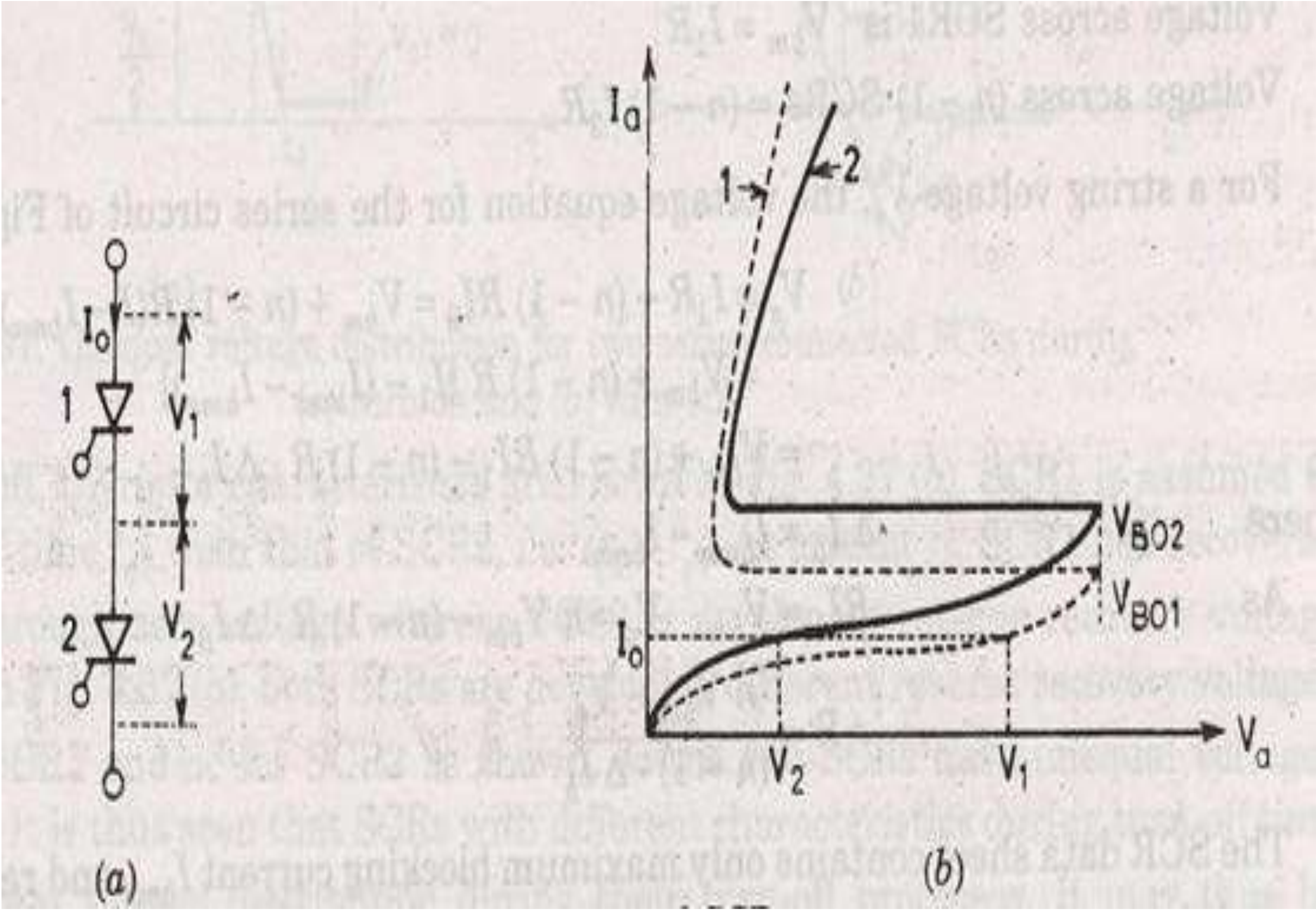
t_{d_f} = Time during which the gate emitter voltage falls to the threshold value V_{GET}.

Collector current falls from Ic to 0.9Ic at the end of the t_{d_f} collector emitter voltage begins to rise.

Turn off time = Collector current falls from 90% to 20% of its initial value Ic OR The time during which collector emitter voltage rise from V_{CE} to $0.1V_{CE}$.

t_{f_2} = collector current falls from20% to 10% of Ic.

Insulated Gate Bipolar Transistor (IGBT)



1 – string efficiency.

If DRF more then

no. of SCRs will more, so string is more reliable.

Let the rated blocking voltage of the string of a series connected SCR is $2V_1$ as shown in the figure below, But in the string two SCRs are supplied a maximum voltage of V_1+V_2.

Insulated Gate Bipolar Transistor (IGBT)

Significance of string efficiency .

Two SCRs are have same forward blocking voltage ,When system voltage is more then the voltage rating of a single SCR. SCRs are connected in series in a string.

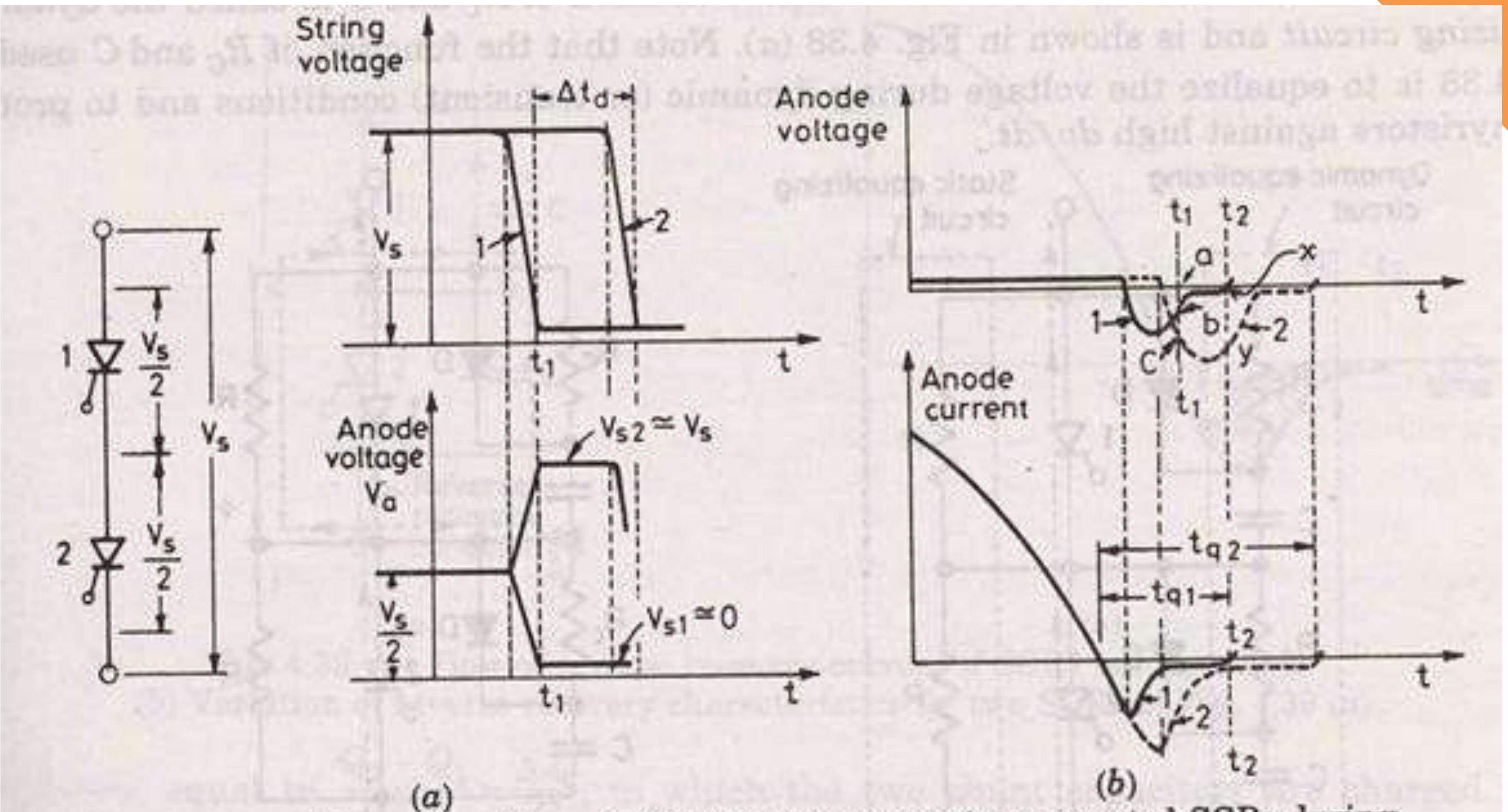
There is a inherent variation in characteristics. So voltage shared by each SCR may not be equal. Suppose, SCR1 leakage resistance > SCR2 leakage resistance. For same leakage current I_0 in the series connected SCRs. For same leakage current SCR1 supports a voltage V_1 , SCR2 supports a voltage V_2, So string η for two SCRs = $\frac{V_1+V_2}{2V_1} = \frac{1}{2}(1 + \frac{V_2}{V_1}) < 1$.

So, $V_1 > V_2$,

The above operation is when SCRs are not turned ON. But in steady state of operation , A uniform voltage distribution in the state can be achieved by connect a suitable resistance across each SCRs , so that parallel combination have same resistance.

But this is a cumbersome work. During steady state operation we connect same value of shunt resistance across each SCRs. This shunt resistance is called ***state equalizing circuit.***

SCRs having unequal dynamic characteristics:



Unequal voltage distribution for two series connected SCRs during (a) turn-on and (b) turn-off.

It may occur that SCRS may have unequal dynamic characteristics so the voltage distribution across the SCR may be unequal during the transient condition.

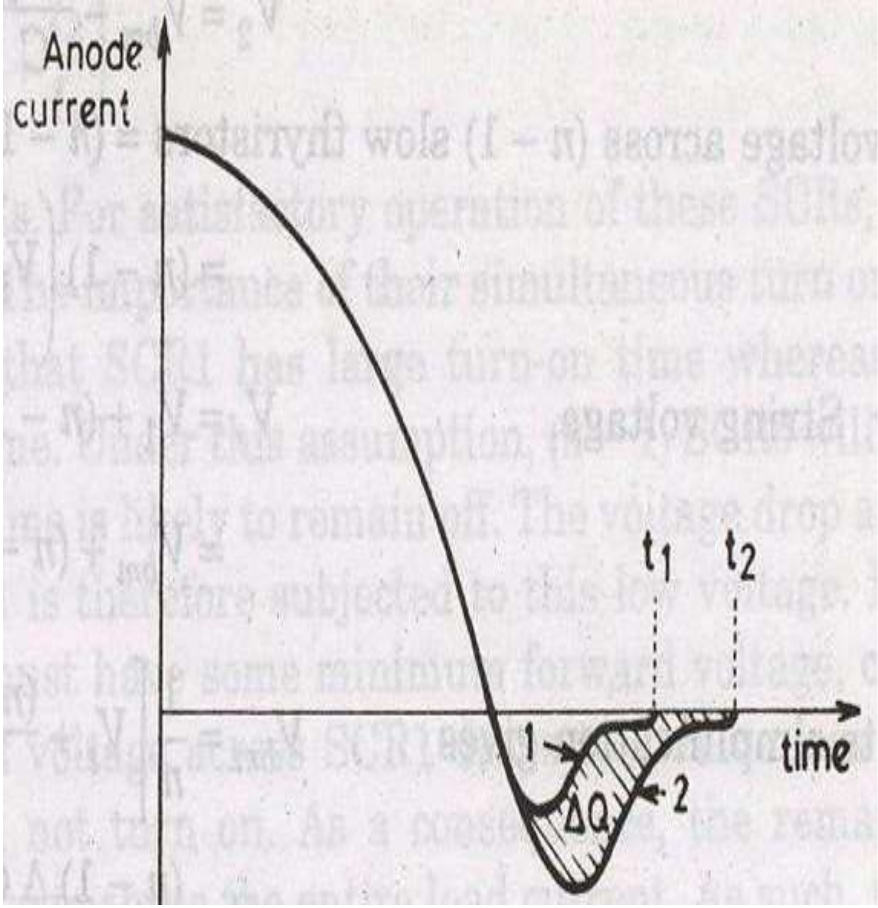
SCRs having unequal dynamic characteristics:

SCR 1 and SCR 2 have different dynamic characteristics. Turn ON time of SCR 2 is more than SCR 1 by time Δt_d .

As string voltage is V_S so voltage shared by each SCRs be $V_S/2$. Now both are gated at same time so SCR 1 will turn ON at t_1 its voltage fall nearly to zero so the voltage shared by SCR 2 will be the string voltage if the break over voltage of SCR 2 is less than V_S then SCR 2 will turn ON .

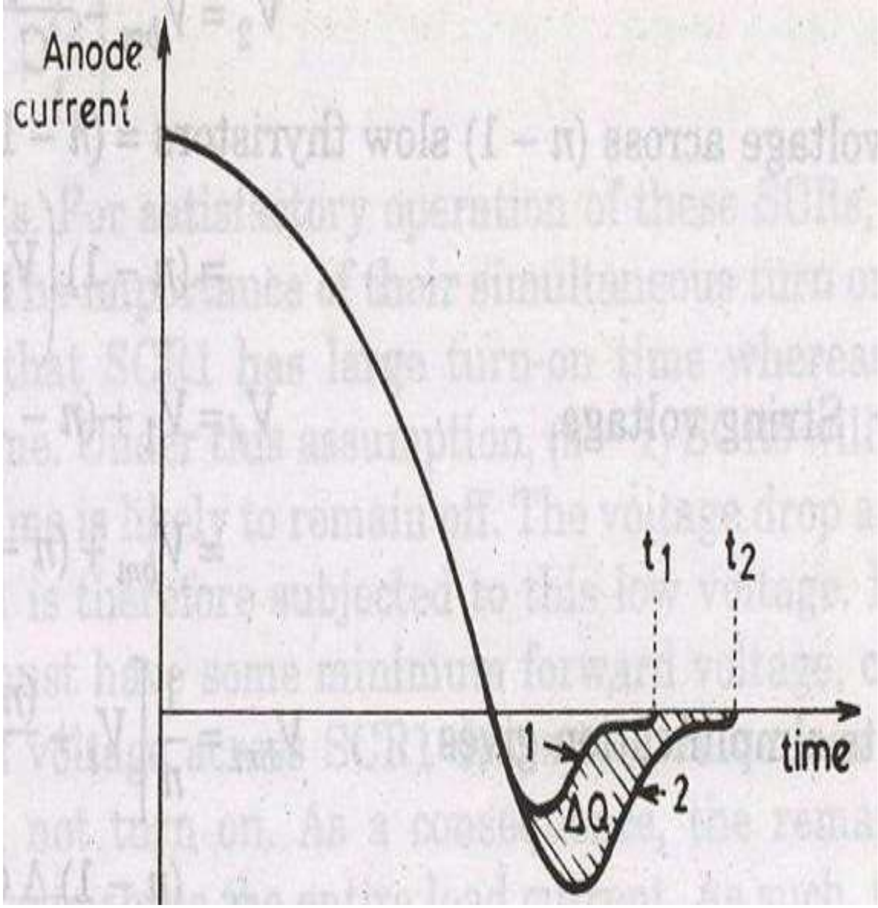
* In case V_S is less than the breakoverer voltage, SCR 2 will turn ON at instant 2. SCR 1 assumed to have less turn off t_{q1} time then SCR 2, so $t_{q1} < t_{q2}$. At t_2 SCR 1 has recovered while SCR 2 is developing recovery voltage at t_1 both are developing different reverse

SCRs having unequal dynamic characteristics:



* Under transient condition equal voltage distribution can be achieved by employing shunt capacitance as this shunt capacitance has the effect of that the resultant of shunt and self capacitance tend to be equal. The capacitor is used to limits the dv/dt across the SCR during forward blocking state. When this SCR turned ON capacitor discharges heavy current through the SCR . The discharge current spike is limited by damping resistor R_c . R_c also damps out high frequency oscilation that may arise due to series combination of R_c ,C and series inductor . R_c & C are called *dynamic equalizing circuit*

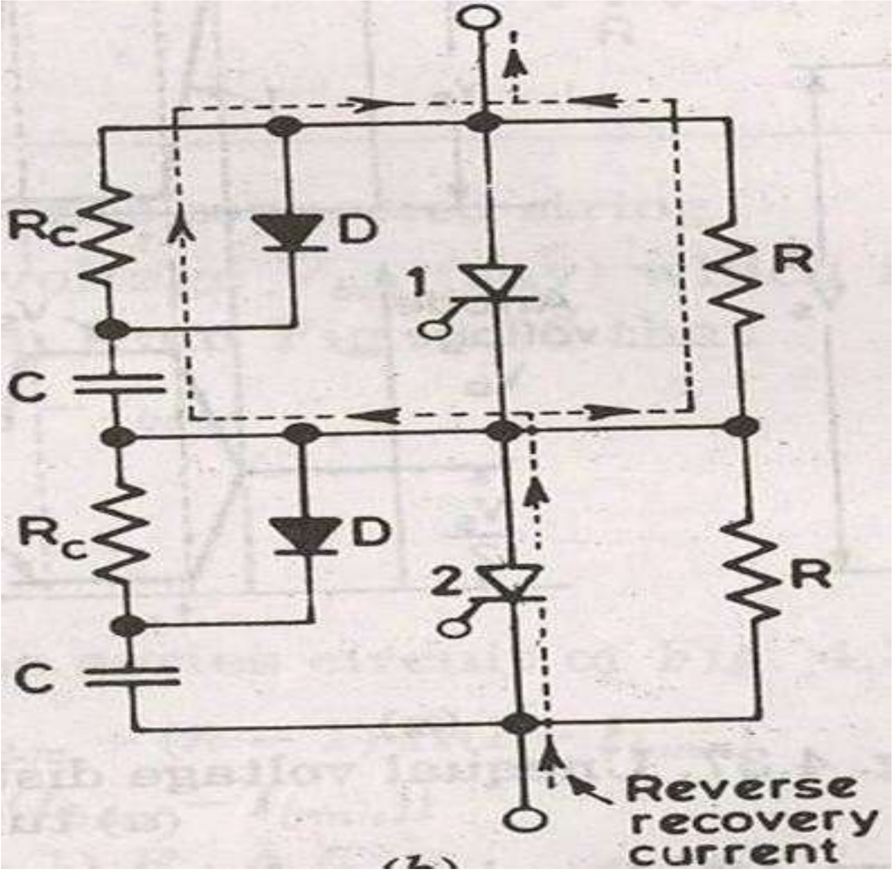
SCRs having unequal dynamic characteristics:



Diode D is used during forward biased condition for more effective charging of the capacitor. During capacitor discharge R_c comes into action for limiting current spike and rate of change of current *di/dt* .

The R, R_c & C component also provide path to flow reverse recovery current. When one SCR regain its voltage blocking capability. The flow of reverse recovery current is necessary as it facilitates the turning OFF process of series connected SCR string. So C is necessary for both during turn ON and turn OFF process. But the voltage unbalance during turn OFF time is more predominant then turn ON time. So choice of C is based on reverse recovery characteristic of SCR .

SCRs having unequal dynamic characteristics:



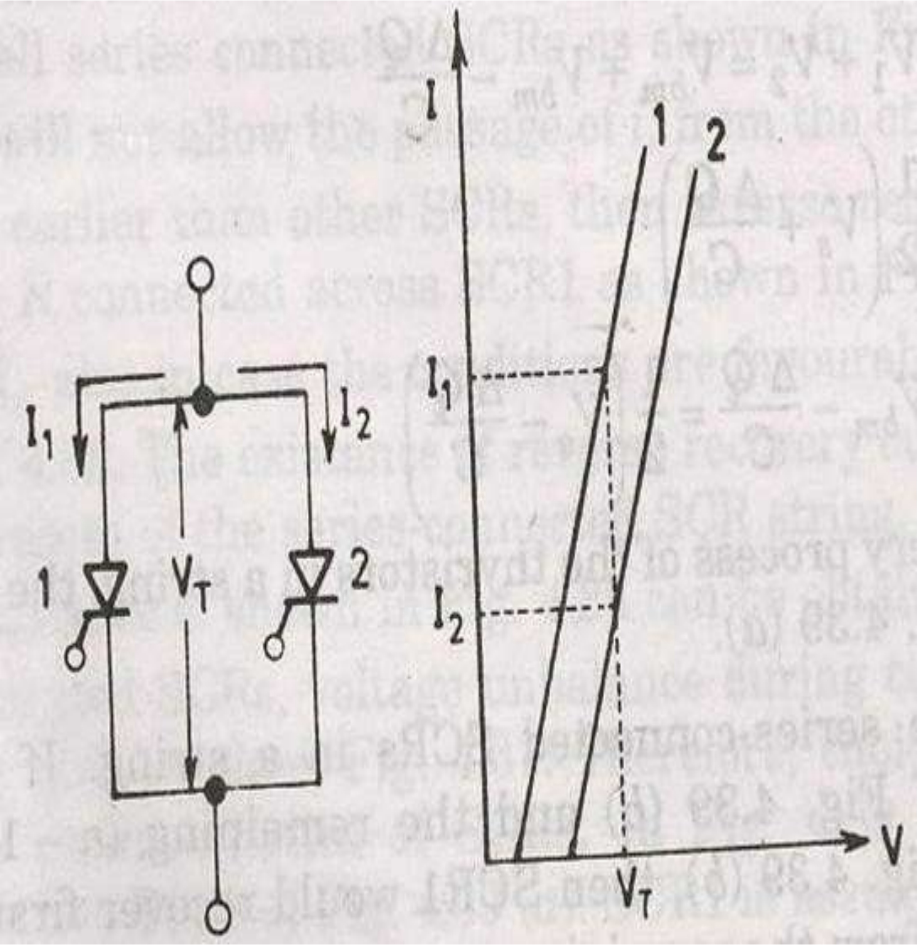
SCR 1 has short recovery time as compared to SCR 2. ΔQ is the difference in reverse recovery charges of two SCR 1 and SCR 2. Now we assume the SCR 1 recovers fast . i.e it goes into blocking state so charge ΔQ can pass through C . The voltage induced by $c1$ is

ΔQ /C , where is no voltage induced across $C2$.

The difference in voltage to which the two shunt capacitor are charged is ΔQ /C .

Now thyristor with least recovery time will share the highest transient voltage say Vbm,

Parallel operation:



When current required by the load is more than the rated current of single thyristor , SCRs are connected in parallel in a string .

Thyristor gate characteristics:-

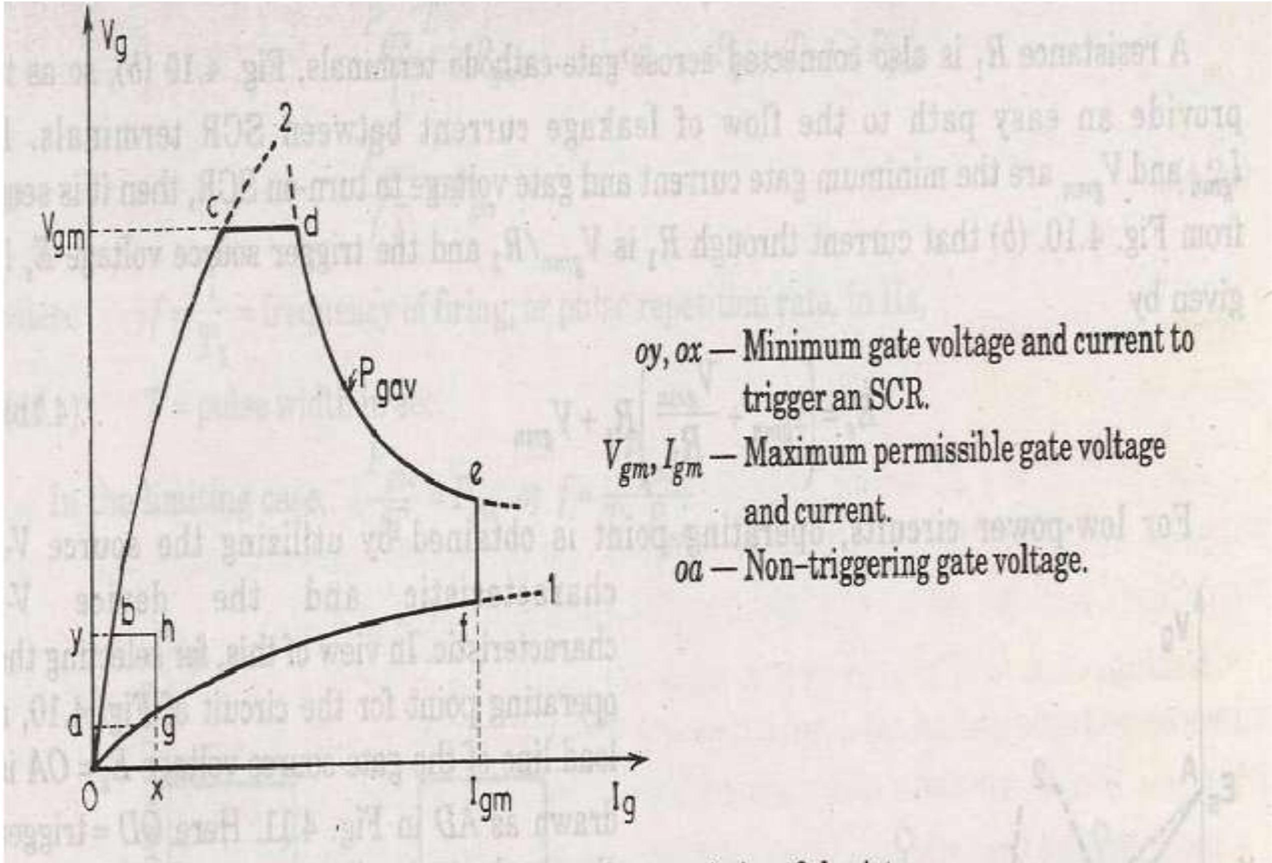


Fig. 4.9. Forward gate characteristics of thyristor.

For equal sharing of current, SCRs must have same $V-I$ characteristics during forward conduction. V_T across them must be same. For same V_T , SCR 1 share I_1 and SCR 2 share I_2 .

If I_1 is the rated current

$$I_2 < I_1$$

The total current I_1+I_2 and not rated current $2I_1$.

Thyristor gate characteristics:-

V_g = +ve gate to cathode voltage.

I_g= +ve gate to cathode current.

As the gate cathode characteristic of a thyrister is a p-n junction, gate characteristic of the device is similar to diode.

Curve 1 the lowest voltage value s that must be applied to turn on the SCR.

Curve 2 highest possible voltage values that can be safely applied to get circuit.

V_{gm}= Maximum limit for gate voltage .

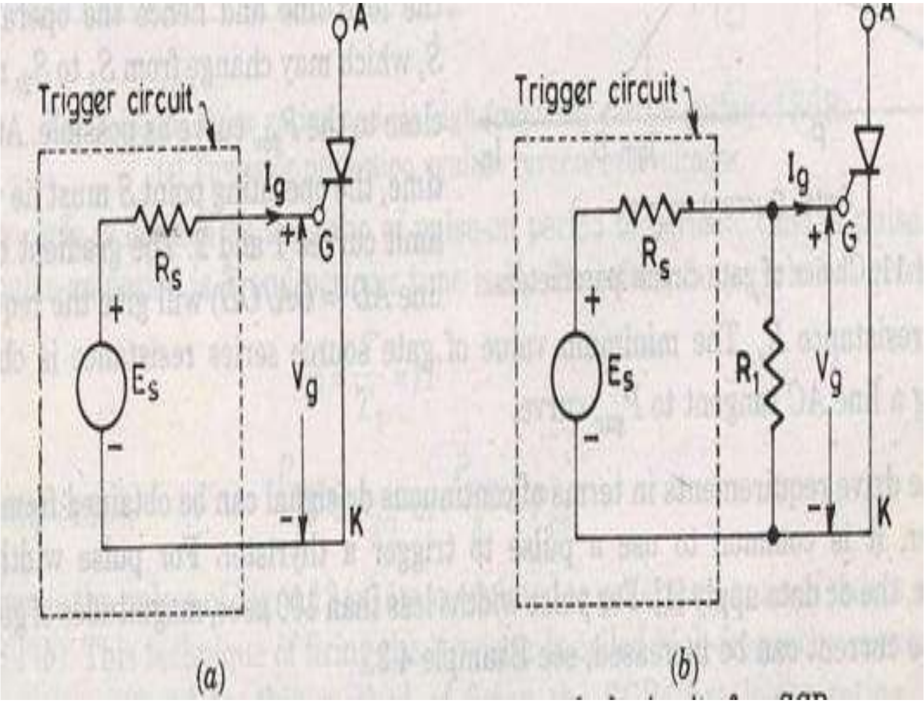
I_{gm}= Maximum imilt for gate current.

P_{gav} = Rated gate power dissipation for each SCR.

These limits should not be crossed in order to avoid the permanent damage of the device junction J_3.

OY = Minimum limit of gate voltage to turn ON . OX = minimum limit of gate current to turn ON.

Thyristor gate characteristics:-



$E_S = V_g + I_g R_S$

E_S =Gate source voltage

V_g = Gate cathode voltage

I_g = Gate current

R_S = Gate source resistance

R_S = The internal resistance of the trigger source

R_1 is connected across the gate cathode terminal, which provides an easy path to the flow of leakage current between SCR terminal. If I_{gmn} , V_{gmn} are the minimum gate current and gate voltage to turn ON the SCR.

$$E_S = (I_{gmn} + V_{gmn} / R_1) R_S + V_{gmn}$$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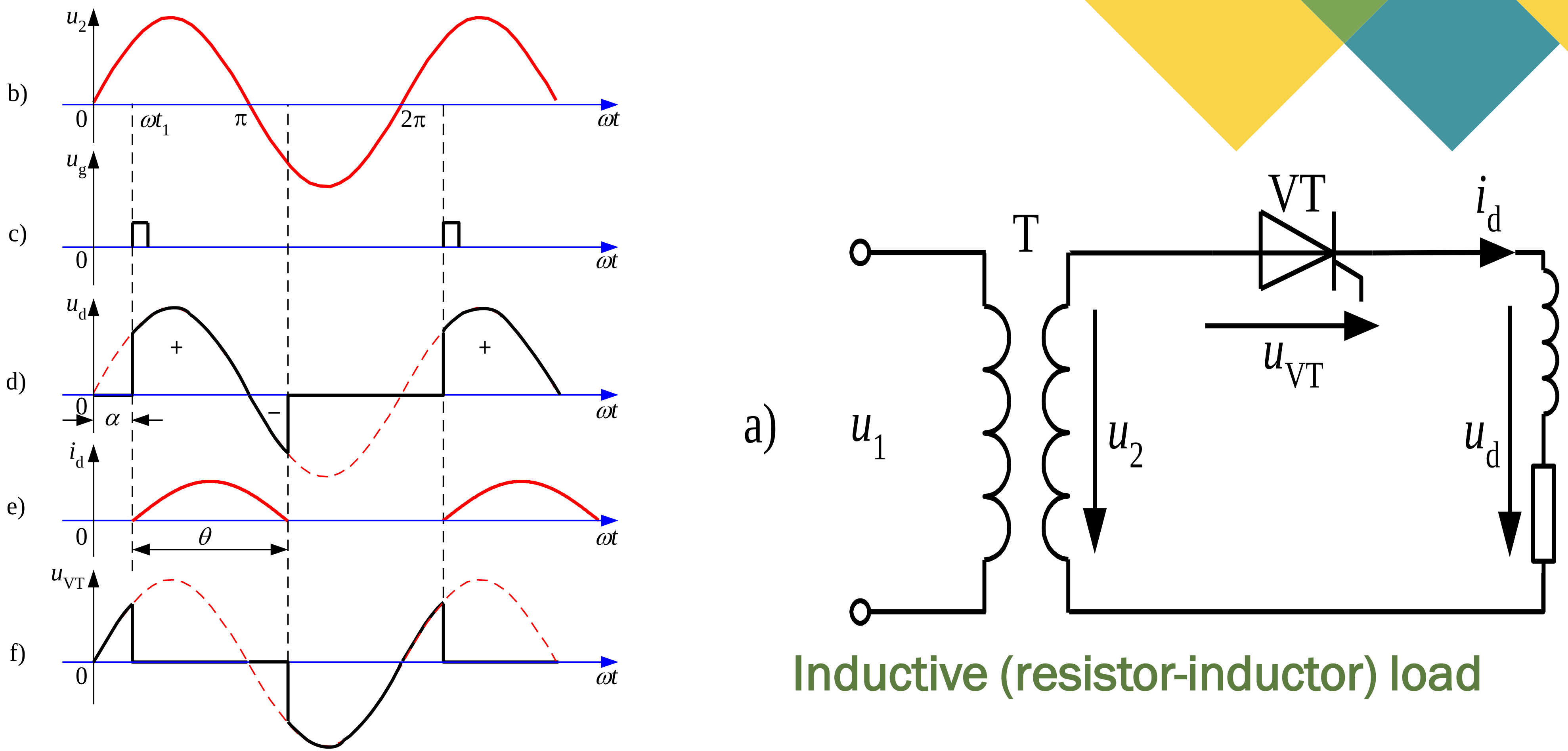
RECTIFIER

RECTIFIER

Rectifier are used to convert A.C to D.C supply.

Rectifiers can be classified as single phase rectifier and three phase rectifier. Single phase rectifier are classified as 1-Φ half wave and 1-Φ full wave rectifier. Three phase rectifier are classified as 3-Φ half wave rectifier and 3-Φ full wave rectifier. 1-Φ Full wave rectifier are classified as1-Φ mid point type and 1-Φ bridge type rectifier. 1-Φ bridge type rectifier are classified as 1-Φ half controlled and 1-Φ full controlled rectifier. 3-Φ full wave rectifier are again classified as 3-Φ mid point type and 3-Φ bridge type rectifier. 3-Φ bridge type rectifier are again divided as 3-Φ half controlled rectifier and 3-Φ full controlled rectifier.

Single-phase half-wave controlled rectifier



Inductive (resistor-inductor) load

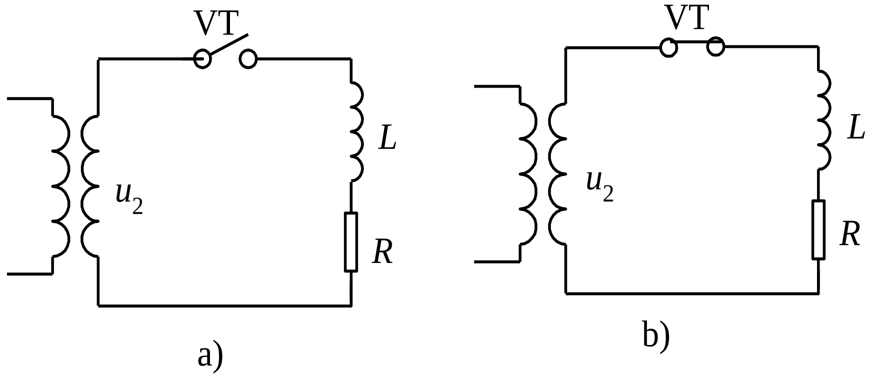
Basic thought process of time-domain analysis for power electronic circuits

- **The time-domain behavior of a power electronic circuit is actually the combination of consecutive transients of the different linear circuits when the power semiconductor devices are in different states.**

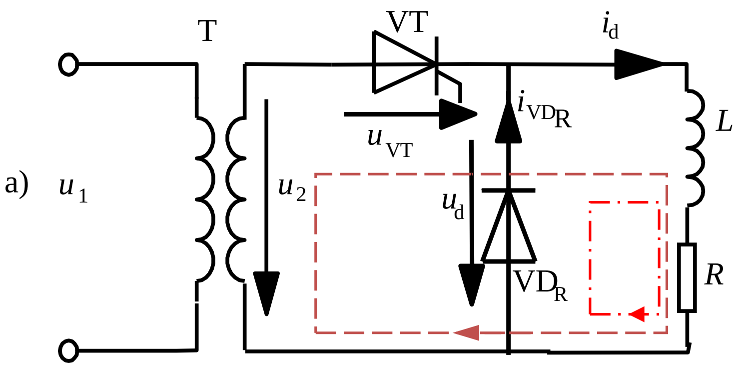
$$L\frac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t}+Ri_{\mathrm{d}}=\sqrt{2}U_{2}\sin\omega t \qquad (3\text{-}2)$$

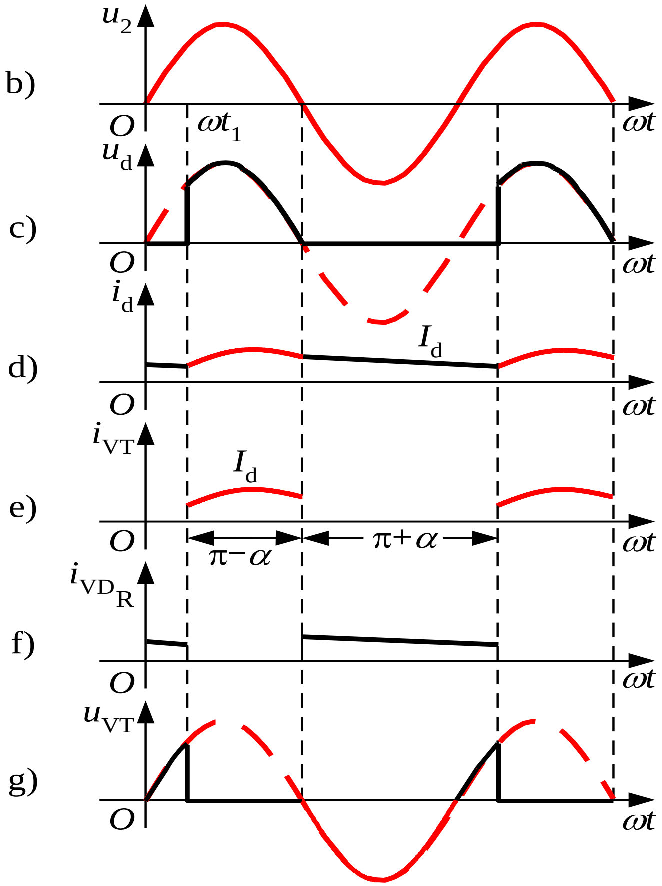
$\omega t=\alpha$, $i_{\mathrm{d}}=0$

$$i_{\mathrm{d}}=-\frac{\sqrt{2}U_{2}}{Z}\sin(\alpha-\varphi)e^{-\frac{R}{\omega L}(\omega t-\alpha)}+\frac{\sqrt{2}U_{2}}{Z}\sin(\omega t-\varphi) \qquad (3\text{-}3)$$



Inductive load (L is large enough)





$$I_{\mathbf{dVT}} = \frac{\pi-\alpha}{2\pi} I_{\mathbf{d}}$$

$$I_{\mathbf{dVDR}} = \frac{\pi+\alpha}{2\pi} I_{\mathbf{d}}$$

$$I_{VT} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi} I_d^2 d(\omega t)} = \sqrt{\frac{\pi-\alpha}{2\pi}} I_d$$

$$I_{\mathbf{VDR}} = \sqrt{\frac{1}{2\pi}\int_{\pi}^{2\pi+\alpha} I_{\mathbf{d}}^2 d(\omega t)} = \sqrt{\frac{\pi+\alpha}{2\pi}} I_{\mathbf{d}}$$

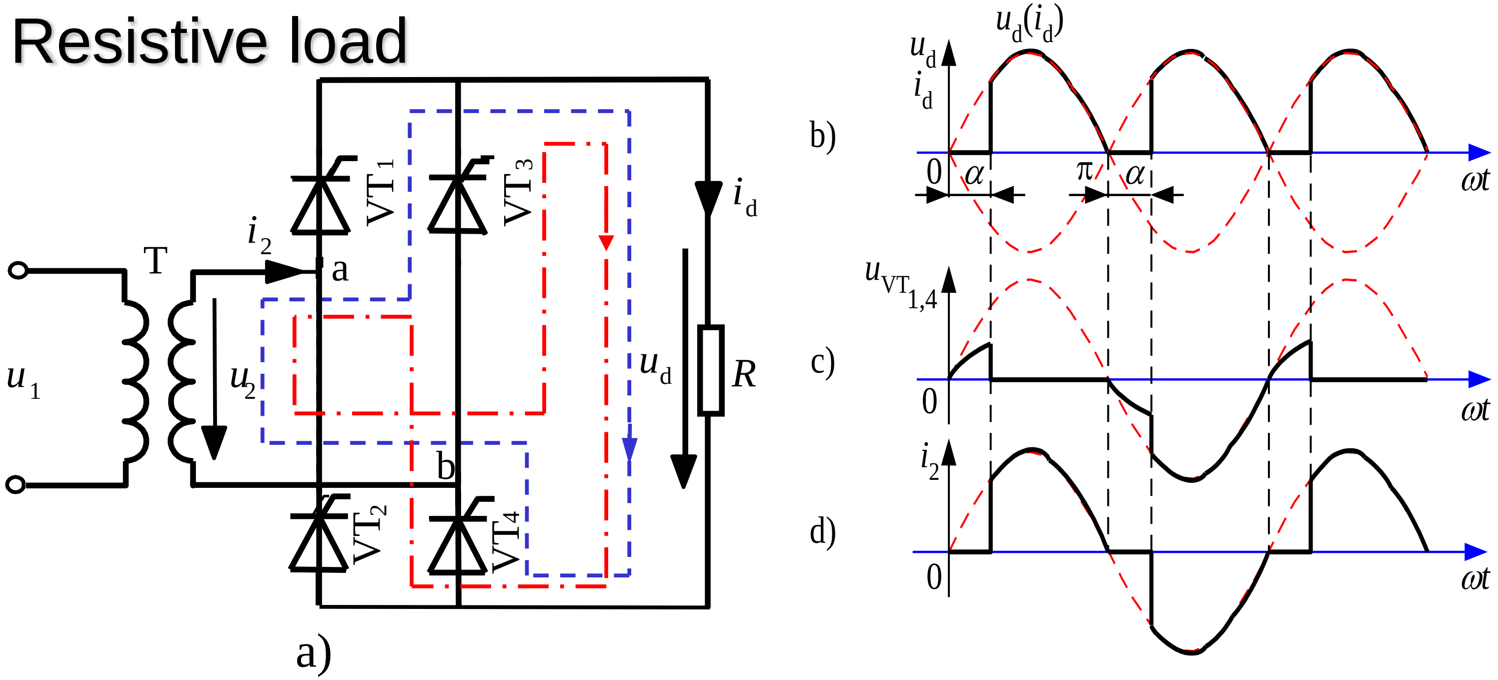
Maximum forward voltage, maximum reverse voltage

Disadvantages:

- Only single pulse in one line cycle
- DC component in the transformer current

Single-phase bridge fully-controlled rectifier

Resistive load



- For thyristor: maximum forward voltage, maximum reverse voltage
- Advantages:
  - 2 pulses in one line cycle
  - No DC component in the transformer current

Single-phase bridge fully-controlled rectifier

Resistive load

- Average output (rectified) voltage

$$U_d = \frac{1}{\pi}\int_{\alpha}^{\pi}\sqrt{2}U_2 \sin \omega t \mathrm{d}(\omega t) = \frac{2\sqrt{2}U_2}{\pi}\frac{1+\cos\alpha}{2} = 0.9U_2\frac{1+\cos\alpha}{2} \quad (3\text{-}9)$$

- Average output current

$$I_d = \frac{U_d}{R} = \frac{2\sqrt{2}U_2}{\pi R}\frac{1+\cos\alpha}{2} = 0.9\frac{U_2}{R}\frac{1+\cos\alpha}{2} \quad (3\text{-}10)$$

- For thyristor

$$I_{dVT} = \frac{1}{2}I_d = 0.45\frac{U_2}{R}\frac{1+\cos\alpha}{2} \quad (3\text{-}11)$$

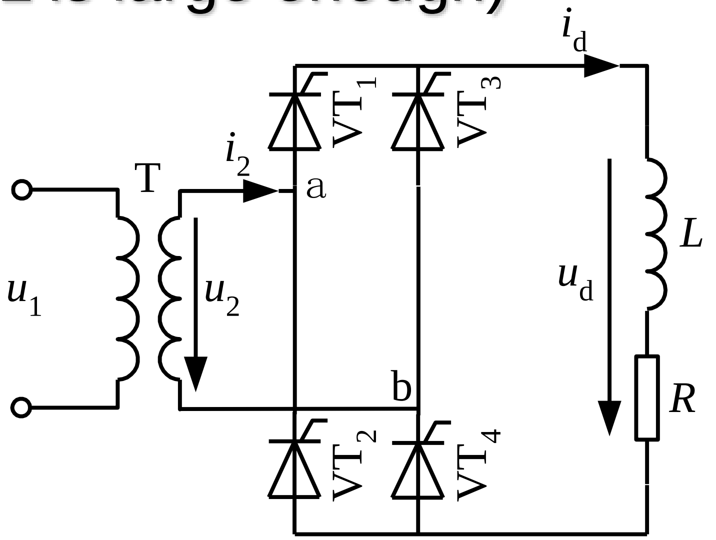
$$I_{VT} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\left(\frac{\sqrt{2}U_2}{R}\sin \omega t\right)^2 \mathrm{d}(\omega t)} = \frac{U_2}{\sqrt{2}R}\sqrt{\frac{1}{2\pi}\sin 2\alpha + \frac{\pi-\alpha}{\pi}} \quad (3\text{-}12)$$

- For transformer

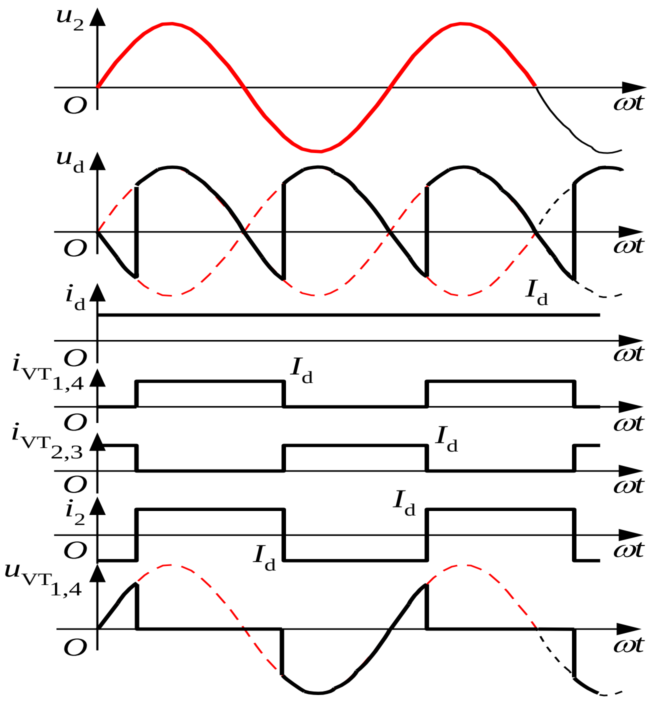
$$I = I_2 = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\frac{\sqrt{2}U_2}{R}\sin \omega t\right)^2 d(\omega t)} = \frac{U_2}{R}\sqrt{\frac{1}{2\pi}\sin 2\alpha + \frac{\pi-\alpha}{\pi}} \quad (3\text{-}13)$$

Single-phase bridge fully-controlled rectifier

Inductive load
(L is large enough)



a)



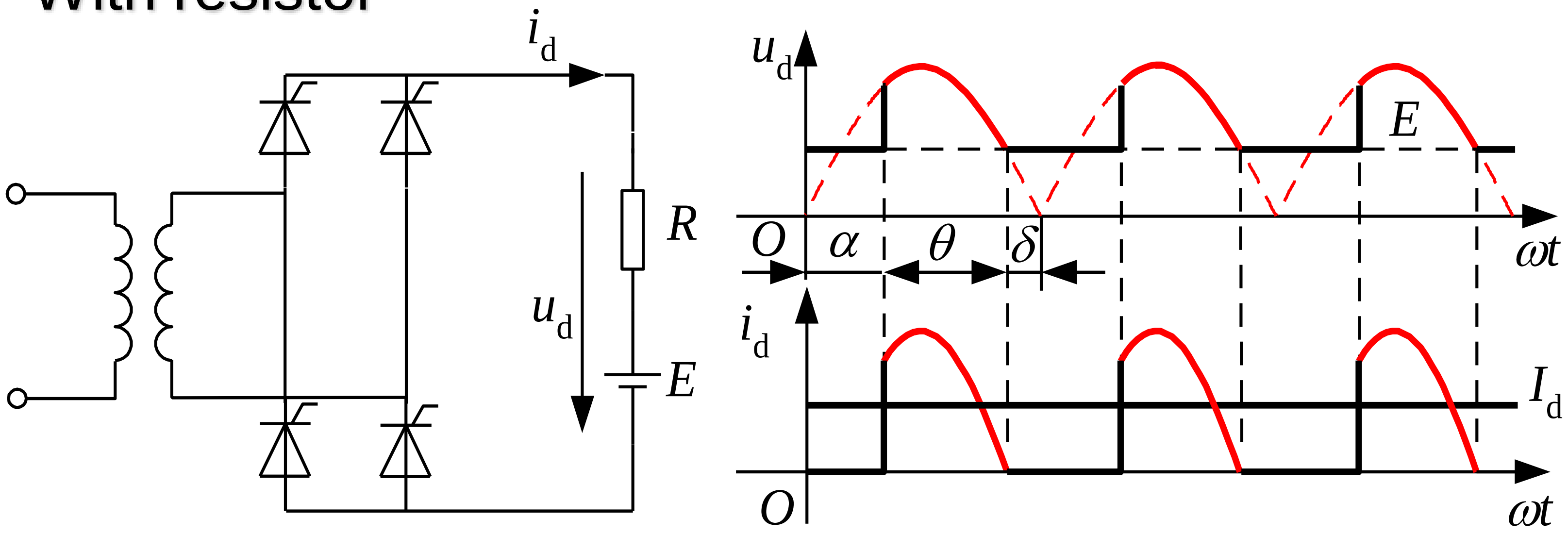
b)

$$U_d = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} \sqrt{2}U_2 \sin \omega t \mathrm{d}(\omega t) = \frac{2\sqrt{2}}{\pi}U_2 \cos\alpha = 0.9U_2 \cos\alpha \qquad (3\text{-}15)$$

- Commutation
- Thyristor voltages and currents
- Transformer current

Electro-motive-force (EMF) load

With resistor



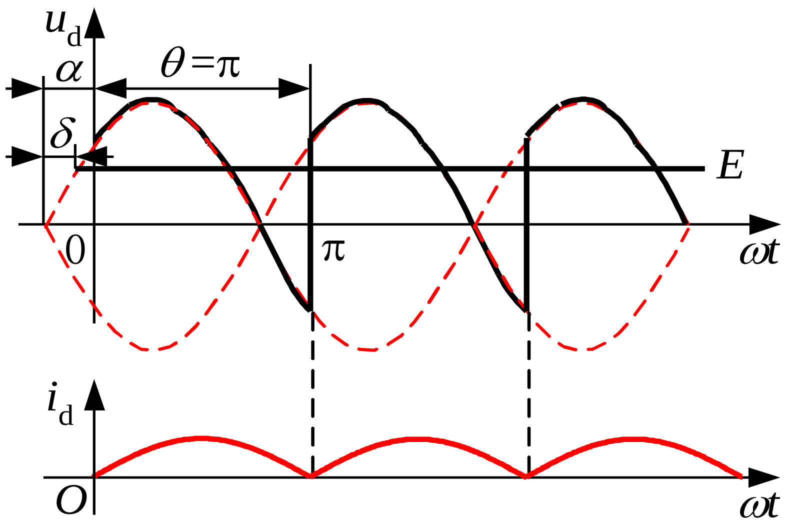
a) b)

- Discontinuous current i_d

Electro-motive-force (EMF) load

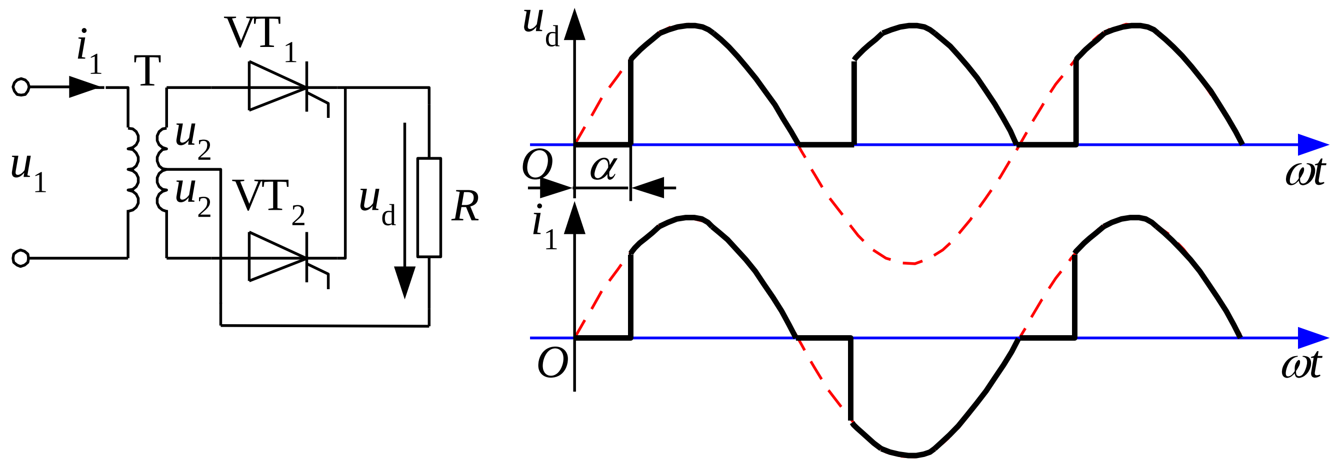
With resistor and inductor

- When L is large enough, the output voltage and current waveforms are the same as ordinary inductive load.
- When L is at a critical value



$$L = \frac{2\sqrt{2}U_2}{\pi \omega I_{dmin}} = 2.87 \times 10^{-3} \frac{U_2}{I_{dmin}} \quad (3\text{-}17)$$

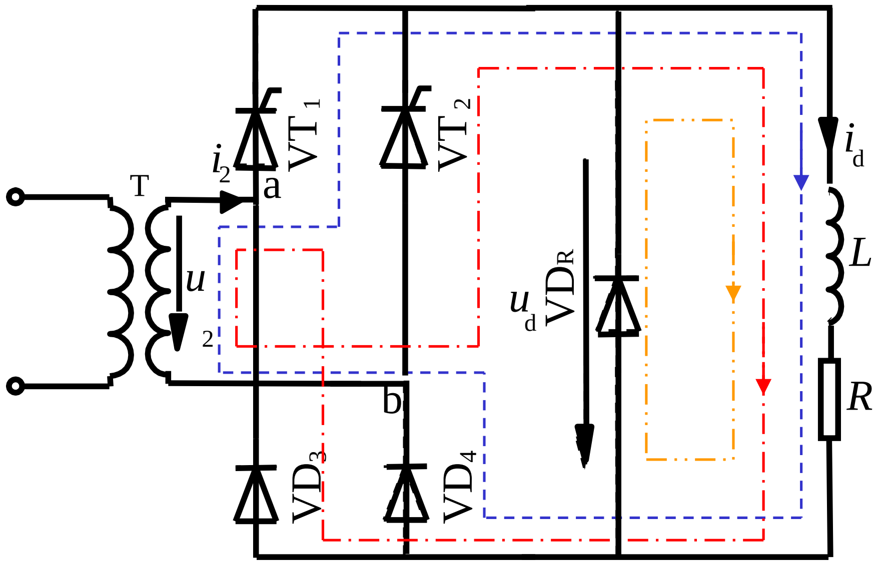
Single-phase full-wave controlled rectifier

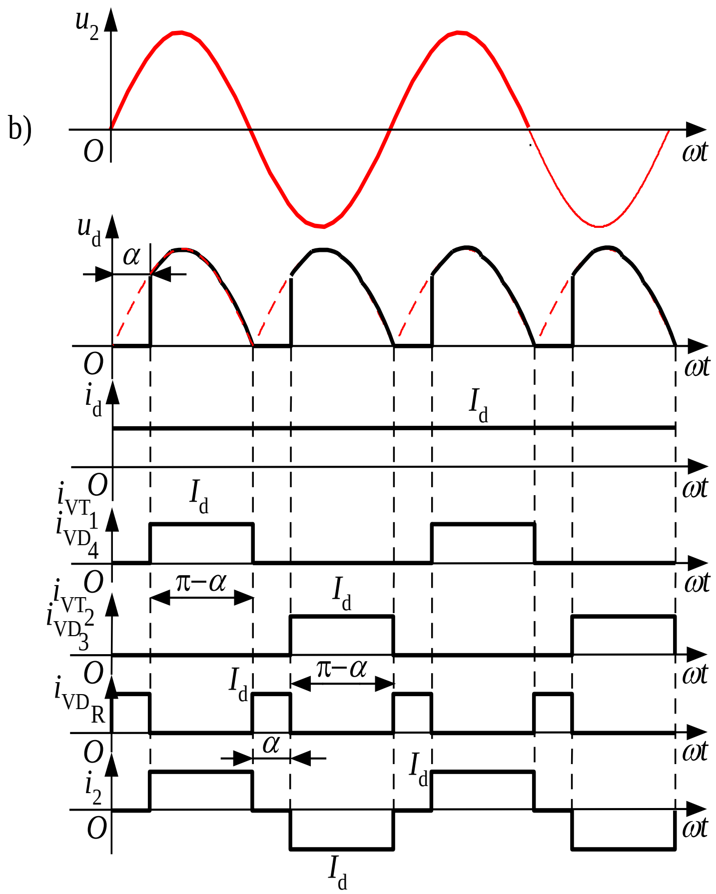


a)　　　　　　b)

- Transformer with center tap
- Comparison with single-phase bridge fully-controlled rectifier

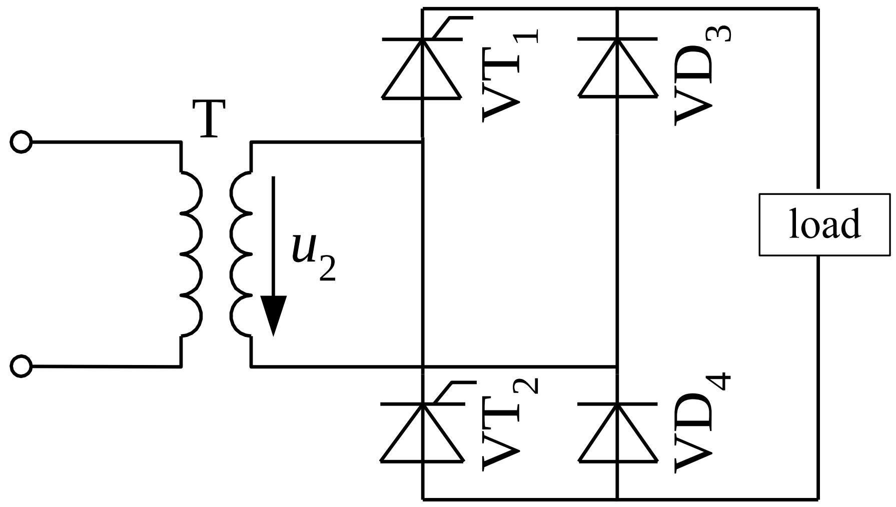
Single-phase bridge half-controlled rectifier





- Half-control
- Comparison with fully-controlled rectifier
- Additional freewheeling diode

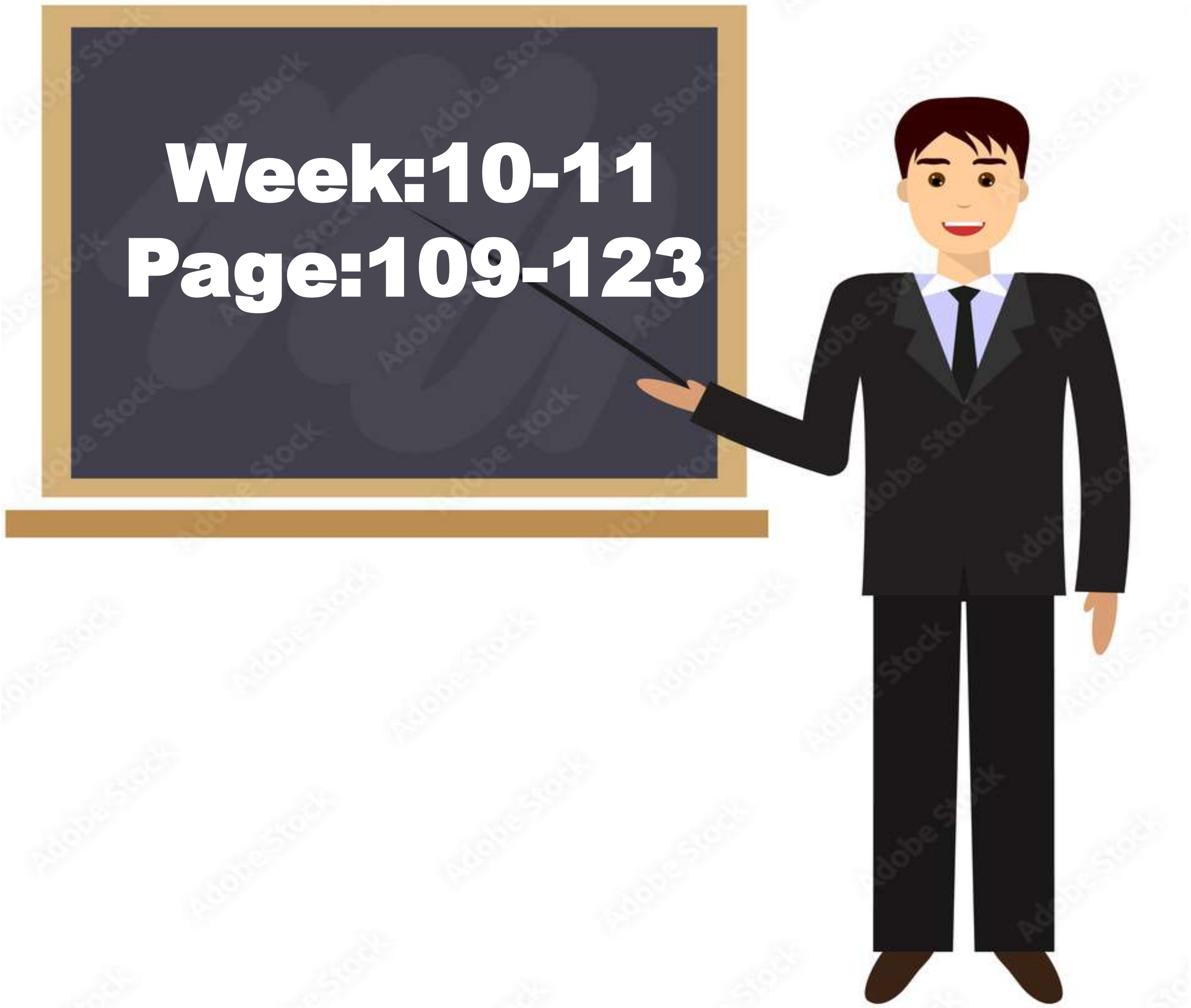
Another single-phase bridge half-controlled rectifier



- Comparison with previous circuit:
  - No need for additional freewheeling diode
  - Isolation is necessary between the drive circuits of the two thyristors

Summary of some important points in analysis

- When analyzing a thyristor circuit, start from a diode circuit with the same topology. The behavior of the diode circuit is exactly the same as the thyristor circuit when firing angle is 0.
- A power electronic circuit can be considered as different linear circuits when the power semiconductor devices are in different states. The time-domain behavior of the power electronic circuit is actually the combination of consecutive transients of the different linear circuits.
- Take different principle when dealing with different load
  - For resistive load: current waveform of a resistor is the same as the voltage waveform
  - For inductive load with a large inductor: the inductor current can be considered constant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Three-phase controlled (controllable) rectifier

Three-phase half-wave controlled rectifier

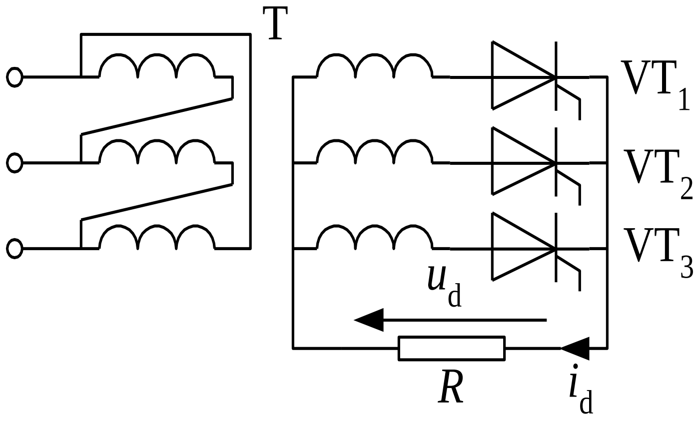
(the basic circuit among three-phase rectifiers)

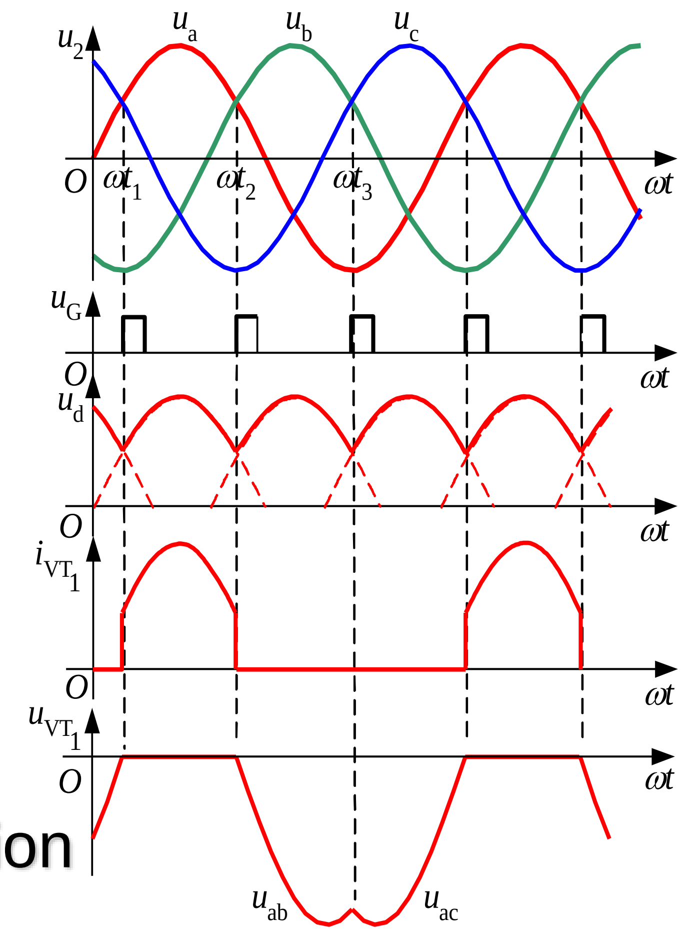
Three-phase bridge fully-controlled rectifier

(the most widely used circuit among three-phase rectifiers)

Three-phase half-wave controlled rectifier

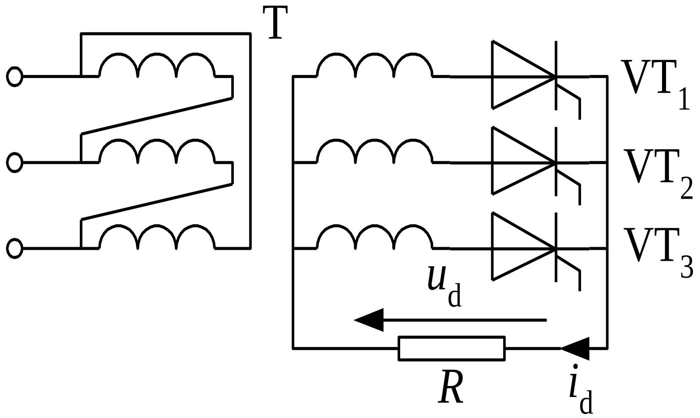
Resistive load, $\alpha = 0^{o}$

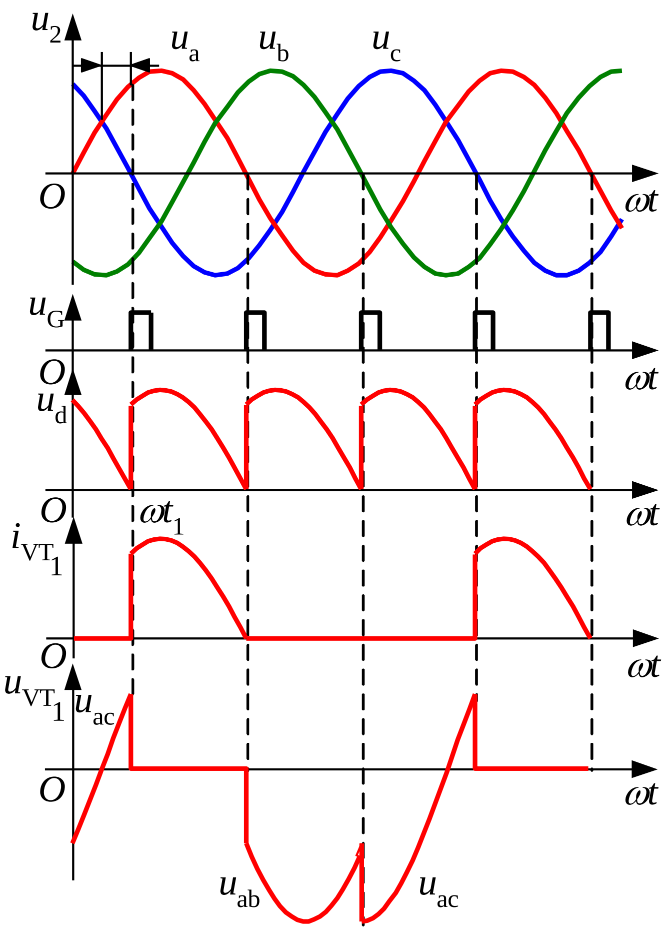




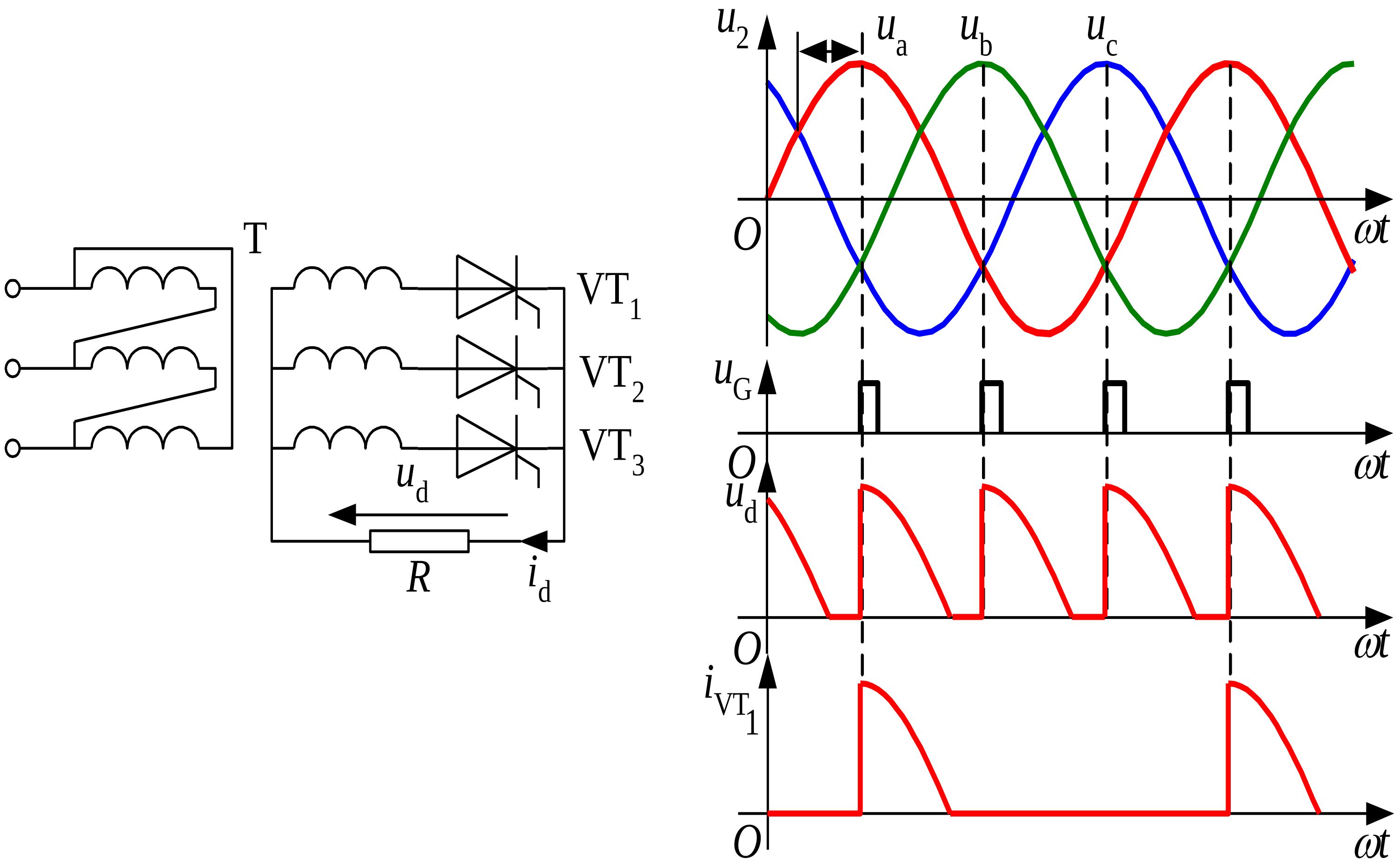
- Common-cathode connection
- Natural commutation point

Resistive load, $\alpha = 30^{o}$





Resistive load, $\alpha = 60°$



Resistive load, quantitative analysis

- When $\alpha \leq 30^{\circ}$, load current i_d is continuous.

$$U_d = \frac{1}{\frac{2\pi}{3}} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} \sqrt{2}U_2 \sin\omega t\, d(\omega t) = \frac{3\sqrt{6}}{2\pi}U_2 \cos\alpha = 1.17U_2\cos\alpha \qquad (3\text{-}18)$$

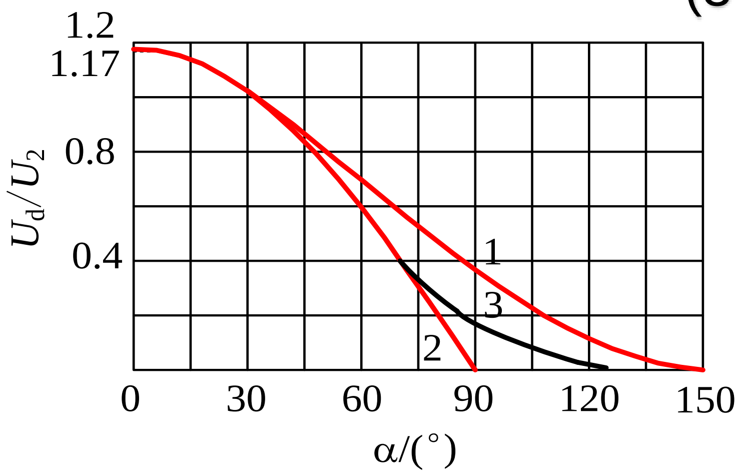
- When $\alpha > 30^{\circ}$, load current i_d is discontinuous.

$$U_d = \frac{1}{\frac{2\pi}{3}} \int_{\frac{\pi}{6}+\alpha}^{\pi} \sqrt{2}U_2 \sin\omega t\, d(\omega t) = \frac{3\sqrt{2}}{2\pi}U_2\left[1+\cos(\frac{\pi}{6}+\alpha)\right] = 0.675\left[1+\cos(\frac{\pi}{6}+\alpha)\right] \qquad (3\text{-}19)$$

- Average load current

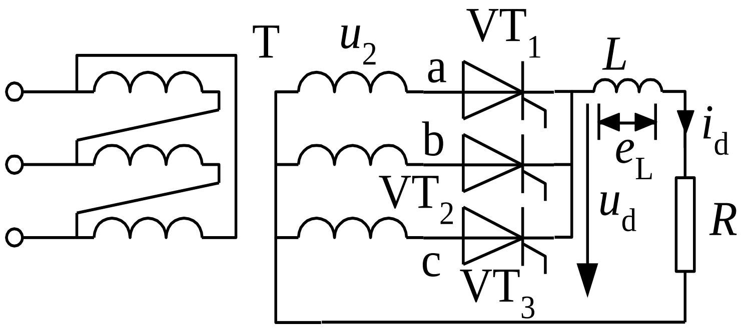
$$I_d = \frac{U_d}{R} \qquad (3\text{-}20)$$

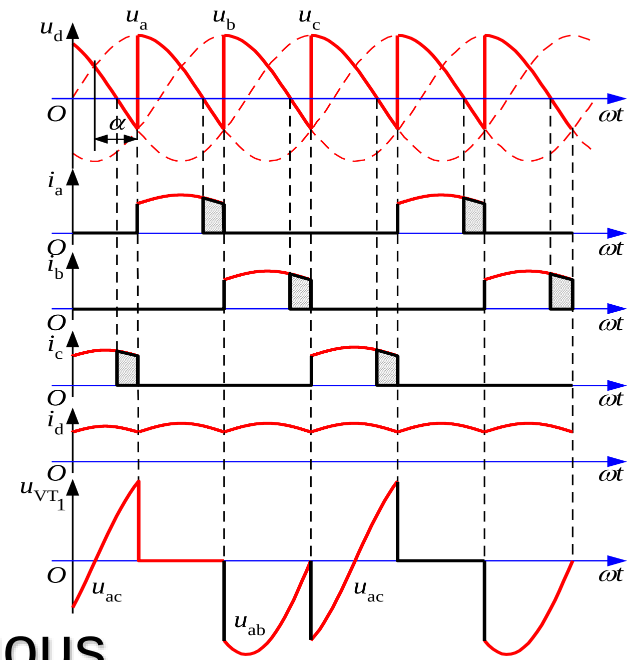
- Thyristor voltages



1- resistor load 2- inductor load
3- resistor-inductor load

Inductive load, L is large enough





- Load current i_d is always continuous.

$$U_d = \frac{1}{\frac{2\pi}{3}} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} \sqrt{2} U_2 \sin \omega t d(\omega t) = \frac{3\sqrt{6}}{2\pi} U_2 \cos\alpha = 1.17 U_2 \cos\alpha \quad (3\text{-}18)$$

- Thyristor voltage and currents, transformer current

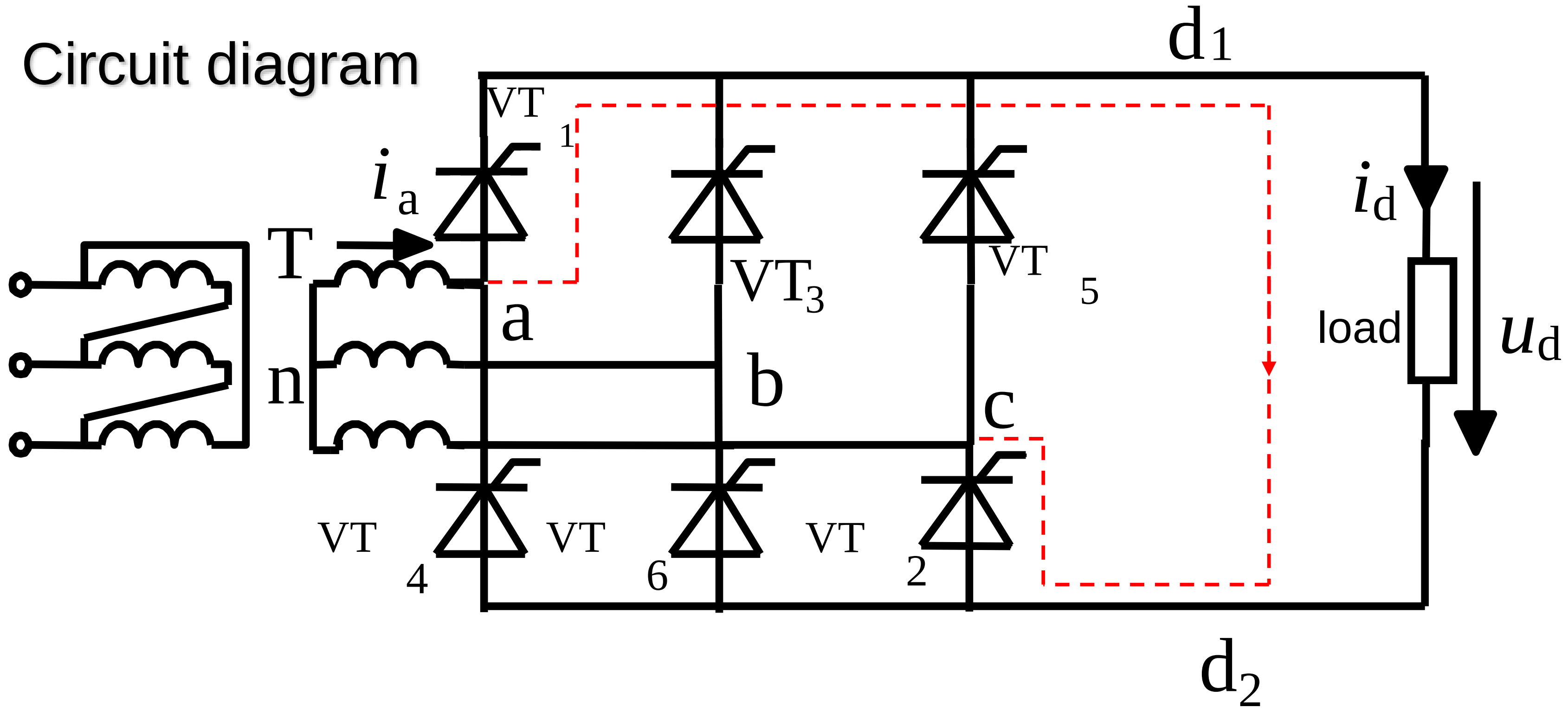
$$I_2 = I_{VT} = \frac{1}{\sqrt{3}} I_d = 0.577 I_d \quad (3\text{-}23)$$

$$I_{VT(AV)} = \frac{I_{VT}}{1.57} = 0.368 I_d \quad (3\text{-}24)$$

$$U_{FM} = U_{RM} = 2.45 U_2 \quad (3\text{-}25)$$

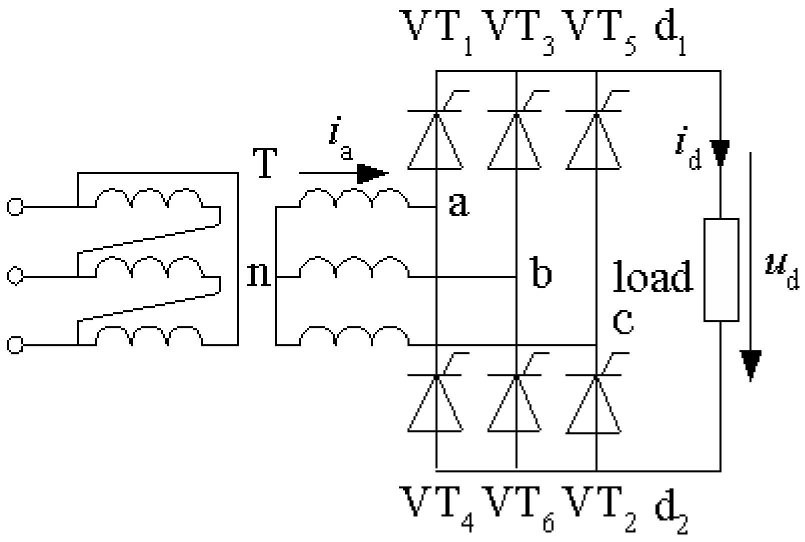
3.2.2 Three-phase bridge fully-controlled rectifier

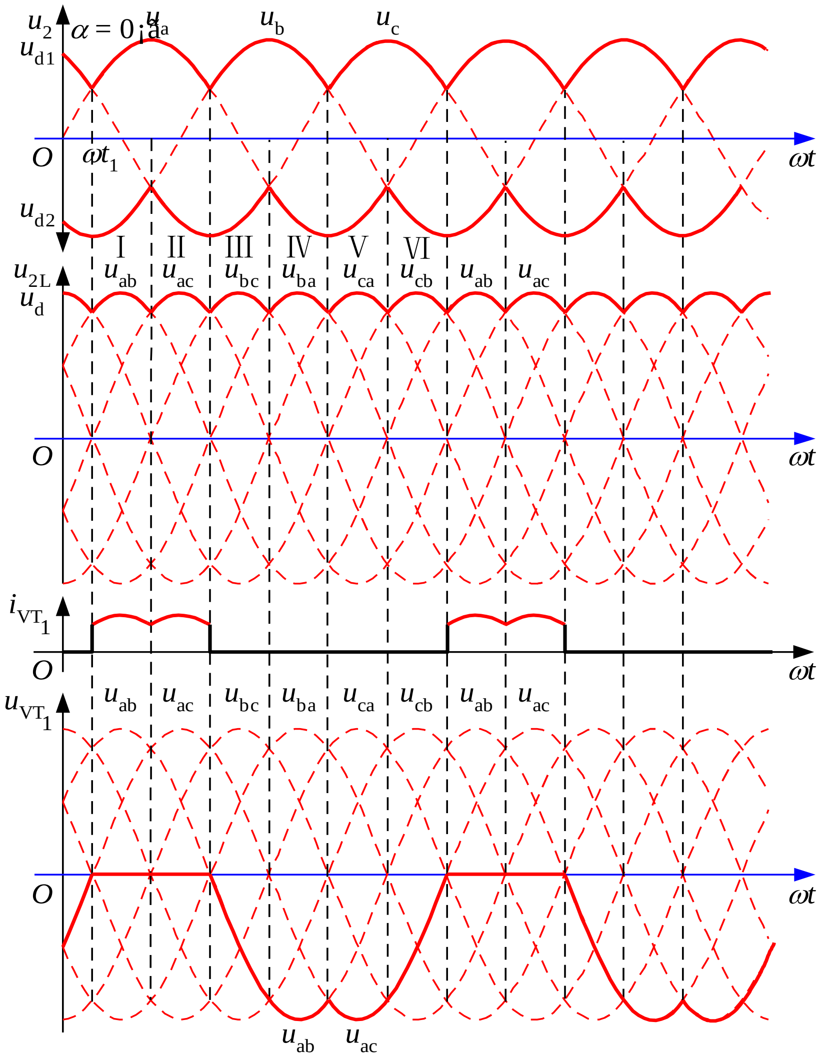
Circuit diagram



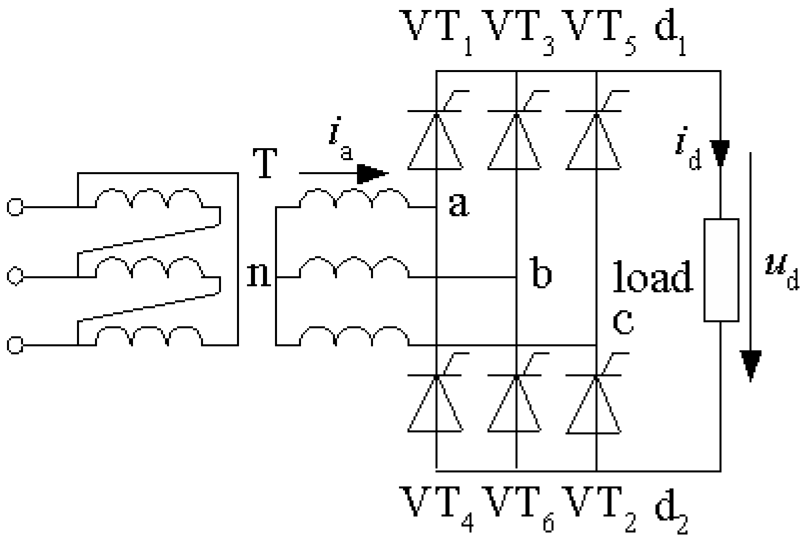
- Common-cathode group and common-anode group of thyristors
- Numbering of the 6 thyristors indicates the trigger sequence.

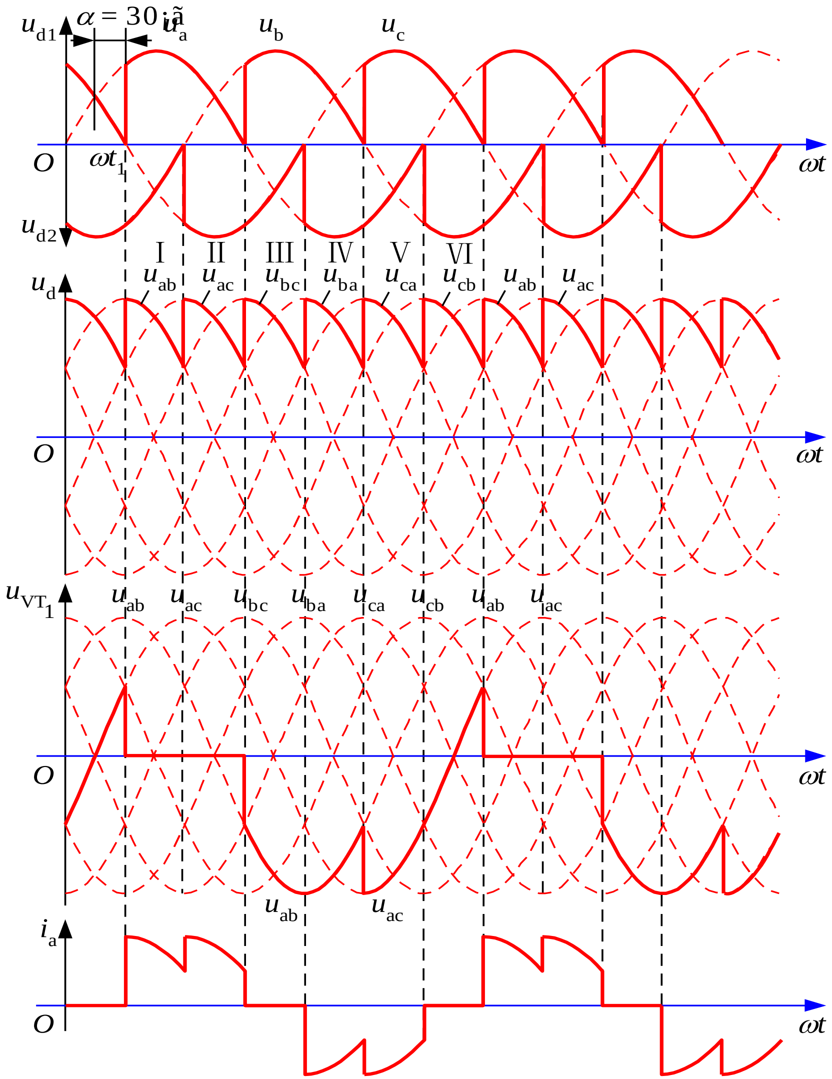
Resistive load, $\alpha = 0^{\circ}$



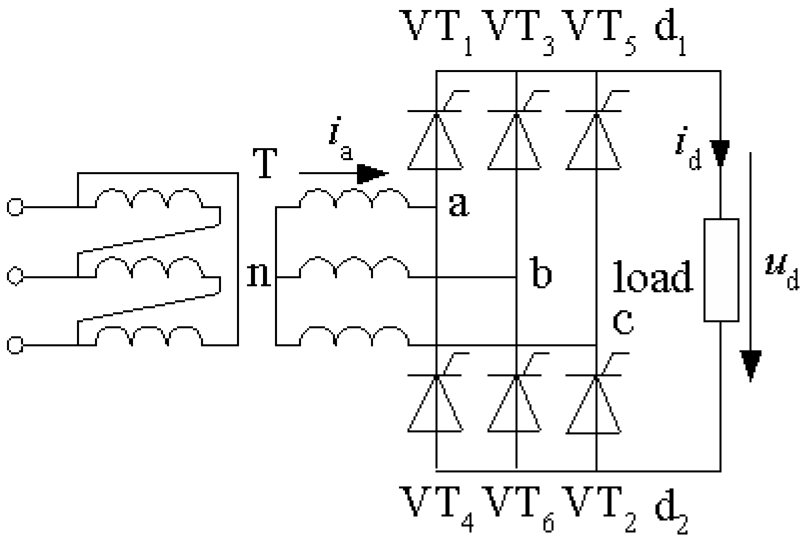


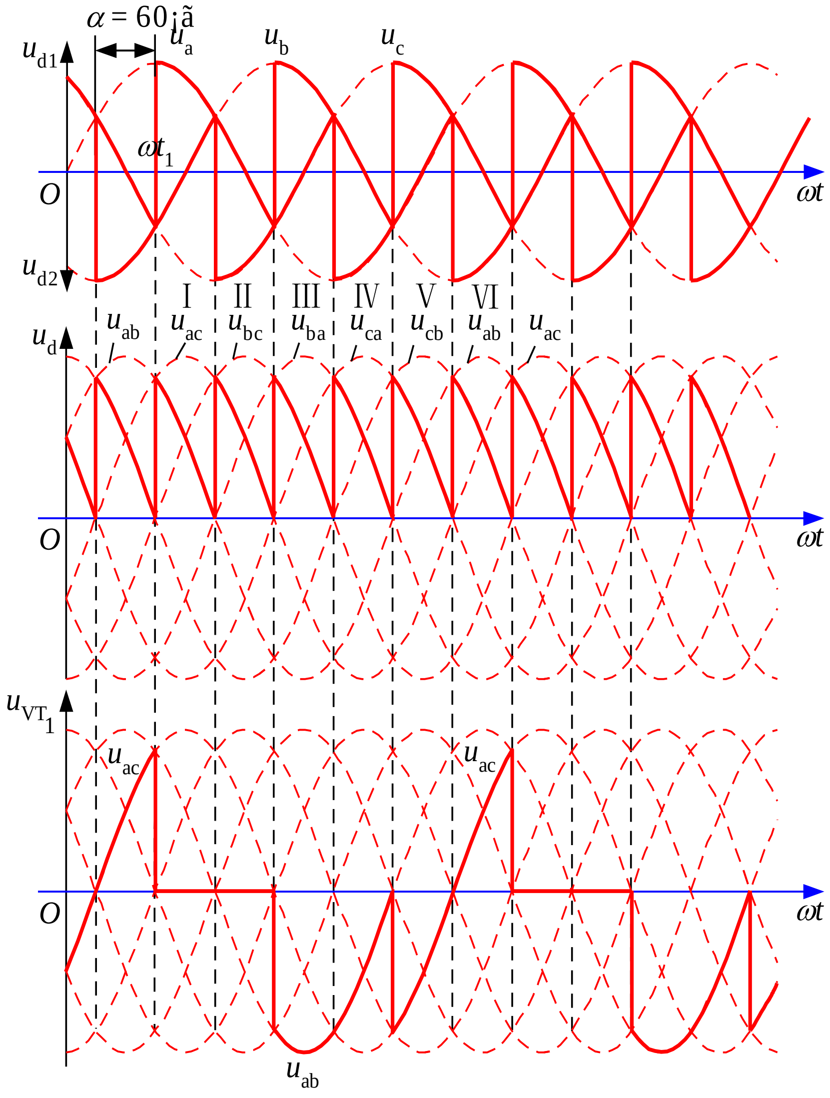
Resistive load, $\alpha = 30°$



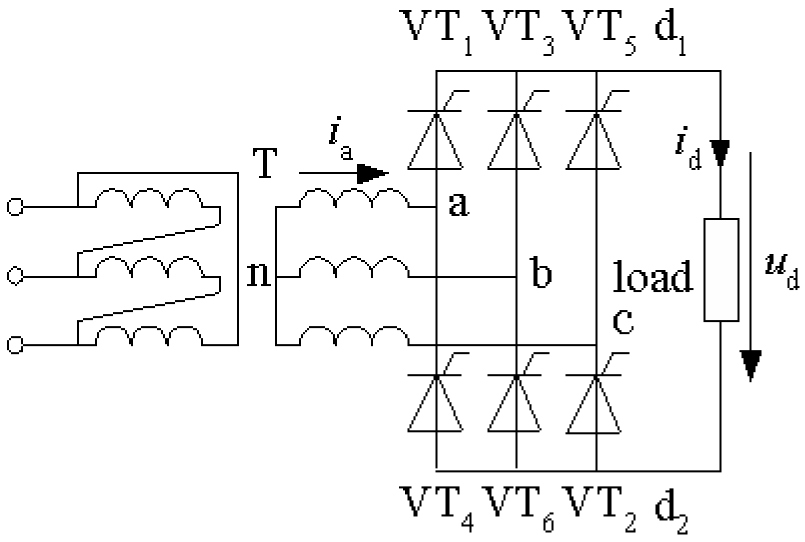


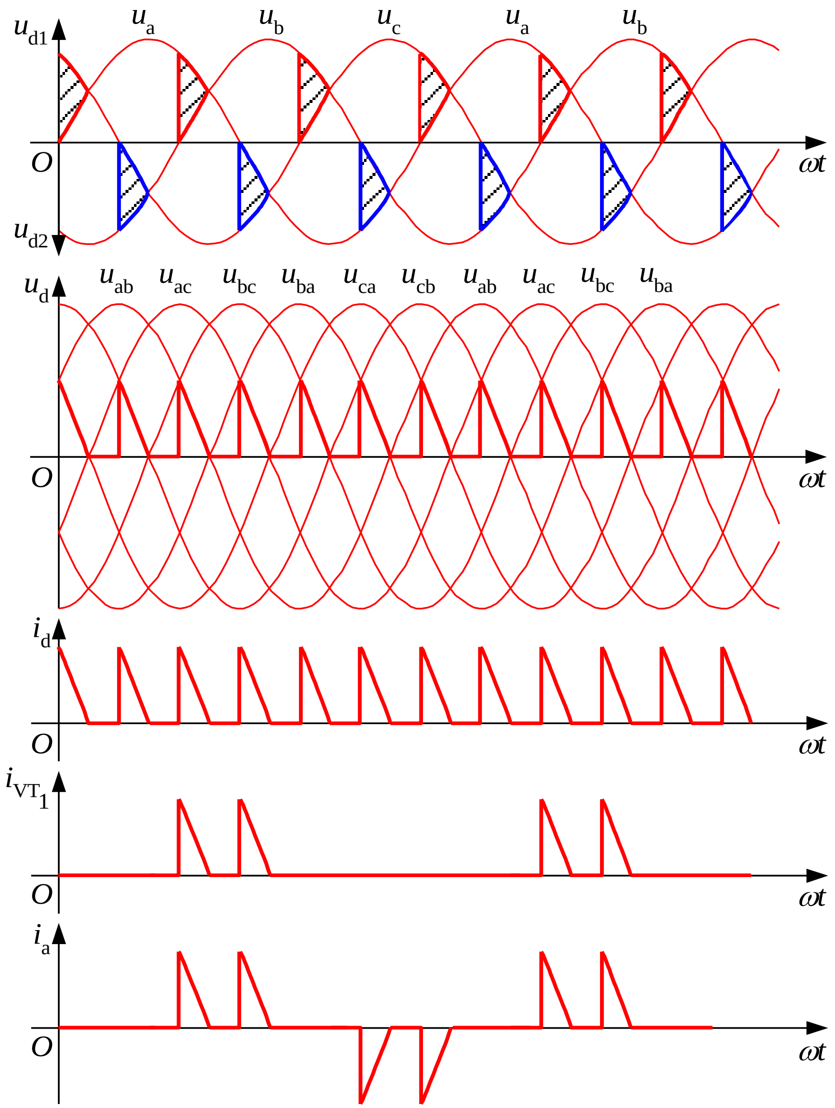
Resistive load, $\alpha = 60^{o}$



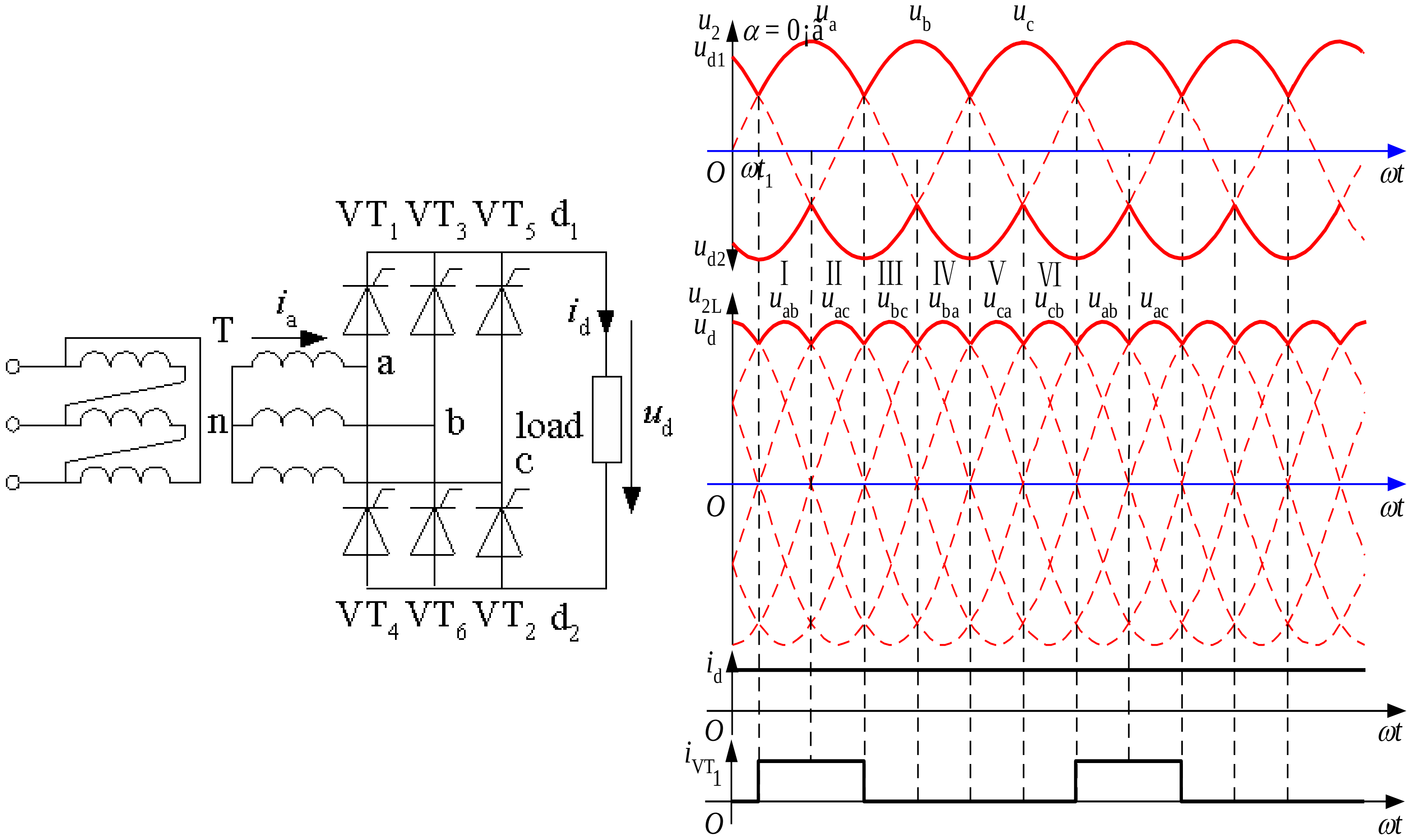


Resistive load, $\alpha = 90^{o}$

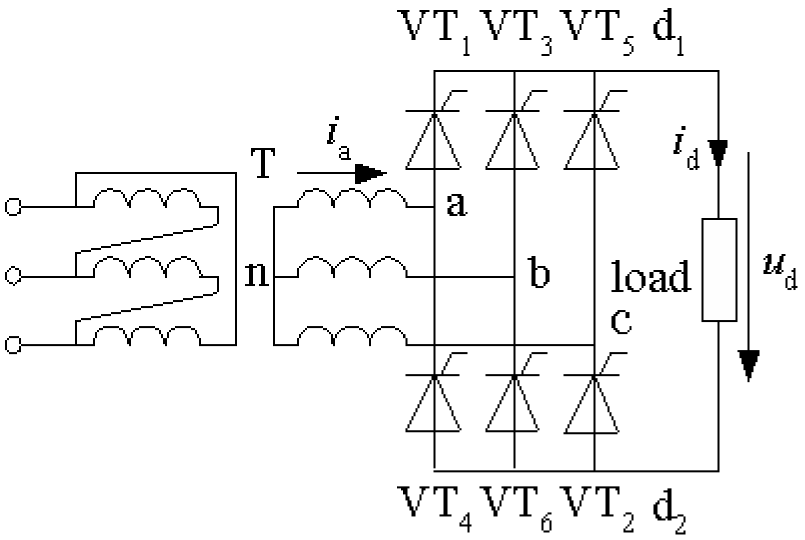


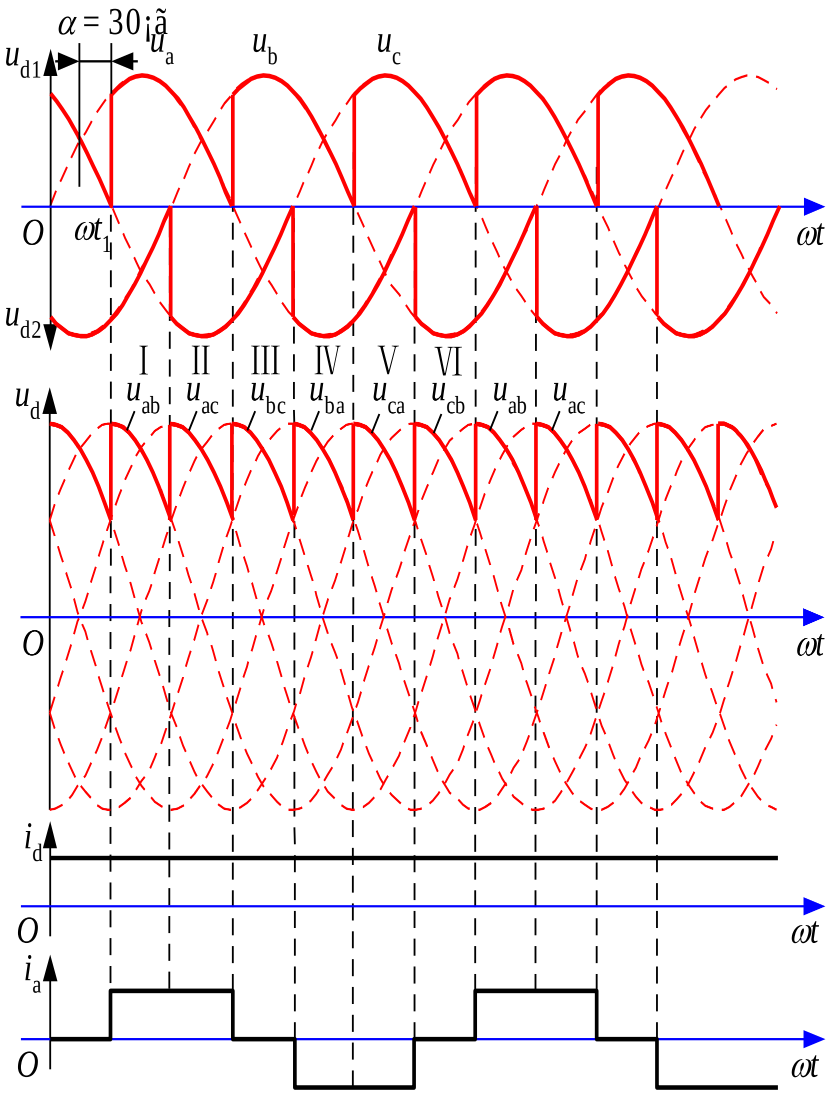


Inductive load, $\alpha = 0^{\circ}$

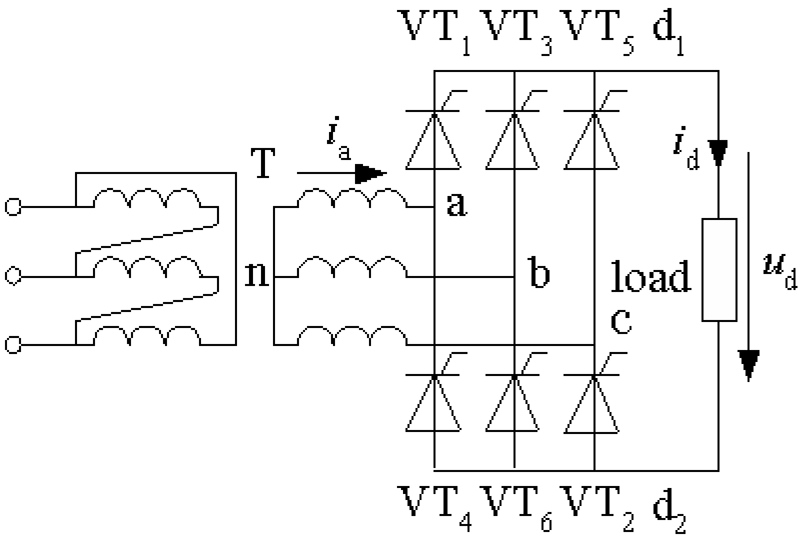


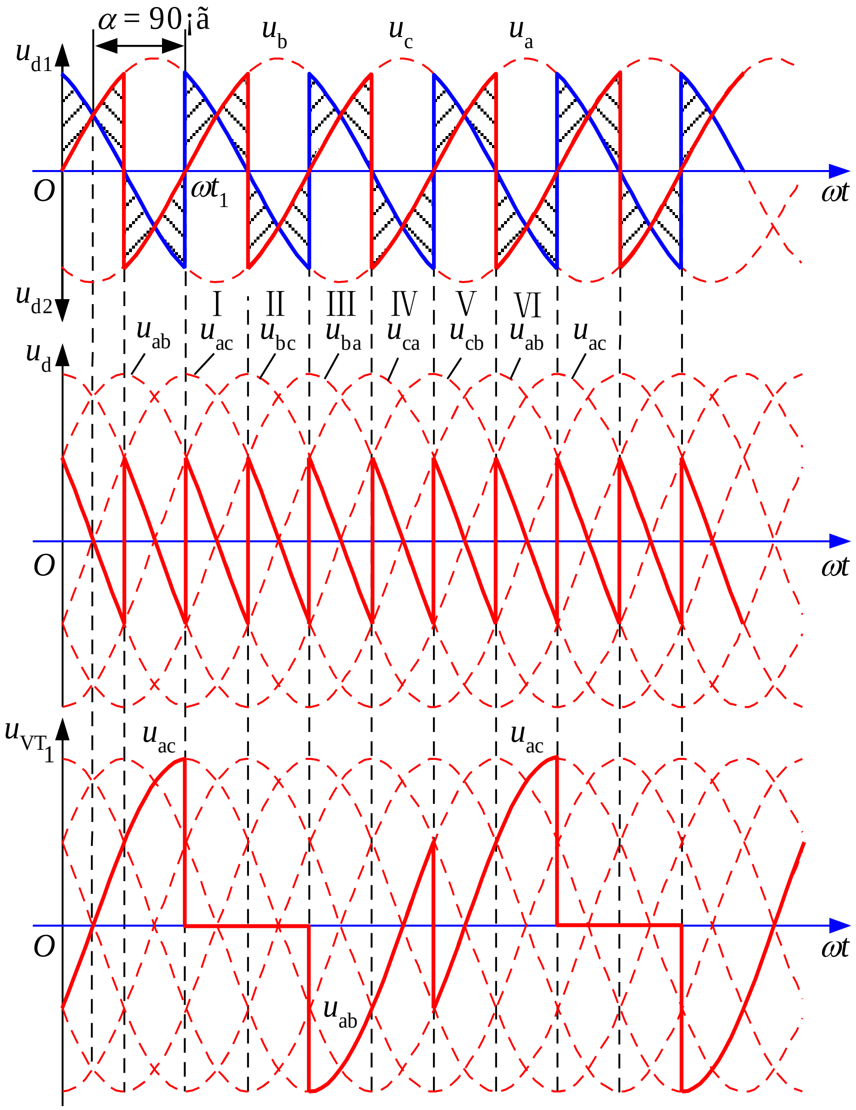
Inductive load, $\alpha = 30°$





Inductive load, $\alpha = 90^{o}$





Quantitative analysis

- Average output voltage

$$U_d = \frac{1}{\frac{\pi}{3}} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sqrt{6} U_2 \sin \omega t d(\omega t) = 2.34 U_2 \cos \alpha \qquad (3\text{-}26)$$

For resistive load, When $a > 60^{o}$, load current i_d is discontinuous.

$$U_d = \frac{3}{\pi} \int_{\frac{\pi}{3}+\alpha}^{\pi} \sqrt{6} U_2 \sin \omega t d(\omega t) = 2.34 U_2 \left[1 + \cos(\frac{\pi}{3} + \alpha) \right] \qquad (3\text{-}27)$$

- Average output current (load current)

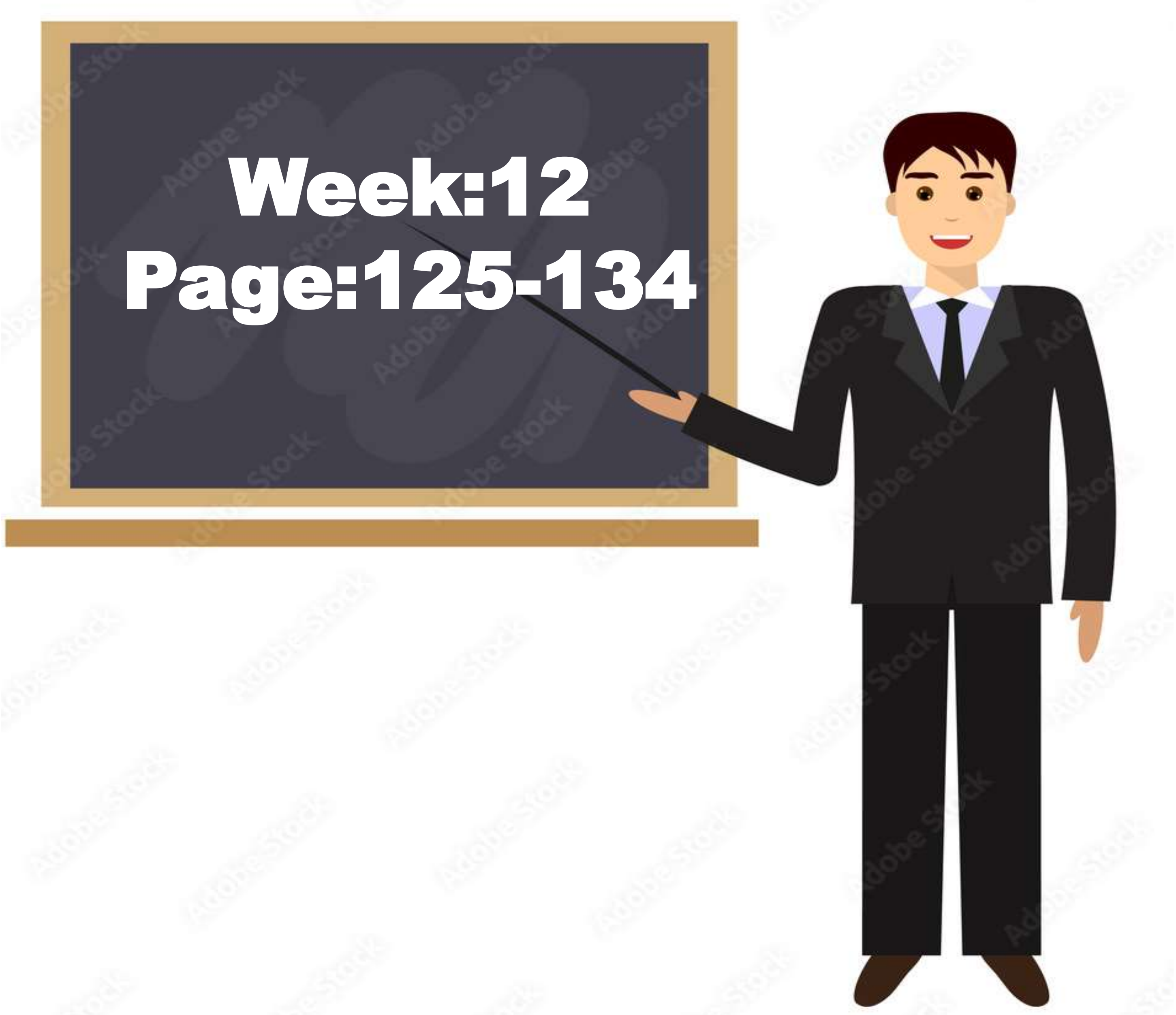
$$I_d = \frac{U_d}{R} \qquad (3\text{-}20)$$

- Transformer current

$$I_2 = \sqrt{\frac{1}{2\pi} \left(I_d^2 \times \frac{2}{3}\pi + (-I_d)^2 \times \frac{2}{3}\pi \right)} = \sqrt{\frac{2\pi}{3}} I_d = 0.816 I_d \qquad (3\text{-}28)$$

- Thyristor voltage and current
  - Same as three-phase half-wave rectifier
- EMF load, L is large enough
  - All the same as inductive load except the calculation of average output current

$$I_d = \frac{U_d - E}{R} \qquad (3\text{-}29)$$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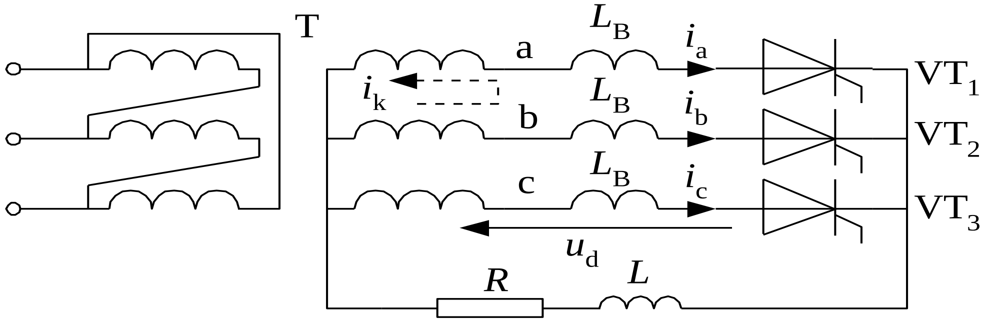
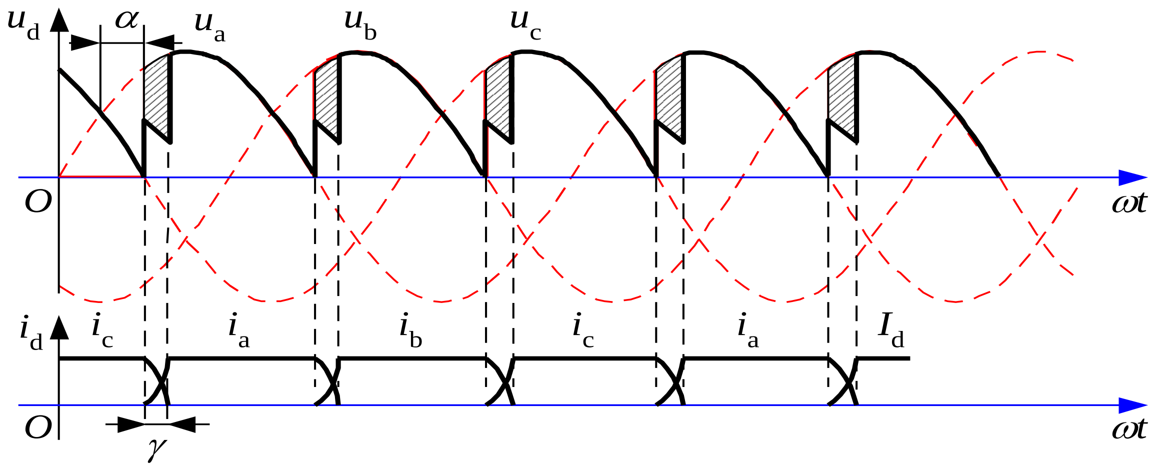
3.3 Effect of transformer leakage inductance on rectifier circuits





- In practical, the transformer leakage inductance has to be taken into account.
- Commutation between thyristors thus can not happen instantly, but with a commutation process.

Commutation process analysis

- Circulating current i_k during commutation

$u_b - u_a = 2 \cdot L_B \cdot di_a/dt$

i_k: 0 $\longrightarrow$ I_d

$i_a = I_d - i_k$: I_d $\longrightarrow$ 0

$i_b = i_k$: 0 $\longrightarrow$ I_d

- Commutation angle
- Output voltage during commutation

$$u_d = u_a + L_B \frac{di_k}{dt} = u_b - L_B \frac{di_k}{dt} = \frac{u_a + u_b}{2} \qquad (3\text{-}30)$$

Quantitative calculation

- Reduction of average output voltage due to the commutation process

$$\Delta U_{\mathrm{d}} = \frac{1}{2\pi/3}\int_{\alpha+\frac{5\pi}{6}}^{\alpha+\gamma+\frac{5\pi}{6}}(u_{\mathrm{b}}-u_{\mathrm{d}})\mathrm{d}(\omega t) = \frac{3}{2\pi}\int_{\alpha+\frac{5\pi}{6}}^{\alpha+\gamma+\frac{5\pi}{6}}[u_{\mathrm{b}}-(u_{\mathrm{b}}-L_{\mathrm{B}}\frac{\mathrm{d}i_{\mathbf{k}}}{\mathrm{d}t})]\mathrm{d}(\omega t)$$

$$= \frac{3}{2\pi}\int_{\alpha+\frac{5\pi}{6}}^{\alpha+\gamma+\frac{5\pi}{6}}L_{\mathrm{B}}\frac{\mathrm{d}i_{\mathbf{k}}}{\mathrm{d}t}\mathrm{d}(\omega t) = \frac{3}{2\pi}\int_{0}^{I_{\mathbf{d}}}\omega L_{\mathrm{B}}\mathrm{d}i_{\mathbf{k}} = \frac{3}{2\pi}X_{\mathrm{B}}I_{\mathrm{d}} \qquad (3\text{-}31)$$

- Calculation of commutation angle

$$\cos\alpha - \cos(\alpha+\gamma) = \frac{2X_{\mathrm{B}}I_{\mathrm{d}}}{\sqrt{6}U_2} \qquad (3\text{-}36)$$

  – $I_d \uparrow$, $\gamma \uparrow$
  – $X_B \uparrow$, $\gamma \uparrow$
  – For $\alpha \le 90^o$, $\alpha \downarrow$, $\gamma \uparrow$

Summary of the effect on rectifier circuits

Circuits	Single-phase full wave	Single-phase bridge	Three-phase half-wave	Three-phase bridge	m-pulse recfifier
ΔU_d	$\frac{X_B}{\pi} I_d$	$\frac{2X_B}{\pi} I_d$	$\frac{3X_B}{2\pi} I_d$	$\frac{3X_B}{\pi} I_d$	$\frac{mX_B}{2\pi} I_d$ ①
$\cos\alpha - \cos(\alpha+\gamma)$	$\frac{I_d X_B}{\sqrt{2}U_2}$	$\frac{2I_d X_B}{\sqrt{2}U_2}$	$\frac{2X_B I_d}{\sqrt{6}U_2}$	$\frac{2X_B I_d}{\sqrt{6}U_2}$	$\frac{I_d X_B}{\sqrt{2}U_2 \sin\frac{\pi}{m}}$ ②

- Conclusions
  - Commutation process actually provides additional working states of the circuit.
  - di/dt of the thyristor current is reduced.
  - The average output voltage is reduced.
  - Positive du/dt
  - Notching in the AC side voltage

Capacitor-filtered uncontrolled (uncontrollable) rectifier

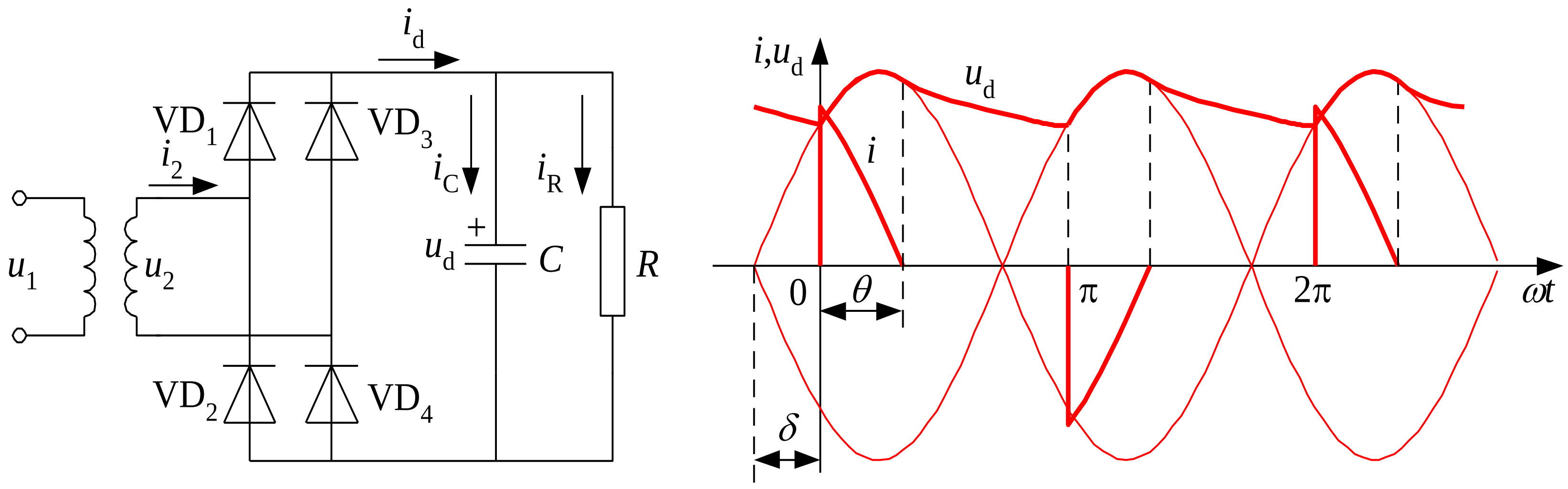
- Emphasis of previous sections
  - Controlled rectifier, inductive load
- Uncontrolled rectifier: diodes instead of thyristors
- Wide applications of capacitor-filtered uncontrolled rectifier
  - AC-DC-AC frequency converter
  - Uninterruptible power supply
  - Switching power supply

3.4.1 Capacitor-filtered single-phase uncontrolled rectifier

3.4.2 Capacitor-filtered three-phase uncontrolled rectifier

Capacitor-filtered single-phase uncontrolled rectifier

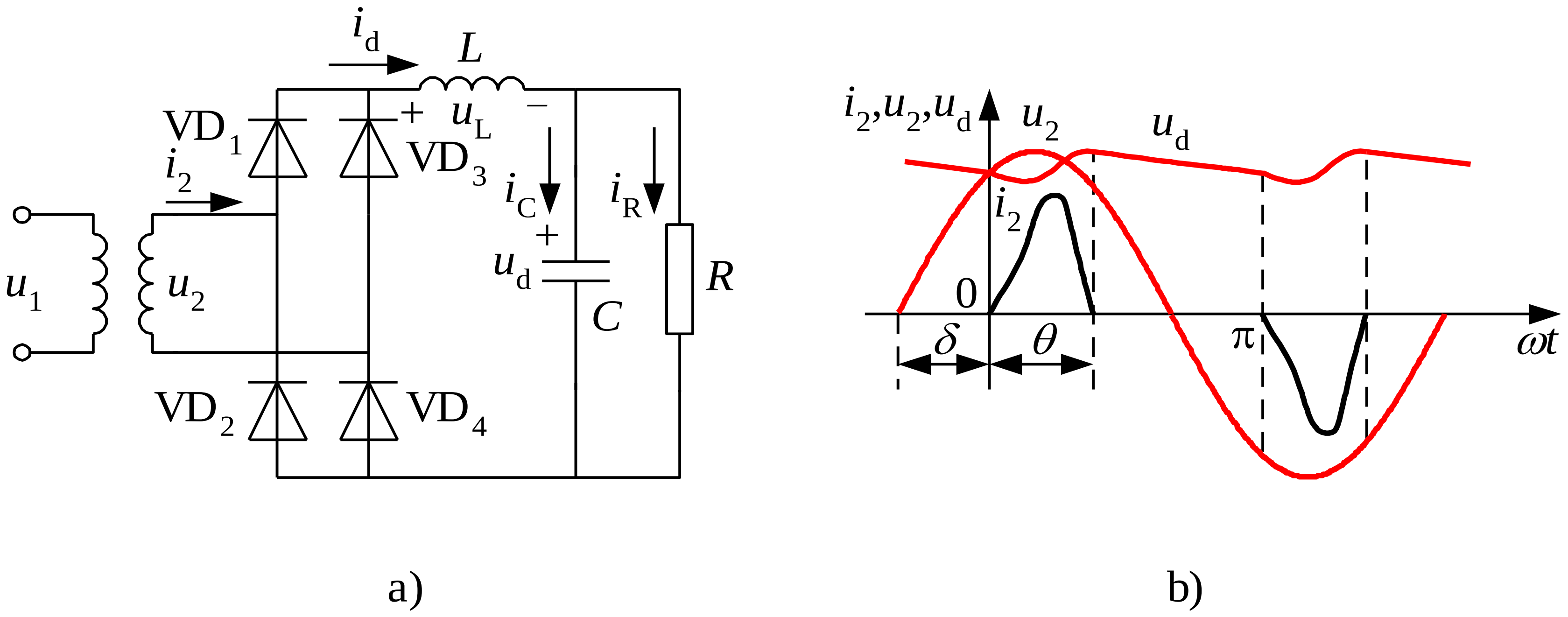
Single-phase bridge, *RC* load



a) b)

Capacitor-filtered single-phase uncontrolled rectifier

Single-phase bridge, *RLC* load



Definition of power and power factor

For sinusoidal circuits

- Active power

$$P = \frac{1}{2\pi}\int_0^{2\pi} ui\,d(\omega t) = UI\cos\varphi \qquad (3\text{-}59)$$

- Reactive power

$$Q = UI\sin\varphi \qquad (3\text{-}61)$$

- Apparent power

$$S = UI \qquad (3\text{-}60)$$

$$S^2 = P^2 + Q^2 \qquad (3\text{-}63)$$

- Power factor

$$\lambda = \frac{P}{S} \qquad (3\text{-}62)$$

$$\lambda = \cos\varphi \qquad (3\text{-}64)$$

Definition of power and power factor

For non-sinusoidal circuits

- Active power

$$P = U I_1 \cos\varphi_1 \qquad (3\text{-}65)$$

- Power factor

$$\lambda = \frac{P}{S} = \frac{UI_1 \cos\varphi_1}{UI} = \frac{I_1}{I}\cos\varphi_1 = \nu \cos\varphi_1 \qquad (3\text{-}66)$$

- Distortion factor (fundamental-component factor)

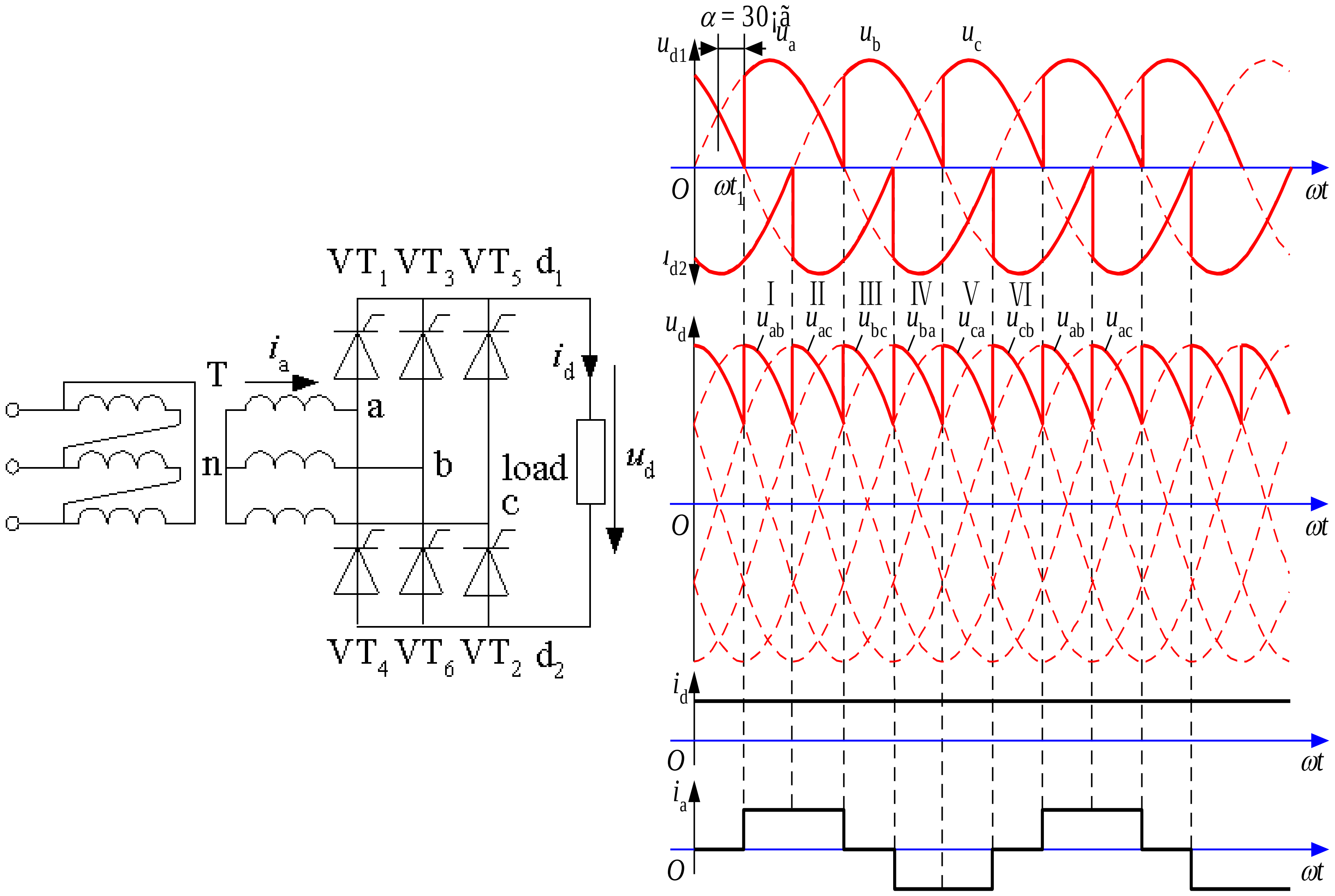
$$\nu = I_1 / I$$

- Displacement factor (power factor of fundamental component)

$$\lambda_1 = \cos\varphi_1$$

- Definition of reactive power is still in dispute.

Three-phase bridge fully-controlled rectifier

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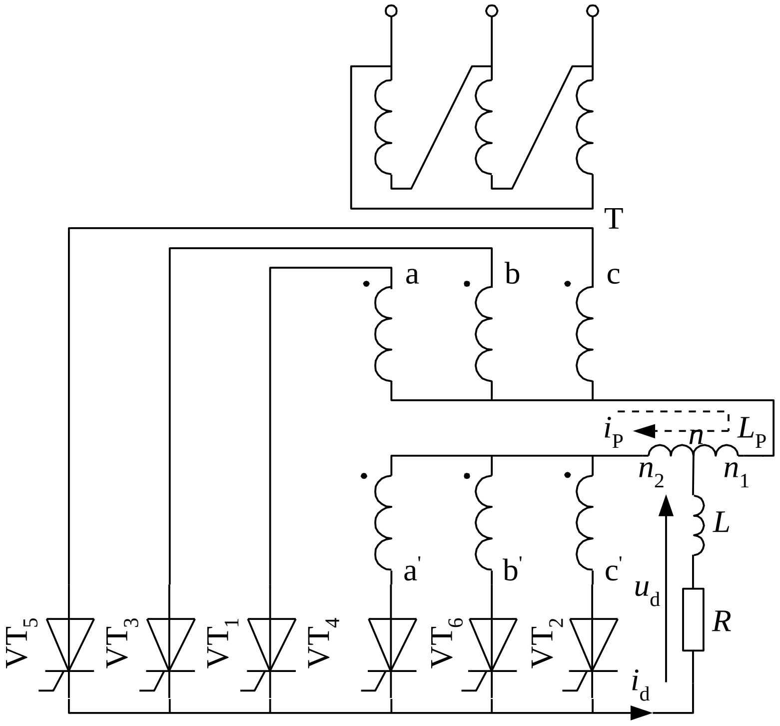
High power controlled rectifier

Double-star controlled rectifier

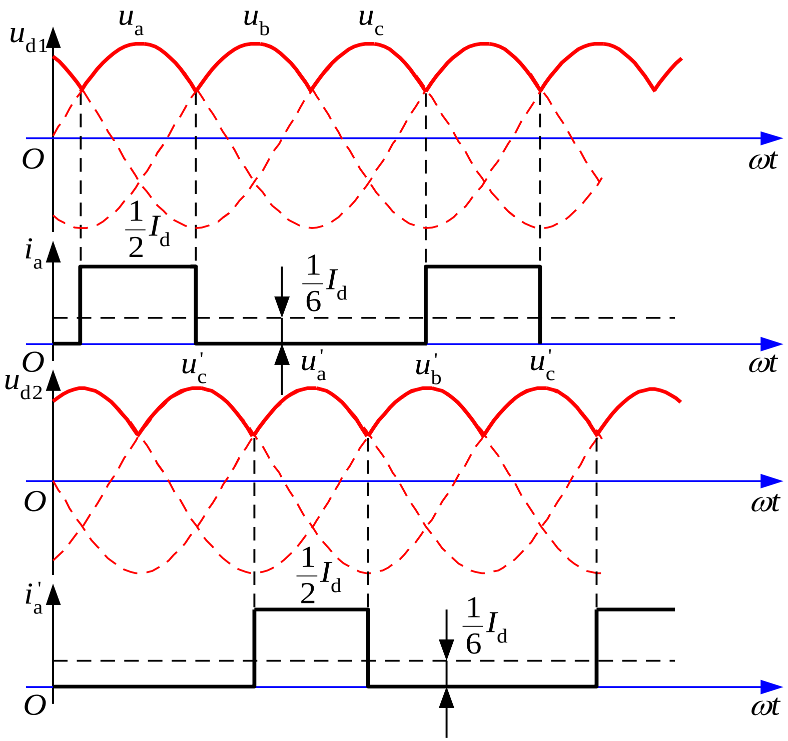
Connection of multiple rectifiers

Double-star controlled rectifier

Circuit



Waveforms When $\alpha = 0^o$



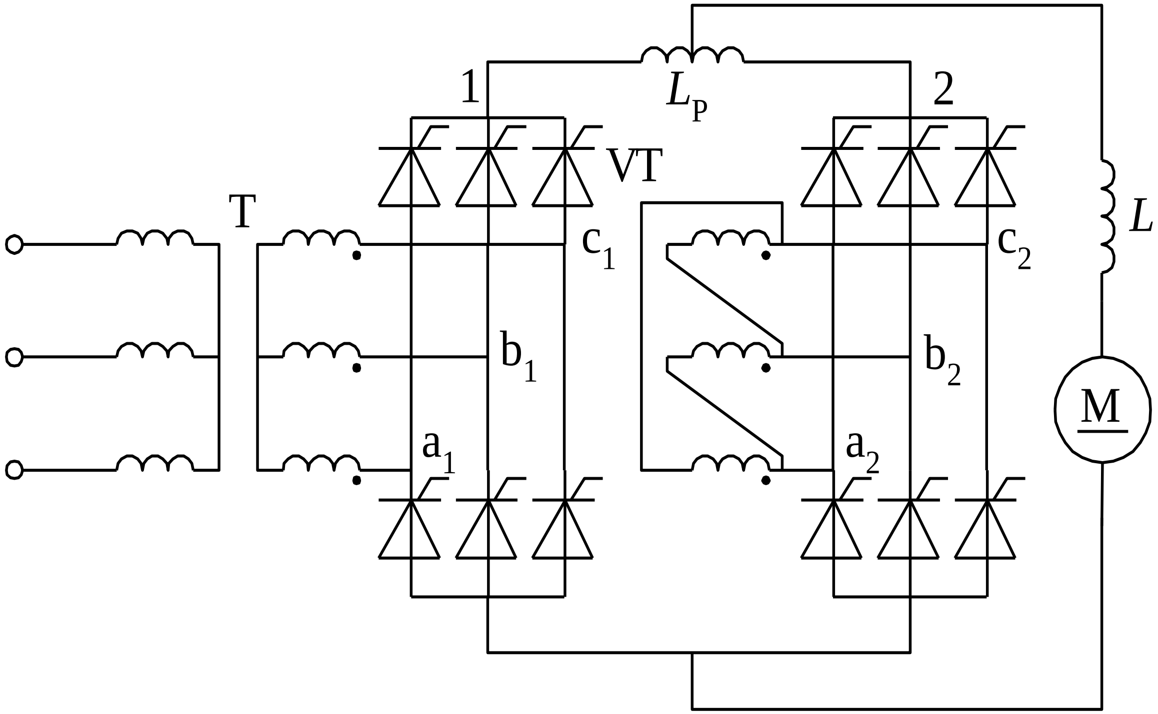
- Difference from 6-phase half-wave rectifier

Connection of multiple rectifiers

- Connection of multiple rectifiers
  - To increase the output capacity
    - Larger output voltage: series connection
    - Larger output current: parallel connection
  - To improve the AC side current waveform and DC side voltage waveform

Phase-shift connection of multiple rectifiers

Parallel connection

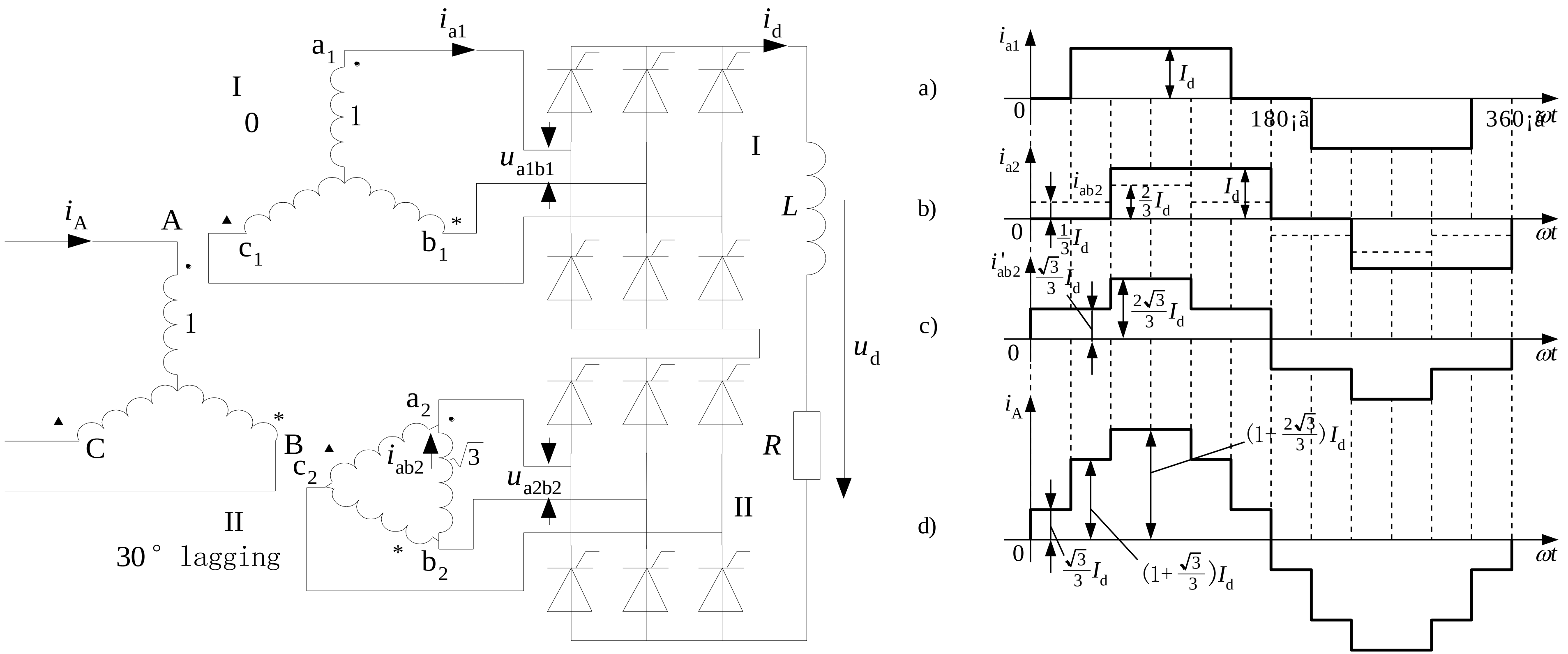


12-pulse rectifier realized by

paralleled 3-phase bridge rectifiers

Phase-shift connection of multiple rectifiers

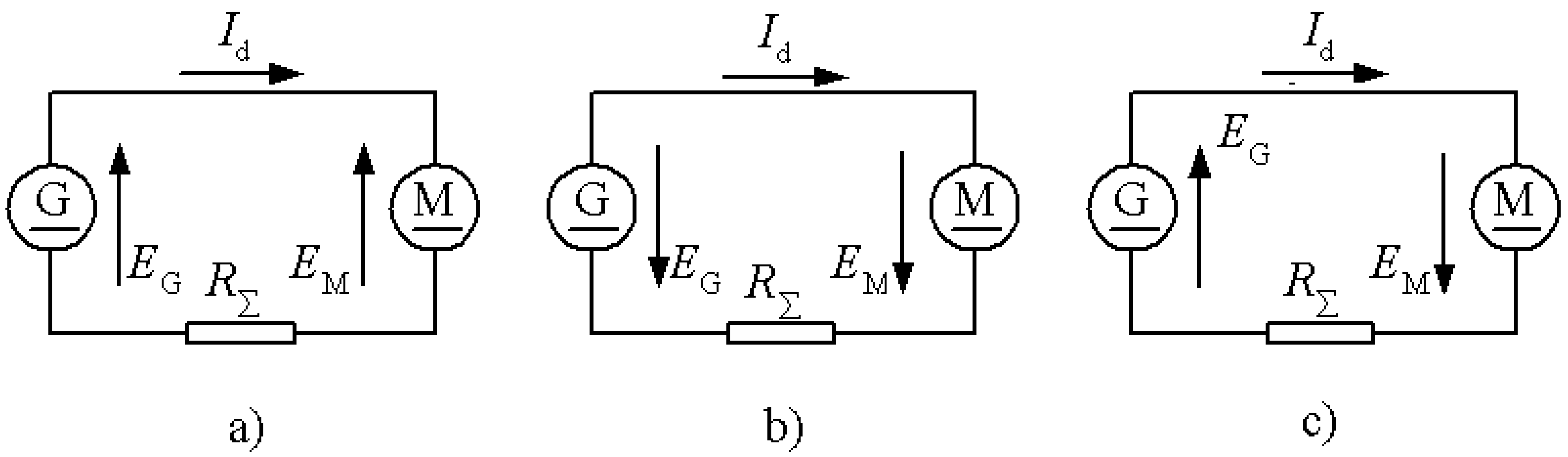
Series connection



12-pulse rectifier realized by
series 3-phase bridge rectifiers

Inverter mode operation of rectifiers

Review of DC generator-motor system



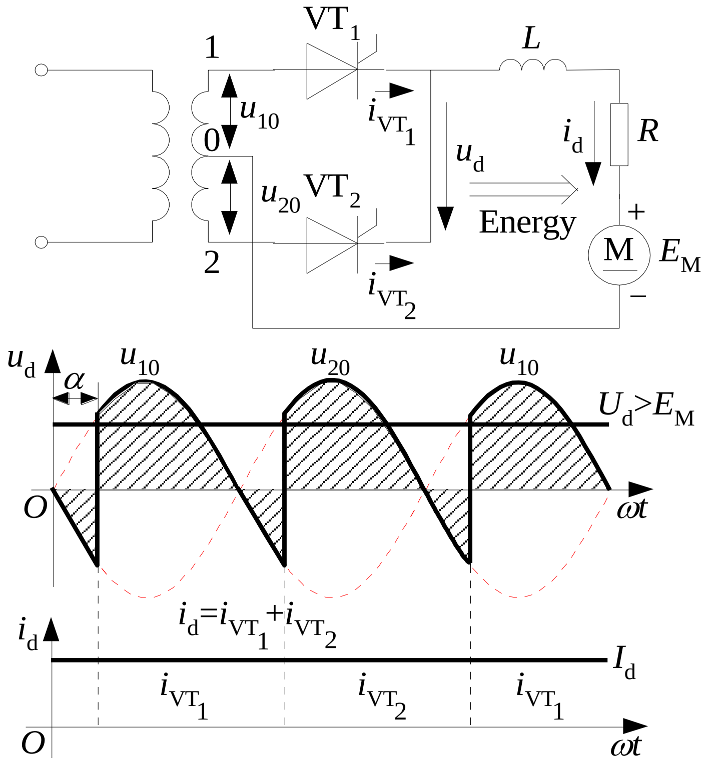
$$I_{\mathbf{d}} = \frac{E_G - E_M}{R_\Sigma}$$

$$I_{\mathbf{d}} = \frac{E_M - E_G}{R_\Sigma}$$

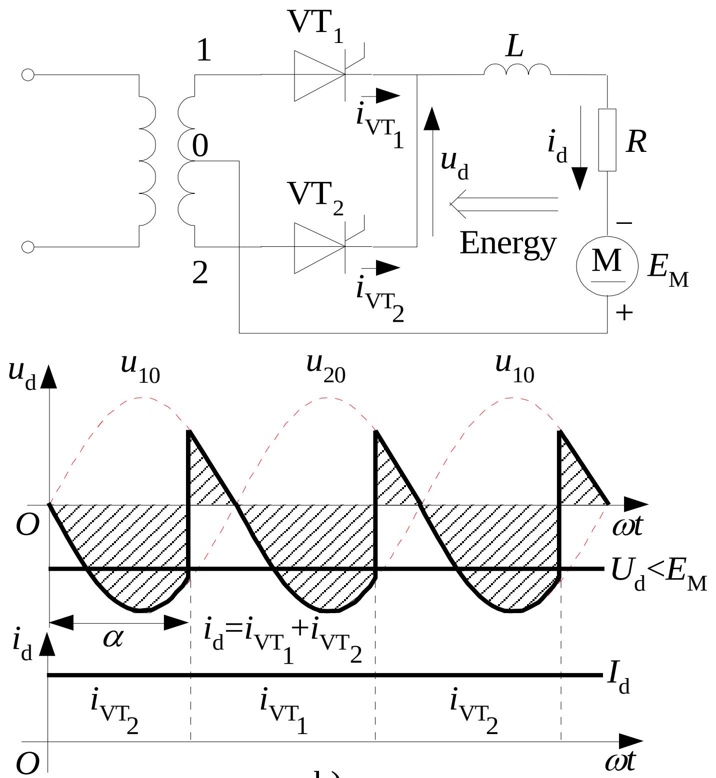
should be avoided

Inverter mode operation of rectifiers

Rectifier and inverter mode operation of single-phase full-wave converter



a)



b)

$$I_{\mathbf{d}} = \frac{U_d - E_G}{R_\Sigma}$$

$$I_{\mathbf{d}} = \frac{|E_M| - |U_d|}{R_\Sigma}$$

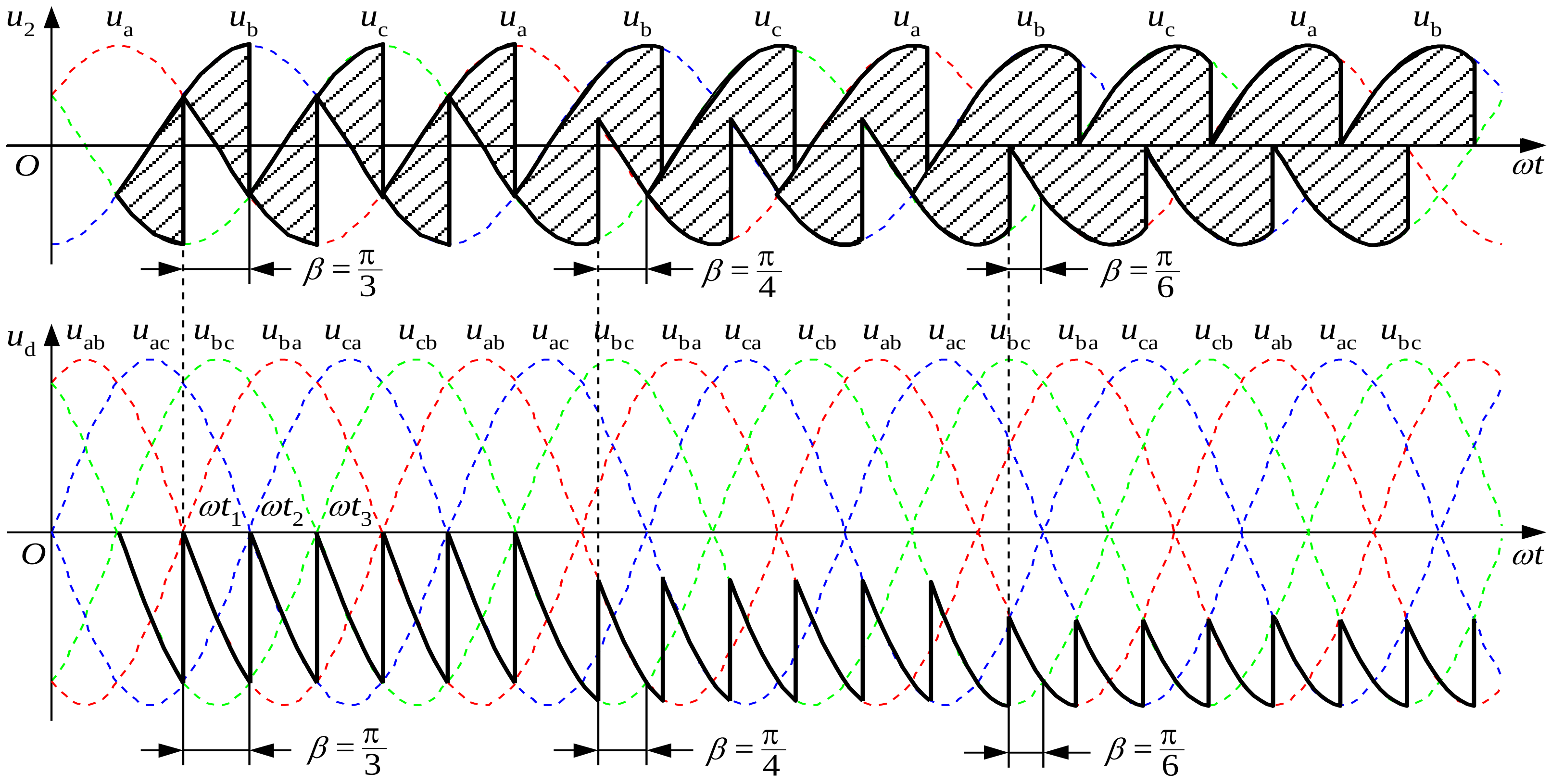
Necessary conditions for the inverter mode operation of controlled rectifiers

- There must be DC EMF in the load and the direction of the DC EMF must be enabling current flow in thyristors. (In other word E_M must be negative if taking the ordinary output voltage direction as positive.)

- $\alpha > 90^{\circ}$ so that the output voltage U_d is also negative.

- $|E_M| > |U_d|$

Inverter mode operation of 3-phase bridge rectifier



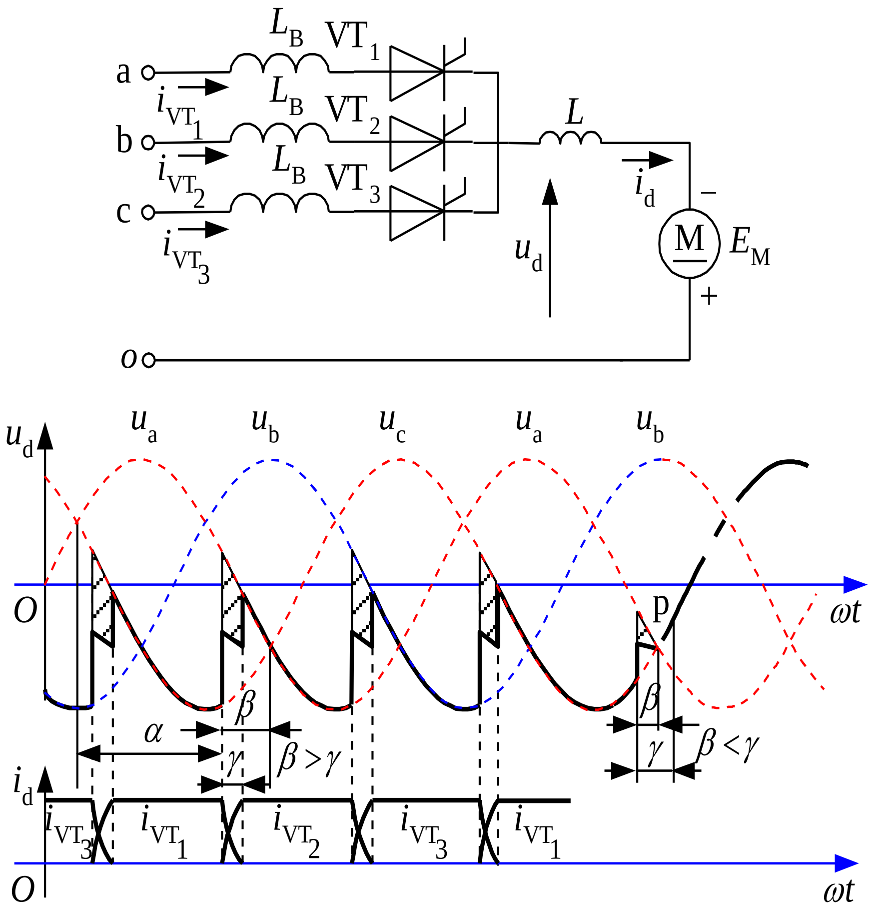
- Inversion angle (extinction angle) β

  $\alpha + \beta = 180^{o}$

Inversion failure and minimum inversion angle

- Possible reasons of inversion failures
  - Malfunction of triggering circuit
  - Failure in thyristors
  - Sudden dropout of AC source voltage
  - Insufficient margin for commutation of thyristors
- Minimum inversion angle (extinction angle)

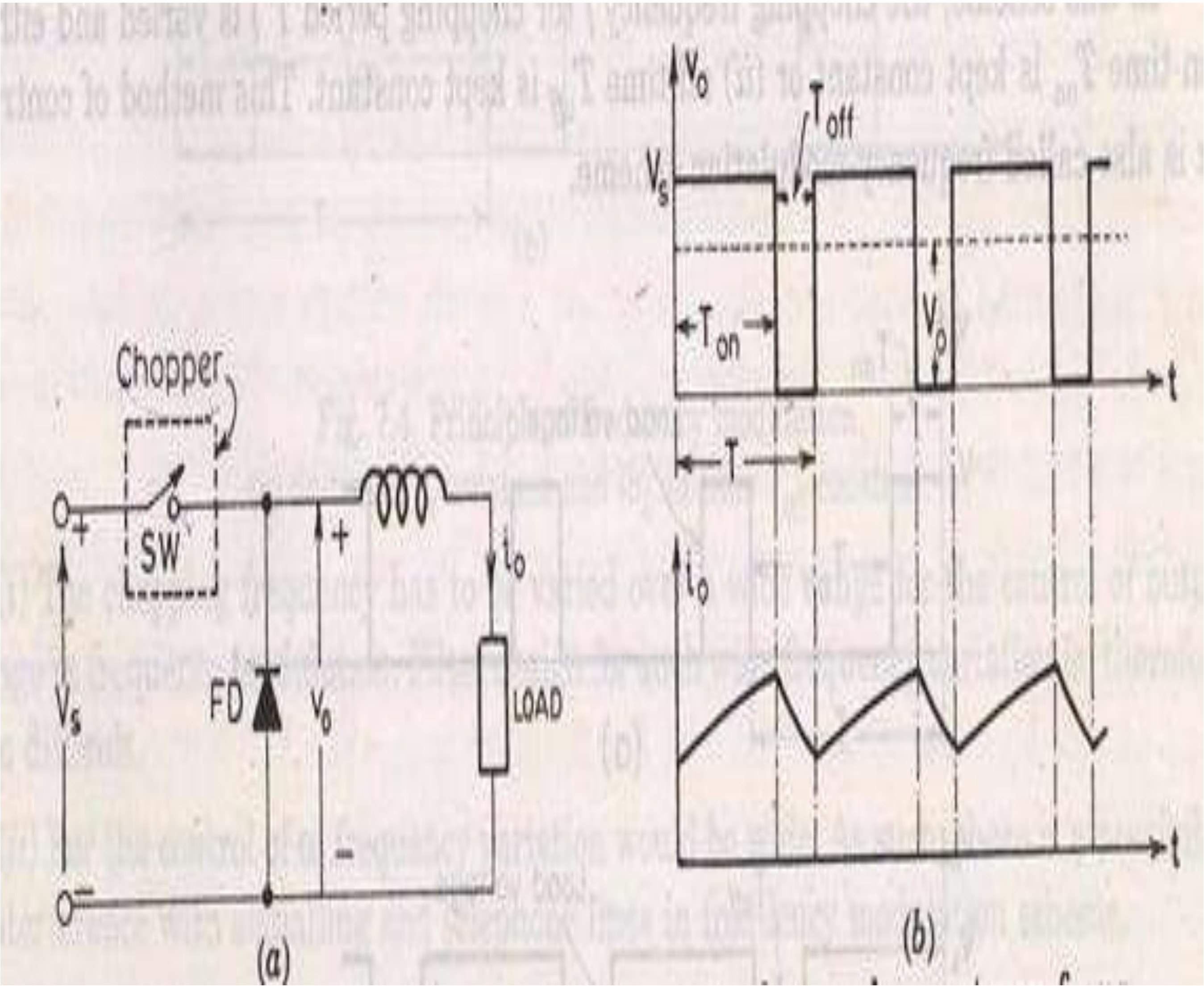
$\beta_{min}=\delta+\gamma+\theta'$ （3-109）

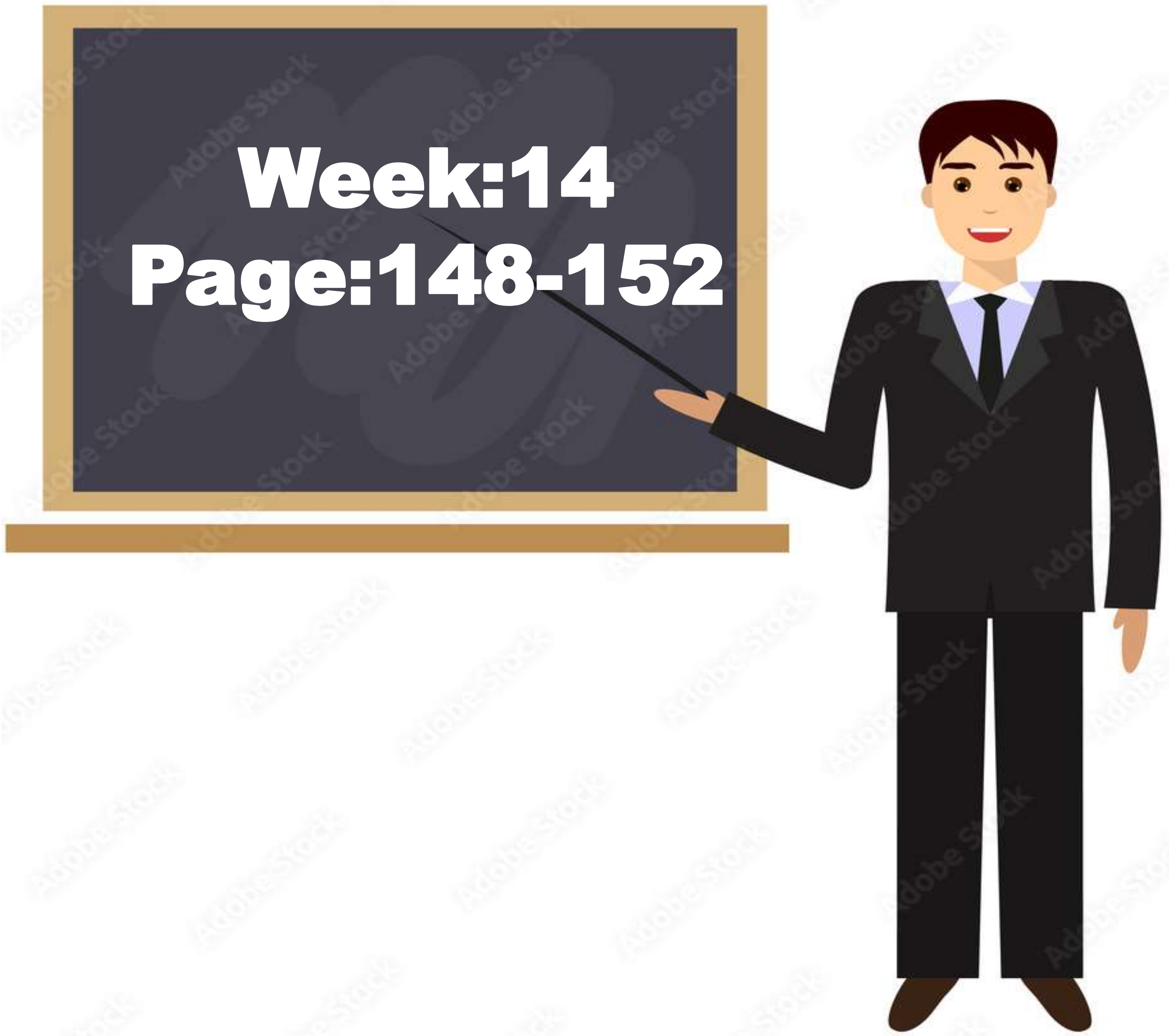


CHOPPER

A chopper is a static device that converts fixed DC input voltage to variable output voltage directly. Chopper are mostly used in electric vehicle, mini haulers.

Chopper are used for speed control and braking. The systems employing chopper offer smooth control, high efficiency and have fast response.

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TYPES OF CHOPPER:

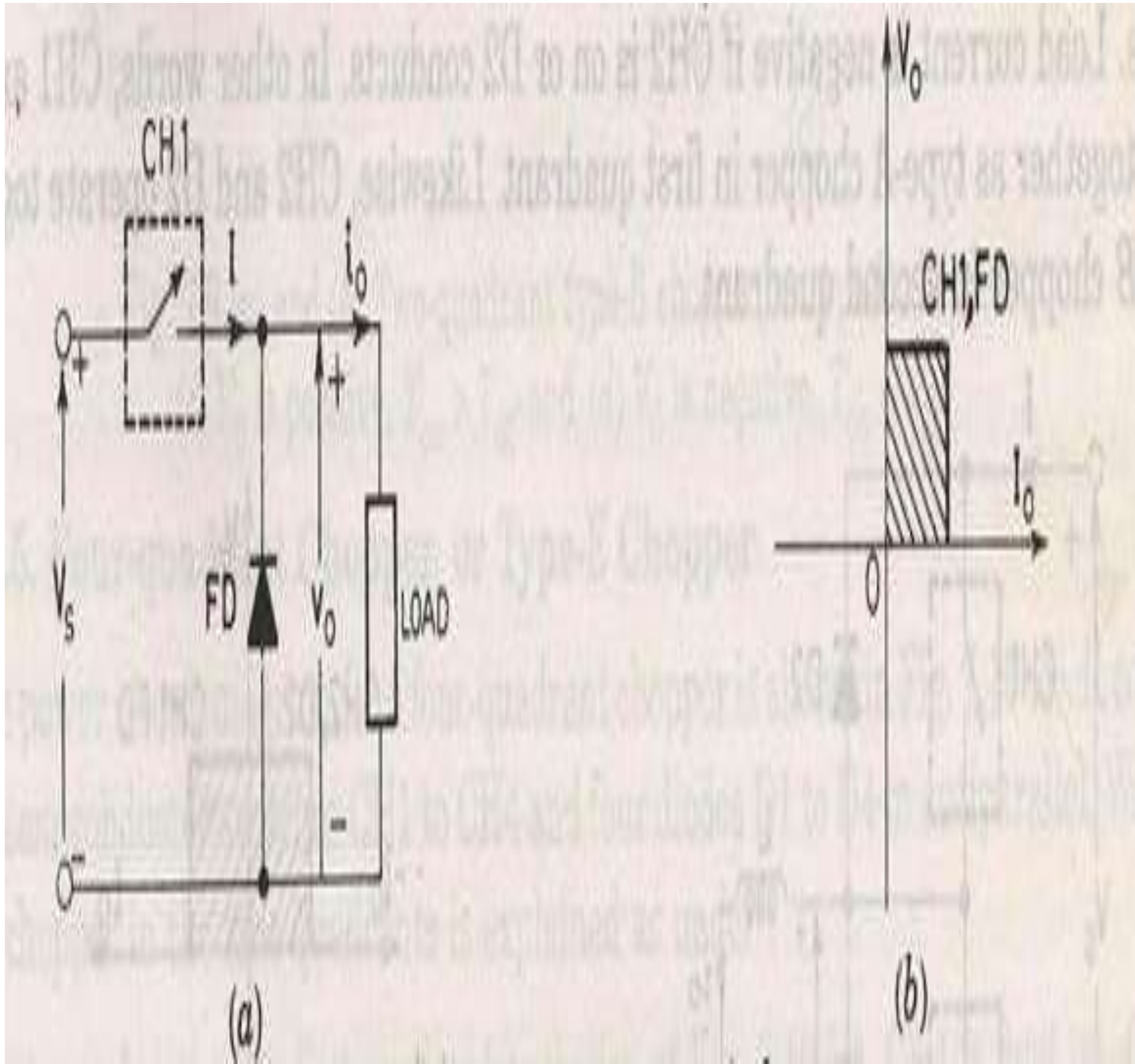
A first quadrant chopper, also known as a Type A chopper, is a DC to DC converter that operates in the first quadrant of the voltage-current plane:

•**Operation**: Both the voltage and current are positive.

•**Working**: When the chopper switch is on, the voltage across the load is equal to the supply voltage. When the switch is off, a freewheeling diode maintains the current in the load.

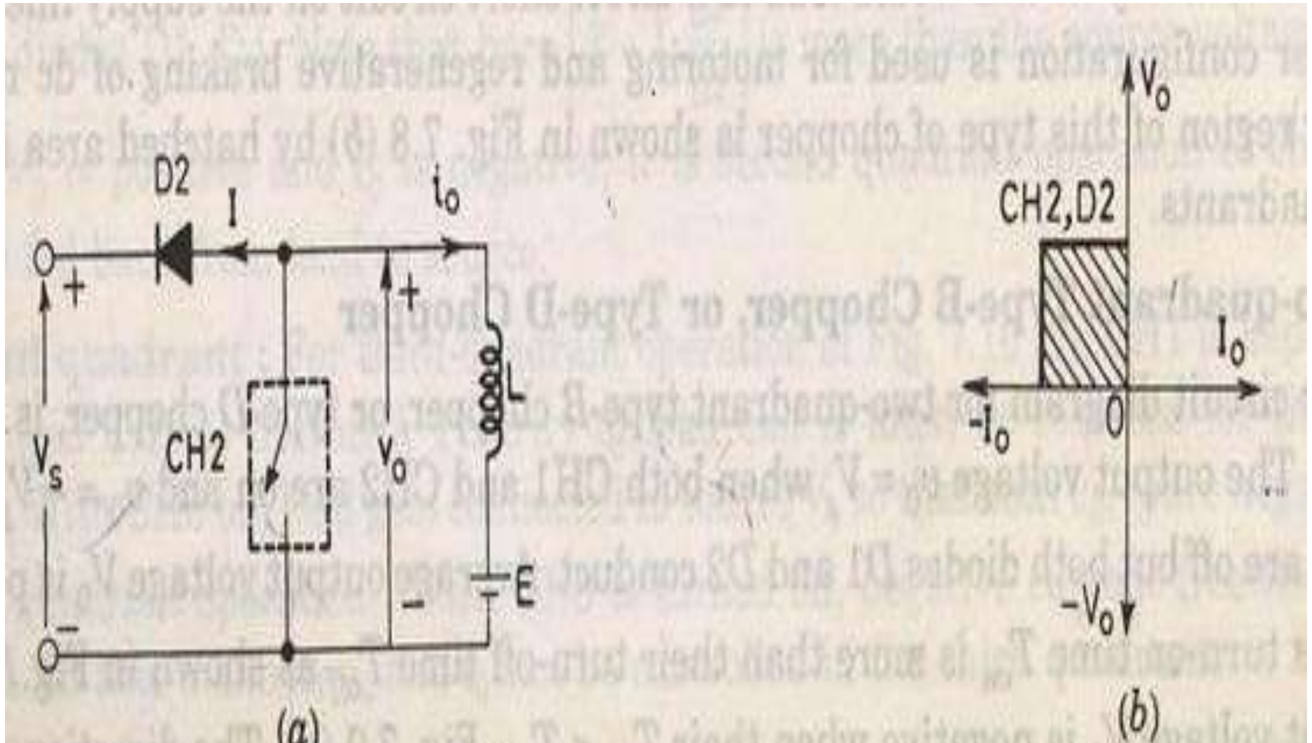
•**Application**: Type A choppers are used in DC motor control, where only forward motoring is needed.

•**Power flow**: Power always flows from source to load.



SECOND QUADRANT OR TYPE B CHOPPER:

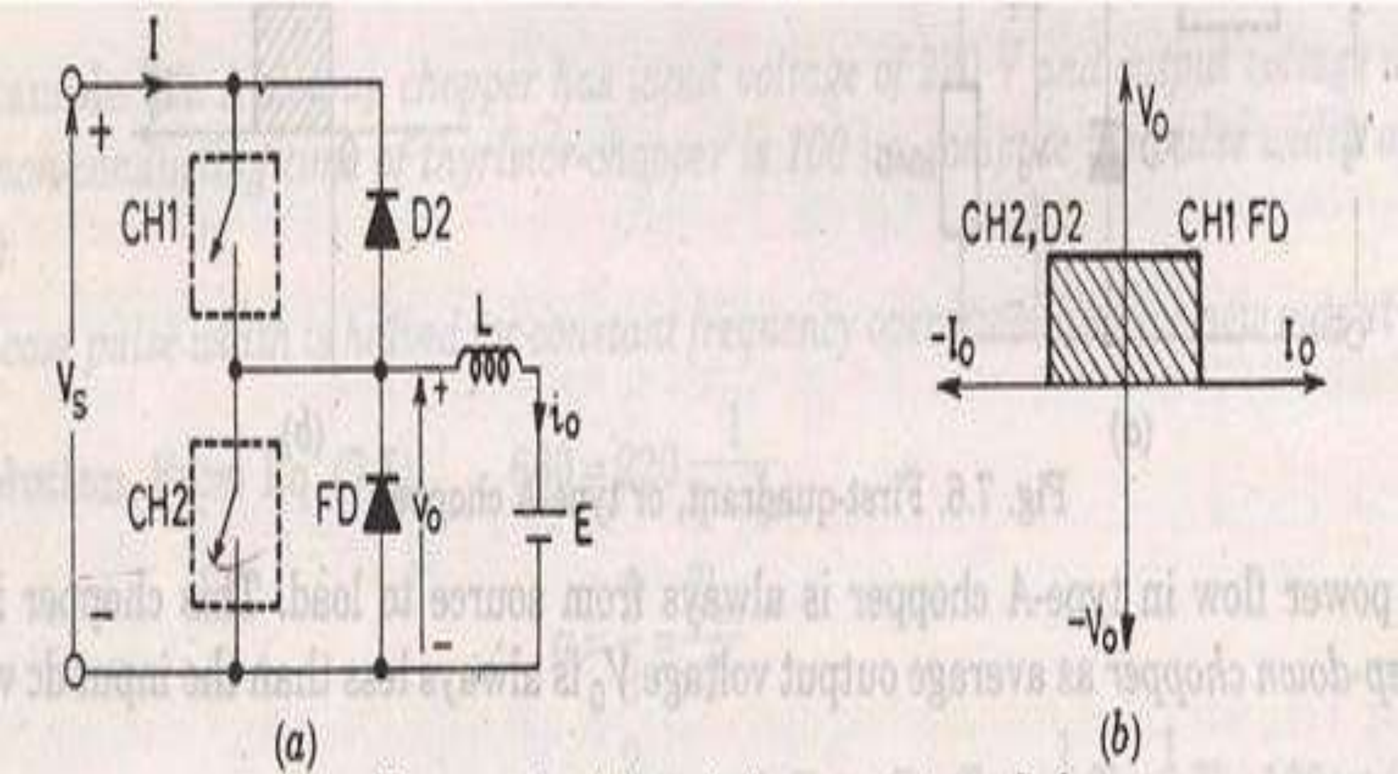
A "second quadrant" or "Type B chopper" refers to a type of chopper circuit that operates solely in the second quadrant of the voltage-current plane, meaning the output voltage is always positive while the output current is always negative, effectively allowing power to flow from the load back to the source, commonly used for regenerative braking in DC motors;



Second-quadrant, or type-B, chopper.

TWO QUADRANT TYPE A CHOPPER OR, TYPE C CHOPPER:

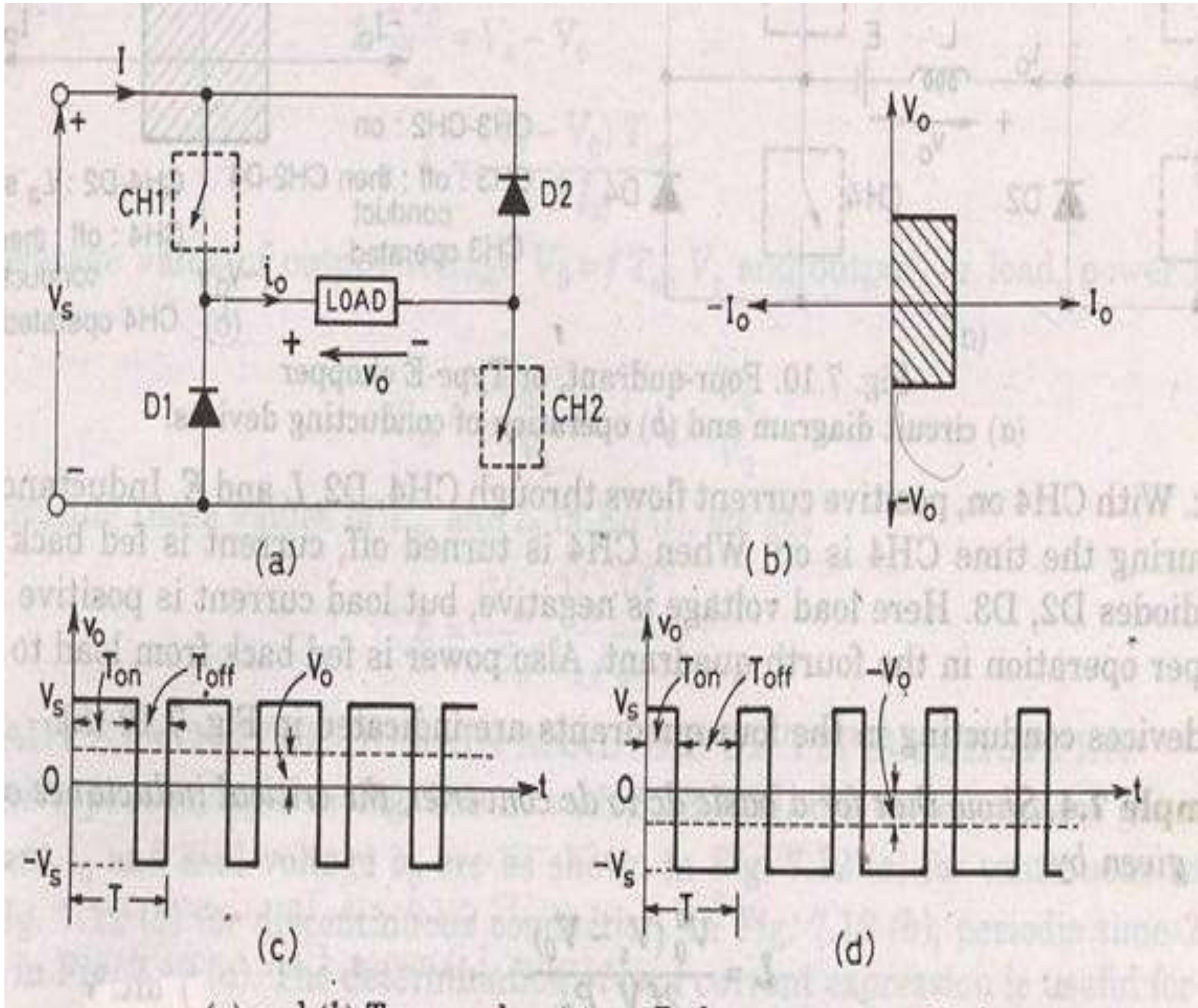
Two-Quadrant Chopper: This is a type of chopper circuit where the average voltage always remains positive but the average load current may be positive or negative. A 2-quadrant Chopper circuit diagram is shown below: 2-Quadrant Chopper Circuit Diagram.



Two-quadrant type-A chopper, or type-C chopper.

TWO QUADRANT TYPE B CHOPPER, OR TYPE D CHOPPER:

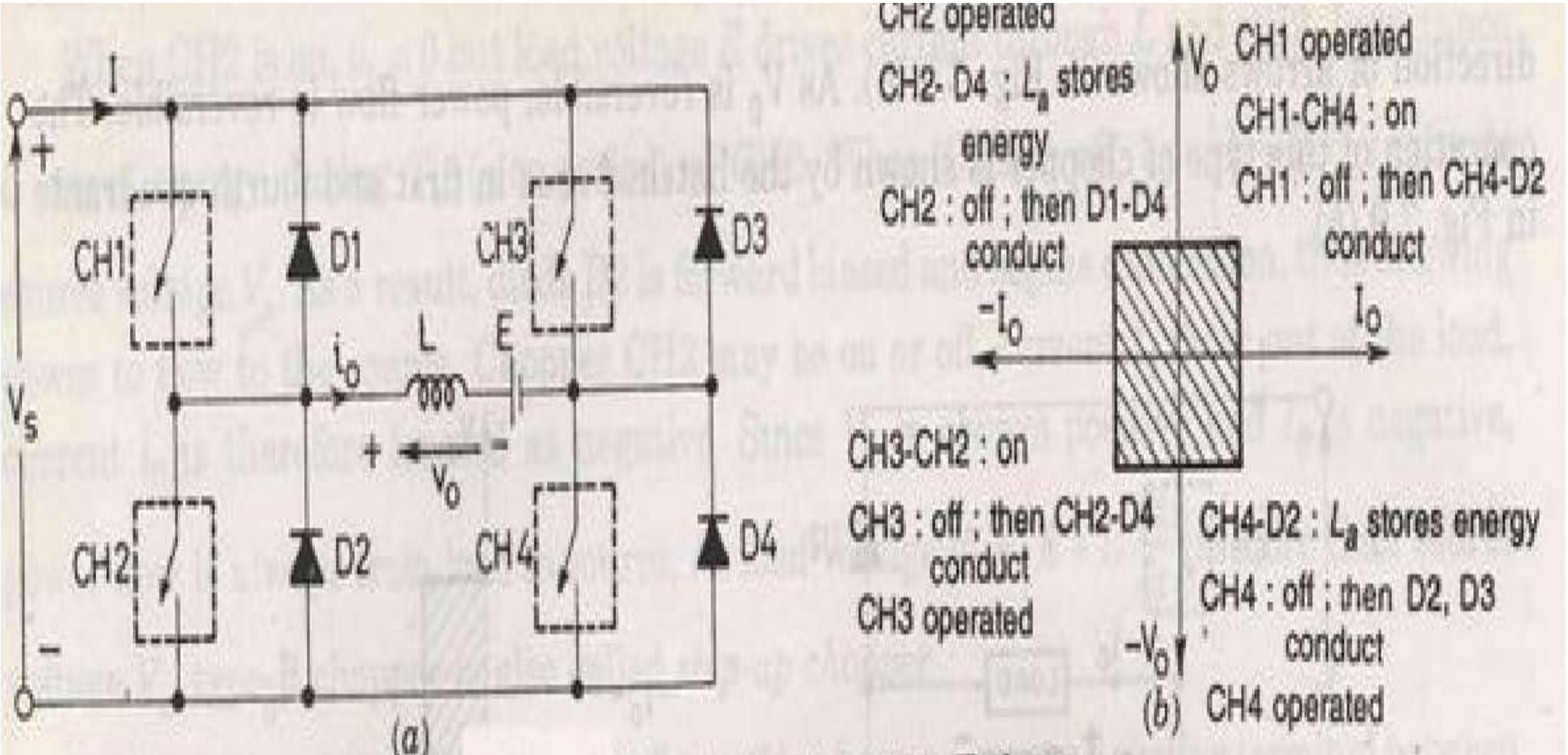
Two-Quadrant Chopper: This is a type of chopper circuit where the average voltage always remains positive but the average load current may be positive or negative. A 2-quadrant Chopper circuit diagram is shown below: 2-Quadrant Chopper Circuit Diagram.



(*a*) and (*b*) Two-quadrant type-B chopper, or type-D chopper
(*c*) V_0 is positive, $T_{on} > T_{off}$ and (*d*) V_0 is negative, $T_{on} < T_{off}$

FOUR QUADRANT CHOPPER, OR TYPE E CHOPPER

A class-E chopper is a type of dc chopper that **has the capability to operate in all four quadrants** of output voltage and current plane.



Four-qudrant, or Type-E chopper
(a) circuit diagram and (b) operation of conducting devices.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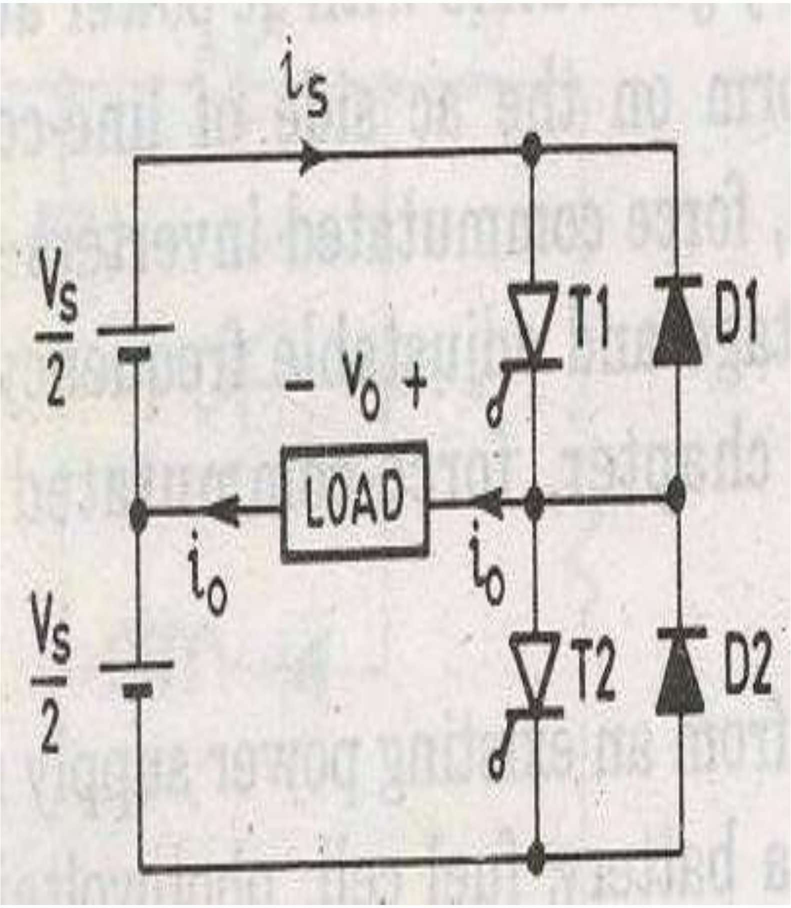
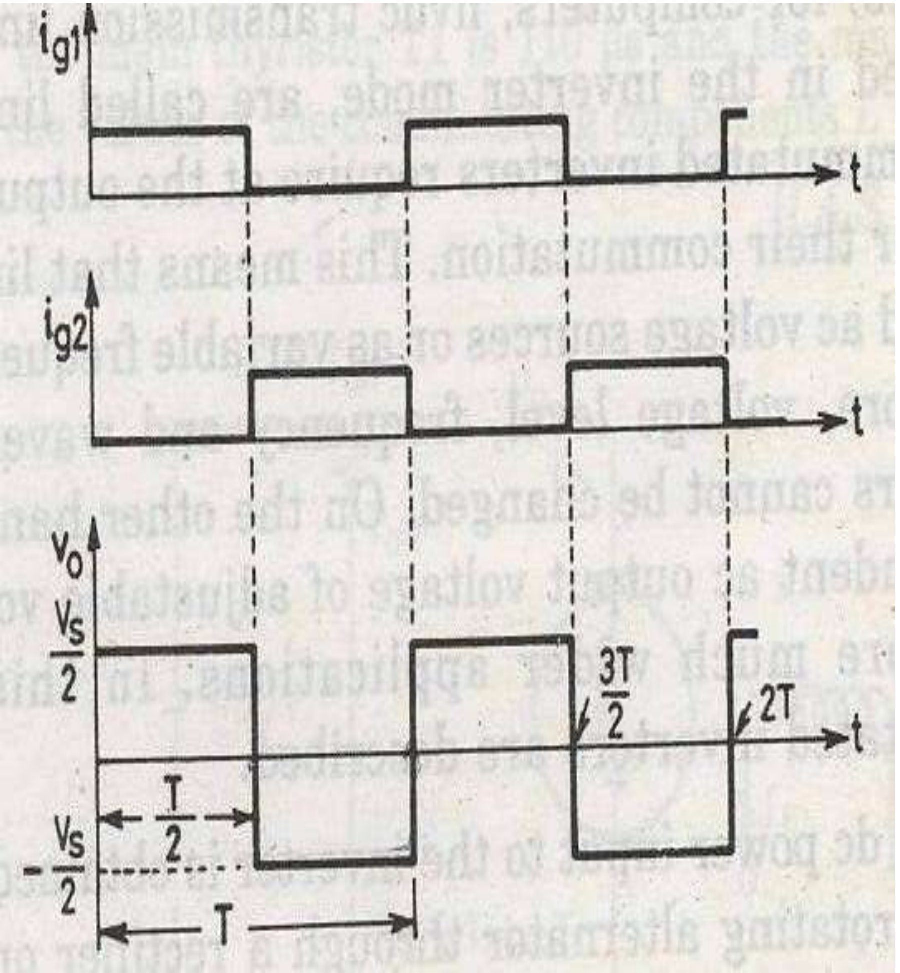
INVERTERS

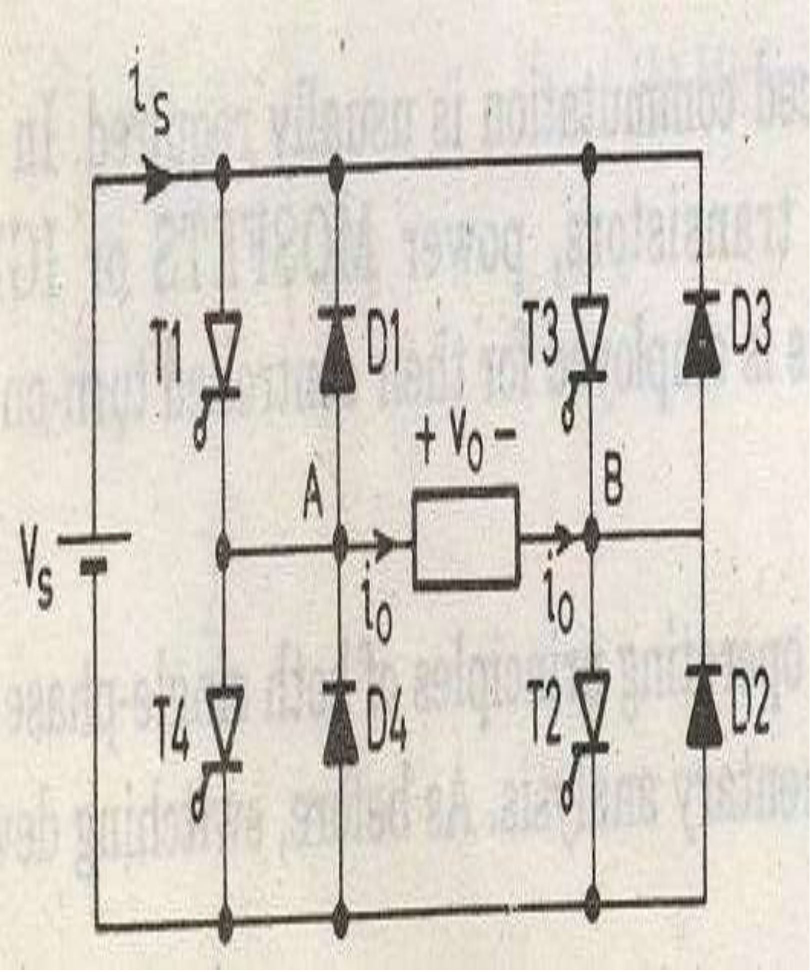
The device that converts dc power into ac power at desired output voltage and frequency is called an inverter.

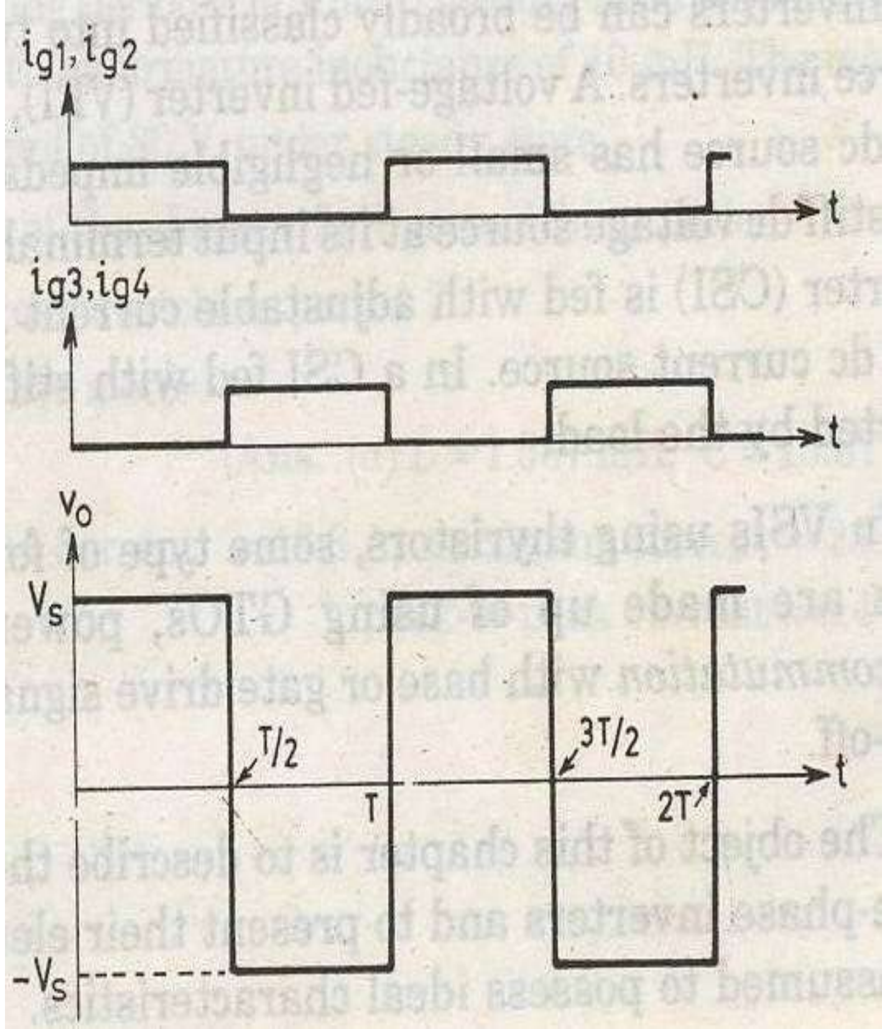




Single phase full bridge inverter

A **single-phase inverter** is a type of **inverter** that converts DC source voltage into **single-phase** AC output voltage at a desired voltage and frequency.





2

T_0

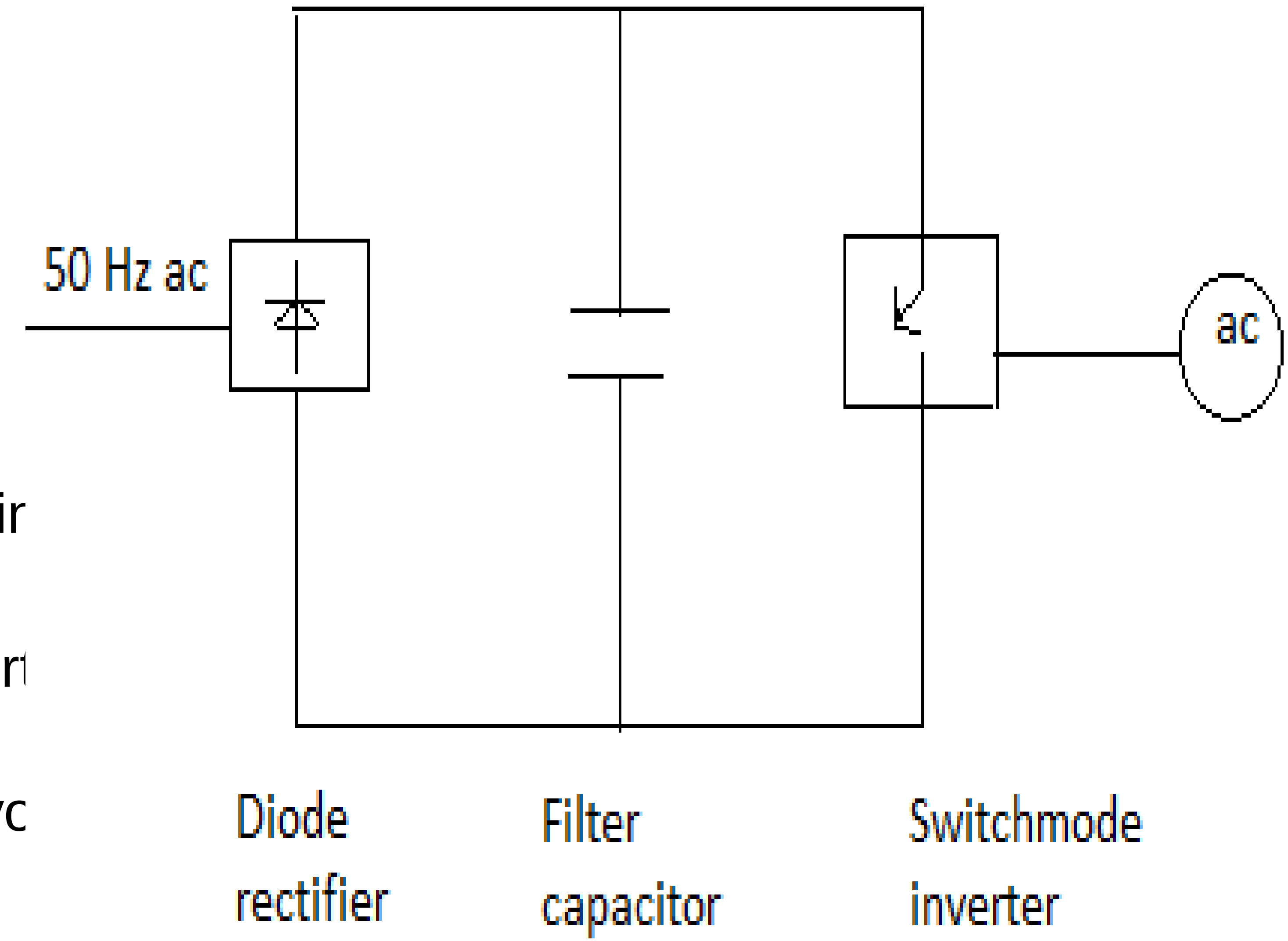
INVERTER

Inverters are of the two types

1)VSI
2)CSI
Pulse width model

The VSI can be further divided ir
general 3 categories:

1.Pulse width modulated invert
2.Square wave inverters
3.Single phase inverter with vc
cancellation



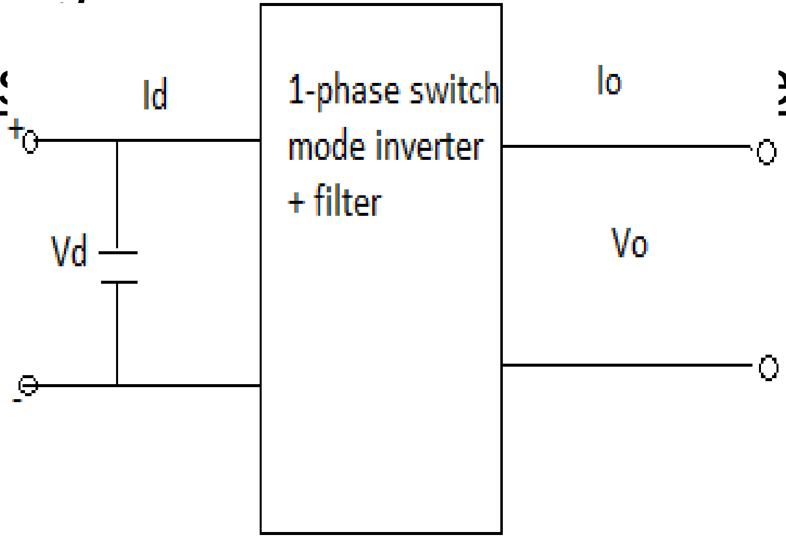
Pulse width modulated inverters

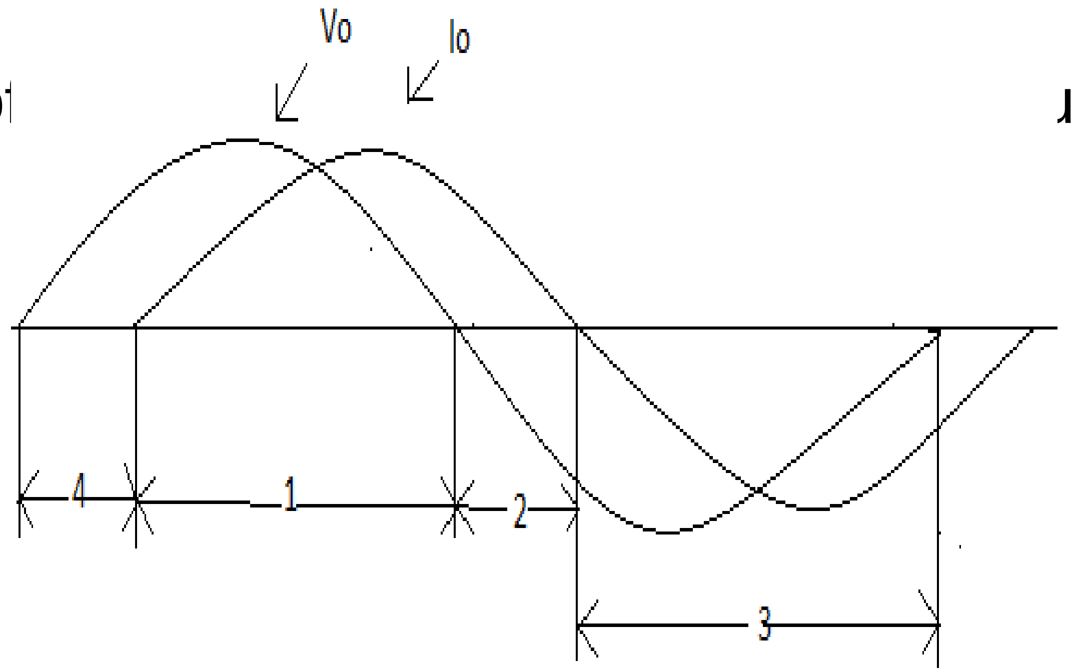
The input dc voltage is of constant magnitude . The diode rectifier is used to rectify the line voltage.The inverter control the magnitude and frequency of the ac output voltage.

This is achieved by PWM technique of inverter switches and this is called PWM inverters.

The sinusoidal PWM technique is one o ... utput voltage to as close as sinusoidal output.

Ba ... e inverter





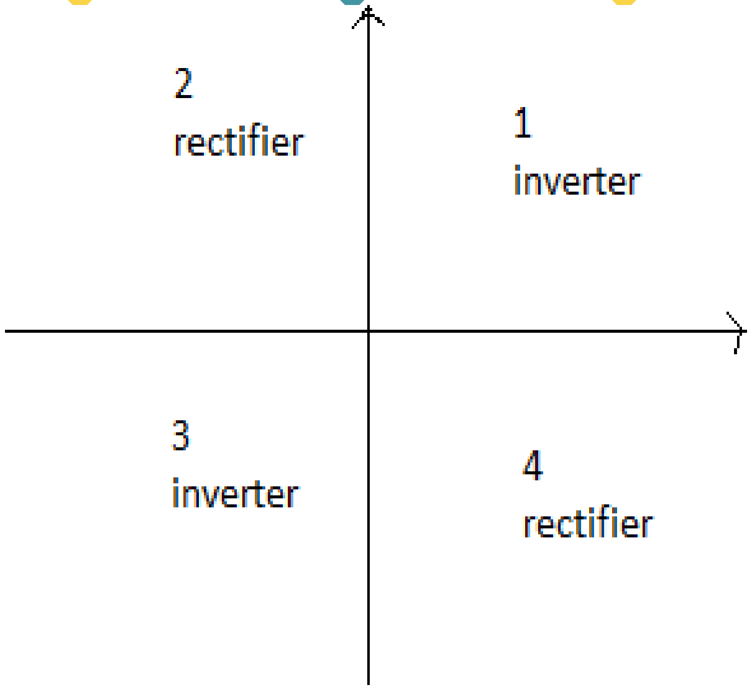
In order to produce sinusoidal output voltage at desired frequency a sinusoidal control signal at desired frequency is compared with a triangular waveform as show.

The frequency of the triangular waveform established the inverter switching frequency.

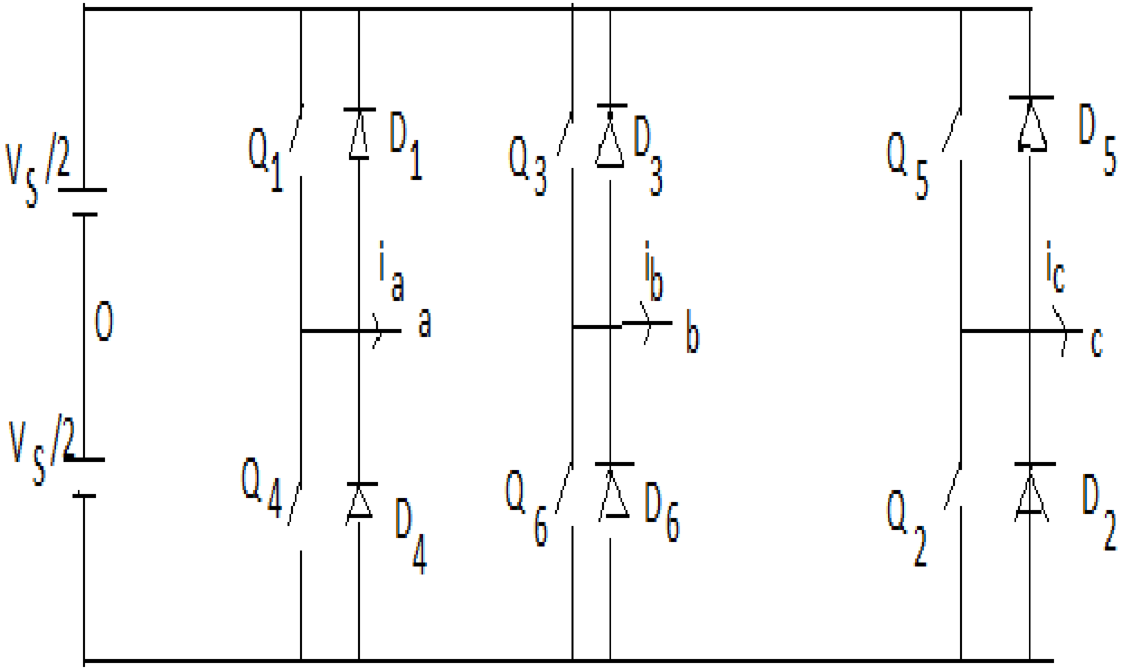
The triangular waveform is called carrier waveform. The triangular waveform establishes switching frequency f_s , which establishes with which the inverter switches are applied.

The control signal has frequency f_s and is used to modulate the switch duty ratio.

f_1 is the desired fundamental frequency of the output voltage.



180-degree conduction

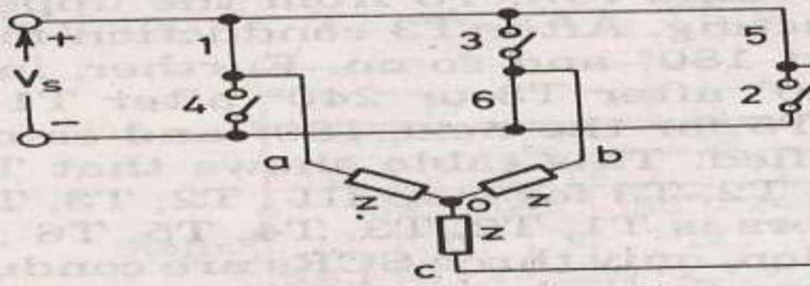


When Q_1 is switched on, terminal a is connected to the positive terminal of dc input voltage.

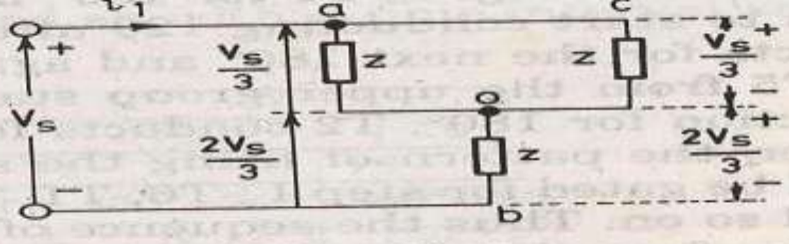
When Q_4 is switched on terminal a is brought to negative terminal of the dc source. There are 6 modes of operation is a cycle and the duration of each mode is 60^0.

The conduction sequence of transistors is 123,234,345,456,561,612. The gating signals are shifted from each other by 60^0 to

Step I



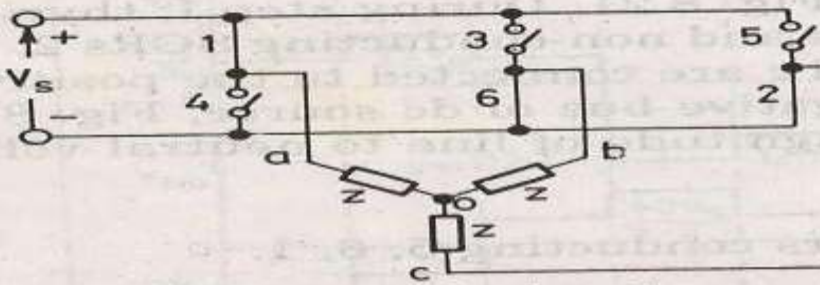
(*a*) 0—60° ; 5, 6, 1 closed.



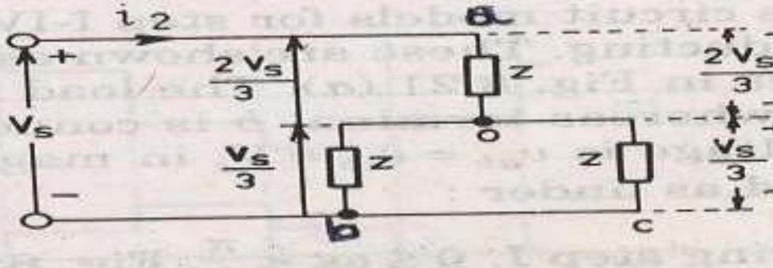
$v_{ao} = v_{co} = V_s/3$

$v_{bo} = -v_{ob} = -2V_s/3$

Step II



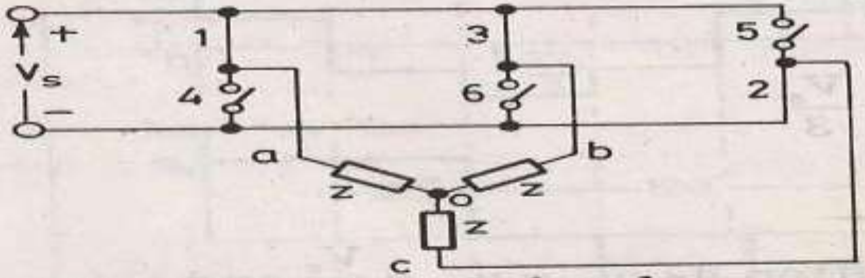
(*b*) 60—120° ; 6, 1,2 closed.



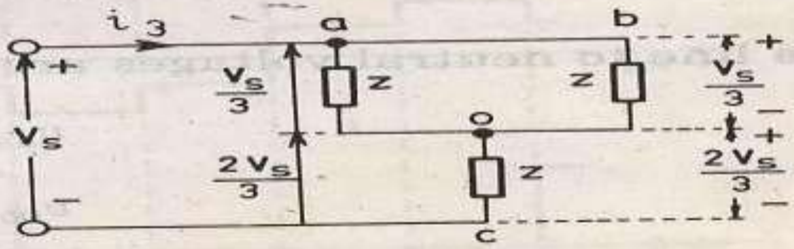
$v_{ao} = 2V_s/3$

$v_{bo} = v_{co} = -V_s/3$

Step III



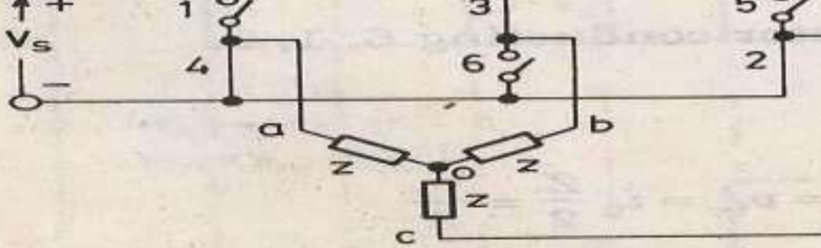
(*c*) 120—180° ; 1, 2, 3 closed.



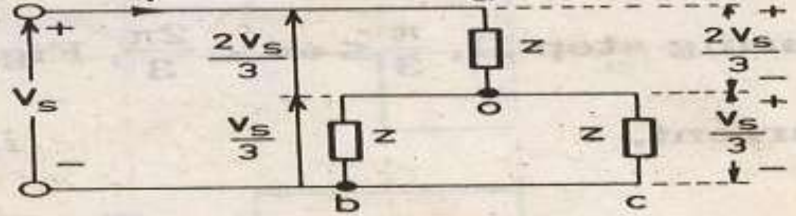
$v_{ao} = v_{bo} = V_s/3$

$v_{co} = -2V_s/3$

Step IV



(*d*) 180—240° ; 2, 3, 4 closed.

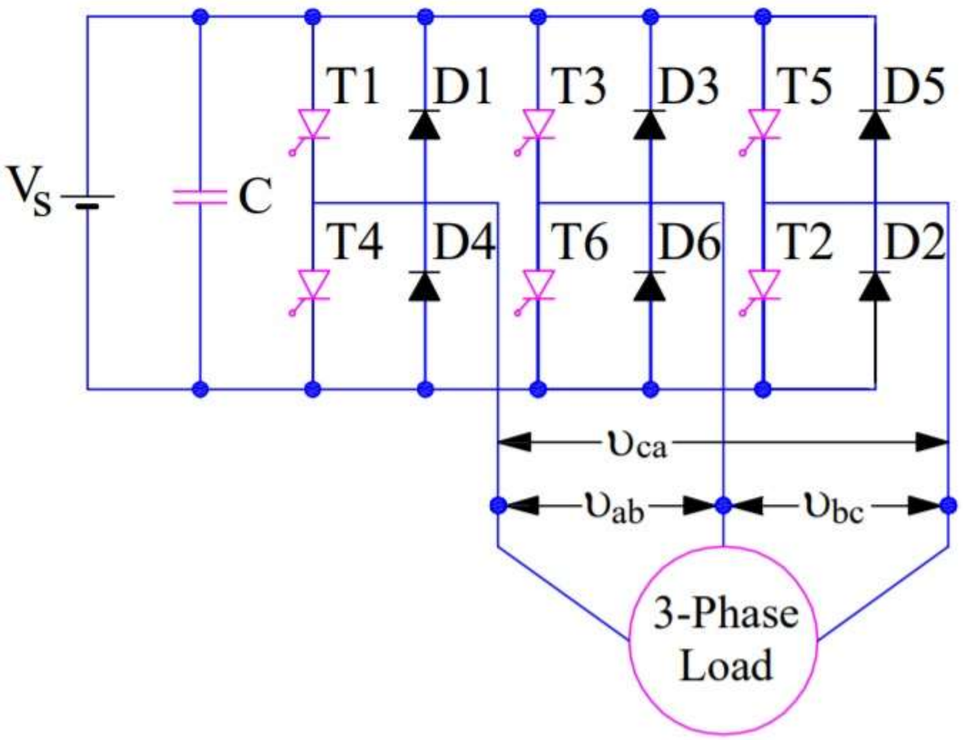


$v_{bo} = 2\ V_s/3$

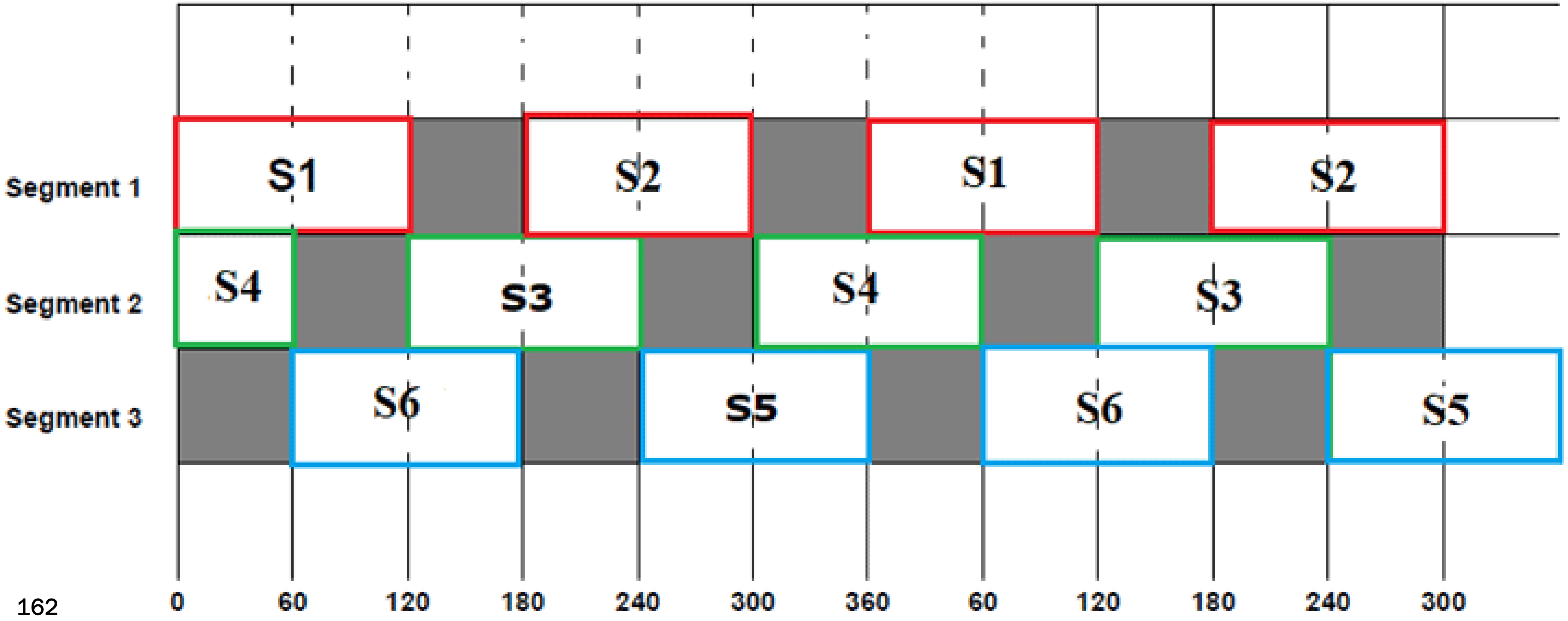
$v_{ao} = v_{co} = -V_s/3$

inverter with a balanced

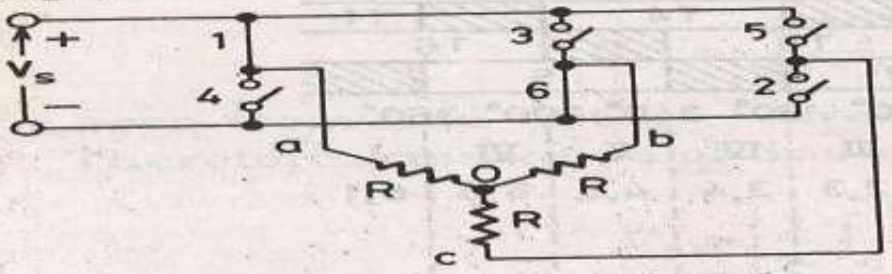
3 Phase Inverter Circuit



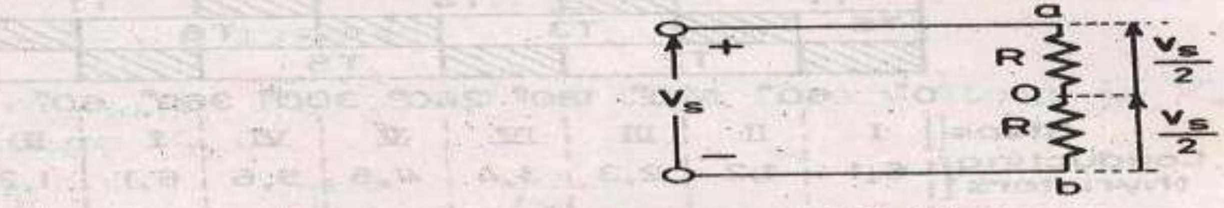
Activation of The SCR



Step I



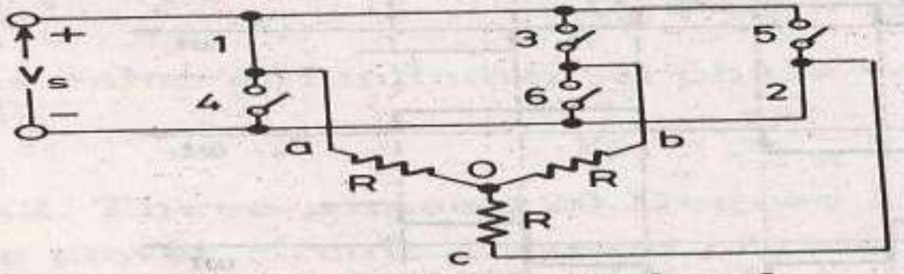
(*a*) 0—60° ; 6, 1 closed



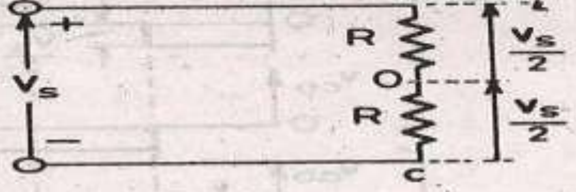
$v_{ao} = V_s/2$

$v_{bo} = -V_s/2$ and $v_{co} = 0$

Step II



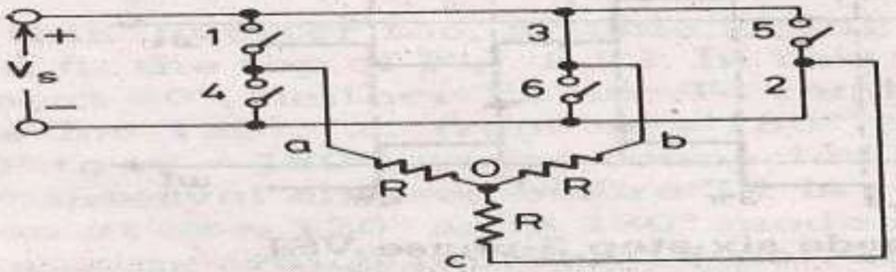
(*b*) 60—120° ; 1, 2 closed



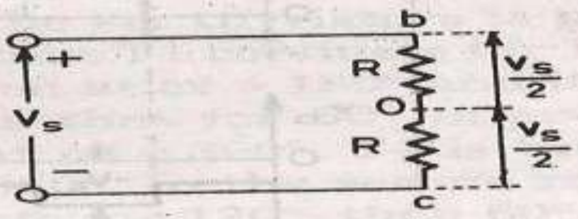
$v_{ao} = V_s/2$

$v_{co} = -V_s/2$ and $v_{bo} = 0$

Step III



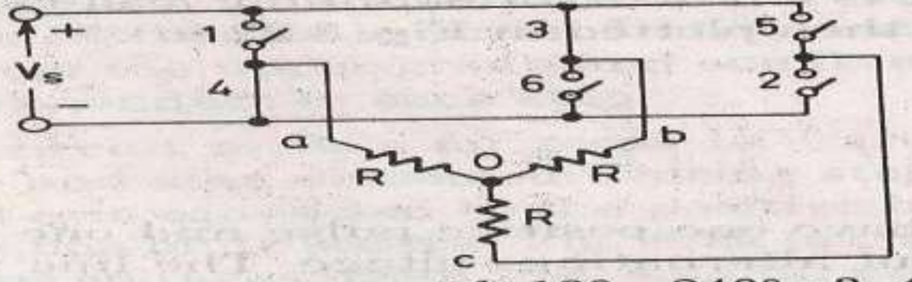
(*c*) 120—180° ; 2, 3 closed



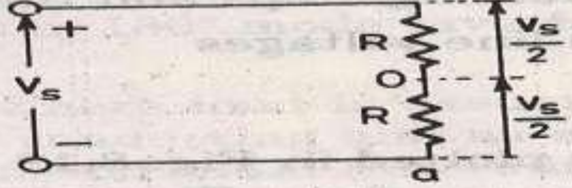
$v_{bo} = V_s/2$

$v_{co} = -V_s/2$ and $v_{ao} = 0$

Step IV



(*d*) 180—240° ; 3, 4 closed



$v_{bo} = V_s/2$

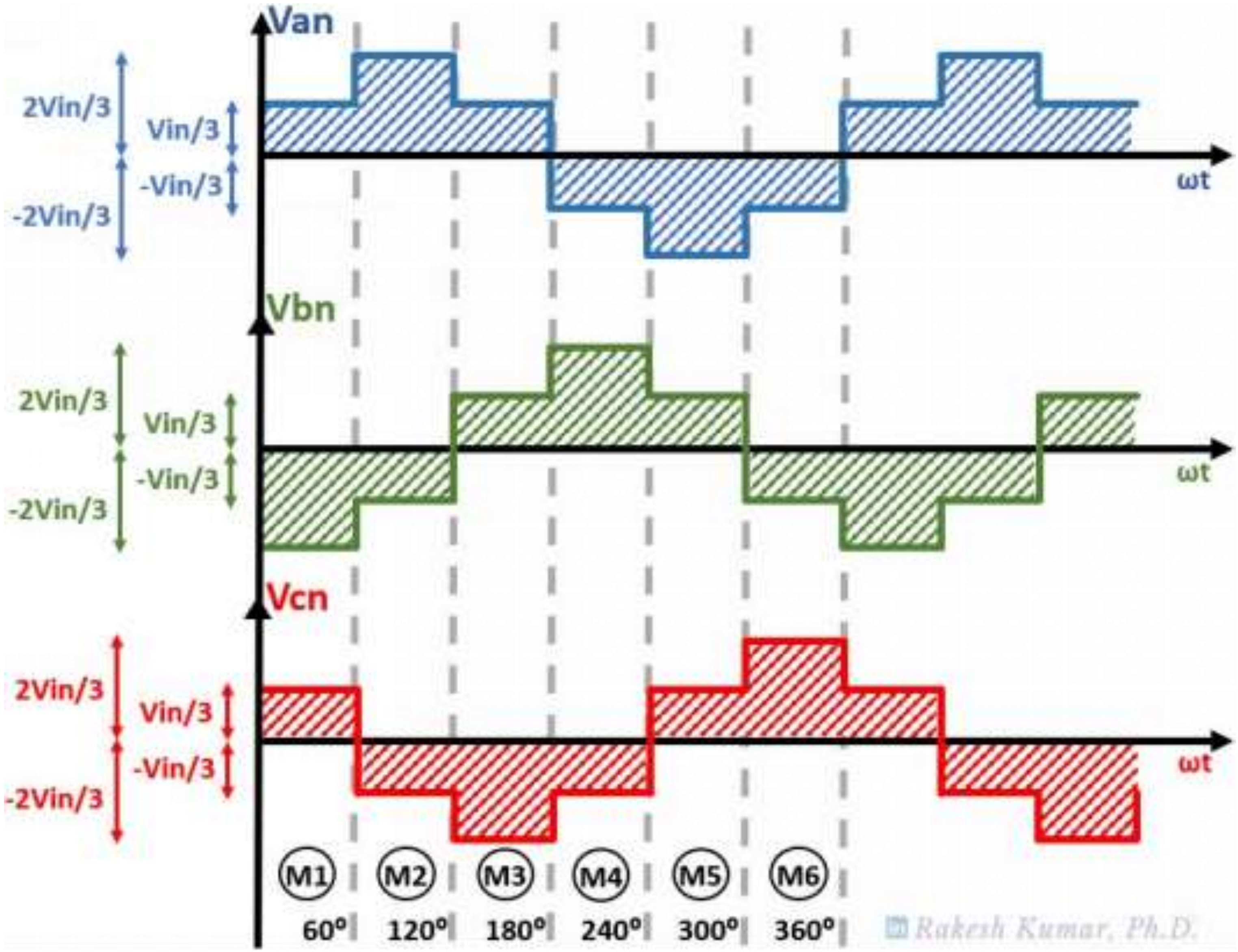
$v_{ao} = -V_s/2$ and $v_{co} = 0$

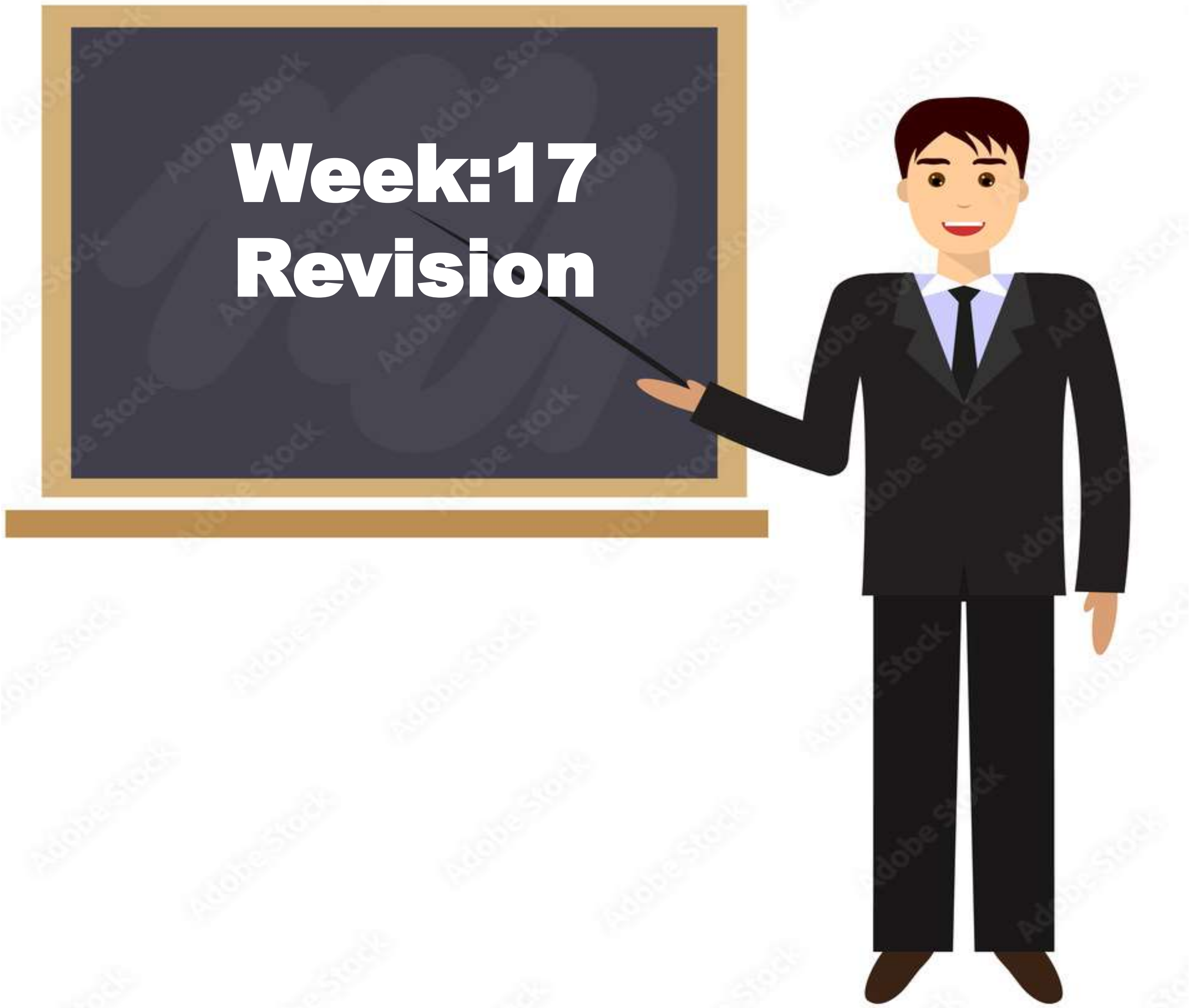
Summary Table

S	$(S_aS_bS_c)$	v_a	v_b	v_c	v_α	v_β	V_0
S_0	(000)	0	0	0	0	0	V_0
S_1	(001)	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$	$-\sqrt{3}V_{DC}/3$	V_1
S_2	(010)	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$	$\sqrt{3}V_{DC}/3$	V_2
S_3	(011)	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$	0	V_3
S_4	(100)	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$	0	V_4
S_5	(101)	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$	$-\sqrt{3}V_{DC}/3$	V_5
S_6	(110)	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$	$\sqrt{3}V_{DC}/3$	V_6
S_7	(111)	0	0	0	0	0	V_7

It can also be observed from Table 1 that the output voltages of V_0 and V_7 are zero, and they are
n theory, considered identical. This reduces the number of total switching states from eight to seven

Output Waveform




Week:17
Revision

Course Review:

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Teaching-Learning Strategies	Sources
Lectures, Open Discussions, Question-and-Answer Sessions	Lecture Notes, Reference Textbooks, Videos (Course Recap)

Comprehensive analysis of power electronics concepts and practical applications

Thank YOU!