Applied Electronics (DI03011021)

Complete Lecture Deck – All 30 Lectures

Milav Dabgar

Lecturer, GP Palanpur

July 22, 2026

Course Agenda I

1. Lecture 1.1: Basic block diagram and working of an operational amplifier
2. Lecture 1.2: Describe IC 741 as an Op-Amp, Pin configuration of IC 741
3. Lecture 1.3: Op-Amp: open loop and closed loop
4. Lecture 1.4: Parameters of Operational Amplifier
5. Lecture 1.5: The Ideal Op.Amp & Equivalent Circuit
6. Lecture 1.6: Inverting, Non-Inverting, and Summing Amplifiers

Course Agenda II

7. Lecture 1.7: Comparator, Integrator, Differentiator, Schmitt Trigger
8. Lecture 2.1: SCR
9. Lecture 2.2: DIAC, TRIAC, and GTO Thyristor
10. Lecture 2.3: IGBT and MOS-Controlled Thyristor (MCT)
11. Lecture 2.4: Two Transistor Analogy of SCR
12. Lecture 2.5: Opto-Isolators, LASCR, and Opto-TRIAC
13. Lecture 2.6: Applications of Optocouplers and SSRs

Course Agenda III

Course Agenda IV

Course Agenda V

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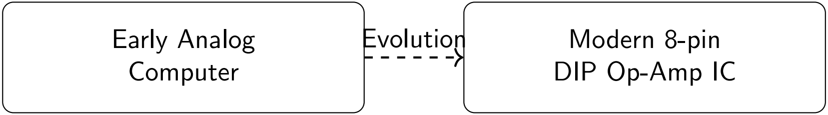
Agenda

- 1. Introduction to the Operational Amplifier (Op-Amp)
- 2. Op-Amp Symbol and Terminals
- 3. Basic Block Diagram of an Op-Amp
- 4. Detailed Stage-by-Stage Analysis
- 5. Ideal Characteristics of an Op-Amp
- 6. Summary and Next Steps

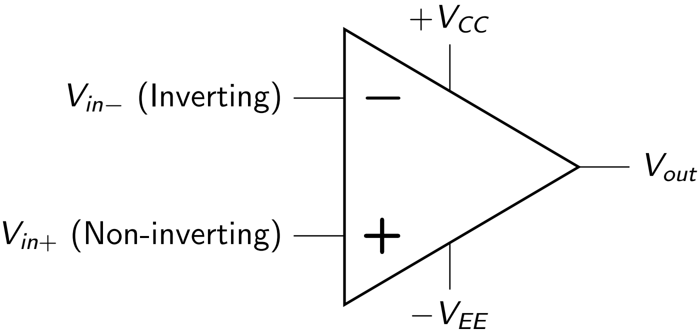
What is an Operational Amplifier?

- A high-gain, direct-coupled voltage amplifier.
- Originally designed to perform mathematical operations (addition, integration, differentiation) in analog computers.
- Amplifies the difference between two input signals.
- Requires dual DC power supplies (usually +Vcc and -Vee) for operation.



Op-Amp Symbol

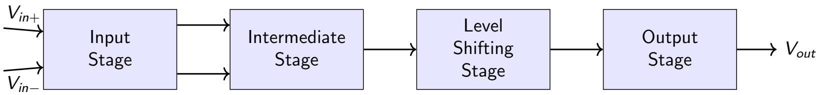
- Triangle symbol representing amplification.
- Two inputs: Inverting (-) and Non-inverting (+).
- One output.
- Power supply connections: +Vcc (positive) and -Vee (negative).



Basic Block Diagram of an Op-Amp

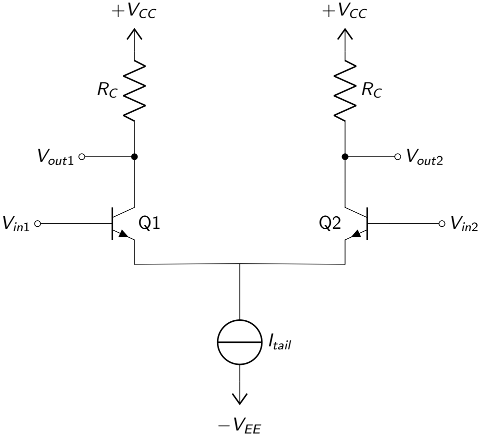
An Op-Amp consists of four main functional stages cascaded together:

1. Input Stage (Differential Amplifier)
2. Intermediate Stage (High-Gain Differential Amplifier)
3. Level Shifting Stage
4. Output Stage (Push-Pull Amplifier)



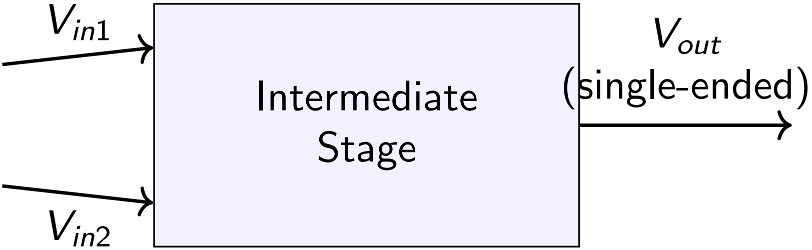
1. Input Stage

- Configuration: Dual-Input, Balanced-Output Differential Amplifier.
- Function: Provides most of the initial voltage gain.
- Determines the input resistance of the Op-Amp (ideally infinite).
- Rejects common-mode signals (noise) effectively.



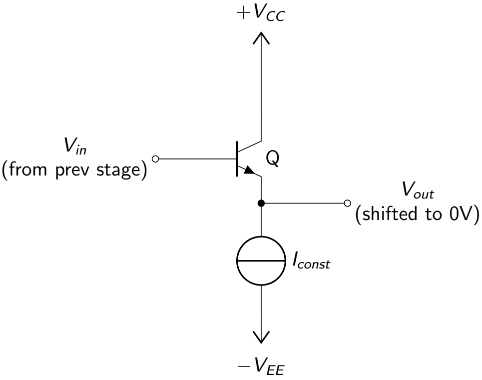
2. Intermediate Stage

- Configuration: Dual-Input, Unbalanced-Output (single-ended) Differential Amplifier.
- Function: Provides additional voltage gain.
- Driven by the balanced output of the input stage.
- Converts the differential signal into a single-ended signal.



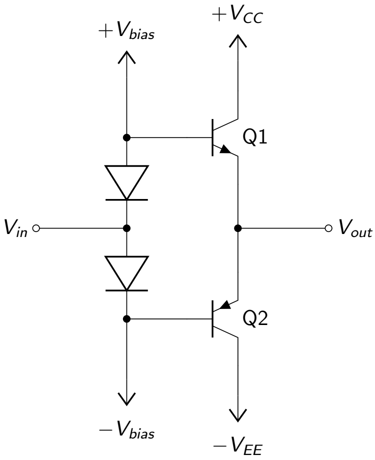
3. Level Shifting Stage

- Function: Shifts the DC level of the signal down to zero (ground) reference.
- Why? Direct coupling in previous stages causes the DC quiescent voltage to build up.
- Prevents output voltage from being non-zero when the input difference is zero.
- Typical circuit: Emitter follower with a constant current source.



4. Output Stage

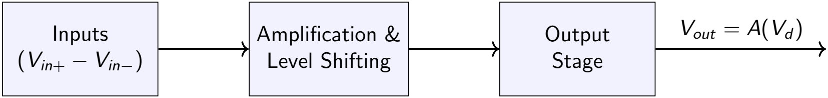
- Configuration: Complementary Symmetry Push-Pull Amplifier (Class B or AB).
- Function: Provides high current driving capability.
- Increases the output voltage swing.
- Provides low output resistance (ideally zero).



Working Principle Summary

1. V_{in+} and V_{in-} are applied.
2. Input stage calculates $(V_{in+}) - (V_{in-})$ and amplifies it.
3. Intermediate stage further amplifies this difference.
4. Level shifter removes internal DC offset.
5. Output stage buffers the signal to drive the load.

Equation: $V_{out} = A \times (V_{in+} - V_{in-})$



Ideal Characteristics of an Op-Amp (Part 1)

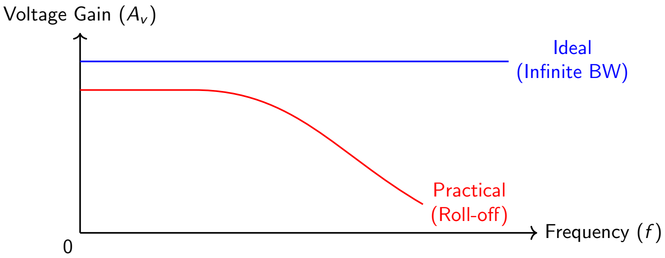
For theoretical circuit analysis, we assume ideal parameters:

- **Infinite Open-Loop Voltage Gain ($A = \infty$):** Even the smallest difference yields maximum output.
- **Infinite Input Impedance ($R_{in} = \infty$):** The inputs draw absolutely zero current.
- **Zero Output Impedance ($R_{out} = 0$):** Can drive any load without voltage drop.

Parameter	Ideal Value	Practical (e.g. 741)
Voltage Gain (A_v)	∞	$\sim 2 \times 10^5$
Input Impedance (R_{in})	∞	2 MΩ
Output Impedance (R_{out})	0	75 Ω

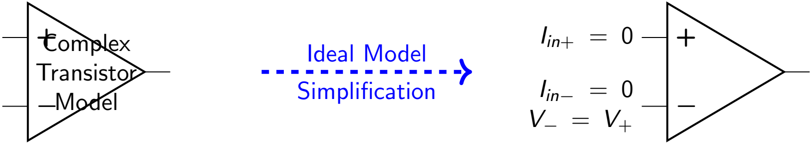
Ideal Characteristics of an Op-Amp (Part 2)

- **Infinite Bandwidth ($BW = \infty$):** Amplifies all frequencies from DC to daylight equally.
- **Infinite Common-Mode Rejection Ratio ($CMRR = \infty$):** Perfectly rejects noise common to both inputs.
- **Infinite Slew Rate ($SR = \infty$):** Output voltage changes instantaneously with input changes.
- **Zero Offset Voltage ($V_{os} = 0$):** Output is exactly zero when inputs are zero.



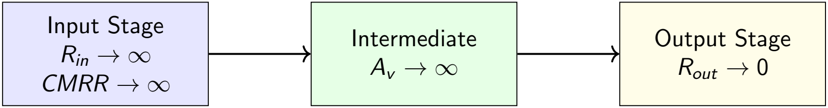
Significance of Ideal Characteristics

- Why do we learn the ideal model?
- Simplifies circuit analysis drastically (Virtual Short and Virtual Ground concepts).
- Practical Op-Amps (like the 741) approach these ideals well enough for low-frequency, low-precision applications.
- Modern Op-Amps (FET inputs) have R_{in} in Tera-ohms, practically infinite.



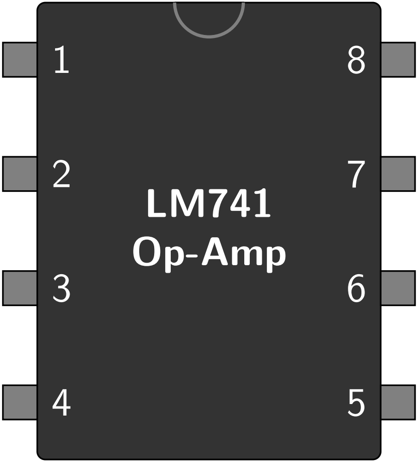
Summary

- An Op-Amp is a multi-stage differential amplifier.
- Internally comprises: Input Stage, Intermediate Stage, Level Shifter, and Output Stage.
- Amplifies the voltage difference: $V_{out} = A \times (V_+ - V_-)$.
- Ideal characteristics: Infinite gain, infinite R_{in}, zero R_{out}, infinite bandwidth, infinite CMRR.



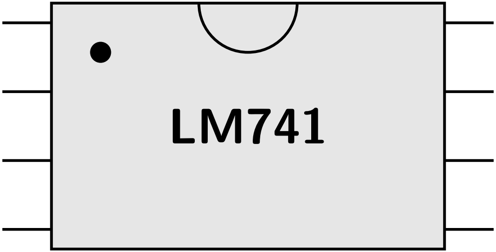
Next Lecture Preview

- Topic: Describe IC 741 as an Op-Amp, Pin configuration of IC 741.
- We will look at the real-world standard Op-Amp.
- Understanding the 8-pin DIP package.
- What do the 'Offset Null' pins do?



Title Slide: IC 741

- Course: Applied Electronics (DI03011021)
- Unit 1: Operational Amplifiers
- Lecture 2: Describe IC 741 as an Op-Amp, Pin configuration of IC 741

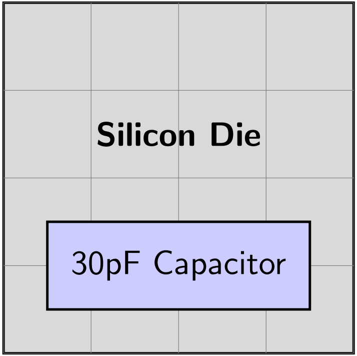


Agenda

- 1. Introduction to the IC 741
- 2. Why the IC 741 is an Industry Standard
- 3. Packaging Types of IC 741
- 4. Pin Diagram (8-Pin DIP)
- 5. Detailed Pin Functions (Pins 1-8)
- 6. Concept of Offset Null
- 7. Summary and Next Steps

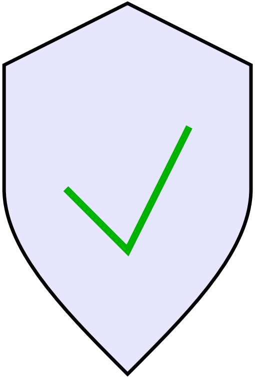
Introduction to IC 741

- Designed by Dave Fullagar at Fairchild Semiconductor in 1968.
- Solved major issues of previous Op-Amps (like the 709).
- Internally compensated: Requires no external components for stability.
- Contains 20 transistors, 11 resistors, and 1 capacitor on a single silicon chip.



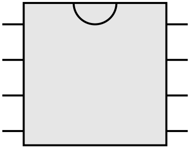
Why is IC 741 so Popular?

- **Ease of Use:** 'Plug and play' for analog circuits.
- **Short-Circuit Protection:** Output won't be destroyed if shorted to ground.
- **Latch-up Free:** Doesn't get stuck in a high-current state.
- **Wide Power Supply Range:** Typically ±5V to ±15V (max ±22V).

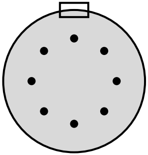


Available in various form factors:

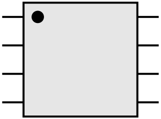
- **8-Pin Dual In-line Package (DIP)** - Most common for breadboarding.
- **TO-99 Metal Can Package** - Better thermal dissipation, used in legacy military/industrial.
- **Surface Mount Device (SMD/SOIC)** - Used in modern PCB manufacturing.



8-Pin DIP



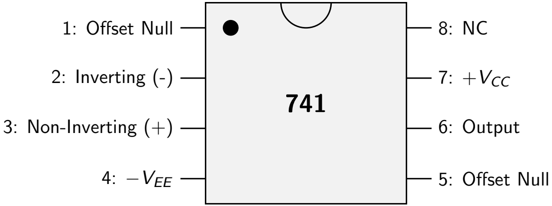
TO-99 Metal Can



SOIC-8

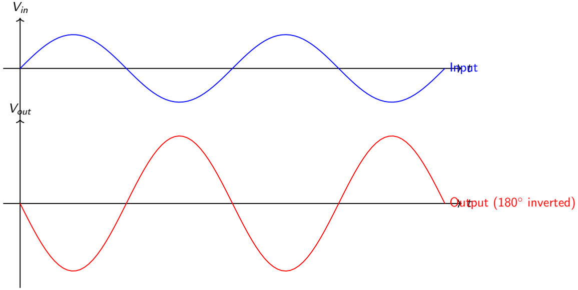
Pin Configuration (8-Pin DIP)

- Top-down view (notch/dot indicates top):
- Pin 1: Offset Null
- Pin 2: Inverting Input (-)
- Pin 3: Non-Inverting Input (+)
- Pin 4: $-V_{EE}$ (Negative Supply)
- Pin 5: Offset Null
- Pin 6: Output
- Pin 7: $+V_{CC}$ (Positive Supply)
- Pin 8: NC (No Connection)



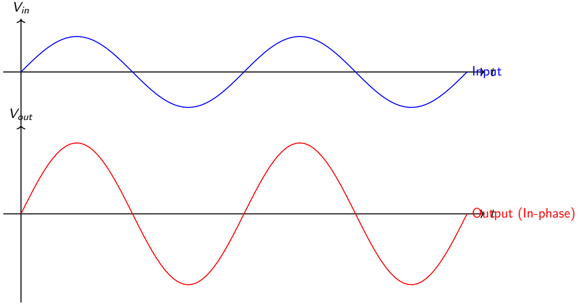
Pin 2: Inverting Input

- Marked with a minus (-) sign in circuit diagrams.
- Signal applied here is amplified and inverted by 180 degrees at the output.
- Example: A +1V DC input yields a negative DC output voltage.



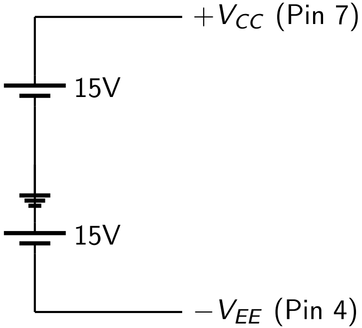
Pin 3: Non-Inverting Input

- Marked with a plus (+) sign in circuit diagrams.
- Signal applied here is amplified but remains in-phase at the output.
- Example: A +1V DC input yields a positive DC output voltage.



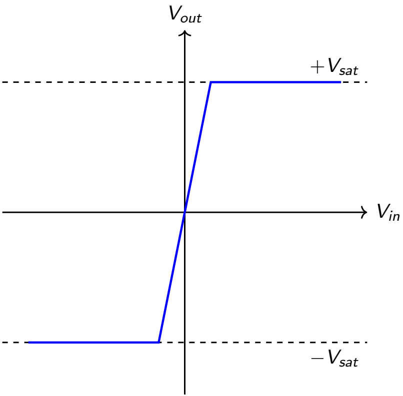
Pins 4 & 7: Power Supply Terminals

- Pin 7 ($+V_{CC}$): Connect to the positive terminal of the DC supply.
- Pin 4 ($-V_{EE}$): Connect to the negative terminal of the DC supply.
- The Op-Amp requires a dual/split power supply (e.g., +15V, Ground, -15V).
- Ground is established externally between the two supplies.



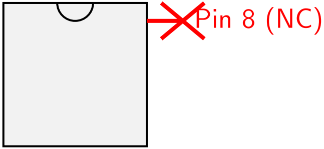
Pin 6: Output

- The terminal where the amplified differential signal is obtained.
- $V_{out} = A \times (V_{pin3} - V_{pin2})$
- Maximum output voltage swing is limited by the power supply voltages (saturation).
- Typically V_{sat} is slightly less than $\pm V_{CC}$ (e.g., $\pm 13V$ or $\pm 14V$ for a $\pm 15V$ supply).



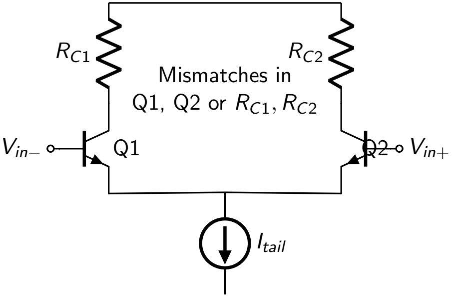
Pin 8: No Connection (NC)

- This pin is physically present but not connected to the internal circuitry.
- Left floating in circuit designs.
- Purpose: Standardizing the 8-pin dual in-line package format.



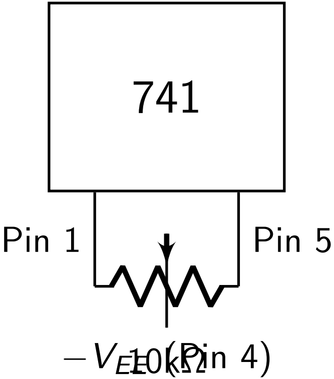
Pins 1 & 5: Offset Null (The Problem)

- In a practical Op-Amp, if $V_{in+} = 0$ and $V_{in-} = 0$, V_{out} should be 0V.
- Due to manufacturing mismatches in internal transistors, a small DC error voltage exists.
- This is called **Input Offset Voltage**.
- This small error is amplified by the massive open-loop gain, causing the output to go to saturation even with no input.



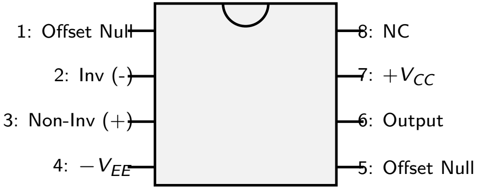
Pins 1 & 5: Offset Null (The Solution)

- To force the output to precisely 0V when inputs are zero, an external potentiometer is used.
- A 10kΩ potentiometer is connected across Pins 1 and 5.
- The wiper (center pin) of the potentiometer is connected to the negative supply ($-V_{EE}$, Pin 4).
- Adjusting the pot balances the internal currents.



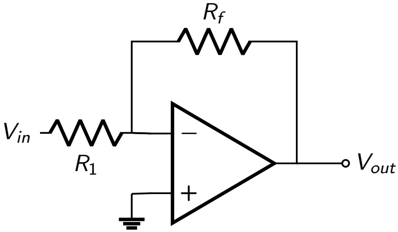
Summary

- IC 741 is a robust, internally compensated, industry-standard Op-Amp.
- 8-Pin DIP configuration is standard for lab use.
- Essential pins: 2(Inv), 3(Non-Inv), 4($-V_{EE}$), 7($+V_{CC}$), 6(Output).
- Pins 1 and 5 are used with a potentiometer to nullify offset voltage.



Next Lecture Preview

- Topic: Op-Amp Open Loop and Closed Loop Configurations.
- What happens when we use the Op-Amp without any feedback (Open Loop)?
- Why is Open Loop generally useless for linear amplification?
- Introduction to the concept of Negative Feedback (Closed Loop).



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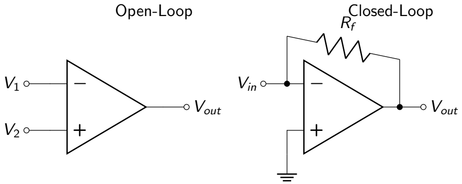
Unit 1: Operational Amplifiers
Lecture 3: Op-Amp: open loop and closed loop

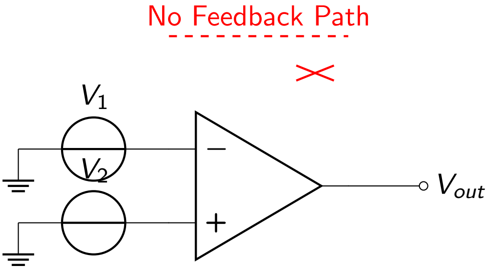


Agenda

- Concept of Open-Loop Operation
- Three Open-Loop Configurations
- Voltage Transfer Characteristics (Open-Loop)
- Limitations of Open-Loop Configuration
- The Concept of Feedback
- Why Use Negative Feedback?
- Introduction to Closed-Loop Configurations
- Summary and Next Steps

What is Open-Loop?

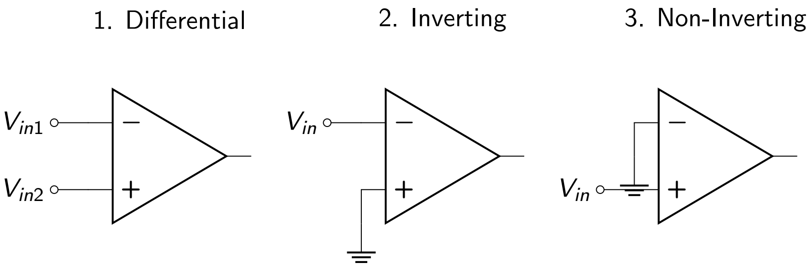
- 'Open-Loop' means there is NO connection (no feedback path) between the output and either of the inputs.
- The Op-Amp operates at its maximum natural gain, denoted as Open-Loop Gain (A_{OL} or A_v).
- For an ideal Op-Amp, A_{OL} is infinite.
- For a practical IC 741, A_{OL} is approximately 200,000 (106 dB).



Open-Loop Configurations

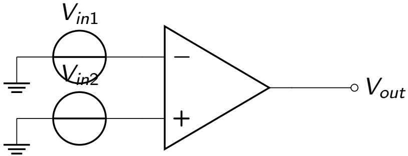
Depending on how we apply the input signal, there are three basic open-loop configurations:

1. Open-Loop Differential Amplifier
2. Open-Loop Inverting Amplifier
3. Open-Loop Non-Inverting Amplifier



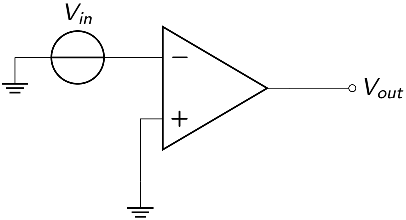
1. Open-Loop Differential Amplifier

- Input signals V_{in1} and V_{in2} are applied to the inverting (-) and non-inverting (+) terminals, respectively.
- $V_{out} = A_{OL} \times (V_{in2} - V_{in1})$
- Amplifies the difference between the two sources.



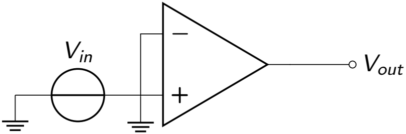
2. Open-Loop Inverting Amplifier

- Non-inverting terminal (+) is grounded (0V).
- Input signal V_{in} is applied to the inverting terminal (-).
- $V_{out} = A_{OL} \times (0 - V_{in}) = -A_{OL} \times V_{in}$
- The output is heavily amplified and phase-shifted by 180°.



3. Open-Loop Non-Inverting Amplifier

- Inverting terminal (-) is grounded (0V).
- Input signal V_{in} is applied to the non-inverting terminal (+).
- $V_{out} = A_{OL} \times (V_{in} - 0) = +A_{OL} \times V_{in}$
- The output is heavily amplified and remains in-phase.



The Problem with Open-Loop Gain

- Let's calculate the input voltage needed to saturate a 741.
- Assume power supply is ± 15V. Max output swing (V_{sat}) $\approx \pm 14$V.
- $V_{in} = \frac{V_{out}}{A_{OL}} = \frac{14\text{V}}{200{,}000} = 70\mu\text{V}$.
- Any input voltage difference greater than 70μV will drive the output into saturation.

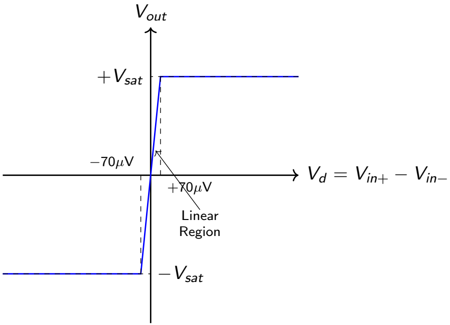
Mathematical Derivation:

$$V_{sat} = 14\text{V}$$
$$A_{OL} = 200,000$$
$$V_{in(max)} = \frac{14}{200{,}000} = \mathbf{70}\,\mu\text{V}$$

70 μV is incredibly small!

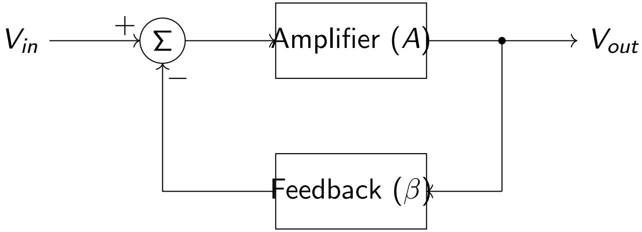
Voltage Transfer Curve (Open-Loop)

- Graph of V_{out} vs. $(V_{in+} - V_{in-})$.
- The linear region is incredibly narrow (only between -70μV and $+70\mu$V).
- Outside this narrow band, the output is saturated at $+V_{sat}$ or $-V_{sat}$.
- Behaves effectively as a 'Comparator'.



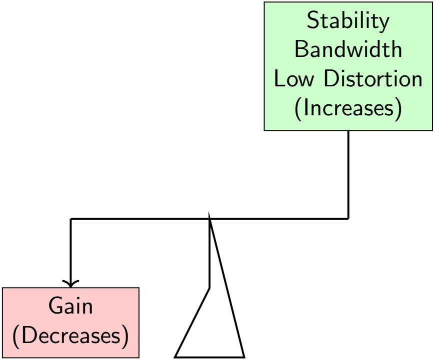
Concept of Feedback

- Feedback is the process of returning a fraction of the output signal back to the input.
- Two types:
  1. **Positive Feedback:** Signal returns to the non-inverting (+) terminal. (Used in oscillators).
  2. **Negative Feedback:** Signal returns to the inverting (-) terminal. (Used in linear amplifiers).



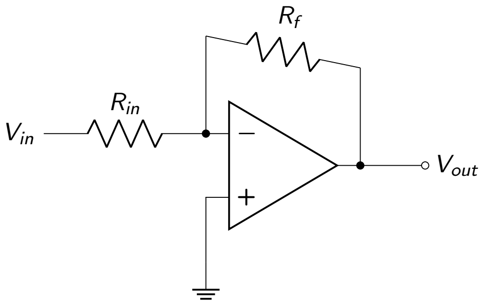
Why Use Negative Feedback?

- Reduces overall voltage gain to a controllable, stable value (Closed-Loop Gain, A_{CL}).
- A_{CL} is determined purely by external resistors, not by the unpredictable internal A_{OL}.
- Increases bandwidth.
- Increases input impedance and decreases output impedance.
- Reduces distortion.



Closed-Loop Configuration

- A circuit with a feedback path connecting the output to the inverting input.
- The 'loop' is closed.
- The massive open-loop gain is suppressed.
- Enables the 'Virtual Ground' and 'Virtual Short' principles for circuit analysis.

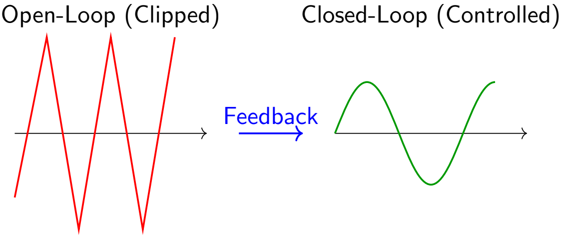


Comparison: Open-Loop vs Closed-Loop

Feature	Open-Loop	Closed-Loop (Negative FB)
Gain	Extremely High ($\approx 10^5$)	Controlled and Low (set by R)
Application	Comparators	Linear Amplifiers, Filters
Stability	Poor (prone to saturation)	Excellent
Bandwidth	Very Narrow	Wide

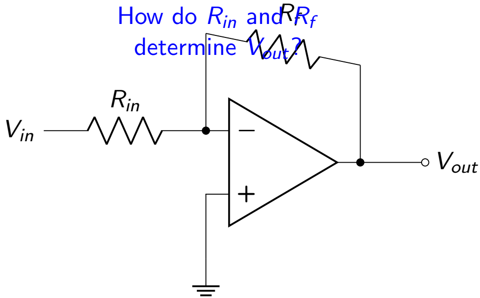
Summary

- Open-loop Op-Amps multiply the input difference by a massive factor (A_{OL}).
- The tiny linear region makes open-loop useless for standard amplification (saturates easily).
- Feedback returns part of the output to the input.
- Negative feedback stabilizes gain, increases bandwidth, and makes linear circuits possible.



Next Lecture Preview

- Topic: Detailed analysis of Closed-Loop configurations.
- Deriving the gain equations for Inverting and Non-Inverting Amplifiers.
- Deep dive into the 'Virtual Short' and 'Virtual Ground' concepts.
- Solving numerical examples.



Applied Electronics (DI03011021)

Complete Lecture Deck – All 30 Lectures

Milav Dabgar

Lecturer, GP Palanpur

July 22, 2026

Agenda

- Introduction to Practical Op-Amp Parameters
- Input Offset Voltage (V_{io})
- Input Bias Current (I_b) and Offset Current (I_{io})
- Common Mode Rejection Ratio (CMRR)
- Slew Rate (SR)

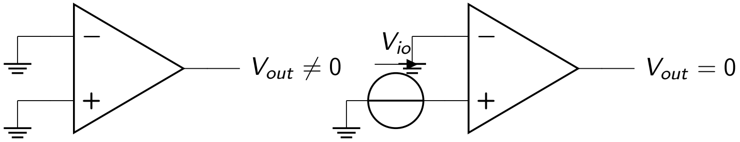
Practical Op-Amp Parameters

- Real Op-Amps deviate from ideal behavior.
- **DC Parameters**: Affect the static operation (e.g., non-zero output when inputs are grounded).
- **AC Parameters**: Affect dynamic operation (e.g., frequency response, large-signal high-frequency limits).
- Understanding these ensures accurate circuit design and troubleshooting.

DC Parameters	AC Parameters
V_{io}, I_b, I_{io}	CMRR, Slew Rate

Input Offset Voltage (V_{io})

- **Definition**: The differential DC voltage required between the input terminals to force the output to exactly zero volts.
- Arises due to mismatches in the base-emitter voltages (V_{BE}) of the input differential transistors.
- Typical value for 741 Op-Amp: $2mV$ to $6mV$.

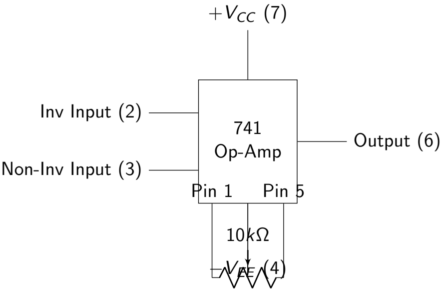


Real Op-Amp

Offset Nulling

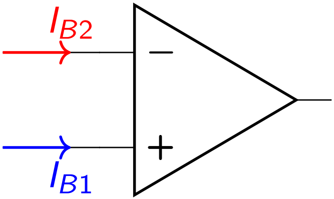
Effect of Input Offset Voltage

- The offset voltage is amplified by the closed-loop gain of the circuit.
- Error voltage at output: $V_{o(error)} = V_{io} \times (1 + \frac{R_f}{R_1})$
- **Compensation**: Many op-amps provide 'Offset Null' pins to externally trim this voltage using a potentiometer.



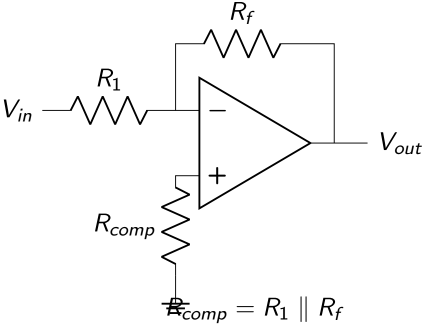
Input Bias Current (I_b)

- **Definition**: The average of the DC base currents entering the non-inverting (I_{B1}) and inverting (I_{B2}) terminals.
- Formula: $I_b = \frac{I_{B1}+I_{B2}}{2}$
- Required to bias the input BJT or JFET transistors into their active region.
- Typical value for 741: $80nA$.



Compensating for Input Bias Current

- Input bias current flowing through input and feedback resistors creates a differential voltage.
- **Solution**: Place a compensating resistor R_{comp} in series with the non-inverting terminal.
- Value of R_{comp} should be the parallel combination of R_1 and R_f: $R_{comp} = R_1 \parallel R_f$



Input Offset Current (I_{io})

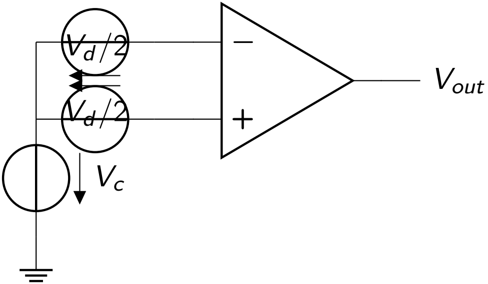
- **Definition**: The algebraic difference between the two input bias currents.
- Formula: $I_{io} = |I_{B1} - I_{B2}|$
- Exists because the two input transistors cannot be perfectly matched in beta (current gain).
- Typical value for 741: $20nA$.

$$I_{io} = |I_{B1} - I_{B2}|$$

If matched perfectly: $I_{io} = 0$

Common Mode Rejection Ratio (CMRR)

- **Definition**: The ability of the op-amp to reject signals that are common to both input terminals.
- Defined as the ratio of differential-mode gain (A_d) to common-mode gain (A_c).
- Formula: $CMRR = \frac{A_d}{A_c}$



CMRR in Decibels

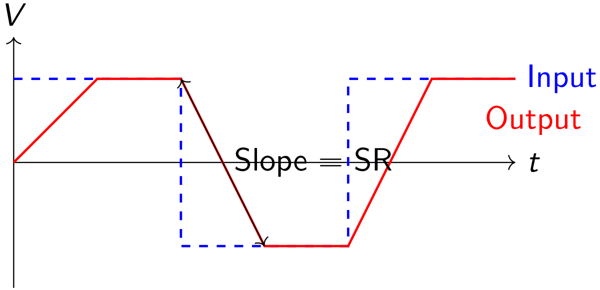
- Usually expressed in decibels (dB).
- Formula: $CMRR(dB) = 20\log_{10}\left(\frac{A_d}{A_c}\right)$
- Higher CMRR means better rejection of common-mode noise (like 50/60 Hz power line hum).
- Typical value for 741: $90dB$.

Example: If $A_d = 10^5$ and $A_c = 1$

$$CMRR(dB) = 20\log_{10}(10^5) = 100 \text{ dB}$$

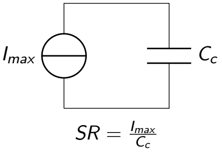
Slew Rate (SR)

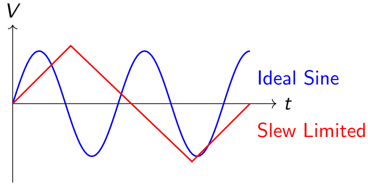
- **Definition**: The maximum rate of change of output voltage with respect to time.
- Formula: $SR = \frac{dV_{out}}{dt}\Big|_{max}$
- Expressed in Volts per microsecond ($V/\mu s$).
- Limits the high-frequency, large-signal operation of the op-amp.



Cause and Effect of Slew Rate

- **Cause**: Internal compensation capacitor (C_c) charging and discharging with a limited internal maximum current (I_{max}).
- $SR = \frac{I_{max}}{C_c}$
- **Effect**: Sine waves can turn into triangular waves at high frequencies and high amplitudes (Slew Rate Distortion).





Slew Rate: Full Power Bandwidth

- The maximum frequency f_{max} at which an undistorted sine wave of peak amplitude V_p can be obtained.
- Since $v_{out}(t) = V_p \sin(2\pi ft)$, $\frac{dv_{out}}{dt} = 2\pi fV_p \cos(2\pi ft)$.
- Maximum slope is $2\pi fV_p$.
- Equation: $SR = 2\pi f_{max} V_p \implies f_{max} = \frac{SR}{2\pi V_p}$

Full Power Bandwidth

$$f_{max} = \frac{SR}{2\pi V_p}$$

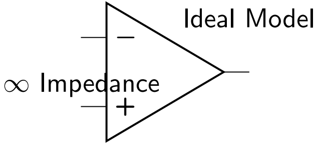
- V_{io}: Input offset voltage (requires compensation).
- I_b, I_{io}: Bias and offset currents (causes DC errors, mitigate with R_{comp}).
- **CMRR**: Ratio of A_d to A_c (rejects common noise).
- **SR**: Maximum output voltage rate of change (limits large-signal bandwidth).

Parameter	Symbol	Typical (741)	Unit
Input Offset Voltage	V_{io}	$2 - 6$	mV
Input Bias Current	I_b	80	nA
Input Offset Current	I_{io}	20	nA
Common Mode Rejection Ratio	CMRR	90	dB
Slew Rate	SR	0.5	$V/\mu s$

Next Lecture Preview

In the next lecture, we will look at:

- **The Ideal Op-Amp Model**
- **Equivalent Circuit of an Op-Amp**
- **Ideal vs Practical Characteristics Comparison**
- Voltage transfer characteristics.



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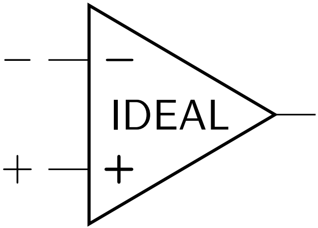
Agenda

- 1. The Ideal Operational Amplifier Concept
- 2. Characteristics of an Ideal Op-Amp
- 3. Ideal vs Practical Characteristics Comparison
- 4. Equivalent Circuit Model of an Op-Amp
- 5. Dependent Voltage Source ($A_v v_d$)
- 6. Op-Amp Transfer Characteristics

The Ideal Operational Amplifier

- An ideal op-amp is a theoretical component used to simplify circuit analysis.
- It assumes perfect behavior with no losses, limits, or non-linearities.
- By assuming ideal behavior, we can easily derive gain equations for complex circuits using standard network theorems.



Characteristics of an Ideal Op-Amp (Part 1)

- **Infinite Open-Loop Gain ($A_v = \infty$)**: Any tiny voltage difference at the inputs results in massive output.
- **Infinite Input Impedance ($R_i = \infty$)**: It draws absolutely zero current from the signal source ($I_{in} = 0$).
- **Zero Output Impedance ($R_o = 0$)**: It can drive any load, delivering infinite current if necessary without voltage drop.

Characteristics of an Ideal Op-Amp (Part 2)

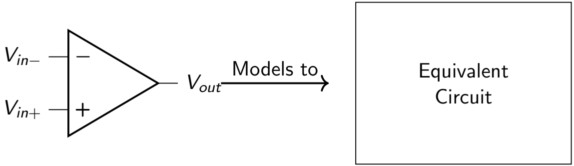
- **Infinite Bandwidth ($BW = \infty$)**: It can amplify AC signals of any frequency, from DC to daylight, without losing gain.
- **Infinite CMRR ($CMRR = \infty$)**: It perfectly rejects any common-mode noise.
- **Infinite Slew Rate ($SR = \infty$)**: The output can change instantaneously in zero time.
- **Zero Offset ($V_{io} = 0$)**: Output is exactly zero when inputs are grounded.

Practical vs Ideal Op-Amp (LM741 Example)

Parameter	**Ideal**	**Practical (LM741)**
Open-Loop Gain (A_v)	∞	$\sim 2 \times 10^5$
Input Impedance (R_i)	∞	2 MΩ
Output Impedance (R_o)	0	75 Ω
Bandwidth	∞	1 MHz
CMRR	∞	90 dB
Slew Rate	∞	0.5 V/μs

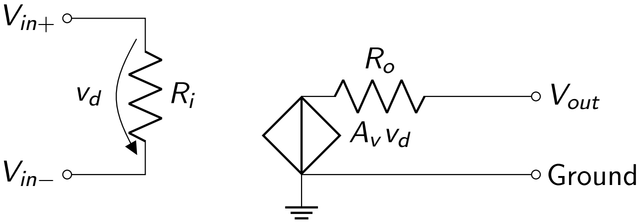
Equivalent Circuit Model

- To perform mathematical analysis, we represent the internal operation of the op-amp as an equivalent circuit.
- The model consists of:
  - An input resistance R_i.
  - An output resistance R_o.
  - A voltage-controlled voltage source (VCVS).



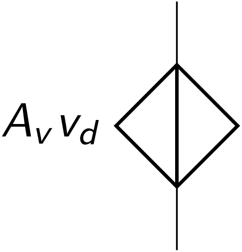
Detailed Equivalent Circuit

- **Input Side**: The resistance R_i is connected between the inverting and non-inverting terminals. Voltage across it is $v_d = V_{in+} - V_{in-}$.
- **Output Side**: The dependent voltage source generates a voltage equal to $A_v v_d$, connected in series with the output resistance R_o.
- **Output Equation**: $V_{out} = A_v v_d - I_{out} R_o$



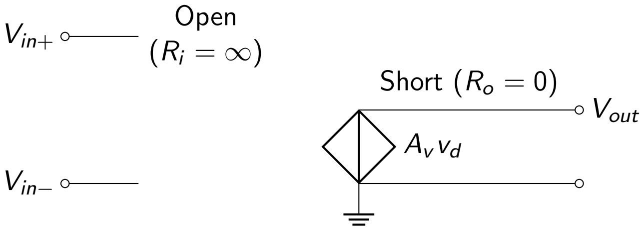
The Dependent Voltage Source ($A_v v_d$)

- It is a **Voltage-Controlled Voltage Source (VCVS)**.
- A_v is the open-loop voltage gain.
- v_d is the differential input voltage ($v_{in+} - v_{in-}$).
- This perfectly captures the differential nature of the op-amp: it only amplifies the difference.



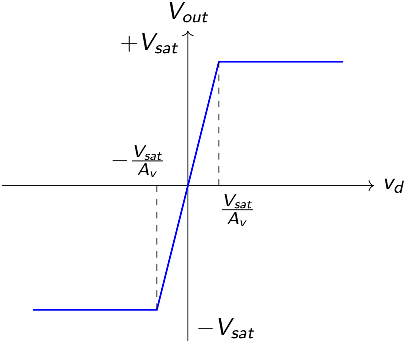
Simplifying to the Ideal Model

- Using the equivalent circuit to represent an ideal op-amp:
- Let $R_i \to \infty$: Input acts as an open circuit (no current flows in).
- Let $R_o \to 0$: Output acts as a perfect voltage source (no voltage drop).
- Ideal Output Equation: $V_{out} = A_v v_d = A_v(V_{in+} - V_{in-})$



Op-Amp Transfer Curve

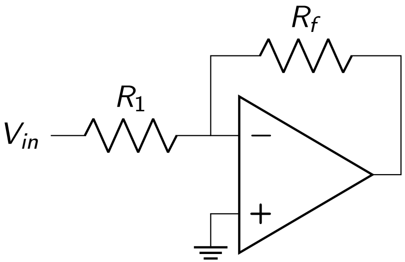
- The transfer curve plots Output Voltage (V_{out}) vs Differential Input Voltage (v_d).
- **Linear Region**: Very narrow region near the origin where $V_{out} = A_v v_d$.
- **Saturation Region**: The output cannot exceed the DC supply voltages ($+V_{CC}$ and $-V_{EE}$).



Linear Region vs Saturation

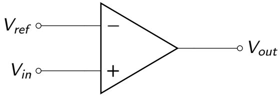
Linear Region

- Requires Negative Feedback.
- Used for amplifiers, filters, and analog math circuits.
- $|v_d| < \frac{V_{sat}}{A_v}$



Saturation Region

- Operates Open-Loop or with Positive Feedback.
- Used for comparators, oscillators, and Schmitt triggers.
- $|v_d| \geq \frac{V_{sat}}{A_v}$



Implications of Infinite Gain (A_v)

- For an op-amp operating in the linear region, the output voltage is finite ($< V_{sat}$).
- Since $V_{out} = A_v v_d$, we can rewrite this as $v_d = \frac{V_{out}}{A_v}$.
- As $A_v \to \infty$, the differential voltage $v_d \to 0$.
- Therefore, $V_{in+} \approx V_{in-}$. This is the foundation of the **Virtual Ground** concept.

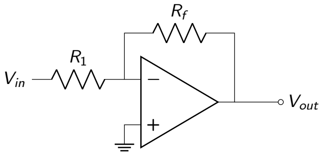
$$v_d = \lim_{A_v \to \infty} \frac{V_{out}}{A_v} = 0 \implies V_{in+} = V_{in-}$$

Summary

- **Ideal Op-Amp**: Infinite gain, infinite input impedance, zero output impedance.
- **Equivalent Circuit**: Models the op-amp using R_i, R_o, and a VCVS ($A_v v_d$).
- **Transfer Curve**: Shows linear amplification restricted by saturation limits (V_{sat}).
- **Key Takeaway**: Ideal characteristics vastly simplify circuit analysis by assuming $v_d = 0$ (when in feedback).

Next Lecture Preview

- In Lecture 6, we will apply these concepts to analyze real circuits:
  - **Virtual Ground Concept in depth**
  - **Inverting Amplifier** ($A_v = -R_f/R_1$)
  - **Non-Inverting Amplifier** ($A_v = 1 + R_f/R_1$)
  - **Summing Amplifier**
  - Numerical design examples.



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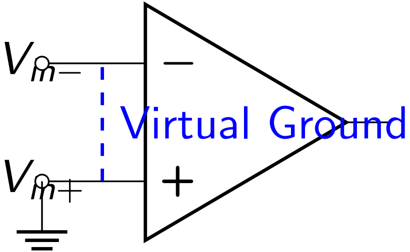
Agenda

- The Virtual Ground Concept
- Inverting Amplifier: Topology & Derivation
- Inverting Amplifier: Numerical Example
- Non-Inverting Amplifier: Topology & Derivation
- Non-Inverting Amplifier: Numerical Example
- Summing Amplifier: Derivation & Example

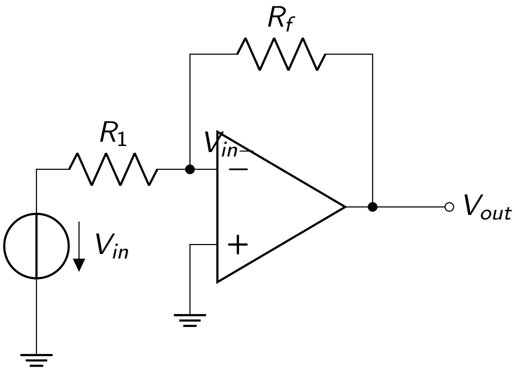
The Virtual Short / Virtual Ground Concept

- In a closed-loop linear circuit (negative feedback), the op-amp adjusts its output to keep $v_d = 0$.
- Therefore, $V_{in+} = V_{in-}$.
- **Virtual Short**: The two input terminals behave as if they are shorted together for voltage calculation, but NO current flows between them.
- **Virtual Ground**: If the non-inverting terminal (V_{in+}) is connected to ground (0V), the inverting terminal (V_{in-}) is also forced to 0V.



Inverting Amplifier: Circuit Topology

- Input signal V_{in} is applied to the inverting (-) terminal through resistor R_1.
- Non-inverting $(+)$ terminal is grounded.
- Negative feedback is provided by resistor R_f from output to the inverting terminal.



Inverting Amplifier: Gain Derivation

1. **Apply Virtual Ground**: Since $V_{in+} = 0\text{V}$, then $V_{in-} = 0\text{V}$.
2. **Apply KCL at node V_{in-}**: The sum of currents leaving the node is zero.

$$\frac{V_{in-} - V_{in}}{R_1} + \frac{V_{in-} - V_{out}}{R_f} + I_{in} = 0$$

3. **Apply Ideal Op-Amp Rule**: $I_{in} = 0$ (Infinite input impedance).

$$\frac{0 - V_{in}}{R_1} + \frac{0 - V_{out}}{R_f} = 0$$

4. **Solve for Gain (A_v)**:

$$\frac{V_{out}}{R_f} = -\frac{V_{in}}{R_1} \implies \boxed{A_v = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}}$$

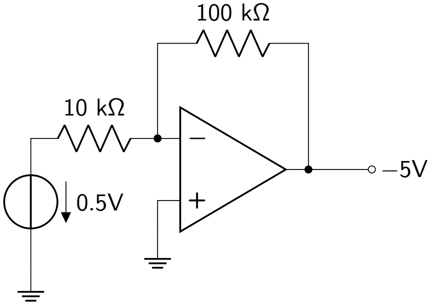
Inverting Amplifier: Numerical Example

Problem: Design an inverting amplifier with a closed-loop gain of -10. Assume $R_1 = 10\ k\Omega$. If $V_{in} = 0.5V$, what is V_{out}?

Solution:

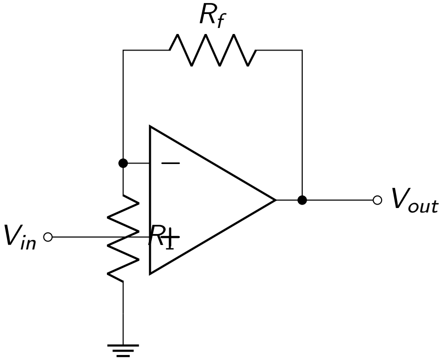
1. Use formula: $A_v = -\frac{R_f}{R_1}$
2. $-10 = -\frac{R_f}{10\ k\Omega} \implies R_f = 100\ k\Omega$
3. Calculate Output: $V_{out} = A_v \times V_{in} = -10 \times 0.5V = -5V$.

The output is -5V (inverted phase).



Non-Inverting Amplifier: Circuit Topology

- Input signal V_{in} is applied directly to the non-inverting (+) terminal.
- Inverting (-) terminal is connected to a voltage divider formed by R_f and R_1.
- R_1 is connected to ground.



Non-Inverting Amplifier: Gain Derivation

1. **Apply Virtual Short**: $V_{in-} = V_{in+} = V_{in}$.
2. **Apply KCL at node V_{in-}**:

$$\frac{V_{in-} - 0}{R_1} + \frac{V_{in-} - V_{out}}{R_f} = 0$$

3. **Substitute V_{in-} with V_{in}**:

$$\frac{V_{in}}{R_1} + \frac{V_{in}}{R_f} - \frac{V_{out}}{R_f} = 0$$

4. **Factor and Solve for Gain**:

$$V_{in}\left(\frac{1}{R_1} + \frac{1}{R_f}\right) = \frac{V_{out}}{R_f}$$

$$V_{out} = V_{in}\left(1 + \frac{R_f}{R_1}\right) \implies \boxed{A_v = 1 + \frac{R_f}{R_1}}$$

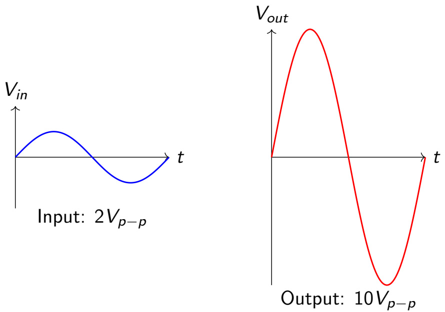
Non-Inverting Amplifier: Numerical Example

Problem: Given a non-inverting amplifier with $R_1 = 5$ kΩ and $R_f = 20$ kΩ, calculate the output voltage if a 2V peak-to-peak AC signal is applied.

Solution:

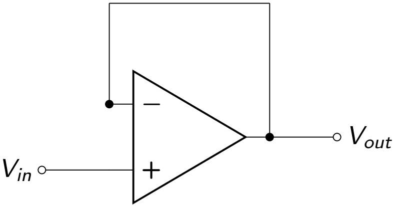
1. Calculate Gain: $A_v = 1 + \frac{R_f}{R_1} = 1 + \frac{20\text{k}}{5\text{k}} = 1 + 4 = 5$.
2. Calculate Output:
   $V_{out(p-p)} = A_v \times V_{in(p-p)} = 5 \times 2\text{V} = 10\text{V}_{p-p}$.

The output is 10V peak-to-peak, in phase with the input.



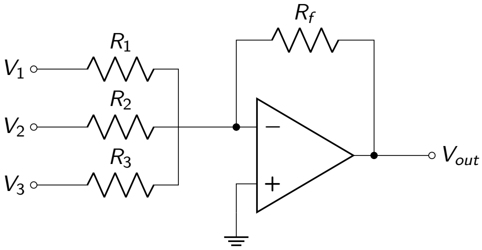
Voltage Follower (Unity Gain Buffer)

- A special case of the non-inverting amplifier where $R_f = 0\ \Omega$ (short circuit) and $R_1 = \infty$ (open circuit).
- **Gain Equation**: $A_v = 1 + \frac{0}{\infty} = 1$.
- Output perfectly follows the input: $V_{out} = V_{in}$.
- **Application**: Used as a buffer for impedance matching (high input impedance, low output impedance).



Summing Amplifier: Circuit Topology

- Based on the inverting amplifier topology.
- Multiple inputs ($V_1, V_2, V_3 \ldots$) are connected to the inverting terminal, each through their own input resistor ($R_1, R_2, R_3 \ldots$).
- The op-amp algebraically adds the input voltages together.



Summing Amplifier: Derivation

1. **Virtual Ground**: Node $V_{in-} = 0V$.
2. **KCL at Node V_{in-}**: Sum of currents is zero.

$$I_1 + I_2 + I_3 + I_f = 0$$

$$\frac{0 - V_1}{R_1} + \frac{0 - V_2}{R_2} + \frac{0 - V_3}{R_3} + \frac{0 - V_{out}}{R_f} = 0$$

3. **Solve for V_{out}**:

$$V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

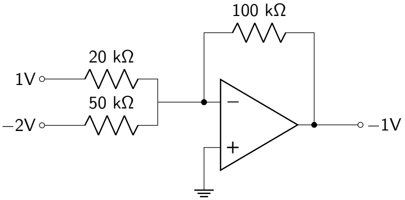
If $R_1 = R_2 = R_3 = R_f = R$, then $V_{out} = -(V_1 + V_2 + V_3)$.

Summing Amplifier: Numerical Example

Problem: A summing amplifier has $R_f = 100\ \text{k}\Omega$, $R_1 = 20\ \text{k}\Omega$, $R_2 = 50\ \text{k}\Omega$. Inputs are $V_1 = 1\text{V}$ and $V_2 = -2\text{V}$. Find V_{out}.

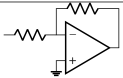
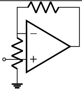
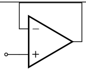
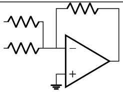
Solution:

1. Formula: $V_{out} = -\left(\frac{100\text{k}}{20\text{k}}(1\text{V}) + \frac{100\text{k}}{50\text{k}}(-2\text{V})\right)$
2. Calculate terms: $V_{out} = -\left(5(1\text{V}) + 2(-2\text{V})\right)$
3. Final Output: $V_{out} = -(5 - 4) = -(1\text{V}) = -1\text{V}$.



Summary

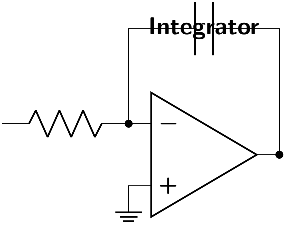
- **Virtual Ground/Short**: Key to analyzing negative feedback circuits.
- **Inverting Amp**: $A_v = -R_f/R_1$. Phase shifted by $180°$.
- **Non-Inverting Amp**: $A_v = 1 + R_f/R_1$. In phase.
- **Voltage Follower**: $A_v = 1$, used for impedance buffering.
- **Summing Amp**: Adds and scales multiple input signals.

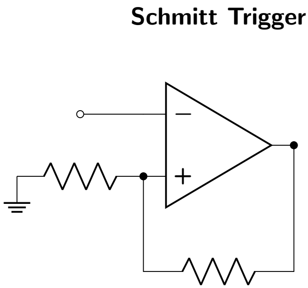
Circuit Name	Schematic	Gain Equation
Inverting Amp		$A_v = -\frac{R_f}{R_1}$
Non-Inverting Amp		$A_v = 1 + \frac{R_f}{R_1}$
Voltage Follower		$A_v = 1$
Summing Amp		$V_{out} = -(V_1 + V_2 + \dots)$

Next Lecture Preview

In Lecture 7, we will explore advanced applications:

- **Op-Amp as a Comparator** (Open-loop operation)
- **Integrator Circuit** (Calculus in analog hardware)
- **Differentiator Circuit**
- **Schmitt Trigger** (Positive feedback & Hysteresis)





Applied Electronics (DI03011021)

Complete Lecture Deck – All 30 Lectures

Milav Dabgar

Lecturer, GP Palanpur

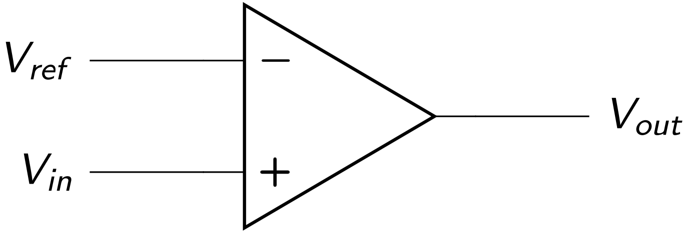
July 22, 2026

Agenda

- Op-Amp as a Comparator
- Integrator: Circuit & Derivation
- Differentiator: Circuit & Derivation
- Introduction to Positive Feedback
- The Schmitt Trigger
- Hysteresis Transfer Characteristics

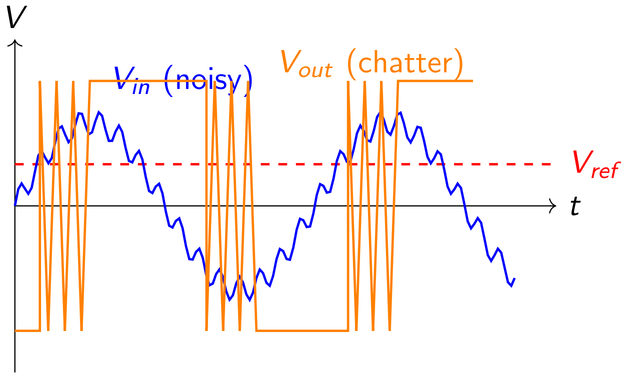
Op-Amp as a Comparator

- Operates in **open-loop** configuration (no feedback resistor).
- Compares an input voltage against a reference voltage.
- Because gain A_v is extremely high, the output immediately saturates to either $+V_{sat}$ or $-V_{sat}$.
- If $V_{in} > V_{ref} \implies V_{out} = +V_{sat}$
- If $V_{in} < V_{ref} \implies V_{out} = -V_{sat}$



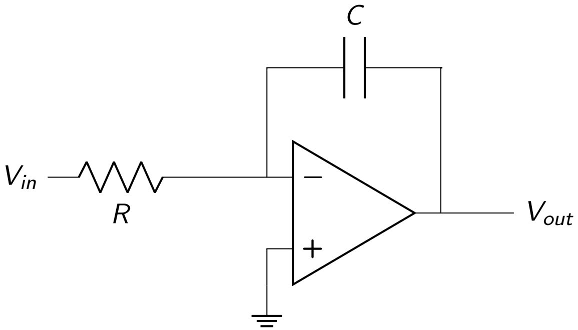
Comparator Transfer Characteristics

- The transfer curve is a sharp step function at $V_{in} = V_{ref}$.
- Ideal comparator has an infinitely steep transition.
- **Drawback**: Highly sensitive to noise. If V_{in} is noisy and sits near V_{ref}, the output will rapidly oscillate (chatter) between $+V_{sat}$ and $-V_{sat}$.



Integrator: Circuit Topology

- Derived from the inverting amplifier, but the feedback resistor R_f is replaced by a capacitor C.
- Performs mathematical integration of the input voltage over time.
- Used in analog computers, waveform generators, and low-pass filters.



Integrator: Mathematical Derivation

1. **Virtual Ground**: $V_{in-} = 0V$.
2. Current through R: $i_{in} = \frac{V_{in}}{R}$
3. Current through C: $i_c = C\frac{d}{dt}(V_{in-} - V_{out}) = -C\frac{dV_{out}}{dt}$
4. **Apply KCL** ($i_{in} = i_c$):

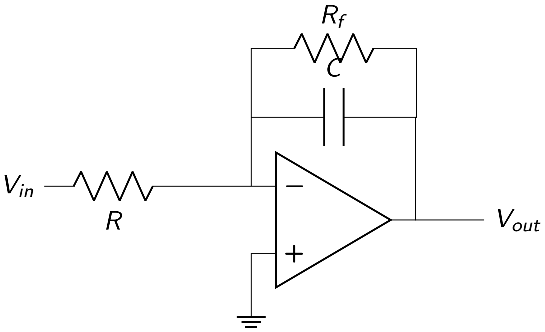
$$\frac{V_{in}}{R} = -C\frac{dV_{out}}{dt}$$

5. **Integrate both sides with respect to time**:

$$V_{out}(t) = -\frac{1}{RC}\int_0^t V_{in}(\tau)d\tau + V_{out}(0)$$

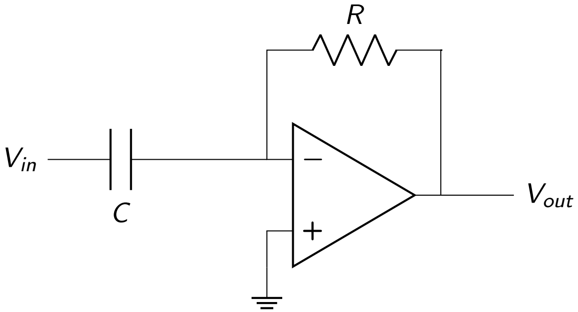
Practical Integrator Considerations

- **The DC Error Problem**: Small DC offset voltages (V_{io}) are integrated constantly, causing the output to slowly drift until it hits saturation (clipping).
- **Solution**: A large resistor R_f is placed in parallel with C to provide DC feedback and limit low-frequency gain.
- **RC Time Constant**: Defines the rate of integration.



Differentiator: Circuit Topology

- Swap the resistor and capacitor from the integrator.
- Input signal passes through capacitor C, and feedback is provided by resistor R.
- Performs mathematical differentiation of the input signal.
- Used for edge detection (converting square waves to sharp spikes) and high-pass filtering.



Differentiator: Mathematical Derivation

1. **Virtual Ground**: $V_{in-} = 0V$.
2. Current through C: $i_{in} = C\frac{d}{dt}(V_{in} - 0) = C\frac{dV_{in}}{dt}$
3. Current through R: $i_R = \frac{0-V_{out}}{R} = -\frac{V_{out}}{R}$
4. **Apply KCL** ($i_{in} = i_R$):

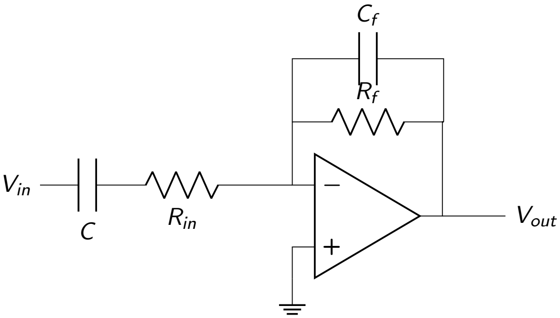
$$C\frac{dV_{in}}{dt} = -\frac{V_{out}}{R}$$

5. **Solve for Output**:

$$V_{out}(t) = -RC\frac{dV_{in}(t)}{dt}$$

Practical Differentiator & Noise

- **The Noise Problem**: The gain of a differentiator increases linearly with frequency. High-frequency noise is amplified massively, drowning out the actual signal.
- **Solution**: A small resistor R_{in} is added in series with the input capacitor to limit high-frequency gain.
- A small capacitor C_f is also often added in parallel with R_f for stability.



Introduction to Schmitt Trigger

- Solves the noise-chatter problem of the standard comparator.
- Uses **Positive Feedback**: A portion of the output is fed back to the non-inverting $(+)$ terminal.
- Positive feedback pushes the op-amp into saturation even faster and creates two distinct threshold voltages.
- This dual-threshold behavior is called **Hysteresis**.

Positive Feedback

$\Downarrow$

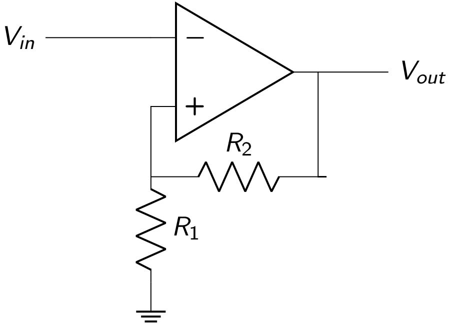
Hysteresis

$\Downarrow$

Noise Immunity

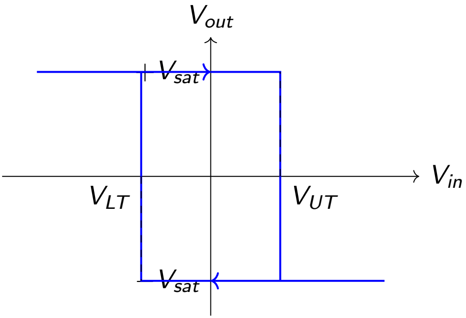
Schmitt Trigger Circuit (Inverting)

- Input signal is applied to the inverting (-) terminal.
- A voltage divider (R_1, R_2) connects the output to the non-inverting (+) terminal.
- Upper Threshold Voltage (V_{UT}): When $V_{out} = +V_{sat}$, $V_{in+} = +V_{sat}\frac{R_1}{R_1+R_2}$
- Lower Threshold Voltage (V_{LT}): When $V_{out} = -V_{sat}$, $V_{in+} = -V_{sat}\frac{R_1}{R_1+R_2}$



Hysteresis and Transfer Characteristics

- The transfer curve looks like a 'loop'.
- If output is HIGH ($+V_{sat}$), input must rise above V_{UT} to switch it LOW.
- Once LOW ($-V_{sat}$), input must fall below V_{LT} to switch it back HIGH.
- **Hysteresis Voltage (V_H)**: The difference between the thresholds. $V_H = V_{UT} - V_{LT}$.
- Noise smaller than V_H cannot cause a false trigger.



Summary

- **Comparator**: Open-loop, compares voltages, suffers from noise chatter.
- **Integrator**: Capacitor in feedback loop, $V_{out} = -\frac{1}{RC} \int V_{in} dt$. Needs DC parallel resistor.
- **Differentiator**: Capacitor at input, $V_{out} = -RC \frac{dV_{in}}{dt}$. Needs HF series resistor to cut noise.
- **Schmitt Trigger**: Positive feedback creates hysteresis, rejecting noise for clean switching.

Comparator
Open-loop

Integrator
C in feedback

Differentiator
C at input

Schmitt Trigger
Positive Feedback

Next Lecture Preview

- This concludes Unit 1 (Operational Amplifiers).
- In Lecture 8, we begin **Unit 2: Introduction to Thyristors**.
- What is a Thyristor?
- Construction of SCR (Silicon Controlled Rectifier)
- Two-transistor analogy
- V-I Characteristics of SCR

Unit 2

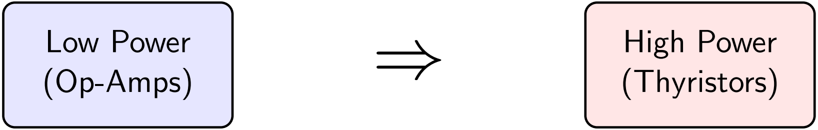
Power Electronics

&

Thyristors

Introduction to Thyristors: The SCR

- Course: Applied Electronics (DI03011021)
- Unit 2: Introduction to Thyristors
- Lecture 8: Construction, Symbol, Working, Characteristics and Applications of SCR



Agenda

- Introduction to Thyristors
- SCR Construction (PNPN Structure)
- SCR Symbol and Terminals
- Two-Transistor Model
- Modes of Operation (Reverse/Forward Blocking, Conduction)
- V-I Characteristics
- Latching vs. Holding Current
- Applications

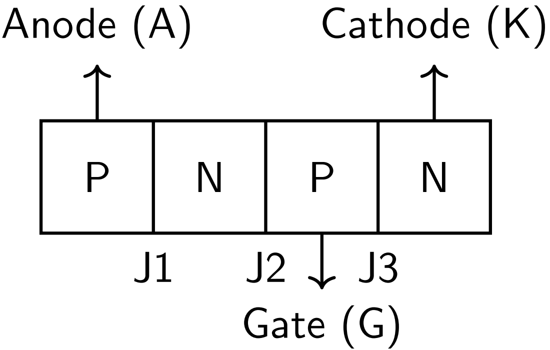
What is a Thyristor?

- A family of solid-state semiconductor devices with four layers of alternating P and N-type materials.
- Acts strictly as a bistable switch (it is either fully ON or fully OFF).
- The SCR (Silicon Controlled Rectifier) is the most widely used thyristor.
- Unlike transistors which can act as amplifiers, thyristors are exclusively used for switching high currents and voltages.

Transistor (BJT)	**Thyristor (SCR)**
Amplifier & Switch	Switch Only (Bistable)
Continuous Control	Latching Action
Low/Medium Power	High Power/Current

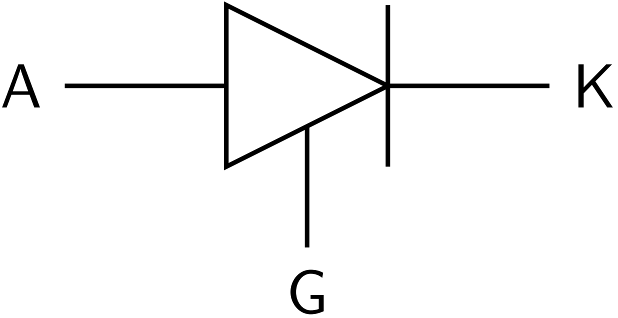
SCR Construction (PNPN)

- The SCR consists of four layers of semiconductor material: P-N-P-N.
- This forms three P-N junctions: J1, J2, and J3.
- The outer P-layer is heavily doped, forming the Anode.
- The outer N-layer is heavily doped, forming the Cathode.
- The inner P-layer is lightly doped and connects to the Gate.



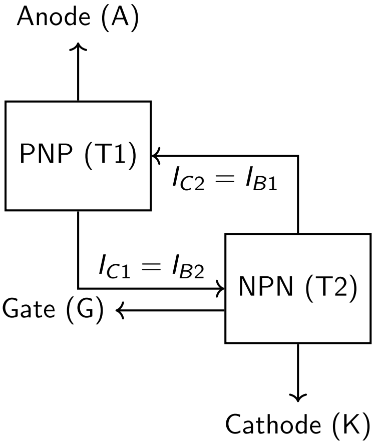
SCR Symbol

- **Anode (A):** Positive terminal.
- **Cathode (K):** Negative terminal.
- **Gate (G):** Control terminal used to trigger the device into conduction.
- The symbol resembles a standard P-N junction diode but with an additional gate terminal branching off near the cathode.



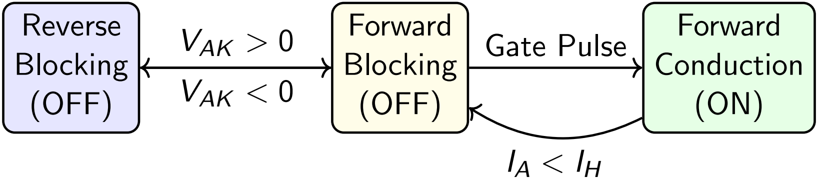
Two-Transistor Analogy

- The PNPN structure can be split into two interconnected transistors: a PNP transistor (T1) and an NPN transistor (T2).
- The collector of T1 feeds the base of T2.
- The collector of T2 feeds the base of T1.
- This creates a positive feedback loop (regenerative action). Once turned on, they keep each other in saturation.



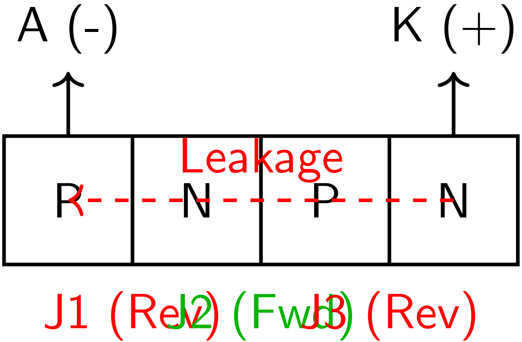
Modes of Operation

- An SCR operates in three primary modes depending on the biasing at the Anode (A) and Gate (G) relative to the Cathode (K):
- 1. **Reverse Blocking Mode:** A is negative wrt K.
- 2. **Forward Blocking Mode:** A is positive wrt K, but Gate is open.
- 3. **Forward Conduction Mode:** A is positive wrt K, and Gate is triggered (or Breakover voltage is reached).



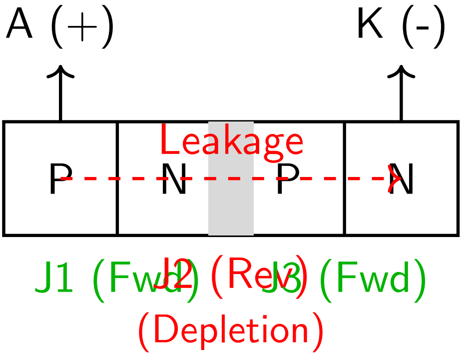
1. Reverse Blocking Mode

- **Condition:** Anode is negative, Cathode is positive.
- Junctions J1 and J3 are reverse biased.
- Junction J2 is forward biased.
- The device behaves like two reverse-biased diodes in series.
- Only a very small reverse leakage current flows.
- If reverse voltage exceeds the Breakdown Voltage (V_{BR}), avalanche breakdown occurs, which can destroy the SCR.



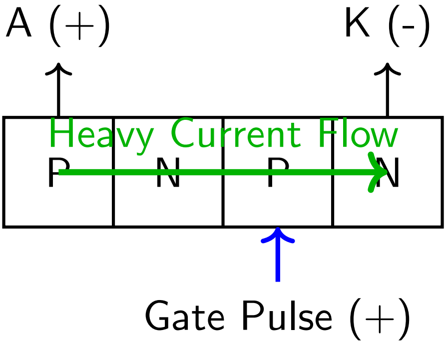
2. Forward Blocking Mode

- **Condition:** Anode is positive, Cathode is negative, Gate current $I_G = 0$.
- Junctions J1 and J3 are forward biased.
- Junction J2 is reverse biased.
- The reverse-biased J2 acts as a barrier, preventing significant current flow.
- Only a small forward leakage current flows.
- The SCR is still OFF.



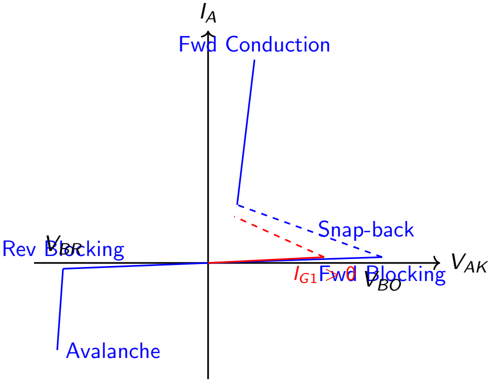
3. Forward Conduction Mode

- **Condition:** Anode is positive, and the SCR is triggered.
- Can be achieved in two ways:
- 1. Increasing V_{AK} beyond the Forward Breakover Voltage (V_{BO}) (causes avalanche breakdown of J2 - not recommended for normal operation).
- 2. Applying a positive pulse to the Gate (injects charge carriers, turning on the two-transistor feedback loop).
- Once in conduction, the voltage drop across the SCR is very small (1-2V), and current is limited by the external load.



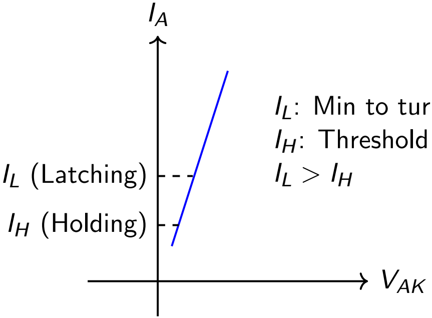
V-I Characteristics of SCR

- The V-I curve shows the relationship between Anode-Cathode voltage (V_{AK}) and Anode current (I_A):
- **First Quadrant (Forward Bias):** Shows forward blocking region, breakover voltage V_{BO}, and forward conduction region.
- **Third Quadrant (Reverse Bias):** Shows reverse blocking region and reverse breakdown voltage V_{BR}.
- Note how increasing Gate Current (I_G) lowers the breakover voltage.



Latching Current vs. Holding Current

- **Latching Current (I_L):** The minimum Anode current required to maintain the SCR in the ON state immediately after it has been turned on and the gate signal is removed. (Associated with Turn-ON).
- **Holding Current (I_H):** The minimum Anode current below which the SCR will turn OFF and return to the forward blocking state. (Associated with Turn-OFF).
- **Important Relation:** $I_L > I_H$ (Latching current is typically 2-3 times higher than holding current).



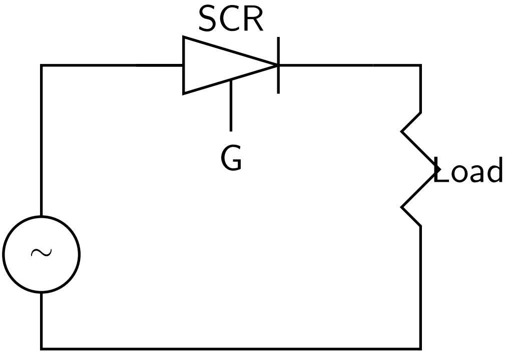
I_L: Min to turn ON
I_H: Threshold to OFF
$I_L > I_H$

Turn-On and Turn-Off of SCR

- **Turn-On (Triggering):**
  - Gate Triggering (Most common)
  - Forward Voltage Triggering (Exceeding V_{BO})
  - dv/dt Triggering (Rapid rise in voltage)
  - Thermal Triggering (High temperature)
  - Light Triggering (LASCR)
- **Turn-Off (Commutation):**
  - The gate CANNOT turn off a standard SCR.
  - To turn off, the Anode current must be reduced below the Holding Current (I_H).
  - Methods: Natural commutation (AC circuits) or Forced commutation (DC circuits).

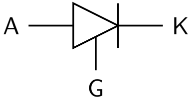
Applications of SCR

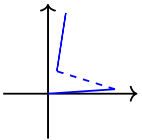
- Due to their high voltage and current ratings, SCRs are used in:
- **Controlled Rectifiers:** Converting AC to variable DC (Phase Control).
- **Motor Control:** Speed control of DC and AC motors.
- **Static Switches:** Solid-state relays for high power.
- **Inverters and Cycloconverters:** Power conversion systems.
- **Overvoltage Protection:** Crowbar circuits in power supplies.



Summary

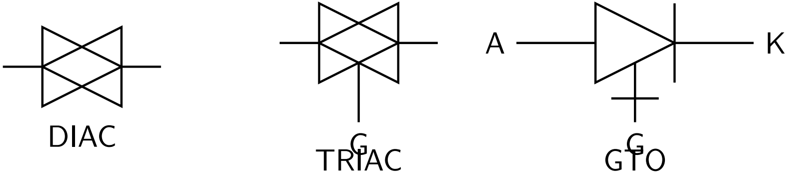
- The SCR is a 4-layer (PNPN), 3-terminal (Anode, Cathode, Gate) bistable switch.
- It operates in reverse blocking, forward blocking, and forward conduction modes.
- It is turned ON by a gate pulse but requires external commutation (reducing $I_A < I_H$) to turn OFF.
- Latching current is the minimum to stay ON initially; Holding current is the threshold to turn OFF.
- Highly applicable in high-power controlled rectification and motor drives.





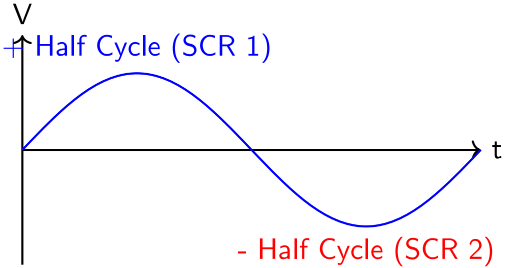
Next Lecture Preview

- **Next Topic: DIAC, TRIAC, and GTO**
- We will explore bidirectional thyristors (DIAC and TRIAC) used primarily for AC control.
- We will also look at the Gate Turn-Off (GTO) thyristor, which solves the problem of needing external commutation circuits to turn OFF the device.



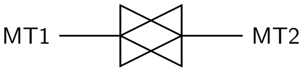
Need for Bidirectional Devices

- An SCR is a **unidirectional** device; it only conducts current in one direction (Anode to Cathode).
- To control AC power (which reverses polarity every half cycle), we would need two SCRs connected in anti-parallel.
- This requires two separate gate triggering circuits, complicating the design.
- **Solution:** A bidirectional device like a TRIAC that can conduct in both directions with a single gate terminal.



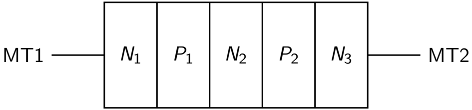
DIAC: Introduction and Symbol

- **DIAC** stands for **DI**ode for **A**lternating **C**urrent.
- It is a bidirectional semiconductor switch that can be turned on in both forward and reverse polarities.
- It has no gate terminal; it turns on simply when the applied voltage exceeds its breakover voltage (V_{BO}).
- **Terminals:** Main Terminal 1 (MT1) and Main Terminal 2 (MT2).



DIAC: Construction and Working

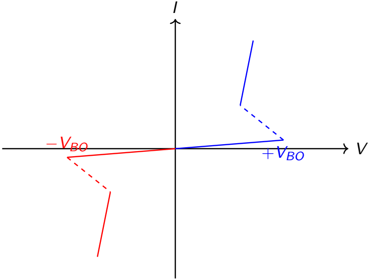
- **Construction:** It has a symmetrical structure (like a PNP with N regions on both sides, or NPN with P regions).
- When MT2 is positive with respect to MT1, one half of the structure acts as a forward-biased PNPN switch.
- When MT1 is positive with respect to MT2, the other half acts as the switch.
- It remains in blocking state until the applied voltage reaches $+V_{BO}$ or $-V_{BO}$.
- Once V_{BO} is reached, it snaps into conduction (negative resistance region) and voltage drops.



Equivalent symmetrical 5-layer structure

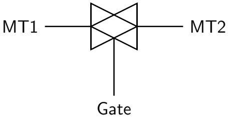
DIAC: V-I Characteristics

- The V-I curve looks like a 'Z' shape, symmetrical in the first and third quadrants.
- **Forward Blocking:** Small leakage current until $+V_{BO}$.
- **Forward Conduction:** Voltage snaps back, current increases sharply.
- **Reverse Blocking:** Small leakage current until $-V_{BO}$.
- **Reverse Conduction:** Voltage snaps back, current increases sharply in the reverse direction.



TRIAC: Introduction and Symbol

- **TRIAC** stands for **TRI**ode for **A**lternating **C**urrent.
- A 3-terminal, bidirectional semiconductor device.
- It is functionally equivalent to two SCRs connected in anti-parallel with a common gate.
- **Terminals:** Main Terminal 1 (MT1), Main Terminal 2 (MT2), and Gate (G).
- Can conduct current in both directions and can be triggered by either a positive or negative gate current.



TRIAC Working Principle & Modes

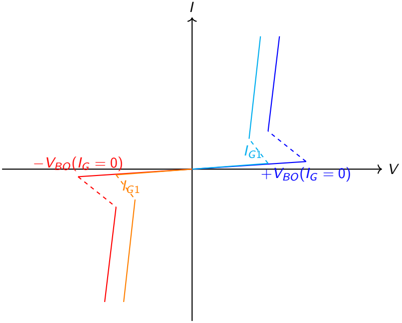
- A TRIAC can be triggered into conduction in four different modes (quadrants), depending on the polarity of MT2 and the Gate, relative to MT1:

Quadrant (Mode)	MT2 Polarity	Gate Polarity	Sensitivity
1. Mode I+ (Quadrant I)	Positive (+)	Positive (+)	High Sensitivity
2. Mode I- (Quadrant II)	Positive (+)	Negative (-)	Medium Sensitivity
3. Mode III+ (Quadrant IV)	Negative (-)	Positive (+)	Low Sensitivity
4. Mode III- (Quadrant III)	Negative (-)	Negative (-)	High Sensitivity

- Modes I+ and III- are the most sensitive (require the least gate current to trigger).

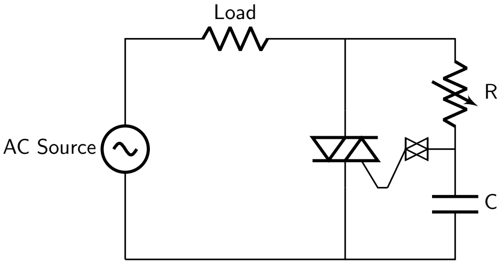
TRIAC V-I Characteristics

- The V-I curve is a combination of two SCR curves: one in the first quadrant, one in the third quadrant.
- In the first quadrant, MT2 is positive wrt MT1.
- In the third quadrant, MT2 is negative wrt MT1.
- Like the SCR, increasing the gate current reduces the breakover voltage in both directions.



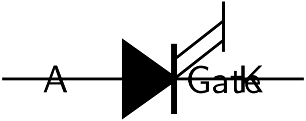
AC Phase Control using DIAC and TRIAC

- TRIACs are heavily used for AC phase control (dimming lights, motor speed).
- **The Problem:** TRIACs have different gate sensitivities in different quadrants, leading to asymmetrical firing and DC harmonics.
- **The Solution:** A DIAC is placed in series with the TRIAC gate. The DIAC ensures that the TRIAC is only triggered when the capacitor voltage reaches a consistent threshold ($\pm V_{BO}$ of the DIAC), resulting in perfectly symmetrical switching.



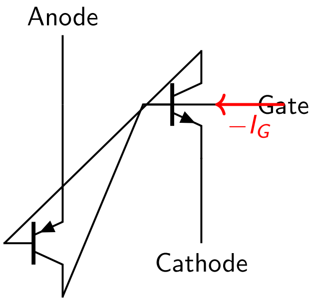
Gate Turn-Off (GTO) Thyristor

- **Problem with SCR:** Once an SCR is triggered ON, the gate loses control. Turning it OFF requires reducing the main current below the holding current (commutation circuit).
- **Solution:** The **GTO (Gate Turn-Off)** thyristor.
- A GTO can be turned ON by a positive gate current pulse (like an SCR).
- Crucially, a GTO can be turned OFF by a **negative gate current pulse**.



GTO Working Principle

- **Turn-ON:** Similar to an SCR, a positive gate current turns on the NPN and PNP transistor pair.
- **Turn-OFF:** A large negative gate current is applied. This extracts holes from the P-base (base of the NPN transistor), breaking the regenerative positive feedback loop.
- **Drawback:** Turning off requires a very large negative gate current (often 1/3 to 1/5 of the Anode current). A GTO carrying 1000A might need a 200A-300A negative gate pulse to turn off!



GTO vs. Standard SCR

Feature	Standard SCR	GTO
Turn-On	Positive Gate Pulse	Positive Gate Pulse
Turn-Off	External Commutation	Negative Gate Pulse
Switching Speed	Slower	Faster
Gate Drive Circuit	Simple (Low Power)	Complex (High Power for turn-off)
On-state Voltage Drop	Lower (1-1.5V)	Higher (2-3V)
Application	AC phase control, HVDC	High power DC drives, inverters

Applications of TRIAC and GTO

TRIAC Applications:

- Domestic light dimmers.
- Speed control of small AC motors (fans, blenders).
- Solid-state relays for AC loads.
- Heating control systems.

GTO Applications:

- Traction systems (electric trains, subways).
- High-power inverters (DC to AC conversion).
- High-performance motor drives.
- Static VAR compensators.

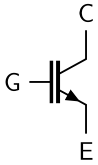
Summary

- **DIAC:** A bidirectional diode used primarily to create clean trigger pulses.
- **TRIAC:** A bidirectional thyristor that controls AC power, functionally equivalent to two anti-parallel SCRs.
- The DIAC-TRIAC combination is the standard for AC phase control circuits to ensure symmetrical switching.
- **GTO:** A thyristor that can be turned OFF by a negative gate pulse, eliminating external commutation circuits, but requiring a powerful gate drive.

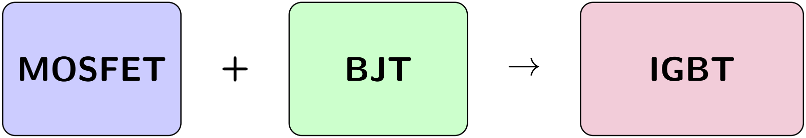
Next Lecture Preview

Next Topic: IGBT and MCT

- We will explore modern power semiconductor devices that combine the best features of different technologies.
- **IGBT (Insulated Gate Bipolar Transistor):** Combines the simple gate drive of a MOSFET with the high current capacity of a BJT.
- **MCT (MOS-Controlled Thyristor):** A thyristor that uses MOSFETs integrated into its structure to control turn-on and turn-off.



- Course: Applied Electronics (DI03011021)
- Unit 2: Introduction to Thyristors
- Lecture 10: IGBT and MOS-Controlled Thyristor (MCT)



Agenda

- Evolution of Power Switches (BJT vs. MOSFET)
- IGBT: Introduction, Symbol, and Construction
- IGBT Equivalent Circuit and Working Principle
- IGBT Characteristics (Output & Transfer)
- Advantages of IGBT
- MCT: Introduction and Symbol
- MCT Working Principle
- Applications of IGBT and MCT

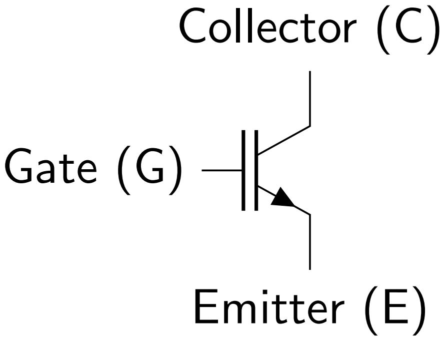
Evolution: BJT vs. Power MOSFET

- **Power BJT (Bipolar Junction Transistor):**
  - *Pros:* High current/voltage handling, low on-state voltage drop.
  - *Cons:* Current controlled device (requires large continuous base current), slower switching speed.
- **Power MOSFET:**
  - *Pros:* Voltage controlled device (almost zero gate current required), extremely fast switching.
  - *Cons:* High on-state resistance at high voltages ($R_{DS(on)}$), leading to high conduction losses in high-power applications.

Feature	Power BJT	Power MOSFET
Control	Current controlled	Voltage controlled
Gate/Base Drive	High continuous current	Near zero gate current
Switching Speed	Slower	Extremely fast
On-state Loss	Low voltage drop	High resistance at high voltage

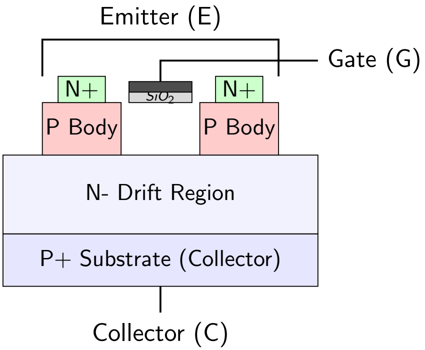
IGBT: Introduction and Symbol

- **IGBT** = **I**nsulated **G**ate **B**ipolar **T**ransistor.
- A hybrid power semiconductor device.
- It combines the insulated gate (voltage control) of a MOSFET with the bipolar conduction (low on-state voltage drop) of a BJT.
- **Terminals:** Gate (G), Collector (C), and Emitter (E).
- Note the naming: Gate from MOSFET, Collector/Emitter from BJT.



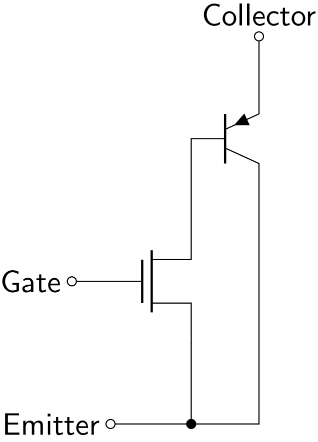
IGBT Construction

- Built on a $P+$ substrate (Injecting layer), unlike a Power MOSFET which is built on an $N+$ substrate.
- Above this is an $N-$ drift layer, which determines the voltage blocking capability.
- Then a P body region containing $N+$ source regions.
- A polysilicon Gate is insulated from the semiconductor by a thin layer of Silicon Dioxide (SiO_2).
- The $P+$ substrate injects holes into the $N-$ drift region, causing 'conductivity modulation', which drastically reduces on-state resistance.



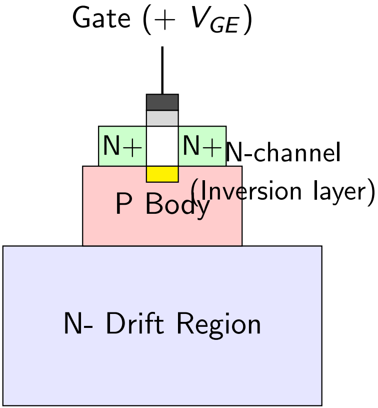
IGBT Equivalent Circuit

- Functionally, an IGBT acts as a PNP bipolar transistor driven by an N-channel MOSFET in a Darlington-like configuration.
- There is also a parasitic NPN transistor formed by the internal layers, creating a parasitic thyristor (PNPN structure).
- Modern IGBT design ensures this parasitic thyristor is suppressed (latch-up prevention) so it behaves purely as a transistor.



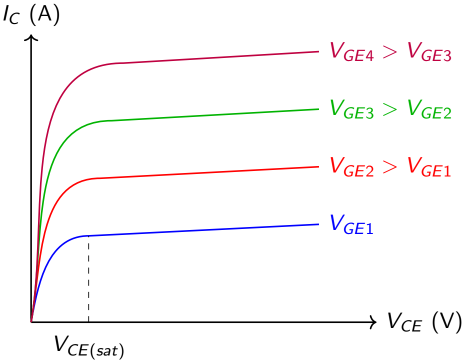
IGBT Working Principle

- **Turn-ON:** Apply a positive voltage V_{GE} (usually +15V) to the Gate relative to Emitter. This creates an inversion layer (N-channel) under the gate, allowing electrons to flow from Emitter to the N- drift region. This base current turns ON the internal PNP transistor.
- **Turn-OFF:** Remove the gate voltage (or apply a negative voltage, e.g., -5V) to remove the inversion layer. The electron supply is cut off, and the PNP transistor turns OFF.



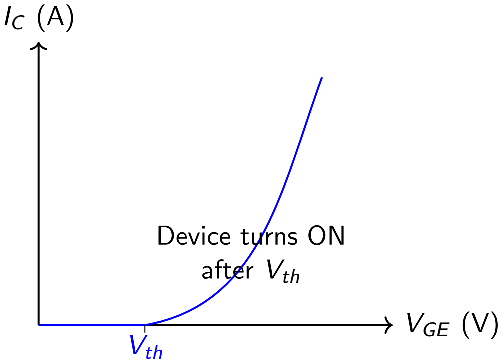
IGBT Output Characteristics

- The plot of Collector Current (I_C) vs. Collector-Emitter Voltage (V_{CE}) for various Gate Voltages (V_{GE}).
- Similar shape to BJT output characteristics.
- Has a forward blocking region (when $V_{GE} < V_{th}$).
- Has an active region and a saturation region.
- In the ON state (saturation), the voltage drop $V_{CE(sat)}$ is very low (typically 1.5V to 2.5V), independent of the device's voltage rating.



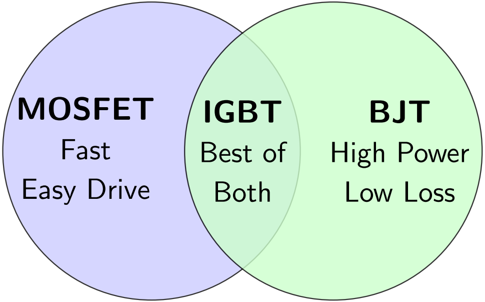
IGBT Transfer Characteristics

- The plot of Collector Current (I_C) vs. Gate-Emitter Voltage (V_{GE}).
- Shows the threshold voltage (V_{th}). The IGBT remains OFF until V_{GE} exceeds V_{th} (typically 3V to 5V).
- Beyond V_{th}, the collector current increases rapidly and linearly with increasing gate voltage.
- This demonstrates the voltage-controlled nature of the device.



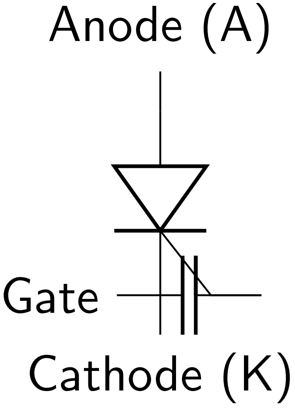
Advantages of IGBT

- Why is the IGBT so dominant in modern power electronics?
- **1. High Input Impedance:** Easy to drive with simple logic-level voltage circuits (like a MOSFET).
- **2. Low On-State Voltage Drop:** Excellent current handling and low conduction losses (like a BJT).
- **3. High Switching Speed:** Faster than BJTs and standard Thyristors (though slightly slower than pure MOSFETs).
- **4. High Voltage and Current Ratings:** Capable of handling thousands of Volts and Amperes.
- **5. Superior Safe Operating Area (SOA):** Robust against short circuits and overloads.



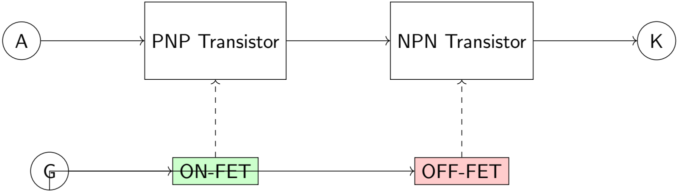
MOS-Controlled Thyristor (MCT): Introduction

- **MCT** is another hybrid device: A Thyristor with integrated MOSFETs for turn-ON and turn-OFF.
- Recall the GTO: It can turn off via the gate, but requires a massive negative current pulse.
- The MCT solves this: It uses a voltage signal applied to a MOS gate to turn the thyristor ON and OFF.
- It combines the ultra-low conduction losses of a thyristor with the easy voltage drive of a MOSFET.



MCT Working Principle

- An MCT contains tens of thousands of parallel microscopic cells.
- Each cell contains a main PNPN thyristor structure, an ON-FET, and an OFF-FET.
- **Turn-ON:** Applying a negative voltage pulse (for P-MCT) to the gate turns on the ON-FET, which provides base current to the internal thyristor, triggering it into latching conduction.
- **Turn-OFF:** Applying a positive voltage pulse to the gate turns on the OFF-FET. The OFF-FET shorts the emitter-base junction of the internal transistor, breaking the regenerative feedback and turning the thyristor OFF.



MCT Characteristics & Limitations

- **Characteristics:**
  - Lowest forward voltage drop of any gate-controlled device (even lower than IGBT).
  - High surge current capability.
  - Requires very little gate power.
- **Limitations:**
  - Switching speed is generally slower than IGBTs.
  - Limited Reverse Blocking capability.
  - Susceptible to accidental turn-on due to high dv/dt.
  - Difficult to parallel devices due to negative temperature coefficient.

Feature	**IGBT**	**MCT**
Conduction Loss	Low	Extremely Low
Gate Control	Voltage (+ to ON, 0 to OFF)	Voltage Pulse (− to ON, + to OFF)
dv/dt **Immunity**	Good	Poor (accidental turn-on)
Paralleling	Easy (Positive Temp. Coeff.)	Difficult (Negative Temp. Coeff.)

Applications of IGBT and MCT

- **IGBT Applications (Widespread):**
  - Electric Vehicle (EV) motor inverters.
  - Variable Frequency Drives (VFD) for industrial motors.
  - UPS Systems (Uninterruptible Power Supplies).
  - Induction heating cooktops.
  - Wind and Solar power inverters.
- **MCT Applications (Niche):**
  - Very high-power, low-frequency switching applications.
  - Solid-state circuit breakers.
  - Pulse power applications.

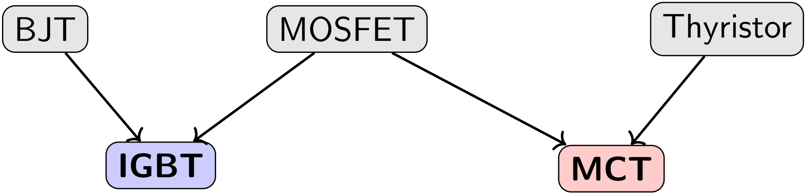
Electric Vehicles
Motor Inverters

VFD Drives
Industrial Motors

UPS Systems
Power Backup

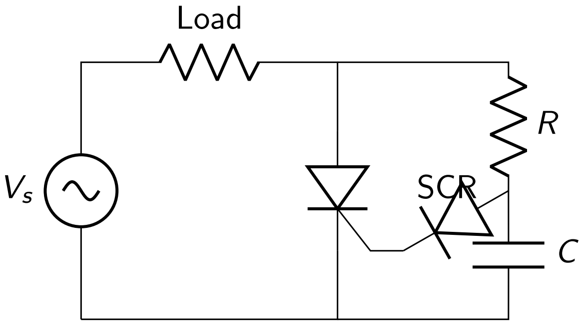
Summary

- The **IGBT** combines the voltage-controlled insulated gate of a MOSFET with the high-current, low-loss output of a BJT.
- It is easy to drive, fast, and handles high power, making it dominant in modern power electronics.
- The **MCT** combines a thyristor structure with MOSFETs to achieve voltage-controlled turn-ON and turn-OFF.
- MCTs have the lowest conduction losses but are limited by slower switching speeds and manufacturing complexities.



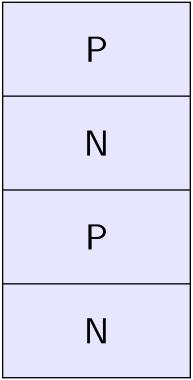
Next Lecture Preview

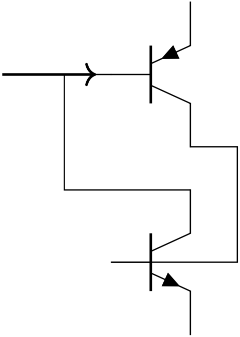
- **Next Topic: Turn ON and Turn OFF methods of Thyristor**
- Unit 3 begins!
- We will dive deeper into the specific circuits used to turn thyristors ON (Triggering/Firing circuits).
- We will explore the complex commutation circuits required to turn standard SCRs OFF in DC applications.



Working of SCR using Two Transistor Analogy

- Unit 2: Introduction to Thyristors
- Lecture 11: Two Transistor Analogy of SCR



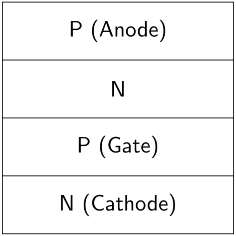


Agenda

- Review of the SCR PNPN Structure
- Splitting PNPN into PNP and NPN Transistors
- Two-Transistor Equivalent Circuit
- Current Components and Transistor Gains (α)
- Mathematical Derivation of Anode Current (I_A)
- Regenerative Feedback Mechanism
- Turn-on (Latching) Condition

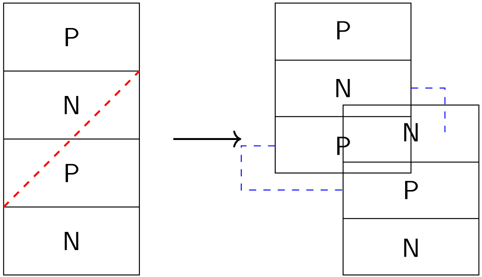
The SCR PNPN Structure

- An SCR consists of four alternating layers of semiconductor material: P-N-P-N.
- It has three terminals: Anode (A), Cathode (K), and Gate (G).
- It forms three distinct PN junctions: J_1, J_2, and J_3.
- During forward blocking, J_1 and J_3 are forward biased, while J_2 is reverse biased.



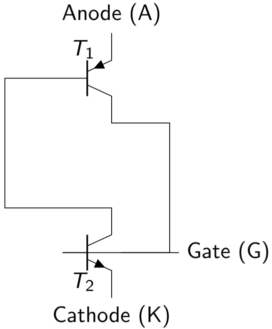
Splitting the PNPN Structure

- To understand the operation, we can conceptually split the middle N and P layers.
- The top three layers (P-N-P) form a PNP transistor (T_1).
- The bottom three layers (N-P-N) form an NPN transistor (T_2).
- The N base of T_1 is shared with the N collector of T_2.
- The P collector of T_1 is shared with the P base of T_2.



Two-Transistor Equivalent Circuit

- **Transistor T_1 (PNP):** Emitter is Anode (A), Base connects to Collector of T_2, Collector connects to Base of T_2.
- **Transistor T_2 (NPN):** Emitter is Cathode (K), Base connects to Collector of T_1 and Gate (G), Collector connects to Base of T_1.
- This cross-coupling creates a feedback loop.



Transistor Current Relations

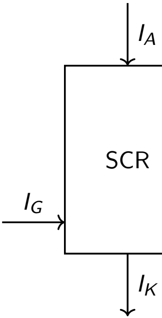
- For any transistor, the collector current I_C is related to the emitter current I_E by the common-base current gain α and leakage current I_{CBO}.
- General equation: $I_C = \alpha I_E + I_{CBO}$
- For T_1 (PNP): $I_{C1} = \alpha_1 I_A + I_{CBO1}$ (since Emitter current is Anode current I_A)
- For T_2 (NPN): $I_{C2} = \alpha_2 I_K + I_{CBO2}$ (since Emitter current is Cathode current I_K)

Key Equations

$$I_{C1} = \alpha_1 I_A + I_{CBO1}$$
$$I_{C2} = \alpha_2 I_K + I_{CBO2}$$

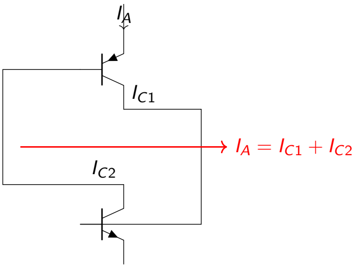
Applying Kirchhoff's Current Law (KCL)

- Looking at the entire device as a single node:
- Total current entering = Total current leaving
- $I_A + I_G = I_K$
- Where:
  - I_A = Anode Current
  - I_G = Gate Current
  - I_K = Cathode Current



Internal Current Node Analysis

- Let's look at the internal connection between the two transistors.
- The total anode current I_A splits into the collector current of T_2 and the base current of T_1.
- Equivalently, across the middle junction J_2, the total current is the sum of the two collector currents.
- $I_A = I_{C1} + I_{C2}$



Substituting the Transistor Equations

- Substitute I_{C1} and I_{C2} into $I_A = I_{C1} + I_{C2}$:

$$I_A = (\alpha_1 I_A + I_{CBO1}) + (\alpha_2 I_K + I_{CBO2})$$

- From our KCL rule, substitute $I_K = I_A + I_G$:

$$I_A = \alpha_1 I_A + I_{CBO1} + \alpha_2(I_A + I_G) + I_{CBO2}$$

- Group the I_A terms:

$$I_A - \alpha_1 I_A - \alpha_2 I_A = \alpha_2 I_G + I_{CBO1} + I_{CBO2}$$

$$I_A(1 - (\alpha_1 + \alpha_2)) = \alpha_2 I_G + I_{CBO1} + I_{CBO2}$$

Equation for Anode Current (I_A)

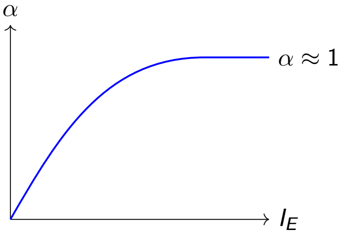
- Solving for I_A, we get the fundamental SCR equation:

$$I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

- Where:
  - α_1, α_2: Common-base current gains of T_1, T_2
  - I_G: Gate current
  - I_{CBO1}, I_{CBO2}: Leakage currents

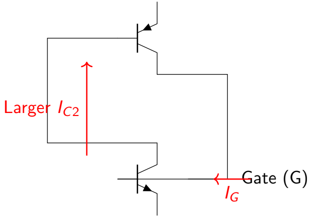
Understanding the Denominator

- Let's analyze the denominator: $1 - (\alpha_1 + \alpha_2)$
- In a standard transistor, α is a function of emitter current (I_E). At low currents, α is very small.
- When the SCR is off (blocking state), I_A is small (only leakage), so α_1 and α_2 are very small.
- Therefore, $(\alpha_1 + \alpha_2) \ll 1$, and I_A remains just the small leakage current.



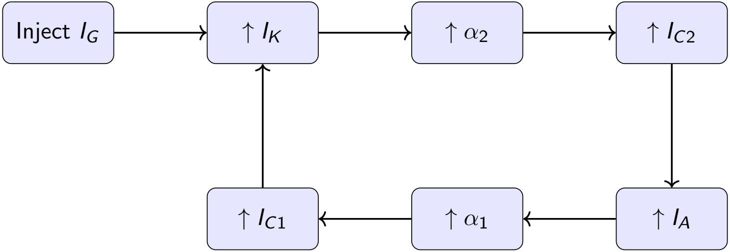
The Role of Gate Current (I_G)

- When a gate pulse I_G is injected, it acts as the base current for NPN transistor T_2.
- This causes T_2 to turn on, increasing its emitter current (I_K).
- As I_K increases, the gain α_2 increases.
- This leads to a larger collector current I_{C2}, which feeds directly into the base of T_1.



Regenerative Feedback Loop

- 1. Gate current increases I_{C2}.
- 2. I_{C2} provides base drive for T_1, increasing T_1's emitter current (I_A).
- 3. Increased I_A raises α_1 and produces a larger I_{C1}.
- 4. I_{C1} feeds back into the base of T_2, further increasing I_{C2}.
- **Result:** This continuous cycle is called positive (regenerative) feedback.



Turn-on (Latching) Condition

- Due to the feedback loop, $(\alpha_1 + \alpha_2)$ rapidly approaches 1.
- Look back at the equation: $I_A = \frac{\text{Numerator}}{1-(\alpha_1+\alpha_2)}$
- As $(\alpha_1 + \alpha_2) \to 1$, the denominator approaches 0.
- The anode current I_A theoretically approaches infinity, but is practically limited only by the external load resistor.
- The SCR is now 'latched' in the ON state.

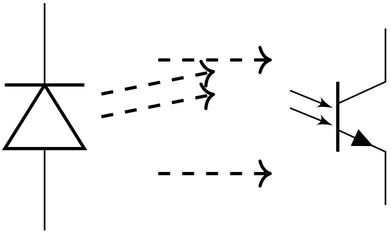
$$\text{If } (\alpha_1 + \alpha_2) \to 1, \text{ then } 1 - (\alpha_1 + \alpha_2) \to 0$$
$$\therefore I_A \to \infty \text{ (Limited by Load)}$$

Summary

- ✓ The SCR can be analyzed as a PNP and an NPN transistor cross-coupled together.
- ✓ The anode current is given by: $I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1-(\alpha_1+\alpha_2)}$
- ✓ A small gate current starts a regenerative feedback loop.
- ✓ When $\alpha_1 + \alpha_2$ approaches 1, the SCR latches ON and the gate loses control.

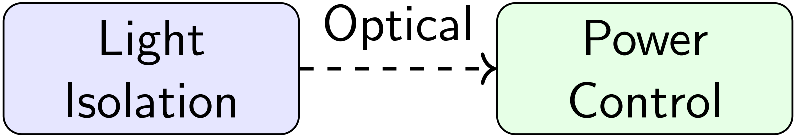
Next Lecture Preview

- Lecture 12: Opto-Isolators & Opto-Coupled Thyristors
- **Topics:**
  - Concept of Galvanic Isolation
  - Working of Opto-Isolators
  - LASCR, Opto-TRIAC, and Opto-Transistor



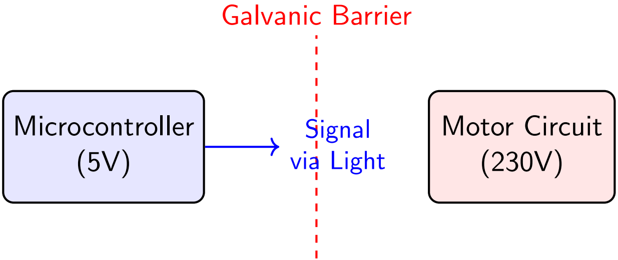
Agenda

- Concept of Galvanic Isolation
- Introduction to Opto-Isolators (Optocouplers)
- Basic Construction & LED-Photodetector Pairings
- Opto-Transistor: Construction & Working
- Light-Activated SCR (LASCR)
- Opto-TRIAC: Construction & Working



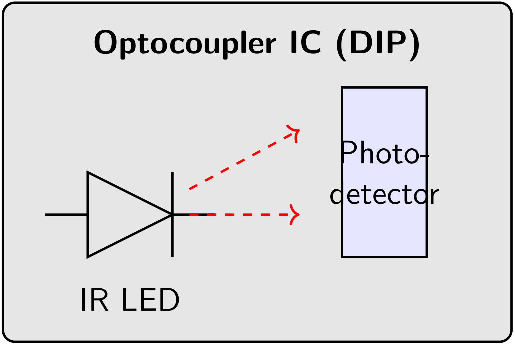
What is Galvanic Isolation?

- **Galvanic Isolation** is the principle of isolating functional sections of electrical systems to prevent current flow between them.
- There is no direct electrical connection (no shared ground) between the input and output.
- Information or power is exchanged via other means (e.g., optical, magnetic, or capacitive).
- **Why it's needed:** Protects low-voltage digital control circuits (like microcontrollers) from high-voltage transients in power circuits.



Introduction to Opto-Isolators

- An **Opto-Isolator** (or Optocoupler) is an electronic component that transfers electrical signals between two isolated circuits by using light.
- It consists of a light emitter (usually an Infrared LED) and a light-sensitive receiver (photodetector).
- Both are enclosed in a single light-proof package.
- When an input electrical signal drives the LED, it emits light. The receiver detects this light and allows current to flow on the output side.



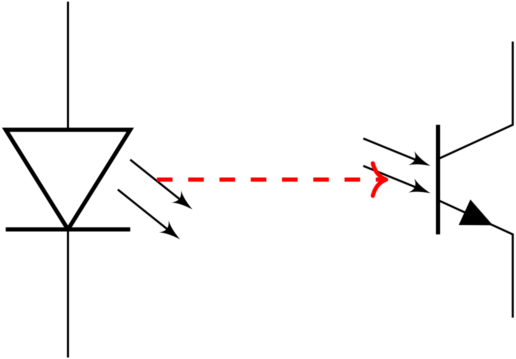
LED and Photodetector Pairings

- The type of opto-isolator is defined by the type of photodetector used inside.
- Common Emitter: **Infrared (IR) LED** (Gallium Arsenide).
- Common Detectors:
  1. **Photodiode**: Very fast, linear response, low output current.
  2. **Phototransistor**: Slower, amplifies the photocurrent.
  3. **Photo-Darlington**: Very high gain, but slower switching.
  4. **Photo-Thyristor (LASCR / Opto-TRIAC)**: Used for switching AC high-power loads.

Receiver Type	**Characteristics**	**Common Applications**
Photodiode	High speed, linear	Fast data transmission
Phototransistor	Moderate speed, gain	General purpose logic
Photo-Darlington	High gain, slow	Low input current driving
Photo-Thyristor	Handles AC power	Solid state relays, AC switching

The Opto-Transistor

- An Opto-Transistor combines an LED with a bipolar junction phototransistor.
- The base terminal of the phototransistor is left floating or internally exposed to light.
- **Working:** Light from the LED hits the base-collector junction of the transistor, generating electron-hole pairs.
- This acts as the base current, causing the transistor to turn ON and conduct collector-to-emitter current.



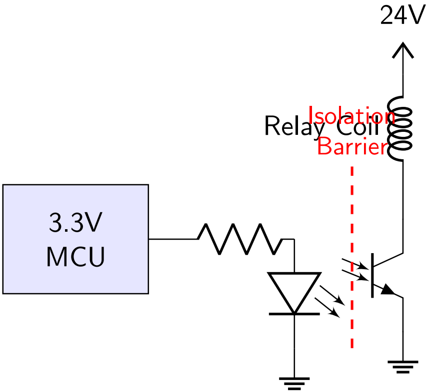
Opto-Transistor Applications

Applications:

- Microprocessor input/output isolation.
- DC motor control interfacing.
- Switch-mode power supply (SMPS) feedback loops.

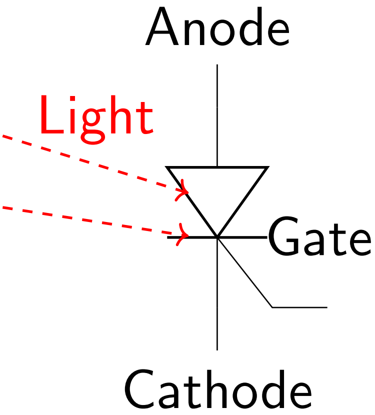
Characteristics:

- Current Transfer Ratio (CTR): The ratio of output collector current to input LED forward current (analogous to h_{FE}).
- Provides isolation up to several kilovolts (kV).



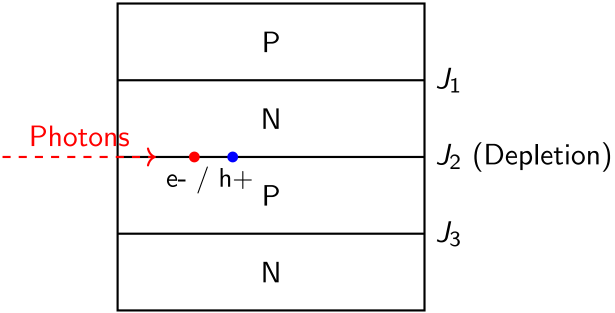
Light-Activated SCR (LASCR)

- A Light-Activated Silicon Controlled Rectifier (LASCR) is an SCR that is triggered by light.
- Like a standard SCR, it has Anode and Cathode terminals, and a Gate.
- However, there is a transparent window in the casing above the J_2 junction (the reverse-biased middle junction).
- Can be triggered either by an electrical gate pulse OR by light.



Working Mechanism of LASCR

- When forward biased (A positive, K negative), junction J_2 blocks current.
- When light photons strike the depletion region of J_2, they create electron-hole pairs.
- These charge carriers are swept across the junction by the electric field, creating a photocurrent.
- This photocurrent acts as an internal gate current (I_G).
- If the light intensity is high enough, this photocurrent triggers the regenerative feedback loop, latching the SCR ON.



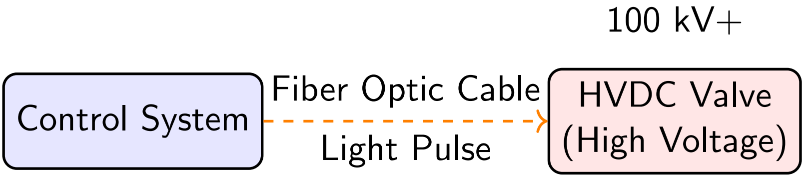
Advantages and Usage of LASCR

Advantages:

- Complete electrical isolation between triggering light source and high power AC/DC circuit.
- Immune to electrical noise at the gate (since triggering is optical).

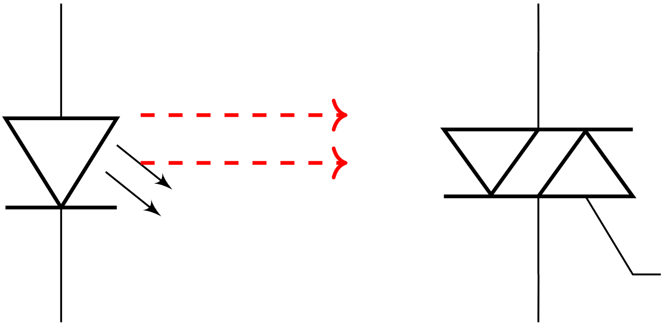
Usage:

- High-voltage direct current (HVDC) transmission lines.
- Optically triggered firing circuits for larger, standard thyristors.



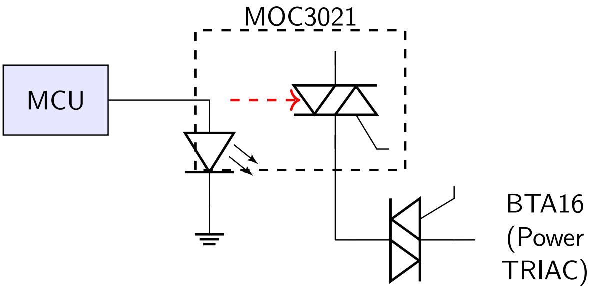
Opto-TRIAC Introduction

- An **Opto-TRIAC** is a TRIAC that is optically coupled to an LED within the same package.
- Also known as a photo-TRIAC.
- Because a TRIAC can conduct in both directions, the Opto-TRIAC is used specifically for switching AC loads.
- Commonly used ICs: MOC3021 (Random-phase), MOC3041 (Zero-crossing).



Opto-TRIAC Operation

- The internal LED is powered by a low-voltage DC signal (e.g., from an Arduino).
- The emitted light strikes the light-sensitive gate area of the internal TRIAC.
- The internal TRIAC turns ON, allowing AC current to flow.
- **Note:** The Opto-TRIAC usually cannot handle massive currents directly (typically handles 100mA - 1A).
- It is mostly used as a **driver** to trigger a larger, external power TRIAC.



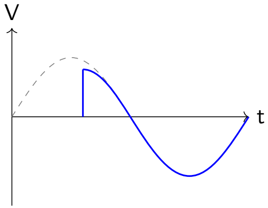
Zero-Crossing vs Random-Phase Opto-TRIACs

Random-Phase (e.g., MOC3021):

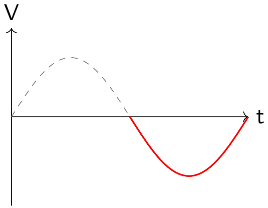
- Turns ON instantly when the LED is lit, regardless of where the AC voltage is in its sine wave.
- Good for phase-control (dimming).

Zero-Crossing (e.g., MOC3041):

- Includes an internal zero-crossing detection circuit.
- Even if the LED is lit, the TRIAC waits until the AC voltage crosses zero volts before turning ON.
- Eliminates switching noise and inrush currents. Ideal for simple ON/OFF relaying.



Random Phase Turn-ON



Zero-Crossing Turn-ON

Summary

- **Galvanic Isolation** prevents dangerous current flow between control and power circuits.
- **Opto-Isolators** use an LED and a photodetector to transfer signals via light.
- **Opto-Transistors** are used for DC signal isolation and analog feedback.
- **LASCRs** are optically triggered SCRs used in high-voltage DC applications.
- **Opto-TRIACs** are used to safely trigger AC power devices, often driving larger external TRIACs.

✓ Isolation ensures safety
✓ Light transfers signals
✓ Match detector to application

Next Lecture Preview

Lecture 13: Applications of Opto-Isolators & Solid State Relays

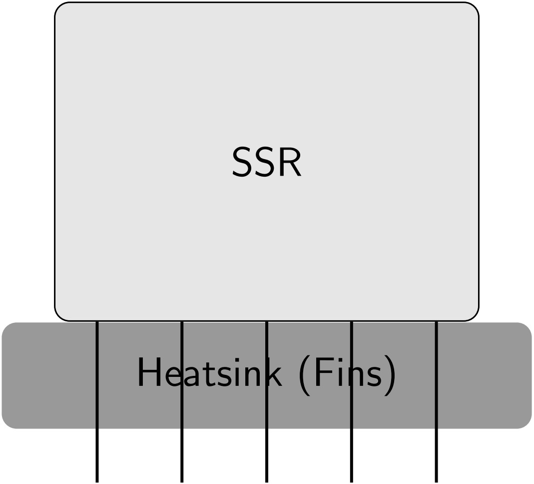
Topics:

- Advantages of Opto-Isolators
- Eliminating Ground Loops
- Solid State Relays (SSR) vs Electromechanical Relays

Electromechanical Relay (Moving Parts) **VS** Solid State Relay (No Moving Parts)

Applications of Opto-Isolators & Solid State Relays

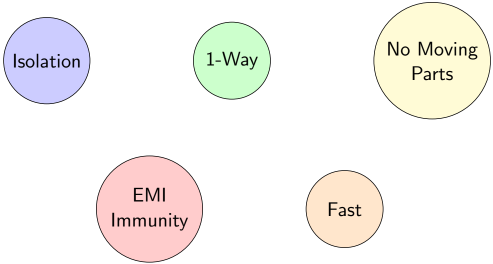
- Unit 2: Introduction to Thyristors
- Lecture 13: Applications of Optocouplers and SSRs



Agenda

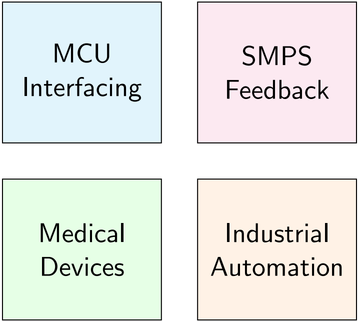
Advantages of Opto-Isolators

- **Complete Electrical Isolation:** Usually provides 2000V to $10,000$V of isolation.
- **Unidirectional Signal Transfer:** Signals only pass from LED to detector, preventing back-EMF or high-voltage transients from feeding back.
- **No Moving Parts:** Solid-state nature means infinite mechanical lifespan.
- **Immunity to EMI:** Optical transfer is unaffected by electromagnetic interference or magnetic fields.
- **Fast Switching:** Capable of much higher switching frequencies compared to mechanical isolation (transformers or relays).



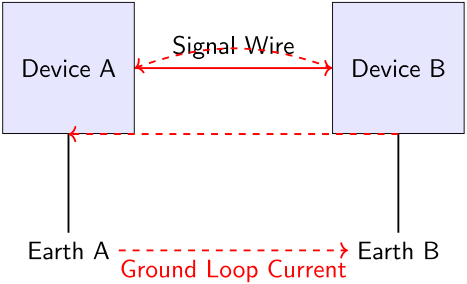
Common Applications of Opto-Isolators

- **Microprocessor Interfacing:** Safely driving high-power AC/DC loads from a 3.3V/5V GPIO pin.
- **Switch-Mode Power Supplies (SMPS):** Providing isolated feedback from the secondary output to the primary switching controller.
- **Medical Equipment:** Ensuring patient safety by isolating patient-connected sensors from main AC power.
- **Industrial Automation:** Interfacing PLCs with heavy machinery in noisy factory environments.



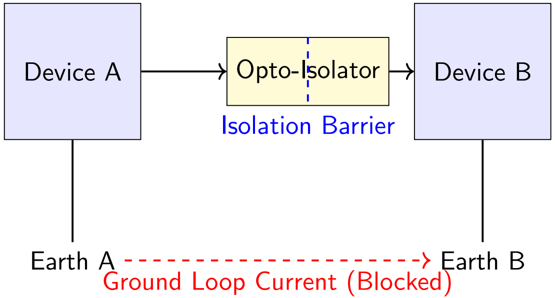
The Problem: Ground Loops

- A **Ground Loop** occurs when two interconnected electrical devices have multiple paths to ground.
- If the two ground points are at slightly different potentials, a spurious current will flow through the ground cables connecting the devices.
- This unintended current introduces noise and interference (like a 50Hz/60Hz hum in audio systems).
- In industrial systems, ground loops can distort analog sensor readings and cause digital communication errors.



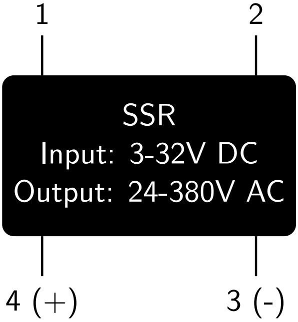
Eliminating Ground Loops with Opto-Isolators

- The most effective way to break a ground loop is to break the electrical connection.
- By inserting an opto-isolator in the signal path, the grounds of Device A and Device B are no longer tied together.
- The signal is passed optically.
- Device A's ground remains isolated from Device B's ground, preventing any loop current from flowing.



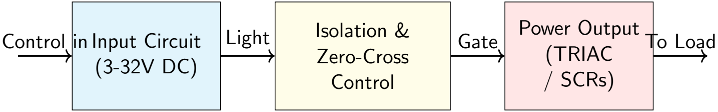
What is a Solid State Relay (SSR)?

- A **Solid State Relay (SSR)** is an electronic switching device that switches on or off when a small external voltage is applied across its control terminals.
- It performs the exact same function as an electromechanical relay, but contains **no moving parts**.
- It uses semiconductor switching elements, such as Thyristors (SCRs/TRIACs) or Transistors, to switch the load current.
- Optical coupling is used internally to provide isolation.



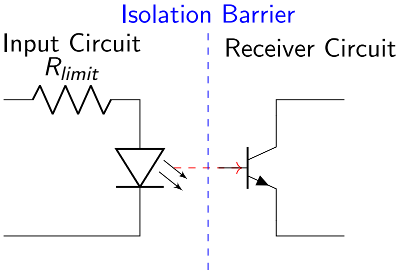
SSR Block Diagram

- A typical AC Solid State Relay consists of three main blocks:
- 1. **Input Circuit:** Current limiter and the LED of the optocoupler.
- 2. **Isolation & Control Circuit:** The photodetector, zero-crossing detection circuit, and driver stage.
- 3. **Power Output Stage:** A pair of anti-parallel SCRs or a high-power TRIAC.



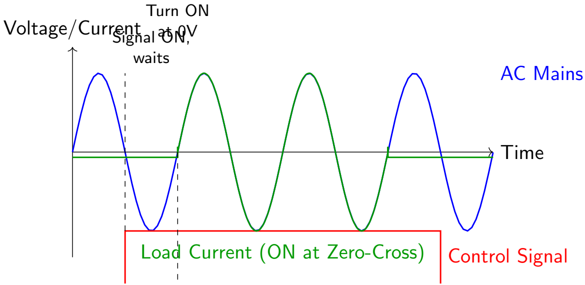
How an SSR Works: Input & Isolation

- **The Input:** A control voltage (e.g., 5V DC from a microcontroller) is applied.
- A series resistor limits the current driving the internal IR LED.
- **The Isolation:** The LED emits infrared light across a transparent gap.
- The receiver (usually an Opto-TRIAC or photo-transistor) detects this light.
- This ensures the 5V control circuit is completely isolated from the 230V AC output.



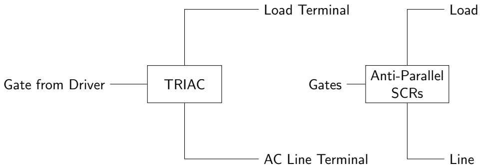
How an SSR Works: Zero-Crossing

- Most AC SSRs feature a **Zero-Crossing Detector**.
- Even if the control signal commands the SSR to turn ON, the detector waits.
- It holds off triggering the main TRIAC until the AC sinusoidal voltage crosses the zero-volt axis (0V).
- **Why?** Turning on exactly at 0V prevents high inrush currents and eliminates Electromagnetic Interference (EMI) / Radio Frequency Interference (RFI).



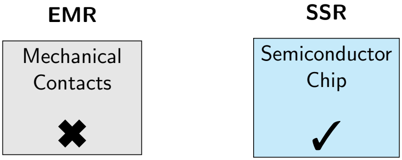
How an SSR Works: Output Stage

- Once the zero-crossing is detected, the internal driver fires the gate of the main power semiconductor.
- For low/medium power, a single **TRIAC** is used.
- For very high power industrial SSRs, two **SCRs in anti-parallel** (inverse-parallel) are used for better heat dissipation and higher dv/dt ratings.
- The semiconductor latches ON and conducts the heavy AC load current.



SSR vs Electromechanical Relay (EMR)

- **Switching Element:**
  - **EMR:** Mechanical contacts (moving armature).
  - **SSR:** Semiconductor (Thyristor/Transistor).
- **Lifespan:**
  - **EMR:** Limited by physical wear and contact arcing (e.g., 100,000 to 1 million operations).
  - **SSR:** Virtually infinite if operated within thermal limits.



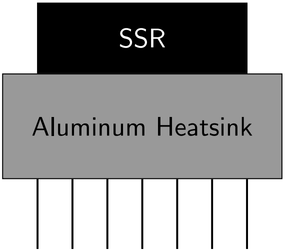
SSR vs EMR (Continued)

- **Switching Speed:**
  - **EMR:** Slow (5ms - 15ms), contact bounce occurs.
  - **SSR:** Extremely fast (microseconds), absolutely no contact bounce.
- **Acoustic Noise:**
  - **EMR:** Makes a distinct 'clicking' sound.
  - **SSR:** Completely silent operation.
- **EMI/RFI Generation:**
  - **EMR:** Arcing generates high electrical noise.
  - **SSR:** Zero-crossing capability eliminates noise.

Feature	EMR	SSR
Speed	Slow, Bounce	Fast, No Bounce
Noise	Clicking Sound	Silent
EMI/RFI	High (Arcing)	Low/Zero

Disadvantages of SSRs

- While SSRs are superior in many ways, they have drawbacks:
- 1. **Heat Generation:** Semiconductors have an ON-state voltage drop (approx 1V – 1.5V). At 40A, it dissipates 40W to 60W of heat. **Large heatsinks are required.**
- 2. **Leakage Current:** Even when OFF, a small leakage current flows (a few mA), which can be unsafe.
- 3. **Cost:** SSRs are generally more expensive than EMRs of the same rating.
- 4. **Vulnerability to Transients:** Can be destroyed by overvoltage spikes (require snubbers/MOVs).



Required for cooling

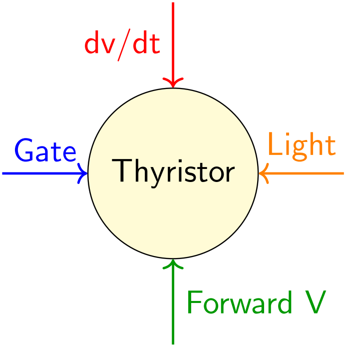
Summary

- Opto-isolators are crucial for safety and for breaking problematic **ground loops**.
- **Solid State Relays (SSRs)** use optocouplers and thyristors to switch heavy loads without moving parts.
- SSRs offer silent, fast, and infinite-life switching, often with **zero-crossing** capabilities.
- However, SSRs require careful thermal management (heatsinks) due to their ON-state voltage drop.

✓ Ground loop elimination
✓ No moving parts in SSR
✓ Zero-crossing capability
✓ Heatsinks required

Next Lecture Preview

- Unit 3: Turn on/off methods of Thyristor
- Lecture 14: Turn-On Methods of Thyristor
- Topics:
  - Forward Voltage Triggering
  - Gate Triggering
  - dv/dt Triggering
  - Light and Temperature Triggering



Triggering (Turn-on) Methods of SCR

- Course: Applied Electronics (DI03011021)
- Unit 3: Turn on/off methods of Thyristor
- Lecture 14

Welcome!

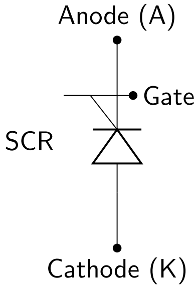
Today we begin Unit 3, focusing on how we turn on or 'trigger' a thyristor (SCR).

Agenda

- Introduction to SCR Triggering
- Forward Voltage Triggering
- Temperature and Light Triggering
- dv/dt Triggering
- Gate Triggering (Most practical)
- RC Half-Wave Firing Circuit
- RC Full-Wave Firing Circuit

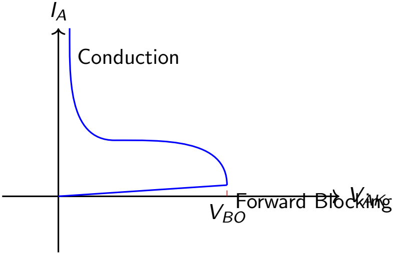
Introduction to SCR Turn-On

- An SCR is turned on when the anode current increases above the latching current.
- To achieve this, charge carriers must be injected into the internal junctions.
- The blocking state (forward blocking) must be broken to transition to the conduction state.
- **Primary goal:** Safely and reliably transition from blocking to conducting state.



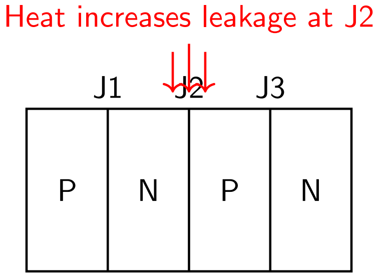
Forward Voltage Triggering

- Anode-to-Cathode voltage (V_{AK}) is increased beyond the Forward Breakover Voltage (V_{BO}).
- At V_{BO}, the reverse-biased junction J2 undergoes avalanche breakdown.
- Large current flows, and the SCR turns on.
- **Drawback:** High voltage can permanently damage the SCR. Not used in practice.



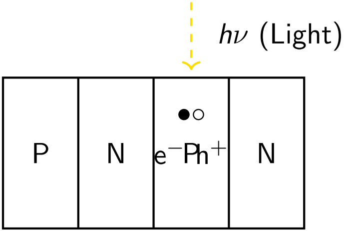
Temperature (Thermal) Triggering

- Reverse-biased junction J2 has a temperature-dependent leakage current.
- As temperature increases, leakage current increases.
- Increased leakage current leads to more charge carriers, which can initiate regenerative action.
- **Drawback:** Highly unpredictable and can cause thermal runaway, leading to device failure.



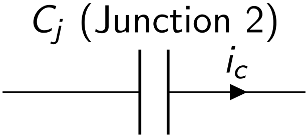
Light Triggering (LASCR)

- Light energy (photons) is directed at the inner P-layer (junction J2).
- Photons create electron-hole pairs, providing the necessary charge carriers.
- Once sufficient carriers are generated, the SCR turns on.
- Used in Light Activated SCRs (LASCR) for high-voltage DC (HVDC) transmission.



dv/dt Triggering

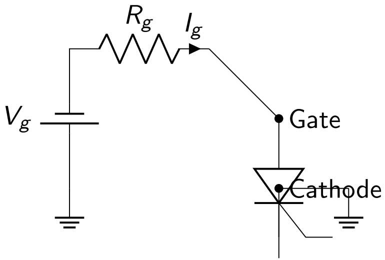
- Junction J2 acts as a capacitor with capacitance C_j.
- Charging current: $i_c = C_j \frac{dv}{dt}$.
- If the rate of rise of anode voltage (dv/dt) is high, the charging current i_c acts like a gate current.
- This false triggering turns the SCR on.
- **Prevention:** Use of Snubber circuits (covered in Lecture 16).



$$i_c = C_j \frac{dv}{dt}$$

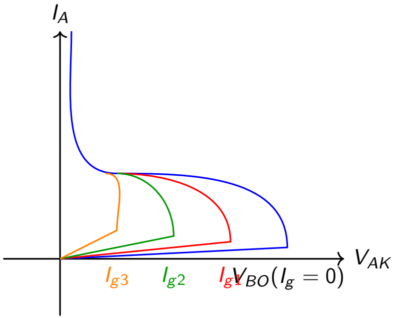
Gate Triggering

- The most common, reliable, and efficient method.
- A positive voltage is applied between Gate (P-layer) and Cathode (N-layer).
- Injects holes into the inner P-layer, providing carriers to forward-bias J2.
- Reduces the forward breakover voltage (V_{BO}) required to turn on the SCR.



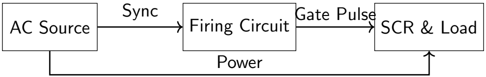
Gate Triggering: V-I Characteristics

- As gate current (I_g) increases, the forward breakover voltage decreases.
- $I_{g3} > I_{g2} > I_{g1} > I_{g=0}$.
- Allows turn-on at normal operating voltages.
- Gate pulse can be removed once anode current exceeds the latching current (I_L).



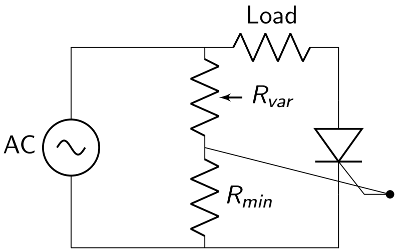
Firing Circuits: Requirements

- The gate signal must have enough amplitude (Voltage and Current).
- The signal must be synchronized with the AC supply for phase control.
- The gate pulse must be maintained until anode current reaches the latching current.
- Must not exceed the maximum gate power dissipation (P_{gm}).



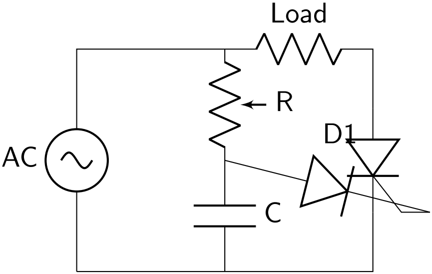
R-Firing Circuit (Resistance Triggering)

- Uses a variable resistor to control the gate current.
- Simple and inexpensive.
- Firing angle (α) is limited to a maximum of 90°.
- Why? Because the gate voltage is in phase with the anode AC voltage.



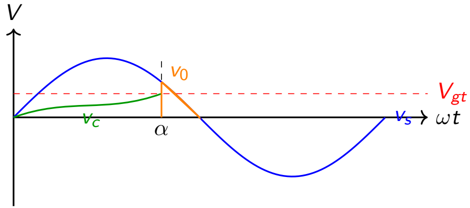
RC Half-Wave Firing Circuit

- Introduces a capacitor to create a phase shift.
- The capacitor voltage lags the supply voltage.
- Allows firing angle (α) to be extended beyond 90° (up to $\approx 180°$).
- A diode is used in the gate circuit to prevent reverse voltage on the gate during the negative half-cycle.



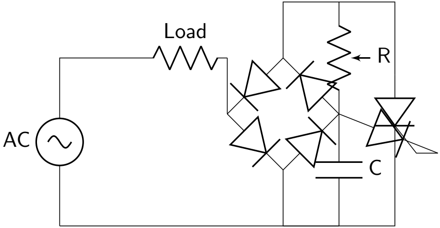
RC Half-Wave Circuit: Waveforms

- Supply voltage $v_s = V_m \sin(\omega t)$.
- Capacitor voltage v_c charges slowly depending on the $R \times C$ time constant.
- When v_c reaches the gate trigger voltage (V_{gt}), the SCR fires.
- Load voltage v_0 appears from α to π.



RC Full-Wave Firing Circuit

- Used to control AC power in both positive and negative half-cycles.
- Typically uses a Diode Bridge Rectifier around the RC network or uses a TRIAC with an RC phase-shift network.
- In a full-wave SCR bridge, the RC circuit is fed from a rectified AC signal.
- Ensures symmetric firing in both half cycles.



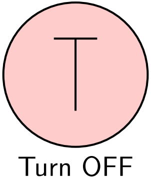
Summary & Next Lecture Preview

Summary:

- We covered five SCR triggering methods: Voltage, Thermal, Light, dv/dt, and Gate.
- Gate triggering is practical; RC circuits allow phase control up to 180°.

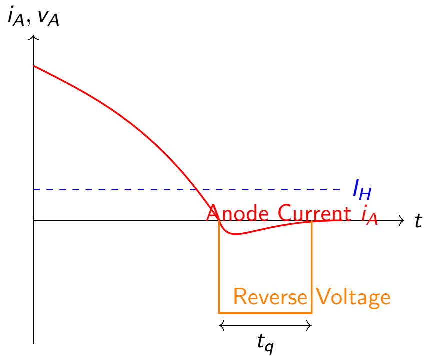
Next Lecture Preview:

- Commutation (Turn-off) Techniques of SCR.
- How do we force an SCR to turn off in DC circuits?



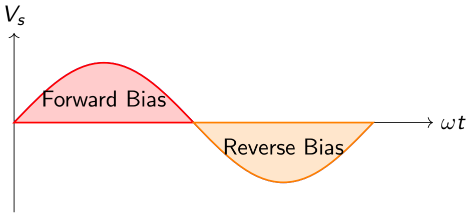
What is Commutation?

- Commutation is the process of turning OFF an SCR.
- Once an SCR is turned on, the gate loses control.
- To turn it off, two conditions must be met:
  1. The anode current (I_A) must be reduced below the holding current (I_H).
  2. A reverse voltage must be applied across the SCR for a sufficient time (t_q) to allow charge carriers to recombine.



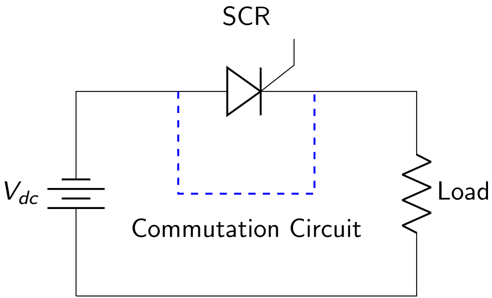
Natural (Line) Commutation

- Occurs naturally in AC circuits.
- During the negative half-cycle of the AC supply, the AC voltage reverses.
- This reverse voltage automatically brings the anode current to zero and reverse-biases the SCR.
- No external commutation circuit is required.
- Used in AC voltage controllers, phase-controlled rectifiers, and cycloconverters.



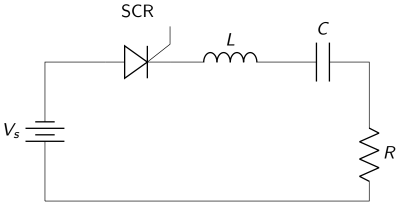
Forced Commutation Overview

- In DC circuits (like choppers and inverters), the supply voltage does not reverse.
- The SCR will stay ON indefinitely unless forced to turn off.
- Forced commutation uses external components (Inductors L and Capacitors C) to force the current to zero or apply a reverse voltage.
- Classified into Class A, B, C, D, (and sometimes E, F).



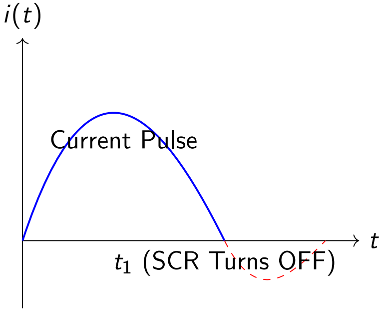
Class A: Load Commutation

- Also known as Self-Commutation by Resonating the Load.
- An L-C network is placed in series with the load (R).
- The circuit forms an underdamped R-L-C series resonant circuit.
- When the SCR triggers, a resonant current pulse flows.
- As the resonant current attempts to reverse direction, the SCR blocks it and turns off.



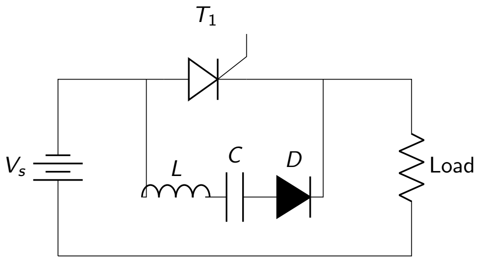
Class A Commutation: Waveforms

- Current waveform $i(t)$ is a damped half-sine wave.
- At $t = t_1$, the current reaches zero.
- Since the SCR cannot conduct in reverse, it turns off.
- Condition for underdamped circuit: $R^2 < \frac{4L}{C}$.
- Mainly used in high-frequency applications like series inverters.



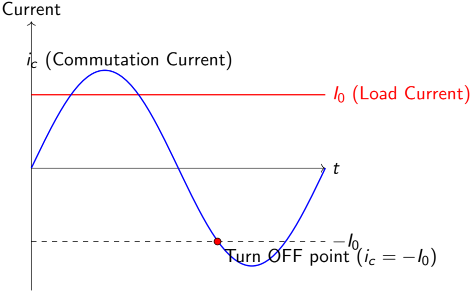
Class B: Resonant Commutation

- Also known as Self-Commutation by an L-C Circuit.
- The L-C resonant circuit is connected in parallel with the SCR.
- The load current is essentially constant.
- The L-C circuit generates a resonant current pulse that flows in the reverse direction through the SCR.
- When reverse resonant current = forward load current, net SCR current is zero.



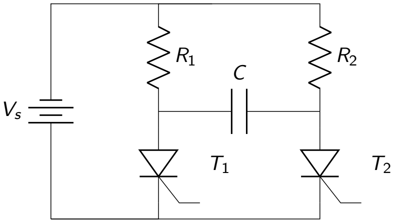
Class B Commutation: Waveforms

- Capacitor is pre-charged.
- Upon triggering, an oscillatory current i_c flows.
- During the negative half of the oscillation, i_c opposes load current I_0.
- SCR turns off when $i_c = I_0$.
- Used in chopper circuits.

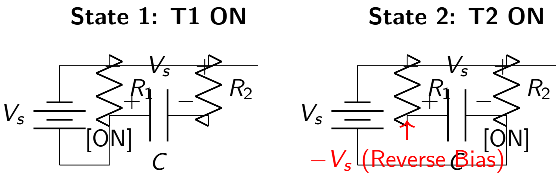


Class C: Complementary Commutation

- Used when two SCRs are operating in a complementary mode (e.g., inverters).
- Turning ON one SCR automatically turns OFF the other SCR.
- Uses a commutating capacitor C connected between the anodes of the two SCRs.
- When SCR2 is turned on, the capacitor voltage is applied in reverse across SCR1.

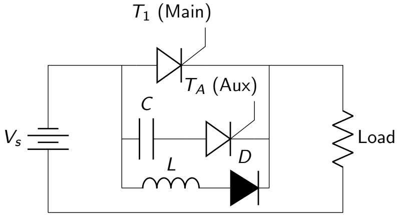


- **State 1:** SCR1 is ON, SCR2 is OFF. Capacitor charges to supply voltage V_s (right plate positive).
- **State 2:** SCR2 is triggered.
- Capacitor voltage $-V_s$ is instantly applied across SCR1.
- SCR1 is reverse biased and turns off.
- Capacitor recharges in the opposite direction through the load, ready for the next cycle.



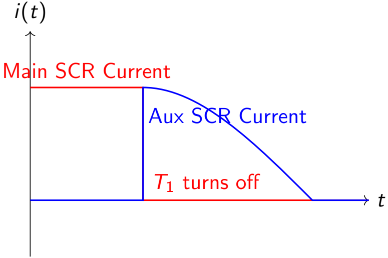
Class D: Impulse Commutation

- Also known as Voltage Commutation.
- Uses an auxiliary SCR to turn off the main SCR.
- Main SCR handles the load current.
- Auxiliary SCR is fired only to initiate the turn-off process.
- A pre-charged capacitor is switched by the auxiliary SCR to apply reverse voltage across the main SCR.



Class D Commutation: Operation

- Capacitor is charged to V_s via a ringing circuit.
- When Auxiliary SCR (TA) is triggered, it places the capacitor directly in parallel with the Main SCR ($T1$).
- The reverse voltage immediately turns off $T1$.
- Load current temporarily flows through the capacitor and TA until the capacitor recharges.
- Allows very precise control of output voltage in DC choppers.



Comparison of Commutation Techniques

Method	Characteristics	Applications
Natural	Simple, no extra components, only works in AC.	Phase-controlled rectifiers, AC voltage controllers.
Class A (Load)	Simple, requires underdamped load, $R^2 < 4L/C$.	High frequency, series inverters, induction heating.
Class B (Resonant)	Load current undisturbed until turn-off.	DC choppers.
Class C (Complementary)	Firing one SCR commutes the other. Efficient for 2-SCR systems.	Square-wave inverters.
Class D (Impulse)	Precise control, uses auxiliary SCR.	DC choppers, motor drives.

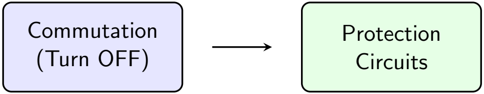
Summary & Next Lecture Preview

Summary

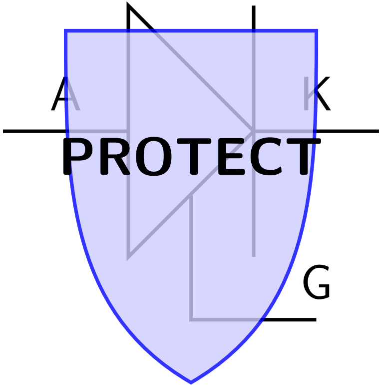
- Commutation is required to turn off an SCR by reducing current and applying reverse voltage.
- DC circuits require forced commutation using LC energy storage.

Next Lecture Preview: Thyristor Protection

- How do we protect these sensitive semiconductor devices from overcurrent, overvoltage, di/dt, and dv/dt faults?



- Course: Applied Electronics (DI03011021)
- Unit 3: Turn on/off methods of Thyristor
- Lecture 16

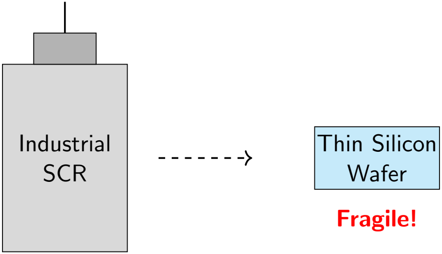


Agenda

- Necessity of Thyristor Protection
- Overcurrent Protection and I^2t Rating
- di/dt Protection using Inductors
- Overvoltage Protection
- dv/dt Protection: The RC Snubber Circuit
- Gate Protection Techniques
- Complete SCR Protection Scheme

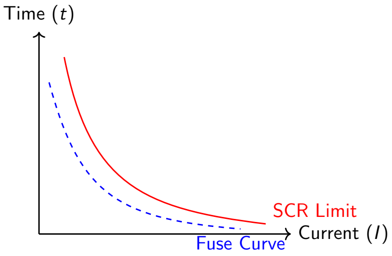
Necessity of Thyristor Protection

- Thyristors are delicate semiconductor devices despite handling high power.
- They have small thermal time constants (they heat up quickly).
- Faults like short circuits or lightning strikes can destroy them in microseconds.
- Replacing high-power SCRs is expensive.
- A well-designed protection circuit ensures reliability and longevity.



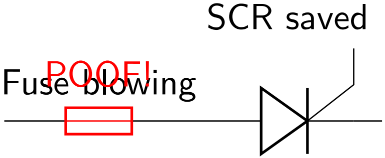
Overcurrent Protection

- Overcurrent causes excessive I^2R heating at the junctions.
- If junction temperature exceeds the maximum limit (e.g., $125^\circ C$), the SCR is destroyed.
- **Methods of Protection:**
- 1. Standard Circuit Breakers (for long-duration overloads).
- 2. Fast-Acting Semiconductor Fuses (for short-circuit protection).



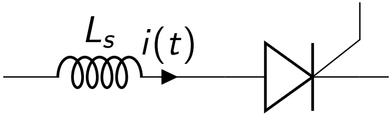
Fuse Selection and I^2t Rating

- Fuses are selected based on the I^2t rating (let-through energy).
- I^2t represents the thermal energy required to melt the fuse or destroy the SCR.
- **Rule for Selection:**
- $(I^2t)_{\text{Fuse}} < (I^2t)_{\text{SCR}}$
- This ensures the fuse blows and clears the fault before the SCR is damaged.



di/dt Protection

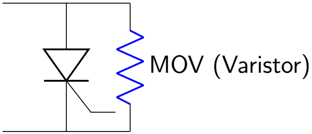
- When an SCR turns on, conduction starts at a small area near the gate.
- If current rises too fast (high di/dt), this small area handles all the current.
- Result: Localized 'hot spots' that melt the silicon.
- **Solution:** Place a small inductor (L_s) in series with the SCR.
- $V = L\frac{di}{dt} \Rightarrow \frac{di}{dt} = \frac{V}{L_s}$



Series Inductor chokes rapid current rise

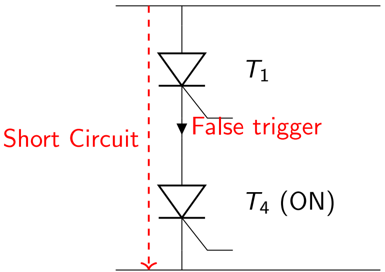
Overvoltage Protection

- Overvoltages can cause reverse breakdown or unwanted forward triggering.
- **Internal Causes:** Reverse recovery transients during turn-off (carrier sweep-out).
- **External Causes:** Lightning strikes, switching of inductive loads on the supply line.
- **Protection:** Non-linear resistors like Varistors (VDR) or Selenium surge suppressors connected in parallel.



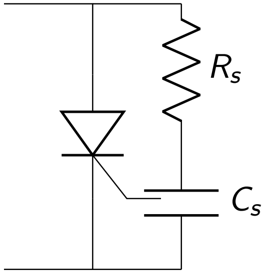
dv/dt Protection: The Threat

- Recall from Lecture 14: High rate of rise of voltage (dv/dt) causes a charging current.
- $i_c = C_j \frac{dv}{dt}$
- If dv/dt is too high, this charging current acts as a gate current and triggers the SCR falsely.
- False triggering can cause short circuits (e.g., in an inverter bridge).
- We must limit the dv/dt across the SCR.



RC Snubber Circuit

- A Snubber circuit consists of a Resistor (R_s) and Capacitor (C_s) in series.
- It is connected in **parallel** with the SCR.
- **How it works:** When a voltage step is applied, the capacitor C_s acts as a short circuit initially.
- The capacitor charges slowly, limiting the rate of rise of voltage (dv/dt) across the SCR.



RC Snubber Circuit Design

- **Role of C_s:** Determines the dv/dt limit. Larger C_s = lower dv/dt.
- **Role of R_s:**
- 1. Damps the LC oscillations between the supply inductance and C_s.
- 2. Limits the discharge current of C_s through the SCR when the SCR is turned on.
- Discharge current: $I_{discharge} = \frac{V_c}{R_s}$.

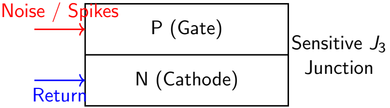
$$\frac{dv}{dt} = \frac{V_s}{R_s C_s}$$

$$\zeta = \frac{R_s}{2}\sqrt{\frac{C_s}{L_s}}$$

$$I_{discharge} = \frac{V_c}{R_s}$$

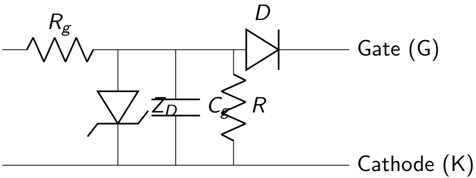
Gate Protection: Challenges

- The gate is the most sensitive terminal of the SCR.
- Requires protection from:
- 1. Overvoltages (can damage the gate-cathode junction).
- 2. Overcurrents (can overheat the gate).
- 3. High-frequency noise (can cause false triggering).



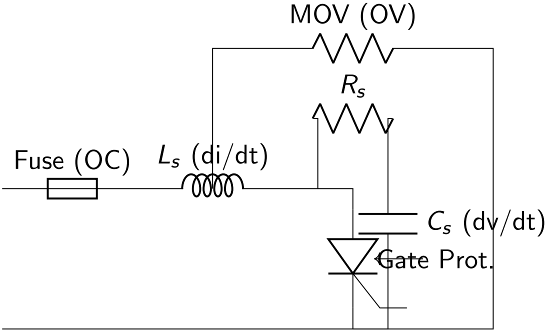
Gate Protection Circuit

- **Overvoltage:** A Zener diode (Z_D) is placed across the gate and cathode to clamp excess voltage.
- **Overcurrent:** A series resistor (R_g) limits the gate current.
- **Noise:** A parallel capacitor (C_g) and resistor (R) act as a low-pass filter to bypass high-frequency noise transients.
- A diode (D) in series ensures current only flows into the gate.



Complete SCR Protection Scheme

- Putting it all together for full industrial reliability:
- 1. Fast-acting fuse in series (Overcurrent).
- 2. Inductor L_s in series (di/dt).
- 3. Varistor in parallel (Overvoltage).
- 4. RC Snubber in parallel (dv/dt).
- 5. Zener + RC filter at the Gate (Gate Protection).



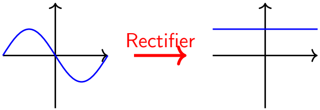
Summary

- I^2t coordination is critical for fuse selection.
- Series Inductor limits di/dt to prevent localized heating.
- RC Snubber limits dv/dt to prevent false triggering.
- Gate circuits require Zener diodes for clamping and capacitors for noise filtering.

Fuse Overcurrent	**Inductor** di/dt
RC Snubber dv/dt	**Zener/MOV** Overvoltage

Next Lecture Preview

- **End of Unit 3.**
- **Starting Unit 4: Power Converters**
- We will apply our knowledge of SCR triggering and commutation to build real-world circuits.
- First topic: Uncontrolled and Controlled Rectifiers (AC to DC conversion).



Title Slide

- Course: DI03011021 Applied Electronics
- Unit 4: Power Converters
- Lecture 17: Single Phase Controlled Rectifiers using SCR

Agenda

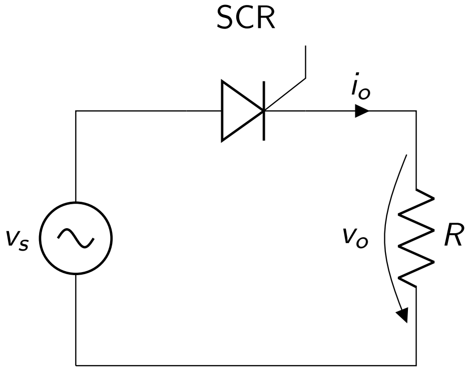
- Introduction to Phase-Controlled Rectifiers
- Single-Phase Half-Wave Controlled Rectifier (R Load)
- Mathematical Analysis for R Load (V_{dc})
- Single-Phase Half-Wave with R-L Load
- Effect of Freewheeling Diode (FWD)
- Single-Phase Full-Wave Controlled Rectifier
- Summary & Next Lecture

Introduction to Phase-Controlled Rectifiers

- Converts fixed AC to variable DC voltage.
- Uses Thyristors (SCRs) instead of diodes.
- Average DC output voltage is controlled by varying the firing angle (α).
- Applications: DC motor speed control, battery chargers, DC power supplies.

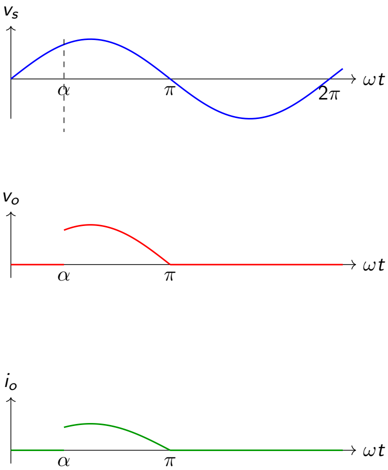
Single-Phase Half-Wave Controlled Rectifier (R Load)

- Circuit Diagram:
- AC source ($V_s = V_m \sin(\omega t)$)
- Single SCR in series with Resistive Load (R)



Waveforms: Half-Wave with R Load

- Input voltage: $V_s = V_m \sin(\omega t)$
- Gate pulses: applied at $\omega t = \alpha, 2\pi + \alpha, \ldots$
- Output voltage (V_o): $V_m \sin(\omega t)$ for $\alpha < \omega t < \pi$, 0 otherwise.
- Output current (I_o): In phase with V_o.

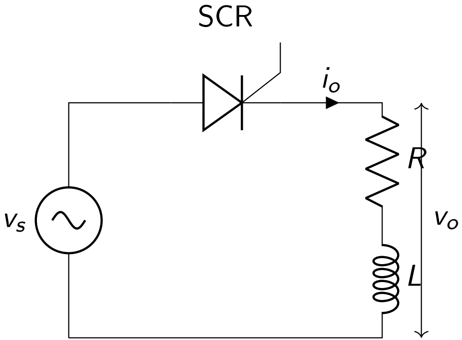


Deriving Average Output Voltage (V_{dc}) for R Load

- Average DC voltage V_{dc}:
- $$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t) d(\omega t)$$
- $$V_{dc} = \frac{V_m}{2\pi}[-\cos(\omega t)]_{\alpha}^{\pi}$$
- $$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$
- Maximum V_{dc} occurs at $\alpha = 0$: $V_{dc(max)} = \frac{V_m}{\pi}$

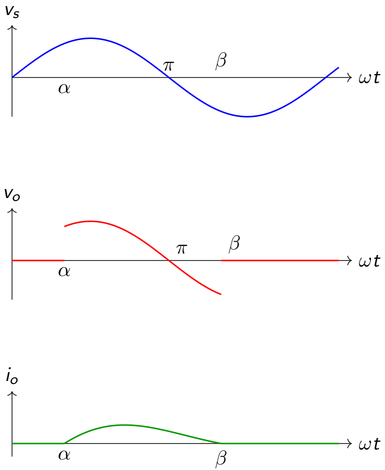
Single-Phase Half-Wave Rectifier with R-L Load

- Circuit Diagram:
- Load contains Resistance (R) and Inductance (L).
- Inductor stores energy during conduction.



Waveforms: Half-Wave with R-L Load

- Conduction extends beyond π due to inductive energy.
- SCR conducts from α to β (extinction angle, $\beta > \pi$).
- Output voltage becomes negative between π and β.
- Average output voltage V_{dc} decreases.

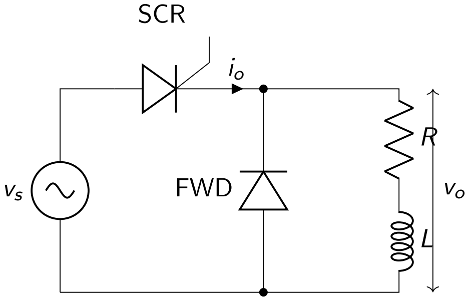


Mathematical Analysis for R-L Load

- Average DC voltage V_{dc}:
- $$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\beta} V_m \sin(\omega t) d(\omega t)$$
- $$V_{dc} = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$$
- Since $\beta > \pi$, $\cos\beta$ is often negative, but the net V_{dc} is lower than the pure R case.

The Solution: Freewheeling Diode (FWD)

- A diode is connected in anti-parallel across the R-L load.
- Prevents output voltage from becoming negative.
- Improves average output voltage (V_{dc}).
- Smoothes the load current.



Operation with Freewheeling Diode

- $\alpha < \omega t < \pi$: SCR conducts, source supplies power to load. FWD is reverse biased.
- $\pi < \omega t < \beta$: Source voltage is negative. FWD conducts, short-circuiting the load. SCR turns off.
- Output voltage V_o is 0 during freewheeling. Negative area is eliminated.

Average Voltage with FWD

- With the FWD, the output voltage waveform is identical to the purely resistive load case.
- Integration is back to α to π.
- $$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$
- Load current becomes much smoother (more continuous) due to the extended decay path.

Single-Phase Full-Wave Controlled Rectifiers

- Uses multiple SCRs to utilize both positive and negative half-cycles of the AC supply.
- Two main configurations:
- 1. Mid-point (Center-tap) configuration (requires 2 SCRs and a center-tapped transformer).
- 2. Bridge configuration (requires 4 SCRs).

Average Voltage for Full-Wave Rectifier

- For a fully controlled bridge with a highly inductive load (continuous conduction):
- $$V_{dc} = \frac{2V_m}{\pi} \cos \alpha$$
- Offers twice the output voltage of a half-wave rectifier for a given α.
- Can operate in two quadrants (rectification and inversion) if no FWD is used.

Summary

- Controlled rectifiers use SCRs to vary DC output voltage.
- Half-wave R load: $V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$
- Inductive loads cause negative voltage excursions, reducing V_{dc}.
- Freewheeling diodes prevent negative V_o and smooth load current.
- Full-wave rectifiers double the output voltage and improve efficiency.

Next Lecture Preview

- Lecture 18: Poly-Phase Rectifiers
- Need for Poly-Phase Systems
- Comparison of Single-Phase vs. Poly-Phase Rectifiers
- Ripple Factor Improvements
- Higher Power Handling Capabilities
- Industrial Applications (DC Motor Drives)

Title Slide

- Course: DI03011021 Applied Electronics
- Unit 4: Power Converters
- Lecture 18: Poly-Phase Rectifiers, Comparisons & Applications

Key Takeaways:

- Introduction to Poly-Phase Rectifiers.
- Understanding industrial requirements.

Agenda

- Need for Poly-Phase Rectifiers
- The Concept of Ripple and Ripple Factor
- Comparison: Single-Phase vs. Poly-Phase Systems
- Advantages of Higher Power Handling
- Effect on AC Source Power Factor
- Typical Industrial Applications
- Focus: DC Motor Drives
- Summary & Next Lecture

The Need for Poly-Phase Rectifiers

- Single-phase rectifiers are limited to lower power applications (typically < 15 kW).
- Large industrial loads require Megawatts of DC power.
- Problems with single-phase at high power:
  - Unacceptable unbalance on the 3-phase AC grid.
  - High ripple voltage requiring massive filters.
  - Large peak currents stressing semiconductor devices.

Understanding Ripple Factor

- **Ripple**: The AC component superimposed on the DC output.
- **Ripple Factor (RF)**: Ratio of the RMS value of the AC component to the DC value.
- $$RF = \frac{V_{ac(rms)}}{V_{dc}} = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1}$$
- High ripple causes heating in DC motors and noise in electronics.

Ripple Improvement with Poly-Phase

- **Single-Phase Half-Wave**: Ripple Factor $\approx 121\%$
- **Single-Phase Full-Wave**: Ripple Factor $\approx 48\%$
- **Three-Phase Half-Wave (3-pulse)**: Ripple Factor $\approx 17\%$
- **Three-Phase Full-Wave (6-pulse)**: Ripple Factor $\approx 4\%$
- More phases = More pulses per cycle = Lower ripple.

Higher Power Handling Capability

- Power is distributed across three phases.
- Current per semiconductor device is reduced for the same total output power.
- Transformers are utilized more efficiently (better Transformer Utilization Factor - TUF).
- Allows for the construction of multi-megawatt DC power supplies.

Comparison: Single-Phase vs Poly-Phase

Feature	Single-Phase	Poly-Phase (3-Phase)
Power Level	Low ($<$ 15kW)	High (Megawatts)
Output Ripple	High (48%)	Very Low ($<$ 5%)
Filter Size	Large & Bulky	Small or Unnecessary
Efficiency	Lower	Higher
Grid Impact	Can cause unbalance	Balanced 3-phase load
Circuit Complexity	Simple (1-4 SCRs)	Complex (3-6+ SCRs)

Harmonics and Power Factor

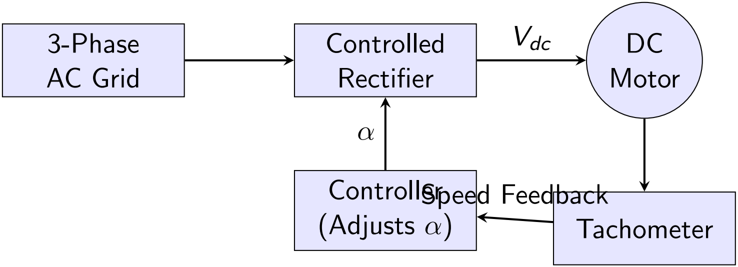
- Phase-controlled rectifiers draw non-sinusoidal currents from the AC grid.
- This introduces **Harmonics** into the power system.
- They also consume reactive power, leading to a poorer **Power Factor (PF)**, especially at high firing angles (α).
- Poly-phase systems inherently cancel some lower-order harmonics (e.g., 6-pulse cancels 3rd harmonics).

Industrial Applications of Poly-Phase Rectifiers

- **DC Motor Drives**: Steel rolling mills, paper mills, traction systems.
- **Electrochemical Processes**: Electroplating, aluminum smelting, electrolysis.
- **HVDC Transmission**: High Voltage DC power transmission over long distances.
- **Large Battery Energy Storage Systems (BESS)**.
- **Uninterruptible Power Supplies (UPS)** for data centers.

Deep Dive: DC Motor Drives

- Historically the most common application for controlled rectifiers.
- Speed of a DC motor is proportional to applied armature voltage.
- By changing firing angle α, V_{dc} changes, thus controlling motor speed seamlessly.
- Four-quadrant drives allow forward/reverse motoring and regenerative braking.



Application Example: Steel Rolling Mill

- Requires extremely precise speed and torque control.
- Motors must rapidly accelerate, decelerate, and reverse.
- Massive inertia requires extremely high peak currents.
- Three-phase (or even 12-pulse) fully controlled rectifiers are mandatory to meet power and response requirements.

Application Example: Electroplating / Smelting

- Processes require constant, high-current, low-voltage DC.
- E.g., Aluminum smelting requires $\approx$ 500 kA at 4 V per cell.
- Ripple must be minimized to ensure uniform plating/smelting quality.
- Multi-pulse rectifiers (12, 18, or 24-pulse) are often used via complex transformer phase-shifting.

Economic Considerations

- **Initial Cost**: Poly-phase systems are more expensive (more thyristors, complex transformers, sophisticated gate drivers).
- **Operational Cost**: Higher efficiency and lower maintenance (no massive filter capacitors to replace) result in lower long-term costs.
- **Grid Compliance**: Fines for poor power factor or high harmonic injection often justify the cost of higher-pulse poly-phase systems.

Summary

- Poly-phase rectifiers are essential for high-power (> 15kW) applications.
- They drastically reduce output ripple (from 48% to 4% or less).
- They provide balanced loading on the 3-phase AC grid.
- Applications span from DC motor drives to HVDC transmission and metal smelting.
- While more complex, their performance benefits are unmatched for heavy industry.

Next Lecture Preview

- Lecture 19: Three-Phase Rectifier Circuit Operations
- Three-Phase Half-Wave Controlled Converter (3-pulse)
- Three-Phase Full Bridge Converter (6-pulse)
- Detailed waveform analysis
- Firing angle control limitations
- Quadrant operations (Rectification vs. Inversion)

Title Slide

- Course: DI03011021 Applied Electronics
- Unit 4: Power Converters
- Lecture 19: Three-Phase Half-Wave & Full-Wave Rectifiers

Key Takeaways

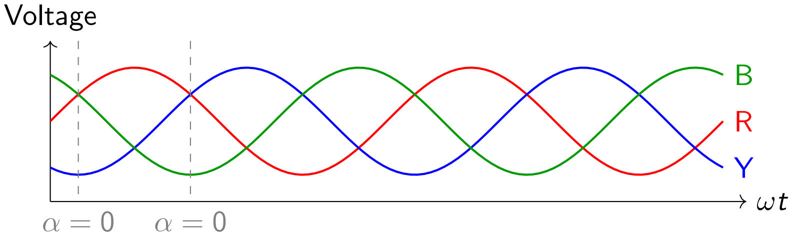
- Detailed analysis of 3-phase rectifiers.
- Understanding 3-pulse and 6-pulse topologies.

Agenda

- Three-Phase AC Fundamentals Recap
- 3-Phase Half-Wave Controlled Converter (3-pulse)
- Derivation of V_{dc} for Half-Wave
- 3-Phase Full Bridge Converter (6-pulse)
- Operation and Firing Sequence of 6-pulse Bridge
- Derivation of V_{dc} for Full Bridge
- Quadrant Operation (Rectification and Inversion)
- Summary

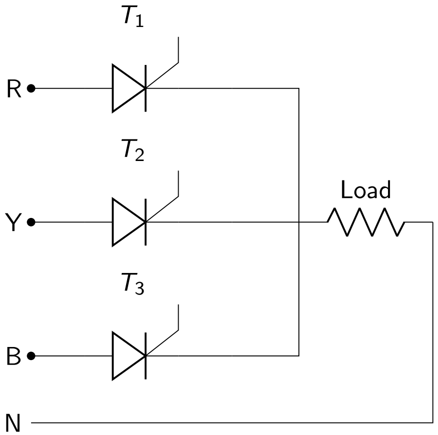
Three-Phase Supply Recap

- Three phase voltages displaced by 120° ($2\pi/3$ radians):
- $V_R = V_m \sin(\omega t)$
- $V_Y = V_m \sin(\omega t - 120^\circ)$
- $V_B = V_m \sin(\omega t - 240^\circ)$
- Line-to-Line voltage is $\sqrt{3}$ times the Phase voltage.
- Natural commutation point is where phase voltages cross each other.



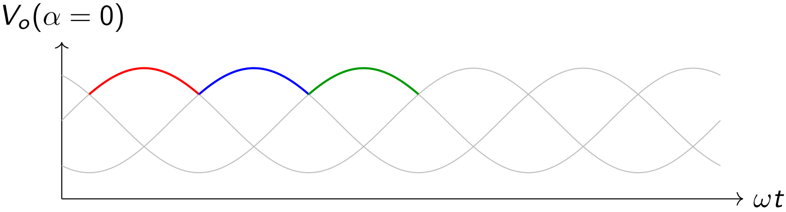
3-Phase Half-Wave Controlled Converter

- Circuit: 3 Thyristors (T_1, T_2, T_3), one in each phase.
- Common cathode connection feeds the load.
- Neutral wire acts as the return path.
- Also known as a **3-pulse converter** (3 output ripples per grid cycle).



Waveforms: 3-Phase Half-Wave

- Each SCR conducts for 120° $(2\pi/3)$.
- For $\alpha = 0$, output follows the peaks of the phase voltages.
- As α increases, the output voltage waveform shifts, cutting deeper into the phase voltage.



Derivation of V_{dc}: 3-Phase Half-Wave

- Integrating one pulse (from $30^\circ + \alpha$ to $150^\circ + \alpha$):

$$V_{dc} = \frac{3}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin(\omega t) d(\omega t)$$

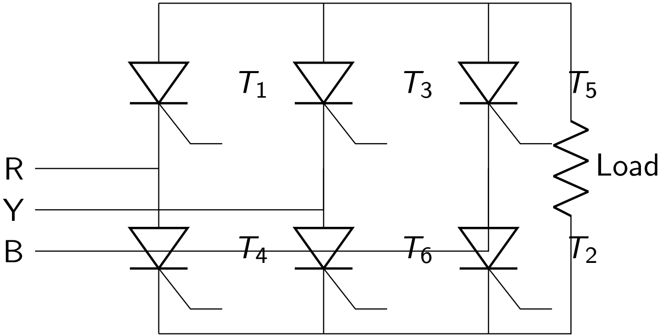
- Result:

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

- Where V_m is the peak **phase** voltage.
- Valid for continuous conduction.

3-Phase Full Bridge Converter (6-pulse)

- Most widely used topology in industry.
- Circuit: 6 Thyristors arranged in three legs (T_1/T_4, T_3/T_6, T_5/T_2).
- Does **not** require a neutral wire.
- Output voltage is formed by Line-to-Line voltages.
- Also known as a **6-pulse converter**.

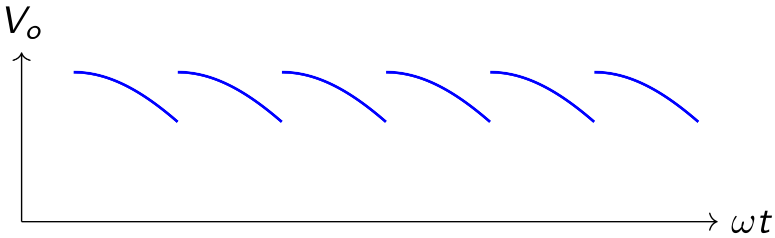


Firing Sequence of the 6-Pulse Bridge

- Thyristors are numbered in the order they are fired: 1, 2, 3, 4, 5, 6.
- Firing interval is 60° ($360^\circ/6$).
- Each SCR conducts for 120°.
- Two SCRs conduct at any given time (one from the top group, one from the bottom group).
- Sequence: $(T_1, T_2) \rightarrow (T_2, T_3) \rightarrow (T_3, T_4) \rightarrow \dots$

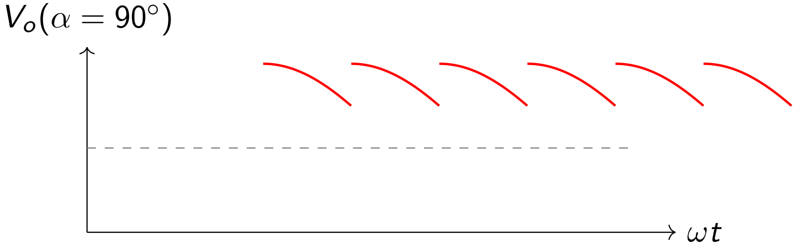
Waveforms: 6-Pulse Bridge ($\alpha = 0^\circ$)

- At $\alpha = 0^\circ$, SCRs act like diodes.
- Output voltage follows the peaks of the 6 line-to-line voltages ($V_{RY}, V_{YB}, V_{BR}, V_{YR}, V_{BY}, V_{RB}$).
- Very low ripple (4.2%).



Waveforms: 6-Pulse Bridge ($\alpha > 0^\circ$)

- As α increases, firing is delayed.
- Average voltage V_{dc} decreases.
- For highly inductive loads, current remains continuous, but output voltage waveform contains negative segments if $\alpha > 60^\circ$.



Derivation of V_{dc}: 6-Pulse Full Bridge

- Integrating one 60° pulse of the line voltage:

$$V_{dc} = \frac{6}{2\pi} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} V_{ml} \sin(\omega t) d(\omega t)$$

- Result:

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

- Where V_{ml} is the peak **Line-to-Line** voltage ($V_{ml} = \sqrt{3}V_m$).
- Max voltage at $\alpha = 0$: $V_{do} = \frac{3V_{ml}}{\pi} \approx 0.955V_{rms(L-L)}$.

Quadrant Operation: Rectification

- Range: $0^\circ < \alpha < 90^\circ$
- $\cos\alpha$ is positive.
- V_{dc} is positive.
- I_{dc} is positive (current only flows one way through SCRs).
- Power ($P = V_{dc} \times I_{dc}$) is positive.
- Power flows from AC Grid $\rightarrow$ DC Load.

Quadrant Operation: Inversion

- Range: $90^\circ < \alpha < 180^\circ$
- $\cos \alpha$ is negative.
- V_{dc} becomes negative.
- I_{dc} remains positive.
- Power ($P = -V_{dc} \times I_{dc}$) is negative.
- Power flows from DC Load $\rightarrow$ AC Grid.
- Requires an active DC source (e.g., motor overhauling, PV array).

Summary

- 3-pulse half-wave rectifiers need a neutral and output $V_{dc} \propto \cos\alpha$.
- 6-pulse full bridge is the standard, using line-to-line voltages.
- 6-pulse equation: $V_{dc} = \frac{3V_{ml}}{\pi}\cos\alpha$.
- Two quadrant operation is possible:
  - Rectification ($0^\circ < \alpha < 90^\circ$)
  - Inversion ($90^\circ < \alpha < 180^\circ$)

Next Lecture Preview

- Lecture 20: Dual Converters & Choppers
- Concept of Four-Quadrant Operation
- Connecting two 3-phase bridges anti-parallel.
- Circulating vs. Non-circulating current modes.
- Introduction to DC-to-DC converters (Choppers).
- Step-down and Step-up chopper basics.

Lecture 20: Inverters - Series, Parallel and Bridge Configurations

- Inverters: Series, Parallel and Bridge Inverters
- **Unit 4: Power Converters**
- Introduction to DC-AC Conversion
- Series Inverter using SCR
- Parallel Inverter
- Single-Phase Half-Bridge Inverter
- Single-Phase Full-Bridge Inverter
- Waveform Analysis

Key Takeaways

- Inverters convert DC to AC.

Agenda

- 1. DC to AC Conversion Basics
- 2. Classification of Inverters
- 3. Series Inverter Circuit & Operation
- 4. Parallel Inverter Circuit & Operation
- 5. Single-Phase Half-Bridge Inverter
- 6. Single-Phase Full-Bridge Inverter
- 7. Performance Metrics & Waveforms
- 8. Summary & Next Steps

DC to AC Conversion Basics

- What is an Inverter?
- A power electronic converter that changes DC input voltage to a symmetric AC output voltage of desired magnitude and frequency.
- **Input:** Constant or variable DC (Battery, Solar Panel, Rectifier output).
- **Output:** Variable or constant AC (Variable frequency, variable magnitude).
- **Applications:** Uninterruptible Power Supplies (UPS), Induction Heating, AC Motor Drives, Renewable Energy Integration.

Key Takeaways

- Inverter function: DC to AC.
- Output frequency and magnitude can be controlled.

Classification of Inverters

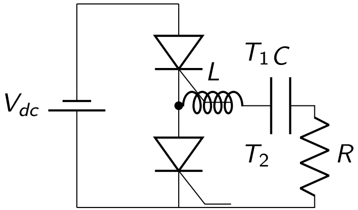
- Based on Output Phase
  - 1. Single-Phase Inverters
  - 2. Three-Phase Inverters
- Based on Source Type
  - 1. **Voltage Source Inverter (VSI):** Stiff DC voltage source at the input (large capacitor).
  - 2. **Current Source Inverter (CSI):** Stiff DC current source at the input (large inductor).
- Based on Commutation
  - 1. Line-commutated (not common for inverters)
  - 2. Forced-commutated (using SCRs with commutation circuits, or fully controlled devices like IGBTs/MOSFETs).

Key Takeaways

- VSI uses a stiff DC voltage source.
- CSI uses a stiff DC current source.

Series Inverter Circuit

- Overview
- The commutating components (L and C) are in series with the load (R).
- Operates in the underdamped region to allow natural zero-current commutation.
- Uses two SCRs (T_1 and T_2) fired alternately.



Key Takeaways

- RLC load must be underdamped.
- Utilizes load commutation (zero-current turn-off).

Series Inverter: Mode 1 Operation

- Mode 1 (Positive Half Cycle)
- **Action:** SCR T_1 is triggered.
- **Current Path:** $V_{dc} \rightarrow T_1 \rightarrow L \rightarrow C \rightarrow R \rightarrow V_{dc}$ return.
- **Behavior:** The current rises to a peak and then falls to zero due to underdamped nature.
- **Turn-off:** T_1 turns off naturally when current reaches zero.
- **Capacitor Voltage:** C charges to a voltage $> V_{dc}$ (e.g., $V_{dc} + V_c$).

Key Takeaways

- T1 conducts positive current pulse.
- Capacitor charges beyond Vdc.

Series Inverter: Mode 2 & 3

- Mode 2 (Dead Time)
- Both T_1 and T_2 are off. Current is zero.
- Necessary to prevent short circuiting the DC source and to provide sufficient turn-off time (t_q) for T_1.
- Mode 3 (Negative Half Cycle)
- **Action:** SCR T_2 is triggered.
- **Current Path:** Capacitor discharges through $R \to C \to L \to T_2$.
- **Behavior:** Current flows in reverse direction through the load.
- **Turn-off:** T_2 naturally commutates when current reaches zero.

Key Takeaways

- Dead time is crucial to prevent short circuits.
- T2 conducts negative current pulse using capacitor energy.

Limitations of Series Inverter

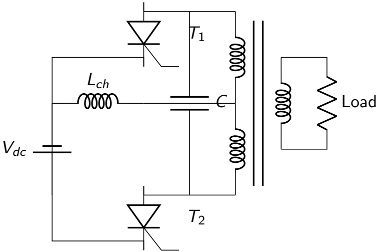
- Disadvantages
- 1. **Distorted Output:** Output is not purely sinusoidal; it consists of discrete positive and negative pulses separated by dead time.
- 2. **Load Dependency:** The commutation relies on the load parameters (R, L, C). If load changes, it may become overdamped, preventing commutation.
- 3. **High Device Ratings:** SCRs and load components must withstand high voltages and currents.

Key Takeaways

- Highly sensitive to load variations.
- Output is a sequence of damped pulses.

Parallel Inverter Circuit

- Overview
- The commutating capacitor C is connected in parallel with the load via a center-tapped transformer.
- Uses two SCRs (T_1, T_2) and operates on Class C (complementary) commutation.
- Commonly used in UPS systems and induction heating.



Key Takeaways

- Uses a center-tapped transformer.
- Employs complementary (Class C) commutation.

Parallel Inverter Operation

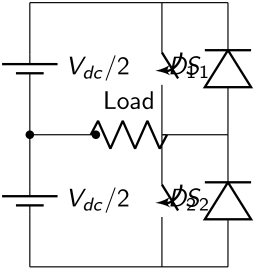
- Working Principle
- **Step 1:** T_1 triggered. Current flows through upper half of primary. Induced voltage in lower half charges capacitor C to $2V_{dc}$.
- **Step 2:** T_2 triggered. The capacitor voltage $2V_{dc}$ applies a reverse bias across T_1, turning it off immediately (commutation).
- **Step 3:** Current now flows through the lower half of primary. C charges in the opposite direction to $-2V_{dc}$.
- **Output:** A square wave voltage is induced in the secondary.

Key Takeaways

- Capacitor charges to twice the supply voltage.
- Firing one SCR automatically commutates the other.

Single-Phase Half-Bridge Inverter

- Circuit Topology
- Requires a 3-wire DC source (or two equal capacitors across a DC source: $+V_{dc}/2$ and $-V_{dc}/2$).
- Uses two fully controlled switches (e.g., IGBTs, MOSFETs) S_1 and S_2.
- Two freewheeling diodes D_1 and D_2 across the switches.



Key Takeaways

- Requires a split DC supply.
- Uses two active switches and two antiparallel diodes.

Half-Bridge Inverter: Operation & Waveforms

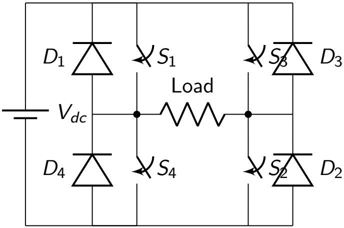
- Operation
- **Positive Cycle:** S_1 ON, S_2 OFF. Output voltage $V_o = +V_{dc}/2$.
- **Negative Cycle:** S_1 OFF, S_2 ON. Output voltage $V_o = -V_{dc}/2$.
- RMS Output Voltage
- $V_{o(rms)} = \frac{V_{dc}}{2}$
- Peak reverse voltage across off-switch $= V_{dc}$.

Key Takeaways

- Output is a square wave alternating between +Vdc/2 and -Vdc/2.
- RMS output voltage is exactly half of the total DC link voltage.

Single-Phase Full-Bridge Inverter

- Circuit Topology
- Uses four switches (S_1, S_2, S_3, S_4) and four diodes in an H-bridge configuration.
- Eliminates the need for a 3-wire split DC supply.
- Load is connected between the midpoints of the two switch legs.



Key Takeaways

- Four switches in an H-bridge.
- Does not require a split DC source.

Full-Bridge Inverter: Operation & Waveforms

- Operation
- **Positive Cycle:** S_1 and S_2 are ON. Output voltage $V_o = +V_{dc}$.
- **Negative Cycle:** S_3 and S_4 are ON. Output voltage $V_o = -V_{dc}$.
- (Never turn on S_1, S_4 or S_3, S_2 simultaneously - causes a short circuit/shoot-through!)
- Output Metrics
- $V_{o(rms)} = V_{dc}$
- Fundamental RMS voltage: $V_{1(rms)} = \frac{4V_{dc}}{\pi\sqrt{2}} \approx 0.9V_{dc}$

Key Takeaways

- Output voltage is a square wave of amplitude Vdc.
- Output power is 4 times that of a half-bridge (for same load and Vdc).

Summary

- **Inverters** convert DC to AC power.
- **Series Inverters:** Simple, but load dependent; uses underdamped RLC for natural commutation.
- **Parallel Inverters:** Uses center-tapped transformer and complementary commutation; good for stable loads.
- **Half-Bridge:** Simple structure, requires split DC source, output voltage is $V_{dc}/2$.
- **Full-Bridge:** H-bridge structure, uses full DC source, output voltage is V_{dc}. Most practical topology.

Key Takeaways

- Bridge inverters are the industry standard for single-phase DC-AC conversion.

Next Lecture Preview

- Lecture 21: Chopper Circuits
- DC to DC Conversion principles.
- Step-down (Buck) Chopper.
- Step-up (Boost) Chopper.
- Control Strategies: Time Ratio Control (PWM vs PFM).
- Traction applications of choppers.

Lecture 21: Chopper Circuits - Principles and Applications

- Principle & Working of Chopper Circuits
- **Unit 4: Power Converters**
- Introduction to DC-DC Conversion
- Step-Down (Buck) Chopper
- Step-Up (Boost) Chopper
- Duty Cycle Control Strategies (PWM vs PFM)
- Applications in Traction and Industry

Agenda

- 1. What is a Chopper?
- 2. Principle of Operation (Switching)
- 3. Step-Down (Buck) Chopper Circuit & Math
- 4. Step-Up (Boost) Chopper Circuit & Math
- 5. Control Strategies: PWM and PFM
- 6. Industrial and Traction Applications
- 7. Summary

What is a Choppper?

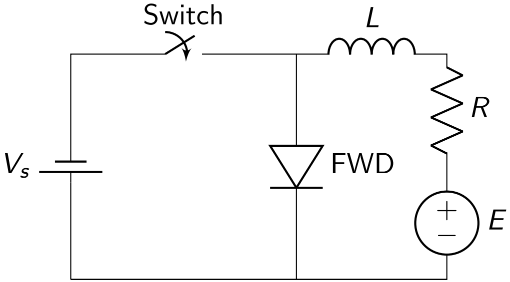
- Definition
  - A chopper is a static power electronics device that converts fixed DC input voltage to a variable DC output voltage directly.
  - Also known as a **DC-to-DC Converter**.
- Why use Choppers?
  - High efficiency (switch operates in saturation/cutoff, minimizing power loss).
  - Smooth and continuous control.
  - Fast response.
  - Replaces bulky, inefficient rheostatic controllers or motor-generator sets.

Principle of Operation

- The Basic Switch
  - A chopper can be modeled as a high-speed semiconductor switch (BJT, MOSFET, IGBT, or SCR).
  - T_{on}: Time duration the switch is closed (conducting).
  - T_{off}: Time duration the switch is open (blocking).
  - **Chopping Period (T)**: Total cycle time, $T = T_{on} + T_{off}$.
  - **Chopping Frequency (f)**: $f = 1/T$.
- Duty Cycle (α or D)
  - The ratio of ON time to total time.
  - $D = \frac{T_{on}}{T} = \frac{T_{on}}{T_{on}+T_{off}}$

Step-Down (Buck) Chopper

- Circuit Topology
  - Switch is in series with the source and load.
  - A Freewheeling Diode (FWD) is placed in parallel with the inductive load.
  - **Function:** Output DC voltage is strictly less than or equal to the input DC voltage ($V_0 \leq V_s$).

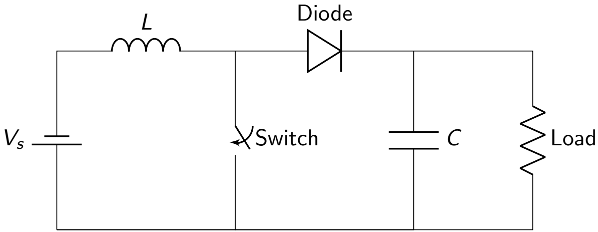


Step-Down Chopper: Mathematical Analysis

- Output Voltage
  - Average Output Voltage (V_0):
  - $V_0 = \frac{1}{T} \int_0^{T_{on}} V_s dt = V_s \left(\frac{T_{on}}{T} \right)$
  - $V_0 = D \cdot V_s$
- Output Current
  - If assuming a lossless switch, Input Power = Output Power.
  - $V_s I_s = V_0 I_0 \implies V_s I_s = (D \cdot V_s) I_0$
  - $I_s = D \cdot I_0$
  - (Notice the current is 'stepped up' as voltage is stepped down, similar to a transformer).

Step-Up (Boost) Chopper

- Circuit Topology
  - A large inductor L is in series with the source.
  - The switch is in parallel with the load.
  - A diode is placed in series to prevent load discharging back into the switch.
  - **Function:** Output DC voltage is strictly greater than or equal to the input DC voltage ($V_0 \geq V_s$).



Step-Up Chopper: Mathematical Analysis

- Energy Balance
  - **Energy stored in L during T_{on}:** $W_{in} = V_s I_s T_{on}$
  - **Energy released by L during T_{off}:** $W_{out} = (V_0 - V_s) I_s T_{off}$
  - Assuming no losses, $W_{in} = W_{out}$:
  - $V_s T_{on} = (V_0 - V_s) T_{off}$
  - $V_s (T_{on} + T_{off}) = V_0 T_{off}$
  - $V_0 = V_s \frac{T}{T_{off}} = V_s \frac{T}{T - T_{on}} = \frac{V_s}{1 - D}$

Control Strategies: Time Ratio Control (TRC)

- 1. Pulse Width Modulation (PWM) - Constant Frequency
  - The chopping period T (and frequency f) is kept constant.
  - The ON time T_{on} is varied to change the duty cycle D.
  - **Pros:** Easy filtering, predictable harmonics.
  - **Cons:** Higher switching losses at low output voltages.
- 2. Pulse Frequency Modulation (PFM) - Variable Frequency
  - T_{on} or T_{off} is kept constant, and the total period T is varied.
  - **Pros:** Can reduce switching losses at light loads.
  - **Cons:** Harmonics are unpredictable and vary with frequency; filter design is very difficult.

Control Strategies: Current Limit Control

- Hysteresis Current Control
  - The chopper switch is turned ON and OFF based on load current limits.
- **Operation:**
  - Switch ON $\rightarrow$ Load current rises. When it hits maximum limit (I_{max}), switch turns OFF.
  - Switch OFF $\rightarrow$ Load current falls (freewheels). When it hits minimum limit (I_{min}), switch turns ON.
- **Result:** Current ripples between I_{min} and I_{max}. Switching frequency is variable.

Applications of Choppers

- 1. Traction Systems (Railways & EVs)
  - Subway cars, trolleybuses, battery-operated vehicles.
  - Choppers allow smooth acceleration and regenerative braking (using step-up chopper mode to feed power back to the battery).
- 2. DC Motor Speed Control
  - Industrial hoists, forklifts, mine haulers.
  - Provides highly efficient step-less speed control compared to old resistive starters.

Applications: SMPS & Lighting

- 3. Switched Mode Power Supplies (SMPS)
  - Found in every computer and modern appliance.
  - Uses isolated chopper circuits (like Flyback or Forward converters) to regulate DC voltages efficiently.
- 4. LED Lighting and Solar
  - **Solar MPPT:** Boost choppers match solar panel voltage to battery banks.
  - **LED Drivers:** Buck or Boost choppers provide constant current to high-power LEDs.

Summary

- **Choppers** are static DC-DC converters offering high efficiency and smooth control.
- **Buck Chopper:** Steps down voltage ($V_0 = D \cdot V_s$). Uses switch in series, FWD in parallel.
- **Boost Chopper:** Steps up voltage ($V_0 = \frac{V_s}{1-D}$). Uses inductor to store energy.
- **Control:** PWM is the dominant control strategy due to fixed frequency operation.
- **Applications:** Dominates DC traction, electric vehicles, and switched-mode power supplies.

Next Lecture Preview

- Lecture 22: Cycloconverters
- Direct AC to AC conversion (without DC link).
- Step-up and Step-down cycloconverters.
- Positive and Negative converter groups.
- Output frequency control and applications.

Lecture 22: Single Phase Cycloconverters

- Single Phase Cycloconverters
- **Unit 4: Power Converters**
- AC to AC Conversion (without DC link)
- Step-up and Step-down Cycloconverters
- Positive and Negative Converter Groups
- Output Frequency Control
- Applications of Cycloconverters

Agenda

- 1. Introduction to AC-AC Conversion
- 2. What is a Cycloconverter?
- 3. Classification (Step-up vs Step-down)
- 4. Operating Principle (Converter Groups)
- 5. Single-Phase to Single-Phase Circuit
- 6. Waveform Analysis & Frequency Control
- 7. Advantages, Disadvantages & Applications
- 8. Summary

Introduction to AC-AC Conversion

- Methods of changing AC frequency
- 1. **Indirect Method (DC Link):** AC $\rightarrow$ Rectifier $\rightarrow$ DC $\rightarrow$ Inverter $\rightarrow$ AC. (Two stage conversion).
- 2. **Direct Method (Cycloconverter):** AC $\rightarrow$ AC. (Single stage conversion).
- Definition of Cycloconverter
- A cycloconverter is a direct-frequency changer that converts AC power at one input frequency (f_i) to output power at a different frequency (f_o) with one-stage conversion.

Classification of Cycloconverters

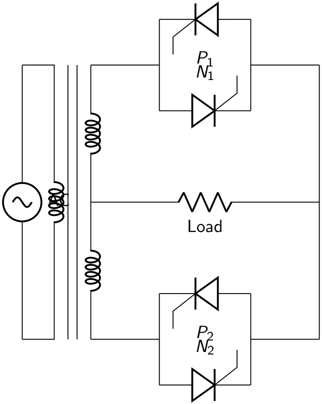
- 1. Step-Down Cycloconverter
  - Output frequency is less than input frequency ($f_o < f_i$).
  - Utilizes **line commutation** (natural commutation). The AC supply naturally turns off the SCRs.
  - Most widely used in industry.
- 2. Step-Up Cycloconverter
  - Output frequency is greater than input frequency ($f_o > f_i$).
  - Requires **forced commutation** circuits since the SCRs must be turned off before the AC cycle zero-crossing.
  - Rarely used due to complex circuitry and high harmonic content.

Operating Principle: Dual Converters

- Positive and Negative Groups
- A single-phase cycloconverter consists of two fully controlled rectifiers (converter bridges) connected in anti-parallel.
- **Positive Group (P-Converter):** Operates to produce the positive half-cycle of the low-frequency output.
- **Negative Group (N-Converter):** Operates to produce the negative half-cycle of the low-frequency output.
- Only one group conducts at a time to prevent short circuits.

Single-Phase to Single-Phase Circuit

- Mid-point Configuration
  - Uses a center-tapped transformer.
  - **P-Group:** Thyristors P_1 and P_2.
  - **N-Group:** Thyristors N_1 and N_2.
  - Load is connected between the common thyristor connection and the center tap.
- Bridge Configuration
  - Uses two full-bridge rectifiers (8 Thyristors total).
  - Eliminates center-tapped transformer but requires more devices.



Output Frequency Control ($f_o = f_i/3$)

- Example: Generating 16.67 Hz from 50 Hz
- We want $f_o = \frac{1}{3} f_i$.
- **Positive Half Cycle:** The P-Group is kept active for 1.5 cycles of the input supply (3 half-cycles).
  - P_1, P_2, P_1 are fired in sequence.
- **Negative Half Cycle:** The N-Group is activated for the next 1.5 cycles of the input supply.
  - N_1, N_2, N_1 are fired in sequence.
- One complete output cycle takes 3 complete input cycles.

Voltage Control (Phase Angle Control)

- Modulating the Firing Angle (α)
- If we keep the firing angle α constant (e.g., $\alpha = 0^\circ$), the output is a square-ish block of voltage. Highly distorted.
- **Cosine Wave Crossing Method:** To get a sinusoidal output, we must continuously vary the firing angle α during the half-cycle.
  - Near the zero-crossing of output, α is close to 90° (low voltage).
  - Near the peak of the output, α is close to 0° (high voltage).
- This produces a stepped wave that closely approximates a sine wave.

Circulating Current Mode vs Non-Circulating

- Non-Circulating Current Mode
  - Only one group (P or N) conducts at any time.
  - A short dead-time is inserted when switching between groups to prevent a dead-short across the supply.
  - Current can become discontinuous, increasing harmonics.
- Circulating Current Mode
  - Both P and N groups are kept active.
  - An Intergroup Reactor (inductor) is placed between them to limit short-circuit circulating current.
  - Output voltage is much smoother, and current is continuous.

Advantages and Disadvantages

- Advantages
  - Direct AC-AC conversion (no DC link capacitor/inductor required).
  - Natural commutation (no forced turn-off circuits needed for step-down).
  - Inherent bidirectional power flow (capable of regenerative braking).
- Disadvantages
  - Requires a very large number of thyristors (e.g., 36 SCRs for a 3-phase to 3-phase cycloconverter).
  - Output frequency is practically limited to $\leq 1/3$ of input frequency to keep harmonics acceptable.
  - Poor input power factor.

Applications of Cycloconverters

- Heavy Industrial Motor Drives
- **Gearless Cement Mills:** Giant low-speed motors (10-15 RPM) requiring massive torque. Cycloconverters drive them directly at 1-5 Hz.
- **Mine Winders & Hoists:** Require high starting torque and precise low-speed control.
- **Ship Propulsion:** High power, low speed propellers.
- **Rolling Mills:** Steel processing requiring rapid torque reversals.

Summary

- **Cycloconverters** directly convert AC frequency without a DC link.
- Built using dual **P and N converter groups**.
- **Step-down** type is practical, utilizing natural line commutation.
- Output frequency is controlled by switching between P and N groups ($f_o \leq f_i/3$).
- Output voltage waveform is shaped by continuously modulating the firing angle α.
- Primarily used in massive, low-speed industrial drives like cement mills and ship propulsion.

Next Lecture Preview

- Lecture 23: UPS & SMPS
- Switched Mode Power Supply (SMPS) block diagram.
- Uninterruptible Power Supply (UPS) architecture.
- Online vs Offline UPS systems.
- Battery banks, inverters, and static switches.
- Applications in IT and commercial sectors.

Lecture 23: Uninterruptible Power Supplies (UPS) & Switched Mode Power Supplies (SMPS)

- UPS & SMPS: Principles and Block Diagrams
- **Unit 4: Power Converters**
- Introduction to reliable power delivery
- Switched Mode Power Supply (SMPS) block diagram & working
- Uninterruptible Power Supply (UPS) basics
- Online vs Offline UPS Topologies
- Key Components: Battery bank, Inverter, Static Switch

Key Takeaways

- SMPS provides efficient DC power.
- UPS provides continuous AC power during outages.

Agenda

- 1. Linear vs. Switched Power Supplies
- 2. SMPS Block Diagram and Operation
- 3. SMPS Advantages & Applications
- 4. What is a UPS?
- 5. Offline (Standby) UPS Block Diagram
- 6. Online (Double-Conversion) UPS Block Diagram
- 7. The Role of the Static Bypass Switch
- 8. Summary of Unit 4

Linear Power Supply vs. SMPS

Linear Power Supply (Traditional)

- AC → Step-down bulky iron Transformer → Rectifier → Linear Regulator (dissipates excess power as heat).
- **Efficiency:** Low (30-40%).
- **Size/Weight:** Very bulky due to 50Hz transformer.

Switched Mode Power Supply (SMPS)

- AC is rectified directly at high voltage, chopped at high frequency (20kHz - 100kHz), passed through a tiny ferrite transformer, then rectified again.
- **Efficiency:** High (80-95%).
- **Size/Weight:** Compact and lightweight.

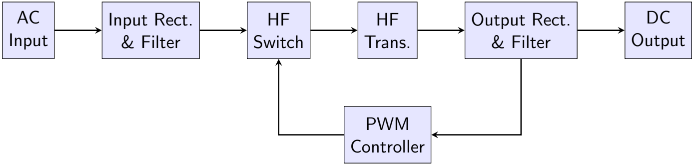
Key Takeaways

- SMPS switching at high frequency reduces transformer size.
- SMPS is much more efficient than linear supplies.

SMPS Block Diagram

Key Stages of SMPS

- 1. **Input Rectifier & Filter:** Converts raw 230V AC to high voltage DC ($\approx 320V$).
- 2. **High-Frequency Switch (Chopper):** MOSFETs switch the DC on/off at 20kHz - 100kHz.
- 3. **High-Frequency Transformer:** Steps down the high-voltage pulsed DC to a low voltage, providing galvanic isolation.
- 4. **Output Rectifier & Filter:** Converts the high-frequency low-voltage pulses back to smooth DC (e.g., 5V, 12V).
- 5. **Control Circuit (PWM):** Senses output voltage, adjusts duty cycle of the switch to maintain regulation.



SMPS Applications

Where are SMPS used?

- **Computers & IT:** ATX power supplies in desktops, laptop charging bricks.
- **Consumer Electronics:** Mobile phone chargers, TV power boards, gaming consoles.
- **Industrial:** DIN-rail power supplies for PLCs, LED lighting drivers, motor drives.

Advantages over Linear

- Smaller footprint.
- Lower heat dissipation.
- Can operate over a wide input AC voltage range (e.g., 100V - 240V universal input).

Introduction to UPS

What is an Uninterruptible Power Supply (UPS)?

- A system that provides emergency power to a load when the input power source or mains power fails.
- **Core Difference from Generators:** A UPS provides near-instantaneous protection by supplying energy stored in batteries. (No engine start-up time).

Primary Components

- 1. **Rectifier/Charger:** Converts AC to DC to charge batteries.
- 2. **Battery Bank:** Stores DC energy.
- 3. **Inverter:** Converts DC from batteries back to AC for the load.
- 4. **Static Switch:** Rapidly transfers the load between mains and inverter.

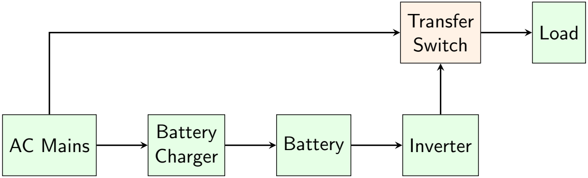
Offline (Standby) UPS Block Diagram

How it works

- **Normal Mode:** The mains AC directly supplies the load through a transfer switch. The rectifier trickles charges the battery.
- **Outage Mode:** When mains fails, the transfer switch toggles to the Inverter. The Inverter draws from the battery to supply the load.

Characteristics

- **Transfer Time:** There is a slight delay (typically 4-10 milliseconds) while the mechanical relay or static switch transitions.
- **Protection:** Limited protection against voltage sags and surges (relies purely on surge suppressors).



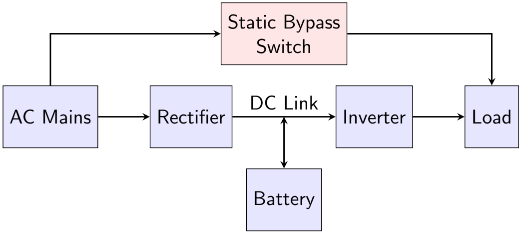
Online (Double-Conversion) UPS Block Diagram

How it works

- **Normal Mode:** AC Mains → Rectifier → DC Bus → Inverter → Load.
- The load is *always* powered by the inverter. The rectifier supplies the inverter and charges the batteries simultaneously.
- **Outage Mode:** The rectifier loses power. The inverter simply continues to draw power from the battery bus seamlessly.

Characteristics

- **Transfer Time:** Zero. (No switching required during blackout).
- **Protection:** Total isolation from grid noise, surges, and frequency fluctuations.



The Role of the Static Bypass Switch

Failsafe Mechanism in Online UPS

- What happens if the UPS inverter fails or the UPS is overloaded?
- The **Static Bypass Switch** (built with anti-parallel Thyristors/TRIACs) automatically and instantaneously connects the load directly to the raw AC mains.
- This bypasses the internal electronics, ensuring the critical load does not drop even if the UPS hardware suffers a catastrophic fault.

Key Takeaways

- Protects the load in case of internal UPS failure.
- Uses ultra-fast solid-state thyristor switches.

Comparison: Online vs Offline UPS

Feature	Offline (Standby) UPS	Online (Double-Conversion) UPS
Transfer Time	4 - 10 ms	Zero
Power Quality	Fair (passes grid noise)	Excellent (rebuilds pure sine wave)
Cost / Size	Low / Small	High / Large
Efficiency	High (~98% in normal mode)	Lower (~85-92% due to constant double conversion)
Application	Home PCs, basic routers	Data centers, medical equipment, industrial servers

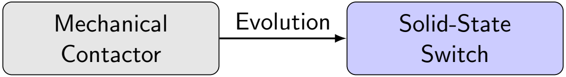
Summary

- **SMPS** uses high-frequency switching to efficiently step-down and regulate DC voltages, minimizing size and heat compared to linear supplies.
- **UPS** systems provide emergency AC power using rectifiers, batteries, and inverters.
- **Offline UPS** routes grid power directly to the load until an outage triggers a switchover (small delay).
- **Online UPS** constantly converts AC to DC and back to AC, providing zero-delay switchover and ultimate power conditioning.
- **Static Switches** provide high-speed, solid-state bypassing for safety.

Next Unit Preview

- Unit 5: Industrial Electronics Applications
- Lecture 24: Timers and Heating Applications
- Dielectric Heating vs Induction Heating
- Welding power supplies
- Looking ahead to real-world industrial implementations of everything we've learned.

- Lecture 24: Static Switch and Circuit Breaker using SCR
- Solid state vs mechanical switches
- AC static switch using anti-parallel SCRs
- DC static circuit breaker
- Fast fault clearing mechanisms

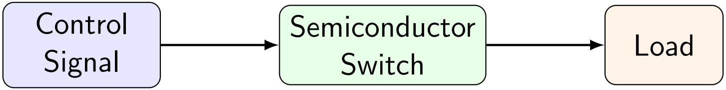


Agenda

1. Introduction to Static Switches
2. Solid State vs Mechanical Switches
3. AC Static Switch using Anti-Parallel SCRs
4. DC Static Switch / Circuit Breaker
5. Commutation in DC Breakers
6. Fast Fault Clearing
7. Summary

Introduction to Static Switches

- What is a Static Switch?
- Uses semiconductor devices (SCRs, TRIACs, Transistors) to turn power on and off.
- **Static:** No moving parts involved in the switching action.
- Used for both AC and DC systems.
- Triggered by low-power control signals (gate pulses).

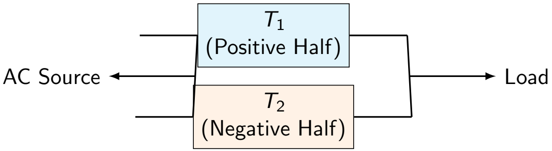


Solid State vs Mechanical Switches

Feature	Mechanical Switch	Solid State (Static) Switch
Moving Parts	Yes (contacts)	No
Switching Speed	Slow (milliseconds)	Fast (microseconds)
Arcing/Sparking	Yes (during switching)	No arcing
Lifespan	Limited (wear and tear)	Extremely long
On-state Voltage Drop	Very low ($\approx$ 0V)	Higher ($\approx$ 1-2V per device)
Isolation	Perfect when open	Leakage current exists when off

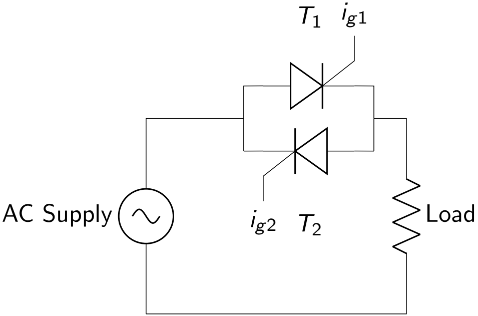
AC Static Switch using Anti-Parallel SCRs

- Why Anti-Parallel SCRs?
- An AC switch must conduct in both directions.
- A single SCR only conducts in one direction (unidirectional).
- **Solution:** Connect two SCRs in inverse-parallel (anti-parallel).
- SCR1 conducts during the positive half-cycle.
- SCR2 conducts during the negative half-cycle.
- TRIACs can also be used, but SCRs offer higher power and voltage ratings.



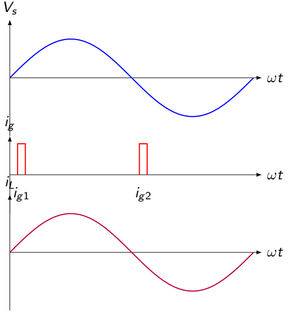
AC Static Switch - Circuit Diagram

- Circuit Configuration
- Two SCRs (T_1, T_2) connected in anti-parallel between the AC supply and the load.
- Control circuits provide gate pulses i_{g1} and i_{g2}.



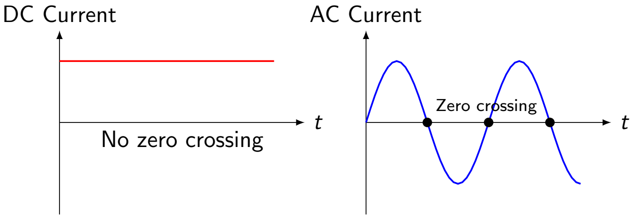
AC Static Switch - Operation

- Working Principle
- **Turn-ON:**
  - Positive half-cycle: T_1 is forward biased. Apply gate pulse i_{g1} $\rightarrow$ T_1 conducts.
  - Negative half-cycle: T_2 is forward biased. Apply gate pulse i_{g2} $\rightarrow$ T_2 conducts.
- **Turn-OFF (Natural Commutation):**
  - In AC circuits, the current naturally crosses zero every half cycle.
  - When current falls below the holding current (I_H), the conducting SCR turns off automatically.
  - No complex forced commutation circuitry is required.



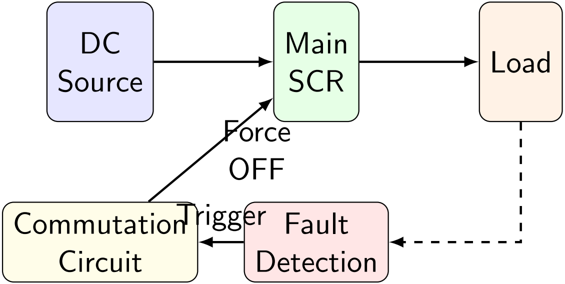
DC Static Switch Overview

- Controlling DC Power
- DC supply has no natural zero-crossing.
- Once an SCR is turned ON in a DC circuit, it stays ON even if the gate signal is removed.
- **Challenge:** Turning the SCR OFF requires driving the anode current below the holding current (I_H).
- **Requirement:** Forced commutation circuits are mandatory for DC static switches.



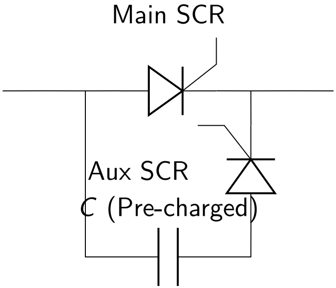
DC Static Circuit Breaker using SCR

- What is a Static Circuit Breaker?
- A protective device that interrupts fault currents (short circuits, overloads) extremely rapidly.
- Uses an SCR as the main interrupting element.
- Can interrupt fault currents in microseconds, compared to milliseconds for mechanical breakers.
- **Crucial for protecting sensitive electronic equipment and DC grids.**



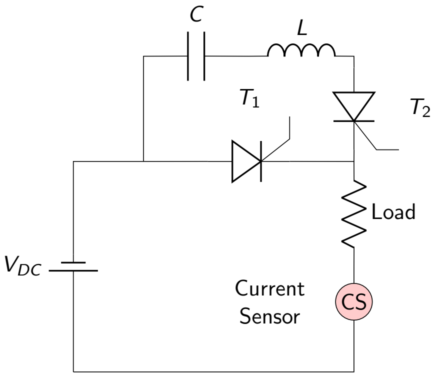
Commutation in DC Static Switches

- Forced Commutation Techniques
- To turn OFF the main SCR, we must momentarily reverse bias it or divert its current.
- **Capacitor Commutation (Class D / Voltage Commutation):**
  - An auxiliary SCR connects a pre-charged capacitor across the main SCR.
  - The capacitor voltage reverse-biases the main SCR, forcing it OFF instantly.
  - The commutation capacitor must store enough energy to handle the peak fault current.



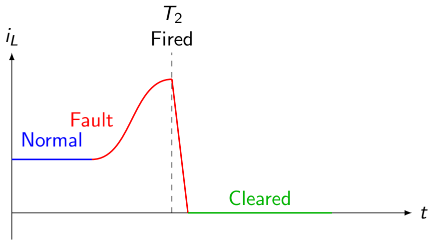
DC Static Circuit Breaker - Circuit Diagram

- Typical Circuit Structure
- **Main SCR (T_1):** Carries the normal load current.
- **Auxiliary SCR (T_2):** Used to initiate turn-off.
- **Commutation Capacitor (C):** Pre-charged to supply reverse voltage.
- **Inductor (L):** Often used with C for resonant current reversal.



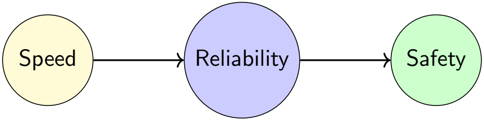
DC Static Circuit Breaker - Fast Fault Clearing

- Fault Interruption Sequence
  1. **Normal Operation:** T_1 is ON, load current flows. Capacitor C is charged.
  2. **Fault Occurs:** Load current spikes dramatically.
  3. **Detection:** Current sensor detects the overcurrent in microseconds.
  4. **Commutation:** Control logic immediately fires Auxiliary SCR T_2.
  5. **Interruption:** Capacitor C discharges across T_1, reverse-biasing it. T_1 turns OFF instantly.
  6. **Clearing:** The fault current is transferred to C temporarily and then drops to zero.



Advantages & Applications

- Why use Static Switches?
- **Advantages:**
  - Ultra-fast response time (crucial for short circuit protection).
  - No moving parts $\rightarrow$ No wear, bounce, or acoustic noise.
  - High reliability and long operational life.
  - Operates safely in explosive environments (no sparking).
- **Applications:**
  - Protection of HVDC systems and DC microgrids.
  - Uninterruptible Power Supplies (UPS) transfer switches.
  - High-frequency induction heating controls.



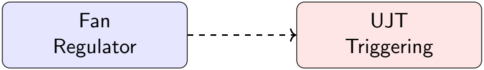
Summary

- Static switches replace mechanical contacts with semiconductors like SCRs.
- AC static switches use anti-parallel SCRs and rely on natural commutation.
- DC static switches require forced commutation circuits (like pre-charged capacitors) to turn off.
- Static circuit breakers provide ultra-fast fault clearing, essential for protecting sensitive DC circuits and systems.

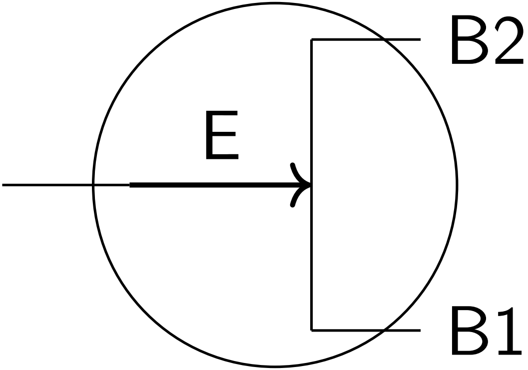
$$\text{AC} = \text{Natural Commutation}$$
$$\text{DC} = \text{Forced Commutation}$$

Next Lecture Preview

- Lecture 25: Phase Control and Triggering
- Single phase AC power control using DIAC and TRIAC.
- Understanding the Fan Regulator / Dimmer circuit.
- DC power control circuits.
- UJT (Unijunction Transistor) relaxation oscillator for SCR gate triggering.



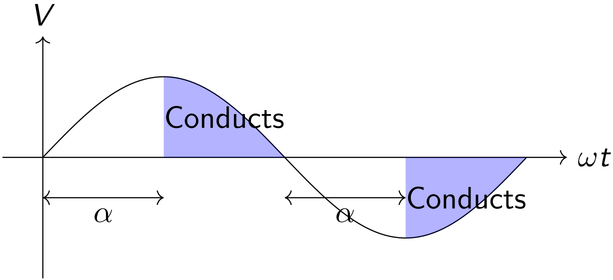
- Lecture 25: AC/DC Power Control & UJT Triggering
- Single phase AC power control using DIAC-TRIAC
- Fan regulator / dimmer circuit
- Firing angle (α) control
- UJT relaxation oscillator for SCR gate triggering
- DC power control circuit using SCR and UJT



Agenda

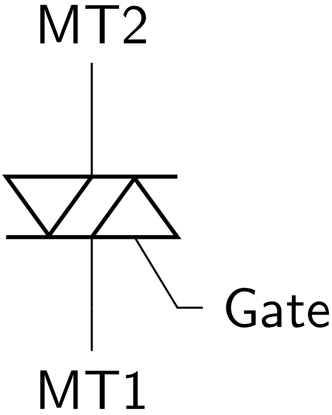
Introduction to Phase Control

- What is Phase Control?
- A method to control the average power delivered to a load from an AC source.
- Achieved by delaying the turn-on point (firing angle, α) of a thyristor during each AC half-cycle.
- The thyristor blocks power for the first part of the cycle and conducts for the remainder.
- **Applications:** Light dimming, motor speed control (fans), heating control.



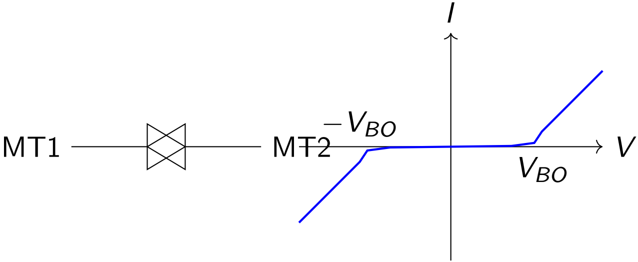
Single Phase AC Power Control

- Using a TRIAC
- A TRIAC is a bidirectional thyristor, ideal for AC phase control.
- It can conduct in both positive and negative half-cycles of the AC supply.
- Requires a gate pulse for both half-cycles.
- The power to the load is controlled by symmetrically adjusting α in both half-cycles.



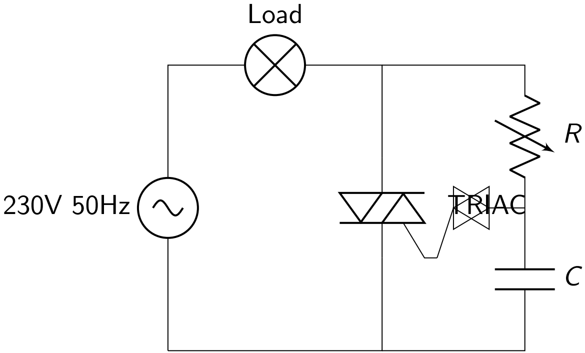
DIAC-TRIAC Phase Control Circuit

- The Role of the DIAC
- A DIAC is a bidirectional trigger diode.
- It does not conduct until the voltage across it reaches its breakover voltage (V_{BO}, typically around 30V).
- Once V_{BO} is reached, it avalanches and provides a sharp pulse of current.
- **Why use a DIAC?** It ensures the TRIAC receives a sharp, consistent gate pulse, preventing erratic firing and ensuring symmetrical triggering in both half-cycles.



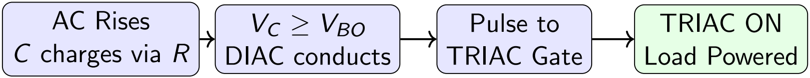
Fan Regulator / Dimmer Circuit

- Circuit Components
- **AC Source:** 230V, 50Hz.
- **Load:** Incandescent bulb or Fan motor.
- **TRIAC:** Main power switch.
- **DIAC:** Trigger device.
- **R-C Network:** Variable Resistor (R) and Capacitor (C) determine the timing (firing angle α).



DIAC-TRIAC Operation

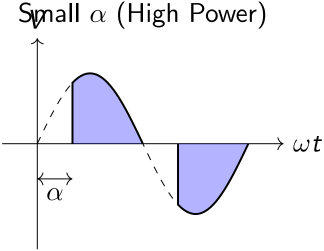
- How it Works
- 1. AC voltage rises. Capacitor C charges through Variable Resistor R.
- 2. The rate of charging is determined by the RC time constant.
- 3. When the voltage across C reaches the DIAC breakover voltage (V_{BO}), the DIAC conducts.
- 4. Capacitor C discharges through the DIAC into the TRIAC gate.
- 5. TRIAC turns ON, completing the circuit to the Load.
- 6. At the zero crossing, TRIAC turns OFF, and the cycle repeats in the reverse direction.



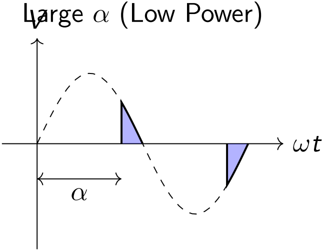
Firing Angle α Control

- Adjusting the Power
- **Small R (Low Resistance):** Capacitor charges quickly. Reaches V_{BO} early in the cycle. Small α. TRIAC conducts for a long time. **High Power (Bright Light / Fast Fan).**
- **Large R (High Resistance):** Capacitor charges slowly. Reaches V_{BO} late in the cycle. Large α. TRIAC conducts for a short time. **Low Power (Dim Light / Slow Fan).**
- By turning the potentiometer, we change R, change α, and thus change the load power.

Small α (High Power)

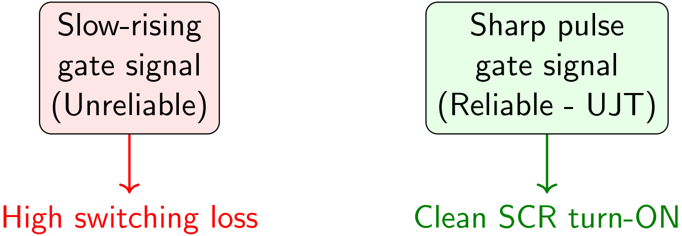


Large α (Low Power)



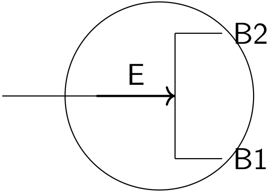
DC Power Control Overview

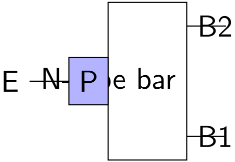
- Triggering SCRs in DC Circuits
- For DC power control (like DC motor drives), we often use SCRs.
- The gate triggering circuit must be reliable and independent of the main power circuit variations.
- A simple resistor voltage divider is often not enough for precise, sharp triggering.
- **Solution:** A relaxation oscillator using a Unijunction Transistor (UJT) provides excellent, sharp pulse trains for SCR gates.



UJT (Unijunction Transistor) Overview

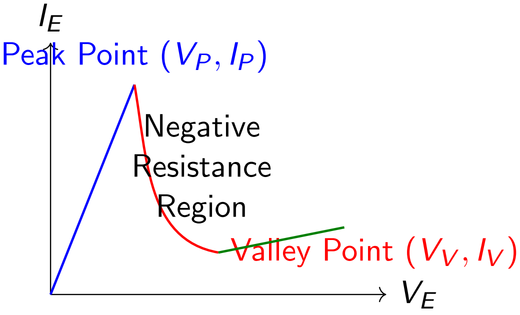
- What is a UJT?
- A three-terminal semiconductor device: Emitter (E), Base 1 (B1), and Base 2 (B2).
- It has only one P-N junction (between Emitter and the N-type bar).
- **Key Characteristic:** Negative resistance region.
- When the Emitter voltage V_E exceeds a peak voltage V_P, the resistance between E and B1 drops drastically.
- This makes it an ideal switch for oscillator circuits.





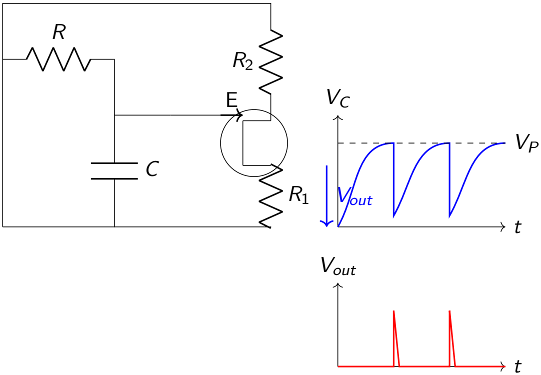
UJT Relaxation Oscillator

- Oscillator Principle
- The UJT acts as a voltage-controlled switch across a capacitor.
- The circuit 'relaxes' (charges) and then suddenly 'fires' (discharges).
- **Intrinsic Stand-off Ratio (η):** A parameter of the UJT that determines the peak voltage V_P.
- $V_P = \eta V_{BB} + V_D$
- V_{BB} is the voltage between B2 and B1.
- V_D is the diode drop (approx 0.7V).



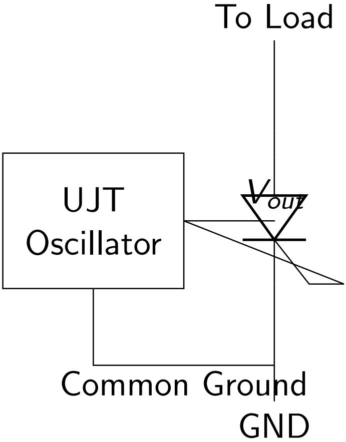
UJT Relaxation Oscillator Circuit

- Circuit and Waveforms
- Capacitor C charges through Resistor R.
- When V_C reaches V_P, UJT turns ON.
- Capacitor discharges rapidly through Base 1 (B_1) and resistor R_1.
- The rapid discharge creates a sharp voltage spike across R_1.
- This spike is ideal for triggering an SCR.



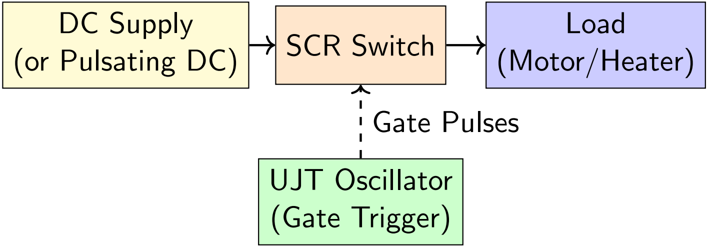
SCR Triggering using UJT

- Connecting to the SCR
- The output from R_1 (Base 1 of UJT) is connected to the Gate of the SCR.
- The sharp pulses ensure fast and reliable turn-ON of the SCR.
- By varying the charging resistor R in the UJT circuit, we vary the frequency of the pulses, or the delay angle α in synchronized circuits.



DC Power Control Circuit using SCR and UJT

- Complete DC Control System
- A typical DC power control (e.g., controlling a DC heater or simple motor) uses an SCR as the main switch.
- The UJT oscillator provides the gating signal.
- **Note:** In pure DC, once the SCR is triggered by the UJT pulse, it stays ON. To achieve *control* (like PWM), a commutation circuit must be added to turn the SCR OFF periodically, or the input must be pulsating DC (from an uncontrolled rectifier).



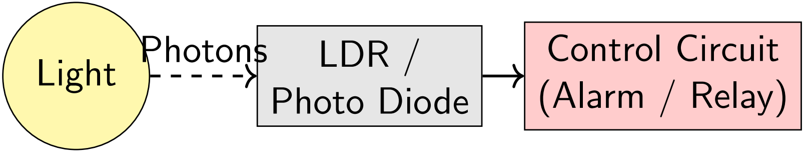
Summary

- **DIAC-TRIAC Circuits:** Used for AC phase control (dimmers, fan regulators). The DIAC ensures symmetrical, sharp triggering of the TRIAC.
- **RC Time Constant:** Changing R varies the firing angle α, controlling the power delivered to the load.
- **UJT (Unijunction Transistor):** A device with negative resistance, ideal for building relaxation oscillators.
- **SCR Triggering:** The UJT oscillator provides the sharp, reliable voltage pulses required to gate SCRs in DC and pulsating DC control circuits.

Feature	**DIAC-TRIAC**	**UJT-SCR**
Application	AC Phase Control	DC / Pulsating DC Control
Trigger Device	DIAC	UJT
Main Switch	TRIAC	SCR
Pulse Type	Avalanche pulse	Relaxation oscillator pulse

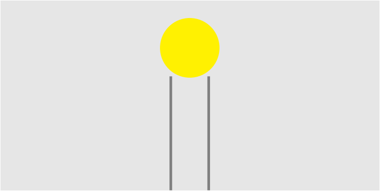
Next Lecture Preview

- Lecture 26: Optoelectronics in Industrial Control
- Light Dependent Resistors (LDR) and their characteristics.
- Photo-electric relays and street light controller circuits.
- Photo diodes vs LDRs.
- Light Activated SCR (LASCR) and alarm circuits.



Lecture 26: Photo Electric Relay and Switch

- Light Dependent Resistor (LDR) characteristics
- Street light controller circuit using LDR
- Photo diode speed and applications
- Light Activated SCR (LASCR) alarm circuits



Automated Street Light

Agenda

- 1. Introduction to Optoelectronics in Control
- 2. Light Dependent Resistor (LDR)
- 3. Photo Electric Relay using LDR
- 4. Street Light Controller Circuit
- 5. Photo Diode Characteristics and Speed
- 6. Light Activated SCR (LASCR)
- 7. LASCR Alarm Circuit
- 8. Summary

Optoelectronics in Control

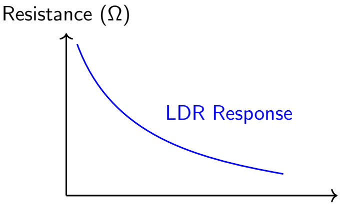
Why use light for control?

- **Isolation:** Light provides perfect electrical isolation between the control circuit (light source) and the power circuit (light detector).
- **Automation:** Systems can react to ambient environmental conditions (day/night).
- **Non-contact sensing:** Can detect presence, position, or speed without physical contact (e.g., optical encoders, safety curtains).
- **Speed:** Photons travel at the speed of light; optoelectronic semiconductor response times can be in the nanosecond range.

Light Dependent Resistor (LDR)

LDR Characteristics

- Also known as a Photoresistor (typically made of Cadmium Sulfide, CdS).
- Principle: **Photoconductivity**.
- **Dark Resistance:** Very high (often in Mega-ohms, $M\Omega$).
- **Light Resistance:** Very low (drops to a few kilo-ohms, $k\Omega$, or hundreds of ohms when illuminated).
- **Speed:** Relatively slow response time (tens of milliseconds). Suitable for slow-changing light like daylight.



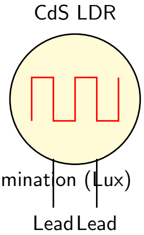
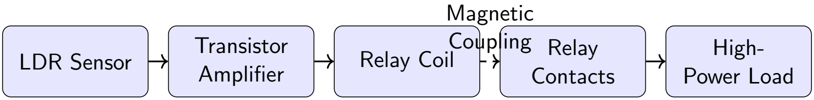


Photo Electric Relay using LDR

Basic Concept

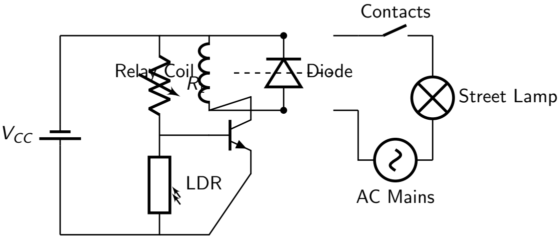
- An LDR is used in a voltage divider network to detect light levels.
- The output of the voltage divider feeds a transistor amplifier.
- The transistor drives an electromechanical relay.
- The relay contacts control the main high-power load (e.g., street lamps).
- The circuit can be configured to turn ON when dark (street light) or turn ON when light (solar tracker).



Street Light Controller Circuit

Circuit Diagram

- **Voltage Divider:** R_1 and LDR.
- **Transistor:** NPN (e.g., BC547) acting as a switch.
- **Load:** Relay coil (with freewheeling diode).
- **Adjustment:** R_1 is usually a potentiometer to set the sensitivity.



Operation of Street Light Controller

How it Works (Turn ON at Dark)

- **1. Daytime:** High light intensity $\rightarrow$ LDR resistance is LOW.
    - Voltage at transistor base is LOW (below 0.7V).
    - Transistor is OFF. Relay is OFF. Street light is OFF.
- **2. Nighttime:** Low light intensity $\rightarrow$ LDR resistance is HIGH.
    - Voltage at transistor base rises as LDR resistance increases.
    - When base voltage $> 0.7V$, Transistor turns ON.
    - Current flows through Relay coil. Contacts close. Street light turns ON.

High-Speed Light Detection

- A PN junction operated in **reverse bias**.
- When light strikes the junction, electron-hole pairs are created, increasing the reverse leakage current (photocurrent).
- Photocurrent is directly proportional to light intensity.
- **Speed:** Extremely fast response time (microseconds to nanoseconds).
- Used in high-speed applications like fiber optic receivers, remote controls, and optical encoders.

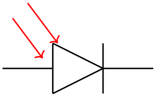


Photo Diode Symbol

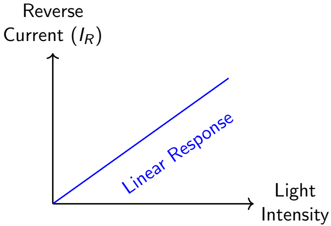


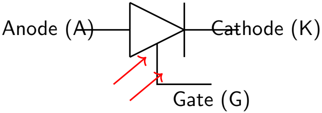
Photo Diode vs LDR

Feature	Light Dependent Resistor (LDR)	Photo Diode
Principle	Photoconductivity (Resistance changes)	Photovoltaic/Photocurrent (Current changes)
Speed / Response	Very Slow (milliseconds)	Very Fast (nanoseconds)
Sensitivity	High sensitivity to visible light	Sensitive to specific wavelengths (IR, visible)
Linearity	Non-linear response	Highly linear response
Applications	Street lights, twilight switches	Fiber optics, remote controls, high-speed counting

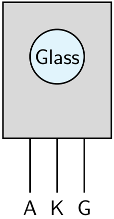
Light Activated SCR (LASCR)

What is a LASCR?

- A thyristor that is triggered ON by light, rather than a gate current.
- Also known as a Photo-SCR.
- It has a clear window in its packaging to allow light to strike the silicon chip (specifically the gate-cathode junction).
- It combines light detection and high-power switching in a single device.



LASCR Symbol

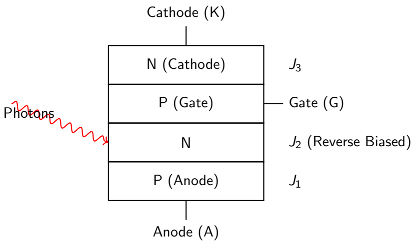


Physical Component

LASCR Operating Principle

Triggering Mechanism

- When forward biased, it blocks current.
- Light photons enter the window and strike the internal reverse-biased junction (J_2).
- Photons generate electron-hole pairs, creating an internal leakage current.
- This internal current acts exactly like a gate current (I_g).
- When light intensity is high enough, internal I_g exceeds the threshold, and the LASCR latches ON.
- Like a standard SCR, in a DC circuit, it stays ON even if the light is removed.

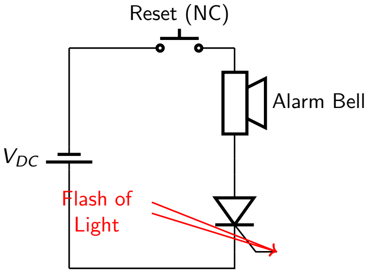


Photons strike J_2, creating electron-hole pairs

LASCR Alarm Circuit

Intruder Alarm Application

- **Setup:** A continuous laser or light beam shines on the LASCR.
- **Normal State:** (If designed to trigger on darkness/beam break) - Requires an inverter circuit.
- **Simpler Latching Alarm (Flash trigger):**
  - LASCR is in darkness (OFF state).
  - A brief flash of light (e.g., from an opening door in a dark room) hits the LASCR.
  - LASCR latches ON instantly.
  - An alarm bell (DC load) connected in series rings continuously until a reset switch is pressed.



Industrial Applications of Opto-Switches

Where are they used?

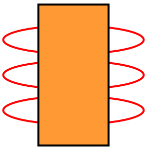
- **Optocouplers (Optoisolators):** Using an LED and a phototransistor/LASCR in a single sealed package to provide complete electrical isolation between logic circuits (microcontrollers) and power circuits.
- **Conveyor Belt Sorting:** Detecting presence and size of objects on a factory line.
- **Safety Curtains:** Beams of light protecting operators from dangerous machinery.
- **Automated Lighting:** Energy-saving daylight harvesting systems.

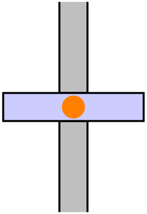
Summary

- **LDR:** Resistance drops with light. Slow response. Used in twilight switches and street light controllers.
- **Photo Diode:** Reverse current increases with light. Extremely fast response. Used in high-speed optical communications and sensing.
- **LASCR:** A light-triggered thyristor. Latches ON upon receiving a light pulse. Excellent for alarm and latching relay applications.
- Optoelectronics provide crucial electrical isolation and enable automated environmental responses in power systems.

Lecture 27: Industrial Heating and Welding

- High-frequency induction heating.
- Dielectric heating principles.
- Resistance welding control circuits using thyristors.
- Application of power electronics in heavy industry.





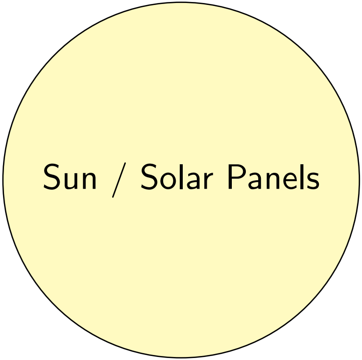
Solar PV Power Generation

- Welcome to Applied Electronics
- Unit 5: Industrial Electronics Applications
- Lecture 27: Solar Photovoltaic (PV) Based Power Generation

Grid-tied Solar Farm with Inverters

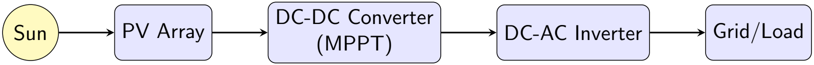
Agenda

- Photovoltaic (PV) Cell Principle
- PV Cell Equivalent Circuit
- I-V and P-V Characteristics
- Maximum Power Point Tracking (MPPT)
- DC-DC Converters in PV Systems
- Grid-Tied vs Standalone Inverters



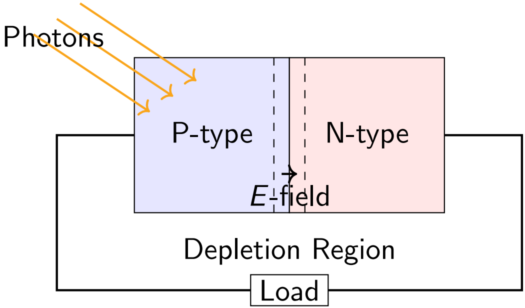
Introduction to Solar PV Systems

- Converts solar irradiance directly into DC electrical energy.
- Modular architecture: Cells $\rightarrow$ Modules (Panels) $\rightarrow$ Arrays.
- Requires power electronic converters for regulation, MPPT, and DC/AC conversion.
- Two main configurations: Standalone (Off-grid) and Grid-tied.



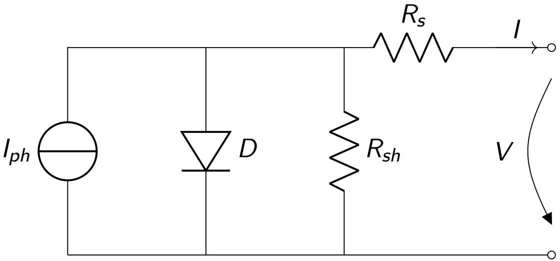
PV Cell Principle (Photovoltaic Effect)

- Based on a P-N junction semiconductor (usually Silicon).
- When photons with energy greater than the bandgap strike, electron-hole pairs are generated.
- The built-in electric field at the depletion region sweeps electrons to the N-side and holes to the P-side.
- This creates a photo-generated current I_{ph} proportional to solar irradiance (G).



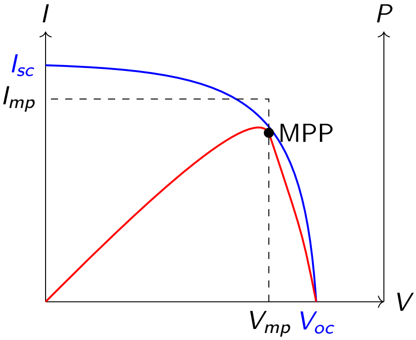
Equivalent Circuit of a Solar Cell

- Modeled as a current source in parallel with a diode and resistances.
- $I = I_{ph} - I_d - I_{sh}$
- Where $I_d = I_0 \left[\exp\left(\frac{q(V+IR_s)}{nkT}\right) - 1\right]$
- I_{ph}: Photocurrent
- R_s: Series resistance (contact/bulk resistance, ideally 0)
- R_{sh}: Shunt resistance (leakage across junction, ideally ∞)



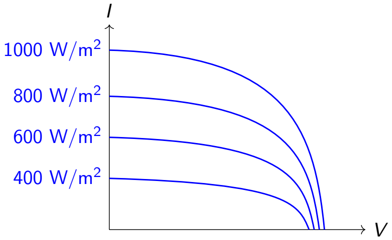
I-V and P-V Characteristics

- **Short Circuit Current (I_{sc})**: Max current when $V = 0$.
- **Open Circuit Voltage (V_{oc})**: Max voltage when $I = 0$.
- **Maximum Power Point (MPP)**: The operating point (V_{mp}, I_{mp}) where output power $P = V \times I$ is maximized.
- **Fill Factor (FF)**: Ratio of maximum power to theoretical power ($FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}}$).



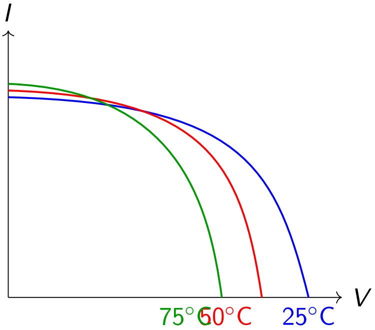
Effect of Irradiance

- Irradiance (G) is the solar power received per unit area (W/m^2).
- **Current**: I_{sc} is directly proportional to irradiance.
- **Voltage**: V_{oc} increases logarithmically with irradiance.
- **Power**: Maximum power output increases significantly as irradiance increases.



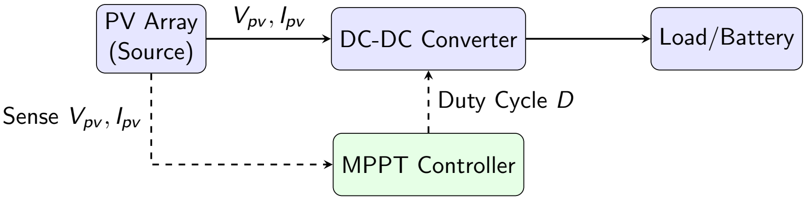
Effect of Temperature

- Solar cells are sensitive to operating temperature.
- **Voltage**: V_{oc} decreases significantly with increasing temperature (Negative temperature coefficient).
- **Current**: I_{sc} increases very slightly with temperature.
- **Power**: Overall, maximum power and efficiency *drop* as the panel heats up.



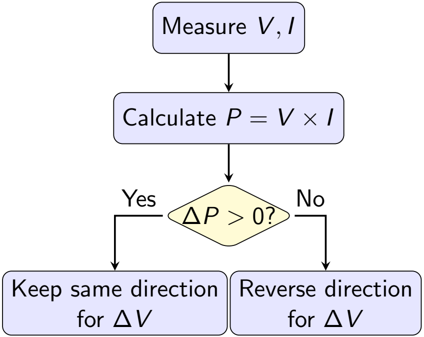
Maximum Power Point Tracking (MPPT)

- The MPP changes continuously with weather conditions (Irradiance and Temperature).
- Direct connection to a load or battery may force the PV panel to operate off its MPP.
- **MPPT**: An electronic system (usually a DC-DC converter with a controller) that forces the PV module to operate at V_{mp} and I_{mp}.
- Efficiency of MPPT ensures maximum ROI on solar panels.



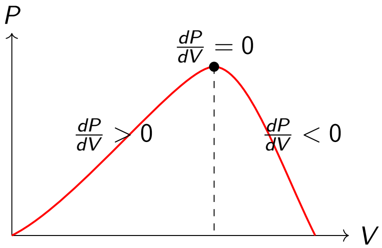
MPPT: Perturb and Observe (P&O)

- Most common MPPT algorithm.
- **Concept**: Perturb the operating voltage and observe the change in power.
- If $\Delta P > 0$: Keep perturbing in the same direction.
- If $\Delta P < 0$: Reverse the perturbation direction.
- **Drawback**: Oscillates around the MPP in steady state; can get confused during rapidly changing irradiance.



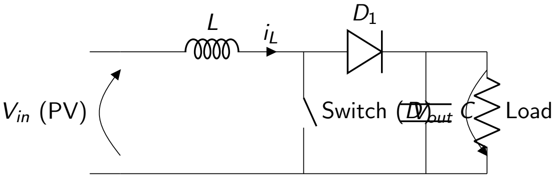
MPPT: Incremental Conductance (IncCond)

- At the MPP, the derivative of power with respect to voltage is zero: $\frac{dP}{dV} = 0$.
- Since $P = VI$, $\frac{d(VI)}{dV} = I + V\frac{dI}{dV} = 0$.
- Therefore, at MPP: $\frac{dI}{dV} = -\frac{I}{V}$.
- Incremental conductance $(\Delta I/\Delta V)$ is compared to instantaneous conductance (I/V).
- No steady-state oscillations; tracks rapidly changing conditions better.



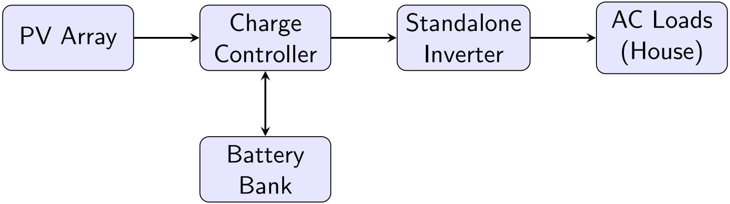
DC-DC Converters in PV Systems

- The MPPT algorithm outputs a duty cycle D.
- A DC-DC converter applies this D to change the input voltage.
- **Boost Converter**: Used when PV array voltage is lower than the required DC bus voltage (common in grid-tied systems).
- **Buck Converter**: Used when charging lower-voltage battery banks from higher-voltage arrays.
- **Buck-Boost / SEPIC**: Used for wide ranges.



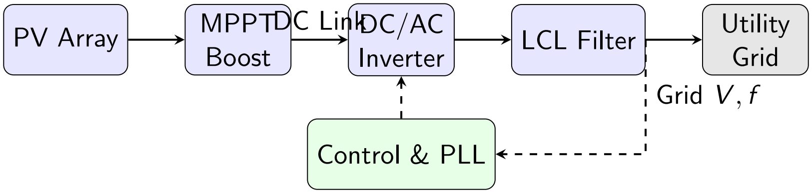
Standalone (Off-Grid) PV Systems

- Used in remote areas without grid access.
- **Components**: PV Array → Charge Controller (MPPT) → Battery Bank → Standalone Inverter → AC Loads.
- **Role of Inverter**: Generates its own voltage and frequency reference (e.g., 230V, 50Hz).
- Must handle surge currents from loads (e.g., motor startups) and manage battery health.



Grid-Tied PV Systems

- Connected directly to the utility grid; no battery required (usually).
- **Components**: PV Array → Grid-Tied Inverter → AC Grid.
- **Role of Inverter**: Must synchronize with grid voltage and frequency (PLL - Phase Locked Loop).
- Operates as a **Current Source**, pushing maximum available active power into the grid.
- **Anti-Islanding Protection**: Must safely shut down if the main grid fails.



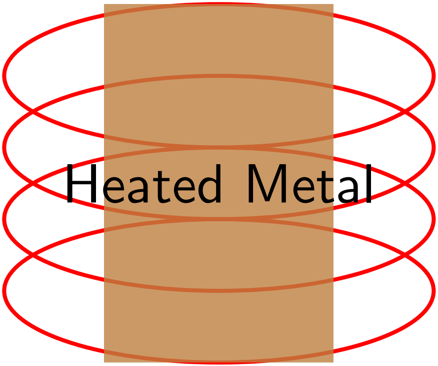
Summary

- Solar cells use the photovoltaic effect to convert irradiance to DC current.
- I-V and P-V curves show a distinct Maximum Power Point (MPP).
- Irradiance primarily affects current, while temperature affects voltage.
- MPPT algorithms (P&O, IncCond) continuously adjust DC-DC converters to extract max power.
- Grid-tied inverters synchronize and push power to the grid, while standalone inverters generate their own AC voltage for local loads.

Key Takeaways:
- Understand the fundamental principles.
- Apply the concepts to practical scenarios.

Next Lecture Preview

- Lecture 28: RF Heating
- Topics:
  - Induction Heating (metals)
  - Eddy Currents and Skin Effect
  - Dielectric Heating (insulators/wood/plastics)
  - Industrial Applications



RF Heating: Induction and Dielectric Heating

- Welcome to Applied Electronics
- Unit 5: Industrial Electronics Applications
- Lecture 28: RF Heating (Induction & Dielectric Heating)

Induction Heating (Metals)	Dielectric Heating (Insulators)

Agenda

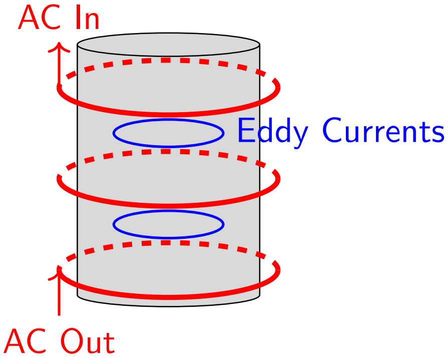
- Introduction to High-Frequency Heating
- Induction Heating Principle & Eddy Currents
- Skin Effect and Depth of Penetration
- Induction Heating Power Supplies
- Dielectric Heating Principle & Loss Mechanism
- Dielectric Heating Formulas and Circuits
- Industrial Applications & Comparisons

Introduction to High-Frequency Heating

- Uses high-frequency AC fields to generate heat directly **inside** the material.
- Unlike conventional heating (conduction/convection), heat transfer is extremely fast and uniform.
- Requires Power Electronics (Inverters) to generate frequencies from a few kHz up to several MHz.
- **Two Main Types**:
- **Induction Heating**: For conductive materials (metals).
- **Dielectric Heating**: For non-conductive materials (plastics, wood, food).

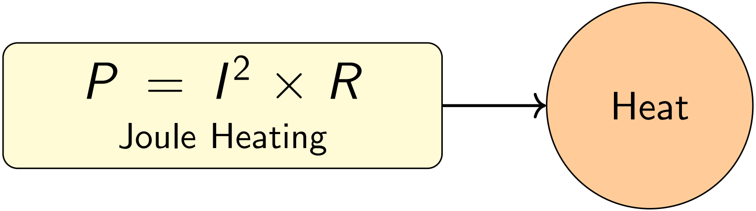
Induction Heating Principle

- Based on Faraday's Law of Electromagnetic Induction.
- An AC current passes through a copper work-coil, generating a rapidly alternating magnetic field.
- The conductive workpiece is placed inside the magnetic field.
- The alternating magnetic flux induces an Electromotive Force (EMF) inside the workpiece.
- This EMF causes circulating currents called **Eddy Currents** within the metal.



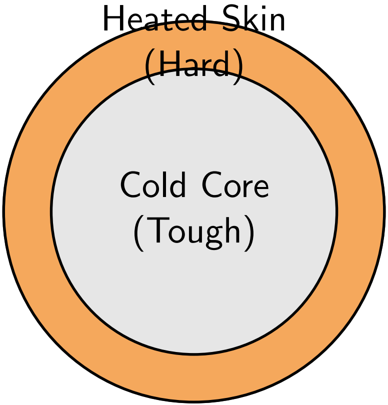
Eddy Currents and Joule Heating

- The induced eddy currents flow against the electrical resistance (R) of the metal.
- Heat is generated by the I^2R loss (Joule heating).
- **Magnetic materials (like Iron/Steel)** also generate heat through **Hysteresis losses**.
- Hysteresis heating occurs due to molecular friction when magnetic domains flip rapidly, but Eddy current heating is dominant at high frequencies.



Skin Effect in Induction Heating

- High-frequency AC does not distribute evenly through a conductor.
- Eddy currents concentrate near the surface of the workpiece. This is known as the **Skin Effect**.
- **Crucial Feature**: Higher frequencies concentrate heat very close to the surface.
- This allows for **surface hardening** of gears and shafts without altering the tough, flexible inner core.

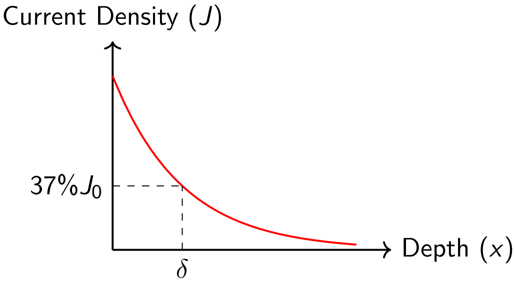


Formulas for Depth of Penetration

- The skin depth (δ) where current density falls to 37% ($1/e$) of the surface value:

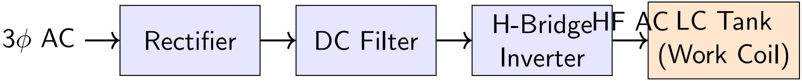
$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

- Where:
  - ρ = Electrical resistivity of the workpiece ($\Omega \cdot m$)
  - f = Frequency of the AC supply (Hz)
  - μ = Absolute magnetic permeability of the workpiece (H/m)
- **Takeaway**: To heat deeper, use lower frequency. For shallow surface heating, use higher frequency.



Induction Heating Power Supply

- Requires frequencies typically from 10 kHz to 500 kHz.
- Generated using High-Frequency Resonant Inverters.
- **Topology**: Rectifier → DC Link → High-Frequency H-Bridge Inverter → Resonant Tank Circuit.
- The resonant tank (L-C circuit) matches the impedance and provides smooth sinusoidal current.

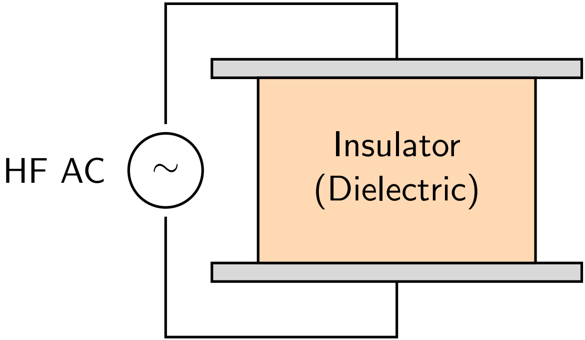


Applications of Induction Heating

- **Surface Hardening**: Gears, camshafts, axles.
- **Brazing and Soldering**: Joining metal parts rapidly.
- **Melting**: Induction furnaces for steel, copper, and precious metals.
- **Forging**: Pre-heating metal billets before stamping.
- **Domestic**: Induction cooktops (heating the magnetic pan directly).

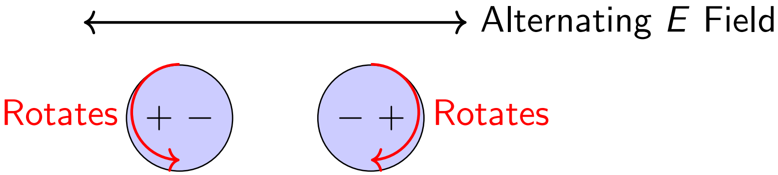
Dielectric Heating Principle

- Used for **insulators** (dielectrics) like wood, plastics, ceramics, and food.
- The workpiece is placed between two metal electrode plates.
- A very high frequency AC voltage (1 MHz to 50 MHz) is applied across the plates.
- The setup forms a capacitor where the workpiece acts as the **dielectric material**.



Dielectric Loss Mechanism

- Insulator molecules are often **dipoles** (e.g., water molecules have positive and negative ends).
- The alternating electric field forces the molecular dipoles to rotate and align with the field.
- At millions of times per second (MHz), this rapid molecular rotation creates internal friction.
- This friction manifests as heat. This is known as **Dielectric Loss**.



Formulas for Dielectric Heating Power

- The heat produced is directly proportional to the dielectric loss.

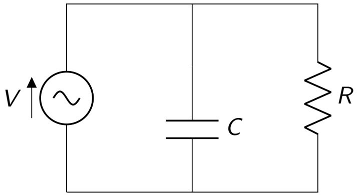
$$P = 2\pi f C V^2 \tan(\delta)$$

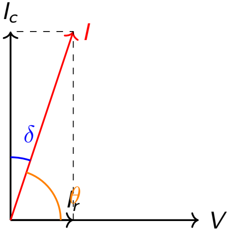
- Where:
  - P = Power converted to heat (Watts)
  - f = Frequency of supply (Hz)
  - C = Capacitance of the setup (F)
  - V = Applied RMS Voltage (V)
  - $\tan(\delta)$ = Dielectric dissipation factor (Loss tangent) of the material.

Power scales $\propto f$ and $\propto V^2$

Dielectric Heating Equivalent Circuit

- An ideal dielectric acts as a pure capacitor (current leads voltage by 90°).
- A practical, lossy dielectric acts as a Capacitor (C) in parallel with a Resistor (R).
- The current I has two components: I_c (capacitive, 90° leading) and I_r (resistive, in phase).
- The angle δ is the angle between the total current I and I_c.
- Power loss $P = VI_r = VI\cos(\theta) = VI\sin(\delta)$.





Applications of Dielectric Heating

- **Woodworking**: Rapid curing of glue in plywood and furniture manufacturing.
- **Plastics**: RF welding of PVC and plastics (e.g., medical blood bags, inflatable toys).
- **Food Industry**: Microwave ovens (a form of dielectric heating using microwaves), baking, and defrosting.
- **Medical**: Diathermy treatments for deep tissue heating.

Comparison: Induction vs. Dielectric Heating

Feature	Induction Heating	Dielectric Heating
Material	Conductors (Metals)	Insulators (Wood, Plastic)
Principle	Faraday's Law (Eddy Currents)	Molecular friction (Dipoles)
Circuit Model	Transformer shorted secondary	Lossy parallel capacitor
Frequencies	10 kHz - 500 kHz	1 MHz - 50 MHz
Heating Profile	Surface/Skin heating	Uniform volume heating

Summary

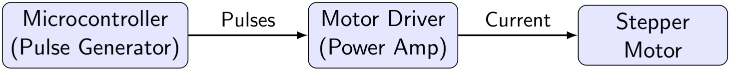
- RF heating leverages high-frequency electromagnetic fields for rapid, non-contact heating.
- **Induction heating** induces eddy currents in metals; heat depth is controlled by frequency via the skin effect.
- **Dielectric heating** subjects insulators to high-frequency electric fields, generating heat via molecular dipole friction.
- Power electronics (inverters) are essential to generate the high frequencies required for both methods.

Next Lecture Preview

- Lecture 29: Stepper Motors
- Topics:
  - Construction and Working
  - Variable Reluctance vs. Permanent Magnet
  - Step Angle Calculation
  - Unipolar vs Bipolar Drive Circuits

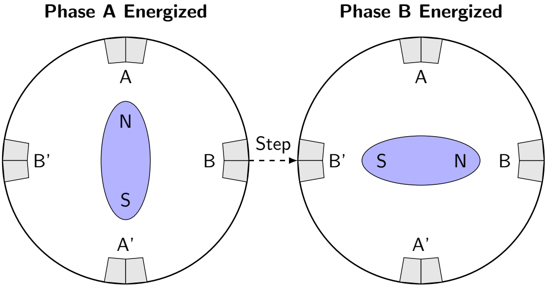
Introduction to Stepper Motors

- An electromechanical device that converts electrical pulses into discrete mechanical movements (steps).
- The shaft rotates by a specific number of degrees for each input pulse.
- **Advantages**:
  - Precise positioning without closed-loop feedback (open-loop control).
  - Excellent holding torque at standstill.
  - Highly reliable (no contact brushes).



Basic Principle of Operation

- The stator has multiple electromagnetic coils.
- The rotor aligns itself with the magnetic field generated by the stator.
- By sequentially energizing the stator coils (phases), the magnetic field rotates.
- The rotor follows this rotating magnetic field, stepping from one aligned position to the next.



Step Angle Calculation

- **Step Angle (α)**: The angle by which the rotor turns for one input pulse.

Standard Formulas

Formula 1: $\alpha = \frac{360^\circ}{N_s \times N_r}$ (Depends on configuration)

Standard Formula: $\alpha = \frac{N_s - N_r}{N_s \times N_r} \times 360^\circ$

Or simply: $\alpha = \frac{360^\circ}{\text{Steps per revolution}}$

Where:

- N_s = Number of stator teeth/poles
- N_r = Number of rotor teeth

Example Calculation:

Let $N_s = 8$, $N_r = 6$

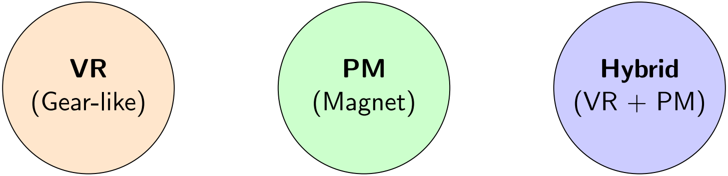
$\alpha = \frac{8-6}{8 \times 6} \times 360^\circ$

$\alpha = \frac{2}{48} \times 360^\circ = 15^\circ$

Types of Stepper Motors

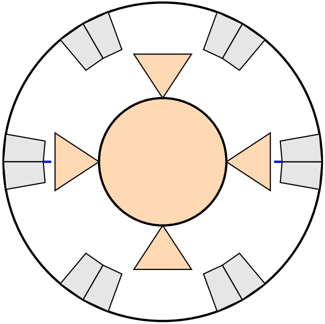
1. **Variable Reluctance (VR)** Stepper Motor
2. **Permanent Magnet (PM)** Stepper Motor
3. **Hybrid (HB)** Stepper Motor

Each type differs in rotor construction and the magnetic principles they exploit to generate torque.



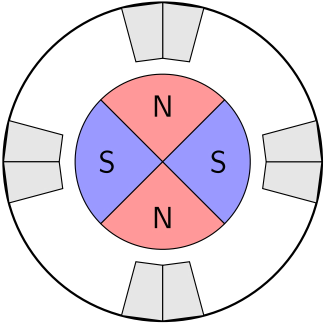
Variable Reluctance (VR) Stepper Motor

- **Rotor**: Soft iron multi-toothed cylinder (NO permanent magnet).
- **Principle**: Magnetic flux seeks the path of least reluctance. The rotor teeth align with energized stator poles to minimize the air gap.
- **Pros**: Fast dynamic response, high-speed capability, simple construction.
- **Cons**: Low torque, no holding torque when unpowered.



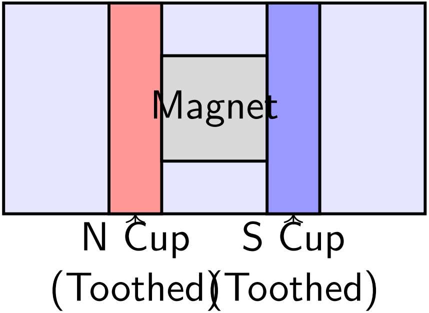
Permanent Magnet (PM) Stepper Motor

- **Rotor**: A cylindrical permanent magnet, magnetized radially with alternating North/South poles.
- **Principle**: Attraction and repulsion between the permanent magnet rotor and the electromagnetic stator.
- **Pros**: High torque at low speeds, provides holding (detent) torque even when unpowered.
- **Cons**: Large step angles (typically 7.5° to 15°), limited high-speed performance.



Hybrid (HB) Stepper Motor

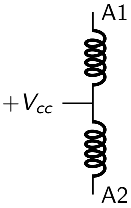
- Combines the best features of VR and PM motors.
- **Rotor**: An axial permanent magnet with soft iron toothed cups on each end (one for North, one for South).
- **Pros**: Very fine step angles (e.g., 0.9° or 1.8°), excellent torque, good holding torque.
- **Cons**: More complex construction, higher cost.
- The standard for most robotics, CNCs, and 3D printers.



Stepper Motor Drive Circuits

- A microcontroller cannot drive a stepper motor directly (too much current).
- Drive circuits use power transistors (MOSFETs/BJT) to switch the coil currents.
- The two primary winding configurations dictate the drive circuit:
  1. **Unipolar**: Current flows in only one direction through the coils (requires center-tapped coils).
  2. **Bipolar**: Current flows in both directions (requires H-Bridge circuits).

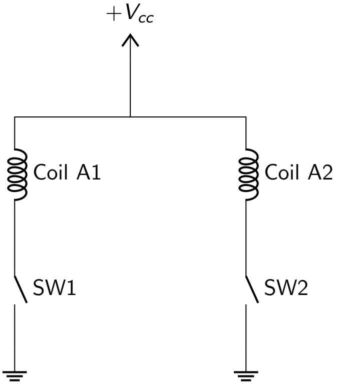
Unipolar (5/6 Wire)



Bipolar (4 Wire)

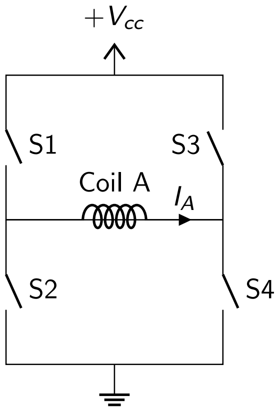
Unipolar Drive Circuit

- Uses motors with 5 or 6 wires (coils have a center tap connected to Vcc).
- **Circuit**: Uses 4 simple transistors (e.g., NPN or N-MOSFET) acting as switches to ground.
- **Pros**: Very simple control circuit; no H-bridges needed.
- **Cons**: Only half of the coil is used at a time, resulting in lower torque for a given motor size.



Bipolar Drive Circuit (H-Bridge)

- Uses motors with 4 wires (two independent coils).
- **Circuit**: Requires two full H-Bridge circuits (8 transistors total).
- To reverse magnetic polarity, the H-Bridge reverses the current flow through the entire coil.
- **Pros**: Uses 100% of the coil windings, resulting in significantly higher torque.
- **Cons**: More complex control and higher component count (solved by ICs like A4988 / DRV8825).



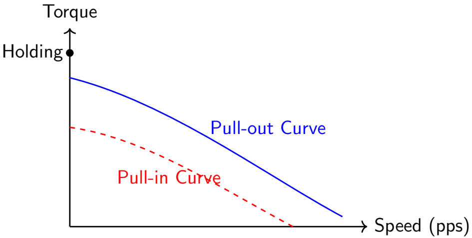
Stepping Modes

- **Wave Drive (1-Phase On)**: One coil energized at a time. Low power, low torque.
- **Full Step (2-Phase On)**: Two coils energized simultaneously. Maximum torque.
- **Half Step**: Alternates between 1-phase and 2-phase on. Doubles the resolution (e.g., 400 steps/rev).
- **Microstepping**: Uses PWM to send sine-wave proportional currents to the coils. Can divide a single step into 16, 32, or 256 microsteps.

Mode	Step 1	Step 2	Step 3	Step 4
Wave Drive	A	B	A'	B'
Full Step	AB	BA'	A'B'	B'A
Half Step	A	AB	B	BA'

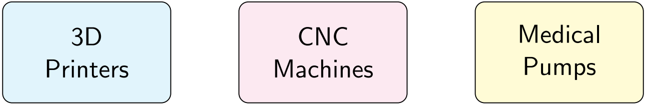
Torque-Speed Characteristics

- **Holding Torque**: Torque required to move the rotor when powered and stationary.
- **Pull-in Torque**: Maximum torque at which the motor can start from zero without missing steps.
- **Pull-out Torque**: Maximum torque the motor can provide while running without losing sync.
- **Observation**: Stepper torque drops rapidly at high speeds due to coil inductance preventing fast current rise.



Applications of Stepper Motors

- **Robotics**: Robotic arms, AGVs (Automated Guided Vehicles).
- **CNC Machines**: Moving X, Y, and Z axes precisely.
- **3D Printers**: Extruders and positioning systems.
- **Medical Equipment**: Syringe pumps, automated pipettes.
- **Consumer Electronics**: Camera focus mechanisms, scanners.



Summary

- Stepper motors move in discrete angular steps per electrical pulse.
- Hybrid steppers are most common, offering fine step angles and high torque.
- Unipolar drives are simple but inefficient; Bipolar drives use H-Bridges for maximum torque.
- Advanced drivers use Microstepping for smooth, quiet, and high-resolution motion.
- Ideal for open-loop precision positioning systems.

Next Lecture Preview

Lecture 30: Course Wrap-up & Advanced Applications

Topics:

- Review of major power electronic converters
- Emerging trends in Industrial Electronics
- Final Q&A

Programmable Logic Controllers (PLC) & Course Recap

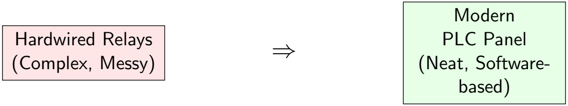
- Unit 5: Industrial Electronics Applications
- Topic: Programmable Logic Controllers (PLC)
- Course Wrap-up and Summary

Agenda

- ❖ Introduction to PLCs and Relay Logic Replacement
- ❖ PLC Architecture (CPU, I/O Modules, Memory)
- ❖ Working Principle and Scan Cycle
- ❖ Introduction to Ladder Logic
- ❖ Advantages and Industrial Applications
- ✓ Full Course Recap (Units 1 to 5)
- ✓ Conclusion

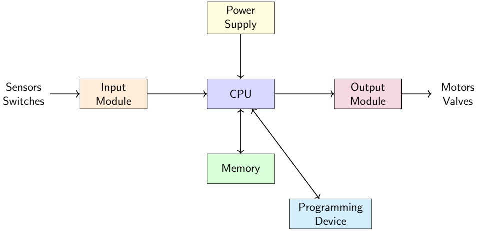
What is a Programmable Logic Controller (PLC)?

- A specialized industrial computer used for control and automation.
- Designed to operate in harsh industrial environments (temperature, vibration, noise).
- Replaces complex, hardwired electromechanical relay panels.
- Programmable memory for storing instructions to implement logic, sequencing, timing, and counting.
- Monitors inputs (sensors/switches) and controls outputs (motors/valves) based on a user-defined program.



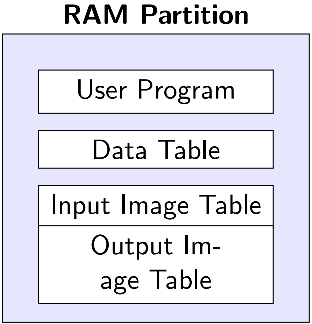
PLC Block Diagram & Architecture

- **Central Processing Unit (CPU):** The brain of the PLC, executes the control program.
- **Memory (RAM/ROM):** Stores the operating system, user program, and temporary I/O status data.
- **Input Modules:** Interface between external field devices (sensors, switches) and the CPU.
- **Output Modules:** Interface between the CPU and external field actuators (motors, solenoids, lamps).
- **Power Supply:** Converts AC line voltage to low DC voltage (e.g., 5V, 24V) required by the CPU and I/O modules.
- **Programming Device:** Used to enter, modify, and troubleshoot the PLC program (e.g., PC with software).



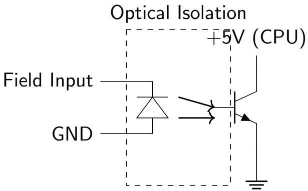
The CPU and Memory Organization

- **Microprocessor-based CPU:** Evaluates logic, performs math operations, and manages communications.
- **Read-Only Memory (ROM):**
  - Non-volatile memory.
  - Stores the PLC's operating system and built-in instruction set (timers, counters).
- **Random Access Memory (RAM):**
  - Volatile memory (usually battery-backed).
  - **User Program:** Stores the ladder logic written by the engineer.
  - **Data Table:** Stores intermediate values, timer/counter accumulators.
  - **I/O Image Table:** Crucial area that holds the 'snapshots' of current input states and desired output states.



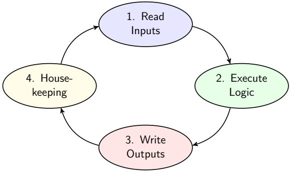
Input and Output (I/O) Modules

- **Input Modules (Sensors to CPU):**
  - Provide optical isolation to protect the CPU from voltage spikes.
  - Examples of input devices: Pushbuttons, limit switches, proximity sensors, temperature sensors.
  - Signal conversion: 24V DC or 120V AC from field to 5V DC for CPU.
- **Output Modules (CPU to Actuators):**
  - Use relays, transistors, or TRIACs to switch power to field devices.
  - Examples of output devices: Contactors, motor starters, solenoid valves, indicator lights.
  - Optical isolation prevents back-EMF from inductive loads from damaging the PLC.



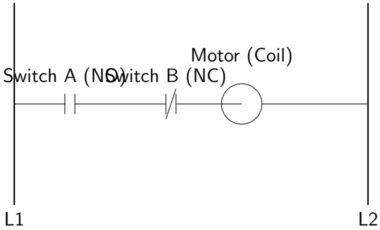
The PLC Scan Cycle

- The PLC operates in a continuous loop called the 'Scan Cycle'.
- **Step 1: Read Inputs (Input Scan)** - The CPU reads the physical state of all input terminals and updates the input image table in memory.
- **Step 2: Execute Program (Logic Execution)** - The CPU executes the user program rung by rung, using the input image table, and updates the output image table.
- **Step 3: Write Outputs (Output Scan)** - The CPU transfers the output image table to the physical output terminals.
- **Step 4: Housekeeping** - Internal diagnostics and communication with programming devices.
- Scan time is typically very fast (milliseconds).



Introduction to Ladder Logic

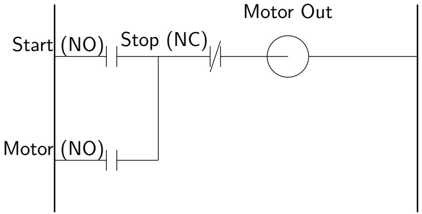
- The most common PLC programming language (IEC 61131-3 standard).
- Resembles the schematic diagrams of hardwired relay circuits, making it easy for electricians to learn.
- **Power Rails:** Two vertical lines represent power supply (L1 and L2).
- **Rungs:** Horizontal lines connecting the rails; each rung represents a single logical operation.
- **Instructions:**
  - **Normally Open (NO) Contact (-— —-):** True when input is ON (logic 1).
  - **Normally Closed (NC) Contact (-—/—-):** True when input is OFF (logic 0).
  - **Coil (-( )-):** Output energized when the rung condition is true.



Relay Logic vs. Ladder Logic Example

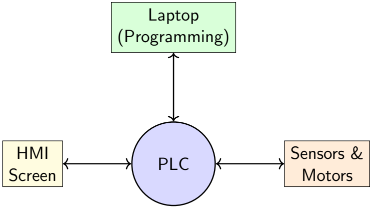
Motor Start/Stop Control (Self-Latching Circuit)

- **Requirements:** 'Start' Pushbutton (NO), 'Stop' Pushbutton (NC), Motor Contactor Output
- **Ladder Logic Implementation:**
  1. **Series Logic:** Start button (NO) in series with Stop button (NC) driving the Motor coil.
  2. **Parallel Latching:** A NO contact addressed to the Motor coil is placed in parallel with the Start button.
- **Action:** Pressing 'Start' completes the circuit. The motor turns on, closing its parallel contact, 'latching' the circuit so the button can be released. Pressing 'Stop' breaks the circuit.



Advantages of PLCs

- **Flexibility:** Logic can be changed by modifying software without altering physical wiring.
- **High Reliability:** Solid-state components instead of moving mechanical relay parts.
- **Troubleshooting:** Built-in diagnostics and real-time monitoring via programming software.
- **Compact Size:** Replaces large relay cabinets, saving significant floor space.
- **Communication:** Easily interfaces with HMI (Human-Machine Interface), SCADA systems, and other PLCs.
- **Advanced Functions:** Built-in timers, counters, PID controllers, and math functions that basic relays cannot perform.



Applications of PLCs

- **Manufacturing Automation:** Conveyor belt synchronization, robotic assembly lines, packaging machines.
- **Process Control:** Chemical plants, oil refineries, water treatment facilities (controlling valves, pumps, mixing tanks).
- **Building Automation:** HVAC control, smart lighting systems, elevator control sequencing.
- **Power Industry:** Substation automation, backup generator control, power routing.
- **Traffic Systems:** Complex traffic light sequencing and railway crossing safety controls.

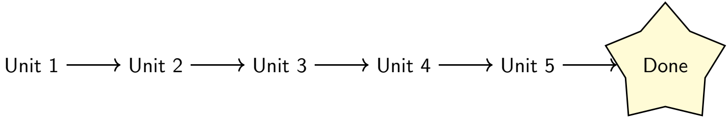
Manufacturing Automation

Process Control

Building Automation

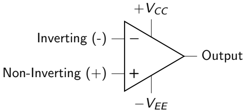
Applied Electronics: Course Recap

- We have reached the end of the technical content for this course.
- The following slides provide a high-level summary of the 5 units covered:
- **Unit 1:** Operational Amplifiers
- **Unit 2:** Introduction to Thyristors
- **Unit 3:** Turn On/Off Methods of Thyristors
- **Unit 4:** Power Converters
- **Unit 5:** Industrial Electronics Applications
- Let's review the key concepts from each unit to reinforce your learning.



Recap: Unit 1 - Operational Amplifiers

- **Core Concept:** High-gain, DC-coupled voltage amplifiers with differential inputs.
- **Key Characteristics (Ideal):** Infinite input impedance ($Z_{in} = \infty$), zero output impedance ($Z_{out} = 0$), infinite open-loop gain ($A_{OL} = \infty$).
- **Basic Configurations:**
  - **Inverting Amplifier:** Output is 180° out of phase, Gain $= -R_f/R_1$.
  - **Non-Inverting Amplifier:** Output is in phase, Gain $= 1 + (R_f/R_1)$.
- **Linear Applications:** Adders, subtractors, voltage followers, integrators, differentiators.
- **Non-Linear Applications:** Comparators, Schmitt triggers (hysteresis).
- **Waveform Generators:** RC phase shift oscillators, Wein bridge oscillators, 555 Timer IC basics.



Recap: Unit 2 - Introduction to Thyristors

- **Core Concept:** Solid-state semiconductor devices used for high-power switching.
- **SCR (Silicon Controlled Rectifier):**
  - 4-layer (PNPN), 3-terminal (Anode, Cathode, Gate) unidirectional device.
  - V-I characteristics: Forward blocking, forward conduction (requires gate pulse), reverse blocking.
  - Latching current (I_L) to turn ON, Holding current (I_H) to stay ON.
- **TRIAC:** Bidirectional thyristor, conducts in both halves of AC cycle. Equivalent to two inverse-parallel SCRs.
- **DIAC:** Bidirectional trigger device, used to provide a sharp gate pulse to a TRIAC.
- **UJT (Unijunction Transistor):** Negative resistance device, used for generating relaxation oscillator triggering pulses.

SCR

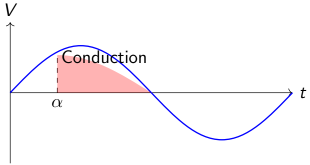
TRIAC

DIAC

DIAC Symbol

Recap: Unit 3 - Turn On/Off Methods of Thyristor

- **Turn-On Methods (Triggering):**
  - **Gate Triggering:** Most efficient and common method. Applying a positive gate-to-cathode pulse.
  - Types of Gate Triggering: DC, AC, and Pulse triggering.
  - R and RC triggering circuits to control firing angle (α).
  - UJT Relaxation Oscillator triggering for precise, temperature-stable synchronization.
- **Turn-Off Methods (Commutation):**
  - Turning OFF an SCR requires reducing Anode current below Holding Current (I_H).
  - **Natural Commutation:** Occurs naturally in AC circuits at the zero-crossing point.
  - **Forced Commutation:** Required in DC circuits; uses resonant components (L and C) to force current to zero (Class A, B, C, D, etc.).



Recap: Unit 4 - Power Converters

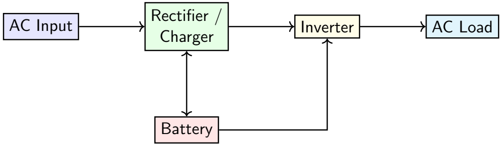
- **Core Concept:** Converting electrical energy from one form to another using power semiconductor switches.
- **Phase Controlled Rectifiers (AC to DC):**
  - Half-wave and Full-wave (bridge) controlled rectifiers using SCRs.
  - Output DC average voltage is controlled by varying firing angle (α).
- **Choppers (DC to DC):**
  - Step-down (Buck) and Step-up (Boost) converters.
  - Duty cycle control using PWM ($V_{out} = V_{in} \times D$ for buck).
- **Inverters (DC to AC):**
  - Single-phase half-bridge and full-bridge inverters.
  - Producing square wave or PWM sine wave outputs.
- **Cycloconverters (AC to AC):** Directly converts AC of one frequency to another without an intermediate DC link.

AC to DC (Rectifier)	DC to DC (Chopper)
DC to AC (Inverter)	AC to AC (Cycloconverter)

Recap: Unit 5 - Industrial Applications

- **Timers:** Industrial time-delay relays and electronic timers for sequencing operations.
- **Heating Applications:**
  - **Induction Heating:** Heating conductive materials via eddy currents (surface hardening, melting).
  - **Dielectric Heating:** Heating insulating materials via high-frequency alternating electric fields (plastic welding, wood drying).
- **Welding:** Resistance welding control using thyristors for precise heat energy delivery.
- **Power Supplies:**
  - **SMPS (Switched Mode Power Supply):** High efficiency, compact size, high-frequency switching.
  - **UPS (Uninterruptible Power Supply):** Online and Offline topologies providing backup AC power.
- **PLCs:** Programmable logic controllers uniting all these concepts for factory automation.

Online UPS Concept



Conclusion & Final Thoughts

- **From Signals to Systems:** We journeyed from microampere op-amp signals to kiloampere thyristor controls.
- **The Foundation of Automation:** Understanding these electronic building blocks is crucial for modern electrical and control engineering.
- **Continuous Evolution:** Industrial electronics rapidly evolves with better semiconductors (SiC, GaN) and smarter control systems (IoT integrated PLCs).
- **Next Steps:** Apply this knowledge to your lab work, projects, and future courses in power electronics, drives, and control systems.
- **Thank you for your attention and participation throughout the semester!**

Thank You!