

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

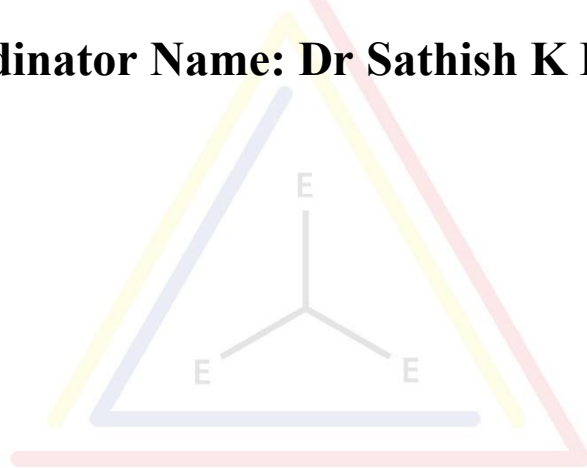
NOTES

Academic Year: 2026-27

Course Code: BEE503

Course Title: Power Electronics

Course Co-ordinator Name: Dr Sathish K R



Department of EEE
Emitting Elite Energy

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Vision of the Institute Development of academically excellent, culturally vibrant, socially responsible and globally competent human resources. Mission of the Institute • To keep pace with advancements in knowledge and make the students competitive and capable at the global level. • To create an environment for the students to acquire the right physical, intellectual, emotional and moral foundations and shine as torch-bearers of tomorrow's society. • To strive to attain ever-higher benchmarks of educational excellence	Vision of the Department To create Electrical and Electronics Engineers who excel to be technically competent and fulfil the cultural and social aspirations of the society. Mission of the Department • To provide knowledge to students that builds a strong foundation in the basic principles of electrical engineering, problem solving abilities, analytical skills, soft skills and communication skills for their overall development. • To offer outcome based technical education. • To encourage faculty in training & development and to offer consultancy through research & industry interaction.
Program Educational Objectives (PEO's) • PEO1: To produce competent and ethical Electrical and Electronics Engineers who will exhibit the necessary technical and managerial skills to perform their duties in society. • PEO2: To make graduates continuously acquire and enhance their technical and socio-economic skills. • PEO3: To aspire graduates on R&D activities leading to offering solutions and excel in various career paths. • PEO4: To produce quality engineers who have the capability to work in teams and contribute to real time projects.	Program Specific Outcomes (PSO's) • PSO1: Apply the concepts of Electrical & Electronics Engineering to evaluate the performance of power systems and also to control industrial drives using power electronics. • PSO2: Demonstrate the concepts of process control for Industrial Automation, design models for environmental and social concerns and also exhibit continuous self- learning.

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

Program Outcomes (PO's)

PO1: Engineering Knowledge: Apply knowledge of mathematics, natural science, computing, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to develop to the solution of complex engineering problems.

PO2: Problem Analysis: Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions with consideration for sustainable development. (WK1 to WK4)

PO3: Design/Development of Solutions: Design creative solutions for complex engineering problems and design/develop systems/components/processes to meet identified needs with consideration for the public health and safety, whole-life cost, net zero carbon, culture, society and environment as required. (WK5)

PO4: Conduct Investigations of Complex Problems: Conduct investigations of complex engineering problems using research-based knowledge including design of experiments, modelling, analysis & interpretation of data to provide valid conclusions. (WK8).

PO5: Engineering Tool Usage: Create, select and apply appropriate techniques, resources and modern engineering & IT tools, including prediction and modelling recognizing their limitations to solve complex engineering problems. (WK2 and WK6)

PO6: The Engineer and The World: Analyze and evaluate societal and environmental aspects while solving complex engineering problems for its impact on sustainability with reference to economy, health, safety, legal framework, culture and environment. (WK1, WK5, and WK7).

PO7: Ethics: Apply ethical principles and commit to professional ethics, human values, diversity and inclusion; adhere to national & international laws. (WK9)

PO8: Individual and Collaborative Team work: Function effectively as an individual, and as a member or leader in diverse/multi-disciplinary teams.

PO9: Communication: Communicate effectively and inclusively within the engineering community and society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations considering cultural, language, and learning differences

PO10: Project Management and Finance: Apply knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, and to manage projects and in multidisciplinary environments.

PO11: Life-Long Learning: Recognize the need for, and have the preparation and ability for i) independent and life-long learning ii) adaptability to new and emerging technologies and iii) critical thinking in the broadest context of technological change. (WK8)

POWER ELECTRONICS

BEE503

MODULE 1

Introduction | Power Diodes | Diode Rectifiers

Topics Covered in This Module

- Introduction to Power Electronics: Applications, Ideal & Practical Switches
- Thyristor Family: SCR, GTO, SITH, MCT, TRIAC, LASCR, RCT, GATT
- Transistor Family: BJT, MOSFET, IGBT, SIT — Control Characteristics
- Types of Power Electronic Circuits & Peripheral Effects
- Power Diodes: Structure, VI Characteristics, Reverse Recovery, Types, SiC Diodes
- Freewheeling Diodes with RL Load
- Diode Rectifiers: Single-Phase Half-Wave & Full-Wave with R and RL Loads

Dept. of Electrical & Electronics Engineering
ATME College of Engineering, Mysuru

SECTION A: INTRODUCTION TO POWER ELECTRONICS

1.1 What is Power Electronics?

Power Electronics is the branch of electrical engineering that deals with the processing of high voltages and currents to deliver power that supports a variety of needs. It involves converting electrical power from one form to another using power semiconductor switches and control mechanisms to supply regulated and controlled power.

Key Insight

Power Electronics forms the backbone of modern energy systems — from compact SMPS units (prioritising power density, reliability, efficiency) to motor drives increasingly used in electrification of transportation systems where precise control and efficiency are paramount.

1.2 Applications of Power Electronics

Sector	Typical Applications
Commercial	Heating & Ventilation, Air Conditioners, Central Refrigeration, Lighting, Computers, UPS, Elevators
Domestic	Cooking Equipment, Lighting, Heating, AC, Refrigerators, Personal Computers, Entertainment, UPS
Industrial	Pumps, Compressors, Blowers, Fans, Machine Tools, Arc/Induction Furnaces, Lasers, Welding Equipment
Aerospace	Space Shuttle Power Supplies, Satellite Power Systems, Aircraft Power Systems
Telecommunications	Battery Chargers, DC Power Supplies, UPS, Mobile Phone Chargers
Transportation	EV Traction Control, EV Battery Chargers, Electric Locomotives, Trolley Buses, Automobile Engine Controls

1.3 Power Semiconductor Devices & Characteristics

Power semiconductor devices are used as ON/OFF switches in power control circuits. They are classified into the Thyristor Family and the Transistor Family.

1.3.1 Thyristor Family (8 Types)

Device	Symbol	Turn ON	Turn OFF	Key Feature
SCR (Silicon Controlled Rectifier)	SCR	Positive gate pulse	External circuit (anode $\leq$ cathode potential)	Latching; gate loses control after turn-ON
GTO (Gate Turn-Off Thyristor)	GTO	Positive gate pulse	Negative gate pulse	Full gate control; no commutation circuit needed
RCT (Reverse Conducting Thyristor)	RCT	Gate pulse	External circuit	SCR + anti-parallel diode; suitable for inductive loads
SITH (Static Induction Thyristor)	SITH	Positive gate pulse	Negative gate pulse	Medium power converters; self-commutating
GATT (Gate Assisted Turn-Off Thyristor)	GATT	Gate pulse	Forced turn-off	High-speed, medium power; requires forced commutation
LASCR (Light Activated SCR)	LASCR	Light signal on gate	External circuit	Optical isolation; used in HVDC transmission
MCT (MOS Controlled Thyristor)	MCT	Negative gate voltage	Positive gate voltage	Lower power rating than GTO/SITH
TRIAC	TRIAC	Gate pulse (either polarity)	Zero crossing / gate	Bilateral conduction; heat/light/motor controls

1.3.2 Device Details — Thyristor Family

A. Silicon Controlled Rectifier (SCR)

Structure: Three terminals — Anode (A), Cathode (K), Gate (G). Internally a 4-layer PNP structure.

Operation: Forward biased when anode is positive w.r.t. cathode. A small positive gate-cathode voltage turns it ON. Once ON, gate loses control — device latches. Forward voltage drop is 0.5–2 V.

Advantages

- Very small gate drive required
- High voltage and current ratings available
- Reduced ON-state losses

Disadvantages

- Gate loses control after turn-ON
- External circuits required for turn-OFF
- Very low operating frequencies
- RC snubbers required for dv/dt protection

SCR Applications

- Controlled rectifiers (AC-DC converters)
- AC regulators, lighting and heating control
- DC motor drives, large power supplies, electronic brakes

B. Gate Turn-Off Thyristor (GTO)

- Turned ON by positive gate pulse; turned OFF by negative gate pulse.
- Full gate control — no external commutation circuits required.
- Gate drive for turn-OFF is very large (requires high-power driver circuits).
- Used for low-power applications.

C. Static Induction Thyristor (SITH)

- Positive gate pulse → turn ON; Negative gate pulse → turn OFF.
- Self-commutating — no external commutation circuit needed.
- Used in medium-power converter circuits.

D. MOS Controlled Thyristor (MCT)

- Negative gate voltage → turn ON.
- Positive gate voltage → turn OFF.
- Lower power ratings compared to GTO and SITH.

E. TRIAC

- Equivalent to two anti-parallel SCRs with a single gate.
- Conducts in both directions — current can flow in either direction through load.
- Widely used in heat controls, light dimmers, motor controls, and AC switches.

F. LASCR (Light Activated SCR)

- Turned ON by light signal on photosensitive gate.
- Provides complete electrical isolation between gate and drive circuit.
- Used in HVDC transmission systems.

G. RCT (Reverse Conducting Thyristor)

- Integrates an SCR with an anti-parallel diode.
- High forward current capability; lower reverse capability.
- Particularly suitable for inductive loads.

H. GATT (Gate Assisted Turn-Off Thyristor)

- High-speed switching device for medium-power applications.
- Requires forced turn-off circuits.

1.3.3 Transistor Family

The transistor family includes: Bipolar Junction Transistors (BJT), MOSFETs, IGBTs, and Static Induction Transistors (SIT).

Device	Turn ON	Turn OFF	Frequency / Rating	Key Use
BJT (Bipolar Junction Transistor)	Positive base-emitter voltage	Zero base-emitter voltage	Moderate	Common emitter switch; 0.5–1.5 V forward drop
MOSFET (N-Channel)	Positive gate-source voltage	Zero gate-source voltage	Very high (tens of kHz)	Low power, high-speed applications
IGBT (Insulated Gate Bipolar Transistor)	Positive gate-emitter voltage	Zero gate-emitter voltage	Up to 20 kHz; 1200 V, 400 A	High current, high frequency — best of BJT + MOSFET
SIT (Static Induction Transistor)	Gate signal	Gate signal	Up to 100 kHz; 1200 V, 300 A	High-power, high-frequency; audio, VHF/UHF, microwave

1.4 Control Characteristics of Power Semiconductor Devices

Control characteristics describe how each device is turned ON and OFF using gate/base/drive signals and the resulting output (load) voltage waveform.

Device	Turn ON Signal	Turn OFF Signal	Output Behaviour
SCR	Positive gate-cathode voltage ($V_g > 0$)	Anode $\leq$ Cathode potential (external)	V_s appears across load when ON; gate loses control after turn-ON
GTO / SITH	Positive gate-cathode voltage	Negative gate-cathode voltage	V_s across load when ON; output = 0 when OFF; full gate control
MCT	Negative gate-cathode voltage	Positive gate-cathode voltage	Inverse polarity convention; V_s across load when ON
BJT	Positive base-emitter voltage ($V_{be} > 0$)	Zero base-emitter voltage ($V_{be} = 0$)	V_s across load when saturated (ON); output = 0 when OFF

MOSFET	Positive gate-source voltage ($V_{gs} > 0$)	Zero gate-source voltage ($V_{gs} = 0$)	Load voltage = V_s when ON; = 0 when OFF
IGBT	Positive gate-emitter voltage ($V_{ge} > 0$)	Zero gate-emitter voltage ($V_{ge} = 0$)	V_s across load when ON; = 0 when OFF

1.5 Types of Power Electronic Circuits

Converter Type	Input	Output	Devices Used	Applications
Diode Rectifier (AC→DC, Uncontrolled)	Fixed AC (1 Φ or 3 Φ)	Fixed DC voltage	Diodes	Fixed DC supplies, battery chargers
Controlled Rectifier (AC→DC)	Fixed AC (1 Φ or 3 Φ)	Variable DC (controlled by firing angle α)	SCR	DC drives, UPS, HVDC
Inverter (DC→AC)	Fixed DC (battery)	Variable AC (frequency & magnitude)	Transistors, IGBTs	UPS, induction motor speed control
Chopper (DC→DC)	Fixed DC (battery/rectifier)	Fixed or variable DC	Transistors	DC drives, SMPS
Cycloconverter (AC→AC)	Fixed AC, fixed frequency	Variable AC, lower frequency	SCR	AC traction drives
AC Regulator (AC→AC)	Fixed AC mains	Variable AC, same frequency	TRIAC/SCR	Light dimmers, heaters

1.6 Peripheral Effects

When power converters switch, they create electrical disturbances that affect both the supply and the load.

Effects of Switching Actions

- Switching voltage/current pulses induced in the power supply
- Harmonics induced in the power supply due to non-sinusoidal waveforms
- Load contains voltage/current spikes and harmonics
- Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI) radiated due to fast switching

Mitigation: Filters placed before and after converters attenuate harmonics and noise spikes. Quality is evaluated using:

- Total Harmonic Distortion (THD)
- Displacement Factor / Harmonic Factor (HF)
- Input Power Factor (PF)

Advantages of PE Controllers

- Fast dynamic response (static devices)
- High conversion efficiency (low device losses)
- Compact, lightweight design
- Long operating life — no moving parts
- Digital/microprocessor-based flexible control
- Reduced electromagnetic & acoustic noise

Disadvantages of PE Controllers

- Generates harmonics affecting other loads
- Low power factor in some converters — PF correction needed
- May be costly for simple conversion tasks

SECTION B: POWER DIODES

2.1 Introduction to Power Diodes

Power diodes are uncontrolled semiconductor switching devices essential in most power converters. They are used in rectifiers, freewheeling, feedback, and commutation circuits.

Forward Biased (Conducting) - Anode (A) positive w.r.t. Cathode (K) - Forward bias ≈ 1 V triggers conduction - Current flows $A \rightarrow K$	Reverse Biased (Blocking) - Anode negative w.r.t. Cathode - Only a tiny leakage current flows - Blocks voltage up to reverse breakdown voltage
---	---

2.2 Structure of Power Diode

The structure of a power diode differs from small-signal diodes to handle high power.

Layer	Type	Doping Level	Function
Substrate (bottom)	n+ (heavily doped)	$\sim 10^{19} / \text{cm}^3$	Forms the Cathode; provides low-resistance ohmic contact
Drift Region (middle)	n ⁻ (lightly doped)	Low	Supports reverse voltage; undergoes conductivity modulation
Top layer	p+ (heavily doped)	High	Forms the Anode

Conductivity Modulation of Drift Region

When forward biased, holes injected from p+ into drift region attract electrons from n+ substrate. Both holes and electrons flood the drift region simultaneously, significantly reducing its resistance. Diode current rises but drift resistance stays nearly constant — reducing ON-state losses. This phenomenon is called conductivity modulation and is present in almost all power devices.

2.3 V-I Characteristics of Power Diode

The V-I characteristic shows the relationship between voltage and current in both forward and reverse bias conditions.

Region	Behaviour	Key Parameter
Forward Bias ($V > 0$)	Current rises linearly with voltage (due to ohmic resistance of n^- drift layer)	Forward voltage threshold ≈ 1 V
Linear Rise	Unlike low-power diodes (exponential rise), power diodes have linear I - V due to lightly doped n^- layer acting as internal resistance	Drift region resistance
Reverse Bias ($V < 0$)	Very small leakage current flows	Leakage current $\ll 1$ mA
Reverse Breakdown	Current rises rapidly $\rightarrow$ large power dissipation $\rightarrow$ diode damaged	Rated Reverse Breakdown Voltage (VRRM)

V-I Characteristic Summary

$\leftarrow$ Reverse Breakdown | Leakage Region | Threshold ($\approx 1V$) | Linear Conduction $\rightarrow$
 $V_{RRM} \leftarrow \text{---} 0 \text{---} 1V \text{---} \rightarrow$ (Forward)
 Current: $\uparrow \uparrow$ Large $\leftarrow$ Tiny leakage $\rightarrow 0 \rightarrow$ Linear Rise $\uparrow$

2.4 Reverse Recovery Characteristics

Power diodes are mainly used in commutation and freewheeling circuits. The reverse recovery characteristic describes what happens when the diode transitions from conduction to blocking.

Time Period	Current Behaviour	Voltage Behaviour	Physical Cause
t_1 (Forward conduction start)	Current rises from 0 to steady state	Voltage overshoots (high)	No conductivity modulation yet; high drift resistance + inductance
t_2 (Steady state established)	Current at steady state	Voltage drops to minimum	Conductivity modulation begins; drift resistance decreases
t_3 – t_4 (Current reducing, di/dt negative)	Current decreasing but still positive	Small voltage drop	Excess carriers still present in drift region
t_4 – t_5 (Reverse recovery period)	Current goes NEGATIVE	Voltage turns negative	Excess carriers being removed; depletion region forming
End of t_5 (Recovery complete)	Current returns to zero	Voltage = $-V_R$ (reverse bias)	All excess carriers removed; junctions fully reverse biased

Reverse Recovery Time (t_{rr})	Significance
------------------------------------	--------------

The period from t_4 to t_5 during which excess carriers are removed and reverse voltage builds up. This is the reverse recovery period.

Shorter t_{rr} = faster switching = usable at higher frequencies. Key parameter for selecting diodes in high-speed applications.

2.5 Types of Power Diodes

Type	Reverse Recovery Time	Frequency Range	Voltage / Current Rating	Applications
1. General Purpose Diodes	$\sim 25 \mu\text{s}$ (high)	Up to 1 kHz	1 A/50 V to 1000 A/500 V	Line-frequency rectifiers, converters
2. Fast Recovery (High Speed) Diodes	$< 5 \mu\text{s}$ (low)	High speed (kHz range)	1 A/50 V to 100 A/3 kV	Choppers, inverters, high-speed circuits
3. Schottky Diodes	Near zero (no pn junction)	Very high (MHz range)	Low voltage, low current	Low-voltage converters, feedback, freewheeling

Schottky Diode — Key Principle

In a Schottky diode, the pn junction is replaced by a metal-semiconductor junction (e.g., Aluminium on n-type Si). Since there is no pn junction, minority carrier storage time is absent, giving near-zero turn-off time. Only majority carriers conduct. No reverse leakage current in SiC Schottky types.

2.6 Silicon Carbide (SiC) Diodes

SiC diodes are manufactured by Infineon Technologies. Silicon Carbide has superior physical properties compared to Silicon (Si) and Gallium Arsenide (GaAs).

Features of SiC Diodes

- No reverse recovery time
- Extremely fast switching
- Switching behaviour unaffected by temperature
- Very small power loss

Advantages of SiC Diodes

- High efficiency
- Reduced solution size
- High switching frequencies
- Reduced / small EMI

- High reliability

SiC Diode Applications

- Energy-saving power supplies
- Efficient solar energy conversion
- Welding equipment
- Air conditioning systems
- Transportation / EV systems

2.6.1 SiC Schottky Diodes

SiC Schottky diodes use Silicon Carbide as semiconductor with a thin film of gold, platinum, or silver deposited on n-type SiC — creating a metal-semiconductor junction instead of a pn junction.

Characteristic	Detail
Carrier Type	Majority carriers only — no minority carriers
Leakage Current	No reverse leakage current
Conduction Mechanism	Higher-energy electrons from n-SiC injected into metal region when forward biased
Speed	Very high switching speed
Reliability	Highly reliable and rugged
Temperature Stability	Stable at high surge currents; operates at high frequencies
Cost Advantage	No additional cooling required — reduced system cost

2.7 Applications of Power Diodes

Key Applications

- Uncontrolled rectifiers (AC to DC without control)
- Feedback diodes and freewheeling diodes in choppers, inverters, and controlled converters
- Commutating circuits for SCRs
- Half-controlled converters and half-bridge inverters

2.8 Diode Circuit with RL Load & Freewheeling Diodes

2.8.1 Diode Switched RL Circuit

When switch S1 closes at $t=0$ with no initial current, applying KVL to the RL circuit gives the differential equation:

Voltage KVL

$$V_s = R \cdot i + L \cdot (di/dt)$$

Current $i(t)$

$$i(t) = (V_s/R) \cdot [1 - e^{(-Rt/L)}] = (V_s/R) \cdot [1 - e^{(-t/\tau)}], \quad \tau = L/R$$

Inductor Voltage $v_L(t)$

$$v_L(t) = V_s \cdot e^{(-Rt/L)} = V_s \cdot e^{(-t/\tau)}$$

The current rises exponentially from 0 toward a maximum of V_s/R as the inductance saturates. The initial rate of rise of current = V_s/L .

⚠ Problem Without Freewheeling Diode

When switch S1 opens, the energy stored in the inductor ($= \frac{1}{2}Li^2$) produces a very high reverse voltage spike across S1 and D1. This can damage the diode. Solution: Add a freewheeling diode across the RL load.

2.8.2 Freewheeling Diode with Switched RL Load

A freewheeling diode (DFW) is connected in antiparallel across the RL load to provide a path for inductor current when the main switch opens.

Phase	Time Period	Current Path	Equation
Switch S1 CLOSED (charge)	0 to t_1	$V_s \rightarrow S1 \rightarrow \text{Load } (R+L) \rightarrow \text{return}$	$i_1(t) = (V_s/R) \cdot [1 - e^{(-Rt/L)}]$; reaches $I_1 = V_s/R$ at $t = t_1$
Switch S1 OPEN (freewheeling)	t_1 to t_1+t_2	Inductor $\rightarrow R \rightarrow \text{DFW} \rightarrow \text{Inductor}$	$i_2(t) = I_1 \cdot e^{(-R(t-t_1)/L)}$; decays exponentially to 0

Why Freewheeling Diode is Important

- Provides a safe path for inductor current when switch opens — prevents voltage spikes
- Protects the switch and main diode from damage

- Maintains continuity of load current — reduces ripple in load voltage
- Allows energy stored in inductor to be dissipated in the load resistance

SECTION C: DIODE RECTIFIERS

3.1 Introduction to Diode Rectifiers

A rectifier converts AC input voltage to DC output voltage. When the input AC voltage is fixed, the output DC voltage is also fixed (uncontrolled rectifier).

Advantages

- Simple circuits available at all power levels
- No control circuits required
- Available in 1 Φ and 3 Φ configurations
- High and low frequency types available
- Low cost

Disadvantages

- Output voltage is uncontrolled
- Power flow is unidirectional
- High ripple content for 1 Φ rectifiers

Rectifier Applications

- Uninterruptible Power Supplies (UPS)
- Simple electronic circuits
- Low-power battery chargers
- Simple low-power DC supplies

3.1.1 Classification of Rectifiers

Category	Types
1-Phase (1 Φ) Diode Rectifiers	Half-wave rectifier Full-wave (center-tap) rectifier Bridge rectifier
3-Phase (3 Φ) Diode Rectifiers	Half-wave rectifier Full-wave rectifier Bridge rectifier

3.2 Performance Parameters of Rectifiers

The following parameters quantify rectifier performance:

Parameter	Symbol	Definition / Formula
Rectification Efficiency	η	$\eta = (P_{DC} / P_{rms}) = (V_{oav} \times I_{oav}) / (V_{orms} \times I_{orms})$ — Ratio of DC output power to total AC input power

Form Factor	FF	$FF = V_{rms} / V_{oav}$ — Measure of the waveshape of output voltage
Ripple Factor	RF	$RF = \sqrt{(FF^2 - 1)}$ — Measure of ripple (AC) content in output; lower = better
Transformer Utilization Factor	TUF	$TUF = P_{avg} / (V_{s_{rms}} \times I_{s_{rms}})$ — Ratio of DC load power to transformer VA rating
Displacement Factor / DPF	DF or DPF	$DPF = \cos(\phi_1)$ — Cosine of angle between fundamental supply current and voltage
Harmonic Factor / THD	HF or THD	$HF = \sqrt{[(I_{s_{rms}}^2 - I_{s1_{rms}}^2)]} / I_{s1_{rms}}$ — Measure of harmonic distortion in supply current
Crest Factor	CF	$CF = I_{s(peak)} / I_{s(rms)}$ — Ratio of peak to rms supply current
Power Factor	PF	$PF = (P_{avg}) / (V_{s_{rms}} \times I_{s_{rms}})$ — Measure of reactive power in supply

3.3 Single-Phase Full-Wave Rectifier (Center-Tap)

3.3.1 With Resistive (R) Load

Circuit: Two diodes D1 and D2, load connected between the diode junction and center-tap of secondary transformer.

Half Cycle	Conducting Diode	Output
Positive half cycle ($V_s > 0$)	D1 conducts	Positive voltage across load
Negative half cycle ($V_s < 0$)	D2 conducts	Still positive voltage across load (full-wave rectification)

Vout (avg) — R Load	$V_{oav} = (2 \times V_m) / \pi \approx 0.636 \times V_m$
----------------------------	---

Vout (rms) — R Load	$V_{orms} = V_m / \sqrt{2} \approx 0.707 \times V_m$
----------------------------	--

Form Factor (FF)	$FF = V_{orms} / V_{oav} = \pi / (2\sqrt{2}) \approx 1.11$
-------------------------	--

Ripple Factor (RF)	$RF = \sqrt{(FF^2 - 1)} \approx 0.482$
---------------------------	--

Rectification Efficiency	$\eta = 8 / \pi^2 \approx 81.2\%$
---------------------------------	-----------------------------------

PIV (Peak Inverse Voltage)

$$PIV = 2 \times V_m \quad (\text{for center-tap configuration})$$

3.3.2 With Inductive (RL) Load

- Since load is inductive, current waveform is sinusoidal but lags voltage.
- Supply current waveform of both phases (i_{s1} and i_{s2}) is approximately square wave.
- The inductor causes current to continue flowing even after the voltage reverses — extending conduction angle beyond 180° .

3.4 Single-Phase Bridge Rectifier

Uses four diodes arranged in a bridge configuration. No center-tap transformer required.

3.4.1 With Resistive (R) Load

Half Cycle	Conducting Diodes	Current Path
Positive ($V_s > 0$)	D1 and D2	Supply (+) → D1 → Load → D2 → Supply (-)
Negative ($V_s < 0$)	D3 and D4	Supply (-) → D3 → Load → D4 → Supply (+)

V_{out} (avg)

$$V_{oav} = (2 \times V_m) / \pi \approx 0.636 \times V_m \quad (\text{same as center-tap})$$

PIV (Bridge)

$$PIV = V_m \quad (\text{lower than center-tap — advantage of bridge})$$

Bridge vs. Center-Tap Comparison

Parameter	Center-Tap Full-Wave	Bridge Rectifier
No. of Diodes	2	4
Transformer	Center-tap required	Ordinary (no center-tap)
PIV per diode	$2 \times V_m$	V_m
TUF	Lower (poor utilization)	Higher (better utilization)
Supply current waveshape	Sinusoidal (for R load)	Sinusoidal
Output waveform	Same	Same

3.4.2 Bridge Rectifier with RL Load

- D1 and D2 conduct in the positive half cycle; D3 and D4 in the negative half cycle.
- Waveforms of bridge rectifier for RL load are the same as for center-tap full-wave rectifier with RL load.
- The inductor L smooths the current, reducing ripple in load current.
- In RL load, current may continue flowing even when supply voltage reverses — extending the conduction period.

3.5 Summary: Rectifier Performance Parameters

Parameter	Half-Wave Rectifier	Full-Wave (CT) — R Load	Bridge — R Load
V_{oav}	$(V_m/\pi) \approx 0.318 V_m$	$(2V_m/\pi) \approx 0.636 V_m$	$(2V_m/\pi) \approx 0.636 V_m$
V_{orms}	$V_m/2 = 0.5 V_m$	$V_m/\sqrt{2} \approx 0.707 V_m$	$V_m/\sqrt{2} \approx 0.707 V_m$
Form Factor (FF)	$\pi/2 \approx 1.57$	$\pi/(2\sqrt{2}) \approx 1.11$	$\pi/(2\sqrt{2}) \approx 1.11$
Ripple Factor (RF)	≈ 1.21	≈ 0.482	≈ 0.482
Rectification Efficiency (η)	$\approx 40.6\%$	$\approx 81.2\%$	$\approx 81.2\%$
PIV	V_m	$2V_m$	V_m
No. of Diodes	1	2	4

End of Module 1 Notes

Power Electronics (BEE503) | Dept. of EEE, ATMECE, Mysuru

POWER ELECTRONICS

BEE503

MODULE 2

Power Transistors

BJT | MOSFET | IGBT | Drive Circuits | Isolation Techniques

Syllabus — Module 2

- Power Transistors: Introduction, Classification
- Bipolar Junction Transistors (BJT): Steady-State Characteristics, Switching Characteristics, Switching Limits
- Base Drive Control: Turn-ON, Turn-OFF, Proportional, Anti-Saturation
- Power MOSFETs: Steady-State Characteristics, Switching Characteristics, Gate Drive
- IGBT: Structure, V-I Characteristics, Switching Characteristics
- di/dt and dv/dt Limitations and Protection
- Isolation of Gate and Base Drives: Pulse Transformers and Optocouplers
- Comparison: BJT vs SCR, BJT vs MOSFET

Dept. of Electrical & Electronics Engineering
ATME College of Engineering, Mysuru

SECTION 1: INTRODUCTION TO POWER TRANSISTORS

BJT · MOSFET · SIT · IGBT — Fully Controlled Switching Devices

1.1 Why Power Transistors?

Unlike thyristors (SCRs), power transistors have fully controlled turn-ON and turn-OFF behaviour. They do NOT need external commutation components. Due to advances in solid-state manufacturing technology, modern power transistors offer:

High Operating Frequency	Low ON-State Losses	Higher Current/Voltage Ratings
Tens of kHz to MHz	Suitable for SMPS & PWM Inverters	Up to 1200 V, 400 A (IGBT)

1.2 Classification of Power Transistors

Type	Full Name	Control Signal	Primary Advantage	Key Application
BJT	Bipolar Junction Transistor	Base current (I_B)	Low ON-state drop; bipolar	DC drives, SMPS, Inverters
MOSFET	Metal-Oxide-Semiconductor FET	Gate voltage (V_{GS})	Fast switching; simple drive	High-freq SMPS, Choppers
SIT	Static Induction Transistor	Gate signal	Very high frequency; low noise	Audio, VHF/UHF, Microwave
IGBT	Insulated Gate Bipolar Transistor	Gate voltage (V_{GE})	Best of BJT + MOSFET	AC drives, UPS, SMPS

SECTION 2: BIPOLAR JUNCTION TRANSISTOR (BJT)

Structure · Steady-State Characteristics · Switching · Limits · Base Drive

2.1 Introduction to Power BJT

The Power BJT (also called Power Transistor) is a bipolar device available in two polarities — NPN and PNP. It has three terminals: Collector (C), Base (B), and Emitter (E). The gate (base) has FULL control over conduction — no commutation circuits are required.

NPN BJT Operation

- Base-Emitter forward biased → Transistor turns ON
- Collector current flows: C → E direction
- $V_{CE(on)} \approx 0.3\text{--}0.4\text{ V}$ (saturation drop)
- Base drive removed → Transistor turns OFF

PNP BJT Operation

- Base-Emitter forward biased → Transistor turns ON
- Current flows: E → C direction (opposite to NPN)
- Base drive removed → Transistor turns OFF
- Drive has full control — no external commutation needed

2.2 Structure of Power BJT

The Power BJT uses a vertical-oriented 4-layer structure of alternating p-type and n-type regions. Vertical orientation maximises cross-sectional area for current flow, reducing ON-state resistance and power dissipation.

Layer / Region	Type	Doping Level	Thickness	Function
Emitter	n ⁺ (heavily doped)	$\sim 10^{19} / \text{cm}^3$	$\sim 10\text{ }\mu\text{m}$	Electron emitter; low resistance contact
Base	p (moderately doped)	$\sim 10^{16} / \text{cm}^3$	5–20 μm	Controls conduction; thin = high gain, but lower BV
Collector Drift Region	n ⁻ (lightly doped)	$\sim 10^{14} / \text{cm}^3$	Determines BV	Supports reverse voltage; drift region
Collector Contact	n ⁺ (heavily doped)	$\sim 10^{19} / \text{cm}^3$	—	External collector contact; low resistance

Design Note

In practical power transistors, emitters and bases are interleaved to reduce current crowding effects and minimize the risk of second breakdown. Thin base provides higher current gain (β) but reduces breakdown voltage capability.

2.3 Steady-State (V-I) Characteristics of BJT

The output characteristics plot I_C (collector current) vs V_{CE} (collector-emitter voltage) for various base current (I_B) values.

2.3.1 Operating Regions

Region	Base Drive (I_B)	Transistor State	Collector Current (I_C)	VCE Condition	Use in Power Electronics
Cut-Off Region	$I_B \approx 0$	OFF (Open switch)	≈ 0 (only I_{CEO} leakage)	$V_{CE} = V_s$ (full supply)	Switch OFF state
Active Region	$I_B > 0$, small	Amplifying	$I_C = \beta \times I_B$	V_{CE} intermediate	NEVER used in PE (amplifier mode)
Quasi-Saturation	I_B large	Partially ON	I_C limited by collector circuit	V_{CE} slightly above $V_{CE(sat)}$	Soft saturation mode
Hard Saturation	I_B very large	Fully ON (closed switch)	$I_{C(sat)} = V_s/R_L$	$V_{CE} \approx 0.3\text{--}0.4\text{ V}$	Switch ON state

⚡ Key Principle: BJT as a Switch

In power electronics, BJT is operated ONLY between Cut-Off (OFF) and Saturation (ON). The Active region (amplifier mode) is NEVER used. This binary switching ensures minimum power dissipation.

2.3.2 Breakdown Voltages

Symbol	Name	Condition	Definition
BV_{SUS}	Sustained Voltage	BJT carrying substantial I_C	Maximum V_{CE} that can be sustained during conduction
BV_{CEO}	Collector-Emitter BV	Base open-circuited ($I_B = 0$)	Maximum V_{CE} with base open — most common specification
BV_{CBO}	Collector-Base BV	Emitter open-circuited	Collector-base breakdown voltage — highest of the three

2.3.3 Primary vs. Second Breakdown

Primary Breakdown

- Caused by avalanche breakdown of collector-base junction
- Occurs due to large power dissipation at high VCE
- Large power dissipation leads to thermal runaway
- Device damages if current not limited externally

Second Breakdown (SB)

- Caused by current crowding into small base regions
- Creates localized hot spots → localized thermal runaway
- Energy-dependent phenomenon (voltage × current × time)
- Occurs at specific VCE-IC combinations — shown on FBSOA

2.3.4 Mathematical Relationships

Current Gain (β)

$$\beta = I_C / I_B \quad (\text{hFE} - \text{DC current gain})$$

Terminal Currents

$$I_E = I_C + I_B \quad ; \quad I_C \approx \beta \cdot I_B \quad (\text{since } I_{CEO} \text{ is negligible})$$

Emitter Current

$$I_E = (\beta + 1) \cdot I_B = I_C + I_B$$

$I_C(\text{sat})$ — Saturation

$$I_C(\text{sat}) = (V_s - V_{CE(\text{sat})}) / R_L \approx V_s / R_L$$

$I_B(\text{min})$ for Saturation

$$I_B(\text{min}) = I_C(\text{sat}) / \beta \quad (\text{minimum base current to saturate})$$

2.4 Switching Characteristics of BJT

During switching, the internal junction capacitances C_{cb} (collector-base) and C_{be} (base-emitter) play a critical role. These capacitances must charge/discharge during turn-ON and turn-OFF transitions.

2.4.1 Turn-ON Sequence

Phase	Signal Applied	What Happens Physically	Time Parameter
Delay (t_d)	$V_{BE(\text{on})}$ applied; $I_B = I_{B(\text{on})}$	C_{be} begins charging from 0 V toward 0.7 V; I_C remains at 0	t_d = delay time
Rise (t_r)	C_{be} charges to 0.7 V	I_C starts rising from 0 to $I_C(\text{sat})$; V_{CE} starts falling	t_r = rise time
Fully ON	$I_C = I_C(\text{sat})$	BJT in saturation; $V_{CE} \approx V_{CE(\text{sat})} \approx 0.3\text{--}0.4$ V	—

Turn-ON Time

$$t_{on} = t_d + t_r$$

t_d = delay time (C_{be} charges to 0.7 V); t_r = rise time (I_C rises to full value)

2.4.2 Turn-OFF Sequence

Phase	Signal Applied	What Happens Physically	Time Parameter
Storage (ts)	VBE made negative	Excess stored charge in base being removed; I_C unchanged	t_s = storage time (longest!)
Fall (tf)	Stored charge removed; C_{be} discharges	I_C starts falling from $I_C(sat)$ to 0; VCE rises to V_s	t_f = fall time
Fully OFF	VBE negative; $I_C = 0$	BJT in cut-off; VCE = V_s (full supply voltage)	—

Turn-OFF Time

$$t_{off} = t_s + t_f$$

t_s = storage time (dominant); t_f = fall time; $t_{off} \gg t_{on}$ typically

⚠ Storage Time Issue

Storage time (t_s) is the dominant factor in BJT turn-OFF. It arises because excess minority carriers stored in the base region during saturation must be removed before the collector current falls. Longer $t_s \rightarrow$ lower switching frequency. Anti-saturation techniques reduce t_s .

BJT Switching Waveform Summary

```

Gate Voltage: _____ HIGH _____ LOW (negative) _____
Base Current: _____  $I_B(on)$  _____  $I_B(off)$  (neg) _____ 0
Coll. Current: 0 _____  $t_d$  _____  $t_r$  _____  $I_C(sat)$  _____  $t_s$  _____  $t_f$  _____ 0
VCE: _____  $V_s$  _____  $V_{CE(sat)}$  _____  $V_s$ 
Time events: [Gate ON] --  $t_d$  --  $t_r$  -- [Steady ON] -- [Gate OFF] --  $t_s$  --  $t_f$  -- [OFF]
  
```

2.5 Switching Limits of BJT**2.5.1 Forward Biased Safe Operating Area (FBSOA)**

The FBSOA defines the safe I_C vs VCE operating boundary during turn-ON and ON-state conditions. Operation outside FBSOA risks second breakdown or thermal damage.

FBSOA Boundary	Limiting Factor	Description
Maximum I_C (horizontal)	Maximum current rating	Absolute maximum collector current the device can carry

Thermal limit (slope)	Average junction temperature	Power = $V_{CE} \times I_C$ must not exceed thermal capacity
Second breakdown (slope)	SB energy limit	Must not exceed V_{CE} - I_C combinations causing localized heating
BV_{CEO} (vertical)	Breakdown voltage	Maximum V_{CE} with open base — absolute voltage limit

Pulsed Operation Advantage

The FBSOA expands for shorter pulse widths (pulsed operation vs DC). With shorter switching times, junction temperature rise is less, allowing larger peak I_C - V_{CE} combinations. This is shown as expanding FBSOA boundaries for pulsed vs DC operation.

2.5.2 Reverse Biased Safe Operating Area (RBSOA)

The RBSOA defines safe I_C vs V_{CE} limits during turn-OFF when the base-emitter junction is reverse biased. The RBSOA is larger than FBSOA because at low I_C levels, the reverse base current reduces β , pushing breakdown voltage toward BV_{CBO} (which is higher than BV_{CEO}).

2.5.3 Power Derating and Thermal Analysis

The transistor's maximum power dissipation (P_T) depends on the thermal path from junction to ambient. The thermal equivalent circuit is:

Junction Temp	$T_J = T_A + P_T \times (R_{JC} + R_{CS} + R_{SA})$ <i>P_T = total average power loss (specified at $T_C = 25^\circ\text{C}$)</i>
Case Temp	$T_C = T_J - P_T \times R_{JC}$
Sink Temp	$T_S = T_C - P_T \times R_{CS}$

Symbol	Parameter	Units	Description
R_{JC}	Junction-to-Case thermal resistance	$^\circ\text{C/W}$	Intrinsic to device (data sheet value)
R_{CS}	Case-to-Sink thermal resistance	$^\circ\text{C/W}$	Depends on mounting method and thermal interface material
R_{SA}	Sink-to-Ambient thermal resistance	$^\circ\text{C/W}$	Depends on heatsink size and airflow
$T_J(\text{max})$	Maximum junction temperature	$^\circ\text{C}$	Typically $150\text{--}200^\circ\text{C}$ for Si power transistors

2.6 BJT Base Drive Control

Optimal base drive is critical. Too little base current → BJT may not saturate (high V_{CE} , high losses). Too much → excess stored charge in base → longer storage time → slower turn-OFF.

2.6.1 Turn-ON Control

A peaking capacitor C_1 in parallel with R_2 provides high initial base current for fast turn-ON, then reduces to a steady lower value.

Phase	C1 State	Effective Resistance	Base Current	Effect
Initial turn-ON	C1 acts as short circuit	Only R_1 in path	$I_B(\text{initial}) = V_B / R_1$ (high)	Fast, hard drive → quick saturation
After turn-ON	C1 charges up (open)	$R_1 + R_2$ in path	$I_B(\text{steady}) = V_B / (R_1 + R_2)$ (low)	Prevents excess stored charge buildup
Turn-OFF	C1 voltage reverses I_B	Negative base current	I_B goes negative momentarily	Helps remove stored charge faster

Initial I_B	$I_B(\text{initial}) = V_B / R_1$ (C1 acts as short)
---------------	--

Steady I_B	$I_B(\text{steady}) = V_B / (R_1 + R_2)$ (C1 fully charged)
--------------	---

C1 charge τ	$\tau(\text{charge}) = R_1 \times C_1$
------------------	--

C1 discharge τ	$\tau(\text{discharge}) = R_2 \times C_1$ (during turn-OFF)
---------------------	---

2.6.2 Turn-OFF Control

An additional voltage source during turn-OFF adds C_1 voltage as reverse voltage across base-emitter, producing negative base current peaking. Diode D_1 isolates the forward and reverse drive circuits.

Turn-OFF Enhancement

Applying negative base voltage (reverse drive) actively extracts stored charge from the base region, significantly reducing storage time (t_s) and hence t_{off} . This technique is essential in high-frequency converters like SMPS and PWM inverters.

2.6.3 Proportional Base Drive Control

As load changes, collector current changes. Proportional base drive automatically adjusts I_B in proportion to I_C using magnetic coupling (transformer with turns ratio $n_1:n_2$ between collector and base circuits).

Turns Ratio Condition

$$n_2 / n_1 = 1 / \beta \quad (\text{base coil} / \text{collector coil turns ratio})$$

- A short trigger pulse initiates turn-ON.
- IC flowing through collector coil magnetically induces IB in base coil.
- IB automatically tracks IC — no excess or deficient base drive.
- Negative pulse through RC circuit turns BJT OFF.

2.6.4 Anti-Saturation (Quasi-Saturation) Control

Excess base current causes hard saturation — large stored charge → long storage time → slow turn-OFF. Anti-saturation diodes (Baker clamp) prevent hard saturation by clamping VCE above VCE(sat).

Anti-Sat Condition

$$V_{CE} = V_{BE} \approx 0.7 \text{ V} \quad (\text{BJT in quasi-saturation, not hard saturation})$$

Anti-Saturation Advantage

- Reduced storage time (t_s)
- Faster turn-OFF
- Higher switching frequency capability
- Less heat generated during switching transitions

Anti-Saturation Disadvantage

- VCE is raised from ~0.3 V to ~0.7 V
- Higher ON-state VCE → increased conduction losses
- Power dissipation during ON state increases
- Additional diodes add circuit complexity

2.7 Merits, Demerits & Applications of BJT

Merits of BJT

- Small turn-ON and turn-OFF times → higher switching frequencies
- Small turn-ON losses
- Full gate (base) control over operation
- No commutation circuits required
- Bipolar device — both NPN and PNP available
- Available at reduced costs

Demerits of BJT

- Drive circuit is complex (current-controlled)
- Stored charge in base reduces max switching frequency
- Negative temperature coefficient → paralleling is difficult
- Second breakdown risk at high IC-VCE combinations

BJT Applications

- Switched Mode Power Supplies (SMPS)
- Bridge inverters
- DC-to-DC converters (choppers)
- Power factor correction circuits

2.8 BJT vs SCR — Comparison

Parameter	BJT (Power Transistor)	SCR (Thyristor)
Control type	Bipolar (current controlled base)	Unipolar (current controlled gate)
Turn-ON	Base current (continuous)	Short gate pulse sufficient
Turn-OFF	Remove base drive	External commutation circuit needed
Commutation circuit	Not required	Required (for DC circuits)
Switching frequency	High (kHz range)	Low (50–500 Hz typical)
Current rating	Lower than SCR	Very high (up to kA)
Voltage rating	Lower than SCR	Very high (up to kV)
Gate/Base drive power	Higher (continuous I_B needed)	Lower (short pulse sufficient)
Cost	Lower for same current	Lower for very high current/voltage
Applications	SMPS, inverters, choppers	Rectifiers, AC regulators, HVDC

SECTION 3: POWER MOSFET

Metal-Oxide-Semiconductor Field Effect Transistor

3.1 Introduction to Power MOSFET

The MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor) combines field effect concepts with MOS technology. It has three terminals: Gate (G), Drain (D), Source (S). It is a VOLTAGE-CONTROLLED device — only voltage (not current) is needed to switch it.

MOSFET Turn-ON

- Apply positive V_{GS} (gate-source voltage)
- $V_{GS} > V_{GS(th)}$ → channel forms in p-body
- Drain current flows: $D \rightarrow S$ (n-channel)
- Very small gate current flows (just charges C_{GS})

MOSFET Turn-OFF

- Remove V_{GS} (make zero or negative)
- Gate capacitance C_{GS} discharges
- Channel disappears → drain current stops
- Full gate control — no commutation needed

3.2 Structure of Power MOSFET

Two main types: (1) Depletion-type MOSFET and (2) Enhancement-type MOSFET (used in power electronics). Both available as N-channel or P-channel. The N-channel enhancement type is most common in power applications.

Region / Component	Type	Doping Level	Function
Source (S) and Drain (D)	n+ (heavily doped)	$\sim 10^{19} / \text{cm}^3$	Current terminal contacts
Body (Channel) Region	p-type	$\sim 10^{16} / \text{cm}^3$	Forms inversion channel when $V_{GS} > V_{GS(th)}$
Gate Insulation Layer	SiO_2 (oxide)	N/A (insulator)	Insulates gate metal from semiconductor — zero DC gate current
Gate Metal	Metal (Al or polysilicon)	N/A	Control electrode — applies electric field to body

Key Structural Insight

The SiO_2 insulating layer between gate metal and the p-body is the key distinguishing feature of MOSFET. It means virtually NO gate current flows (only displacement current to charge/discharge gate capacitance). This makes drive circuits very simple compared to BJT.

3.3 Steady-State (V-I) Characteristics of MOSFET

Output characteristics: i_D (drain current) vs V_{DS} (drain-source voltage) plotted for various V_{GS} values.

Region	Condition	MOSFET State	Behaviour	Power Electronics Use
Cut-Off Region	$V_{GS} < V_{GS(th)}$	OFF	$i_D \approx 0$ (negligible drain current)	Switch OFF state
Active (Pinch-Off) Region	$V_{GS} > V_{GS(th)}$; $V_{DS} > V_{GS} - V_{GS(th)}$	Amplifying	$i_D = f(V_{GS})$ — independent of V_{DS}	NEVER used in PE (amplifier mode)
Ohmic (Linear) Region	$V_{GS} \gg V_{GS(th)}$; V_{DS} small	ON (conducting)	i_D proportional to V_{DS} ; acts as resistance $R_{DS(on)}$	Switch ON state
Breakdown	$V_{DS} > BVDSS$	Damaged	Sudden increase in i_D — device failure	Must be avoided; use within rating

⚡ BVDSS — Drain-Source Breakdown Voltage

BVDSS is the maximum drain-to-source voltage when the gate is open-circuited. Exceeding BVDSS causes irreversible device failure. Always design with sufficient derating margin (typically 20–30% below BVDSS).

ON-State Resistance

$V_{DS(on)} = i_D \times R_{DS(on)}$ [Ohmic region — MOSFET acts as a resistor]

$R_{DS(on)}$ increases with temperature and with voltage rating — key limitation for high-power applications

3.4 Switching Characteristics of MOSFET

The internal parasitic capacitances C_{GS} (gate-source) and C_{GD} (gate-drain, Miller capacitance) control MOSFET switching speed. These have no effect in steady state but dominate transient behaviour.

3.4.1 Turn-ON Sequence

Phase	V_{GS} Behaviour	i_D Behaviour	Time Parameter
Turn-ON Delay [$t_d(on)$]	V_{GS} rises from 0 to $V_{GS(th)}$; C_{GS} charges	$i_D = 0$ (not yet turned on)	$t_d(on)$ = time for V_{GS} to reach $V_{GS(th)}$
Current Rise [t_r]	V_{GS} rises from $V_{GS(th)}$ to $V_{GS(plateau)}$	i_D rises from 0 to I_0 (full load current)	t_r = rise time; i_D reaches full value

Voltage Fall [tfv]	VGS stays at plateau (Miller effect)	$i_D = I_0$; VDS starts falling	tfv = voltage fall time
Fully ON	VGS = VGS(on) (overdrive)	$i_D = I_0$; VDS = VDS(on) = $I_0 \times R_{DS(on)}$	MOSFET fully conducting

Turn-ON Time	$t_{on} = t_d(on) + t_r$ $t_d(on)$ = CGS charges to VGS(th); t_r = CGS charges from VGS(th) to full gate voltage VGSp
---------------------	--

3.4.2 Turn-OFF Sequence

Phase	VGS Behaviour	iD Behaviour	Time Parameter
Turn-OFF Delay [td(off)]	VGS falls from VGS(on) to VGSp (pinch-off)	$i_D = I_0$ (unchanged)	td(off) = discharge of CGS from overdrive to VGSp
Voltage Rise [trv]	VGS stays at plateau (Miller plateau)	$i_D = I_0$; VDS rises to Vs	trv = voltage rise time (Miller effect dominant)
Current Fall [tf]	VGS falls from VGSp to VGS(th)	i_D falls from I_0 to 0	tf = fall time; drain current decreases
Fully OFF	VGS = 0 (discharged)	$i_D = 0$; VDS = Vs	MOSFET fully blocking

Turn-OFF Time	$t_{off} = t_d(off) + t_f$ $t_d(off)$ = CGS discharges from overdrive to VGSp; t_f = CGS discharges from VGSp to VGS(th)
----------------------	---

MOSFET Switching Waveform Summary

```

Gate voltage: 0 → /td(on) \ VGS(on) | PLATEAU | \td(off) \ 0
Drain current: 0 → /tr/ I0 (full) | \tf \ 0
VDS: Vs → Vs → \trv \ VDS(on) → /trv/ Vs
Events: [Gate +] [td(on)] [tr] [Conducting] [Gate 0] [td(off)] [tf] [OFF]

```

3.5 MOSFET Gate Drive Circuit

The gate drive circuit must rapidly charge and discharge the gate-source capacitance (CGS) to achieve fast switching.

Requirement	Circuit Element	How It Works
Fast turn-ON: rapid CGS charging	Capacitor C1 in parallel with R1	At turn-ON, C1 acts as short; full VG applied through R1 only → high initial gate current → fast charging of CGS

Steady ON state: maintain VGS	R1 + R2 after C1 charges	After C1 charges, gate current settles to low steady value through R1+R2 in series
Fast turn-OFF: rapid CGS discharge	C1 applies reverse voltage	When Vab=0, C1 voltage appears as reverse on CGS → fast discharge → quick turn-OFF
Discharge path	Resistance R2	Provides discharge path for C1 after turn-OFF

MOSFET Gate Drive Requirements

- Gate-source capacitance (CGS) must be charged quickly for fast turn-ON
- MOSFET turns ON when VGS exceeds threshold voltage VGS(th)
- To turn OFF quickly, negative gate current must discharge CGS rapidly
- Gate resistor RG limits dVGS/dt to prevent oscillations (Miller effect management)

3.6 Merits, Demerits & Applications of MOSFET

Merits of MOSFET

- Majority carrier device → no minority carrier storage
- Positive Temperature Coefficient (PTC) → easy paralleling
- Very simple voltage-controlled drive circuits
- Very short turn-ON and turn-OFF times → very high frequencies
- No commutation circuits required
- Full gate control over operation
- No second breakdown in normal operation

Demerits of MOSFET

- High RDS(on) → high conduction losses at high currents
- Limited to low-power applications (high RDS(on) at high voltage ratings)
- Susceptible to static charge damage (ESD sensitive)
- Higher gate input capacitance — drive current needed for fast switching

MOSFET Applications

- High-frequency and low-power inverters
- High-frequency Switched Mode Power Supplies (SMPS)
- High-frequency choppers
- Low-power AC and DC drives

3.7 BJT vs MOSFET — Comparison

Parameter	BJT	MOSFET
Device type	Bipolar (both carriers)	Unipolar (majority carriers only)
Control type	Current-controlled (I_B)	Voltage-controlled (V_{GS})
Drive circuit	Complex (continuous base current)	Simple (voltage only; capacitive input)
Switching speed	Moderate (storage time limits)	Very fast (no minority carrier storage)
ON-state loss	Low ($V_{CE(sat)} = 0.3\text{--}0.4\text{ V}$)	High ($I^2 \times R_{DS(on)}$; increases with voltage rating)
Temperature coefficient	Negative (paralleling difficult)	Positive (easy paralleling)
Second breakdown	Susceptible	Immune (no second breakdown)
Operating frequency	Moderate (kHz)	Very high (tens to hundreds of kHz)
Power handling	High current capable	Best for low to medium power
Commutation circuit	Not required	Not required
Cost	Lower	Higher (for same voltage rating)

SECTION 4: INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

The Best of BJT + MOSFET in a Single Device

4.1 Introduction to IGBT

The IGBT (Insulated Gate Bipolar Transistor) is the most widely used power device in modern power electronics. It combines the simple voltage-controlled gate drive of MOSFET with the low ON-state conduction losses of BJT.

MOSFET Contribution	IGBT = Combined	BJT Contribution
- Simple voltage-controlled gate - Very simple drive circuit - Fast turn-ON / turn-OFF - No base current needed	- Gate (G), Collector (C), Emitter (E) $V_{GE} > V_{GE(th)} \rightarrow$ turns ON $V_{GE} = 0 \rightarrow$ turns OFF - Gate has full control	- Low ON-state $V_{CE(sat)}$ - Handles high collector currents - PNP transistor inside structure - Minority carrier injection

4.2 Structure of IGBT

The IGBT structure is very similar to Power MOSFET, with one critical addition: a p+ collector (drain) layer added at the bottom. This p+ layer injects minority carriers (holes) into the n-drift region, creating conductivity modulation that dramatically lowers ON-state resistance.

Layer	Type	Doping Level	IGBT Function
Collector (bottom)	p+ (heavily doped)	$\sim 10^{19} / \text{cm}^3$	Injects holes into drift region $\rightarrow$ conductivity modulation $\rightarrow$ low $V_{CE(on)}$
n+ Buffer Layer (optional)	n+ (heavily doped)	—	Present in PT-IGBT (punch-through); enables faster turn-OFF
Drift Region	n ⁻ (lightly doped)	$\sim 10^{14} / \text{cm}^3$	Supports reverse voltage; undergoes conductivity modulation
Body Region	p-type	$\sim 10^{16} / \text{cm}^3$	n-channel forms here when $V_{GE} > V_{GE(th)}$
Emitter Regions	n+ (heavily doped)	$\sim 10^{19} / \text{cm}^3$	Current terminal (electron source)
Gate Oxide (SiO_2)	Insulator	N/A	Insulates gate; zero DC gate current

4.2.1 IGBT Types

PT-IGBT (Punch Through) — with n+ buffer

- Asymmetric voltage blocking capability (forward > reverse)
- Faster turn-OFF time (n+ buffer speeds up minority carrier recombination)
- Lower $V_{CE(sat)}$
- Used in choppers and inverters (unidirectional voltage)

NPT-IGBT (Non-Punch Through) — without n+ buffer

- Symmetric voltage blocking capability (forward = reverse)
- Slower turn-OFF (no buffer to accelerate carrier removal)
- Higher $V_{CE(sat)}$ than PT-IGBT
- Used in rectifiers and symmetric-blocking applications

4.2.2 IGBT Equivalent Circuit

The IGBT can be represented as a combination of a MOSFET (for gate control) driving the base of a PNP transistor (for current handling). The n-channel formed by the MOSFET short-circuits the n⁻ drift region with the n+ emitter, enabling hole injection from the p+ collector.

Conductivity Modulation in IGBT

When the IGBT turns ON, holes injected from the p+ collector flood the n-drift region. This dramatically reduces the drift region resistance (same as in power diodes and BJTs), enabling very low $V_{CE(on)}$ even for high-voltage rated IGBTs. This is the key advantage over MOSFET for high-power applications.

4.3 Steady-State (V-I) Characteristics of IGBT

The IGBT characteristics are plotted as i_D (drain/collector current) vs V_{DS} (V_{CE} — collector-emitter voltage) for various V_{GS} (V_{GE}) values.

Condition	V_{GE} Value	IGBT State	Current/Voltage
OFF State (Cut-Off)	$V_{GE} < V_{GE(th)}$	Blocking	$i_C \approx 0$; $V_{CE} = \text{supply voltage}$
ON State (Active)	$V_{GE} > V_{GE(th)}$	Conducting	i_C flows; $V_{CE} = V_{CE(on)} \approx 1.5\text{--}3\text{ V}$
Threshold	$V_{GE} = V_{GE(th)}$	Threshold transition	Channel just begins to form
Breakdown	$V_{CE} > BVDSS$ (gate open)	Damage	Irreversible breakdown — must avoid

IGBT ON-State Drop vs MOSFET

IGBT has $V_{CE(on)} \approx 1.5\text{--}3\text{ V}$ (relatively fixed, like BJT's $V_{CE(sat)}$), while MOSFET has $V_{DS(on)} = i_D \times R_{DS(on)}$ (increases quadratically with current). At high currents ($>10\text{--}20\text{ A}$), IGBT has significantly lower ON-state losses than equivalent MOSFET, making it preferred for high-power applications.

4.4 Switching Characteristics of IGBT

IGBT switching is similar to MOSFET turn-ON but has a characteristic 'current tail' during turn-OFF due to minority carrier stored charge in the drift region (like BJT).

4.4.1 Turn-ON

Phase	Gate Signal	Collector Current (i_C)	Collector-Emitter Voltage (V_{CE})	Time
Turn-ON Delay	V_{GE} rises to $V_{GE(th)}$	$i_C = 0$ (unchanged)	$V_{CE} = V_s$ (unchanged)	$t_{d(on)}$
Current Rise (t_{ri})	$V_{GE} > V_{GE(th)}$	i_C rises from 0 to full value I_o	V_{CE} still high (supply voltage)	t_{ri}
Voltage Fall (t_{fv})	V_{GE} at plateau	$i_C = I_o$ (full)	V_{CE} falls from V_s to $V_{CE(on)}$	t_{fv}
Fully ON	$V_{GE} = V_{GE(on)}$	$i_C = I_o$	$V_{CE} = V_{CE(on)}$ (low)	Steady state

Turn-ON Time

$$t_{on} = t_{d(on)} + t_{ri} + t_{fv}$$

4.4.2 Turn-OFF (with characteristic current tail)

Phase	Gate Signal	VCE Behaviour	i_C Behaviour	Time
Turn-OFF Delay	V_{GE} falls toward V_{GS1}	V_{CE} begins rising	i_C unchanged	$t_{d(off)}$
Voltage Rise	V_{GE} at V_{GS1} (saturation edge)	V_{CE} rises to V_s	i_C unchanged (still full)	t_{rv}
Fast Current Fall	V_{GE} falls below V_{GS1}	$V_{CE} \approx V_s$ (full)	i_C drops rapidly (internal MOSFET turns OFF)	t_{fi} (fast)
Current Tail (KEY!)	$V_{GE} < V_{GE(th)}$	$V_{CE} \approx V_s$	i_C decays slowly to 0 (minority carrier recombination)	tail time

Turn-OFF Time

$$t_{off} = t_{d(off)} + t_{fi} + \text{tail time}$$

Tail current is due to stored minority carriers in drift region — this makes IGBT turn-OFF slower than MOSFET

⚠ IGBT Turn-OFF Tail Current

Unlike MOSFET (no minority carriers), IGBT has a current 'tail' during turn-OFF. The p+ collector layer injects minority carriers (holes) into the drift region. These holes must recombine or be swept out before i_C reaches zero. The tail time limits IGBT switching frequency to typically 20–50 kHz (much less than MOSFET's MHz capability).

IGBT Turn-OFF Waveform (showing current tail)

```
VGE:  VGE(on)  ___|___ PLATEAU ___|___ \VGS1\ ___ 0 ___
VCE:  VCE(on)  ___|___ /trv/ ___ Vs ___
iC:   IO (full) ___|___ \tft\ I_tail \ tail ___ / ___ 0
Note: After MOSFET inside turns off (tft), minority carrier tail persists!
[Gate 0]--[td(off)]--[trv]--[tft: MOSFET off]--[TAIL: BJT off]--[Done]
```

4.5 Merits, Demerits & Applications of IGBT

Merits of IGBT

- Voltage-controlled → very simple drive circuit (like MOSFET)
- Low ON-state losses (low $V_{CE(on)}$ → like BJT)
- Higher switching frequency than thyristors
- No commutation circuits required
- Full gate control
- Approximately flat temperature coefficient → easier thermal design
- Available up to 1200 V, 400 A and beyond

Demerits of IGBT

- Current tail during turn-OFF limits switching frequency
- Slower turn-OFF than MOSFET (due to minority carrier storage)
- Susceptible to static charge (ESD sensitive)
- More expensive than BJT and MOSFET at same ratings

IGBT Applications

- AC motor drives (inverters) — most common application
- DC-to-DC power supplies (choppers)
- UPS (Uninterruptible Power Supply) systems
- Harmonic compensators and active filters
- Electric vehicle (EV) motor controllers

SECTION 5: di/dt AND dv/dt LIMITATIONS

Protection Against Switching Stress in Power Transistors

5.1 Definition and Significance

When power transistors switch, current and voltage do not change instantaneously — they have finite rates of change. Excessive rates cause device damage.

5.1.1 di/dt — Rate of Change of Current

When a BJT switches from OFF to ON, collector current rises from 0 to $I_C(\text{max})$ in rise time t_r . The rate of rise is di/dt .

di/dt Definition

$$di/dt = I_C(\text{max}) / t_r \quad [\text{A/s or A/}\mu\text{s}]$$

During turn-ON: $V_{CE} = V_s$, $i_C = 0$ initially; as base drive applied, i_C rises at rate di/dt

⚠ Why Excessive di/dt is Dangerous

A fast rate of rise of collector current (high di/dt) causes localized heating within the transistor. If di/dt exceeds the device rating, the transistor can be permanently damaged. This is particularly critical in BJTs due to current crowding effects.

5.1.2 dv/dt — Rate of Change of Voltage

When a BJT switches from ON to OFF, collector-emitter voltage rises from $V_{CE(\text{on})} \approx 0$ to V_s in fall time t_f . The rate of rise is dv/dt .

dv/dt Definition

$$dv/dt = V_s / t_f \quad [\text{V/s or V/}\mu\text{s}]$$

During turn-OFF: i_C falls, V_{CE} rises. Fast rise = high dv/dt = potential device damage

⚠ Why Excessive dv/dt is Dangerous

A fast rate of rise of collector-emitter voltage (high dv/dt) may cause false triggering, capacitive displacement currents, and can damage the transistor. In thyristors, high dv/dt can cause false turn-ON even without gate signal.

5.2 Protection Against di/dt and dv/dt

Snubber circuits are used to limit di/dt (during turn-ON) and dv/dt (during turn-OFF).

5.2.1 di/dt Protection — Series Inductance (L_s)

A series inductor L_s limits the rate of rise of current during turn-ON. The inductor opposes instantaneous changes in current.

di/dt with L_s

$$di/dt = V_s / L_s \quad \Rightarrow \quad L_s = V_s / (di/dt)_{\max}$$

L_s is chosen so that di/dt stays within device rating

5.2.2 dv/dt Protection — RC Snubber (C_s , R_s , D_s)

A capacitor C_s (with series diode D_s) is placed across the transistor. During turn-OFF, C_s acts as a short initially (through D_s), absorbing the rising voltage slowly.

Snubber Time Constant

$$R_s \times C_s < (1/3) \times t_{\text{switching}}$$

R_s limits discharge current when transistor turns ON (C_s discharges through transistor and R_s)

Component	Role During Turn-OFF	Role During Turn-ON
C_s (Snubber capacitor)	Acts as short through $D_s \rightarrow$ absorbs voltage rise $\rightarrow$ reduces dv/dt	Discharges through transistor and $R_s \rightarrow$ energy dissipated in R_s
D_s (Snubber diode)	Allows C_s to charge quickly without R_s impedance in series	Blocks during C_s discharge (C_s discharges only through R_s)
R_s (Snubber resistor)	Not in series during turn-OFF (bypassed by D_s)	Limits discharge current of C_s to protect transistor
L_s (Series inductor)	No effect during turn-OFF (current is falling)	Limits di/dt during turn-ON; protects against current surge

Snubber Design Summary

The RC snubber (C_s , R_s , D_s) limits dv/dt during turn-OFF by providing a low-impedance path for displacement current. The series L_s limits di/dt during turn-ON. Together, they form a complete protection scheme. The energy stored in L_s and C_s is eventually dissipated in R_s — this is a loss mechanism that reduces overall efficiency slightly.

SECTION 6: ISOLATION OF GATE AND BASE DRIVES

Pulse Transformers · Optocouplers · Necessity of Isolation

6.1 Necessity of Electrical Isolation

Drive/trigger circuits operate at very low voltage levels (3–12 V). Power devices operate at high voltage levels (100s of volts). Direct connection creates a serious safety and reliability problem:

⚠ Risk Without Isolation

If BJT collector-base junction is damaged and shorts internally, the high collector voltage (e.g., 200 V) will directly appear on the trigger circuit (designed for 5 V). This destroys the entire trigger/control board — cascading failure!

Therefore: Electrical isolation **MUST** be provided between low-power control circuits and high-power switching circuits.

6.2 Isolation Using Pulse Transformers

A pulse transformer has one primary winding (connected to trigger circuit) and one or more secondary windings (connected to gate/base of power device). Electrical isolation is achieved through magnetic coupling — no direct electrical connection.

Advantages

- No external power supply required for isolation
- Very simple to implement
- Can drive multiple gates with one primary (multiple secondaries)
- Good for high-frequency pulsed triggering
- Provides galvanic isolation — no DC path

Disadvantages

- Saturates at low frequencies → only suitable for high-frequency operation
- Signal distortion due to magnetic coupling (waveform not perfectly preserved)
- Bulky at low frequencies (large core needed)
- Cannot transmit DC signals

6.3 Isolation Using Optocouplers

An optocoupler consists of an infrared LED and a phototransistor housed in the same package with an optical (light) link between them. Electrical isolation is achieved through photon transmission — zero electrical connection between input and output.

6.3.1 Structure and Operation

Component	Material/Type	Function
Infrared LED (Input side)	GaAs / AlGaAs LED	Converts electrical input signal to infrared light pulses
Optical cavity	Transparent medium	Transmits infrared light from LED to phototransistor
Phototransistor (Output side)	Si phototransistor	Converts received light back to electrical current; isolates output

6.3.2 Optocoupler Gate Drive Circuit Operation

V _g (Input)	LED State	Phototransistor State	Transistor T1 State	MOSFET Gate	MOSFET State
V _g > 0 (positive)	LED turns ON; emits IR	Phototransistor conducts	T1 base → 0 V; T1 turns ON	VCC applied to gate	MOSFET turns ON
V _g = 0 (zero)	LED turns OFF; no IR	Phototransistor OFF	T1 base → VCC; T1 turns OFF	Gate voltage → 0	MOSFET turns OFF

Advantages of Optocoupler

- Excellent response at low frequencies (from DC to moderate frequencies)
- Compact — available in small IC packages
- Low cost — optocoupler ICs are widely available
- Complete electrical isolation (no magnetic coupling)
- Can transmit both DC and pulse signals
- Simple circuit implementation

Disadvantages of Optocoupler

- Requires external biasing power supply for output side
- Poor high-frequency response (switching speed limited by phototransistor response time)
- LED degrades over time → reduced light output → reliability concern
- Propagation delay between input and output

Optocoupler Applications

- Inverters (PWM gate drive isolation)
- Switched Mode Power Supplies (SMPS)
- DC choppers
- AC motor drives

6.4 Pulse Transformer vs Optocoupler — Comparison

Parameter	Pulse Transformer	Optocoupler
Isolation mechanism	Magnetic (inductive coupling)	Optical (photon coupling)
External power required	No	Yes (for output/phototransistor side)
Low frequency response	Poor (saturates at low freq)	Excellent (down to DC)
High frequency response	Excellent	Limited (phototransistor speed)
Signal distortion	Some (magnetic coupling)	Minimal
Size	Larger at low frequencies	Compact (IC package)
DC signal transmission	No	Yes
Cost	Higher	Lower
Multiple outputs	Yes (multiple secondaries)	One output per optocoupler
Applications	High-frequency pulsed triggering	General purpose; DC + pulse isolation

End of Module 2 Notes

Power Electronics (BEE503) | Dept. of EEE, ATMECE, Mysuru

POWER ELECTRONICS

BEE503

MODULE 3

Thyristors

SCR · GTO · LASCR · RCT · TRIAC · DIAC · Series/Parallel · Firing Circuits · UJT

Syllabus — Module 3

- Introduction to Thyristors: Structure, Symbol, Terminal Identification
- Static V-I Characteristics of SCR: Reverse Blocking, Forward Blocking, Forward Conduction
- Latching Current and Holding Current
- Two-Transistor Model of Thyristor
- Thyristor Turn-ON: 5 methods and Dynamic Turn-ON Characteristics
- Thyristor Turn-OFF: Natural & Forced Commutation, Dynamic Turn-OFF Characteristics
- Thyristor Types: GTO, LASCR, RCT, TRIAC, DIAC
- Series & Parallel Operation: Problems, Equalization, String Efficiency
- di/dt and dv/dt Protection: Snubber Circuits, Series Inductance
- Firing Circuits: R, RC, Full-Wave RC; Features of Firing Circuits
- UJT Triggering Circuit: Operation, Relaxation Oscillator, Mathematical Analysis

Dept. of Electrical & Electronics Engineering
ATME College of Engineering, Mysuru

SECTION 1: INTRODUCTION TO THYRISTORS

Four-Layer PNPN Semiconductor Switching Device

1.1 What is a Thyristor?

A thyristor is a four-layer, three-junction PNPN semiconductor switching device with three terminals. It is the most fundamental member of the thyristor family and is widely known as the Silicon Controlled Rectifier (SCR).

Terminal	Connected To	Symbol	Function
Anode (A)	Outer p-region	A	Main positive current terminal
Cathode (K)	Outer n-region	K	Main negative current terminal
Gate (G)	Inner p-region	G	Control terminal — triggers turn-ON

SCR Internal Structure

- Four semiconductor layers: P–N–P–N
- Three PN junctions: J1 (P1-N1), J2 (N1-P2), J3 (P2-N2)
- J1 and J3 are in same direction; J2 opposes
- Silicon used for construction
- Operates as a rectifier — controlled by gate

SCR Ratings & Cooling

- Voltage rating: up to 10 kV
- RMS current rating: up to 3000 A
- Power handling: up to 30 MW
- Mounted on heat sinks for better cooling
- Unlike diodes, blocks current until triggered by gate

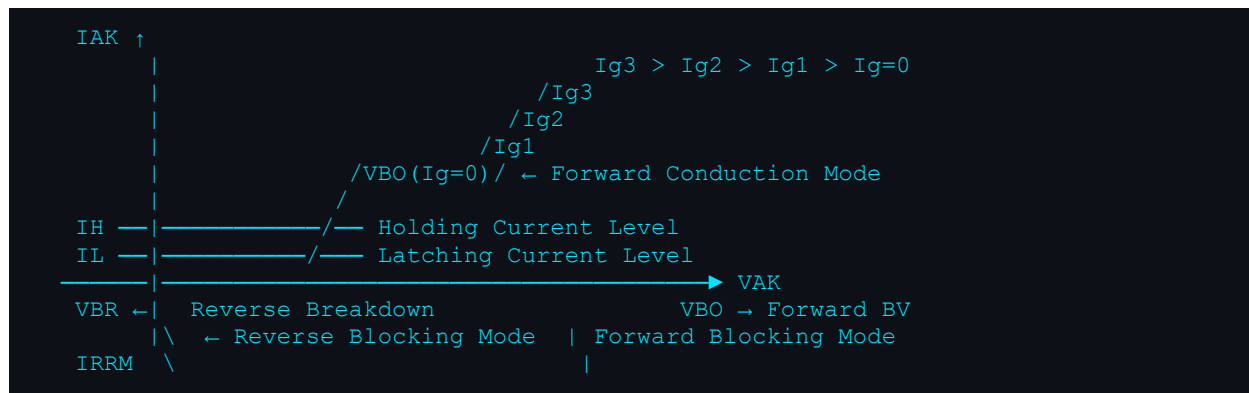
SCR vs Diode — Key Difference

A power diode conducts whenever forward biased ($V_{AK} > 0.7 \text{ V}$). An SCR, however, remains in the forward blocking state even when forward biased until a gate signal is applied. Gate controls the turn-ON; but once turned ON, gate loses control. The SCR can only be turned OFF by reducing anode current below holding current.

1.2 Static V-I Characteristics of SCR

The static V-I characteristic plots Anode-to-Cathode current (I_A) against Anode-to-Cathode voltage (V_{AK}) for various gate currents (I_{g1} , I_{g2} , I_{g3}). Three distinct operating modes are observed.

SCR Static V-I Characteristic — Schematic Representation



Parameter	Symbol	Typical Value	Significance
Forward Breakover Voltage	VBO	600 V – 10 kV (device rating)	VAK at which SCR turns ON without gate (avoided in normal operation)
Reverse Breakdown Voltage	VBR	Similar to VBO	VAK at which reverse current increases rapidly — causes damage
Latching Current	IL	10–15 mA	Min. forward current at triggering to stay ON — must be exceeded
Holding Current	IH	8–10 mA	Min. forward current in ON state — drops below this → turns OFF
Forward ON-state voltage drop	VT	1–2 V	Voltage across SCR when fully conducting
Reverse Leakage Current	IRRM	Very small (μ A)	Current in reverse blocking mode — must remain below rated value

1.3 Operating Modes of SCR

Mode 1: Reverse Blocking Mode

Condition: Anode (A) negative with respect to Cathode (K); Gate open.

Junction	Bias State	Effect on Current
J1 (P1–N1)	Reverse biased	Blocks forward current flow
J2 (N1–P2)	Forward biased	Allows some leakage
J3 (P2–N2)	Reverse biased	Blocks forward current flow

- Only reverse leakage current flows (cathode to anode direction — very small).
- At reverse breakdown voltage (V_{BR}): reverse current increases rapidly → excessive power dissipation → thyristor damaged.

- Positive gate signal in reverse mode should NOT be applied — it increases reverse leakage and dissipation.

⚠ Reverse Blocking Warning

The thyristor MUST NOT be subjected to reverse voltage exceeding VBR. Doing so causes irreversible thermal damage due to massive reverse current and junction temperature exceeding the maximum permissible value.

Mode 2: Forward Blocking Mode

Condition: Anode (A) positive with respect to Cathode (K); Gate open; $V_{AK} < V_{BO}$.

Junction	Bias State	Effect
J1 (P1–N1)	Forward biased	Allows carrier movement
J2 (N1–P2)	Reverse biased	BLOCKS forward current — SCR stays OFF
J3 (P2–N2)	Forward biased	Allows carrier movement

- SCR is forward biased but does NOT conduct — J2 acts as blocking junction.
- Only a very small forward leakage current flows (order of milliamperes).
- V_{AK} can be increased up to V_{BO} — at V_{BO} , SCR automatically turns ON (even without gate) due to avalanche breakdown of J2.

💡 VBO Turn-ON is Safe

Unlike reverse breakdown (which damages SCR), exceeding V_{BO} simply turns the SCR ON — it does NOT damage it. The device transitions from forward blocking to forward conduction mode. However, uncontrolled V_{BO} triggering is not preferred; gate triggering is the standard method.

Mode 3: Forward Conduction Mode

Condition: Gate pulse applied (or $V_{AK} \geq V_{BO}$); Anode positive with respect to Cathode.

- SCR conducts current from anode to cathode with a very small forward voltage drop (1–2 V).
- SCR behaves like a closed switch — anode current limited by load impedance only.
- Voltage drop increases slightly with increasing anode current (ohmic drop across four layers).
- Once conducting, GATE LOSES CONTROL — cannot be used to turn OFF the SCR.
- SCR turns OFF only when: (a) anode current falls below I_H (natural commutation), or (b) external forced commutation reverses anode-cathode voltage.

1.4 Latching Current (I_L) vs Holding Current (I_H)

Latching Current (I_L) $\approx 10\text{--}15\text{ mA}$

The minimum forward current that must flow through the thyristor at the instant of triggering (gate pulse) to ensure it stays in the ON state after the gate pulse is removed.

- Relevant at: Turn-ON instant only
- If $I_{AK} < I_L$ when gate pulse applied $\rightarrow$ SCR does NOT latch ON
- $I_L > I_H$ always (latching > holding)

Holding Current (I_H) $\approx 8\text{--}10\text{ mA}$

The minimum forward current that must continue to flow through the thyristor to keep it in the ON state once already conducting.

- Relevant at: During conduction (turn-OFF condition)
- If I_{AK} falls below $I_H \rightarrow$ SCR turns OFF automatically
- $I_H < I_L$ always (holding < latching)

SECTION 2: TWO-TRANSISTOR MODEL OF THYRISTOR

Explaining Regenerative (Latching) Action via PNP–NPN Pair

2.1 Formation of the Two-Transistor Model

The PNPN thyristor structure can be split at the middle two layers, yielding two coupled transistors: a PNP transistor (T1) and an NPN transistor (T2). This model elegantly explains how the thyristor turns ON and stays latched.

Transistor	Type	Emitter	Base	Collector	Connected To
T1	PNP	P1 (Anode side)	N1	P2	Base of T1 ↔ Collector of T2
T2	NPN	N2 (Cathode side)	P2	N1	Base of T2 ↔ Collector of T1

Regenerative (Positive Feedback) Action

The collector of T1 drives the base of T2, and the collector of T2 drives the base of T1. This creates a regenerative feedback loop. Once $(\alpha_1 + \alpha_2)$ approaches unity, the loop gain exceeds 1 and the thyristor switches ON suddenly — latching into full conduction.

2.2 Mathematical Analysis

Let I_D = total anode-to-cathode current; α_1 = current gain of T1 (PNP); α_2 = current gain of T2 (NPN); I_{CBO1} , I_{CBO2} = leakage currents of T1 and T2 respectively.

T1 Collector Current	$I_{C1} = \alpha_1 \cdot I_D + I_{CBO1}$
-----------------------------	--

T2 Collector Current	$I_{C2} = \alpha_2 \cdot I_D + I_{CBO2}$
-----------------------------	--

KCL at Node	$I_D = I_{C1} + I_{C2} = \alpha_1 \cdot I_D + I_{CBO1} + \alpha_2 \cdot I_D + I_{CBO2}$
--------------------	---

Total Thyristor Current	$I_D = (I_{CBO1} + I_{CBO2}) / [1 - (\alpha_1 + \alpha_2)] \quad \leftarrow \text{Key equation}$
--------------------------------	--

Analysis of the Key Equation

- When $(\alpha_1 + \alpha_2) \rightarrow 0$ (gate open, low VAK): $I_D \approx I_{CBO1} + I_{CBO2}$ = small leakage current $\rightarrow$ Forward Blocking Mode
- When $(\alpha_1 + \alpha_2) \rightarrow 1$ (gate pulse or high VAK): denominator $\rightarrow 0$, so $I_D \rightarrow \infty \rightarrow$ SCR turns ON, current limited by external circuit only
- Gate current (I_G) adds to base of T2, increasing α_2 , making $(\alpha_1 + \alpha_2) \rightarrow 1 \rightarrow$ triggers turn-ON at lower VAK
- Once ON, $(\alpha_1 + \alpha_2) > 1$ and the SCR latches — gate loses control completely

SECTION 3: THYRISTOR TURN-ON AND TURN-OFF

Dynamic Characteristics · Methods · Timing

3.1 Methods of Turning ON a Thyristor

Method	Trigger Mechanism	Practical Use	Notes
1. Gate Drive (Preferred)	Positive gate-cathode voltage ($V_{GK} > 0$)	Standard method — all converters	Pulsed gate drive preferred to reduce gate losses
2. High Forward Voltage	VAK exceeds VBO (forward breakover)	Not used intentionally	Uncontrolled; used as overvoltage protection in some cases
3. dv/dt Triggering	Rapid rate of rise of VAK — internal capacitive current	Undesired (accidental turn-ON)	Must be avoided; use snubber circuits to limit dv/dt
4. Light (Photo-triggering)	Light beam on gate-cathode junction	LASCR only	Induces electron-hole pairs; provides optical isolation
5. High Temperature	Elevated junction temperature increases leakage	Undesired (thermal runaway)	Junction temperature must be controlled by heat sinking

★ Gate Triggering is the Standard Method

In all practical converter circuits, gate triggering is the only controlled method. A short positive gate pulse is sufficient to trigger the SCR — the gate does not need continuous drive after turn-ON. Pulsed gate drive is preferred over DC gate bias to minimize power dissipation in the gate-cathode junction.

3.2 Turn-ON Dynamic Characteristics

When a gate pulse is applied at $t = 0$, the SCR transitions from forward blocking to full conduction through three distinct phases.

Phase	Time Period	IAK Behaviour	VAK Behaviour	Physical Process	Turn-ON Effect
Delay Time (t_d)	0 to t_d	Rises slowly; flows near gate region only	Remains at forward blocking value	Electron-hole pairs being injected near J3 by gate current	Current spreads from gate vicinity outward

Rise Time (tr)	td to td+tr	Rises rapidly to full ON value	Falls rapidly from VBO toward VT (1–2V)	Avalanche breakdown of J2 propagates; current spreads	Large $V \times I$ product → HIGH switching loss
Spread Time (tp)	tr to tr+tp	Reaches maximum (load-limited)	Falls to minimum (1–2 V)	Conduction spreads across full junction area	Device fully conducting; dissipation reduces

Turn-ON Time

$$t_{on} = t_d + t_r + t_p \quad [\text{typically } 1\text{--}3 \mu\text{s}]$$

t_{on} = time from gate drive initiation to IAK reaching full ON value; switching loss occurs during tr

Switching Loss During Rise Time

During rise time (tr), both high voltage ($V_{AK} \approx V_{BO}$) and high current (IAK rising rapidly) co-exist in the thyristor. The resulting instantaneous power = $V_{AK} \times I_{AK}$ is very large. This is called switching loss. Higher gate current reduces tr, lowering switching loss.

How to Reduce Turn-ON Time

- Apply higher gate current (IG) — more electron-hole pairs injected near J3 → faster J2 avalanche breakdown
- Higher IG → faster rise time (tr) → reduced total ton
- High di/dt limit still applies — series inductance Ls limits current rise rate
- Typical ton range: 1–3 microseconds for standard SCRs

3.3 Thyristor Turn-OFF Methods

Natural Commutation

- Supply voltage becomes zero or negative naturally
- SCR becomes reverse biased → turns OFF
- Applicable in AC circuits only (supply reverses every half cycle)
- No external components needed — simplest turn-OFF
- Example: AC regulators, controlled rectifiers from AC supply

Forced Commutation

- Used when DC supply is present (voltage never reverses naturally)
- External commutation components used to temporarily reverse anode-cathode voltage
- OR: negative current impulse injected through SCR to bring IAK below IH
- More complex — requires LC commutation circuit or forced current reversal

- Example: DC choppers, DC motor drives, inverters

3.4 Turn-OFF Dynamic Characteristics

The SCR turn-OFF process requires that the reverse voltage be held across the SCR for a sufficient duration (turn-off time t_q) to completely restore forward blocking capability.

Phase	Duration	IAK Behaviour	Physical Process
Conduction (before turn-OFF)	—	Positive; full ON	SCR flooded with minority carriers; acts as short circuit
Reverse Recovery (trr)	~5–100 μ s	Goes NEGATIVE briefly	Negative current removes excess carriers from J1 and J3; these junctions recover blocking capability
Gate Recovery (tgr)	part of tq	IAK returns to zero	Excess carriers near J2 recombine; if negative voltage removed too early, J2 carriers act as gate drive → SCR re-triggers!
Fully OFF (end of tq)	—	IAK = 0; VAK = -VR	All junctions recover; forward blocking capability restored

Turn-OFF Time	$t_q = t_{rr} + t_{gr}$ [typically 5-200 μs] <i>t_q = total time from commutation initiation to full forward blocking capability restoration</i>
---------------	--

Circuit Turn-OFF Condition	$t_c > t_q$ [Circuit turn-off time MUST exceed device turn-off time] t_c = time for which commutation circuit holds reverse voltage across SCR; if $t_c < t_q \rightarrow$ SCR re-triggers
-----------------------------------	---

SCR Turn-OFF Dynamic Waveform

Circuit Turn-Off Time Requirement

The commutation circuit must maintain reverse voltage across the SCR for a duration t_c greater than the device turn-off time t_q . If $t_c < t_q$, excess carriers near J2 are not fully recombined —

they act as internal gate drive and the SCR spontaneously turns back ON (false turn-ON), causing converter malfunction.

SECTION 4: THYRISTOR FAMILY — TYPES AND CHARACTERISTICS

GTO · LASCR · RCT · TRIAC · DIAC

4.1 Overview of Thyristor Family

Device	Full Name	Terminals	Conduction Direction	Key Feature	Gate Control
SCR	Silicon Controlled Rectifier	A, K, G	Unidirectional (A→K)	Latching; gate triggers only	Turn-ON only
GTO	Gate Turn-Off Thyristor	A, K, G	Unidirectional (A→K)	Gate can turn ON and OFF	Full gate control
LASCR	Light Activated SCR	A, K, G (photosensitive)	Unidirectional (A→K)	Light-triggered gate	Turn-ON by light
RCT	Reverse Conducting Thyristor	A, K, G	Bidirectional (SCR + anti-parallel diode)	Built-in feedback diode	SCR gate (forward only)
TRIAC	Bidirectional Triode Thyristor	MT1, MT2, G	Bidirectional	Equivalent to 2 anti-parallel SCRs	Both half-cycles
DIAC	Bidirectional Trigger Diode	T1, T2 (no gate)	Bidirectional	No control terminal	Self-triggering at VBO

4.2 Gate Turn-Off Thyristor (GTO)

The GTO overcomes the major limitation of SCR — the need for external commutation circuits. In GTO, the gate has full control: it can turn the device both ON (positive gate pulse) and OFF (negative gate pulse).

4.2.1 Structural Differences from SCR

GTO vs SCR — Key Structural Differences

- Gate and cathode are highly interdigitated (comb-like geometry) — maximizes cathode periphery and minimizes gate-to-cathode distance for better turn-OFF control
- Anode shorts: n⁺ regions at regular intervals in the p⁺ anode layer make direct contact with n-drift region — speeds up carrier recombination during turn-OFF
- Reduced regenerative gain: pnp transistor gain (α_1) is deliberately reduced — makes $(\alpha_1 + \alpha_2) < 1$ achievable with negative gate current, enabling gate turn-OFF

4.2.2 GTO V-I Characteristics

Direction	Characteristic	Key Detail
Forward Direction	Similar to SCR	Turns ON with positive gate pulse; same forward conduction characteristics
Reverse Direction	Virtually no blocking capability	Anode short structure makes reverse breakdown voltage only 20–30 V; GTO conducts in reverse after very small reverse voltage
Result: Asymmetric voltage blocking	Forward: high BV; Reverse: ~20–30 V only	GTO has asymmetric voltage blocking — NOT suitable where high reverse voltage must be blocked

GTO Advantages

- Higher voltage blocking capability
- Full gate control — turn ON and OFF
- Low ON-state losses
- High surge current ratio (ITSM/IT)
- High ON-state current gain
- No commutation circuits required

GTO Limitations

- Requires very large negative gate current for turn-OFF → high gate drive power
- Very small reverse voltage blocking capability (~20–30 V)
- Low switching frequency capability
- Gate drive circuit is complex and lossy

GTO Applications

- Motor drives (mainly induction heating and variable speed drives)
- Low-power converter applications
- Where SCR commutation circuits would be too complex or bulky

4.3 Light Activated SCR (LASCR)

The LASCR uses a beam of light to trigger conduction. The gate region is made photosensitive (usually a window in the package allows light to reach the junction).

LASCR Turn-ON Mechanism

Photons of light strike the gate-cathode junction (J3). The photon energy induces electron-hole pairs in the depletion region. These free carriers start current flow across J3, which acts exactly like a conventional gate current. Once sufficient photocurrent flows, the regenerative turn-ON process begins and the LASCR switches ON fully. After turn-ON, gate (light) has no further control — same as SCR.

LASCR Advantages

- Complete electrical isolation between control circuit and power circuit
- No electrical connection to gate — driven by light
- Immune to noise (optical triggering ignores electrical interference)
- Ideal for high-voltage applications where isolation is critical

LASCR Applications

- HVDC (High Voltage DC) transmission systems
- Static VAR compensation (SVC/FACTS devices)
- High-power applications in electrically noisy environments
- Multiple series-connected SCRs (light-triggered simultaneously)

4.4 Reverse Conducting Thyristor (RCT)

An RCT integrates an SCR with an anti-parallel diode within the same silicon wafer. It is also called Asymmetric SCR (ASCR) or Thyristor with Built-In Diode.

Direction	Device Active	Characteristics	Control
Forward (A→K)	SCR portion conducts	Controlled by gate — same as standard SCR characteristics	Gate controls turn-ON
Reverse (K→A)	Anti-parallel diode conducts	Uncontrolled diode conduction — similar to power diode reverse characteristics	No control — automatically conducts

RCT Applications & Benefits

- Chopper circuits: freewheeling diode function built into the same device — saves space and reduces thermal resistance
- Inverter circuits: anti-parallel diode provides return path for reactive current from inductive loads
- Reduces external component count and improves converter reliability
- Higher forward current capability than equivalent separate SCR + diode combination

4.5 TRIAC (Bidirectional Triode Thyristor)

The TRIAC is equivalent to two anti-parallel SCRs with a single shared gate terminal. It can conduct current in BOTH directions, making it ideal for AC power control applications.

Terminal	Name	Function
MT1	Main Terminal 1	One main current terminal (analogous to cathode reference)
MT2	Main Terminal 2	Other main current terminal (analogous to anode)

G	Gate	Single gate terminal controls conduction in both directions
---	------	---

Half Cycle	MT2 vs MT1	Conducting Device	Gate Required	Current Direction
Positive half cycle	MT1 is positive	First SCR (equivalent) conducts	Positive gate pulse	MT1 → MT2
Negative half cycle	MT2 is positive	Second SCR (equivalent) conducts	Gate pulse (either polarity usually)	MT2 → MT1
Turn-OFF	Current falls to zero naturally	Both SCRs OFF	Not required	Zero crossing = automatic turn-OFF

TRIAC Merits

- Bidirectional — conducts in both directions
- Turns OFF automatically at zero current crossing (natural commutation)
- Single gate controls conduction in both half-cycles
- Available in high voltage and current ratings
- Eliminates need for anti-parallel SCR pairs

TRIAC Demerits

- Latching device like SCR — not suitable for DC applications
- Gate loses control after turn-ON
- Very low switching frequencies
- Not suitable for high-power, high-frequency converters
- Reverse voltage blocking limited (like GTO)

TRIAC Applications

- AC power controllers (light dimmers, fan speed controllers, heater regulators)
- Motor speed controllers for AC induction and universal motors
- Used as triggering device for other SCRs in AC circuits
- Domestic appliance control: washing machines, mixers, power tools

4.6 DIAC

The DIAC (Diode for Alternating Current) is a two-terminal, four-layer bilateral trigger device. It has NO gate terminal and NO control — it self-triggers at VBO in either polarity. Primarily used to trigger TRIACs.

Parameter	Details
Terminals	T1 and T2 only — no gate, no polarity (interchangeable)

Conduction	Bidirectional — triggers at VBO in both positive and negative voltage
V-I Characteristics	Exactly symmetric for positive and negative voltages/currents
Turn-ON Mechanism	Voltage exceeds VBO (breakover) → DIAC turns ON → voltage drops to near zero
Turn-OFF	Current falls below holding current → DIAC turns OFF
Primary Use	Triggering TRIACs — provides sharp, reliable trigger pulse at fixed VBO

DIAC + TRIAC Combination

DIAC is almost always used in conjunction with TRIAC in phase control circuits. The RC phase-shift network charges a capacitor. When capacitor voltage reaches VBO of DIAC, it fires and delivers a sharp trigger pulse to the TRIAC gate. This gives precise, repeatable firing angles in both half-cycles.

SECTION 5: SERIES & PARALLEL OPERATION OF THYRISTORS

Voltage Sharing · Current Sharing · String Efficiency · Equalization

5.1 Necessity of Series/Parallel Connection

Series Connection — Purpose

- Required when operating voltage exceeds single thyristor rating
- Example: System needs 1000 V; available thyristors rated 600 V
- Solution: Connect 2 thyristors in series → each handles 500 V
- Increases effective voltage rating of the string

Parallel Connection — Purpose

- Required when load current exceeds single thyristor rating
- Example: Circuit current = 80 A; available thyristors rated 50 A
- Solution: Connect 2 thyristors in parallel → each carries 40 A
- Increases effective current rating of the string

5.2 Series Connection of Thyristors

5.2.1 Problem: Voltage Imbalance

Even thyristors of the same rating have slight differences in forward breakover voltage, internal resistance, leakage current, and turn-ON/OFF timing. This causes unequal voltage sharing in series connection.

Why Voltage Imbalance Occurs

- The thyristor with the HIGHEST internal resistance has the MINIMUM leakage current in the OFF state.
- With lower leakage current, less current flows through the string → higher voltage drops across that device.
- This thyristor may exceed its rated VBO while others are still well below their ratings → catastrophic failure of one device, then overstressing the rest.

5.2.2 Static Equalization — Resistor Method

An equalizing resistor R is connected in parallel with each thyristor. This forces equal voltage distribution in the static (steady-state OFF) condition.

**Voltage Across T1
(highest resistance)**

$$VD1 = VD2 + \Delta ID \times R$$

ΔID = difference in leakage currents; $VD2$ = voltage across other thyristors

Equalizing Resistance Value

$$R = [(n-1) \times V_D(\max)] / [n \times \Delta I_D(\max)]$$

n = number of thyristors in series; $V_D(\max)$ = maximum allowable voltage per device

5.2.3 Dynamic Equalization — RC Circuit Method

During turn-ON and turn-OFF transients, thyristors with different switching times see voltage imbalance even if static equalization is perfect. The thyristor that turns ON LAST sees full supply voltage briefly.

Component	Connected	Purpose During Turn-ON/OFF
Capacitor C1	Across each thyristor	Absorbs voltage transient; provides equalization during switching; slows rate of voltage rise across slow-switching thyristor
Resistor R1	In series with C1	Limits the discharge current of C1 when thyristor turns ON (prevents excessive di/dt from capacitor discharge)

Value of C1

$$C1 = \Delta Q / \Delta V = \Delta I_D \times \Delta t / \Delta V$$

ΔI_D = difference in off-state currents; ΔV = allowable voltage imbalance

Voltage Imbalance

$$\Delta V = \Delta I_D \times R \quad (\text{static case})$$

5.2.4 String Efficiency and Derating Factor

String Efficiency (η)

$$\eta = V_{\text{string}} / (n \times V_{\text{device}}) \times 100\%$$

V_{string} = total voltage across string; n = number of devices; V_{device} = individual device voltage rating

Derating Factor (D)

$$D = 1 - \eta \quad \text{OR} \quad D = (n \times V_{\text{device}} - V_{\text{string}}) / (n \times V_{\text{device}})$$

D = fraction by which the string is derated from ideal; lower D = better utilization

String Efficiency Insight

In an ideal string of n thyristors, total voltage = $n \times V_{\text{device}}$ and efficiency = 100%. In practice, due to non-uniform voltage sharing, string efficiency is less than 100%. Higher equalizing resistance R improves voltage balance (improves η) but increases power loss. Design is a trade-off between efficiency and equalization quality.

5.3 Parallel Connection of Thyristors

5.3.1 Problem: Current Imbalance

Thyristors in parallel do not share current equally because their forward voltage drops differ slightly. The device with the lower forward drop carries more current — causing thermal runaway.

Thermal Runaway Mechanism in Parallel Connection

T1 carries more current → more power dissipation → temperature rises
 Higher temperature → internal resistance reduces (NTC behaviour)
 Lower resistance → even more current flows through T1
 Cycle repeats: more current → more heat → less resistance → MORE current
 Result: T1 is destroyed; T2 then overloaded → catastrophic failure

5.3.2 Equalization Methods for Parallel Connection

Method	How It Works	Advantage	Disadvantage
Common Heat Sink	All thyristors mounted on shared heat sink; temperature equalized	Simple; maintains equal junction temperature; passive	Does not directly equalize current — only thermal
Static Current Sharing (Series Resistors)	Resistors R1, R2 in series with each thyristor; higher current device sees higher voltage drop → reduces its current	Positive feedback control; simple	High power loss in R1, R2 — very inefficient
Dynamic Current Sharing (Coupled Inductors)	Inductors L1, L2 in series; magnetically coupled with opposing polarity	If $I(T1)$ increases, L2 sees opposing EMF → forces $I(T2)$ to increase; actively balances currents	More complex; uses transformer-like coupling; effective for fast transients

SECTION 6: di/dt AND dv/dt PROTECTION

Snubber Circuits · Series Inductance · Overcurrent Protection

6.1 di/dt Protection

At the instant of SCR turn-ON, gate current triggers conduction near the gate region first. The anode current has not yet spread across the full junction area. This localized high current density creates hot spots.

di/dt Damage Mechanism

During turn-ON, anode current rises rapidly. The current spreads from the gate area outward — this spreading takes time (spread time t_p). If di/dt is too high, the initial high current density at the small conduction area near the gate creates local hot spots. If junction temperature in these hot spots exceeds maximum permissible value, the thyristor is permanently damaged.

di/dt Limitation

$$di/dt = V_s / L \rightarrow L = V_s / (di/dt)_{\text{rated}}$$

A series inductance L_s limits di/dt ; L includes stray inductance of the circuit

Component	Location	Function
Series Inductor (L_s)	In series with SCR and load	Opposes rapid rise of anode current; limits di/dt to safe level
Stray Inductance	Inherent in PCB/wiring	Provides some natural di/dt limiting — should be accounted for in L calculation

6.2 dv/dt Protection — Snubber Circuits

Rapid rate of rise of anode-cathode voltage (dv/dt) can turn ON the SCR without a gate signal. This is because the SCR junction capacitance passes a displacement current $i = C(dv/dt)$ which acts like a gate current, triggering spurious turn-ON.

6.2.1 Basic RC Snubber

An RC snubber network is connected in parallel across the SCR. It acts as a low-pass filter for voltage transients.

Event	Snubber Behaviour	Protection Provided
-------	-------------------	---------------------

Voltage transient across SCR	Capacitor C absorbs the spike (charges up); R limits peak charging current	Transient voltage is diverted away from SCR terminals
dv/dt exceeds limit	Capacitor acts as short for high dv/dt; slows the voltage rise	Limits rate of voltage rise; prevents spurious turn-ON
SCR turns ON	Capacitor discharges through SCR and R	R limits discharge current (protects SCR from di/dt due to C discharge)

6.2.2 RC Snubber with Diode (Preferred Circuit)

A diode D is added in parallel with R to improve snubber effectiveness.

Component	During Voltage Transient/dv/dt	During SCR Turn-ON
Capacitor (C)	Charges through D (diode); voltage rise across SCR is limited	Discharges through R into SCR
Diode (D)	Forward biased: C charges quickly WITHOUT R in series → very fast snubbing	Reverse biased: blocks; C must discharge through R only
Resistor (R)	Not in series during charging (bypassed by D) → maximum snubbing speed	In series during discharge; limits discharge di/dt; dissipates C energy

Snubber Design — dv/dt limit	$dv/dt = (1/C) \times i_{max} \rightarrow C = i_{max} / (dv/dt)_{rated}$
-------------------------------------	--

Snubber Discharge Time Constant	$\tau = R \times C$ should be $\leq t_{switching} / 3$ <i>R is chosen so C fully discharges in less than 1/3 of minimum ON time</i>
--	--

💡 RC + Diode Snubber is Preferred

The R-C-D (Resistor-Capacitor-Diode) snubber is the most commonly used protection circuit for thyristors in practice. The diode ensures maximum effectiveness during transients (bypassing R for fast charging), while R controls the energy during discharge when the thyristor turns ON.

6.3 Overcurrent Protection

Short circuit conditions (shorted load, misaligned firing pulses, device failure) can generate current levels far exceeding thyristor ratings. Standard circuit breakers are too slow.

Protection Method	Response Time	How It Works	Limitation
-------------------	---------------	--------------	------------

Fast-Acting Fuse (HRC)	Very fast (μs –ms)	Melts at current below SCR rating; disconnects circuit before SCR is damaged	Must be replaced after operation; choose rating carefully
Current limiting reactor	Immediate (passive)	Series inductance limits di/dt and peak fault current	Adds cost, weight, and voltage drop
Gate inhibit circuit	Fast (μs)	Monitoring circuit detects overcurrent and immediately disables gate pulses	Only effective for turn-ON; cannot protect already-conducting SCR

⚡ Fuse Selection Rule

The fast-acting fuse must be rated such that: (1) it does NOT blow during normal load currents or allowable surge currents, and (2) it DOES blow before the SCR is damaged during fault conditions. The I^2t (current-squared-time) rating of the fuse must be less than the I^2t rating of the SCR.

SECTION 7: THYRISTOR FIRING CIRCUITS

R-Firing · RC-Firing · UJT Triggering Circuit

7.1 Features of Firing Circuits

Firing circuits (triggering circuits) generate gate pulses at the correct instants to control thyristor conduction. A complete firing system consists of: control circuit → pulse amplifier → isolation circuit → thyristor gate.

Required Features of a Firing Circuit

- Must produce triggering pulses for EACH thyristor at the correct (desired) firing angle α
- Must provide gate pulses of sufficient voltage ($> V_{GT}$) and current ($> I_{GT}$) to ensure reliable turn-ON
- Gate pulse power is small — must be amplified by pulse amplifier before isolation circuit
- Electrical isolation MUST be provided (firing circuit operates at 5–20 V; thyristor at 250+ V)
- Isolation achieved by pulse transformer or optocouplers
- Must be synchronized with supply frequency (zero-crossing reference)
- Gate pulse width must be sufficient to ensure I_{AK} exceeds latching current I_L

7.2 R-Firing Circuit

Simplest firing circuit. Uses a resistor R in series with the gate to limit gate current. The supply voltage directly drives the gate through R .

Parameter	Description
Circuit Elements	R (variable resistor) in series with gate G ; voltage divider from supply to gate-cathode
Firing Angle Control	Vary R → change gate current → limited firing angle range
Firing Angle Range	0° to $\sim 90^\circ$ only (limited — only positive half-cycle triggering)
Advantage	Simple; low cost; minimal components
Disadvantage	Very limited firing angle range; sensitive to supply voltage variations; poor isolation

7.3 RC-Firing Circuit

Adds a capacitor C in series with R to provide phase-shift capability, extending the firing angle range beyond 90° .

Parameter	Description
Circuit Elements	R and C in series; gate triggered when capacitor voltage $V_G > V_{GT}$
Firing Angle Control	Vary R $\rightarrow$ change RC time constant $\rightarrow$ change phase angle of gate voltage
Firing Angle Range	0° to $\sim 180^\circ$ (wider than R-firing)
Advantage	Better range; phase shift provided by RC circuit
Disadvantage	Firing angle sensitive to supply voltage variations; poor for large loads

7.4 Full-Wave RC-Firing Circuit

A full-wave rectifier is added before the RC circuit to provide DC-referenced gate pulses for both positive and negative half-cycles in AC power control applications.

Parameter	Description
Circuit Elements	Full-wave bridge rectifier + R + C + isolation transformer to gate
Firing Angle Control	R controls phase shift for both half-cycles simultaneously
Firing Angle Range	0° to $\sim 180^\circ$ for both half-cycles
Advantage	Symmetric firing in both half-cycles; improved performance over half-wave RC
Use	AC regulators, TRIAC firing circuits

SECTION 8: UNIJUNCTION TRANSISTOR (UJT) TRIGGERING CIRCUIT

Relaxation Oscillator · Synchronized Firing · Mathematical Analysis

8.1 Introduction to UJT

The Unijunction Transistor (UJT) is a three-terminal semiconductor device used primarily as a relaxation oscillator for generating trigger pulses. It is NOT an amplifier device.

Terminal	Name	Symbol	Function
E	Emitter	E	Main control terminal — connected to capacitor
B1	Base-1	B1	Lower base terminal — output pulse taken here
B2	Base-2	B2	Upper base terminal — connected to positive supply

UJT Key Parameters

- Intrinsic Standoff Ratio (η): $\eta = RB1/(RB1+RB2)$ — typically 0.5 to 0.8
- Peak Voltage (V_P): $V_P = \eta \times V_{BB} + V_D$ where $V_D \approx 0.7 \text{ V}$ (forward diode drop)
- Valley Voltage (V_V): Voltage at which UJT turns OFF (very low, $\sim 1\text{--}2 \text{ V}$)
- When $V_E = V_P$: UJT turns ON abruptly; emitter-B1 junction breaks down $\rightarrow$ heavy current flows through B1

8.2 UJT Triggering Circuit — Construction

The UJT firing circuit consists of: AC supply $\rightarrow$ Full-wave rectifier $\rightarrow$ Zener regulator $\rightarrow$ UJT relaxation oscillator $\rightarrow$ Pulse transformer $\rightarrow$ SCR gate.

Block	Components	Function
Power Supply & Rectifier	AC input + Full-wave diode bridge	Converts AC to pulsating DC
Zener Voltage Regulator	Zener diode (V_Z)	Clamps pulsating DC to fixed Zener voltage V_Z — provides stable supply for UJT circuit
UJT Relaxation Oscillator	Capacitor C (charges through RC); UJT (E, B1, B2)	Generates periodic trigger pulses at frequency determined by RC time constant
Pulse Output	Primary of pulse transformer connected B1-to-ground	Current pulse through B1 induces trigger pulse in secondary $\rightarrow$ applied to SCR gate

Synchronization	Zener voltage becomes zero at supply zero-crossings ($0, \pi, 2\pi, \dots$)	Capacitor voltage also resets to zero at supply zero-crossings $\rightarrow$ firing synchronized to supply
-----------------	---	--

8.3 UJT Relaxation Oscillator — Operation

The UJT acts as a relaxation oscillator — it repeatedly charges and discharges a capacitor to generate periodic output pulses.

Phase	Capacitor Voltage V_E	UJT State	Current Through B1	Output Pulse
Charging	V_E rises from V_V toward V_P	OFF (blocking)	Zero — no current through B1	No trigger pulse
At Peak Voltage V_P	$V_E = V_P = \eta \cdot V_{BB} + V_D$	Turns ON (breaks down)	Heavy current: B1 current spike	TRIGGER PULSE generated $\rightarrow$ drives SCR gate via pulse transformer
Discharge	V_E falls rapidly from V_P to V_V	ON (conducting)	Current flows; energy in C dissipated	Pulse ends as C discharges
At Valley Voltage V_V	$V_E = V_V$	Turns OFF	Current reduces below valley current	No pulse; C begins charging again
Repeat	Cycle repeats with period T	—	—	Continuous stream of trigger pulses

UJT Relaxation Oscillator Waveforms

V_Z (supply): 0 V_{BB} 0 V_{BB}
 V_E (cap): V_V V_P V_V V_P V_V V_P
 V_{B1} (pulses): $t=0$ α π 2π $2\pi+\alpha$ $2\pi+\pi$ 4π
 Firing angle α is varied by changing RC (charging resistor value)

8.4 Firing Angle Control

The delay angle α (firing angle) is the angle at which the first trigger pulse is generated in each half-cycle. It is controlled by varying the charging resistance R_C .

Capacitor Charging Equation	$V_E(t) = V_Z \cdot (1 - e^{-(t/RC)})$ $V_Z = \text{Zener voltage (= effective supply); } RC = R \times C = \text{time constant}$
At Turn-ON: $V_E = V_P$	$V_Z \cdot (1 - e^{-(t_{on}/RC)}) = V_P \rightarrow t_{on} = RC \cdot \ln[V_Z / (V_Z - V_P)]$
Firing Angle α	$\alpha = \omega \cdot t_{on} = \omega \cdot RC \cdot \ln[V_Z / (V_Z - V_P)] \quad [\text{radians}]$ $\omega = 2\pi f = \text{angular frequency; } \alpha \text{ can be varied } 0^\circ \text{ to } 180^\circ \text{ by adjusting } RC$
Oscillation Frequency	$f = 1/T \approx 1 / (RC \cdot \ln[1/(1-\eta)])$ $\eta = \text{intrinsic standoff ratio; } T = \text{period of relaxation oscillation}$

RC Value	Time to reach V_P	Firing Angle α	SCR Conduction Angle	Output Power
Small RC	Short (fast charging)	Small α (early firing)	Large (long conduction)	High output power
Large RC	Long (slow charging)	Large α (late firing)	Small (short conduction)	Low output power

8.5 Synchronization with Supply

The Zener voltage V_Z becomes zero at every zero-crossing of the supply (0° , 180° , 360° ...). At these instants, the capacitor voltage also resets to zero because the Zener supply drops to zero. This automatic reset synchronizes the firing circuit with the supply frequency.

Advantages of UJT Triggering Circuit

- Wide firing angle range: 0° to 180° (full range)
- Automatic synchronization with supply zero-crossings
- Sharp, well-defined trigger pulses (fast rise time $\rightarrow$ reliable SCR turn-ON)
- Simple, low-cost circuit
- Can be used for 1Φ controlled converters and 1Φ AC regulators
- RC value easily adjustable — simple firing angle control

UJT Circuit Applications

- 1Φ Half-wave and full-wave controlled rectifiers
- 1Φ AC voltage regulators
- TRIAC firing circuits
- DC motor speed control via SCR

UJT Circuit Limitations

- Only suitable for single-phase (1Φ) applications
- Firing angle stability affected by temperature (V_Z and V_P both vary with temperature)

- Battery chargers with voltage regulation

- Not suitable for 3 Φ firing (needs separate circuit for each phase)
- Pulse width is fixed by RC — not adjustable independently

End of Module 3 Notes

Power Electronics (BEE503) | Dept. of EEE, ATMECE, Mysuru

POWER ELECTRONICS

BEE503

MODULE 4

Controlled Rectifiers & AC Voltage Controllers

1 Φ Half-Wave · Semi-Converter · Full-Converter · Dual Converter · Phase Control · AC Controllers

Part A — Controlled Rectifiers

- 1 Φ Half-Wave: R, RL, and RLE Loads
- Freewheeling Diode with RL Load
- Single-Phase Semi-Converter (Half-Bridge)
- Single-Phase Full Converter with R, RL, RLE Loads
- Continuous and Ripple-Free Current Mode
- Single-Phase Dual Converters
- Three-Phase Dual Converters

Part B — AC Voltage Controllers

- Principle of Phase Control
- Principle of Integral Cycle Control
- 1 Φ Half-Wave Controller (Phase Control)
- 1 Φ Full-Wave Controller — R Load
- 1 Φ Full-Wave Controller — RL Load
- 3 Φ Full-Wave AC Voltage Controllers
- Advantages, Disadvantages & Applications

Dept. of Electrical & Electronics Engineering
ATME College of Engineering, Mysuru

SECTION 1: INTRODUCTION TO CONTROLLED RECTIFIERS

AC-to-DC Converters with Adjustable Output Voltage

1.1 What is a Controlled Rectifier?

A controlled rectifier is a power electronic circuit that converts AC voltage to DC voltage, where the output DC voltage magnitude is controllable. The control is achieved by varying the triggering angle (firing angle) α of the thyristors used in the circuit.

Input	Control	Output
Fixed AC mains (1 Φ or 3 Φ supply)	Firing angle α (0° to 180°)	Adjustable DC voltage $V_o = f(\alpha)$

Parameter	Uncontrolled Rectifier	Controlled Rectifier
Devices used	Diodes only	Thyristors (SCRs)
Output voltage	Fixed (depends on input only)	Adjustable (varies with firing angle α)
Control	None — fully uncontrolled	Gate firing angle α provides full control
Power flow	Unidirectional only	Can be bidirectional (dual converter)
Typical applications	Fixed DC supplies, battery chargers	DC motor drives, variable DC power supplies

Applications of Controlled Rectifiers

- DC motor speed control (most common application)
- Battery chargers with controlled charging current/voltage
- Adjustable DC power supplies for industrial equipment
- HVDC transmission systems
- Electrochemical processes (electroplating, electrolysis)
- UPS (Uninterruptible Power Supply) charging circuits

SECTION 2: SINGLE-PHASE HALF-WAVE CONTROLLED RECTIFIER

R Load · RL Load · Freewheeling Diode · RLE Load

2.1 Circuit Configuration

The single-phase half-wave controlled rectifier consists of one thyristor (SCR T1) connected in series between the AC supply (through a transformer) and the load. The gate of T1 is controlled by the firing circuit.

Circuit Elements

Supply: $V_s = V_m \sin(\omega t)$ where V_m = peak supply voltage, ω = angular frequency

Element	Connection	Function
Transformer	Primary to AC mains; Secondary to SCR	Provides isolation; steps up/down voltage to required level
SCR T1	Series with load (anode to supply +ve)	Controls power flow — conducts only when triggered at angle α
Load	Series with T1 (R, RL, or RLE)	Consumes DC power; type determines current waveform shape

2.2 With Resistive (R) Load

2.2.1 Operation

Period	Supply V_s	SCR T1 State	Output V_o	Output Current i_o
0 to α	Positive, rising	Forward biased but NOT triggered	$V_o = 0$	$i_o = 0$
α to π	Positive	Triggered at $\alpha \rightarrow$ Conducts	$V_o = V_s = V_m \sin(\omega t)$	$i_o = V_s/R = V_m \sin(\omega t)/R$
π	Zero crossing	Supply voltage = 0 $\rightarrow$ $i_o = 0 \rightarrow$ T1 turns OFF naturally	$V_o = 0$	$i_o = 0$ (natural commutation)
π to 2π	Negative half cycle	T1 is reverse biased — does NOT conduct	$V_o = 0$	$i_o = 0$
Next cycle	Positive again	T1 triggered again at α	Repeats	Repeats

Key Observation — R Load

For resistive load, output current i_o is exactly proportional to output voltage V_o at all times ($i_o = V_o/R$). Therefore the waveforms of V_o and i_o are identical in shape. SCR turns OFF naturally at π every cycle — no forced commutation needed. Ripple frequency = supply frequency (only one pulse per cycle).

2.2.2 Performance Equations — R Load

Output Voltage (avg)

$$V_{dc} = (V_m/2\pi) \times (1 + \cos \alpha)$$

$V_m = \text{peak supply voltage}; \alpha = \text{firing angle}$

RMS Output Voltage

$$V_{rms} = (V_m/2) \times \sqrt{[(\pi - \alpha)/\pi + \sin(2\alpha)/(2\pi)]}$$

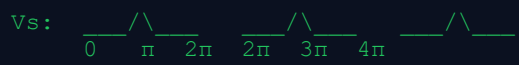
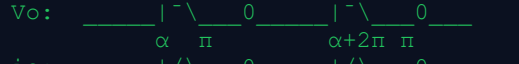
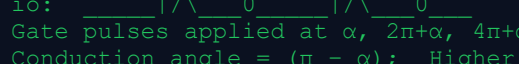
Average Output Current

$$I_{dc} = V_{dc} / R = (V_m/2\pi R) \times (1 + \cos \alpha)$$

Ripple Frequency

$$f_{ripple} = f_{supply} \quad (\text{one pulse per AC cycle})$$

1Φ Half-Wave R Load — Waveforms

V_s :  (supply sinusoid)
 V_o :  (output = V_s from $\alpha \rightarrow \pi$)
 i_o :  ($i_o = V_o/R$; same shape)
 Gate pulses applied at $\alpha, 2\pi + \alpha, 4\pi + \alpha \dots$
 Conduction angle = $(\pi - \alpha)$; Higher $\alpha \rightarrow$ lower V_{dc}

2.3 With RL Load

2.3.1 Operation

Inductance in the load causes the output current i_o to lag behind the output voltage. Crucially, i_o continues flowing even after V_s goes negative (after π), because the inductor's stored energy maintains it.

Period	Supply V_s	SCR T1 State	Output V_o	Output Current i_o	Energy Source
0 to α	Positive	Forward biased, not triggered	0	0	—
α to π	Positive	Triggered at $\alpha \rightarrow$ Conducting	$V_o = V_s$ (positive)	Rises slowly (L opposes change)	Supply
π	Zero	$V_s = 0$; but $L \times di/dt$ keeps T1 ON	0 momentarily	At maximum (peak)	Inductor
π to β	NEGATIVE	T1 still ON! (inductor maintains forward current)	$V_o = V_s$ (NEGATIVE)	Decreasing (but >0)	Inductor energy partially fed back to supply

β (extinction angle)	Negative	i_o reaches 0 $\rightarrow$ T1 turns OFF naturally	$V_o = 0$	$i_o = 0$	—
β to $2\pi + \alpha$	Negative then positive	T1 off; reverse biased then forward biased	$V_o = 0$	0	—

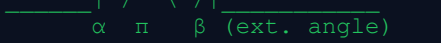
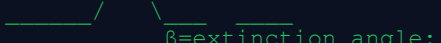
⚡ Inductor Effect — Extended Conduction Beyond π

The critical difference with RL load vs R load: SCR T1 does NOT turn off at π . The inductor acts as an energy source and keeps T1 conducting into the negative half-cycle (from π to β). During this period, output voltage V_o is NEGATIVE. This reduces the average output voltage V_{dc} compared to the R-load case. The extinction angle β depends on L/R ratio — higher L $\rightarrow$ larger $\beta \rightarrow$ more negative V_o area $\rightarrow$ lower V_{dc} .

2.3.2 Key Equations — RL Load

Load Impedance	$Z = \sqrt{R^2 + (\omega L)^2}$; $\phi = \tan^{-1}(\omega L/R)$ (load angle)
Instantaneous Current	$i_o(t) = (V_m/Z) \times [\sin(\omega t - \phi) - \sin(\alpha - \phi) \times e^{(-R(t-\alpha)/\omega)/L}]$ Valid from α to β
Extinction Angle β	Solve: $\sin(\beta - \phi) = \sin(\alpha - \phi) \times e^{(-R(\beta-\alpha)/(\omega L))}$ (transcendental – solve numerically)
Average Output Voltage	$V_{dc}(RL) = (V_m/2\pi) \times [\cos(\alpha) - \cos(\beta)]$ Lower than R-load case because $\beta > \pi$; negative V_o area reduces average

1 Φ Half-Wave RL Load — Waveforms

V_s :  (supply sinusoid)
 V_o :  V_o NEGATIVE from π to β !
 i_o :  i_o starts at α , peaks after π
 β = extinction angle: $i_o \rightarrow 0$; T1 turns OFF
 $\beta > \pi$ always for RL load (extends into negative half cycle)
 Higher L/R ratio $\rightarrow$ larger $\beta \rightarrow$ more negative $V_o \rightarrow$ lower V_{dc}

2.4 With RL Load and Freewheeling Diode (FWD)

2.4.1 Circuit Modification

A freewheeling diode DFW (also called bypass diode or commutation diode) is connected in anti-parallel across the RL load. This prevents the negative output voltage problem seen with RL load.

Period	Supply Vs	SCR T1	Freewheeling Diode DFW	Output Vo	io Path
α to π	Positive	ON (conducting)	Reverse biased (OFF)	$V_o = V_s$ (positive)	Supply $\rightarrow$ T1 – Load $\rightarrow$ Supply
π to $2\pi + \alpha$	Negative	Tries to turn OFF	DFW becomes forward biased $\rightarrow$ turns ON	$V_o \approx 0$ (clamped)	Inductor $\rightarrow$ DFW $\rightarrow$ Load (circulating)
$2\pi + \alpha$	Supply goes positive again	Re-triggered at $2\pi + \alpha$	DFW reverse biased $\rightarrow$ turns OFF	$V_o = V_s$ again	Supply $\rightarrow$ T1 – Load $\rightarrow$ Supply

☑ Four Key Advantages of Freewheeling Diode

- Prevents negative output voltage across load — output voltage V_o is clamped to zero when negative
- Maintains continuity of load current — i_o flows continuously through DFW during negative half-cycle
- Circulates inductor energy within load circuit — does not feed back to supply
- Helps commutate SCR T1 — when DFW turns ON, it imposes near-zero voltage across T1, reducing its reverse recovery stress

Output Voltage with FWD

$$V_{dc} (FWD) = (V_m/2\pi) \times (1 + \cos \alpha)$$

Same as R-load formula — negative V_o is eliminated by DFW clamping

1 Φ Half-Wave RL+FWD — Waveforms

2.5 With RLE Load

RLE load includes a back-EMF source (E) in series with R and L . This represents a DC motor load where E is the back-EMF (CEMF) of the motor.

Condition	Behaviour	Significance
E = 0 (motor at standstill)	Same as RL load; T1 fires when $V_s > 0$ at angle α	Normal RL load behavior

$E > 0$ (motor running)	T1 can only turn ON when $V_s > E$ i.e. when $V_m \sin(\alpha) > E$	Minimum firing angle $\alpha_{min} = \sin^{-1}(E/V_m)$
$\alpha < \alpha_{min}$	$V_s < E$ at firing instant $\rightarrow$ T1 does not fire (reverse biased)	SCR cannot fire below minimum angle
$\alpha > \alpha_{min}$	$V_s > E$ at $\alpha \rightarrow$ T1 turns ON; current flows charging motor	Normal controlled operation

Minimum Firing Angle

$$\alpha_{min} = \sin^{-1}(E / V_m)$$

$E = \text{back-EMF}$; $V_m = \text{peak supply voltage}$; α_{min} ensures $V_s > E$ at firing

Output Voltage (avg)

$$V_{dc} = (V_m/2\pi) \times [\cos(\alpha) - \cos(\beta)] - E$$

$\beta = \text{extinction angle}$; net V_{dc} must exceed E for current to flow

RLE Load — DC Motor Application

In a DC motor drive, E represents the back-EMF (proportional to motor speed). As motor accelerates, E increases. The controlled rectifier adjusts firing angle α to maintain the desired current and hence torque. When α is decreased, V_{dc} increases $\rightarrow$ more current $\rightarrow$ more torque $\rightarrow$ motor accelerates. This is the fundamental principle of DC motor speed control using thyristor converters.

SECTION 3: SINGLE-PHASE SEMI-CONVERTER (HALF-CONTROLLED)

2 SCRs + 2 Diodes · Inherent Freewheeling · R and RL Loads

3.1 Circuit Configuration

The single-phase semi-converter (half-controlled bridge rectifier) uses two thyristors (T1, T2) and two diodes (D1, D2) in a bridge arrangement. It is cheaper than a full converter as it uses only two SCRs, but has inherent freewheeling action.

Device	Position in Bridge	Conduction Half-Cycle	When Triggered/Conducts
SCR T1	Upper left arm	Positive half-cycle	Triggered at α in positive half-cycle (with D2 in lower right)
Diode D2	Lower right arm	Positive half-cycle	Conducts automatically with T1 during positive half-cycle
SCR T2	Upper right arm	Negative half-cycle	Triggered at $\pi + \alpha$ in negative half-cycle (with D1 in lower left)
Diode D1	Lower left arm	Negative half-cycle	Conducts automatically with T2 during negative half-cycle

3.2 Operation with Resistive Load

Period	Conducting Devices	Current Path	Output V_o	$i_o = V_o/R$
0 to α	None (T1 not yet triggered)	No path	0	0
α to π	T1 and D2	AC(+) $\rightarrow$ T1 $\rightarrow$ Load $\rightarrow$ D2 $\rightarrow$ AC(-)	$V_o = V_s$ (positive)	Rising then falling with V_s
π to $\pi + \alpha$	No SCR (both T1, T2 off; no negative drive)	$V_o = 0$ (R load turns off naturally at π)	0	0
$\pi + \alpha$ to 2π	T2 and D1	AC(-) $\rightarrow$ D1 $\rightarrow$ Load $\rightarrow$ T2 $\rightarrow$ AC(+)	$V_o = V_s $ (still positive!)	Positive, same shape
2π to $2\pi + \alpha$	Off again	—	0	0

💡 Key Feature of Semi-Converter

In the semi-converter, output voltage V_o is ALWAYS positive (never goes negative) because: in positive half-cycle T1-D2 provide positive V_o ; in negative half-cycle T2-D1 still provide positive

V_o (polarity is flipped by bridge). This gives TWO pulses per cycle — double the ripple frequency of half-wave rectifier. Output resembles full-wave rectification but with controlled firing angle.

**Output Voltage (avg) —
R Load**

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

Two pulses per cycle; ripple frequency = $2 \times$ supply frequency

3.3 Operation with RL Load — Continuous Current Mode

For RL load with continuous conduction, the load current flows without interruption. Each SCR fires at its designated angle and the outgoing SCR is commutated naturally by the incoming SCR.

Period	Firing Event	Devices Conducting	V_o	i_o
0 to α	Waiting for T1 trigger	Freewheeling through bridge diodes	≈ 0 (FWD clamping)	Continuous at previous level
α to π	T1 triggered	T1 + D2	$V_o = V_s$ (positive)	Increases (supply drives load)
π to $\pi + \alpha$	T1 still ON (RL load)	T1 + D2 (inductor keeps T1 on briefly)	V_o goes slightly negative	Decreasing but continuous
$\pi + \alpha$	T2 triggered	T2 fires, naturally commutates T1	T2 + D1 now	Continues smoothly
$\pi + \alpha$ to 2π	T2 + D1 conducting	T2 + D1	$V_o = V_s $ (positive)	Continuous

**Output Voltage — RL
Continuous Mode**

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

Same formula; continuous current means no extinction angle problem

Semi-Converter Advantages

- Only 2 SCRs needed (lower cost than full converter)
- Inherent freewheeling — no need for external FWD
- Output voltage never goes negative (single quadrant)
- Two-pulse output — less ripple than half-wave
- Simple control circuit

Semi-Converter Limitations

- Single-quadrant operation only (V_o always +ve, i_o always +ve)
- No regenerative (braking) capability
- Limited to applications where power reversal is not needed
- Higher ripple than full converter

SECTION 4: SINGLE-PHASE FULL CONVERTER

4-SCR Full Bridge · R Load · RL Load · RLE Load · Continuous Mode

4.1 Circuit Configuration

The single-phase full converter (fully controlled bridge rectifier) uses four thyristors in a bridge arrangement. All four SCRs are controlled, enabling full control of output voltage including negative V_{dc} for regenerative operation.

SCR Pair	Conducts During	Firing Angle	Current Path
T1 and T2	Positive half-cycle (0 to π)	Triggered at α	AC(+) $\rightarrow$ T1 $\rightarrow$ Load $\rightarrow$ T2 $\rightarrow$ AC(-)
T3 and T4	Negative half-cycle (π to 2π)	Triggered at $\pi + \alpha$	AC(-) $\rightarrow$ T3 $\rightarrow$ Load $\rightarrow$ T4 $\rightarrow$ AC(+)

Full Converter vs Semi-Converter

In the full converter, ALL four devices are SCRs — there are no uncontrolled diodes. This means output voltage CAN go negative (when $\alpha > 90^\circ$). This enables REGENERATIVE operation (power fed back to supply) — essential for DC motor 4-quadrant drives. The semi-converter cannot go negative.

4.2 With Resistive (R) Load

4.2.1 Positive Half-Cycle (T1-T2 conducting)

Period	T1-T2 State	Supply V_s	Output V_o	Supply Current i_s	Load Current i_o
0 to α	Not triggered	Positive	0	0	0
α to π	Triggered at α ; conducting	Positive: $V_m \sin(\omega t)$	$V_o = V_s = V_m \sin(\omega t)$	$i_s = i_o$ (same loop)	$i_o = V_o/R$
π	Supply crosses zero	$V_s = 0$	0	0	0 (R load)

4.2.2 Negative Half-Cycle (T3-T4 conducting)

Period	T3-T4 State	Supply V_s	Output V_o	Supply Current i_s	Load Current i_o
--------	-------------	--------------	--------------	----------------------	--------------------

π to $\pi+\alpha$	Not triggered	Negative	0	0	0
$\pi+\alpha$ to 2π	Triggered at $\pi+\alpha$	Negative: $V_m \sin(\omega t)$ (negative)	$V_o = V_s =$ positive!	$i_s = -i_o$ (opposite)	$i_o = V_o/R$ (positive)

Output Voltage (avg) — R Load

$$V_{dc} = (2V_m/\pi) \times \cos(\alpha)$$

Two pulses per cycle; valid for α from 0° to 90° (positive V_{dc} range)

RMS Output Voltage

$$V_{rms} = V_m \times \sqrt{[(1/2\pi) \times ((\pi-\alpha) + \sin(2\alpha)/2)]}$$

Ripple Frequency

$$f_{\text{ripple}} = 2 \times f_{\text{supply}} \quad (\text{two pulses per cycle})$$

Higher ripple frequency $\rightarrow$ smaller filter inductance needed

4.3 With RL Load — Continuous Conduction

For large inductive loads, the load current i_o flows continuously without reaching zero. This simplifies analysis significantly.

Period	Active SCR Pair	Output V_o	i_o Behaviour	$i_s = ?$
α to π	T1 and T2	$V_o = V_s$ (positive)	Increasing gradually (supply drives it)	$i_s = +i_o$
π to $\pi+\alpha$	T1 and T2 (still ON due to L)	$V_o = V_s$ (negative)	Decreasing but continuous (L maintains it)	$i_s = +i_o$ (against V_s)
$\pi+\alpha$	T3-T4 triggered	Commutates T1-T2	i_o continues without interruption	—
$\pi+\alpha$ to 2π	T3 and T4	$V_o = V_s =$ positive	Increasing again	$i_s = -i_o$ (reversal in supply)
2π	T1-T2 triggered again	—	Continuous cycle repeats	—

Output Voltage — RL Continuous Mode

$$V_{dc} = (2V_m/\pi) \times \cos(\alpha)$$

Same formula as R load; valid when load current is continuous

Output Current (avg)

$$I_{dc} = (V_{dc} - E) / R \quad \text{for RLE load} \quad \text{OR} \quad I_{dc} = V_{dc} / R \quad \text{for R load}$$

4.4 Ripple-Free (Large Inductive) Load

When load inductance L is very large ($L \rightarrow \infty$), the ripple in i_o becomes negligible. Load current is essentially constant $DC = I_{dc}$. This simplifies the analysis: $i_o = I_{dc} = \text{constant}$.

Large Inductance Simplifications

Parameter	With Large L	Without Large L
i_o waveform	Perfectly flat $DC = I_{dc}$ (no ripple)	Pulsating (follows V_o shape partly)
i_s waveform	Square wave alternating $+I_{dc}$ and $-I_{dc}$ at each firing	Non-sinusoidal but pulsating
Fourier analysis of i_s	Fundamental + odd harmonics only	Complex harmonic content
Average V_o	$(2V_m/\pi) \times \cos \alpha$ — unchanged	Same formula but instantaneous varies
Filter required	Minimal (L already provides filtering)	External LC filter often needed

Supply Current (large L)

$i_s = +I_{dc}$ from α to $\pi + \alpha$; $i_s = -I_{dc}$ from $\pi + \alpha$ to $2\pi + \alpha$
Square wave; displacement angle = α

Power Factor

$PF = V_{dc} \times I_{dc} / (V_{s_rms} \times I_{s_rms}) = (2\sqrt{2}/\pi) \times \cos(\alpha) \times (1/\sqrt{2})$
Decreasing as α increases

4.5 Full Converter with RLE Load — DC Motor Drive

The RLE load represents a DC motor: R = armature resistance, L = armature inductance, E = back-EMF.

Operating Mode	α Range	V_{dc}	i_a (armature current)	Power Flow	Quadrant
Rectification (motoring)	0° to 90°	Positive (+)	Positive (+)	AC supply $\rightarrow$ DC Motor	Quadrant 1
Inversion (regeneration)	90° to 180°	Negative (–)	Positive (+) (continuous)	DC Motor $\rightarrow$ AC supply (braking)	Quadrant 2

⚙️ Two-Quadrant Operation of Full Converter

The full converter operates in Quadrants 1 and 2. In Q1 ($\alpha < 90^\circ$): $V_{dc} > 0$, $i_a > 0$ — motor runs forward with motoring torque. In Q2 ($\alpha > 90^\circ$): $V_{dc} < 0$, $i_a > 0$ (kept positive by inductive load) — motor acts as generator returning power to the supply (regenerative braking). For full four-quadrant operation, a DUAL CONVERTER is required.

SECTION 5: SINGLE-PHASE AND THREE-PHASE DUAL CONVERTERS

Four-Quadrant DC Motor Drive · Circulating & Non-Circulating Current Modes

5.1 What is a Dual Converter?

A dual converter consists of TWO fully controlled converters connected in anti-parallel across the same load. Converter 1 provides positive output voltage ($V_{dc} > 0$) and Converter 2 provides negative output voltage ($V_{dc} < 0$). Together they enable full four-quadrant operation.

Converter 1 (P-converter)

- Provides positive output: $+V_{dc}$
- Firing angle: α_1
- Motor forward motoring (Q1)
- Motor reverse regeneration (Q2)

Converter 2 (N-converter)

- Provides negative output: $-V_{dc}$
- Firing angle: $\alpha_2 = \pi - \alpha_1$
- Motor reverse motoring (Q3)
- Motor forward regeneration (Q4)

Quadrant	V_{dc}	I_a	Motor Operation	Active Converter
Q1 (Forward Motoring)	$+ V_{dc}$	$+ I_a$	Forward speed, forward torque	Converter 1 ($\alpha_1 < 90^\circ$)
Q2 (Forward Braking/Regen)	$- V_{dc}$	$+ I_a$	Forward speed, reverse torque (braking)	Converter 2 ($\alpha_2 > 90^\circ$)
Q3 (Reverse Motoring)	$- V_{dc}$	$- I_a$	Reverse speed, reverse torque	Converter 2 ($\alpha_2 < 90^\circ$)
Q4 (Reverse Braking/Regen)	$+ V_{dc}$	$- I_a$	Reverse speed, forward torque (braking)	Converter 1 ($\alpha_1 > 90^\circ$)

5.2 Operating Modes of Dual Converter

Mode 1 — Without Circulating Current

- Only ONE converter operates at a time (never both simultaneously)
- Inter-converter reactor NOT needed (no simultaneous conduction)
- Transition between converters: outgoing converter gates inhibited, incoming converter gates enabled

Mode 2 — With Circulating Current

- BOTH converters operate simultaneously at all times
- Inter-converter reactor (L_r) is ESSENTIAL — limits circulating current
- Firing angle constraint: $\alpha_1 + \alpha_2 = \pi$ (to make instantaneous voltages equal)
- Faster response — no dead-time delay during quadrant changeover

- Dead time: brief pause during switchover to prevent short circuit
- Slower response due to dead-time delay
- More economical (no reactor needed)

- More expensive (reactor + larger SCR ratings needed)
- Continuous and smooth transition between quadrants

Circulating Current Mode Constraint

$$\alpha_1 + \alpha_2 = \pi \rightarrow \alpha_2 = \pi - \alpha_1$$

This ensures: $V_{dc1} = -V_{dc2}$ i.e. both converters give same magnitude output

Instantaneous Voltage Constraint

$$v_P(t) + v_N(t) = 0 \quad \text{at all times (ideally)}$$

In practice: small instantaneous voltage difference $\rightarrow$ circulating current through reactor L_r

⚠ Circulating Current Limitation

Even with $\alpha_1 + \alpha_2 = \pi$, the instantaneous output voltages of the two converters are not perfectly equal due to ripple. The difference ($v_P - v_N$) drives a circulating current through the inter-converter reactor L_r . The reactor L_r limits this circulating current to a safe value. Without L_r , the circulating current would be extremely large (effectively a short-circuit between converters).

5.3 Three-Phase Dual Converter

The three-phase dual converter uses two three-phase fully controlled bridge converters connected in anti-parallel. It provides much higher power capability than single-phase dual converters.

Feature	1 Φ Dual Converter	3 Φ Dual Converter
Number of SCRs	8 (4 per converter)	12 (6 per converter)
Ripple frequency	$2 \times 50 \text{ Hz} = 100 \text{ Hz}$	$6 \times 50 \text{ Hz} = 300 \text{ Hz}$ (much smoother)
Power rating	Low to medium	High power (MW range)
Output smoothness	Requires larger filter	Naturally smoother output
Applications	Small DC motor drives	Large DC motor drives, HVDC, rolling mills

Half-Cycle	Converter 1 (α_1)	Converter 2 ($\alpha_2 = \pi - \alpha_1$)	SCRs Active (P-group)	SCRs Active (N-group)
Positive half-cycle at Converter 1	T1, T3 conduct (with 3 Φ supply)	T5, T6 conduct	T1, T3	T5, T6
Negative half-cycle at Converter 1	T3, T4 conduct	T7, T8 conduct	T3, T4	T7, T8

Dual Converter Applications

- High-power DC motor drives requiring four-quadrant operation
- Rolling mills in steel plants (forward/reverse with braking)
- Cranes and hoists (lowering = regenerative braking)
- Elevators and traction systems
- Not recommended for low-power applications (high cost of two full converters + reactor)

SECTION 6: AC VOLTAGE CONTROLLERS — INTRODUCTION

AC-to-AC Power Control · Phase Control · Integral Cycle Control

6.1 What is an AC Voltage Controller?

An AC voltage controller (AC voltage regulator) is a power electronic circuit that converts fixed AC input voltage to a variable AC output voltage of the SAME frequency. The magnitude of output voltage is controlled by varying the firing angle α of the thyristors.

Parameter	AC Voltage Controller	Controlled Rectifier
Input	Fixed AC (50 Hz)	Fixed AC (50 Hz)
Output	Variable AC (still 50 Hz)	Variable DC
Devices	TRIACs or anti-parallel SCRs	SCRs
Frequency change	None (output = input frequency)	N/A (output is DC)
Control method	Firing angle α or integral cycle	
AC $\rightarrow$ DC	AC $\rightarrow$ variable AC	

6.2 Principle of Phase Control

In phase control, the thyristor is triggered at a controlled delay angle α in every half-cycle. Only a portion of the sinusoidal AC cycle is delivered to the load — the rest is blocked.

Half-Cycle	SCR Action	Load Receives	Conduction Angle	Effect
Positive	T1 triggered at α	V_s from α to π	$(\pi - \alpha)$	Partial positive half-cycle
Negative	T2 triggered at $\pi + \alpha$	V_s from $\pi + \alpha$ to 2π	$(\pi - \alpha)$	Partial negative half-cycle
Result: both half-cycles controlled	Same α for both	Symmetric output	$2(\pi - \alpha)$ total per cycle	Adjustable RMS voltage

RMS Output Voltage — Phase Control

$$V_{o_rms} = V_m / \sqrt{2} \times \sqrt{[(1/\pi) \times (\pi - \alpha + \sin(2\alpha)/2)]}$$

V_m = peak supply voltage; reduces as α increases from 0 to π

Output Voltage Range

$$\alpha = 0^\circ \rightarrow V_{o_rms} = V_{s_rms} \text{ (full voltage)} \quad ; \quad \alpha = 180^\circ \rightarrow V_{o_rms} = 0$$

Full range of control from 0 to V_{s_rms}

6.3 Principle of Integral Cycle Control (On-Off Control)

In integral cycle control (also called burst firing or on-off control), the supply is connected to the load for a complete number of cycles (n cycles ON) and then disconnected for another number of cycles (m cycles OFF). No partial cycles are used.

Phase Control

- Partial cycles delivered — firing at angle α
- Output voltage waveform is chopped sinusoid
- Generates sub-harmonics and inter-harmonics
- Higher harmonic content in supply current
- Suitable for lighting, heating, motor control
- Response is fast (cycle-by-cycle control)

Integral Cycle Control

- Complete cycles only — no partial half-cycles
- Output waveform is burst of complete sinusoids
- No sub-harmonics — harmonics at multiples of supply freq only
- Lower harmonic content — better power quality
- Best for purely resistive heating loads
- Response is slow (requires multiple cycles)

Integral Cycle — Duty Ratio

$$\delta = n / (n + m) \quad \text{where } n = \text{ON cycles, } m = \text{OFF cycles}$$

RMS Output Voltage (Integral Cycle)

$$V_{o_rms} = V_{s_rms} \times \sqrt{\delta} = V_{s_rms} \times \sqrt{[n / (n+m)]}$$

RMS Current & Power

$$\frac{I_{o_rms}}{V_{s_rms}^2 / R} = \frac{V_{o_rms}}{V_{s_rms}^2 / R} ; \quad P = \frac{V_{o_rms}^2}{R} = \delta \times \frac{V_{s_rms}^2}{R}$$

💡 Integral Cycle Control — Best for Heating

Integral cycle control produces no phase distortion — only complete sinusoidal cycles are applied. This means the power factor at the supply is always unity (for R loads) during ON periods. It is ideal for heating applications (electric furnaces, water heaters) where thermal inertia makes the slow response acceptable. NOT suitable for motor control (torque pulsations at low frequencies).

SECTION 7: SINGLE-PHASE FULL-WAVE AC VOLTAGE CONTROLLERS

Bidirectional Control · R Load · RL Load · Waveform Analysis

7.1 Circuit Configuration

The single-phase full-wave AC voltage controller uses two SCRs (T1, T2) connected in anti-parallel, OR a single TRIAC, between the AC supply and the load. This provides control in BOTH half-cycles — giving symmetric output.

Configuration	Devices	Positive Half-Cycle	Negative Half-Cycle	Typical Use
Anti-parallel SCRs	T1 (positive) + T2 (negative)	T1 triggered at α	T2 triggered at $\pi + \alpha$	Higher power applications
TRIAC	Single TRIAC (MT1-MT2-G)	TRIAC triggered at α (positive gate)	TRIAC triggered at $\pi + \alpha$ (negative gate)	Lower power, simpler circuit

Why Full-Wave Controller is Preferred over Half-Wave

A half-wave controller (SCR + diode) only controls the positive half-cycle. The negative half-cycle passes uncontrolled through the diode. This creates an asymmetric output with a DC component — which saturates transformer cores and induction motor windings. The full-wave controller (two anti-parallel SCRs or TRIAC) controls BOTH half-cycles symmetrically — no DC component in output.

7.2 With Resistive (R) Load

Half-Cycle	Triggered SCR	Conduction Period	Output V_o	Supply Current i_s
Positive (0 to π)	T1 at angle α	α to π	$V_o = V_s$ (positive, partial cycle)	$i_s = i_o = V_o/R$
π to $\pi + \alpha$	None	Off (waiting for T2)	$V_o = 0$	$i_s = 0$
Negative (π to 2π)	T2 at $\pi + \alpha$	$\pi + \alpha$ to 2π	$V_o = V_s$ (negative, partial cycle)	$i_s = i_o$ (negative)
2π to $2\pi + \alpha$	None	Off (waiting for T1)	$V_o = 0$	$i_s = 0$

RMS Output Voltage — R Load

$$V_{rms} = V_m / \sqrt{2} \times \sqrt{[(1/\pi) \times ((\pi - \alpha) + \sin(2\alpha)/2)]}$$

RMS Output Current — R Load

$$I_{rms} = V_{rms} / R$$

Average Output Voltage

$V_{avg} = 0$ (symmetric waveform — equal positive and negative areas cancel)
 Full-wave controller output has ZERO DC component — no transformer saturation

Power Delivered

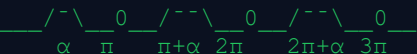
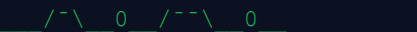
$$P = I_{rms}^2 \times R = V_{rms}^2 / R$$

Power Factor

$$PF = P / (V_{s_rms} \times I_{s_rms}) = V_{rms}^2 / (V_{s_rms} \times R \times I_{rms}) = V_{rms} / V_{s_rms}$$

PF reduces as α increases (more reactive power due to phase shift)

1 Φ Full-Wave Controller — R Load Waveforms

V_s :  Supply sinusoid
 V_o :  Partial cycles (symmetric)
 i_o :  $i_o = V_o/R$ (same shape)
 i_s :  $i_s = i_o$ (bidirectional)
 Note: waveform is symmetric → Zero DC component ✓

7.3 With Inductive (RL) Load

Inductive loads significantly change the behavior of AC voltage controllers. The load power factor angle $\phi = \tan^{-1}(\omega L/R)$ plays a critical role.

Period	Supply V_s	T1 State	i_o Behaviour	Physical Reason
0 to α	Positive	Forward biased, NOT triggered	$i_o = 0$	Waiting for gate pulse
α to π	Positive	Triggered — conducting	i_o rises from 0, lags V_s due to L	Inductor opposes current change
π	Zero crossing	Still ON (L forces it)	i_o still positive but decreasing	L maintains current into negative V_s

π to β	NEGATIVE V_s	Still conducting (natural commutation not yet)	i_o decreasing but > 0	Stored L energy sustains current
β	Negative V_s	$i_o = 0 \rightarrow T1$ turns OFF naturally	$i_o = 0$ (extinction)	All inductor energy exhausted
β to $\pi+\alpha$	Negative V_s	T2 forward biased but not triggered	$i_o = 0$	Waiting for T2 gate pulse at $\pi+\alpha$
$\pi+\alpha$ to $2\pi+\beta$	Negative V_s then positive	T2 triggered at $\pi+\alpha$	Negative i_o (mirror image)	Same process in reverse

⚡ Critical Constraint — Minimum Firing Angle for RL Load

For RL load, the firing angle α MUST be greater than the load angle ϕ ($\alpha > \phi$). If $\alpha < \phi$, the SCR that was conducting in the previous half-cycle is still conducting when the next SCR is triggered — both SCRs conduct simultaneously, creating a short-circuit through the anti-parallel pair. This is called LOSS OF CONTROL. Minimum controllable $\alpha = \phi$ (load power factor angle).

Condition for Controlled Operation

$$\alpha \geq \phi = \tan^{-1}(\omega L/R)$$

If $\alpha < \phi$: simultaneous conduction $\rightarrow$ uncontrolled full-wave output (no voltage reduction)

Extinction Angle β (RL load)

$$\text{Determined by: } \sin(\beta - \phi) = \sin(\alpha - \phi) \times e^{(-R(\beta - \alpha) / (\omega L))}$$

Transcendental equation — solved numerically or from graphs

Conduction Angle (each SCR)

$$\gamma = \beta - \alpha \quad [\text{conduction angle per SCR}]$$

Increases as α approaches ϕ ; decreases as α approaches π

1 Φ Full-Wave Controller — RL Load Waveforms

```

Vs:  /\      /\      Supply sinusoid
Vo:  -/-\ / -\ / -\  Vo negative from  $\pi$  to  $\beta$  (RL effect)
       $\alpha$   $\pi$   $\beta$   $\pi+\alpha$   $\pi+\beta$   $\beta =$  extinction angle  $> \pi$ 
io:  __/  \ /  __/  \ /  io continuous but asymmetric
T1 conducts:  $\alpha \rightarrow \beta$  (includes negative  $V_s$  portion  $\pi$  to  $\beta$ )
T2 conducts:  $\pi+\alpha \rightarrow \pi+\beta$  (mirror image in negative half-cycle)
Range:  $\alpha \geq \phi = \tan^{-1}(\omega L/R)$  for controlled operation

```

SECTION 8: THREE-PHASE AC VOLTAGE CONTROLLERS

Star-Connected R Load · 3-Pair Anti-Parallel SCRs · Firing Sequence

8.1 Circuit Configuration

The three-phase full-wave AC voltage controller uses anti-parallel SCR pairs (or TRIACs) in each phase line, connecting the three-phase supply to the three-phase load. The load is typically star-connected.

Phase Line	Anti-Parallel SCR Pair	Positive Half-Cycle SCR	Negative Half-Cycle SCR
R (Red phase)	T1 (forward) / T4 (reverse)	T1 triggered at α from VR zero-crossing	T4 triggered at $\pi + \alpha$
Y (Yellow phase)	T3 (forward) / T6 (reverse)	T3 triggered at α from VY zero-crossing	T6 triggered at $\pi + \alpha$
B (Blue phase)	T5 (forward) / T2 (reverse)	T5 triggered at α from VB zero-crossing	T2 triggered at $\pi + \alpha$

At Any Instant: Current Flows in Exactly TWO Phases

In a 3 Φ AC voltage controller with star-connected resistive load, at any given instant only TWO phase SCRs are conducting simultaneously. The third phase is open (its SCR pair is not triggered). This is because SCRs from DIFFERENT phases conduct in pairs — one from a positive group and one from a negative group. The load voltage is the corresponding LINE voltage divided across two load resistors.

8.2 Firing Sequence

The SCRs are fired in sequence with 60° spacing between successive firings (for 3-phase, 6-pulse operation).

Firing Sequence	SCR Triggered	Phase Controlled	Voltage Applied to Load	Conducting SCR Pairs
Firing 1 (at α)	T1	R phase positive	VR applied	T1 + previously conducting negative SCR
Firing 2 (at $\alpha + 60^\circ$)	T2	B phase negative	VB applied (negative)	T2 + T1 or T3
Firing 3 (at $\alpha + 120^\circ$)	T3	Y phase positive	VY applied	T3 + T2

Firing 4 (at $\alpha+180^\circ$)	T4	R phase negative	VR negative	T4 + T3
Firing 5 (at $\alpha+240^\circ$)	T5	B phase positive	VB positive	T5 + T4
Firing 6 (at $\alpha+300^\circ$)	T6	Y phase negative	VY negative	T6 + T5

3Φ Controller — Ripple Frequency

$$f_{\text{ripple}} = 6 \times f_{\text{supply}} = 6 \times 50 = 300 \text{ Hz (for 6-pulse)}$$

Much smoother than 1Φ; much less filtering required

8.3 Supply Phase and Line Voltages

For a 3-phase star supply with phase voltage V_{ph} (RMS):

Voltage Type	Expression	Value (230V phase)	Usage
Phase voltage VR	$VR = V_{ph} \times \sin(\omega t)$	230 V RMS	Reference phase
Phase voltage VY	$VY = V_{ph} \times \sin(\omega t - 120^\circ)$	230 V RMS	Lagging R by 120°
Phase voltage VB	$VB = V_{ph} \times \sin(\omega t - 240^\circ)$	230 V RMS	Lagging R by 240°
Line voltage VR _Y	$VR_Y = \sqrt{3} \times V_{ph} \times \sin(\omega t + 30^\circ)$	400 V RMS	R to Y line
Line voltage VR _B	$VR_B = \sqrt{3} \times V_{ph} \times \sin(\omega t - 30^\circ)$	400 V RMS	R to B line
Line voltage VY _B	$VY_B = \sqrt{3} \times V_{ph} \times \sin(\omega t - 90^\circ)$	400 V RMS	Y to B line

8.4 Advantages, Disadvantages and Applications

Advantages of 3Φ AC Controllers

- Higher power delivery capability (3-phase supply provides 3× more power)
- Less harmonic content in output for high power compared to 1Φ
- 6-pulse output means very smooth load voltage and current
- Suitable for large industrial loads (motors, furnaces)
- Standard for high-power speed and temperature control

Disadvantages of 3Φ AC Controllers

- Control circuit is more complex (6 SCRs, synchronized 3Φ firing)
- Not suitable for resistive loads requiring precise control (firing angle interaction between phases)
- Minimum firing angle limited by load power factor angle ϕ
- Harmonics generated in supply current — may need filtering
- Higher cost than single-phase controllers

3Φ AC Voltage Controller Applications

- Induction motor speed control (fan drives, pump drives, compressors)
- Large fan and blower speed control in HVAC systems
- Industrial heating systems (electric arc furnaces, induction heaters)
- Soft-starter circuits for large induction motors (reduces starting current surge)
- Lighting control for large commercial/industrial installations

8.5 Full Module Summary — Performance Parameters

Circuit	No. of Pulses/Cycle	Ripple Freq	Average Vdc	RMS Vo Formula	Notes
1Φ Half-Wave (R)	1	f _s	$(V_m/2\pi)(1+\cos\alpha)$	Complex formula	Min control; one SCR
1Φ Semi-Converter	2	2f _s	$(V_m/\pi)(1+\cos\alpha)$	$(V_m/\pi)(1+\cos\alpha)/\sqrt{?}$	Two SCR + two diode
1Φ Full Converter (R)	2	2f _s	$(2V_m/\pi)\cos\alpha$	—	Four SCR; bipolar Vdc
1Φ Full Converter (RL)	2	2f _s	$(2V_m/\pi)\cos\alpha$	—	Continuous current
1Φ Dual Converter	2	2f _s	$\pm(2V_m/\pi)\cos\alpha$	—	4-quadrant; two converters
3Φ Dual Converter	6	6f _s	$(3\sqrt{3}V_m/\pi)\cos\alpha$	—	High power; 12 SCRs
1Φ AC Controller (R)	2/cycle AC	2f _s	0 (no DC)	$V_m/\sqrt{2} \times \sqrt{[(\pi-\alpha+\sin 2\alpha/2)/\pi]}$	AC in, AC out
3Φ AC Controller	6/cycle AC	6f _s	0 (no DC)	$3V_{ph_rms} \times \sqrt{[...]}$	Large industrial loads

End of Module 4 Notes

Power Electronics (BEE503) | Dept. of EEE, ATMECE, Mysuru

POWER ELECTRONICS

BEE503

MODULE 5

DC-DC Converters & DC-AC Converters (Inverters)

Choppers · Step-Down · Step-Up · Class A–E · VSI · CSI · PWM · Bridge Inverters

Part A — DC-DC Converters

- Introduction to Choppers
- Principle of Step-Down Chopper (R & RL Load)
- Continuous & Discontinuous Current Modes
- Principle of Step-Up Chopper (R Load)
- Chopper Control Strategies (TRC)
- Performance Parameters of Choppers
- DC-DC Converter Classification: Class A–E

Part B — DC-AC Converters

- Introduction to Inverters
- VSI vs CSI — Types of Inverters
- Single-Phase Bridge Inverter (R & RL Load)
- Performance Parameters of Inverters
- Three-Phase Bridge Inverters
- Voltage Control of Single-Phase Inverters
- Harmonic Reduction Techniques
- Current Source Inverters (CSI)

Dept. of Electrical & Electronics Engineering
ATME College of Engineering, Mysuru

SECTION 1: DC-DC CONVERTERS — INTRODUCTION

Choppers · Principle · Applications · Advantages

1.1 What is a DC Chopper?

A DC chopper converts a fixed or variable DC input voltage into a fixed or variable DC output voltage. Since the output can be greater or less than the input, choppers can be step-down (buck) or step-up (boost) types. They use fast-switching semiconductor devices, giving high efficiency and fast dynamic response.

Input	Chopper	Output
Fixed or Variable DC (V_s)	Duty cycle δ controls V_o $V_o = \delta \times V_s$ (step-down)	Fixed or Variable DC (V_o)

Applications of DC Choppers

- DC traction drives (electric locomotives, metro trains)
- Trolley cars and marine hoists
- Battery-operated electric vehicles (EVs)
- DC motor speed control systems
- Switched Mode Power Supplies (SMPS)
- Switched-mode battery chargers

Advantages of Choppers

- High efficiency — switching principle minimizes losses
- Fast dynamic response — due to switching nature of devices
- Smooth and stepless DC voltage control
- Compact and lightweight — no bulky transformers
- Regenerative braking possible — energy fed back to supply

Disadvantages / Limitations

- Generates harmonics in supply current
- Requires filtering components (L and C)
- EMI/RFI due to high-frequency switching
- More complex control circuit than resistive control
- Device ratings limit maximum voltage and current

SECTION 2: STEP-DOWN (BUCK) CHOPPER

R Load · RL Load · Continuous & Discontinuous Current

2.1 Principle of Step-Down Operation — R Load

In the step-down chopper, the average output voltage $V_o(av)$ is always less than or equal to the supply voltage V_s . The switch (SW) — which can be a BJT, MOSFET, GTO, IGBT, or SCR — is turned ON and OFF repeatedly at high frequency.

Period	Switch State	Output Voltage V_o	Output Current i_o	Load (R) Behaviour
0 to δT (TON)	ON — conducts	$V_o = V_s$ (supply connected)	$i_o = V_s/R$ (rising)	Current flows through R; energy delivered
δT to T (TOFF)	OFF — open circuit	$V_o = 0$ (supply disconnected)	$i_o = 0$ (R load — decays instantly)	No current (R load has no energy storage)
T (start of next cycle)	ON again	Repeats from V_s	Repeats	Pulsating output waveform

Duty Cycle δ

$$\delta = T_{ON} / T = T_{ON} / (T_{ON} + T_{OFF})$$

$0 \leq \delta \leq 1$; controls fraction of cycle output is connected to supply

Average Output Voltage

$$V_o(av) = \delta \times V_s = (T_{ON} / T) \times V_s$$

Step-down: $V_o \leq V_s$ always; when $\delta = 1 \rightarrow V_o = V_s$; when $\delta = 0 \rightarrow V_o = 0$

Average Output Current (R)

$$I_o(av) = V_o(av) / R = \delta \times V_s / R$$

Step-Down Chopper — R Load Waveforms

```

Switch:  ___|----|___|----|___|----|___  ON = TON;  OFF = TOFF
Vo:  0  |Vs|  0  |Vs|  0  |Vs|  0  Rectangular pulses between 0 & Vs
      ↳TON↳TOFF↳ T (period) ↳
io:  /---\ 0 /---\ 0 /---\ 0  R load: io follows Vo exactly
Vo(av) - - - - - Average =  $\delta \times V_s$  (dashed line)
Ripple frequency =  $1/T$  = chopper frequency
  
```

2.2 Step-Down Chopper — RL Load (DC Motor Drive)

When the load is inductive (R-L, or R-L-E representing a DC motor with back-EMF), a freewheeling diode DFW is connected in anti-parallel across the load to provide a current path when the switch is OFF.

Load Element	Symbol	Physical Meaning in Motor Context
Resistance	R	Armature resistance of DC motor
Inductance	L	Armature inductance — opposes current change; maintains continuity
Back-EMF	E	Counter-electromotive force proportional to motor speed
Freewheeling Diode	DFW	Provides return path for inductor current when switch is OFF — prevents voltage spikes

2.2.1 Continuous Current Mode

When load inductance L is sufficiently large, current flows without interruption throughout the cycle — it never reaches zero.

Period	Switch State	DFW State	V_o	i_o Behaviour	Energy Source
0 to δT	ON	Reverse biased (OFF)	$V_o = V_s$	i_o rises from I_{min} to I_{max}	Supply V_s drives current
δT to T	OFF	Forward biased (ON)	$V_o = 0$	i_o falls from I_{max} to I_{min} (but > 0)	Inductor L maintains current through DFW
At T	ON again	Turns OFF	$V_o = V_s$	i_o begins rising again from I_{min}	Supply V_s again

Average Output Voltage

$$V_o(av) = \delta \times V_s$$

Same formula as R load; valid for continuous current mode

Output Current (avg)

$$I_o(av) = (V_o(av) - E) / R = (\delta \times V_s - E) / R$$

$E = \text{back-EMF}$; must have $\delta \times V_s > E$ for current to flow

Current Ripple

$$\Delta I = (V_s - V_o) \times \delta T / L = V_s \times \delta \times (1 - \delta) / (f \times L)$$

Ripple decreases with higher f (switching frequency) and larger L

💡 Freewheeling Diode — Why Essential

When the switch turns OFF in an RL load, the inductor generates a large back-EMF ($L \times di/dt$) to maintain current in the same direction. Without DFW, this voltage would appear as a destructive spike across the switch. DFW provides a safe circulating path: i_o flows through $L \rightarrow \text{DFW} \rightarrow R \rightarrow \text{back to } L$. This maintains continuous output current and protects the switch.

2.2.2 Discontinuous Current Mode

When load inductance L is small, the inductor cannot sustain current for the entire TOFF period — current drops to zero before the next ON period.

Period	Switch State	DFW	io Behaviour	Output V_o
0 to δT	ON	OFF	io rises from 0 to I_{max} (starts from zero each cycle)	$V_o = V_s$
δT to t_1	OFF	ON	io falls from I_{max} toward 0 (inductor freewheels)	$V_o = 0$
t_1	OFF	OFF	io reaches 0 → DFW stops conducting	$V_o = E$ (back-EMF)
t_1 to T	OFF	OFF	io = 0 (completely discontinuous)	$V_o = E$ (no source, no inductor)

⚠ Discontinuous Mode Effects

In discontinuous mode: (1) Output voltage $V_o(av)$ is HIGHER than $\delta \times V_s$ — no longer equals $\delta \times V_s$ formula. (2) Motor speed regulation is poor — speed varies significantly with load. (3) More ripple in current. (4) Analysis requires solving for t_1 (extinction time). High L or high switching frequency f prevents discontinuous mode.

Continuous vs Discontinuous Current Comparison

```

CONTINUOUS:
io: —/\ —/\ —/\ —/\ — io never reaches zero; ripple  $\Delta I$  around  $I_o(av)$ 
    Imin———— Imin > 0 always

DISCONTINUOUS:
io: —/\ 0 /\ 0 /\ 0 — io reaches zero in each cycle ( $t_1 < T$ )
    ←  $\delta T \rightarrow t_1 \rightarrow T \rightarrow$  Dead period: io=0 from  $t_1$  to  $T$ 
 $V_o(av) > \delta \times V_s$  in discontinuous mode!
  
```

SECTION 3: STEP-UP (BOOST) CHOPPER

Inductor Energy Storage · $V_o \geq V_s$ Always

3.1 Principle of Step-Up Operation

In the step-up chopper, the average output voltage $V_o(av)$ is ALWAYS greater than or equal to the supply voltage V_s . This is achieved by storing energy in an inductance L during the ON period and adding it to the supply voltage during the OFF period.

Circuit Element	Connection	Function
Inductor L	In series with supply V_s	Stores energy during ON; releases it as boosted voltage during OFF
Switch (T1)	Across inductor + supply	When ON: shorts inductor to supply; energy stored in L
Diode D1	Between inductor and output	Prevents reverse flow from capacitor to supply during ON period
Capacitor C	Across load (output)	Filters output; maintains V_o smooth; supplies i_o when T1 is ON (D1 blocked)

3.1.1 Switch ON Period (0 to δT)

The transistor (switch) is turned ON. Current i_L flows through L from the supply V_s . Inductor stores energy. Voltage $V_{AB} = 0$ (switch shorts A to B). Diode D1 is reverse biased — capacitor C supplies the load current i_o .

Inductor Voltage (ON)

$$V_L = V_s = L \times (di_L/dt) \quad \rightarrow \quad di_L/dt = V_s/L$$

(rising)
L stores energy = $\frac{1}{2}Li_L^2$; i_L rises linearly at rate V_s/L

3.1.2 Switch OFF Period (δT to T)

The transistor turns OFF. The inductor generates a large voltage ($L \times di/dt$) to maintain i_L in the same direction. Diode D1 becomes forward biased. The combined voltage of $V_s + V_L$ appears across the output.

Output Voltage (OFF)

$$V_o = V_s + V_L \quad \text{where } V_L = L \times (di_L/dt) \text{ during turn-OFF}$$

Inductor adds its EMF to supply voltage → output EXCEEDS supply

3.2 Derivation of Average Output Voltage

Applying volt-second balance to the inductor (in steady state, net flux change = 0 over one cycle):

Volt-Second Balance

$$V_s \times \delta T = (V_o - V_s) \times (1 - \delta) \times T$$

Energy stored (0 to δT) = Energy released (δT to T)

Average Output Voltage

$$V_o = V_s / (1 - \delta)$$

Step-up: $V_o \geq V_s$ always; as $\delta \rightarrow 1$, $V_o \rightarrow \infty$ (theoretical)

Boosted Voltage Relation

$$V_o/V_s = 1/(1 - \delta) \quad \text{OR} \quad \delta = 1 - (V_s/V_o)$$

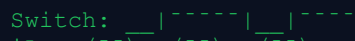
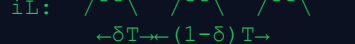
Voltage gain = $1/(1 - \delta)$; increases non-linearly with duty cycle

Duty Cycle δ	Voltage Gain (V_o/V_s)	Example ($V_s = 100V$)	Operating Mode
0	1.0×	$V_o = 100 V$	No boost — pass-through
0.25	1.33×	$V_o = 133 V$	Slight boost
0.50	2.0×	$V_o = 200 V$	Moderate boost
0.75	4.0×	$V_o = 400 V$	High boost
0.90	10.0×	$V_o = 1000 V$	Very high boost
$\rightarrow 1$	$\rightarrow \infty$	—	Theoretical limit — inductor shorts supply

⚠ Step-Up Chopper Practical Limit

As duty cycle δ approaches 1, theoretical output voltage approaches infinity. In practice, parasitic resistance in the inductor and switch ON-resistance limit the maximum achievable V_o . Typical practical boost ratio is 5:1 to 10:1. Never operate at $\delta = 1$ (switch permanently ON) — this short-circuits the supply through the inductor.

Step-Up Chopper — Operating Waveforms

Switch:  ON= δT ; OFF= $(1 - \delta) T$
 i_L :  Inductor current rises during ON; falls during OFF
 $\leftarrow \delta T \leftarrow (1 - \delta) T \rightarrow$
 V_L : $+V_s$ | $-(V_o - V_s)$ | i_L charges then discharges
 V_o : Capacitor maintains V_o smooth = $V_s/(1 - \delta)$ (output > V_s always)
 $D1$: Blocked during ON; Conducts during OFF (charges capacitor)

SECTION 4: CHOPPER CONTROL STRATEGIES

TRC — Time Ratio Control · Constant Freq · Variable Freq · Current Limit

4.1 Time Ratio Control (TRC) Techniques

The duty cycle $\delta = \text{TON}/T$ is varied to control the output voltage. This is called Time Ratio Control (TRC). Two fundamental approaches exist based on whether the switching frequency is held constant or varied.

4.1.1 Constant Frequency (Pulse Width Modulation — PWM)

The chopper frequency $f = 1/T$ is kept constant. Total period T remains unchanged. TON and TOFF are both varied to change the duty cycle δ while T stays fixed.

Aspect	Detail
Frequency	Fixed: $f = 1/T = \text{constant}$
Variable	TON varies; TOFF adjusts automatically ($\text{TOFF} = T - \text{TON}$)
Duty Cycle	$\delta = \text{TON}/T$; increased by increasing TON
Advantage	Filter components (L and C) are easy to design — fixed ripple frequency
Disadvantage	None significant — this is the preferred method
Waveform	Fixed period T ; pulse width (TON) changes

4.1.2 Variable Frequency Operation

The switching frequency $f = 1/T$ varies as duty cycle is changed. Two sub-variants exist:

Sub-Type	What Varies	What is Fixed	Duty Cycle Change	Issue
Constant TON	TOFF varies	TON = constant	$\delta = \text{TON}/T$; increase $T \rightarrow$ decrease δ	T varies widely; ripple frequency changes — difficult filter design
Constant TOFF	TON varies	TOFF = constant	$\delta = \text{TON}/T$; increase TON $\rightarrow$ increase δ	T varies; same filter difficulty

Filter Design Challenge in Variable Frequency

With variable frequency operation, the ripple frequency (= switching frequency) changes as the duty cycle changes. This means filter inductors and capacitors must be designed for the worst-case (lowest frequency) condition, making them unnecessarily large for other operating points. PWM (constant frequency) avoids this problem entirely.

4.1.3 Current Limit Control

The output current i_o is sensed and used to control the switch. The chopper maintains i_o within a hysteresis band $[i_o(\min), i_o(\max)]$.

Event	Condition	Switch Action	Result
Current too high	i_o exceeds $i_o(\max)$	Switch turned OFF	i_o starts decreasing (inductor freewheels through DFW)
Current too low	i_o falls below $i_o(\min)$	Switch turned ON	i_o starts increasing again (supply drives current up)
Steady state	i_o oscillates between $i_o(\min)$ and $i_o(\max)$	Switches at variable frequency	Current maintained in hysteresis band

Hysteresis Band

$$\Delta i = i_o(\max) - i_o(\min)$$

Smaller $\Delta i \rightarrow$ more frequent switching; larger $\Delta i \rightarrow$ less frequent but more ripple

4.2 Comparison of Control Strategies

Control Method	Frequency	TON	TOFF	Filter Design	Primary Use
PWM (Constant Freq)	Fixed	Variable	Variable	Easy — fixed ripple freq	Standard — SMPS, motor drives
Constant TON	Variable	Fixed	Variable	Difficult — varying ripple	Rarely used
Constant TOFF	Variable	Variable	Fixed	Difficult — varying ripple	Some speed controllers
Current Limit	Variable	Variable	Variable	Complex — unpredictable freq	DC motor current control

SECTION 5: PERFORMANCE PARAMETERS OF CHOPPERS

Duty Cycle · Frequency · Device Speed · Ripple

5.1 Key Performance Parameters

Parameter	Symbol	Formula / Value	Effect on Performance
Duty Cycle	δ	$\delta = T_{ON} / T \quad (0 \leq \delta \leq 1)$	Primary control variable — determines output voltage directly
Switching Frequency	f	$f = 1/T \text{ (Hz)}$	Higher $f \rightarrow$ smaller ripple $\rightarrow$ smaller L and $C \rightarrow$ lower cost and size
ON-time	T_{ON}	$T_{ON} = \delta \times T$	Duration switch is closed; energy delivered to load per cycle
OFF-time	T_{OFF}	$T_{OFF} = (1-\delta) \times T$	Duration switch is open; freewheeling period
Output Voltage Ripple	ΔV_o	$\Delta V_o = V_s \times \delta(1-\delta) / (f \times C)$	Decreases with higher f and larger C
Output Current Ripple	ΔI_o	$\Delta I_o = V_s \times \delta(1-\delta) / (f \times L)$	Decreases with higher f and larger L
Device Turn-ON time	t_{on}	Device-dependent	Limits maximum operating frequency
Device Turn-OFF time	t_{off}	Device-dependent	Critical — determines switching losses

5.2 Device Speed Comparison

Device	Turn-ON Time	Turn-OFF Time	Max Frequency	Suitability for Choppers
Power MOSFET	Very small (ns)	Very small (ns)	Up to 1 MHz	Excellent — preferred for high-frequency SMPS
IGBT	Small (μs)	Small (μs)	Up to 50 kHz	Very good — standard for motor drives

GTO	Moderate	Moderate	5–10 kHz	Moderate — suitable for high-power, lower-frequency
BJT	Moderate	Moderate (storage time)	5–20 kHz	Good — but storage time limits speed
SCR	Small	Large (requires forced commutation)	Low (<1 kHz)	Poor — needs external commutation circuit

Effect of Frequency on Ripple

$$\Delta V_o \propto 1/f \quad \text{and} \quad \Delta I_o \propto 1/f$$

Higher switching frequency → proportionally lower ripple → continuous current mode maintained at lower L

Effect of Increasing Switching Frequency

- Ripple frequency increases → filter components (L and C) are smaller and less expensive
- Output current tends to become continuous (continuous mode even at light loads)
- Harmonics in output are reduced in magnitude
- Switching losses INCREASE — higher f means more ON/OFF transitions per second
- Electromagnetic interference (EMI) increases with frequency
- Device must handle more switching cycles — limits maximum usable frequency

SECTION 6: DC-DC CONVERTER CLASSIFICATION

Class A · B · C · D · E Choppers — Quadrant Operation

6.1 Quadrant Classification Overview

Choppers are classified based on the polarity of output voltage (V_o) and output current (i_o) they can handle. Each combination of V_o and i_o polarity corresponds to a quadrant in the V_o – i_o plane.

Quadrant II Forward Regeneration • V_o positive; i_o NEGATIVE • Energy flows: Load $\rightarrow$ Source • Motor brakes (forward speed) • Class B, C choppers	Quadrant I Forward Motoring (Rectifying) • V_o positive; i_o POSITIVE • Energy flows: Source $\rightarrow$ Load • Standard motor drive mode • Class A, C, D, E choppers
Quadrant III Reverse Motoring • V_o NEGATIVE; i_o NEGATIVE • Energy flows: Source $\rightarrow$ Load • Motor runs in reverse • Class E chopper only	Quadrant IV Reverse Regeneration • V_o NEGATIVE; i_o POSITIVE • Energy flows: Load $\rightarrow$ Source • Motor brakes (reverse speed) • Class D, E choppers

Chopper Class	Quadrant(s)	V_o	i_o	Operation	Circuit Elements
Class A	I only	+	+	Forward motoring (rectifying)	1 switch + 1 FWD diode
Class B	II only	+	–	Forward regenerative braking	1 switch + 1 diode
Class C	I and II	+	$\pm$	Forward motoring + forward regen	2 switches + 2 diodes (A+B combined)
Class D	I and IV	$\pm$	+	Forward motoring + reverse regen	2 switches + 2 diodes
Class E	I, II, III, IV	$\pm$	$\pm$	Four-quadrant — full motor drive	4 switches + 4 diodes (H-bridge)

6.2 Class A Chopper — First Quadrant

The Class A chopper is the basic step-down chopper. It operates exclusively in the first quadrant — both V_o and i_o are always positive.

Class A — Key Properties - Quadrant I only: $V_o > 0$, $i_o > 0$ - Energy flows from SOURCE → LOAD always - Also called: Forward Motoring or Rectifying operation - Equivalent to basic step-down (buck) chopper - Freewheeling diode DFW provides path for i_o during TOFF - Applications: DC motor forward drive, battery charging	Circuit Operation - Switch ON (0 to δT): supply $V_s \rightarrow$ load; i_o increases - Switch OFF (δT to T): DFW conducts; i_o decreases through load $V_o = \delta \times V_s$ (average) i_o always ≥ 0 (unidirectional) V_o always ≥ 0 (supply is positive)
---	--

6.3 Class B Chopper — Second Quadrant

The Class B chopper operates in the second quadrant — V_o is positive but i_o is NEGATIVE (current flows out of the load back to the supply). This represents forward regenerative braking of a DC motor.

Period	Switch State	Diode D1	Current i_o Direction	Operation
0 to δT	ON	Reverse biased	Negative current flows: $E_b \rightarrow R \rightarrow L \rightarrow$ Switch	Inductor stores energy from back-EMF E_b
δT to T	OFF	Forward biased	Negative current flows through D1 → supply V_s	Energy transferred from load ($E_b + L$) → supply V_s

Regenerative Braking — Class B

In Class B, the motor back-EMF (E_b) drives current in NEGATIVE direction through the circuit. When switch is ON, current builds up in negative direction through E_b -R-L-switch. When switch turns OFF, Diode D1 conducts and this negative current is FORCED through supply V_s — effectively feeding power back to the supply. The motor decelerates (brakes) while its kinetic energy is returned to the supply.

6.4 Class C Chopper — Quadrants I and II

Class C = Class A + Class B combined. It can operate in both the first quadrant (forward motoring) and second quadrant (forward regenerative braking). V_o is always positive; i_o can be positive or negative.

Conducting Devices	Quadrant	V_o	i_o	Operation
T1 (switch) + D2 (diode)	Quadrant I	+	+	Forward Motoring: energy source $\rightarrow$ motor
T2 (switch) + D1 (diode)	Quadrant II	+	–	Forward Regen Braking: energy motor $\rightarrow$ source

Key Rule for Class C

In Class C, T1 and T2 must NOT be ON simultaneously — this would short-circuit the supply. Dead-time (blanking time) is always inserted between turning OFF one transistor and turning ON the other. T1-D2 pair handles forward motoring; T2-D1 pair handles forward regeneration.

6.5 Class D Chopper — Quadrants I and IV

Class D operates in the first quadrant (forward motoring) and fourth quadrant (reverse regeneration). Output current i_o is always positive; output voltage V_o can be positive or negative.

Conducting Devices	Quadrant	V_o	i_o	Operation
T1 + T2 both ON	Quadrant I	+	+	Forward Motoring: V_s drives load; both switches conduct
D1 + D2 both conduct (T1-T2 OFF)	Quadrant IV	–	+	Reverse Regen: Load inductance drives current through D1, D2 back to source; V_o reverses

6.6 Class E Chopper — Four Quadrants (H-Bridge)

The Class E chopper is a FULL FOUR-QUADRANT chopper, also known as the H-bridge chopper. It allows complete bidirectional control of both voltage and current — enabling full four-quadrant motor drive capability.

Conducting Pair	Quadrant	V_o	i_o	Motor Operation
T1 and T2	I	+	+	Forward Motoring
D1 and D2	II	+	–	Forward Regenerative Braking

T3 and T4	III	–	–	Reverse Motoring
D3 and D4	IV	–	+	Reverse Regenerative Braking

Class E (H-Bridge) Applications

- Full four-quadrant DC motor drives (forward/reverse with motoring and braking)
- CNC machine tool servos requiring precise bidirectional control
- Rolling mills requiring forward/reverse operation with regeneration
- Electric vehicle traction systems
- Robotic joint drives

SECTION 7: DC-AC CONVERTERS — INVERTERS

Introduction · VSI · CSI · Types · Applications

7.1 What is an Inverter?

An inverter is a power electronic circuit that converts a DC input voltage into an AC output voltage of desired frequency and magnitude. Inverters are commonly powered by batteries, fuel cells, solar panels, or controlled rectifiers.

DC Input	Inverter	AC Output
Fixed V_s (battery, rectifier, fuel cell)	Switches control frequency & magnitude <i>PWM controls voltage</i>	Square/quasi-square/sine wave Variable V and f

Applications of Inverters

- Variable speed AC motor drives (induction and synchronous motors)
- Uninterruptible Power Supplies (UPS) — converts battery DC to AC during mains failure
- Standby power systems and emergency lighting
- Induction heating systems
- HVDC (High Voltage DC) transmission terminal equipment
- Solar PV grid-connected inverters
- Aircraft/aerospace onboard power systems

7.2 Types of Inverters

Voltage Source Inverter (VSI)

- Input DC voltage is constant and well-regulated (stiff voltage source)
- Output AC voltage waveform is controlled by switching pattern
- Output current waveform depends on load impedance
- Requires capacitor across DC bus to maintain stiff voltage
- More common — used in most motor drives and UPS
- Also called: Voltage Fed Inverter (VFI)

Current Source Inverter (CSI)

- Input DC current is constant and well-regulated (stiff current source)
- Output AC current waveform is controlled by switching pattern
- Output voltage waveform depends on load impedance
- Requires large inductor in DC link to maintain stiff current
- Used in high-power drives; load must be able to withstand voltage spikes
- Also called: Current Fed Inverter (CFI)

Feature	VSI (Voltage Source)	CSI (Current Source)
DC source type	Constant voltage (capacitor filtered)	Constant current (inductor filtered)
Output parameter controlled	Voltage waveform	Current waveform
Protection on failure	Short-circuit risk — needs current limit	Open-circuit risk — needs voltage clamp
Commutation	No forced commutation (with self-commutating devices)	Requires load commutation or forced commutation
Power factor correction	Good — capacitor at DC bus	Moderate
Typical applications	Motor drives, UPS, solar inverters	High-power induction motor drives, current-source drives

SECTION 8: SINGLE-PHASE FULL BRIDGE INVERTER

R Load · RL Load · Waveforms · Performance

8.1 Circuit Configuration

The single-phase full bridge inverter uses FOUR transistors (T1–T4) and FOUR diodes (D1–D4) in an H-bridge arrangement. The diodes are anti-parallel (freewheeling) diodes — essential for inductive loads to provide path for reactive current.

Device Group	Transistors	Freewheeling Diodes	Conduction Period	Output Polarity
Group 1 (Positive half)	T1 and T2	D1, D2 (for RL load)	First half-cycle (0 to T/2)	$V_o = +V_s$
Group 2 (Negative half)	T3 and T4	D3, D4 (for RL load)	Second half-cycle (T/2 to T)	$V_o = -V_s$

8.2 Operation with Resistive (R) Load

For purely resistive load, output current i_o is always in phase with output voltage V_o . No freewheeling diodes conduct — the transistors carry all the current.

Period	Triggered Pair	Current Path	Output V_o	Output i_o
0 to T/2	T1 and T2	$V_s(+) \rightarrow T1 \rightarrow \text{Load}(A \rightarrow B) \rightarrow T2 \rightarrow V_s(-)$	$V_o = +V_s$	$i_o = +V_s/R$
T/2 to T	T3 and T4	$V_s(+) \rightarrow T3 \rightarrow \text{Load}(B \rightarrow A) \rightarrow T4 \rightarrow V_s(-)$	$V_o = -V_s$	$i_o = -V_s/R$
Result	Square wave	Alternating polarity	$\pm V_s$ amplitude	$\pm V_s/R$ amplitude

Fundamental Output Voltage

$$V_{o1} = (4V_s/\pi) \times \sin(\omega t)$$

Fundamental component of square wave; amplitude = $4V_s/\pi \approx 1.273 V_s$

RMS Output Voltage

$$V_{o_rms} = V_s$$

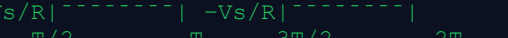
Square wave RMS = peak value = V_s

Harmonic Content

$$V_{o_n} = (4V_s/n\pi) \text{ for } n = 1, 3, 5, 7, \dots$$

Only ODD harmonics present in square wave; no even harmonics

Single-Phase Bridge Inverter — R Load Waveforms

Gate T1,T2:  (ON for first half)
 Gate T3,T4:  (ON for second half)
 Vo:  Square wave $\pm V_s$
 io:  io follows Vo for R load
 0 T/2 T 3T/2 2T

8.3 Operation with Inductive (RL) Load

With inductive load, output current i_o LAGS behind output voltage V_o by the load angle $\phi = \tan^{-1}(\omega L/R)$.

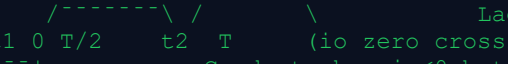
This lag causes current to still flow in the previous direction when voltage reverses — freewheeling diodes conduct during this overlap.

Mode	Period	Active Devices	Current Direction	Voltage V_o	Energy Flow
Mode I	0 to t_1	D1 and D2 (freewheeling)	i_o negative (from previous half-cycle)	$V_o = +V_s$	Energy: Load $\rightarrow$ Source (D1-D2 conduct)
Mode II	t_1 to $T/2$	T1 and T2	i_o positive (rises to peak)	$V_o = +V_s$	Energy: Source $\rightarrow$ Load (T1-T2 conduct)
Mode III	$T/2$ to t_2	D3 and D4 (freewheeling)	i_o positive (from previous half-cycle)	$V_o = -V_s$	Energy: Load $\rightarrow$ Source (D3-D4 conduct)
Mode IV	t_2 to T	T3 and T4	i_o negative (rises in -ve direction)	$V_o = -V_s$	Energy: Source $\rightarrow$ Load (T3-T4 conduct)

💡 Role of Freewheeling Diodes in Inverter

In an inverter with inductive load, when transistors T1-T2 are turned OFF (at $T/2$), the load inductance maintains positive current. This current cannot immediately reverse — it flows through D3-D4 (freewheeling path) even though V_o has reversed. Without these diodes, the inductor would generate destructive voltage spikes. Diodes D1-D4 provide the reactive current return path essential for safe operation.

Bridge Inverter — RL Load Waveforms

Vo:  Square wave $\pm V_s$
 io:  Lagging current ($\phi = \text{lag angle}$)
 t1 0 T/2 t2 T (io zero crossings lag Vo by angle ϕ)
 D1-D2:  Conduct when $i_o < 0$ but $V_o > 0$ (Mode I)
 D3-D4:  Conduct when $i_o > 0$ but $V_o < 0$ (Mode III)
 T1,T2:  T3,T4: 

8.4 Performance Parameters of Inverters

Parameter	Symbol	Formula	Significance
Harmonic Factor (nth)	HF _n	$HF_n = V_n / V_1$	Ratio of nth harmonic to fundamental; lower = better
Total Harmonic Distortion	THD	$\%THD = (\sqrt{V_2^2 + V_3^2 + \dots}) / V_1 \times 100\%$	Overall harmonic content; <5% desired for motor drives
Distortion Factor	DF	$DF = (\sqrt{\sum (V_n/n^2)^2}) / V_1$	Weighted harmonic distortion; accounts for attenuation by load
Crest Factor	CF	$CF = V_{peak} / V_{rms}$	Square wave: CF = 1.0; Sine wave: CF = $\sqrt{2} \approx 1.414$
Fundamental Power	P ₁	$P_1 = V_{1_rms} \times I_{1_rms} \times \cos(\phi_1)$	Power due to fundamental component only
Displacement Power Factor	DPF	$DPF = \cos(\phi_1)$	Power factor of fundamental component

SECTION 9: THREE-PHASE BRIDGE INVERTER

6-Pulse Operation · 180° and 120° Modes · Line Voltages

9.1 Circuit Configuration

The three-phase bridge inverter uses SIX transistors (T1–T6) and SIX freewheeling diodes (D1–D6) arranged in three legs (one per phase). Each leg has two transistors in series between the positive and negative DC rails.

Leg (Phase)	Upper Switch	Lower Switch	Phase Output
Phase R (Leg 1)	T1 (conducts when +ve half)	T4 (conducts when -ve half)	VRN = voltage of phase R
Phase Y (Leg 2)	T3 (conducts when +ve half)	T6 (conducts when -ve half)	VYN = voltage of phase Y
Phase B (Leg 3)	T5 (conducts when +ve half)	T2 (conducts when -ve half)	VBN = voltage of phase B

Key Rule: Never Simultaneously ON in Same Leg

In any leg, the upper and lower transistors (e.g., T1 and T4) must NEVER be turned ON simultaneously. This would short-circuit the DC supply. A dead-time is always inserted between turning one OFF and the other ON.

9.2 180° Conduction Mode

In 180° conduction mode, each transistor conducts for 180° of the output cycle. Each transistor is ON for half the period. The firing sequence is T1, T2, T3, T4, T5, T6 with each consecutive firing delayed by 60°.

Firing Sequence	Transistor	Phase	Firing Angle	Conduction Duration
1st firing	T1	R phase (upper)	0°	180° (conducts from 0° to 180°)
2nd firing	T2	B phase (lower)	60°	180° (conducts from 60° to 240°)
3rd firing	T3	Y phase (upper)	120°	180° (conducts from 120° to 300°)
4th firing	T4	R phase (lower)	180°	180° (conducts from 180° to 360°)

5th firing	T5	B phase (upper)	240°	180° (conducts from 240° to 420°)
6th firing	T6	Y phase (lower)	300°	180° (conducts from 300° to 480°)

Fundamental Phase Voltage

$$VRN1 = (2Vs/\pi) \times \sin(\omega t)$$

V_s = DC supply voltage; fundamental RMS = 0.45 V_s

Fundamental Line Voltage

$$VRY1 = \sqrt{3} \times VRN1 = (2\sqrt{3} \cdot Vs/\pi) \times \sin(\omega t + 30^\circ)$$

Line voltage leads phase voltage by 30°; RMS = 0.7797 V_s

Ripple Frequency

$$f_{\text{ripple}} = 6 \times f_{\text{fundamental}}$$

Six-pulse output — much smoother than single-phase; very suitable for motor drives

9.3 At Any Instant — Three Transistors Conduct

In 180° mode, at any given instant, THREE transistors are conducting simultaneously (one from each leg, but not both from the same leg). This means the load is always connected between the DC supply and a return path through the third leg.

0°–60°	T5, T6, T1	T5(upper B), T6(lower Y), T1(upper R)	VRN=+Vs/3+?, load connected across 3 phases
60°–120°	T6, T1, T2	T6(lower Y), T1(upper R), T2(lower B)	Different 3-phase configuration
120°–180°	T1, T2, T3	T1(upper R), T2(lower B), T3(upper Y)	—
180°–240°	T2, T3, T4	T2(lower B), T3(upper Y), T4(lower R)	—
240°–300°	T3, T4, T5	T3(upper Y), T4(lower R), T5(upper B)	—
300°–360°	T4, T5, T6	T4(lower R), T5(upper B), T6(lower Y)	—

SECTION 10: VOLTAGE CONTROL & HARMONIC REDUCTION

PWM · Multiple Pulse · Sinusoidal PWM · Notching

10.1 Why Voltage Control?

In many applications (AC motor drives, UPS), both the voltage magnitude AND frequency of the inverter output must be variable. Several techniques control output voltage without changing the DC supply voltage.

Method	Principle	Harmonic Content	Implementation Complexity
Variable DC Link (External)	Vary DC input voltage (using controlled rectifier)	Low — waveform not distorted	Simple inverter; complex supply
Single-Pulse PWM	One notch per half-cycle cuts output width	Reduces fundamental; odd harmonics remain	Simple
Multiple-Pulse PWM	Multiple equal-width notches per half-cycle	Reduces specific harmonics; ripple increases	Moderate
Sinusoidal PWM (SPWM)	Sine-wave reference compared with triangular carrier	Excellent — best harmonic spectrum	Most complex but preferred
Selective Harmonic Elimination	Specific notch positions eliminate chosen harmonics	Targeted reduction of 5th, 7th harmonics	Complex pre-calculation needed

10.2 Sinusoidal PWM (SPWM) — Most Common

SPWM generates multiple variable-width pulses per half-cycle by comparing a sinusoidal reference waveform with a high-frequency triangular carrier wave. The intersections determine switch ON/OFF instants.

Signal	Description	Role
Reference (Sine wave)	Desired output sine wave at fundamental frequency f	Sets the desired output voltage waveform shape
Carrier (Triangle wave)	High-frequency triangular wave at switching frequency f_c	Sets switching frequency; determines number of pulses per half-cycle
Modulation Index (m_a)	$m_a = V_{ref_peak} / V_{carrier_peak}$	Controls output voltage magnitude; $0 \leq m_a \leq 1$

Frequency Ratio (mf)	$mf = f_c / f$ (carrier:reference)	Sets number of pulses per half-cycle; higher mf $\rightarrow$ higher switching freq
-----------------------------	------------------------------------	---

Fundamental Output Voltage	$V_{o1} = m_a \times V_s / 2$ (half-bridge) OR $V_{o1} = m_a \times V_s$ (full bridge) $m_a = \text{modulation index}; V_s = \text{DC supply}; \text{control range: } 0 \leq V_{o1} \leq V_s \text{ (linear range)}$
-----------------------------------	---

Linear Modulation Range	$0 \leq m_a \leq 1 \rightarrow V_{o1} \text{ proportional to } m_a$ Over-modulation: $m_a > 1 \rightarrow \text{non-linear; approaches square wave at } m_a \gg 1$
--------------------------------	---

Sinusoidal PWM — Concept Diagram

```

V_ref (sine):  _____/-----\_____/-----\_____ Reference sine at frequency f
V_carrier:    /\ /\ /\ /\ /\ /\ /\ /\ /\ /\ /\ /\ /\ /\ /\ Triangle at frequency f_c >> f
Output:       |__|_||__|_||__|_||__|_||__|_||__|_||__|_||__| Variable-width pulses
Logic: ref > carrier  $\rightarrow$  switch ON; ref < carrier  $\rightarrow$  switch OFF
Result: pulse widths vary sinusoidally  $\rightarrow$  fundamental =  $m_a \times V_s$ 
Harmonics clustered around mf and 2mf – easily filtered
Advantage: harmonics at HIGH frequencies  $\rightarrow$  small filter size needed

```

10.3 Harmonic Reduction Techniques

Methods for Reducing Harmonics in Inverter Output

- Sinusoidal PWM (SPWM): pushes harmonics to high frequencies (around $mf \times f$) — easily filtered; best method
- Multiple-Pulse Modulation: several equal pulses per half-cycle reduce lower-order harmonics
- Selective Harmonic Elimination (SHE): notch positions calculated to eliminate specific harmonics (5th, 7th, 11th)
- Output filters (LC low-pass): filter inductor and capacitor attenuate harmonics above cutoff frequency
- Transformer with multiple secondary windings: phase-shifted outputs cancel specific harmonics
- Three-phase inverter: 6-pulse output naturally eliminates 5th and 7th harmonics from line voltage

10.4 Current Source Inverter (CSI)

In a Current Source Inverter (CSI), the DC input current is maintained constant by a large series inductor L_d . The inverter switches direct this constant current to the load in alternating fashion.

CSI Characteristics

- DC link has large inductor L_d — maintains constant current I_d
- Switches direct I_d to load alternately in positive and negative directions
- Output is a current square wave (or quasi-square)
- Load voltage waveform depends on load impedance
- Requires load commutation or forced commutation of SCRs
- Overvoltage protection needed — load must not open-circuit

CSI vs VSI Summary

Feature	VSI	CSI
DC link	Capacitor C_d	Inductor L_d
Output controlled	Voltage	Current
Fault risk	Short circuit	Open circuit
Device type	Self-commutating (IGBT/MOSFET)	SCR or GTO
Applications	Most drives, UPS	High-power drives

End of Module 5 Notes

Power Electronics (BEE503) | Dept. of EEE, ATMECE, Mysuru