Energy Efficiency & Audit (DI04009021)

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Semester 4

Outline

Introduction to India's Energy Scenario (2024)

- India is the world's third-largest energy consumer.
- Rapid economic growth and urbanization drive massive energy needs.
- The energy mix is transitioning towards renewables, though coal remains dominant.
- Significant policy shifts focus on energy efficiency and sustainability.

India's Energy Demand in 2024

Key Facts

- Total electricity generation capacity exceeds 425 GW.
- Peak electricity demand crossed 240 GW in 2024.
- Industrial sector remains the largest consumer of energy.
- Renewable energy capacity (including large hydro) is over 180 GW.

Per Capita Energy Consumption

- Per capita consumption indicates the average energy use per person.
- Calculated as: Per Capita Consumption $= \frac{\text{Total Energy Consumption}}{\text{Total Population}}$
- India's per capita electricity consumption is around 1,300 to 1,400 kWh/year (as of 2024 estimates).
- Despite being the 3rd largest consumer, per capita use is about one-third of the global average.

Global Comparison: Per Capita Electricity Consumption

Country / Region	**Per Capita Consumption (kWh/yr)**
USA	$\sim 12,000$
China	$\sim 6,000$
World Average	$\sim 3,300$
India	$\sim 1,350$

Table: Indicative Global Per Capita Electricity Consumption

Terminology: Power

Definition

- **Power** is the rate at which electrical energy is transferred by an electric circuit.
- The SI unit of power is the Watt (W), which is one Joule per second.
- Formula: $P = \frac{E}{t}$ or $P = V \times I$ (in DC circuits)
- It represents the capacity or instantaneous demand.

Terminology: Energy

Definition

- **Energy** is the total amount of work done or heat transferred over a period of time.
- It is the product of power and time.
- Formula: $E = P \times t$
- Common unit in electrical billing: Kilowatt-hour (kWh).

Example: Power vs. Energy

Example

- Consider a motor with a power rating of 10 kW.
- **Power Demand:** When the motor is running, it demands 10 kW from the grid.
- **Energy Consumption:**
- If the motor runs for 5 hours, the energy consumed is:
- $E = 10 \text{ kW} \times 5 \text{ hours} = 50 \text{ kWh}$
- If the tariff is Rs. 5 per kWh, the cost is $50 \times 5 =$ Rs. 250.

Energy Audit

Definition

- An **Energy Audit** is the verification, monitoring, and analysis of use of energy.
- It includes the submission of a technical report containing recommendations for improving energy efficiency.
- It provides a cost-benefit analysis and an action plan to reduce energy consumption.
- As per the Energy Conservation Act, 2001, it is mandatory for designated consumers.

Phases of an Energy Audit

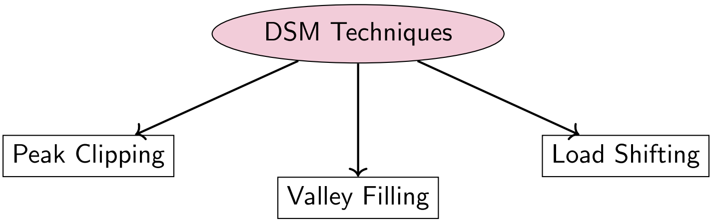
Pre-Audit Phase → Audit Phase → Post-Audit Phase

Demand Side Management (DSM)

Definition

- **Demand Side Management (DSM)** involves modifying consumer demand for energy through various methods such as financial incentives and behavioral change through education.
- Goal: To encourage the consumer to use less energy during peak hours, or to move the time of energy use to off-peak times (load shifting).
- Helps utilities avoid building new power plants.

DSM Strategies



PAT Scheme (Perform, Achieve and Trade)

Definition

- The **PAT Scheme** is a regulatory instrument introduced by the Bureau of Energy Efficiency (BEE) in India.
- Objective: To reduce specific energy consumption (SEC) in energy-intensive industries.
- It provides a market-based mechanism to enhance cost effectiveness through certification of excess energy savings.
- These certificates (ESCerts) can be traded.

How the PAT Scheme Works

- 1. **Target Setting:** Baseline specific energy consumption is established for a Designated Consumer (DC).
- 2. **Performance:** The DC is given a target to reduce SEC over a 3-year cycle.
- 3. **Achieve & Trade:**
- - If DC overachieves target → Earns Energy Saving Certificates (ESCerts).
- - If DC underachieves target → Must buy ESCerts or face penalties.

Terminology: Energy Intensity

Definition

- **Energy Intensity** is a measure of the energy inefficiency of an economy.
- It is calculated as units of energy per unit of GDP.
- Formula: Energy Intensity $= \frac{\text{Total Energy Consumption}}{\text{Gross Domestic Product (GDP)}}$
- High energy intensity indicates a high price or cost of converting energy into GDP.

India's Energy Intensity Trends

Key Facts

- India has committed to reducing the emissions intensity of its GDP by 45
- Energy intensity has been steadily declining due to the service sector's growth and energy efficiency measures.
- However, industrialization still applies upward pressure on total energy demand.
- Schemes like PAT directly contribute to lowering national energy intensity.

First Law of Thermodynamics

Definition

- The First Law of Thermodynamics states that energy can neither be created nor destroyed; it can only be transferred or changed from one form to another.
- Also known as the Law of Conservation of Energy.

First Law: Mathematical Formulation

Key Facts

- For a closed system undergoing a cycle:
- $$\oint \delta Q = \oint \delta W$$
- For a process in a closed system:
- $$Q - W = \Delta U$$
- Where:
- - Q = Heat added to the system
- - W = Work done by the system
- - ΔU = Change in internal energy

First Law: Numerical Example

Example

- **Problem:** A gas in a cylinder is heated with 200 J of thermal energy. The gas expands and does 50 J of work on the piston. Calculate the change in internal energy.
- **Solution:**
- 1. Identify knowns: $Q = 200$ J (heat added), $W = 50$ J (work done).
- 2. Apply the First Law equation: $\Delta U = Q - W$
- 3. Calculate: $\Delta U = 200 \text{ J} - 50 \text{ J} = 150 \text{ J}$
- **Result:** The internal energy of the gas increases by 150 J.

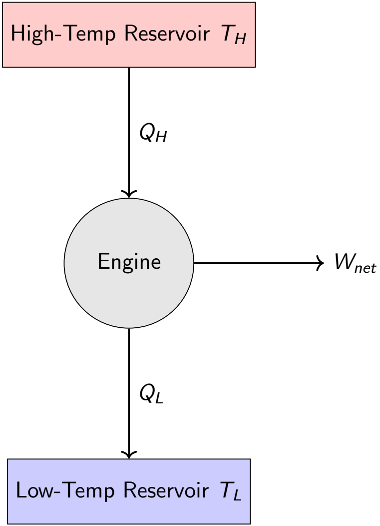
The Need for the Second Law

- The First Law states energy is conserved, but it does not restrict the direction of energy transfer.
- For example, heat naturally flows from a hot body to a cold body, but never the reverse spontaneously, even though both would satisfy the First Law.
- The **Second Law of Thermodynamics** dictates the direction of processes and establishes the concept of quality of energy (entropy).

Second Law: Two Classical Statements

Kelvin-Planck Statement	Clausius Statement
It is impossible to construct a device operating in a cycle that produces no other effect than the extraction of heat from a single reservoir and the performance of an equivalent amount of work.	It is impossible to construct a device operating in a cycle that produces no other effect than the transfer of heat from a lower-temperature body to a higher-temperature body.
Applies to Heat Engines	Applies to Refrigerators / Heat Pumps

Heat Engine Schematic



Lecture 3: BEE Schemes and NMEEE

Topics Covered:

- 1.4 Scheme of BEE under Energy Conservation Act
- Energy Intensive Industries
- National Mission for Enhanced Energy Efficiency (NMEEE)

Energy Conservation Act, 2001

Definition

- **Energy Conservation Act (EC Act):** Enacted by the Government of India in 2001 to provide for efficient use of energy and its conservation. It established the Bureau of Energy Efficiency (BEE) as the nodal agency.

Role of Bureau of Energy Efficiency (BEE)

The mission of BEE is to assist in developing policies and strategies with a thrust on self-regulation and market principles, within the overall framework of the EC Act, 2001.

- Primary goal: Reduce energy intensity of the Indian economy.
- Regulatory and promotional functions.

1.4 Schemes of BEE under EC Act (Part 1)

Key schemes initiated by BEE (names only):

- Standards and Labeling (S&L) Scheme
- Energy Conservation Building Code (ECBC)
- Perform Achieve and Trade (PAT) Scheme
- State Energy Conservation Fund (SECF)

1.4 Schemes of BEE under EC Act (Part 2)

Further promotional and regulatory schemes by BEE:

- Demand Side Management (DSM) (Agri, Muni, DISCOMs)
- SME Program (Small and Medium Enterprises)
- Certification Examination for Energy Managers and Auditors
- Student Capacity Building Programme (Energy Clubs)

Energy Intensive Industries

Key Facts

- An **Energy Intensive Industry** is a sector where energy costs constitute a significant portion of total production costs, or which consumes massive absolute quantities of energy.

Designated Consumers (DCs)

Under the EC Act, the central government identifies certain energy-intensive industries as **Designated Consumers (DCs)**.

- DCs are legally bound to comply with energy consumption norms.
- They must appoint a certified Energy Manager.
- They must undergo mandatory energy audits by Accredited Energy Auditors.

Key Energy Intensive Industries in India

Sector	Primary Energy Use
Thermal Power Plants	Coal, Natural Gas
Iron and Steel	Coal, Electricity
Cement	Coal, Electricity
Aluminum	Electricity, Coal
Fertilizer	Natural Gas, Naphtha
Paper and Pulp	Biomass, Coal, Electricity

Table: Common Designated Consumer Sectors

Characteristics of Energy Intensive Industries

- **High Thermal Energy Demand:** Processes require extreme heat (e.g., kilns in cement, blast furnaces in steel).
- **Continuous Operation:** Plants often run 24/7, making baseline load very high.
- **Significant GHG Emissions:** Direct correlation between energy consumption (mostly fossil fuels) and carbon footprint.

National Mission for Enhanced Energy Efficiency (NMEEE)

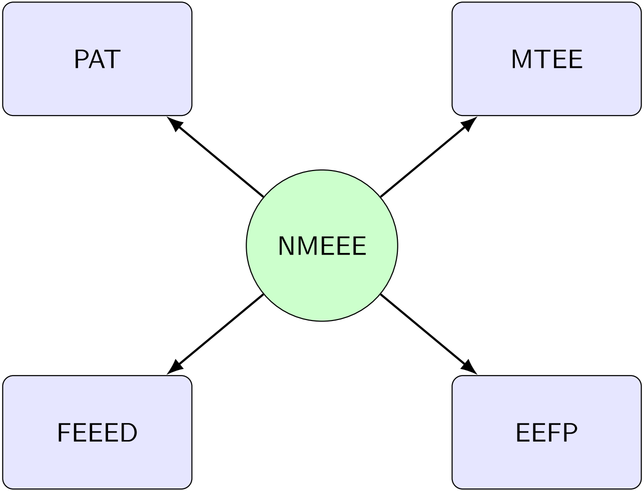
Definition

- **NMEEE:** One of the eight national missions under the National Action Plan on Climate Change (NAPCC). It aims to strengthen the market for energy efficiency by creating conducive regulatory and policy regimes and fostering innovative business models.

Objectives of NMEEE

- Achieve large-scale energy savings in energy-intensive industries.
- Stimulate investment in energy efficiency across sectors.
- Promote the adoption of energy-efficient appliances through market mechanisms.
- Mitigate greenhouse gas emissions.

The Four Initiatives of NMEEE



NMEEE Pillar 1: PAT Scheme

Perform Achieve and Trade (PAT):

- A regulatory instrument to reduce specific energy consumption in energy-intensive industries.
- Assigns specific energy reduction targets to Designated Consumers.
- Over-achievers receive Energy Saving Certificates (ESCerts).
- Under-achievers must buy ESCerts to comply.

NMEEE Pillars: MTEE, EEFP, FEEED

- **MTEE (Market Transformation for Energy Efficiency):** Accelerates shift to energy-efficient appliances in designated sectors.
- **EEFP (Energy Efficiency Financing Platform):** Creates mechanisms to finance demand-side management programmes.
- **FEEED (Framework for Energy Efficient Economic Development):** Develops fiscal instruments to promote energy efficiency (e.g., Partial Risk Guarantee Fund).

Case Study: PAT Scheme Impact in Cement Industry

Example

Scenario: A cement plant (Designated Consumer) is assigned a target to reduce its Specific Energy Consumption (SEC) by 5%.

- Target SEC: 700 kcal/kg clinker.
- Achieved SEC: 680 kcal/kg clinker.

Result: The plant over-achieved its target by 20 kcal/kg. It receives ESCerts corresponding to the extra energy saved, which it can sell on the Indian Energy Exchange (IEX) to plants that failed to meet their targets.

Need for Energy Audit

Key Facts

An **Energy Audit** is the key to a systematic approach for decision-making in the area of energy management. **Why is it needed?**

- **Cost Reduction:** Identifies areas of energy waste to lower operating expenses.
- **Productivity:** Optimizes equipment performance, leading to improved production.
- **Environmental Impact:** Reduces greenhouse gas emissions and carbon footprint.
- **Benchmarking:** Compares energy consumption with industry standards.
- **Preventive Maintenance:** Highlights equipment requiring maintenance or replacement.

Preliminary vs. Targeted Energy Audit

Preliminary Energy Audit (Walk-through Audit):

- Simplest and quickest type of audit.
- Relies on visual inspection and basic data (utility bills).
- Identifies low-cost/no-cost energy conservation measures.
- Estimates the scope for a detailed audit.

Targeted Energy Audit:

- Focuses on a specific system or piece of equipment (e.g., boilers, compressors).
- Requires detailed measurement and analysis for that specific target.
- Used when a particular system is known to be inefficient.

Detailed Energy Audit

Definition

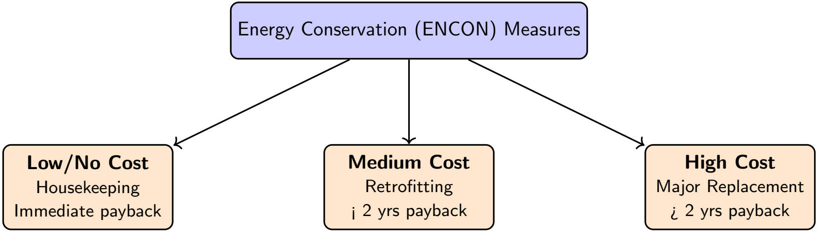
A **Detailed Energy Audit** evaluates all systems and equipment that consume energy, offering a comprehensive energy project implementation plan. **Key Characteristics:**

- Establishes a detailed energy and material balance.
- Requires extensive use of portable energy monitoring instruments.
- Evaluates interactive effects of multiple systems.
- Delivers a rigorous financial analysis for each proposed measure (ROI, NPV, Payback period).
- Typically conducted over 3 phases: Pre-audit, Audit, and Post-audit.

Pre-Audit vs. Post-Audit Phases

Pre-Audit Phase	Post-Audit Phase
Plan and organize the audit	Assist in implementation of ENCON measures
Walk-through audit	Monitor and review performance
Inform facility managers	Verify estimated energy savings
Identify required instruments	Train staff on new operational practices
Gather historical energy data	Continual improvement and feedback

Classification of ENCON Measures



Introduction to Plant Energy Performance

- Energy performance is a crucial metric for evaluating the efficiency of industrial operations.
- It provides a quantitative measure of how well a plant utilizes its energy inputs to produce desired outputs.
- Monitoring energy performance helps in identifying inefficiencies and potential areas for cost reduction.
- Under ISO 50001, continuous improvement in energy performance is a mandatory requirement.

Plant Energy Performance

Definition

- **Plant Energy Performance:** A broad concept comprising energy efficiency, energy use, and energy consumption.
- It is often evaluated using specific metrics such as Specific Energy Consumption (SEC).
- $\text{SEC} = \frac{\text{Total Energy Consumed}}{\text{Total Useful Output (Production)}}$

Common Energy Performance Indicators (EnPIs)

Indicator	**Formula**	**Application**
Specific Energy Consumption	Energy / Production Unit	Cement, Steel, Textiles
Energy Cost per Unit	Total Energy Cost / Production	Economic analysis
Carbon Intensity	CO_2 Emissions / Production Unit	Environmental reporting

Understanding Production Factor

Definition

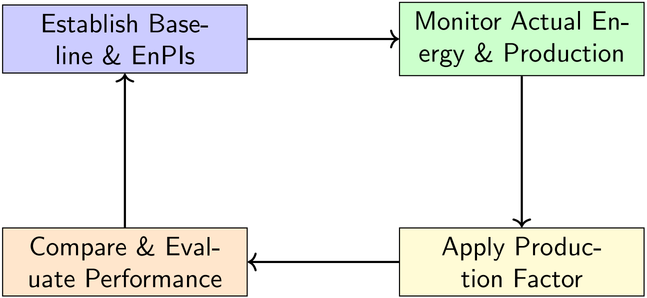
- **Production Factor (PF):** A ratio that compares the current production level to a reference or baseline production level.
- Formula: $PF = \frac{\text{Current Year Production}}{\text{Reference Year Production}}$
- It is used to normalize energy consumption data, ensuring fair comparisons between different operational periods regardless of fluctuating output volumes.

Case Study: Calculating Production Factor and Target Energy

Example

- **Scenario:**
- Reference Year (2022) Production: 10,000 tonnes
- Reference Year Energy Use: 50,000 GJ
- Current Year (2023) Production: 12,000 tonnes
- **Calculation:**
- 1. $PF = \frac{12{,}000}{10{,}000} = 1.2$
- 2. Expected Energy Use = Reference Energy × PF
- Expected Energy Use $= 50,000 \times 1.2 = 60,000$ GJ
- If actual 2023 energy use is 58,000 GJ, the plant improved its real energy performance.

Energy Performance Evaluation Cycle



The Impact of Baseload (Fixed) Energy

Key Facts

- Total Energy = (Variable Energy $\times$ Production) + Fixed Energy
- Fixed energy (baseload) includes lighting, HVAC, and keeping equipment at idle.
- Because of fixed energy, linear scaling using just the Production Factor might introduce minor inaccuracies at very low or very high production extremes.
- Advanced normalization uses regression analysis instead of simple ratios.

Introduction to Advanced Measuring Instruments

Modern electrical and industrial maintenance requires non-intrusive, highly accurate diagnostic tools. Key benefits of advanced instruments:

- **Safety:** Measuring without physical contact (e.g., high voltage equipment).
- **Speed:** Instantaneous readings for real-time monitoring.
- **Accuracy:** Digital processing reduces human error.

This lecture covers Infrared Thermometers, Stroboscopes, Lux Meters, Smart Energy Meters, and Thermography.

Non-contact Infrared Thermometer

Definition

- An **Infrared (IR) Thermometer** infers temperature from a portion of the thermal radiation sometimes called black-body radiation emitted by the object being measured.
- It consists of a lens to focus the infrared thermal radiation on to a detector, which converts the radiant power to an electrical signal.

Principles of IR Temperature Measurement

Key Facts

- **Stefan-Boltzmann Law:** The total energy radiated per unit surface area of a black body across all wavelengths per unit time is directly proportional to the fourth power of the black body's thermodynamic temperature.
- Formula: $j^{\star} = \sigma T^4$
- Where $\sigma = 5.67 \times 10^{-8}\,\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-4}$.
- Emissivity (ϵ) must be accounted for in real-world objects: $P = \epsilon \sigma A T^4$.

Stroboscope: Overview

Definition

- A **Stroboscope** is an instrument used to make a cyclically moving object appear to be slow-moving, or stationary.
- It works by illuminating the object with short, brilliant flashes of light at a frequency that matches the rotational or vibrational speed of the object.

Stroboscope Measurement Example

Example

- **Scenario:** Measuring the RPM of a motor shaft.
- 1. Place a single reflective mark on the shaft.
- 2. Point the stroboscope at the shaft and turn on the flashes.
- 3. Adjust the flash frequency (f) until the mark appears completely stationary.
- 4. The rotational speed N (in RPM) is exactly equal to the flash frequency (in flashes per minute) if it's the fundamental frequency.
- **Warning:** Harmonics (e.g., flashing twice per revolution) will also make the mark appear stationary. Always verify with the highest frequency that gives a single image.

Lux Meter

Definition

- A **Lux Meter** is used to measure illuminance, which is the total luminous flux incident on a surface, per unit area.
- It consists of a photo cell (photodiode or photovoltaic cell) that converts incident light into an electrical current.
- Unit of measurement: **Lux** (1 lux = 1 lumen / m^2).

Lux Meter: Spectral Response

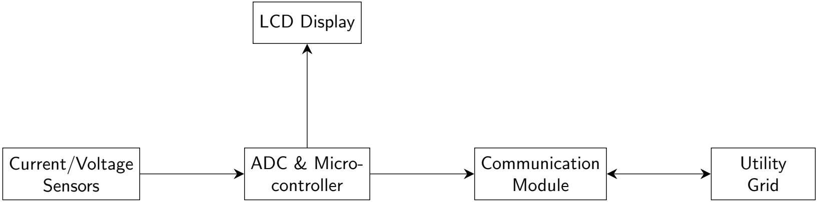
- A high-quality lux meter must have a spectral response that matches the human eye.
- The **CIE Standard Luminosity Curve** peaks at 555 nm (green light), where the human eye is most sensitive.
- Lux meters use specialized color filters over the photodiode to attenuate infrared and ultraviolet light, ensuring the reading matches human perception.

Smart Energy Meter

Definition

- A **Smart Energy Meter** is an advanced electronic device that records consumption of electric energy and communicates that information back to the utility for monitoring and billing.
- Unlike traditional electromechanical meters, they enable two-way communication between the meter and the central system.

Smart Energy Meter Architecture



Advantages of Smart Energy Meters

- **Automated Billing:** Eliminates manual meter reading.
- **Demand Response:** Allows utilities to offer Time-of-Use (TOU) pricing.
- **Tamper Detection:** Instant alerts for bypassing or magnetic interference.
- **Power Quality Monitoring:** Can record voltage sags, swells, and outages.

Thermography (Thermal Imaging)

Definition

- **Thermography** is the use of an infrared imaging and measurement camera to s̈eeänd m̈easureẗhermal energy emitted from an object.
- Thermal, or infrared energy, is light that is not visible because its wavelength is too long to be detected by the human eye; it's the part of the electromagnetic spectrum that we perceive as heat.

Thermography vs. IR Thermometer

Key Facts

- **IR Thermometer:** Measures average temperature of a single spot. Like a ¨flashlightöf temperature measurement.
- **Thermal Camera (Thermography):** Measures thousands of spots simultaneously to create an image (thermogram). Provides spatial context.

An uncooled microbolometer array is typically used as the sensor in modern thermal cameras.

Comparison of Industrial Measurement Tools

Instrument	Parameter Measured	Primary Use Case
IR Thermometer	Temperature (Spot)	Quick check of motor bearings
Stroboscope	Speed (RPM) / Frequency	Inspecting rotating gears
Lux Meter	Illuminance (Lux)	Auditing workspace lighting
Smart Meter	Electrical Energy (kWh)	Automated grid monitoring
Thermography	Temperature Map (2D)	Detecting loose electrical panels

Case Study: Electrical Panel Audit

Example

- **Problem:** Frequent unexplained tripping of a 3-phase industrial circuit breaker.
- **Investigation using Thermography:**
- 1. A thermal camera is aimed at the energized, under-load electrical panel.
- 2. The thermogram reveals Phase B connection is 35°C hotter than Phase A and C.
- **Diagnosis:**
- The elevated temperature indicates high electrical resistance, likely due to a loose connection or corroded terminal.
- **Action:** Tightening the connection prevents catastrophic failure and fire.

Conclusion & Review

Modern electrical measurement instruments bridge the gap between mechanical state and digital analysis.

- **Optical Tools (Stroboscope, Lux Meter)** help assess dynamic mechanical states and environmental quality.
- **Thermal Tools (IR Thermometer, Thermography)** provide safe, non-contact insights into thermodynamic stress and electrical faults.
- **Smart Meters** form the backbone of the modern Smart Grid.

Introduction to Power Flow

- An induction motor converts electrical power input into mechanical power output.
- The conversion involves various power stages and associated losses.
- Key stages include: Stator electrical input, Stator losses, Air gap power (Rotor input), Rotor losses, Mechanical power developed, and Mechanical losses.
- Understanding power flow is essential for calculating motor efficiency and overall performance characteristics.

What is a Sankey Diagram?

Definition

- A Sankey diagram is a specific type of flow diagram in which the width of the arrows is proportional to the flow quantity.
- In the context of electrical machines, it visually represents the flow of power from the electrical input to the mechanical output.
- The main power stream decreases in width as various losses (stator, rotor, friction) are branched off from it.
- This graphical representation makes it intuitively easy to grasp where and how much energy is dissipated in a system.

Stator Power Stages and Losses

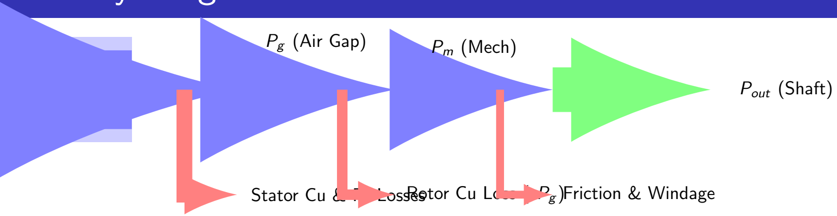
Key Facts

- Total Electrical Input to Stator (P_{in}): $P_{in} = \sqrt{3} V_L I_L \cos\phi$
- Stator Copper Loss (P_{scl}): Caused by the resistance of stator windings ($3I_1^2 R_1$).
- Stator Iron Loss (P_{sil}): Comprises eddy current and hysteresis losses in the stator core due to alternating magnetic flux.
- Air Gap Power (P_g): The net power transferred to the rotor across the air gap.
- $P_g = P_{in} - (P_{scl} + P_{sil})$

Rotor Power Stages and Losses

- Air Gap Power (P_g) serves as the input to the rotor.
- Rotor Copper Loss (P_{rcl}): Proportional to slip, $P_{rcl} = 3I_2^2 R_2 = sP_g$.
- Rotor Iron Loss is usually negligible during normal operating conditions because the rotor frequency ($f_r = sf_s$) is very low (1-3 Hz).
- Mechanical Power Developed (P_m): $P_m = P_g - P_{rcl} = (1 - s)P_g$.
- Net Shaft Output Power (P_{out}): $P_{out} = P_m - P_{mech}$, where P_{mech} encompasses friction and windage losses.

Sankey Diagram of 3-Phase Induction Motor



Case Study: Power Flow Calculation

Example

- Given: A 3-phase, 4-pole, 50 Hz induction motor operates at 1440 rpm. Input power = 50 kW, Stator losses = 2 kW.
- Step 1: Calculate Synchronous Speed (N_s).
- $N_s = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500$ rpm
- Step 2: Calculate Slip (s).
- $s = \frac{N_s - N_r}{N_s} = \frac{1500-1440}{1500} = 0.04$
- Step 3: Determine Air Gap Power (P_g).
- $P_g = P_{in} -$ Stator Losses $= 50$ kW $- 2$ kW $= 48$ kW
- Step 4: Calculate Rotor Copper Loss and Mechanical Power.
- $P_{rcl} = s \times P_g = 0.04 \times 48 = 1.92$ kW
- $P_m = P_g - P_{rcl} = 48 - 1.92 = 46.08$ kW

Introduction to Financial Management & Cash Flow

Financial management in energy projects evaluates the economic viability of energy conservation measures. **Cash Flow:** The net amount of cash moving in and out of a business.

- **Cash Inflows:** Savings generated by the new energy-efficient equipment, incentives, or revenue from generated energy.
- **Cash Outflows:** Initial capital cost, maintenance costs, and operating expenses.

Positive cash flow indicates that the investment is generating more money than it costs to operate and finance.

Simple Payback Period (SPP)

Definition

- The Simple Payback Period is the time required to recover the initial investment through the net cash flow generated by the project.
- **Formula:**
  - $$SPP = \frac{\text{Initial Capital Cost}}{\text{Annual Net Cash Flow (Savings)}}$$
- **Advantages:**
- Simple to understand and calculate. Good for quick initial assessments.
- **Disadvantages:**
- Ignores the time value of money (TVM) and ignores cash flows occurring after the payback period is reached.

Case Study: Simple Payback Period

Example

Scenario: A textile plant considers replacing an old boiler with a high-efficiency boiler.

- **Initial Cost of New Boiler:** \$120,000
- **Annual Fuel Savings:** \$35,000
- **Annual Maintenance Increase:** \$5,000

Net Annual Savings: \$35,000 - \$5,000 = \$30,000 **Payback Period Calculation:**

$$SPP = \frac{\$120,000}{\$30,000/\text{year}} = 4 \text{ years}$$

Decision: If the company's threshold is 5 years, the project is acceptable.

Net Present Value (NPV)

Key Facts

NPV addresses the Time Value of Money by discounting future cash flows to their present value.

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} - C_0$$

Where:

- C_t = Net cash flow during the period t
- C_0 = Initial investment
- r = Discount rate (cost of capital)
- n = Project lifetime

Decision Rule: If $NPV > 0$, the investment adds value and should be accepted.

Return on Investment (ROI)

ROI is a performance measure used to evaluate the efficiency of an investment or compare the efficiency of several investments.

$$ROI = \left(\frac{\text{Net Profit from Investment}}{\text{Cost of Investment}} \right) \times 100\%$$

Characteristics:

- Expressed as a percentage, making it easy to compare across different project sizes.
- Usually calculated on an annualized basis for energy projects.
- Like SPP, traditional ROI may not account for the time value of money unless calculated using discounted cash flows.

Internal Rate of Return (IRR)

Definition

The Internal Rate of Return (IRR) is the discount rate that makes the Net Present Value (NPV) of all cash flows from a particular project equal to zero.

$$0 = \sum_{t=1}^{n} \frac{C_t}{(1 + IRR)^t} - C_0$$

Interpretation:

- Represents the annualized effective compounded return rate.
- **Decision Rule:** Accept the project if $IRR >$ Minimum Acceptable Rate of Return (MARR).
- Useful for comparing projects when the discount rate is unknown or uncertain.

Comparison of Financial Metrics

Metric	Accounts for TVM?	Considers Entire Life?	Best Used For
Payback Period	No	No	Quick screening, liquidity check
ROI	No	Sometimes	Comparing profitability of different sizes
NPV	Yes	Yes	Absolute value creation, primary decision tool
IRR	Yes	Yes	Comparing percentage returns, when discount rate is uncertain

Lecture 9: Overview of Standards & Labeling Program

- The Bureau of Energy Efficiency (BEE) initiated the Standards & Labeling (S&L) program in May 2006.
- Primary Objective: Provide consumers with informed choices about energy saving and cost-saving potential of marketed appliances.
- Legal Framework: Mandated and enforced under the Energy Conservation Act, 2001.
- Key Outcomes: Substantial reduction in national energy consumption and peak demand.

2.1 Defining Standards and Labels

Definition

- **Minimum Energy Performance Standards (MEPS):** Prescribed limits on the energy consumption of a manufactured product. It establishes the minimum efficiency level acceptable in the market.
- **Energy Labels:** Informative tags affixed to manufactured products describing their energy performance.
- **Comparative Label:** Allows consumers to compare energy efficiency across different models (e.g., the 1 to 5 Star Rating).
- **Endorsement Label:** A 'seal of approval' defining products that meet highly specific, elite energy conservation criteria.

2.1 Technical Details of Standards & Labels

- **Test Procedures:** Appliances are tested in NABL (National Accreditation Board for Testing and Calibration Laboratories) accredited labs under strict standard conditions (e.g., IS standards).
- **Efficiency Metrics:** Distinct parameters are used for distinct appliances. E.g., ISEER (Indian Seasonal Energy Efficiency Ratio) for ACs, Efficacy (lumens/watt) for lamps.
- **Label Information:** Contains the Star rating, estimated annual electricity consumption, brand, model number, and manufacturing year.
- **Validity and Upgrades:** BEE periodically tightens the standards (e.g., every 2 years) to push technological advancement. Yesterday's 5-Star might be today's 3-Star.

2.2 Mandatory vs. Voluntary Appliances

Mandatory Appliances (Examples)	Voluntary Appliances (Examples)
Room Air Conditioners	Washing Machines
Frost Free Refrigerators	Ceiling Fans
Tubular Fluorescent Lamps	Agricultural Pump Sets
Distribution Transformers	Induction Cookstoves
Electric Geysers	Computer Monitors
Color TVs	Deep Freezers

Table: Classification of Appliances under BEE S&L Program

The Impact of the Star Rating System

Key Facts

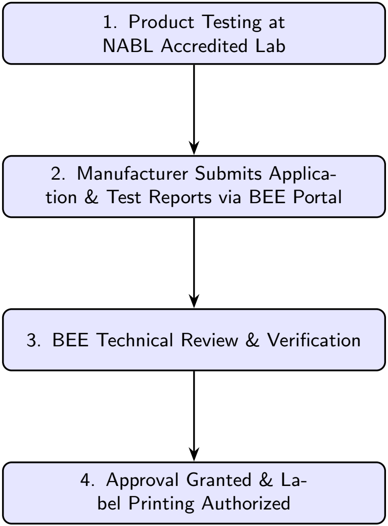
- **Visual Indicator:** Ratings range from 1 Star (least efficient) to 5 Stars (most efficient).
- **National Energy Savings:** During 2019-20, the S&L scheme led to savings of around 56 Billion Units (BU) of electricity.
- **Carbon Mitigation:** Saved roughly 46 Million Tonnes of CO_2 equivalent emissions in a single year.
- **Consumer Perception:** Over 75% of consumers now check for the Star Label before purchasing heavy appliances.

Case Study: Economics of 5-Star vs. 3-Star AC

Example

- Let us compare two 1.5 Ton Split Air Conditioners over a year (assuming 1600 hours of operation):
-
- **3-Star AC:**
- ISEER = 3.8
- Annual Energy Consumption $\approx$ 1050 kWh
-
- **5-Star AC:**
- ISEER = 5.2
- Annual Energy Consumption $\approx$ 750 kWh
-
- **Savings Analysis:**
- Annual Energy Saved = 1050 − 750 = 300 kWh.
- At Rs. 8/kWh, Monetary Savings = Rs. 2,400 per year.
- If the 5-Star AC costs Rs. 6,000 more upfront, the payback period is exactly 2.5 years!

Appliance Certification Process Flow



Overview of BEE Star Labeling System

The Bureau of Energy Efficiency (BEE) under the Ministry of Power, Government of India, initiated the Standards and Labeling (S&L) program. **Objective:**

- To provide consumers with informed choices about energy saving and thereby the cost-saving potential of the relevant marketed product.
- To impact the energy savings in the medium and long term.
- To position India's energy efficiency standards globally.

The program covers a wide range of appliances, categorizing them into mandatory and voluntary labeling schemes.

Significance of 1 to 5 Star Labels

Definition

The Star Rating Scale

1 Star: Meets the minimum energy performance standard. Lowest energy efficiency, highest energy consumption.
2 Star: Marginally better than 1 star. Slightly reduced energy bills.
3 Star: Average energy efficiency. A balanced choice for moderate usage, offering a reasonable payback period.
4 Star: High energy efficiency. Significant energy savings, recommended for high-usage appliances.
5 Star: Highest energy efficiency. Lowest energy consumption, minimal running cost, though initial capital cost is highest.

Rule of Thumb: The higher the number of stars, the more energy-efficient the appliance is, leading to lower electricity bills.

Star Ratings in High-Usage Home Appliances

Appliance	Efficiency Metric	Significance of 5-Star
Frost-Free Refrigerator	Annual Energy Consumption (kWh/year)	Uses up to 40% less energy than a 1-star model. Advanced compressors.
Room Air Conditioner	Indian Seasonal Energy Efficiency Ratio (ISEER)	High ISEER (> 4.5). Inverter compressors optimize cooling and power.
Washing Machine	Energy (kWh/cycle) & Water consumption	Optimized motor cycles and heating, drastically reducing per-wash energy.
Color TV	Annual Energy Consumption (kWh) based on screen size	Efficient LED backlighting, low standby power ($< 0.5W$).

Table: Comparison of Efficiency Metrics for Household Appliances

Lighting, Fans, and Ballasts

Key Facts

Efficiency in Lighting and Ventilation

Tubular Fluorescent Lamps (TFL): Efficacy is measured in Lumens/Watt. A 5-star TFL provides maximum brightness per watt, minimizing heat dissipation.

Electronic / Magnetic Ballast: Electronic ballasts are highly efficient compared to magnetic ones, reducing flicker and power loss. Star ratings signify reduced internal power consumption.

Ceiling Fans: Star rating based on Service Value ($SV = \frac{\text{Air Delivery (m}^3\text{/min)}}{\text{Power Input (W)}}$). A 5-star fan uses BLDC (Brushless DC) motor technology, consuming $\sim 28W$ instead of the traditional $75W$.

Industrial and Agricultural Equipment

Energy efficiency in heavy equipment has a massive impact on the national grid.

- **Distribution Transformers:** Rated based on maximum allowable total losses at 50% and 100% loading. 5-star transformers use amorphous core materials to drastically reduce no-load (core) losses.
- **Induction Motors:** Labeling is aligned with IE (International Efficiency) classes (IE2, IE3, IE4). 5-star (IE4) motors have reduced copper and iron losses, essential for continuous industrial processes.
- **Agricultural Pump Sets:** Efficiency depends on the overall pump-motor combination. Star labeling encourages farmers to replace inefficient, oversized pumps with right-sized, highly efficient units, saving heavily subsidized rural electricity.

Modern Systems: Inverters & EV Chargers

Example

Solid State Inverters & EV Chargers With the rise of renewable energy and electric mobility, labeling for power electronics is critical. **Case**

Study: EV Charger Efficiency

- **Scenario:** A 1-star EV charger has an efficiency of 85%, while a 5-star charger operates at 95%.
- **Energy to Battery:** To deliver 50 kWh to an EV battery.
- **1-Star Consumption:** $50/0.85 = 58.8$ kWh drawn from the grid.
- **5-Star Consumption:** $50/0.95 = 52.6$ kWh drawn from the grid.
- **Savings:** 6.2 kWh per full charge. Over 1000 charging cycles, savings $= 6,200$ kWh.

Conclusion: 5-star solid-state devices reduce switching and thermal losses, optimizing the energy transfer from grid to battery/load.

Energy Efficient Water Pumps

- Pumping systems account for nearly 20
- BEE Star rating for pumps evaluates the overall efficiency of the pump set (motor and pump combined).
- Higher star ratings indicate higher efficiency, reducing power consumption and operating costs.
- Key factors contributing to efficiency: high-efficiency motors, optimal hydraulic design, and proper sizing.

Case Study: Energy Saving in a Star-Rated Water Pump

Example

- **Scenario:** Replacing a standard 5 kW (approx 6.7 HP) pump with a 5-Star rated pump.
- **Standard Pump:** Efficiency = 40
- **5-Star Pump:** Efficiency = 55
- **New Annual Energy:** 3.63 kW * 10 hrs/day * 300 days = 10,890 kWh.
- **Energy Saved:** 15,000 - 10,890 = 4,110 kWh/year.
- **Cost Saving (at Rs. 8/kWh):** Rs. 32,880 per year.

Distribution Transformers & Star Ratings

- Distribution Transformers (DTs) are energized 24/7, making no-load (core) losses continuous regardless of the load.
- BEE mandates star labeling for DTs up to 200 kVA to minimize both core and copper losses.
- High star-rated DTs use Amorphous core materials and superior CRGO (Cold Rolled Grain Oriented) steel.
- Performance is evaluated based on maximum allowable losses specified at 50

Case Study: Energy Saving in a 100 kVA Distribution Transformer

Example

- **Standard DT (Non-Star):** Total losses at 50
- **5-Star Rated DT:** Total losses at 50
- **Loss Reduction:** 200 W = 0.2 kW.
- **Annual Energy Saving:** 0.2 kW * 24 hrs/day * 365 days = 1,752 kWh.
- **Financial Saving:** 1,752 kWh * Rs. 8/kWh = Rs. 14,016 per year.
- **Payback Period:** The premium cost of a 5-Star DT is typically recovered within 1.5 to 3 years.

Window vs. Split Air Conditioners

- **Window AC:** A compact, single unitary system housing the compressor, condenser, expansion valve, and evaporator in one box.
- Installation typically requires mounting in a window sill or wall cavity.
- **Split AC:** Divided into two distinct units: an indoor unit (evaporator & cooling fan) and an outdoor unit (compressor & condenser).
- Offers better aesthetics, significantly lower indoor noise, and flexible installation without blocking windows.
- Both systems utilize the standard vapor compression refrigeration cycle.

Comparison: Window AC vs. Split AC

Parameter	Window AC	Split AC
Installation	Requires window/wall opening	Flexible, requires small hole for pipes
Noise Level	Higher (compressor is indoors)	Very Low (compressor is outdoors)
Aesthetics	Bulky, blocks window	Sleek, wall-mounted
Cooling Capacity	Limited (usually up to 2 tons)	Available in much higher capacities
Maintenance	Easier, single unit access	Requires professional servicing of two units

Energy Efficiency in Air Conditioners (ISEER)

Key Facts

- **ISEER (Indian Seasonal Energy Efficiency Ratio):** The ratio of the total annual amount of heat removed from the indoor air to the total annual energy consumed during the same period.
- **Inverter Technology:** Modern Split ACs often use inverter compressors that vary their speed to maintain temperature, avoiding the energy-intensive ON/OFF cycles of traditional non-inverter models.
- **Efficiency Impact:** A 5-Star Split Inverter AC can save up to 30-40

Air Conditioning Cycle Overview

The fundamental operating principle of an air conditioner is based on the **Vapour Compression Refrigeration Cycle (VCRC)**. It transfers heat from a lower temperature region to a higher temperature region.

- Utilizes a working fluid called a **refrigerant**.
- The cycle consists of four continuous processes:
  1. Evaporation (Heat absorption)
  2. Compression (Work input)
  3. Condensation (Heat rejection)
  4. Expansion (Pressure reduction)

Stage 1: Evaporation

Definition

Evaporator Function

The **evaporator** absorbs heat from the indoor space, causing the low-pressure liquid refrigerant to boil and turn into a low-pressure vapor.

Process Details:

- **State Change:** Liquid-vapor mixture $\rightarrow$ Saturated or Superheated Vapor.
- **Heat Transfer:** Heat (Q_{in}) is extracted from the room air.
- **Thermodynamics:** Constant pressure heat addition process.

Stage 2: Compression

The compressor is the heart of the air conditioning system, driving the refrigerant through the circuit. **Key Functions:**

- Draws in low-pressure, low-temperature refrigerant vapor from the evaporator.
- Compresses it into a **high-pressure, high-temperature superheated vapor**.
- Requires mechanical work input (W_{in}), typically from an electric motor.
- Process is ideally isentropic (constant entropy).

Formula for Compressor Work:

$$W_{in} = h_2 - h_1$$

Where h represents the enthalpy of the refrigerant.

Stage 3: Condensation

Key Facts

Condenser Operation

The condenser rejects the absorbed heat (Q_{out}) to the outdoor environment, converting the high-pressure vapor back into a high-pressure liquid.

Process Breakdown:

1. **Desuperheating:** Temperature of vapor drops to saturation temperature.
2. **Condensation:** Vapor turns into liquid at constant temperature and pressure.
3. **Subcooling:** Liquid temperature drops slightly below saturation temperature to ensure pure liquid enters the expansion valve.

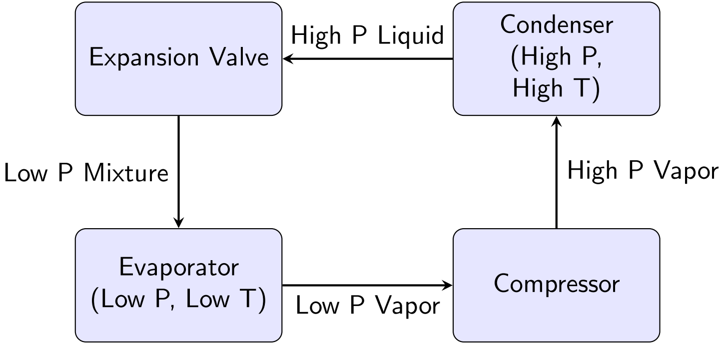
Stage 4: Expansion

The expansion valve (or capillary tube) reduces the pressure of the liquid refrigerant before it enters the evaporator. **Characteristics of the**

Expansion Process:

- **Throttling Process:** It is an isenthalpic process (constant enthalpy, $h_3 = h_4$).
- **Pressure Drop:** High pressure drops abruptly to low pressure.
- **Temperature Drop:** The sudden pressure drop causes a portion of the liquid to flash into vapor (flash gas), significantly lowering the mixture's temperature.
- Prepares the refrigerant to absorb heat again in the evaporator.

Schematic of Air Conditioning Cycle



Introduction to Room Air Conditioners (RAC)

- Room Air Conditioners (RACs) are decentralized HVAC systems designed to cool individual rooms or specific spaces.
- They operate on the standard vapor compression refrigeration cycle, absorbing indoor heat and dissipating it outdoors.
- The primary functions include temperature control, dehumidification, air filtration, and proper air distribution.
- RACs are widely used in residential, commercial, and small office applications due to their relatively low initial cost and ease of installation.
- The two most common configurations of RACs are Window Air Conditioners and Split Air Conditioners.

Window Air Conditioner

Definition

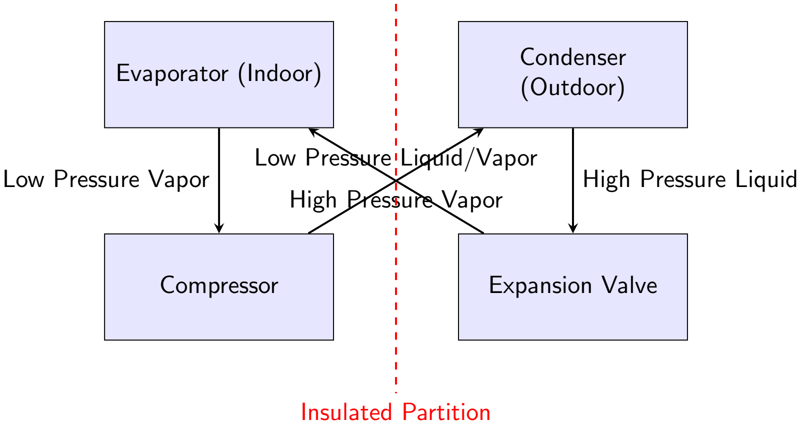
- A Window Air Conditioner is a unitary cooling system where all the primary components—compressor, condenser, expansion valve, and evaporator—are housed within a single compact casing.
- It is designed to be mounted in a window sill or a dedicated slot in a wall.
- The unit is divided into two distinct compartments by an insulated partition: the room side (cooling) and the outdoor side (heat rejection).

Window AC: Essential Components

Key Facts

- Compressor: Typically a hermetically sealed rotary or reciprocating compressor.
- Condenser Coil: Finned tube heat exchanger exposed to ambient air.
- Evaporator Coil: Finned tube heat exchanger exposed to room air.
- Expansion Device: Usually a capillary tube for pressure reduction.
- Fan Motor: A double-shafted motor driving both the indoor centrifugal blower and the outdoor axial fan.

Schematic Diagram of Window AC



Working Principle of Window AC

- Room air is drawn in by the centrifugal blower through the front grille and air filter.
- The air passes over the cold evaporator coils, where heat and moisture are absorbed by the refrigerant (typically R-22, R-32, or R-410A).
- The cooled and dehumidified air is discharged back into the room.
- Simultaneously, the axial fan draws ambient outdoor air over the hot condenser coils, absorbing heat from the high-pressure refrigerant.
- Condensate water from the evaporator often drains to the base pan and is slung onto the condenser by the fan blades to improve heat rejection efficiency.

Window AC: Advantages and Disadvantages

Advantages	**Disadvantages**
Low initial cost	High noise level (compressor is indoors)
Easy installation (no refrigerant piping required)	Blocks window view and natural light
Compact, unitary design	Limited to rooms with suitable windows/external walls
Easy to relocate	Aesthetically bulky

Split Air Conditioner

Definition

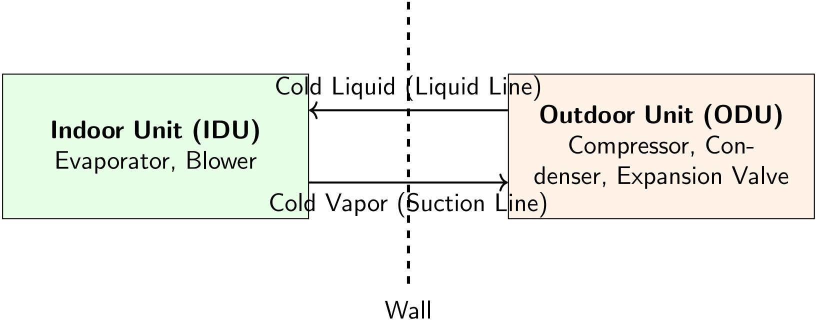
- A Split Air Conditioner is a system where the components of the vapor compression cycle are separated into two distinct units: an Indoor Unit (IDU) and an Outdoor Unit (ODU).
- The IDU contains the evaporator coil, cooling fan (blower), and air filter.
- The ODU houses the compressor, condenser coil, condenser fan, and expansion device (in some configurations, the expansion valve is in the IDU).
- The two units are connected by insulated copper tubing (refrigerant lines) and electrical wiring.

Split AC Components

Key Facts

- Indoor Unit (Evaporator Unit): Sleek, wall-mounted (or ceiling/floor mounted) casing containing a cross-flow fan, evaporator coil, and control electronics.
- Outdoor Unit (Condenser Unit): Weather-resistant casing containing the compressor, condenser heat exchanger, axial fan, and capillary tube/electronic expansion valve.
- Refrigerant Piping: Liquid line (smaller diameter) and suction line (larger diameter, heavily insulated to prevent condensation).
- Interconnecting Cable: Provides power and control signals between the IDU and ODU.

Schematic Diagram of Split AC



Working Principle of Split AC

- The working principle follows the same vapor compression cycle as the Window AC.
- High-pressure liquid refrigerant flows from the ODU through the expansion device and enters the IDU via the liquid line.
- Inside the IDU, the refrigerant evaporates, absorbing heat from the room air blown over the coils by the cross-flow fan.
- The low-pressure vapor travels back to the ODU via the insulated suction line.
- The compressor in the ODU compresses the vapor, and the condenser coil rejects the heat to the outside atmosphere.

Comparison: Window AC vs. Split AC

Parameter	Window AC	Split AC
Installation	Easy, requires window/hole	Complex, requires masonry work
Noise Level	High (compressor inside)	Very Low (compressor outside)
Aesthetics	Bulky, blocks window	Sleek, blends with interior
Cost	Lower initial cost	Higher initial cost
Flexibility	Limited to outer walls	High, IDU can be placed anywhere

Inverter Technology in Split ACs

- Traditional ACs use fixed-speed compressors that cycle ON and OFF to maintain temperature, causing temperature fluctuations and high starting power surges.
- Inverter ACs use a Variable Frequency Drive (VFD) to control the speed of the compressor motor.
- The compressor runs continuously but adjusts its speed to precisely match the cooling load of the room.
- Benefits include: significant energy savings (up to 30-50

Case Study: Tonnage Calculation for a Room

Example

- Problem: Select a suitable AC for a bedroom measuring 15 ft x 12 ft x 10 ft.
- Step 1: Calculate Volume = 15 x 12 x 10 = 1800 cubic feet.
- Step 2: Rule of thumb for residential cooling is roughly 1 Ton of Refrigeration (TR) per 1000 cubic feet of volume (varies by insulation and sun exposure).
- Step 3: Base Tonnage = 1800 / 1000 = 1.8 TR.
- Step 4: Factoring in occupancy, lighting, and a top-floor location, we apply a 10
- Conclusion: A 2.0 Ton Split AC is recommended for this space.

Calculation: EER and COP

Example

- Problem: A 1.5 TR Window AC consumes 1600 Watts of electrical power.
- Given: 1 Ton of Refrigeration (TR) = 3517 Watts of cooling capacity.
- Cooling Capacity = 1.5 * 3517 = 5275.5 W.
- Coefficient of Performance (COP) = Cooling Capacity (W) / Power Input (W)
- COP = 5275.5 / 1600 = 3.29.
- Energy Efficiency Ratio (EER) is often used, defined as Cooling Capacity (BTU/hr) / Power Input (W). (1 TR = 12000 BTU/hr)
- Cooling Capacity = 1.5 * 12000 = 18000 BTU/hr.
- EER = 18000 / 1600 = 11.25 BTU/hr/W.

Conclusion and Summary

- Room Air Conditioners are essential for localized comfort cooling.
- Window ACs provide a compact, low-cost solution but suffer from noise and aesthetic limitations.
- Split ACs separate the noisy compressor from the indoor environment, offering quiet operation, better air distribution, and versatile installation.
- Advancements like Inverter technology have drastically improved the energy efficiency of RACs.
- Proper selection, sizing, and installation are critical to maximizing performance, efficiency, and lifespan of both Window and Split AC systems.

Lecture 14: Energy Efficiency Terminology and ISEER

- Welcome to Lecture 14.
- Today we will cover:
- - 2.8 Terminology: Energy Efficiency Ratio (EER)
- - Indian Seasonal Energy Efficiency Ratio (ISEER)
- - 2.9 Methods of evaluation of ISEER and its significance

Need for Energy Efficiency Metrics

- Air conditioning accounts for a major portion of building energy consumption.
- Evaluating the performance of cooling equipment requires standardized metrics.
- Metrics help consumers make informed decisions.
- Metrics allow policymakers to set Minimum Energy Performance Standards (MEPS).

Energy Efficiency Ratio (EER)

Definition

- **Energy Efficiency Ratio (EER)** is the ratio of the cooling capacity (in British thermal units [Btu] per hour or Watts) to the power input (in Watts).
- It represents the efficiency of a cooling system at a specific, single operating condition.

EER Formula & Conditions

Key Facts

- Formula: $EER = \frac{Q_c}{W_{in}}$
- Where:
- Q_c = Cooling capacity
- W_{in} = Electrical power input
- Standard test condition: Outdoor temperature of $35^\circ C$ ($95^\circ F$) and indoor temperature of $27^\circ C$ ($80^\circ F$) at 50% relative humidity.

Limitations of EER

- EER assumes the AC runs at full load all the time.
- In reality, outdoor temperatures fluctuate significantly throughout the day and season.
- Most ACs (especially inverter types) operate at partial loads most of the time.
- Therefore, EER does not accurately reflect annual or seasonal energy consumption.

Indian Seasonal Energy Efficiency Ratio (ISEER)

Definition

- **ISEER (Indian Seasonal Energy Efficiency Ratio)** is the ratio of the total annual amount of heat that the equipment may remove from the indoor air when operated for cooling in active mode to the total annual amount of energy consumed by the equipment during the same period.

Why Seasonal Efficiency?

Key Facts

- India has diverse climatic zones.
- Cooling requirements vary from month to month.
- ISEER factors in a predefined 'temperature bin' representing the Indian climate.
- It accurately measures the performance of variable-speed (inverter) compressors.

Comparison: EER vs ISEER

Feature	**EER**	**ISEER**
Load Condition	Full load (Single point)	Partial and Full loads (Multiple points)
Temperature	Fixed ($35°C$ outdoor)	Variable (Range of $24°C$ to $43°C$)
Best Suited For	Fixed-speed ACs	Inverter (variable-speed) ACs
Accuracy	Low for annual energy	High for annual energy

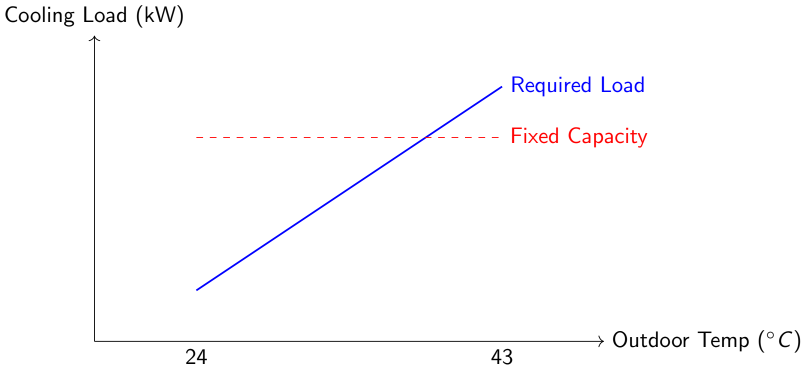
Methods of Evaluation of ISEER

- The evaluation of ISEER involves ISO 16358 standards adapted for Indian weather data.
- It requires calculation of:
- 1. Cooling Seasonal Total Load (CSTL)
- 2. Cooling Seasonal Energy Consumption (CSEC)
- Formula: $ISEER = \frac{CSTL}{CSEC}$

Evaluation Step 1: Defining Temperature Bins

- A 'temperature bin' is a range of outdoor temperatures.
- The standard defines the number of hours per year the outdoor temperature falls into each bin.
- For India, the reference temperature range is typically $24^{\circ}C$ to $43^{\circ}C$.
- Total fractional bin hours are standardized based on Indian meteorological data (1600 hours of cooling operation).

Cooling Load vs Outdoor Temperature



Evaluation Step 2: Testing at Various Capacities

- For Inverter ACs, testing is done at different capacities:
- 1. 100
- 2. 50
- The capacity and power consumption at intermediate bin temperatures are interpolated.
- This captures the high efficiency of the compressor running at lower speeds.

Numerical Example: Calculating ISEER

Example

- Assume a 1.5 Ton AC (5275 W capacity).
- Calculated Cooling Seasonal Total Load (CSTL) over 1600 hours = 3,200,000 Wh.
- Calculated Cooling Seasonal Energy Consumption (CSEC) = 800,000 Wh.
- ISEER = $CSTL/CSEC$
- ISEER = $3,200,000/800,000 = 4.0$

Significance of ISEER: Consumer Perspective

- Enables fair comparison between fixed-speed and inverter ACs.
- Directly correlates with the annual electricity bill.
- Higher ISEER = Lower operating cost.
- Helps consumers justify the higher initial cost of inverter ACs through ROI calculations.

Significance of ISEER: Policy and Environment

- Star Labeling Program: BEE uses ISEER to assign Star Ratings (1-Star to 5-Star).
- Grid Stability: Higher efficiency reduces peak electricity demand during summer.
- Emissions: Reduced energy consumption translates to lower greenhouse gas emissions from power plants.
- Continuous Improvement: BEE periodically upgrades the ISEER baseline, forcing manufacturers to innovate.

What is a Variable Frequency Drive (VFD) Compressor?

Definition

- A Variable Frequency Drive (VFD) compressor is a type of air or gas compressor that uses a drive system to control the speed of the motor.
- **Core Principle:** It adjusts the motor speed (RPM) by varying the frequency and voltage of the electrical power supplied to it, directly matching the compressed air supply to the demand.

Operating Principle

- **1. Rectification:** Incoming AC power is converted to DC power using a rectifier.
- **2. DC Bus:** The DC power is smoothed and stored in capacitors.
- **3. Inversion:** The inverter converts the DC power back into AC power, but with variable frequency and voltage.
- **4. Speed Control:** By changing the output frequency (using Pulse Width Modulation - PWM), the motor speed (N) changes according to the formula: $N = \frac{120 \times f}{P}$, where f is frequency and P is the number of motor poles.

Energy Efficiency and Cost Savings

Key Facts

- VFD compressors can yield energy savings of up to **35% to 50%** compared to fixed-speed compressors.
- **Affinity Laws:** The power consumption of a centrifugal compressor is proportional to the cube of the speed. A 20% reduction in speed can lead to nearly a 50% reduction in energy usage.
- Reduces starting current and peak demand charges, as VFDs offer a 'soft start' capability.

VFD vs. Fixed Speed Compressors

Feature	**Fixed Speed**	**VFD Compressor**
Motor Speed	Constant	Variable
Energy Efficiency	Low (at partial load)	High (at partial load)
Starting Current	Very High (up to 6x full load)	Low (Soft Start)
Initial Cost	Lower	Higher
Wear and Tear	Higher (frequent start/stop)	Lower

Case Study: Industrial Plant Upgrade

Example

- **Scenario:** A manufacturing plant operates a 100 HP fixed-speed compressor, running at an average of 60% capacity.
- **Fixed Speed Consumption:** Operating in load/unload mode, energy usage at 60% capacity is roughly 80% of full load power.
- **VFD Solution:** Replacing with a 100 HP VFD compressor.
- **VFD Consumption:** Energy usage at 60% capacity drops to roughly 63% of full load power.
- **Result:** A net energy saving of 17% of full load power. For continuous operation, this translates to thousands of dollars saved annually, with an ROI of 1.5 to 2 years.

Introduction to AC Star Ratings

- Star ratings indicate the energy efficiency of air conditioners.
- Higher star rating means greater energy efficiency and lower electricity bills.
- In India, these ratings are standardized by the Bureau of Energy Efficiency (BEE).
- The rating system applies to both Window and Split Air Conditioners.
- Upgraded periodically to ensure manufacturers adopt more energy-efficient technologies.

Bureau of Energy Efficiency (BEE)

Definition

BEE Definition

The **Bureau of Energy Efficiency (BEE)** is an agency of the Government of India, under the Ministry of Power, created in March 2002 under the provisions of the nation's 2001 Energy Conservation Act. **Primary Objective:** To reduce energy intensity in the Indian

economy through regulatory and promotional strategies.

ISEER (Indian Seasonal Energy Efficiency Ratio)

Key Facts

ISEER Concept

Modern star ratings for ACs are based on **ISEER**.

ISEER Formula:

$$\text{ISEER} = \frac{\text{CSTL (Cooling Seasonal Total Load)}}{\text{CSEC (Cooling Seasonal Energy Consumption)}}$$

Fact: ISEER accounts for the variance in temperature across different seasons in India, providing a more realistic efficiency measure compared to the older EER (Energy Efficiency Ratio).

ISEER Rating Thresholds (Split AC Example)

Star Rating	Minimum ISEER	Maximum ISEER
1 Star	3.30	3.49
2 Star	3.50	3.79
3 Star	3.80	4.39
4 Star	4.40	4.99
5 Star	5.00	Above

Table: Sample ISEER thresholds for Split ACs (Valid from recent BEE periods)

Window vs. Split AC Energy Efficiency

- **Window ACs:**
  - Generally have lower ISEER values for the same cooling capacity.
  - Compact design restricts the size of condenser and evaporator coils, limiting efficiency gains.
- **Split ACs:**
  - Can achieve much higher ISEER values (up to 5+).
  - Larger surface area for heat exchange due to separated indoor and outdoor units.
  - More commonly feature Inverter technology, which dynamically adjusts compressor speed.

Case Study: Calculating Energy Savings

Example

Scenario: Comparing a 1.5 Ton 3-Star AC vs. a 1.5 Ton 5-Star AC running for 1600 hours/year. **Data:**

- 3-Star AC Annual Energy Consumption: $\approx$ 1050 kWh
- 5-Star AC Annual Energy Consumption: $\approx$ 800 kWh
- Electricity Cost: Rs. 8 per kWh

Calculation:

$$\text{Savings} = (1050 - 800) \times 8 = 250 \times 8 = \text{Rs. } 2000 \text{ per year}$$

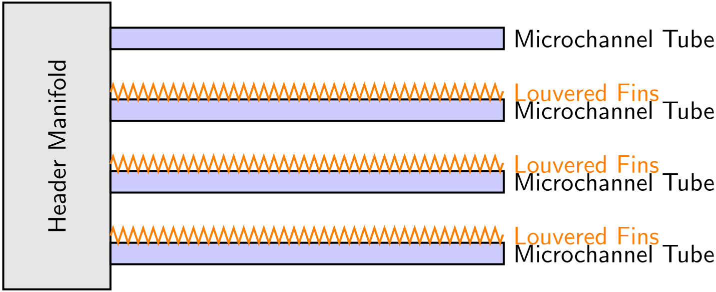
Conclusion: The initial higher cost of a 5-Star AC can be recovered in a few years through electricity savings.

Improving RAC Efficiency: An Overview

Introduction to High-Efficiency Room Air Conditioners

- Global energy demand necessitates high Seasonal Energy Efficiency Ratio (SEER) in RAC systems.
- Efficiency is improved by optimizing the vapor compression cycle components and adopting smart control strategies.
- **Key Focus Areas:**
  1. Advanced Heat Exchangers (MCHE, enhanced fins)
  2. Variable-speed advanced compressors
  3. Electronic Expansion Valves (EEV)
  4. High-efficiency motors (BLDC)
  5. Innovative features (Dual Barrier, Power Plasma)
  6. Low Global Warming Potential (GWP) Refrigerants

Advanced Heat Exchangers: Microchannel (MCHE)



MCHE provides high heat transfer coefficient, requires less refrigerant charge, and offers lower air-side pressure drop.

Advanced Compressors & High Efficiency Motors

Definition

Brushless DC (BLDC) Motors & Inverter Compressors

Inverter Compressors: Unlike fixed-speed compressors that experience on/off cycling losses, inverter-driven compressors modulate their speed using Variable Frequency Drives (VFD). This matches cooling capacity precisely to the thermal load, significantly improving part-load efficiency.

High Efficiency Motors (BLDC): Brushless DC motors use permanent magnets in the rotor and electronically commutated electromagnets in the stator.

- Eliminates rotor I^2R (copper) losses present in AC induction motors.
- Provides higher torque-to-weight ratio and precise speed control.
- Up to 30% more efficient than standard AC induction motors.

Transition to Low GWP Refrigerants

Refrigerant	ODP	GWP (100 yr)	Safety Class	Efficiency Characteristics
R22	0.055	1810	A1	Baseline, high latent heat (Phased out)
R410A	0	2088	A1	High pressure, good volumetric capacity
R32	0	675	A2L (Mildly Flammable)	10% higher capacity than R410A, better COP
R290 (Propane)	0	~ 3	A3 (Highly Flammable)	Excellent thermodynamic properties, low charge

Table: Comparison of traditional and modern low-GWP refrigerants in RAC systems.

RAC Enhancements: Dual Barrier & Power Plasma

Key Facts

Fact: Enhancing Durability and Air Quality

Dual Barrier Coating:

- *Mechanism:* Uses a two-layer approach on condenser coils. A hydrophilic layer prevents water droplet bridging (reducing air flow resistance), while an anti-corrosive epoxy/gold layer protects against salt and acids.
- *Efficiency Impact:* Maintains optimal heat transfer coefficient (α) over the RAC lifespan, preventing the typical 10-15% capacity drop caused by corrosion.

Power Plasma (Cold Plasma Technology):

- *Mechanism:* Generates positive and negative ions (H^+ and O_2^-) that bond with airborne pathogens and VOCs, destroying their molecular structure.
- *Efficiency Impact:* Replaces dense HEPA filters, reducing the air-side pressure drop (ΔP_{air}) across the evaporator, which lowers fan motor power consumption while maintaining Indoor Air Quality (IAQ).

Example: EEV vs Capillary Tube Part-Load Efficiency

Example

Case Study: 1.5 TR (5.27 kW) Split AC at 50% Load Scenario 1:

Capillary Tube (Fixed Restriction)

- At part load, lower ambient temperatures cause the condenser pressure to drop.
- Mass flow rate ($\dot{m}$) through capillary drops significantly, starving the evaporator.
- Evaporator superheat rises to 12°C, reducing effective heat exchange area. System COP = 2.9.

Scenario 2: Electronic Expansion Valve (EEV)

- EEV stepper motor adjusts opening based on a thermistor reading at the evaporator exit (PID control).
- Maintains optimal 5°C superheat, fully utilizing the evaporator coil.
- Reduced compressor lift and optimal mass flow yield a system COP = 3.6.
- **Result:** A 24% improvement in part-load efficiency (SEER) using active expansion control.

Introduction to IoT in RAC

- Overview of IoT integration in Refrigeration and Air Conditioning.
- Shifts from reactive maintenance to proactive, predictive system management.
- Enables real-time remote monitoring of thermodynamic parameters.
- Facilitates demand-response integration with smart electric grids.

What is an IoT-enabled RAC System?

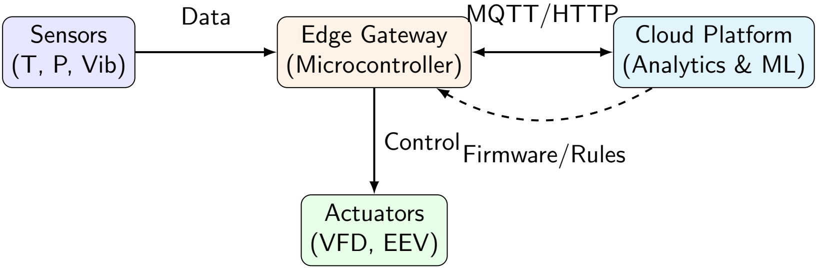
Definition

- An IoT-enabled RAC system connects physical components (compressors, expansion valves, fans) to the internet via sensors and microcontrollers. It facilitates remote monitoring, big data analytics, and autonomous control to optimize energy efficiency, ensure thermal comfort, and reduce downtime.

Core Components of IoT RAC

- 1. **Data Acquisition:** Smart sensors measuring parameters (NTC thermistors for temperature, pressure transducers, vibration sensors).
- 2. **Edge Computing:** Local microcontrollers (e.g., ESP32, industrial PLCs) for immediate fault detection and localized control loops.
- 3. **Cloud Processing:** Data lakes for historical trend analysis and machine learning (ML) model execution.
- 4. **Actuation:** Variable Frequency Drives (VFDs) and Electronic Expansion Valves (EEVs) responding to cloud-optimized signals.

IoT RAC Architecture



Impact of IoT on Energy Savings

Key Facts

- Implementing IoT-based adaptive control in commercial HVAC/RAC systems yields energy savings of 15

Real-Time Thermodynamic Monitoring

- IoT allows continuous plotting of the actual vapor compression cycle on a P-h diagram.
- Superheat and subcooling are monitored dynamically to prevent liquid floodback.
- **Instantaneous Capacity:** $Q_e = \dot{m}(h_1 - h_4)$
- **Instantaneous COP:** $COP = \frac{h_1 - h_4}{h_2 - h_1}$
- Deviations from baseline trigger maintenance alerts (e.g., refrigerant leak detection).

Traditional vs. IoT-based RAC Systems

Feature	Traditional RAC	IoT-based RAC
Control	On/Off Thermostatic	Continuous, Predictive
Maintenance	Reactive / Time-based	Predictive (Condition-Based)
Efficiency	Static Baseline	Dynamically Optimized
Data Logging	Manual / None	Real-time Cloud Streaming

Case Study: Predictive Maintenance

Example

- **Scenario:** A commercial cold storage facility (Ammonia system).
- **Issue:** Gradual micro-leak of refrigerant charge.
- **IoT Detection:** Suction pressure transducers noted a 10
- **Action:** Cloud ML algorithm flagged an anomaly in superheat values before actual compressor overheating occurred.
- **Result:** Avoided complete compressor failure. $3,500 savedinreplacementcostsandprevented 10,000+$ in spoiled inventory.

Introduction to Super-Efficient ACs (SEAC)

- Super-Efficient Air Conditioners (SEACs) operate at significantly higher efficiencies than standard 5-star market models.
- **Key goal:** Reduce climate impact by addressing both direct (refrigerant GWP) and indirect (grid electricity) emissions.
- Incorporates advanced heat exchangers, highly efficient compressors, and ultra-low GWP refrigerants (e.g., R-290, R-32).
- Often utilizes hybrid technologies like evaporative pre-cooling.

Inverter Technology in SEACs

Definition

- Inverter technology utilizes a Variable Frequency Drive (VFD) to continuously adjust the rotational speed of the compressor's motor. Instead of traditional on/off cycling, it modulates cooling capacity to match the exact thermal load of the room, minimizing starting surge losses and maintaining tighter temperature bands ($\pm 0.5^\circ$C).

Enabling Technologies for SEACs

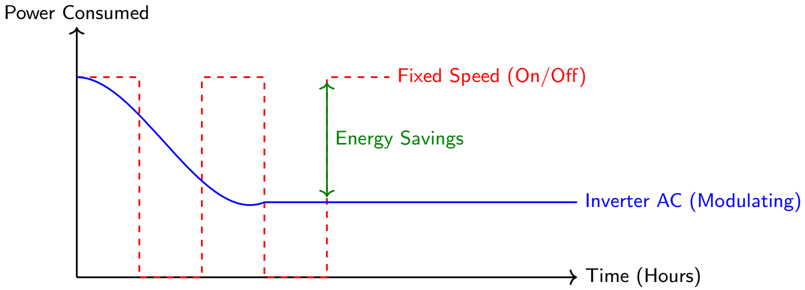
- 1. **Brushless DC (BLDC) Motors:** Used in indoor and outdoor fans. Eliminates rotor copper losses, operating at up to 90% electrical efficiency.
- 2. **Electronic Expansion Valves (EEV):** Replaces static capillary tubes. Modulates refrigerant flow dynamically in response to varying evaporator superheat via stepper motors.
- 3. **Microchannel Heat Exchangers (MCHX):** Aluminum construction with flattened tubes. Offers reduced internal volume (less refrigerant charge) and higher heat transfer coefficients.

The Global Cooling Prize

Key Facts

- The Global Cooling Prize was an innovation competition aimed at developing residential cooling solutions with at least 5X less climate impact. Winning prototypes achieved over an 80

Variable Speed vs Fixed Speed Power Consumption



ISEER Ratings for ACs (India Context)

Star Rating (Split AC)	**ISEER (Indian Seasonal Energy Efficiency Ratio)**
3 Star (Standard)	3.80 - 4.39
4 Star (High Efficency)	4.40 - 4.99
5 Star (Premium)	$\geq$ 5.00
SEAC (Future Tech)	**ISEER $>$ 7.00**

Energy Savings Calculation: SEAC vs 3-Star

Example

- **Given:** 1.5 TR cooling load (≈ 5.275 kW).
- **Standard 3-Star AC (ISEER 3.8):**
- Power Input $= \frac{5275}{3.8} = 1388$ W
- **Super-Efficient AC (ISEER 7.0):**
- Power Input $= \frac{5275}{7.0} = 753$ W
- **Calculation:**
- Power saved $= 1388 - 753 = 635$ W
- Annual Savings (1600 hours operation):
- $635 \text{ W} \times 1600 \text{ h} = 1016 \text{ kWh/year}$
- **Conclusion:** Over 45% energy reduction annually, yielding massive grid-level impact.

3.1 Concept of Reactive Power

Definition

Reactive Power (Q): The portion of electricity that establishes and sustains the electric and magnetic fields of alternating-current equipment.

- Measured in volt-amperes reactive (VAR) or kVAR.
- Essential for inductive loads (motors, transformers) to function, but performs no useful work.
- **Power Factor (PF):** The ratio of Real Power (P in kW) to Apparent Power (S in kVA). $PF = \cos(\phi) = \frac{P}{S}$.
- A low power factor means the system draws more current to perform the same amount of real work.

Causes of Low Power Factor

Key Facts

Primary culprits for low power factor in industrial settings:

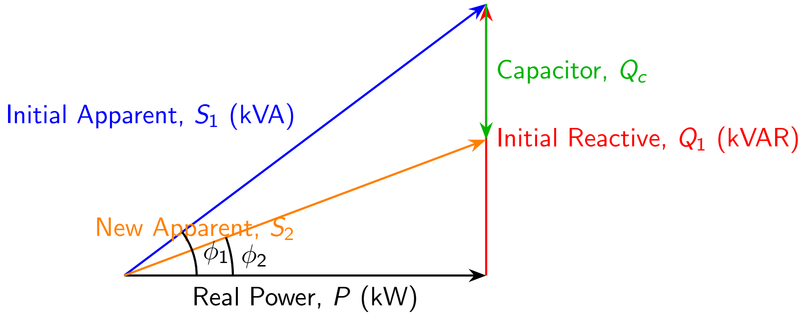
- **Induction Motors:** Especially when operated at less than full load (e.g., a lightly loaded induction motor can have a PF as low as 0.3 to 0.5).
- **Transformers:** Require reactive power for magnetization, which lowers the PF when idling or lightly loaded.
- **Arc Lamps and Furnaces:** Inherently highly inductive.
- **Welding Equipment:** Draw high reactive currents during operation.
- **Harmonic Currents:** From non-linear electronic loads like Variable Frequency Drives (VFDs) and rectifiers, leading to distortion power factor.

Advantages of Reactive Power Management by Capacitor

By installing power factor correction capacitors, we generate leading reactive power that cancels out lagging reactive power from inductive loads. **Key Advantages:**

1. **Reduction in Electricity Bills:** Avoids utility penalties for low power factor and reduces maximum kVA demand charges.
2. **Increased System Capacity:** Frees up capacity in transformers and distribution lines ($kVA = kW/PF$), allowing additional loads without upgrading infrastructure.
3. **Reduced I^2R Losses:** Lower current transmission decreases copper losses in cables.
4. **Improved Voltage Regulation:** Decreases voltage drop across distribution lines, leading to healthier equipment operation.

Power Triangle and Correction



Formula: $Q_c = P(\tan\phi_1 - \tan\phi_2)$

3.2 Reactive Power Compensation Methods

Capacitor banks can be installed at different levels of the distribution system, depending on load characteristics and economic considerations.

- **Individual (Load) Compensation:** Capacitors are connected directly to the terminals of individual inductive loads (like large motors). Switched on/off with the equipment.
- **Group Compensation:** Capacitors are connected to the distribution board or Motor Control Center (MCC) supplying a group of motors operating simultaneously.
- **Centralized Compensation:** Large capacitor banks (often Automatic Power Factor Correction - APFC panels) are connected at the main incoming distribution board (PCC).

Comparison of Compensation Strategies

Method	Advantages	Disadvantages
Individual	Maximum line loss reduction, no separate switching needed.	High cost per kVAR, capacitors underutilized if load is often off.
Group	Better utilization than individual, reduces MCC line losses.	Intermediate cost, line losses downstream of MCC not reduced.
Centralized	Lowest cost per kVAR, automatic control (APFC), high utilization.	Does not reduce line losses within the internal plant distribution network.

Table: Comparison of Compensation Methods

Case Study: Sizing a Capacitor Bank

Example

Problem: A 50 kW induction motor operates at a power factor of 0.70 lagging. Determine the required capacitor rating (in kVAR) to improve the power factor to 0.95 lagging. **Solution:**

- Real Power $P = 50$ kW
- Initial PF
  $\cos\phi_1 = 0.70 \implies \phi_1 = \cos^{-1}(0.70) = 45.57^\circ \implies \tan\phi_1 = 1.020$
- Target PF
  $\cos\phi_2 = 0.95 \implies \phi_2 = \cos^{-1}(0.95) = 18.19^\circ \implies \tan\phi_2 = 0.328$
- **Capacitor Rating** Q_c**:**

$$Q_c = P(\tan\phi_1 - \tan\phi_2)$$

$$Q_c = 50 \times (1.020 - 0.328) = 50 \times 0.692 = 34.6 \text{ kVAR}$$

Result: A 35 kVAR standard capacitor bank is required for individual compensation.

3.3 Capacitor Rating for Power Factor Improvement

- Improving the power factor of an electrical installation requires connecting a capacitor bank in parallel.
- The capacitor draws a leading current that neutralizes the lagging reactive component of the load current.
- The required size of the capacitor bank is expressed in reactive power (kVAR).
- Two common methods to determine the required kVAR rating:
- 1. Analytical calculation using standard trigonometric formulas.
- 2. Direct estimation using standard multiplying factor tables.

Power Triangle & Power Factor Fundamentals

Definition

Power Factor ($\cos\phi$) is the ratio of Real Power to Apparent Power:

$$\cos\phi = \frac{P}{S} = \frac{\text{kW}}{\text{kVA}}$$

The relationship between the powers forms a right-angled triangle:

- **Real Power (P):** Measured in kW, it does the actual work.
- **Reactive Power (Q):** Measured in kVAR, it sustains the electromagnetic field.
- **Apparent Power (S):** Measured in kVA, the total power supplied.

$$S^2 = P^2 + Q^2$$

Formula Method for Capacitor Rating

- Let P = Real power consumed (kW)
- Let ϕ_1 = Initial phase angle before correction (lagging)
- Let ϕ_2 = Final desired phase angle after correction
- Initial reactive power: $Q_1 = P \tan \phi_1$
- Desired reactive power: $Q_2 = P \tan \phi_2$
- The required rating of the capacitor bank Q_c (in kVAR) is the difference:
- $$Q_c = Q_1 - Q_2 = P(\tan \phi_1 - \tan \phi_2)$$
- This formula assumes the real power P remains constant during correction.

Standard Multiplying Factor Table Method

Instead of calculating tangents, industrial standards provide a multiplying factor (K).

$$Q_c = P \times K$$

Initial PF	Final 0.90	Final 0.95	Final 1.00
0.70	0.536	0.691	1.020
0.75	0.398	0.553	0.882
0.80	0.266	0.421	0.750
0.85	0.136	0.291	0.620

Table: Multiplying Factor K for kW to kVAR

Numerical Example: Using Formula

Example

- **Problem:** A 3-phase, 50 kW induction motor operates at a power factor of 0.75 lagging. Calculate the kVAR rating of the capacitor required to improve the power factor to 0.95 lagging.
- **Solution:**
- 1. $P = 50$ kW
- 2. $\cos\phi_1 = 0.75 \implies \phi_1 = 41.41^\circ \implies \tan\phi_1 = 0.8819$
- 3. $\cos\phi_2 = 0.95 \implies \phi_2 = 18.19^\circ \implies \tan\phi_2 = 0.3286$
- 4. Calculate Q_c:
  - $$Q_c = P(\tan\phi_1 - \tan\phi_2)$$
  - $Q_c = 50 \times (0.8819 - 0.3286) = 50 \times 0.5533 = 27.665$ kVAR

Numerical Example: Using Standard Table

Example

- **Problem:** Using the standard table method, find the required capacitor rating for the previous 50 kW motor (Initial PF = 0.75, Final PF = 0.95).
- **Solution:**
- 1. Identify the Initial PF row in the table: 0.75
- 2. Identify the Final PF column: 0.95
- 3. The intersection gives the multiplying factor $K = 0.553$.
- 4. Apply the formula:
- $$Q_c = P \times K$$
- $$Q_c = 50 \times 0.553 = 27.65 \text{ kVAR}$$
- *Note: The result closely matches the analytical calculation (27.665 kVAR), with minor round-off differences inherent in standard tables.*

Important Considerations for Capacitor Selection

Key Facts

When specifying a capacitor rating for GTU engineering designs, remember:

- **Standard Ratings:** Capacitors are available in standard discrete ratings (e.g., 5, 10, 25, 50 kVAR). Choose the nearest standard rating (usually rounding down to prevent leading PF).
- **Over-compensation Risk:** If $Q_c > Q_1$, the system becomes leading, causing over-voltage issues (Ferranti effect at light loads).
- **Location:** Capacitors should ideally be placed near the inductive load to minimize line losses.
- **Voltage Rating:** The capacitor voltage rating must match or exceed the highest steady-state line voltage.

Effect of Power Factor in Three-Phase Systems

Welcome to Lecture 21. Today we will explore the critical role of Power Factor (PF) in three-phase power systems. Specifically, we will cover:

- **3.4** Effect of power factor on three-phase line current
- **3.5** Effect of power factor on copper losses
- Case studies demonstrating these effects numerically

Power Factor Fundamentals

Definition

- **Power Factor ($\cos\phi$):** The ratio of Real Power (P) to Apparent Power (S).
- In a three-phase system:
  - $$P = \sqrt{3} V_L I_L \cos\phi$$
  - $$S = \sqrt{3} V_L I_L$$
  - $$Q = \sqrt{3} V_L I_L \sin\phi$$
- Where P is Real Power (kW), S is Apparent Power (kVA), and Q is Reactive Power (kVAR).

3.4 Effect of Power Factor on Line Current

Example

Rearranging the real power formula for Line Current (I_L):

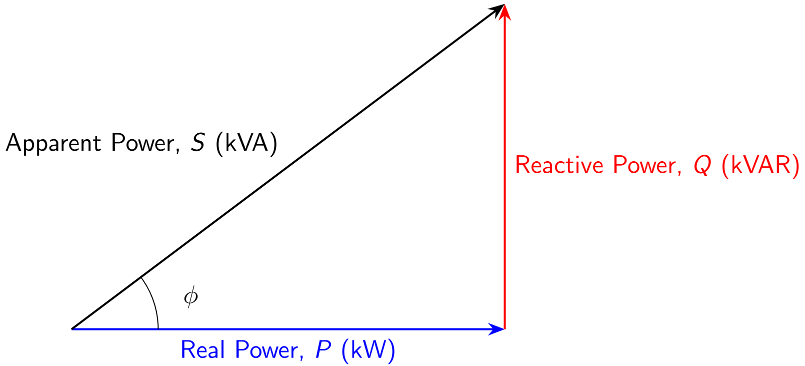
$$I_L = \frac{P}{\sqrt{3} V_L \cos \phi}$$

For a constant real power demand (P) and constant line voltage (V_L), the line current is **inversely proportional** to the power factor. **Case Study:** A 3-phase motor requires 50 kW at 415 V.

- **Case 1 (PF = 0.95 lag):** $I_L = \frac{50{,}000}{\sqrt{3} \times 415 \times 0.95} = 73.22$ A
- **Case 2 (PF = 0.60 lag):** $I_L = \frac{50{,}000}{\sqrt{3} \times 415 \times 0.60} = 115.93$ A

Conclusion: A drop in PF from 0.95 to 0.60 causes a 58% increase in line current!

Power Triangle Visualization



3.5 Effect of Power Factor on Copper Losses

Example

Copper losses (P_{cu}) in the three-phase transmission lines are given by:

$$P_{cu} = 3I_L^2 R$$

Substituting $I_L = P/(\sqrt{3}V_L \cos\phi)$:

$$P_{cu} = \frac{P^2 R}{V_L^2 \cos^2\phi}$$

Thus, copper losses are **inversely proportional to the square** of the power factor. **Case Study (continued from previous):** Assume line resistance $R = 0.5\Omega$ per phase.

- **Case 1 (PF = 0.95):**
  $P_{cu} = 3 \times (73.22)^2 \times 0.5 = 8,041$ W $= 8.04$ kW
- **Case 2 (PF = 0.60):**
  $P_{cu} = 3 \times (115.93)^2 \times 0.5 = 20,159$ W $= 20.16$ kW

Conclusion: The copper losses increased by 150% due to the poor power factor.

Consequences of Low Power Factor

Key Facts

- **Increased Conductor Size:** Higher line currents require thicker, more expensive conductors.
- **Higher KVA Rating of Equipment:** Transformers and alternators must be sized larger to handle the increased apparent power.
- **Greater Voltage Drop:** High currents cause excessive voltage drop (IZ) in lines, leading to poor voltage regulation.
- **Reduced Efficiency:** High copper losses directly reduce the overall efficiency of the power system.

Introduction to Power Factor Correction Capacitors

- In three-phase industrial electrical systems, power factor correction is typically achieved using capacitor banks.
- Capacitor banks supply reactive power (kVAR) to offset the inductive reactive power demanded by motors and transformers.
- The capacitors in a 3-phase bank can be connected in either a **Star (Wye)** or **Delta (Δ)** configuration.
- The choice of connection impacts the required capacitance value, the voltage rating of individual capacitors, and the overall reliability of the bank.

Capacitor Rating (kVAR)

Definition

- **Reactive Power Rating (Q_c):**
- The rating of a capacitor bank is expressed in kilo-Volt-Amperes Reactive (kVAR).
- $$Q_c = \sqrt{3} V_L I_c = 3 V_{ph} I_{ph}$$
- Where V_L is the line voltage, and I_c is the line current drawn by the capacitor bank.
- The required kVAR to improve the power factor from $\cos\phi_1$ to $\cos\phi_2$ for a real power P (kW) is:
- $$Q_c = P(\tan\phi_1 - \tan\phi_2)$$

Star vs. Delta Connection: Key Parameters

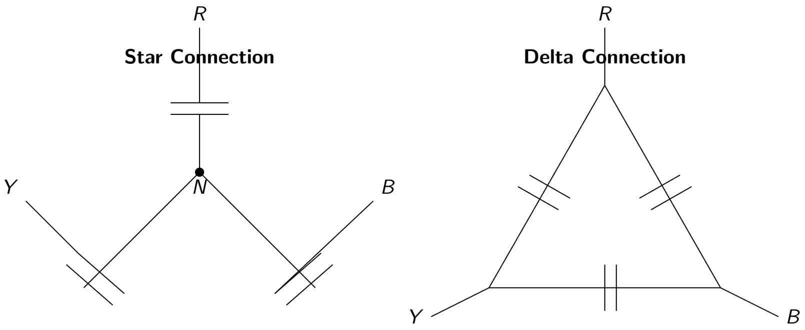
Parameter	**Star (Y) Connection**	**Delta (Δ) Connection**
Phase Voltage (V_{ph})	$V_L/\sqrt{3}$	V_L
Capacitance (C_{ph}) per phase	$3 \times C_\Delta$	$C_Y/3$
Dielectric Stress	Lower	Higher
Suitability	High Voltage ($>$ 11 kV)	Low/Medium Voltage ($\leq$ 11 kV)

Why Delta Connection is Preferred at Low Voltage

Key Facts

- For a given kVAR rating and Line Voltage (V_L), the capacitance required in a Delta connection is exactly **one-third** of the capacitance required in a Star connection.
- $$C_\Delta = \frac{C_Y}{3}$$
- Since the physical size and cost of a capacitor are directly proportional to its capacitance value, a Delta-connected bank is significantly cheaper and less bulky for low to medium voltage applications (up to roughly 11 kV).
- Additionally, if one phase fails in a Delta bank, the remaining two phases still provide partial compensation.

Circuit Diagrams: Star and Delta Banks



Mathematical Derivation of Capacitance

- Total required reactive power: Q_c. Power per phase: $Q_{ph} = \frac{Q_c}{3}$
- We know $Q_{ph} = \frac{V_{ph}^2}{X_c}$ and $X_c = \frac{1}{2\pi fC}$
- Therefore, $C = \frac{Q_{ph}}{2\pi f V_{ph}^2} = \frac{Q_c}{3 \cdot 2\pi f V_{ph}^2}$
-
- **For Star Connection:**
- $V_{ph} = \frac{V_L}{\sqrt{3}} \implies V_{ph}^2 = \frac{V_L^2}{3}$
- $C_Y = \frac{Q_c}{3 \cdot 2\pi f (V_L^2/3)} = \frac{Q_c}{2\pi f V_L^2}$
-
- **For Delta Connection:**
- $V_{ph} = V_L \implies V_{ph}^2 = V_L^2$
- $C_\Delta = \frac{Q_c}{3 \cdot 2\pi f V_L^2}$
-
- Conclusion: $C_\Delta = \frac{C_Y}{3}$

Example: Calculating Capacitor Rating

Example

- **Problem:**
- A 3-phase, 50 Hz, 400 V motor draws 50 kW at a power factor of 0.6 lagging. Calculate the phase capacitance required to improve the power factor to 0.9 lagging if the capacitors are connected in (a) Star and (b) Delta.
-
- **Solution:**
- 1. Calculate required kVAR: $\phi_1 = \cos^{-1}(0.6) = 53.13^\circ$, $\phi_2 = \cos^{-1}(0.9) = 25.84^\circ$
- $Q_c = P(\tan\phi_1 - \tan\phi_2) = 50(1.333 - 0.484) = 42.45$ kVAR
- 2. Calculate for Star (C_Y):
- $C_Y = \frac{Q_c}{2\pi f V_L^2} = \frac{42450}{2\pi \times 50 \times 400^2} = 844.5\ \mu$F per phase
- 3. Calculate for Delta (C_Δ):
- $C_\Delta = \frac{C_Y}{3} = \frac{844.5}{3} = 281.5\ \mu$F per phase

Power Factor & Current Relationship

Definition

Power Factor ($\cos\phi$) is the ratio of true power (kW) to apparent power (kVA). For a three-phase system, the load current I is given by:

$$I = \frac{P}{\sqrt{3} \cdot V \cdot \cos\phi}$$

Where:

- P = Active Power in Watts (W)
- V = Line Voltage in Volts (V)
- $\cos\phi$ = Power Factor

Key Observation: For a constant active power requirement and supply voltage, the current I is inversely proportional to the power factor. A drop in power factor directly increases the current drawn by the load.

Effect of Power Factor on Cable Size

Key Facts

Cables are sized based on their **ampacity**—the maximum current they can safely carry without exceeding thermal limits.

- **Increased Current:** Low PF increases the total current drawn from the grid.
- **Larger Cross-Sectional Area:** To carry this higher current, cables with a larger copper or aluminum cross-section are required.
- **Capital Cost:** Thicker cables significantly increase the initial capital expenditure (CAPEX) for the electrical installation.
- **Voltage Drop:** Higher currents also lead to greater voltage drops ($I \cdot Z$) along the cable, potentially violating grid codes.

Impact of PF on Current and I^2R Losses

Power Factor	Relative Current (I)	Relative I^2R Losses	Cable Size Requirement
1.00	1.00 p.u.	1.00 p.u.	Base Size
0.90	1.11 p.u.	1.23 p.u.	+11% Capacity
0.80	1.25 p.u.	1.56 p.u.	+25% Capacity
0.70	1.43 p.u.	2.04 p.u.	+43% Capacity
0.60	1.67 p.u.	2.78 p.u.	+67% Capacity

Table: Comparison at constant active power and voltage

Numerical Analysis: Cable Sizing & Current

Example

- **Problem:** An industrial facility requires 150 kW of active power at 415 V (3-phase). Compare the current drawn at 0.65 PF versus 0.95 PF.
-
- **Case 1: Uncorrected PF (0.65)**
  - $$I_1 = \frac{150,000}{\sqrt{3} \times 415 \times 0.65} = 321.1 \text{ A}$$
- Requires approx. 185 sq.mm aluminum cable.
-
- **Case 2: Corrected PF (0.95)**
  - $$I_2 = \frac{150,000}{\sqrt{3} \times 415 \times 0.95} = 219.7 \text{ A}$$
- Requires approx. 95 sq.mm aluminum cable.
-
- **Result:** Improving the PF reduces the current by **101.4 A (31.5%)**, allowing the use of a cable with half the cross-sectional area!

Energy Saving Mechanisms

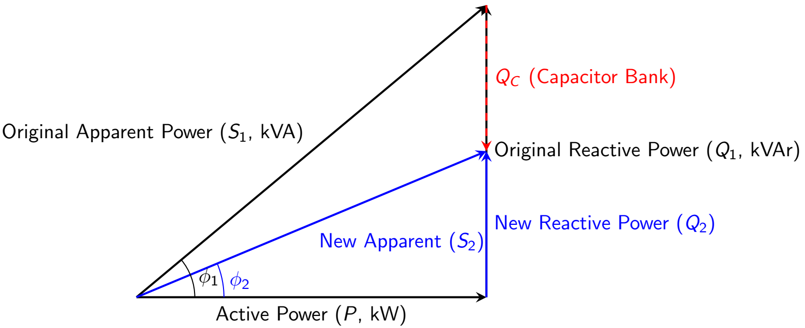
Improving power factor doesn't just save capital costs; it provides continuous energy savings (OPEX reduction).

1. **Reduction of I^2R Losses:** Active power losses in transformers and distribution cables are reduced.

$$\text{Loss Reduction } \% = 100 \times \left(1 - \left(\frac{PF_{old}}{PF_{new}}\right)^2\right)$$

2. **Avoidance of Maximum Demand Penalties:** Utilities charge industrial consumers based on maximum kVA demand. Higher PF reduces kVA ($kVA = kW/PF$), avoiding heavy tariff penalties.
3. **Increased System Capacity:** Frees up capacity on existing transformers and switchgear, delaying the need for infrastructure upgrades.

Power Triangle Visualization



Case Study: Cement Plant Optimization

Example

Background: A cement plant operated at an average load of 1200 kW with a lagging power factor of 0.72. **Initial Conditions:**

- Maximum Demand: $1200/0.72 = 1666$ kVA
- Transformer Capacity: 2000 kVA (Operated at 83% load, high thermal stress)
- Tariff Penalty: Rs. 350 per kVA above 1500 kVA.

Intervention: Installed an Automatic Power Factor Correction (APFC) panel of 600 kVAr, improving PF to 0.97. **Results & Savings:**

- New Maximum Demand: $1200/0.97 = 1237$ kVA
- Demand savings: $1666 - 1237 = 429$ kVA reduction.
- Monthly Financial Savings: 429 kVA $\times$ Rs. $350 =$ Rs. $1,50,150$ per month.
- ROI on Capacitor Bank: Less than 7 months.

4.1 Major Energy-Consuming Loads Overview

- Industrial and commercial facilities consume massive amounts of electrical and thermal energy.
- The primary consumers are categorized into five major systems:
- 1. **Electric Motors & Drive Systems**: Account for approx. 60-70
- 2. **HVAC Systems**: Major consumer in commercial spaces; involves chillers, AHUs, and cooling towers.
- 3. **Lighting Systems**: While modernized by LEDs, still substantial in large-scale floor plans.
- 4. **Air Compressors**: Often referred to as the 'fourth utility'; highly inefficient thermodynamically (only 10-15
- 5. **Distribution Transformers**: Constantly energized, contributing to continuous core losses regardless of facility output.

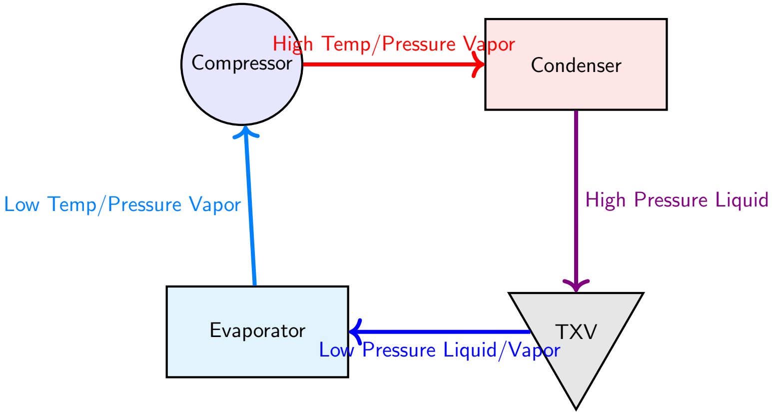
Key Facts

- Input Power: $P_{in} = \frac{\sqrt{3} \cdot V \cdot I \cdot \cos(\phi)}{\eta}$
- Motor slip (s) indicates efficiency; larger slip typically corresponds to higher I^2R rotor losses: $s = \frac{N_s - N_r}{N_s}$
- **Energy Saving Opportunities:**
- - Replacing standard motors with NEMA Premium Efficiency motors (Efficiency $\eta > 93\%$ for ¿10 HP).
- - Implementation of Variable Frequency Drives (VFDs) for variable torque loads (pumps, fans) adhering to Affinity Laws: $P \propto N^3$.

Efficiency Metrics: HVAC and Lighting

System	Metric	Typical Values/Formulas
Lighting	Luminous Efficacy	$15 - 20$ lm/W (Incand.), > 100 lm/W (LED)
Lighting	Room Cavity Ratio (RCR)	$RCR = \frac{5h(L+W)}{L \times W}$
HVAC	Coefficient of Performance (COP)	$COP = \frac{Q_c}{W_{in}}$, Typically $2.5 - 4.0$
HVAC	Energy Efficiency Ratio (EER)	$EER = 3.412 \times COP$ (Btu/W-hr)
HVAC	kW/Ton (Chillers)	$kW/Ton = \frac{12}{EER}$, Premium: < 0.60 kW/Ton

HVAC Vapor Compression Cycle Diagram



Air Compressors: Energy Dynamics

Definition

- **Compressor Specific Power:** Evaluated as kW per 100 cfm (cubic feet per minute).
- **Isentropic Work of Compression (W):**
- $W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$
- Where:
- - $P_1, P_2 =$ Absolute suction and discharge pressures
- - $V_1 =$ Volumetric flow rate
- - $n =$ Polytropic index (1.4 for adiabatic, 1.0 for isothermal)
- **Efficiency gap:** Isothermal compression is ideal (least work). Actual operation is closer to adiabatic. Cooling (intercoolers) helps bring the process closer to isothermal, saving energy.

4.2 Distribution Transformers: Losses and Efficiency

- Distribution transformers step down voltage for end-use equipment. Their efficiency is critical because they are energized 24/7.
- **Total Losses (P_{loss})** consists of:
- 1. **Core (Iron) Losses (P_i):** Hysteresis and eddy current losses. Constant independent of load. $P_i \propto V^2$.
- 2. **Copper (I^2R) Losses (P_c):** Variable losses proportional to the square of the load current.
- **Efficiency (η):**
- $\eta = \frac{x \cdot S \cdot \cos(\phi)}{x \cdot S \cdot \cos(\phi) + P_i + x^2 P_c}$
- Where x is the per-unit load (fraction of full load), and S is the transformer kVA rating.
- **Maximum Efficiency Condition:** Occurs when variable losses equal constant losses ($x^2 P_c = P_i$).
- Optimal load fraction: $x = \sqrt{\frac{P_i}{P_c}}$

Case Study: Transformer Efficiency Optimization

Example

- **Problem Statement:**
- A 500 kVA distribution transformer has constant core loss $P_i = 1.5$ kW and full-load copper loss $P_c = 6.0$ kW. It operates at 0.8 lagging power factor.
- **1. Find load at maximum efficiency (x_{max}):**
- $x_{max} = \sqrt{\frac{P_i}{P_c}} = \sqrt{\frac{1.5}{6.0}} = \sqrt{0.25} = 0.5$ (or 50
- **2. Calculate Maximum Efficiency (η_{max}):**
- Output at $x = 0.5$: $0.5 \times 500 \text{ kVA} \times 0.8 = 200$ kW
- Losses at $x = 0.5$:
  $P_i + x^2 P_c = 1.5 + (0.5)^2(6.0) = 1.5 + 1.5 = 3.0$ kW
- $\eta_{max} = \frac{200}{200+3.0} = \frac{200}{203} \approx 98.52\%$
- **Conclusion:** Replacing an oversized, under-loaded transformer to match this 50

Lecture 25: Energy Efficient Distribution Transformers

Topics Covered:

- 4.3 Energy efficient distribution transformers
- 4.4 Methods of reducing core loss and load loss

Course: Energy Conservation and Audit

What is an Energy Efficient Transformer?

Definition

- An **Energy Efficient Transformer** is a transformer designed to minimize no-load (core) and load (copper/winding) losses compared to standard designs.
-
- They typically utilize superior magnetic materials like Amorphous metal or high-grade CRGO (Cold Rolled Grain Oriented) silicon steel for the core, and higher conductivity copper for windings.

Need for Energy Efficiency in Transformers

Distribution transformers are energized 24 hours a day, 365 days a year.

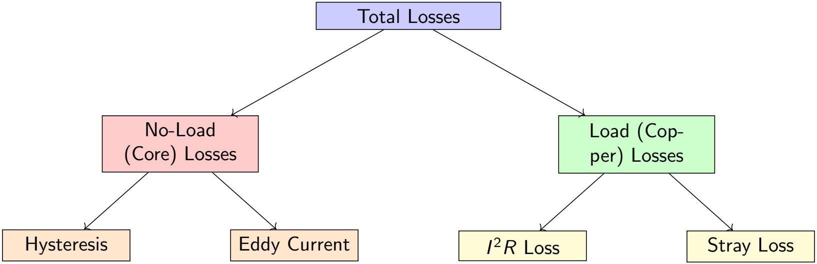
- Even a small percentage of energy loss translates to massive energy waste over its 25-30 year lifespan.
- Distribution transformers typically operate at low load factors (30% - 50%).
- Hence, no-load (core) losses dominate the total energy lost over time.

By mandating energy efficiency (like Star ratings in India by BEE), significant grid-level carbon emissions can be avoided.

Standard vs Energy Efficient Transformers

Parameter	Standard Transformer	Energy Efficient Transformer
Core Material	Standard CRGO Steel	Hi-B CRGO or Amorphous Metal
Winding Material	Aluminum or Standard Copper	High purity Copper
Losses	Higher	Up to 40-50% lower
Initial Cost	Lower	Higher (15-30% premium)
Payback Period	N/A	2 to 5 years

Classification of Transformer Losses



Understanding Core (No-Load) Losses

Key Facts

- Core losses occur continuously as long as the transformer is energized, regardless of the load.
- **Hysteresis Loss (P_h):** Caused by the continuous reversal of magnetization in the core. $P_h \propto B_{max}^{1.6} f$
- **Eddy Current Loss (P_e):** Caused by circulating currents induced in the core material. $P_e \propto B_{max}^2 f^2 t^2$
- *Where t is the thickness of the core laminations.*

Methods of Reducing Core Loss: Material Selection

1. Use of High-Grade CRGO Steel:

- Cold Rolled Grain Oriented (CRGO) steel aligns magnetic domains, reducing hysteresis loss.
- Hi-B (High permeability) CRGO offers even lower losses than conventional CRGO.

2. Use of Amorphous Metal:

- Amorphous metal has a non-crystalline structure.
- It offers extremely low hysteresis loss because domain walls move easily.
- Eddy current losses are also minimal due to extremely thin ribbons (approx. 0.025 mm compared to 0.23 mm for CRGO).

Comparison: CRGO vs Amorphous Metal Core

Property	CRGO Steel	Amorphous Metal
Structure	Crystalline	Non-crystalline (Glassy)
Lamination Thickness	0.23 mm to 0.30 mm	$\sim$ 0.025 mm
Core Loss	Base Reference	60% - 70% lower
Saturation Flux Density	1.9 - 2.0 Tesla	1.56 Tesla
Manufacturing	Standard Stacking	Wound Core (Brittle)

Methods of Reducing Core Loss: Construction Techniques

Apart from material, construction practices influence core losses:

- **Thinner Laminations:** Reduces eddy current losses ($P_e \propto t^2$).
- **Mitred Joints:** Using step-lap joints at the corners of the core reduces flux crowding and cross-fluxing, lowering localized losses and noise.
- **Annealing:** Proper annealing of core laminations relieves mechanical stress introduced during cutting and punching, restoring magnetic properties.
- **Optimal Flux Density:** Designing for a slightly lower operating flux density reduces hysteresis and eddy losses, though it increases the physical size and cost of the core.

Understanding Load (Copper) Losses

Key Facts

- Load losses vary with the square of the load current ($P \propto I^2$).
- I^2R **Losses:** Direct ohmic loss in the primary and secondary windings.
- **Stray Losses:** Eddy currents induced in the conductors, tank walls, and clamping structures due to leakage flux.
- Total Load Loss $= I^2R_{primary} + I^2R_{secondary} + P_{stray}$

Methods of Reducing Load Loss: Winding Material & Size

1. **Lower Resistance Materials:**
   - Using Copper instead of Aluminum reduces I^2R losses due to copper's higher electrical conductivity.
   - Using Oxygen-Free High Conductivity (OFHC) Copper provides slight additional efficiency gains.
2. **Increasing Cross-Sectional Area:**
   - Increasing the conductor cross-section reduces resistance ($R = \rho L/A$).
   - Trade-off: Larger conductors increase the overall size of the transformer and the mean length of turn, which can partially offset the gains and increase core size.

Methods of Reducing Load Loss: Stray and Eddy Losses

Reducing Conductor Eddy Losses:

- Use of **Continuously Transposed Conductors (CTC)**: Subdividing the winding conductor into multiple insulated strands and transposing them ensures uniform current distribution and reduces eddy currents in the winding.

Reducing Structural Stray Losses:

- Using magnetic shunts or non-magnetic steel for clamping structures and tank walls to prevent leakage flux from inducing high eddy currents in these structural parts.

Total Cost of Ownership (TCO) Approach

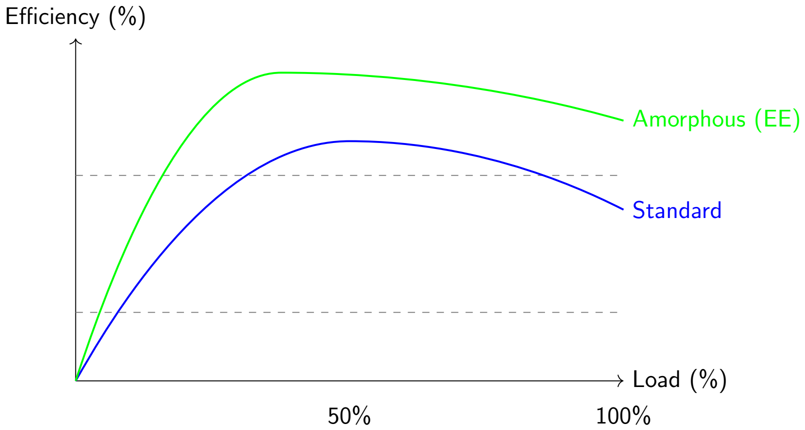
Example

When purchasing a transformer, utility companies evaluate the **Total Cost of Ownership (TCO)** or Capitalized Cost, rather than just the initial price. TCO = Initial Cost (IC) + $(A \times P_i) + (B \times P_c)$

- P_i = No-load (Iron) loss in Watts
- P_c = Load (Copper) loss in Watts
- A = Capitalization rate for no-load loss ($/Watt)
- B = Capitalization rate for load loss ($/Watt)

Note: Typically, $A > B$ because no-load losses occur 100% of the time, whereas load losses vary.

Efficiency Curve: Standard vs Energy Efficient



Conclusion

- **Energy Efficient Transformers** are vital for reducing technical losses in power distribution networks.
- **Core Loss Reduction** is achieved primarily through advanced materials like Amorphous metal or Hi-B CRGO, and using step-lap joints.
- **Load Loss Reduction** is achieved by increasing conductor cross-sections, using high-purity copper, and employing CTC to reduce eddy currents.
- While initial capital costs are higher, the **Total Cost of Ownership (TCO)** justifies the investment through rapid payback periods.

4.5 Introduction: Transformer Core Materials

- The core of a transformer is critical for minimizing energy losses (core loss).
- Two predominant materials are used for modern transformer cores:
- **1. CRGO (Cold Rolled Grain Oriented) Steel**: Traditional material with aligned crystal grains to reduce hysteresis.
- **2. Amorphous Metal**: A non-crystalline alloy structure that lacks a regular atomic structure, leading to extremely low hysteresis loss.
- Amorphous cores typically reduce no-load losses by 70-80% compared to CRGO.

4.5 Comparison: Amorphous vs. CRGO Core Material

Parameter	CRGO Steel	Amorphous Metal
Atomic Structure	Crystalline (Grain Oriented)	Non-crystalline (Random)
Thickness	$\sim$ 0.23 to 0.30 mm	$\sim$ 0.025 mm (Extremely thin)
Core Loss	Moderate (Base reference)	70% to 80% lower than CRGO
Saturation Flux Density	Higher (1.9 to 2.0 Tesla)	Lower ($\sim$ 1.56 Tesla)
Acoustic Noise	Lower	Slightly Higher
Manufacturing	Easier to cut and stack	Brittle, harder to process

4.6 Defining Liquid-Filled and Dry-Type Transformers

Definition

- **Liquid-Filled Transformer**: A transformer where the core and coils are submerged in a dielectric fluid (typically mineral oil, silicone, or synthetic esters). The fluid serves dual purposes: electrical insulation and heat dissipation.
- **Dry-Type Transformer**: A transformer whose active parts are not immersed in a liquid. Cooling occurs via natural or forced air circulation, and insulation is achieved through materials like cast resin (Cast Resin Dry Type) or VPI (Vacuum Pressure Impregnation).

4.6 Efficiency and Choice of Transformer Type

Key Facts

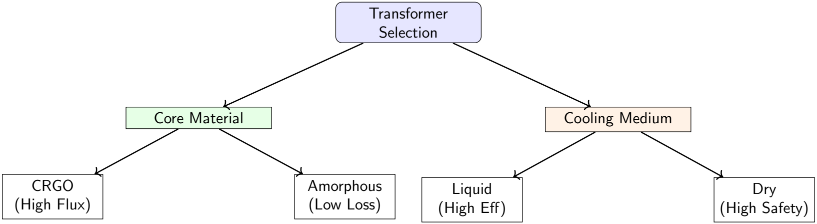
- **Liquid-Filled Efficiency**: Generally higher efficiency at all load levels compared to dry-type counterparts of the same rating. Oil is a more efficient cooling medium, allowing for closer coil packing and reduced I^2R (copper) losses.
- **Dry-Type Efficiency**: Typically have higher core and coil losses due to required design clearances for air cooling and insulation. However, they are safer for indoor use (no fire/spill risk).
- **Total Cost of Ownership (TCO)**: When evaluating efficiency, the reduced energy losses of liquid-filled must be weighed against their maintenance requirements (oil testing/leaks) versus the lower maintenance but higher running cost (due to lower efficiency) of dry-type.

Efficiency Case Study: 1000 kVA Transformer

Example

- Consider a 1000 kVA, 11 kV / 433 V transformer at 50% load:
-
- **Option A: Liquid-Filled (Mineral Oil)**
- No-Load Loss: 1.2 kW
- Load Loss (at 50%): 2.5 kW
- Total Loss: 3.7 kW
- Efficiency: $\frac{500}{500+3.7} \approx 99.26\%$
-
- **Option B: Dry-Type (Cast Resin)**
- No-Load Loss: 1.8 kW
- Load Loss (at 50%): 3.2 kW
- Total Loss: 5.0 kW
- Efficiency: $\frac{500}{500+5.0} \approx 99.01\%$
-
- **Conclusion**: Option A saves 1.3 kW continuously. Over a year (8760 hours), this is $11,388$ kWh of energy saved. However, if installed inside a commercial building, fire codes may mandate Option B regardless of the efficiency penalty.

Summary Diagram: Transformer Selection



Lecture 27: Transformer Loading & Power Factor

- Overview of today's topics:
- **4.7 Effect of loading on transformer rating**: How operating load impacts the thermal and electrical rating.
- **4.8 Reduction of load loss due to increase in power factor**: Exploring the mathematical relationship between power factor, current, and I^2R losses.

Transformer Rating and Loading

Definition

- **Transformer Rating (S):** The apparent power capability of a transformer, typically given in kVA or MVA.
- $$S = \sqrt{3} V_L I_L$$
- The rating is fundamentally limited by the maximum allowable temperature rise, which is determined by the total losses (core loss + copper loss) and the cooling system efficiency.

4.7 Effect of Loading on Transformer Rating

Transformers are often subjected to varying loads.

- **Continuous Loading:** Must not exceed nameplate rating to ensure a typical lifespan (20-30 years).
- **Cyclic Overloading:** Acceptable if the ambient temperature is low or if preceded by a period of light load.
- **Loss of Life:** Operating above rated temperature exponentially increases insulation degradation (e.g., Montsinger's rule: life halves for every 6°C rise).

4.8 The Role of Power Factor

Key Facts

- For a given active power demand P (in kW) at a constant voltage V, the load current I is inversely proportional to the power factor $\cos\phi$.
- $$I = \frac{P}{\sqrt{3}V\cos\phi}$$
- Therefore, a low power factor draws higher current for the same active power, leading to increased I^2R (copper) losses in the transformer windings.

Load Loss vs. Power Factor

Power Factor ($\cos\phi$)	**Current (pu)**	**Relative Load Loss** (I^2R **pu)**
1.0	1.00	1.00
0.9	1.11	1.23
0.8	1.25	1.56
0.7	1.43	2.04
0.6	1.67	2.78

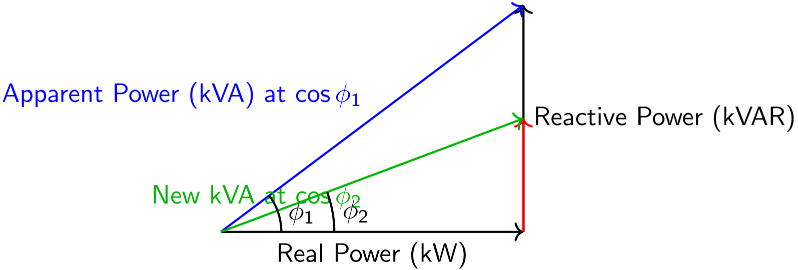
Table: Impact of decreasing power factor on current and losses for a constant kW load.

Numerical Example: Power Factor Improvement

Example

- **Problem:**
- A 500 kVA transformer supplies a 300 kW load at a power factor of 0.6 lagging. The full-load copper loss is 5 kW. Calculate the load loss. Then calculate the loss if the power factor is improved to 0.9 lagging.
- **Solution:**
- 1. Apparent power at 0.6 pf: $S_1 = 300/0.6 = 500$ kVA.
- Load is 100% of full load. Loss $= 5$ kW $\times (1.0)^2 = 5$ kW.
- 2. Apparent power at 0.9 pf: $S_2 = 300/0.9 = 333.33$ kVA.
- Loading ratio $x = 333.33/500 = 0.667$.
- New Loss $= 5$ kW $\times (0.667)^2 = 5 \times 0.444 = 2.22$ kW.
- **Conclusion:** Improving pf from 0.6 to 0.9 reduces losses by 55.6%!

Power Triangle Visualization



Improving the power factor reduces the apparent power (kVA) required for the same real power (kW), thus reducing transformer loading and losses.

Star Level of Distribution Transformer

- Bureau of Energy Efficiency (BEE) in India mandates energy performance standards for distribution transformers.
- The star rating program aims to reduce energy losses in the distribution network.
- Ratings range from 1 Star to 5 Stars, with 5 Stars being the most energy-efficient.
- Applicable for Oil type, naturally cooled, three-phase distribution transformers up to 2500 kVA.
- Higher star rating implies lower maximum allowable no-load and load losses.

Why Star Ratings Matter?

Key Facts

- Distribution transformers account for a significant portion of technical losses in power systems.
- Even a 1
- Using a 4-star or 5-star rated transformer significantly reduces the Total Cost of Ownership (TCO) over a 25-30 year lifespan.

Typical Loss Limits (e.g., 100 kVA, 11/0.433 kV)

Star Rating	Max Total Loss @ 50% Load (W)	Max Total Loss @ 100% Load (W)
1 Star	520	1800
2 Star	475	1650
3 Star	435	1500
4 Star	395	1350
5 Star	360	1200

Table: Maximum allowable losses for different star ratings (Illustrative)

Total Cost of Ownership (TCO)

Definition

Total Cost of Ownership (TCO) of a transformer is the sum of its initial purchase price and the present value of the cost of losses (iron and copper losses) incurred over its operational lifetime.
Formula:

$$TCO = IC + (A \times P_i) + (B \times P_c)$$

Where:

- IC = Initial Capital Cost of the transformer
- A = Capitalized cost of No-Load (Iron) loss per watt (Rs/W)
- P_i = Guaranteed No-Load loss (W)
- B = Capitalized cost of Load (Copper) loss per watt (Rs/W)
- P_c = Guaranteed Load loss at full load (W)

Case Study: Standard vs Star Rated Transformer

Example

Scenario: Evaluate two 100 kVA transformers. Life = 25 years. Let A = Rs 350/W, B = Rs 150/W.

Transformer X (Standard/1-Star):

- Initial Cost (IC) = Rs 1,50,000
- No-Load Loss (P_i) = 200 W
- Load Loss (P_c) = 1600 W

$$TCO_X = 1,50,000 + (350 \times 200) + (150 \times 1600) = 1,50,000 + 70,000 + 2,40,000 = \textbf{Rs 4,60,000}$$

Transformer Y (3-Star):

- Initial Cost (IC) = Rs 1,80,000
- No-Load Loss (P_i) = 150 W
- Load Loss (P_c) = 1350 W

$$TCO_Y = 1,80,000 + (350 \times 150) + (150 \times 1350) = 1,80,000 + 52,500 + 2,02,500 = \textbf{Rs 4,35,000}$$

4.11 Energy Efficient Induction Motors

- Energy Efficient Induction Motors (EEIMs) are designed to operate with significantly lower power losses compared to standard motors.
- Modifications span across electrical, magnetic, and mechanical designs.
- Key improvements include: use of thinner stator/rotor laminations, larger copper cross-sections, optimized air gap, and improved cooling fan designs.
- Result: 20-30

Loss Breakdown in Induction Motors

Key Facts

- **Stator I^2R Losses (30-40%):** Reduced by increasing conductor cross-sectional area.
- **Rotor I^2R Losses (15-20%):** Reduced by increasing rotor slot area and using die-cast copper.
- **Core Losses (15-20%):** Reduced by using high-grade silicon steel and thinner laminations.
- **Friction & Windage (5-15%):** Minimized by optimized fan design and high-quality bearings.

4.12 International Efficiency Classes (IEC 60034-30-1)

Definition

- **IE1 (Standard Efficiency):** Older technology, currently being phased out globally.
- **IE2 (High Efficiency):** Minimum standard in many developing regions.
- **IE3 (Premium Efficiency):** Current mandate in major industrial nations (EU, US).
- **IE4 (Super Premium Efficiency):** Highest efficiency class for induction motors, often utilizing advanced induction designs or PM synchronous tech.

Efficiency Comparison by IE Class (4-Pole, 50 Hz)

Motor Class	11 kW	55 kW	110 kW
IE1	87.6%	92.1%	93.3%
IE2	89.8%	93.5%	94.5%
IE3	91.4%	94.6%	95.4%
IE4	93.3%	95.7%	96.3%

Losses Reduction Diagram

Case Study: EEIM Payback Period

Example

- **Scenario:** Replacing an 11 kW IE1 motor with an IE3 motor.
- **Operating Hours:** 8,000 hrs/year at full load.
- **Energy Rate:** Rs. 8/kWh.
- **Energy Savings Formula:** $\Delta E = P \times h \times \left(\frac{1}{\eta_1} - \frac{1}{\eta_3}\right)$.
- Calculation: $11 \times 8000 \times \left(\frac{1}{0.876} - \frac{1}{0.914}\right) \approx 4175$ kWh/year.
- **Annual Cost Saving:** $4175 \times 8 =$ Rs. $33,400$.
- **Conclusion:** The premium cost of the IE3 motor is typically recovered in under 1.5 years.

Effect of Load on Motor Efficiency

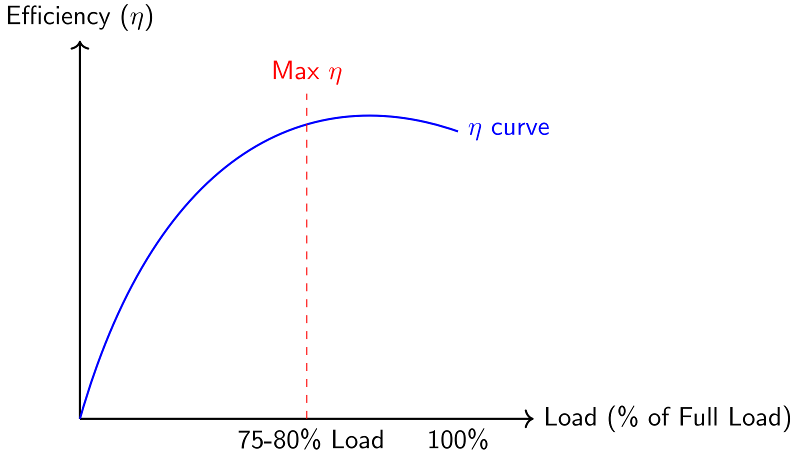
- Efficiency is the ratio of output mechanical power to input electrical power.
- $\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out}+P_{losses}}$
- At no load, efficiency is zero since output power is zero.
- As load increases, efficiency increases, reaching a maximum when variable losses equal constant losses.
- Beyond the maximum efficiency point, I^2R (copper) losses dominate, causing efficiency to decrease at heavy loads.

Effect of Power Factor on Efficiency

Key Facts

- For a given active power P and voltage V, the current I is inversely proportional to the power factor $\cos\phi$:
- $I = \frac{P}{\sqrt{3}V \cos\phi}$
- A lower power factor results in higher current drawn by the motor to deliver the same mechanical power.
- Higher current leads to increased I^2R stator and rotor copper losses.
- Conclusion: Operating at a low power factor reduces the overall efficiency of the motor.

Efficiency vs. Load Characteristics



Classification of Motor Losses

Loss Category	Type	% of Total Losses
Stator Copper Loss	Variable ($I_1^2 R_1$)	25 - 40%
Rotor Copper Loss	Variable ($I_2^2 R_2$)	15 - 25%
Iron/Core Loss	Constant (Hysteresis & Eddy)	15 - 20%
Friction & Windage	Constant (Mechanical)	5 - 15%
Stray Load Loss	Variable (Leakage flux)	10 - 15%

Methods to Minimize Core and Copper Losses

Minimizing Copper Losses (I^2R):

- Use larger cross-sectional area conductors for stator and rotor windings to reduce resistance.
- Employ high-conductivity materials like premium-grade copper instead of aluminum.

Minimizing Core/Iron Losses:

- Use thinner laminations for the stator and rotor cores to reduce eddy current losses.
- Utilize high-grade silicon steel (e.g., M400-50A) which has lower hysteresis coefficients.
- Optimize the air gap length; a smaller air gap reduces the required magnetizing current, lowering both core and stator copper losses.

Methods to Minimize Mechanical and Stray Losses

Minimizing Friction and Windage Losses:

- Use high-quality, low-friction bearings (e.g., sealed ball bearings).
- Optimize the cooling fan design. Modern energy-efficient motors use aerodynamically designed fans that consume less power while maintaining adequate airflow.

Minimizing Stray Load Losses:

- Carefully control the manufacturing process to reduce surface imperfections.
- Optimize slot geometry (e.g., skewed rotor slots) to reduce high-frequency harmonic fluxes.
- Increase the air gap uniformly, though this is a trade-off with power factor.

Efficiency and Load Example

Example

- A 3-phase, 400V, 10 kW motor operates at full load with an efficiency of 88% and a power factor of 0.85.
-
- **Calculate the full-load current and total losses:**
- Output Power $P_{out} = 10,000$ W
- Input Power $P_{in} = \frac{P_{out}}{\eta} = \frac{10{,}000}{0.88} = 11,363.6$ W
-
- **Total Losses:** $P_{in} - P_{out} = 11,363.6 - 10,000 = 1,363.6$ W
-
- **Full Load Current:**
- $I = \frac{P_{in}}{\sqrt{3}V\cos\phi} = \frac{11{,}363.6}{\sqrt{3}\times 400\times 0.85} = \frac{11{,}363.6}{588.89} \approx 19.3$ A

Lecture 31: Voltage Unbalance & Motor Performance

Topics Covered:

- 4.15 Calculate three-phase unbalance voltage
- Effect of voltage unbalance on temperature rise
- Calculation of loading of the motor
- 4.16 Performance of induction motor in Star and Delta connection during light load

What is Voltage Unbalance?

Definition

Definition: Voltage Unbalance

Three-phase voltage unbalance occurs when the phase or line voltages in a three-phase system are not equal in magnitude, or the phase angle differences between them are not exactly 120°.

Common Causes:

- Unequal distribution of single-phase loads across the three phases.
- Open delta transformer connections.
- High-impedance connections or blown fuses on one phase.

NEMA Standard for Calculating Unbalance

Key Facts

NEMA Formula

The National Electrical Manufacturers Association (NEMA) defines voltage unbalance percentage (VUR) as:

$$\%\text{ Voltage Unbalance} = \frac{\text{Maximum Deviation from Average Voltage}}{\text{Average Voltage}} \times 100$$

Steps:

1. Measure the three line-to-line voltages (V_{ab}, V_{bc}, V_{ca}).
2. Calculate the average of these three voltages.
3. Find the maximum absolute difference between any single voltage and the average voltage.

Example: Calculating Voltage Unbalance

Example

Given Line Voltages:

- $V_{ab} = 460$ V
- $V_{bc} = 467$ V
- $V_{ca} = 450$ V

Step 1: Calculate Average Voltage

$$V_{avg} = \frac{460 + 467 + 450}{3} = \frac{1377}{3} = 459 \text{ V}$$

Step 2: Find Maximum Deviation

- $|460 - 459| = 1$ V
- $|467 - 459| = 8$ V (Maximum)
- $|450 - 459| = 9$ V (Maximum)

Wait, max deviation is 9 V. **Step 3: Calculate % Unbalance**

$$\%VU = \frac{9}{459} \times 100 \approx 1.96\%$$

Symmetrical Components Approach

The IEEE definition uses the method of symmetrical components, which is more rigorous than NEMA.

$$\text{Voltage Unbalance Factor (VUF)} = \frac{|V_2|}{|V_1|} \times 100\%$$

Where:

- $V_1 =$ Positive sequence voltage magnitude
- $V_2 =$ Negative sequence voltage magnitude

Impact of Negative Sequence: The negative sequence voltage creates an air-gap flux rotating in the opposite direction to the main (positive sequence) flux. This significantly reduces net torque and increases losses.

Effect of Voltage Unbalance on Motor Performance

Even a small voltage unbalance causes a proportionally much larger current unbalance. **Rule of Thumb:**

$$\%\text{Current Unbalance} \approx (6 \text{ to } 10) \times \%\text{Voltage Unbalance}$$

Consequences:

- **Increased I^2R Losses:** Higher currents in specific phases lead to localized extreme heating.
- **Reduced Torque:** Counter-rotating torque from negative sequence field lowers net mechanical output.
- **Vibration & Noise:** Pulsating torques cause mechanical stress and acoustic noise.

Effect on Temperature Rise

Key Facts

Temperature Rise Approximation

The increase in temperature rise is approximately proportional to the square of the voltage unbalance percentage.

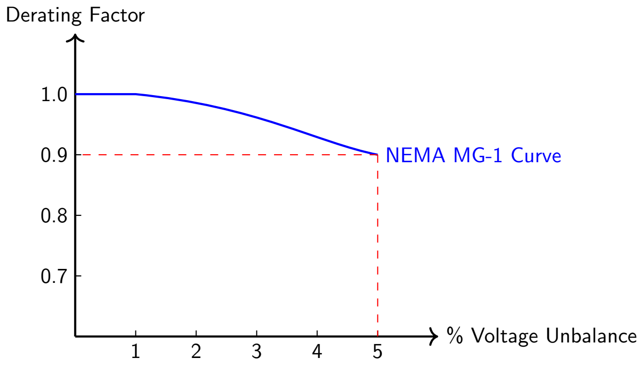
$$\Delta T_{\text{rise, \%}} \approx 2 \times (\%\text{Voltage Unbalance})^2$$

Example: For a motor with a normal temperature rise of 80°C:

- With 3% voltage unbalance:
- Additional rise $\approx 2 \times 3^2 = 18\%$
- New temperature rise $= 80 + (0.18 \times 80) = 94.4$°C

Impact: Every 10°C increase above rated temperature halves the insulation life.

NEMA Derating Curve for Voltage Unbalance



Motors should not be operated above 5% voltage unbalance.

Calculation of Loading of Motor

- To prevent overheating, the motor's effective load must be reduced (derated).
  - Safe Permissible Load = Rated HP × Derating Factor
-
- **Derating Factor (DF) Estimation (Empirical):**
  - $$DF \approx 1 - \frac{(\%VU)^2}{100}$$
- *(For Unbalance between 1% and 5%)*
-
- **Example:** For a 50 kW motor at 4% voltage unbalance:
  - $$DF \approx 1 - \frac{4^2}{100} = 1 - 0.16 = 0.84$$
  - Safe Load = 50 × 0.84 = 42 kW

Standard Derating Factors (NEMA MG-1)

% Voltage Unbalance	**Derating Factor**
$\leq 1.0\%$	1.00
2.0%	0.95
3.0%	0.88
4.0%	0.82
5.0%	0.75
$> 5.0\%$	**Operation Not Recommended**

Note: Always consult the specific manufacturer's curves if available, as modern high-efficiency motors may be more sensitive.

4.16 Performance of Induction Motor: Light Load

Characteristics of Induction Motors at Light Load:

- Induction motors are designed to operate at maximum efficiency near full load.
- At light load (e.g., $< 40\%$ of rated load), the active power required is small.
- However, the magnetizing current (reactive power) remains nearly constant regardless of load.
- **Result:** Poor power factor and poor efficiency at light loads.

To improve performance under prolonged light-load conditions, switching the stator connection from Delta to Star is a common technique.

Motor in Delta Connection (Normal Operation)

Normally, induction motors (especially above 5 HP) run in a Delta (Δ) connection.

- Phase voltage equals line voltage: $V_{phase} = V_{line}$
- Phase current: $I_{phase} = \frac{I_{line}}{\sqrt{3}}$
- The core is fully magnetized, ensuring maximum torque capability.

Drawback at Light Load: Since V_{phase} is high, core losses (which depend on voltage) and magnetizing current remain high, leading to high reactive power draw even when mechanical output is minimal.

Motor in Star Connection (Light Load Operation)

If the motor is reconnected in Star (Y) during light load:

- Phase voltage drops: $V_{phase} = \frac{V_{line}}{\sqrt{3}} \approx 57.7\%$ of V_{line}
- Phase current equals line current.
- The air-gap flux is reduced significantly.

Benefits at Light Load:

- **Core Losses Reduced:** Iron losses drop to about 1/3rd since they are proportional to V^2.
- **Magnetizing Current Reduced:** Less reactive power means improved Power Factor.
- **Efficiency Improved:** Overall losses are minimized.

Torque and Power Capability in Star

Key Facts

Capacity Reduction

In a Star connection, because the voltage is reduced by $1/\sqrt{3}$, the torque capability is reduced to 1/3 of the Delta connection.

$$T \propto V_{phase}^2 \implies T_{star} = \frac{1}{3} T_{delta}$$

Operational Constraint:

- The Star connection can ONLY be used if the mechanical load is less than approximately 30% to 33% of the rated full load.
- If the load increases while in Star, the motor will draw excessive current, stall, or overheat.
- Automatic Star-Delta starters/switches are used to revert to Delta as load increases.

Summary

Voltage Unbalance:

- Defined by NEMA as max deviation from average divided by average.
- Causes severe current unbalance and extreme temperature rise.
- Motors must be derated according to NEMA curves if unbalance exceeds 1%.

Light Load Performance (Star vs Delta):

- Delta connection at light load has poor efficiency and PF due to high constant losses.
- Switching to Star reduces phase voltage, cutting core losses and magnetizing current.
- Star operation improves efficiency but limits torque capacity to 33%.

Lecture 32: Motors and Power Factor

- Welcome to Lecture 32.
- Today we will cover two main topics:
- 1. Case study of payback period for energy efficient motors.
- 2. Selection of proper capacitor bank for power factor improvement.

Energy Efficient Motors (EEM)

Definition

Energy Efficient Motor (EEM): A motor designed to minimize electrical and mechanical losses, typically operating at 2-8% higher efficiency than standard motors. Features include:

- Better quality core materials (thinner laminations).
- Increased copper in stator windings.
- Optimized air gap and improved fan design.

Why Replace Standard Motors?

Key Facts

- Motor systems consume about **70%** of total industrial electricity.
- Even a **1% to 3%** improvement in efficiency can lead to massive cost savings over the motor's lifespan.
- Standard motors lose efficiency over time due to rewinding and wear.

Understanding Simple Payback Period (SPP)

- **Simple Payback Period (SPP):**
- The time required to recover the initial investment through energy savings.
  - $$SPP = \frac{\text{Incremental Capital Cost}}{\text{Annual Savings}}$$
- For motor replacement:
  - Savings = kW saved × Operating Hours × Energy Cost

Case Study: Motor Replacement Data

Example

- **Existing Standard Motor:**
- Rating: 22 kW (30 HP)
- Efficiency: 88%
- **Proposed Energy Efficient Motor (EEM):**
- Efficiency: 93%
- **Operating Parameters:**
- Operating hours: 6000 hrs/year
- Energy Cost: Rs. 8 per kWh
- Cost of new EEM: Rs. 65,000

Case Study: Energy Savings Calculation

Example

- Input power of Standard Motor $= 22/0.88 = 25.0$ kW
- Input power of EEM $= 22/0.93 = 23.65$ kW
- Power Saved $= 25.0 - 23.65 = 1.35$ kW
- Annual Energy Saved $= 1.35$ kW $\times$ 6000 hrs $= 8100$ kWh/year
- Annual Cost Savings $= 8100 \times 8 =$ Rs. $64,800$

Case Study: Payback Period Calculation

Example

- Investment for EEM = Rs. 65,000
- Annual Cost Savings = Rs. 64,800
- $$SPP = \frac{65,000}{64,800} = 1.003 \text{ years}$$
- **Conclusion:**
- The payback period is approximately **12 months**. The investment is highly attractive and recommended.

Power Factor (PF) Basics

Definition

Power Factor ($\cos\phi$): The ratio of Active Power (kW) to Apparent Power (kVA).

$$PF = \frac{kW}{kVA} = \cos\phi$$

Where:

- **kW** = Useful working power
- **kVAR** = Reactive power (creates magnetic fields)
- **kVA** = Total supplied power

Effects of Low Power Factor

Key Facts

Disadvantages of low PF:

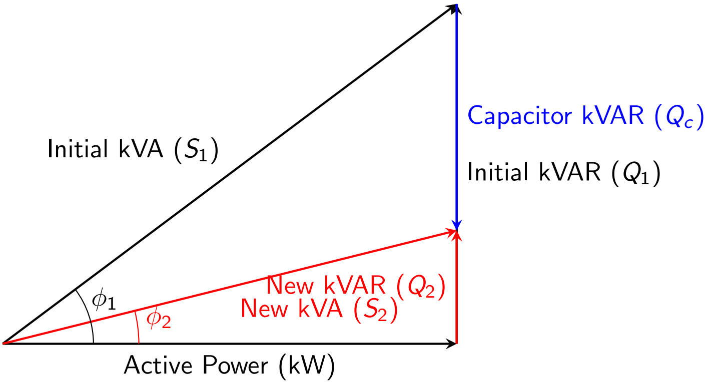
- Increased I^2R (copper) losses in cables and transformers.
- Poor voltage regulation.
- Higher kVA demand charges from utility companies.
- Reduced capacity of the electrical system.

Utilities often impose penalties for PF below a certain threshold (e.g., 0.9).

Power Factor Improvement

- How to improve PF?
- By adding components that draw leading reactive power to cancel out the lagging reactive power drawn by inductive loads (motors, transformers).
- **Common Methods:**
- 1. Static Capacitors (Capacitor Banks) - Most common
- 2. Synchronous Condensers
- 3. Phase Advancers

Power Triangle and PF Correction



Calculation of Capacitor Bank Rating

The required rating of the capacitor bank (Q_c) to improve power factor from $\cos\phi_1$ to $\cos\phi_2$ is given by:

$$Q_c = P(\tan\phi_1 - \tan\phi_2)$$

Where:

- Q_c = Required capacitor rating in kVAR
- P = Active power in kW
- ϕ_1 = Initial power factor angle
- ϕ_2 = Target power factor angle

Multiplying Factors for Capacitor Sizing

Initial PF	Target PF 0.95	Target PF 0.98	Target PF 1.0
0.70	0.691	0.817	1.020
0.75	0.553	0.679	0.882
0.80	0.421	0.547	0.750
0.85	0.291	0.417	0.620

Table: kVAR per kW of Load (*k* factor)

Example: Sizing a Capacitor Bank

Example

- **Problem:**
- A 500 kW industrial load operates at a power factor of 0.75 lagging. Determine the capacitor bank rating required to improve the PF to 0.98 lagging.
- **Solution:**
- 1. Find angles: $\phi_1 = \cos^{-1}(0.75) = 41.41^\circ$, $\phi_2 = \cos^{-1}(0.98) = 11.48^\circ$
- 2. Calculate $\tan\phi_1 = 0.8819$ and $\tan\phi_2 = 0.2031$
- 3. Use formula: $Q_c = 500(0.8819 - 0.2031) = 500(0.6788) = 339.4$ kVAR.
- Select a standard capacitor bank of **350 kVAR**.

Selection of Proper Capacitor Bank

Key considerations when selecting a capacitor bank:

- **Location:** Individual motor correction, group correction, or central correction at the main panel.
- **Harmonics:** Presence of non-linear loads (VFDs) may require detuned reactors to prevent resonance.
- **Automatic Power Factor Correction (APFC):** Use APFC panels for fluctuating loads to automatically switch capacitor steps in/out.
- **Discharge Resistors:** Essential for safety to discharge capacitors when disconnected.

4.19 Methods of Load Survey Methodology

A load survey is systematically collecting and analyzing electrical energy consumption data. **Key Objectives:**

- Understand consumer load profiles and peak demand periods.
- Identify opportunities for energy conservation and demand-side management (DSM).
- Forecast future energy demands for capacity planning.

The methodology comprises three main stages: **Sampling, Measurement, and Analysis**.

Stage 1: Sampling in Load Surveys

Definition

Sampling Methodology Because it is impractical to measure every single consumer, statistical sampling is used to select a representative subset of the population.

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vspace1em **Common Sampling Techniques:**

- **Stratified Random Sampling:** Consumers are divided into homogeneous subgroups (strata) like residential, commercial, and industrial, before sampling.
- **Cluster Sampling:** Geographic or feeder-based grouping.
- **Systematic Sampling:** Selecting every k^{th} consumer from a list.

Stage 2: Measurement Techniques

Instrument	Application	Accuracy
Smart Meters (AMI)	Continuous recording of real-time kW, $kVAr$, and kWh.	High (Class 0.2s or 0.5s)
Portable Data Loggers	Temporary measurement for specific equipment or feeders.	Medium to High
Clamp-on Power Meters	Spot measurements during walk-through energy audits.	Medium

Table: Load Survey Measurement Tools

Stage 3: Load Survey Analysis Example

Example

Analysis of Load Data Analysis involves calculating load factor, diversity factor, and identifying peak periods. **Case Study: Industrial Plant**

- Maximum Demand (MD): 500 kW
- Energy Consumed in 24 hours: 7200 kWh
- Load Factor $(LF) = \frac{\text{Energy Consumed}}{MD \times 24}$
- $LF = \frac{7200}{500 \times 24} = \frac{7200}{12000} = 0.6$ or 60%

Inference: A 60% load factor indicates room for demand response or peak shaving.

4.20 Lighting System Principles

Lighting constitutes a significant portion of commercial and industrial energy consumption (typically 15-20**Key Lighting Terminologies:**

- **Luminous Flux (Lumens):** Total light emitted by a source.
- **Illuminance (Lux):** Luminous flux incident per unit area (1 Lux $= 1$ Lumen$/m^2$).
- **Luminous Efficacy (lm/W):** Efficiency of the lamp in converting electrical power to light.
- **Color Rendering Index (CRI):** Ability of light to reproduce true colors.

Energy Efficient Lighting Technologies

Key Facts

Evolution of Lighting Efficacy The shift towards solid-state lighting has drastically improved energy efficiency in building systems.

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vspace1em **Efficacy Comparison Fact Sheet:**

- **Incandescent Lamps:** $10 - 15$ lm/W (Highly inefficient, 90% energy lost as heat)
- **Fluorescent Tubes (T5/T8):** $60 - 100$ lm/W
- **LED (Light Emitting Diodes):** $100 - 150+$ lm/W (Longest lifespan, highly directional)
- **High-Pressure Sodium (HPSV):** $90 - 130$ lm/W (Used mainly for street lighting due to poor CRI)

Lighting Control Strategies

Automated controls can reduce lighting energy consumption by up to 40%.

Lecture 34: Lighting Fundamentals

- Welcome to Lecture 34.
- Topics Covered:
- 4.21 Relation between watt and lumens
- 4.22 Terminology: luminous flux, Illuminance, inverse square law, luminous efficacy, colour rendering index

What is a Watt?

Definition

- Watt (W) is the SI unit of power.
- In the context of lighting, it refers to the electrical power consumed by a light source.
- $$P = V \times I$$
- Historically, wattage was used to gauge brightness for incandescent bulbs, but it measures energy consumption, not light output.

What is a Lumen?

Definition

- Lumen (lm) is the SI derived unit of luminous flux.
- It measures the total quantity of visible light emitted by a source per unit of time.
- $$\Phi_V$$
  is the symbol for luminous flux.
- 1 lumen is defined as the luminous flux emitted within a unit solid angle (1 steradian) by an isotropic point source with a luminous intensity of 1 candela.

Relation Between Watt and Lumens

Watts and lumens measure different things: power vs. perceived light. There is no direct conversion between watts and lumens without knowing the luminous efficacy of the specific light source. For a typical incandescent bulb:

- 40W $\approx$ 450 lumens
- 60W $\approx$ 800 lumens
- 100W $\approx$ 1600 lumens

Modern LEDs can produce 800 lumens using only 9W-10W of power.

Terminology: Luminous Flux

Definition

- Luminous Flux (Φ_v): The rate of flow of visible light energy from a source.
- It is adjusted to reflect the varying sensitivity of the human eye to different wavelengths of light.
- Unit: Lumen (lm)
- It is evaluated using the luminosity function $V(\lambda)$.

Terminology: Illuminance

Definition

- Illuminance (E): The total luminous flux incident on a surface, per unit area.
- Unit: Lux (lx) or lumens per square meter (lm/m^2).
- $$E = \frac{\Phi_v}{A}$$
- Where Φ_v is luminous flux and A is area.
- 1 Lux is the illumination produced by 1 lumen of flux falling on an area of 1 square meter.

Inverse Square Law of Illuminance

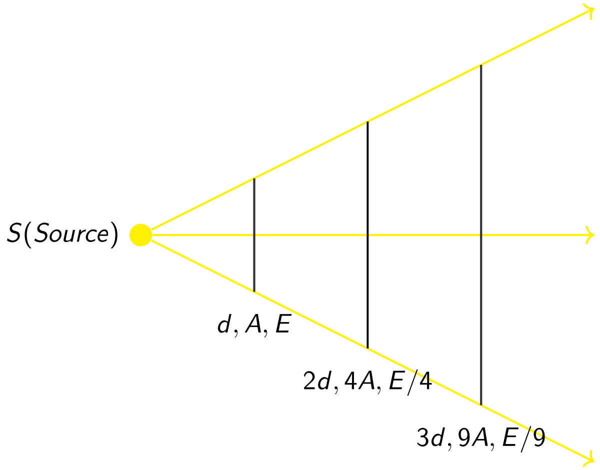
The Inverse Square Law states that the illuminance (E) at a point on a surface is inversely proportional to the square of the distance (d) from a point light source. Assumption: The light source must be a point source, and the surface must be perpendicular to the light rays.

$$E = \frac{I}{d^2}$$

Where:

- E is Illuminance (lux)
- I is Luminous Intensity (candela)
- d is Distance from the source (meters)

Inverse Square Law - Diagram



Example: Inverse Square Law

Example

- A point light source has a luminous intensity of 1000 candela in all directions.
- Calculate the illuminance at a distance of 2 meters and 4 meters.
-
- **At 2 meters:**
  - $$E_1 = \frac{1000}{2^2} = \frac{1000}{4} = 250 \text{ lux}$$
-
- **At 4 meters:**
  - $$E_2 = \frac{1000}{4^2} = \frac{1000}{16} = 62.5 \text{ lux}$$
- Notice that E_2 is $E_1/4$ because distance is doubled.

Terminology: Luminous Efficacy

Definition

- Luminous Efficacy (η): A measure of how well a light source produces visible light.
- It is the ratio of luminous flux to power.
- Unit: Lumens per Watt (lm/W).
- $$\eta = \frac{\Phi_v}{P}$$
- Where Φ_v is luminous flux (lumens) and P is electrical power (watts).

Typical Luminous Efficacy Values

Light Source	Luminous Efficacy (lm/W)
Incandescent bulb	10 - 17
Halogen lamp	16 - 24
Compact Fluorescent (CFL)	50 - 70
Linear Fluorescent Tube	70 - 100
LED	80 - 150+
Low Pressure Sodium	Up to 200

Maximum Possible Efficacy

Key Facts

- The theoretical maximum luminous efficacy is 683 lm/W.
- This would only be achieved by a light source that perfectly converts all electrical energy into monochromatic green light at exactly 555 nanometers.
- At 555 nm, the human eye has its peak sensitivity.

Terminology: Colour Rendering Index (CRI)

Definition

- Colour Rendering Index (CRI): A quantitative measure of the ability of a light source to reveal the colors of various objects faithfully.
- It is compared against an ideal or natural light source (like sunlight).
- Scale: 0 to 100.
- A higher CRI (usually ¿ 80) indicates better color rendering.

Significance of CRI

- **CRI 100:** Sunlight, incandescent lamps (perfect color rendering, but low efficacy).
- **CRI 80-90:** High-quality LEDs, suitable for most indoor applications, homes, and offices.
- **CRI ¡ 70:** Street lights (e.g., sodium vapor lamps) where color recognition is less important than efficiency.

Trade-off: Sometimes, achieving higher CRI means sacrificing some luminous efficacy.

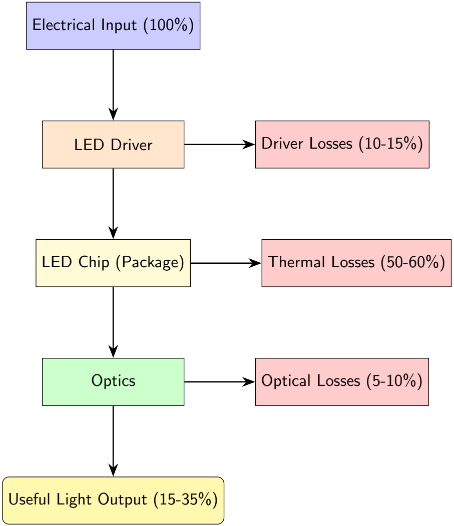
Summary of Key Terms

- **Watt (W):** Electrical power input.
- **Lumen (lm):** Total visible light output.
- **Lux (lx):** Illuminance, light on a surface (lm/m^2).
- **Luminous Efficacy (lm/W):** Efficiency of light production.
- **Inverse Square Law:** $E = I/d^2$.
- **CRI:** Color accuracy (0-100 scale).

4.23 Working Principle of LED

- A Light Emitting Diode (LED) is a semiconductor light source that emits light when current flows through it.
- Electrons in the semiconductor recombine with electron holes, releasing energy in the form of photons (electroluminescence).
- The color of the light (corresponding to the energy of the photons) is determined by the energy required for electrons to cross the band gap of the semiconductor.
- The wavelength of emitted light is given by Planck's equation: $\lambda = \frac{hc}{E_g}$
- Where h is Planck's constant ($6.626 \times 10^{-34} J \cdot s$), c is the speed of light, and E_g is the band gap energy in Joules.

Energy Flow Diagram of an LED System



Electronic Ballast vs. Magnetic Ballast

Parameter	**Electronic Ballast**	**Magnetic Ballast**
Operating Frequency	High (20 kHz to 60 kHz)	Low (50 Hz or 60 Hz)
Efficiency	High (lower internal losses)	Lower (higher I^2R and core losses)
Flicker Effect	Almost zero (due to high freq)	Noticeable stroboscopic effect
Weight & Size	Compact and lightweight	Heavy and bulky (contains iron core/copper)
Power Factor	High (typically > 0.95)	Low (requires capacitor for correction)

4.24 Lighting Design: Key Parameters

Definition

- **Light Reflectance Value (LRV):** A measure of the percentage of visible and usable light that is reflected from a surface when illuminated. Scale is 0 (absolute black) to 100 (pure white).
- **Room Index (RI):** A ratio describing the geometry of a room, used to determine the Utilization Factor. It is calculated as:
- $$RI = \frac{L \times W}{H_m \times (L + W)}$$
- Where L is length, W is width, and H_m is the mounting height of the luminaire above the working plane.
- **Utilization Factor (UF):** The ratio of the total luminous flux reaching the working plane to the total luminous flux emitted by the lamps. It depends on RI, LRV of walls/ceiling, and the luminaire type.

Lumen Method: Number of Light Fittings

Key Facts

- To design a lighting layout, the total number of fixtures (N) required to achieve a desired average illuminance (E, in Lux) on a working plane is calculated using the Lumen Method formula:
- $$N = \frac{E \times A}{\phi \times UF \times MF}$$
- Where:
- • E = Required average illuminance (Lux or lm/m^2)
- • A = Area of the working plane (m^2)
- • ϕ = Initial luminous flux of one luminaire (Lumens)
- • UF = Utilization Factor
- • MF = Maintenance Factor (accounts for dust and lumen depreciation over time, typically 0.7 - 0.8)
-
- **Spacing Rule:** The maximum distance between two fixtures should not exceed $1.5 \times H_m$ (mounting height) to ensure uniform illumination.

Case Study: Classroom Lighting Design (Part 1)

Example

- **Problem Statement:** Design the lighting for a classroom with dimensions $12m \times 8m$. The ceiling height is $3.5m$ and the working plane (desk level) is $0.8m$ above the floor.
- **Given Data:**
- • Required Illuminance (E): 300 Lux (standard for classrooms)
- • Luminaire output (LED panel, ϕ): 3200 Lumens
- • Maintenance Factor (MF): 0.8
- • Utilization Factor (UF): 0.6
-
- **Step 1: Calculate Mounting Height (H_m)**
- $H_m = \text{Ceiling Height} - \text{Working Plane Height} = 3.5m - 0.8m = 2.7m$
- **Step 2: Calculate Room Index (RI)**
- $$RI = \frac{12 \times 8}{2.7 \times (12 + 8)} = \frac{96}{54} \approx 1.77$$

Case Study: Classroom Lighting Design (Part 2)

- **Step 3: Calculate Number of Fixtures (N)**
- $$N = \frac{E \times A}{\phi \times UF \times MF}$$
- $N = \frac{300 \times (12 \times 8)}{3200 \times 0.6 \times 0.8} = \frac{28800}{1536} = 18.75$
- We round up to ensure the minimum lux level is met. Let's use **20 fixtures** to allow for a symmetric grid.
-
- **Step 4: Layout and Spacing**
- Arrange the 20 fixtures in a 5×4 grid.
- • Spacing along length (12m): $\frac{12}{5} = 2.4m$ apart.
- • Spacing along width (8m): $\frac{8}{4} = 2.0m$ apart.
- **Check uniformity rule:** Max spacing is $2.4m$. Allowed max spacing is $1.5 \times H_m = 1.5 \times 2.7 = 4.05m$. Since $2.4m < 4.05m$, the layout is highly uniform.

Lecture 36: Lighting Replacement & Distribution System

Welcome to Lecture 36. Topics Covered:

- 4.25 Replacement of Fluorescent Tube Light (FTL) by LED
- Energy Saving & Payback Period
- Practical Case Study
- 4.26 Distribution System Overview

Fluorescent Tube Light (FTL) vs LED

Key Facts

- **Fluorescent Tube Light (FTL)**:
- Traditional 40W FTL with a magnetic ballast consumes about 50W-55W total.
- Lifespan: 5,000 to 10,000 hours.
-
- **Light Emitting Diode (LED)**:
- Modern 18W or 20W LED tube provides equivalent or better lumens.
- Lifespan: 30,000 to 50,000 hours.
- Contains no toxic mercury, unlike FTLs.

Energy Saving and Payback Period

Definition

- **Energy Saving**:
- The reduction in electrical energy consumption achieved by switching to a more efficient appliance.
- Energy Saved (kWh) $= \frac{(\text{Power}_{old} - \text{Power}_{new}) \times \text{Operating Hours}}{1000}$
-
- **Payback Period**:
- The time required to recover the initial investment through energy savings.
- Payback Period (years) $= \frac{\text{Initial Investment Cost}}{\text{Annual Savings}}$

Case Study: Office Building Setup

Example

Scenario: An office building currently uses 500 conventional 40W FTLs (with 12W magnetic ballast).

- Total power per FTL = 52W
- Proposed LED replacement = 18W
- Operating hours = 10 hours/day, 300 days/year
- Electricity Tariff = Rs. 8 per kWh
- Cost of one 18W LED tube = Rs. 300

Case Study: Energy Consumption (FTL vs LED)

- **Current FTL Consumption**:
- Annual Energy $= 500 \times 52W \times 3000h/1000 = 78,000$ kWh/year
- Annual Cost $= 78,000 \times 8 =$ Rs. $6,24,000$
-
- **Proposed LED Consumption**:
- Annual Energy $= 500 \times 18W \times 3000h/1000 = 27,000$ kWh/year
- Annual Cost $= 27,000 \times 8 =$ Rs. $2,16,000$

Case Study: Savings & Payback Period

- **Savings Calculation**:
- Annual Energy Savings $= 78,000 - 27,000 = 51,000$ kWh
- Annual Cost Savings $= 6,24,000 - 2,16,000 =$ Rs. $4,08,000$
-
- **Investment & Payback**:
- Total Investment $= 500 \times$ Rs. $300 =$ Rs. $1,50,000$
- Payback Period $= \frac{1,50,000}{4,08,000} = 0.367$ years
- ≈ 4.4 months

Comparison Summary Table

Parameter	40W FTL	18W LED
Power Consumed (with ballast)	52 W	18 W
Luminous Efficacy	60 lm/W	100 lm/W
Lifespan	10,000 hrs	50,000 hrs
Annual Operating Cost (500 units)	Rs. 6.24 Lakh	Rs. 2.16 Lakh

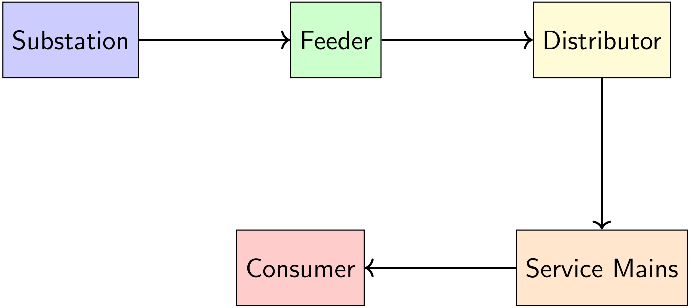
4.26 Distribution System: Introduction

What is a Distribution System? That part of power system which distributes electric power for local use. It connects the transmission network to individual consumers.

Key Components:

- **Distribution Substation**: Steps down voltage (e.g., 66kV to 11kV).
- **Feeders**: Conductors connecting substation to distribution transformers.
- **Distributors**: Conductors from which tappings are taken for consumers.
- **Service Mains**: Small cables connecting distributor to consumer meter.

Distribution System Components Diagram



Classification of Distribution Systems

Distribution systems can be classified based on:

1. **Nature of Current**: AC Distribution, DC Distribution
2. **Type of Construction**: Overhead System, Underground System
3. **Scheme of Connection**: Radial, Ring Main, Interconnected

AC vs DC Distribution

Key Facts

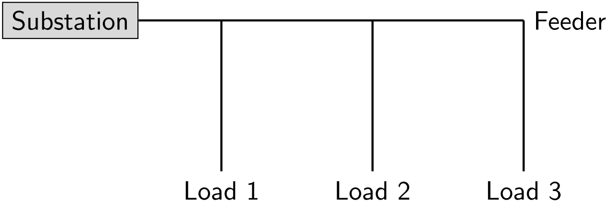
- **AC Distribution**:
- Universally adopted.
- Allows easy voltage step-up/step-down using transformers.
- Primary Distribution: Typically 11 kV or 33 kV.
- Secondary Distribution: 415 V (3-phase) or 240 V (1-phase).
-
- **DC Distribution**:
- Rarely used today except for specific applications (e.g., traction, data centers).
- No skin effect or reactive voltage drop.

Radial Distribution System

Definition

- **Definition**: A system where a separate feeder radiates from a single substation and feeds distributors at one end only.
- **Advantages**:
- - Simplest and cheapest.
- - Easy to plan and calculate.
- **Disadvantages**:
- - Low reliability (a fault on the feeder cuts power to all connected consumers).
- - Voltage fluctuations are high at the far end.

Radial System Layout



Ring Main Distribution System

Definition

- **Definition**: The primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation.
- **Advantages**:
- - Higher reliability (two paths for power to reach any distributor).
- - Less voltage fluctuation at consumer terminals.
- **Disadvantages**:
- - More complex and expensive than radial systems.

Lecture Summary

- Replacing FTLs with LEDs significantly reduces energy consumption (often by ¿50
- Payback periods for such replacements are usually very short, making them economically viable.
- The distribution system delivers power from substations to consumers.
- Key components: Substations, Feeders, Distributors, Service Mains.
- AC Distribution is universally preferred.
- Ring Main systems offer better reliability than Radial systems.

Lecture 37: Energy Loss in Power Systems

Topics Covered:

- 4.27 Methods to determine energy loss
- Direct method
- Indirect method
- 4.28 Causes of technical losses
- Measures to reduce technical losses

What is Energy Loss?

Definition

- Energy loss in a power system refers to the electrical energy that is generated but not successfully delivered to the end consumers.
- It is primarily categorized into **Technical Losses** (physical properties of equipment) and **Non-Technical Losses** (theft, unmetered supply).

4.27 Methods to Determine Energy Loss

There are two primary methods used by utilities to determine the exact amount of energy lost in the distribution network:

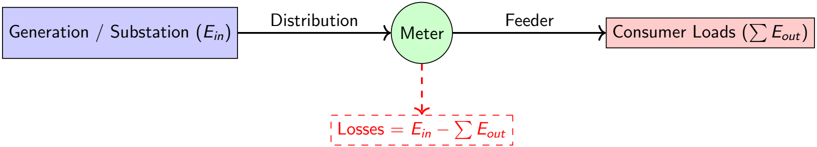
1. **Direct Method:** Based on actual metering at different nodes.
2. **Indirect Method:** Based on estimation and statistical calculations.

Direct Method of Determining Loss

Key Facts

- The Direct Method involves calculating the difference between the total energy injected into a network and the total energy billed to consumers.
  - $\text{Energy Loss (Direct)} = E_{injected} - \sum E_{billed}$
- Requires 100% metering at feeders, distribution transformers, and consumer premises.

Direct Method Visualization



Indirect Method of Determining Loss

The Indirect Method is used when 100% metering is not feasible. It relies on:

- Load flow studies and software simulations.
- Load factors, loss load factors (LLF), and peak demand.
- Statistical sampling of specific feeder segments.

Often calculates technical losses first, then deduces non-technical losses.

Loss Load Factor (LLF)

Key Facts

- The Loss Load Factor is crucial in the indirect method to estimate average energy loss from peak power loss.
  - $\text{LLF} = K \times (\text{Load Factor}) + (1 - K) \times (\text{Load Factor})^2$
- Where K is typically between 0.15 and 0.3 for distribution systems.

Direct vs. Indirect Method

Feature	Direct Method	Indirect Method
Accuracy	High (if metering is perfect)	Moderate (depends on data/models)
Cost	High (requires smart meters)	Low (software based)
Data Required	Billing data, Feeder meters	Network topology, Load curves
Suitability	Modern, smart grids	Legacy, unmetered grids

4.28 Causes of Technical Losses

Technical losses are inherent physical losses that occur during the transmission and distribution of electricity. **Primary Causes:**

- I^2R (Copper) losses in conductors and transformers.
- Dielectric and Corona losses in high voltage lines.
- Magnetic (Iron/Core) losses in transformers.
- Poor joints and connections increasing contact resistance.
- Overloading of lines and transformers.

The Impact of Low Power Factor

Key Facts

- A low power factor (PF) significantly increases technical losses.
- For a given real power demand (P), the current (I) drawn is:
- $$I = \frac{P}{\sqrt{3} V \cos\phi}$$
- Since loss $\propto I^2$, a lower $\cos\phi$ (power factor) drastically increases the $I^2 R$ losses.

Other Technical Loss Factors

- **Unbalanced Phase Loads:** Causes neutral currents, increasing overall line losses.
- **Undersized Conductors:** High resistance ($R = \rho L/A$) leads to higher heating.
- **Lengthy Distribution Lines:** Increases the total resistance of the circuit.
- **Aging Equipment:** Degradation of insulation and magnetic cores.

Measures to Reduce Technical Losses

Engineering interventions can optimize the network and reduce physical losses:

1. **Network Reconfiguration:** Shortening lengthy LT lines.
2. **Conductor Upgrading:** Replacing undersized wires with thicker conductors.
3. **High Voltage Distribution System (HVDS):** Extending HT lines closer to loads.
4. **Reactive Power Compensation:** Installing shunt capacitors.

High Voltage Distribution System (HVDS)

Definition

- HVDS involves restructuring the network to minimize Low Tension (LT) lines.
- Instead of a large transformer serving many loads via long LT lines, HVDS uses smaller capacity transformers located very close to the consumer clusters.
- **Benefit:** Because HT lines operate at higher voltages, the current is lower, reducing I^2R losses drastically.

Example: Loss Reduction via Capacitor Bank

Example

- **Given:**
- A feeder carries 1000 kW at a power factor of 0.707. Line resistance is 1 Ω. Voltage is 11 kV.
- **Current without compensation:** $I = \frac{1000}{\sqrt{3} \times 11 \times 0.707} \approx 74.2$ A
- **Losses:** $3 \times I^2 \times R = 3 \times 74.2^2 \times 1 = 16.5$ kW
- **With compensation (PF = 0.95):**
- Current $I_{new} = \frac{1000}{\sqrt{3} \times 11 \times 0.95} \approx 55.2$ A
- **New Losses:** $3 \times 55.2^2 \times 1 = 9.1$ kW (45% reduction!)

Summary

- **Direct method:** Uses metering data to find Exact Loss = In - Out.
- **Indirect method:** Uses models, LLF, and statistics to estimate losses.
- **Technical losses** are primarily I^2R and transformer core losses.
- **Mitigation:** HVDS, phase balancing, capacitor banks, and optimal conductor sizing.

4.29 Introduction to Commercial Losses

Definition

Commercial Losses (also known as Non-Technical Losses) are the portion of electrical energy that is generated and distributed but not billed or collected.

Unlike technical losses (which occur due to physical properties of the power system components like I^2R heating), commercial losses are strictly related to revenue realization shortfalls.

Key Attributes:

- Directly impact the financial viability of distribution companies (DISCOMs).
- Originate primarily at the retail distribution level.
- Are completely avoidable with stringent administrative and technological measures.

Major Causes of Commercial Losses

Several systemic and administrative loopholes contribute to commercial losses:

- **Electricity Theft:** Direct hooking from distribution lines (L.T. lines) bypassing the meter.
- **Meter Tampering:** Intentional damaging of meter seals, magnetic interference, or altering current transformers (CT) ratios.
- **Defective Meters:** Sluggish or stopped meters that under-record energy consumption.
- **Unmetered Supply:** Flat-rate billing for agricultural pumps or unauthorized slum connections.
- **Billing Errors:** Inaccurate meter readings, delayed billing cycles, and data entry mistakes.
- **Poor Collection Efficiency:** Failure to recover billed amounts, accumulating arrears, and bad debts.

Calculation of AT\&C Losses

Example

- Aggregate Technical and Commercial (AT&C) loss is the standard metric used in India to measure overall DISCOM efficiency.
-
- **Step 1: Billing Efficiency**
  - $$\text{Billing Efficiency} = \left(\frac{\text{Total Energy Billed (kWh)}}{\text{Total Energy Input (kWh)}}\right) \times 100$$
-
- **Step 2: Collection Efficiency**
  - $$\text{Collection Efficiency} = \left(\frac{\text{Total Revenue Collected (Rs)}}{\text{Total Amount Billed (Rs)}}\right) \times 100$$
-
- **Step 3: AT&C Loss Formula**
  - $$\text{AT and C Loss (\%)} = \left[1 - \left(\frac{\text{Billing Efficiency} \times \text{Collection Efficiency}}{10000}\right)\right] \times 100$$
-
- *Example:* If a DISCOM has a Billing Efficiency of 85% and a Collection Efficiency of 90%, the AT&C Loss is:
  - $$[1 - (0.85 \times 0.90)] \times 100 = [1 - 0.765] \times 100 = 23.5\%$$

Measures to Reduce Commercial Losses

Mitigating commercial losses requires a combination of technology, strict vigilance, and legal frameworks:

1. **Technological Interventions:**
   - Replacement of bare conductors with Aerial Bunched Cables (ABC) to prevent direct hooking.
   - Installation of smart meters and prepaid meters.
   - Implementation of Advanced Metering Infrastructure (AMI).
2. **Administrative Actions:**
   - Feeder-level and Distribution Transformer (DT) level energy auditing.
   - Frequent surprise checks and vigilance drives.
3. **IT Integration:**
   - Computerized billing and Spot billing using hand-held devices.
   - Online payment gateways to improve collection efficiency.

4.30 Demand Side Management (DSM)

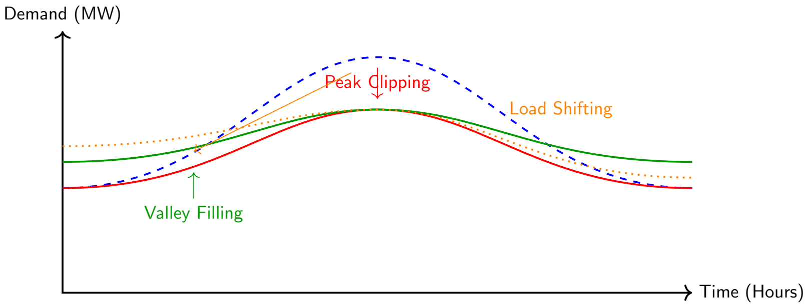
Definition

Demand Side Management (DSM) refers to initiatives and technologies that encourage consumers to optimize their energy usage. Instead of increasing generation capacity (Supply Side Management) to meet peak demand, DSM modifies the consumer's demand profile.

Primary Objectives:

- **Peak Shaving:** Reducing demand during peak hours to avoid operating expensive peaking power plants.
- **Energy Efficiency:** Reducing overall energy consumption through better technology (e.g., LED lighting, BLDC fans).
- **Grid Reliability:** Ensuring the power grid operates within safe limits, preventing blackouts.

DSM Load Shape Objectives



Daily Load Curve Modification

Techniques:

- **Peak Clipping:** Direct load control (shutting off ACs/water heaters).
- **Valley Filling:** Building off-peak load (EV charging at night).
- **Load Shifting:** Moving demand from peak to off-peak periods (Time-of-Use pricing).

Implementation and Benefits of DSM

Key Facts

Implementation Mechanisms:

- **Time of Use (ToU) Tariffs:** Charging higher rates during peak hours and lower rates at night.
- **Incentive Programs:** Rebates for purchasing energy-efficient appliances (e.g., BEE star-rated products).
- **Direct Load Control:** Utilities remotely turning off specific industrial loads or agricultural pumps during grid emergencies.

Strategic Benefits:

- **Utility Level:** Reduces need for capacity expansion, decreases T&D losses during peaks, and improves grid stability.
- **Consumer Level:** Lowers electricity bills through smart usage and off-peak tariffs.
- **Environmental Level:** Reduces reliance on fossil-fuel peaking plants, lowering greenhouse gas emissions.

4.31 Meaning of Demand Side Management (DSM)

Definition

- Demand Side Management (DSM) is the planning, implementation, and monitoring of utility activities designed to encourage consumers to modify patterns of electricity usage.
- This includes both the timing and level of electricity demand.
- Unlike supply-side strategies which increase generation capacity, DSM seeks to optimize the existing capacity by altering the load profile.

Need and Benefits of DSM

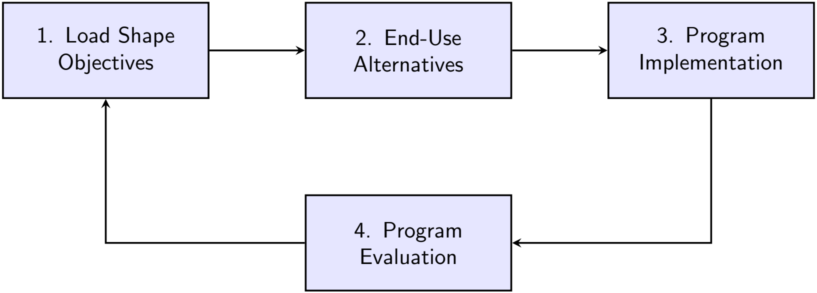
Utility Benefits:

- Defers the need for new power plants and transmission lines.
- Improves grid reliability and reduces blackout risks.
- Lowers overall operating costs by avoiding expensive peak generation.

Consumer Benefits:

- Reduces electricity bills through time-of-use tariffs.
- Promotes energy efficiency and awareness.

DSM Methodology



Meaning of Load Shape Objective

Definition

- A **Load Shape Objective** refers to the desired alteration in the daily, weekly, or seasonal load profile of the utility.
- Utilities analyze their current load curve and determine how they want to reshape it to minimize generation costs and improve load factor.
- The choice of objective depends on the utility's specific generation mix, peak demand periods, and capacity constraints.

Six Core Load Shape Objectives

Strategy	Description
Peak Clipping	Reducing demand during peak hours to avoid using expensive peaking plants.
Valley Filling	Building up off-peak loads to improve the utilization of base-load plants.
Load Shifting	Moving load from peak periods to off-peak periods (combination of clipping and filling).
Strategic Conservation	Overall reduction in sales by encouraging energy efficiency.
Strategic Load Growth	Overall increase in sales during periods of abundant cheap power.
Flexible Load Shape	Reliability-based contracts allowing utilities to interrupt loads during critical peaks.

Case Study: Load Shifting via Thermal Storage

Example

- **Scenario:** A commercial building uses conventional air conditioning, causing a massive peak demand at 2:00 PM.
- **DSM Intervention (Load Shifting):** The building installs an ice-storage system. Ice is generated during the night (off-peak, 1:00 AM) when electricity is cheap.
- **Result:** During the day (peak), the melted ice provides cooling, shutting off the chillers. The load curve shifts from afternoon to midnight.
- **Impact:**
- Utility sees a flattened demand curve. The consumer saves 30% on electricity bills due to Time-of-Use pricing.

Lecture 40: Consumer Categories & Tariff Terminology

- **GTU Engineering Course**
- **Module 5.1:** Category of consumers
- **Module 5.2:** Tariff Terminology
- Understanding electricity billing structures and consumer classification is essential for power system economics.

5.1 Category of Consumers Overview

Electricity boards categorize consumers based on:

- Voltage level of supply (LT or HT)
- Connected load or contract demand
- Purpose of use (Residential, Commercial, Industrial, Agricultural)
- Time of use and seasonal variation

Categories like RGP, GLP, LTMD, and HTP help apply appropriate tariffs.

Residential General Purpose (RGP & RGP Rural)

Definition

- **RGP (Residential General Purpose):**
- Applicable to residential premises, single-phase or three-phase supply.
-
- **RGP (Rural):**
- A subsidized category for residential consumers located in rural areas, managed by gram panchayats.
-
- *Tariff Structure:* Generally follows a block rate tariff (e.g., first 50 units at Rs. 3.20/unit, next 50 at Rs. 3.90/unit).

GLP & Non-RGP Consumers

GLP (General Lighting Purpose):

- Applicable to educational institutions, hospitals, charitable institutions, and public lighting.
- Focuses on essential services rather than commercial profit.

Non-RGP (Non-Residential General Purpose):

- Applicable to shops, offices, clinics, and small businesses.
- Tariffs are higher than RGP as it is used for commercial activities.
- Fixed charges are usually levied based on the connected load.

LTMD: Low Tension Maximum Demand

Definition

LTMD Category: Applicable to consumers having a connected load of typically 15 kW to 100 kW on Low Tension (LT) supply. **Key Features:**

- Billed on a two-part tariff: Demand Charge (based on Max Demand) + Energy Charge (based on kWh consumed).
- Requires a maximum demand indicator (MDI) meter.
- Heavy penalty if actual demand exceeds contract demand.

LTP: Low Tension Power

LTP (Low Tension Power Motive):

- Applicable primarily to small scale industries, workshops, and factories using motive power (motors).
- Usually restricted to a connected load of up to 15 kW or sometimes 50 kW depending on the state.
- Excludes major lighting loads; meant specifically for industrial machinery running on LT supply.

Tariff Note: May include power factor penalties if capacitors are not installed to maintain a minimum PF (e.g., 0.90).

AG: Agricultural Consumers

Key Facts

Agricultural Category (AG): Primarily used for irrigation pumps and tube wells in farming. **Important Facts:**

- Highly subsidized by state governments to support farmers.
- Can be billed based on meter readings or a flat rate per HP (Horse Power) of the motor.
- Often supplied power only during specific hours (e.g., 8 hours a day, staggered to manage grid load).

HTP (High Tension Power) Categories

Category	Description
HTP-I	Regular HT industries (e.g., textiles, chemicals) using power at 11 kV, 22 kV, or 33 kV. Demand ¿ 100 kVA.
HTP-II	HT consumers requiring power for water works, pumping stations operated by local authorities.
HTP-III	HT temporary supply or specific heavy continuous process industries (varies by state).
HTP-IV	HT consumers for lighting/commercial purposes, or bulk supply to residential colonies, traction, etc.

LT & HV Electric Vehicle Categories

Electric Vehicle (EV) Charging Stations: A relatively new consumer category designed to promote e-mobility. **LT-EV:**

- For low tension charging stations (e.g., 230V or 415V).
- Used for 2-wheelers, 3-wheelers, and standard home/commercial AC chargers.

HV-EV:

- For high voltage bulk fast-charging stations.
- Favorable tariff rates compared to normal commercial rates to encourage EV adoption.

5.2 Tariff Terminology Introduction

To calculate an electricity bill accurately, several key terms are defined in the tariff order. Key Terms Include:

- Contract Demand
- Billing Demand
- Maximum Demand
- Energy Charge
- Demand Charge
- Seasonal Consumers
- Power Factor Penalty/Incentive

Contract Demand

Definition

Contract Demand (CD): The maximum kW or kVA that the utility agrees to supply to the consumer, as stipulated in the formal power supply agreement. **Significance:**

- The utility sizes its transformers and lines based on the CD.
- If a consumer exceeds the CD, they are liable for heavy penalty charges (excess demand charges).
- The base fixed charge is often calculated as a percentage of the CD.

Demand Charge

Definition

Demand Charge: A fixed monthly charge levied by the utility, meant to recover capital costs of generation, transmission, and distribution infrastructure. **Calculation:** Normally charged per kW or kVA of the

Billing Demand. **Billing Demand is usually the highest of:**

- Actual Maximum Demand recorded in the month
- 85% (or specific threshold) of the Contract Demand
- A fixed minimum threshold (e.g., 50 kVA)

Energy Charge

Definition

- **Energy Charge (Active Energy Charge):**
- The variable part of the bill based on the actual volume of electricity consumed during the billing cycle.
-
- **Units:**
- Measured in kWh (kilowatt-hours) or kVAh (kilovolt-ampere-hours).
-
- **Structure:**
- Can be a flat rate, or a block-rate tariff (e.g., first 100 units at Rs 4, next 100 at Rs 5), or Time of Day (ToD) tariff varying by peak/off-peak hours.

Seasonal Consumers

Key Facts

Seasonal Consumers: Industries that operate heavily only during certain parts of the year. Examples: Sugar mills, ice factories, cotton ginning.
Tariff Relief:

- Normally, a high Demand Charge is payable year-round.
- Seasonal consumers can declare 'Off-season' months.
- During off-season, they pay a reduced demand charge (e.g., 15% of normal) or their contract demand is temporarily scaled down.

Example: LTMD Bill Calculation

Example

- **Given Data:**
- Contract Demand: 100 kW
- Recorded Max Demand: 90 kW
- Energy Consumed: 15,000 kWh
- Demand Charge Rate: Rs. 150 / kW of Billing Demand
- Energy Charge Rate: Rs. 4.5 / kWh
- Billing Demand = Max(Recorded MD, 85% of CD)
-
- **Calculation:**
- 85% of CD = 85 kW. Since Recorded MD (90 kW) ¿ 85 kW, Billing Demand = 90 kW.
- Demand Charge = 90 kW $\times$ 150 = Rs. 13,500
- Energy Charge = 15,000 kWh $\times$ 4.5 = Rs. 67,500
- **Total Base Bill** = 13,500 + 67,500 = Rs. 81,000

Energy Bill Components: RGP & RGP (Rural)

RGP (Residential General Purpose)

- Applicable to residential premises for lights, fans, and domestic appliances.
- **Fixed Charges**: Typically based on connected load or number of installations.
- **Energy Charges**: Telescopic or slab-based billing (e.g., first 50 units at lower rate, next 50 at higher rate).
- **RGP (Rural)**: Subsidized rates for consumers in rural areas.
- Fixed charges and energy charges are generally lower in RGP (Rural) to promote electrification and affordability.

Energy Bill Components: GLP & Non-RGP

GLP (General Lighting Purpose)

- Applicable for educational institutions, hospitals, and charitable trusts.
- Usually features a uniform energy rate or highly subsidized fixed charges.
- Aimed at supporting social and community services.

Non-RGP (Non-Residential General Purpose)

- Applicable to commercial establishments like shops, offices, and small businesses.
- **Fixed Charges**: Higher than RGP, based on the contracted load (kW).
- **Energy Charges**: Higher per-unit rate compared to residential.
- Often includes a minimum monthly charge regardless of energy consumption.

Tariff for LTMD: Demand & Energy Charges

Definition

LTMD (Low Tension Maximum Demand)

- **Demand Charge**: A fixed charge based on the maximum demand (in kW or kVA) recorded during the billing cycle. It penalizes peak load usage.
- **Energy Charge**: A variable charge based on the actual energy consumed (kWh).
- Designed for medium to large commercial and industrial consumers connected at Low Tension voltage (usually 400V/415V).
- **Formula**: Total Bill $= (P_d \times \text{Max Demand}) + (P_e \times \text{Units Consumed})$

Time of Use & Reactive Energy Charges

Key Facts

Time of Use (ToU) / Time of Day (ToD) Charges

- **Peak Hours**: Higher energy rates to discourage heavy usage during grid peak times.
- **Off-Peak Hours**: Discounted rates (rebates) to encourage shifting load to night time.
- Helps utility companies flatten the load curve.

Reactive Energy Charges

- Penalties applied for poor power factor.
- Billed based on kVARh (Reactive Kilovolt-Ampere hours).
- Encourages consumers to install capacitor banks to improve power factor.

Billing Demand, Minimum Bill & Seasonal Consumer

Billing Demand

- The demand upon which the demand charge is calculated.
- Usually the highest of: (a) Actual maximum demand recorded, (b) 85% of the contract demand, or (c) A minimum specified limit (e.g., 15 kW).

Minimum Bill

- The absolute minimum amount a consumer must pay, even if consumption is zero.
- Ensures the utility recovers basic infrastructure and maintenance costs.

Seasonal Consumer

- Industries operating only during specific seasons (e.g., sugar mills, ice factories).
- Special tariff provisions allow them to pay lower fixed charges during off-season months.

Case Study: LTMD Billing Calculation

Example

Scenario: An LTMD consumer has a contract demand of 50 kW.
Recorded Data: Max Demand = 40 kW, Energy Consumed = 10,000 kWh. **Tariff Rates**:

- Demand Charge: Rs. 150 / kW / month
- Energy Charge: Rs. 4.50 / kWh

Calculation:

- Billing Demand = Max(40 kW, 85% of 50 kW) = Max(40, 42.5) = 42.5 kW
- Demand Charge = 42.5 kW × Rs. 150 = Rs. 6,375
- Energy Charge = 10,000 kWh × Rs. 4.50 = Rs. 45,000
- **Total Bill** = 6,375 + 45,000 = Rs. 51,375 (excluding taxes/duties)

Introduction to LTP Tariff (Lift Irrigation)

- Low Tension Power (LTP) tariff is specifically designed for agricultural and irrigation purposes.
- Lift irrigation involves pumping water from a lower elevation to a higher elevation.
- The energy consumed by pump sets (motors) forms the basis of this tariff category.
- Tariff structures aim to make power affordable for farmers while ensuring revenue recovery for the utility.

What is Lift Irrigation?

Definition

- **Lift Irrigation:** A method of irrigation in which water is not transported by natural flow, but is lifted with pumps or other mechanical means.
- Commonly uses centrifugal or submersible electric pumps.
- Essential in areas where the water source is lower than the agricultural land.

Significance of LTP Tariff in Agriculture

Key Facts

- Agriculture consumes a substantial portion of total generated electricity in many regions.
- LTP tariffs are often heavily subsidized by state governments to support food security.
- The connected load is typically measured in Horse Power (HP) rather than purely in kW.

Structure of the LTP Tariff

- The tariff is typically a two-part tariff system.
- 1. **Fixed Charges (or Demand Charges):** Based on the sanctioned load or connected load.
- 2. **Energy Charges:** Based on the actual energy consumed (kWh).
- Other components may include Fuel Surcharge, Electricity Duty, and Meter Rent.

Understanding Fixed Charges

Definition

- **Fixed Charges:** A recurring, unvarying amount charged per billing cycle based on the consumer's connected load (HP or kW), regardless of actual electricity consumption.
- Purpose: To recover the utility's infrastructure, maintenance, and capital investment costs.

Fixed Charges for Lift Irrigation

- Usually billed at a flat rate per HP per month.
- Example rate: INR 15 to INR 30 per HP/month depending on the state.
- For a 5 HP motor, fixed charges would be $5 \times$ Rate.
- Encourages farmers to optimize their pump sizing rather than over-sizing.

Understanding Energy Charges

Definition

- **Energy Charges:** The variable component of the tariff, calculated based on the actual units of electricity (kWh) consumed during the billing cycle.
- Purpose: To recover the cost of fuel and generation of electricity.

Energy Charges for Lift Irrigation

- Often highly subsidized compared to industrial or commercial rates.
- May have a slab system, though many agricultural tariffs offer a flat, low rate per unit (e.g., INR 0.80 to 1.50 per kWh).
- Some regions offer completely free electricity up to a certain limit or for specific hours.
- Time of Day (ToD) tariffs might be implemented to encourage pumping during off-peak hours.

Typical LTP Tariff Structure for Lift Irrigation

Component	Typical Rate
Fixed Charge	Rs. 20 per HP per month
Energy Charge	Rs. 1.20 per kWh
Fuel Surcharge	Rs. 0.10 per kWh
Electricity Duty	Exempted for Agriculture

Table: Sample Tariff Rates

Calculation of Fixed Charges: Example

Example

- **Scenario:** A farmer has a 7.5 HP submersible pump for lift irrigation.
- **Tariff Rate:** Rs. 25 per HP per month.
- **Calculation:**
- Fixed Charge = Connected Load (HP) $\times$ Rate
- Fixed Charge = 7.5×25
- Fixed Charge = Rs. 187.50 per month.

Calculation of Energy Charges: Example

Example

- **Scenario:** The 7.5 HP pump runs for 5 hours a day for 30 days.
- Power in kW $= 7.5 \times 0.746 = 5.595$ kW.
- Total hours $= 5 \times 30 = 150$ hours.
- Units consumed (kWh) $= 5.595 \times 150 = 839.25$ kWh.
- **Tariff Rate:** Rs. 1.10 per kWh.
- Energy Charge $= 839.25 \times 1.10 = Rs.923.18$.

Total Bill Calculation: Example

Example

- Continuing from previous examples:
- Fixed Charge = Rs. 187.50
- Energy Charge = Rs. 923.18
- Total Bill = Fixed Charge + Energy Charge
- Total Bill $= 187.50 + 923.18 = Rs.1110.68$
- *(Assuming no additional surcharges or taxes)*

Impact of Power Factor on LTP Tariff

Key Facts

- Induction motors used in agricultural pumps often have a poor power factor.
- Utilities may impose a Power Factor Penalty if the PF drops below a specified limit (e.g., 0.85).
- Farmers are encouraged to install capacitors to improve PF, sometimes receiving a rebate.

Billing Cycle and Metering Challenges

- Agriculture billing is often done on a bi-monthly or quarterly basis to reduce administrative overhead.
- Unmetered connections are still prevalent in some areas, leading to flat-rate billing based solely on HP.
- Flat-rate billing can lead to energy and water wastage, prompting a shift towards 100% metering.

Summary and Conclusion

- The LTP tariff for lift irrigation consists of fixed charges (based on HP) and energy charges (based on kWh).
- Fixed charges recover capital investments, while energy charges cover operational fuel costs.
- Tariffs are designed to be affordable but require metering to prevent wastage.
- Understanding these charges helps in sizing equipment and operating efficiently.

5.6 Agricultural (AG) Tariffs: An Overview

Agricultural consumers form a major portion of the electrical load in developing countries, primarily for irrigation pump sets. The electricity tariff for agriculture (AG) is heavily subsidized to support farmers and ensure food security. State Electricity Regulatory Commissions (SERCs) typically define two main types of tariff structures for AG consumers:

- **HP (Horse Power) Based Tariff:** A flat rate tariff based on the capacity of the motor.
- **Metered Tariff:** Tariff based on the actual units (kWh) of electricity consumed.

The shift from HP-based to metered tariff is encouraged to promote energy efficiency and reduce transmission and distribution (T&D) losses.

HP (Horse Power) Based Tariff

Definition

Definition: HP-based tariff is a flat-rate billing system where the consumer pays a fixed amount per month or per year based on the registered Horse Power (HP) capacity of their agricultural pump, irrespective of the actual energy consumed. **Key Characteristics:**

- **No Metering Required:** Eliminates the cost of meter installation, reading, and maintenance.
- **Predictable Cost:** Farmers know their exact electricity expenses in advance.
- **Drawback (Inefficiency):** Since the marginal cost of pumping extra water is zero, it leads to over-exploitation of groundwater and wastage of electricity.
- **Example Rate:** Rs. 300 per HP per month.

Metered Tariff for Agriculture

Key Facts

Fact: Metered tariffs incentivize the use of energy-efficient star-rated pump sets. Mechanism: Consumers are billed based on the

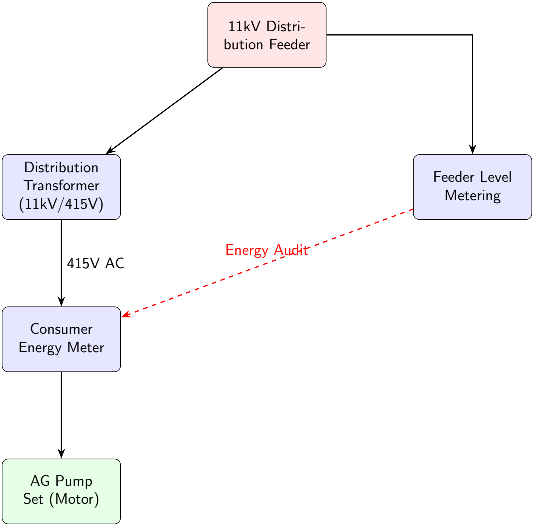
exact number of units (kWh) recorded by the energy meter installed at their premises.

- It generally consists of two parts: a low fixed charge (based on connected load) and an energy charge (Rs. /kWh).
- **Energy Conservation:** Farmers tend to switch off pumps when not required, saving both electricity and groundwater.
- **Accurate Subsidy Accounting:** Helps DISCOMs precisely calculate the agricultural consumption and claim exact subsidies from the state government.
- **Challenges:** High capital cost for meter deployment, risk of meter tampering, and high cost of meter reading in remote areas.

Comparison: HP-based vs. Metered Tariff

Parameter	**HP Based Tariff**	**Metered Tariff**
Basis of Billing	Connected Load (HP)	Energy Consumed (kWh)
Energy Conservation	Very Low	High
Groundwater Impact	Over-exploitation	Controlled usage
Metering Cost	Nil	High
DISCOM Revenue	Fixed, often under-recovered	Proportional to usage

Metering Architecture for AG Consumers



Numerical Example: Tariff Calculation

Example

Scenario: A farmer owns a 5 HP (approx 3.73 kW) pump. It runs for 6 hours a day for 30 days a month. **1. HP Based Tariff Calculation:**

- Rate: Rs. 300 / HP / month
- Monthly Bill = 5 HP $\times$ Rs. 300 = **Rs. 1500 / month**

2. Metered Tariff Calculation:

- Energy Consumed = 3.73 kW $\times$ 6 hrs/day $\times$ 30 days = 671.4 kWh
- Rate: Fixed charge Rs. 20/HP/month + Energy charge Rs. 1.50/kWh
- Fixed Charge = 5 $\times$ 20 = Rs. 100
- Energy Charge = 671.4 $\times$ 1.50 = Rs. 1007.1
- Total Monthly Bill = 100 + 1007.1 = **Rs. 1107.1 / month**

Conclusion: In this scenario, the metered tariff is cheaper, incentivizing the farmer to keep the meter if usage is optimized.

Introduction to HTP-I & HTP-II Tariffs

HTP-I (High Tension Power I):

- Applicable to regular industrial consumers.
- Requires a contract demand of 100 kVA and above.
- Follows a two-part tariff structure: Demand Charges and Energy Charges.

HTP-II (High Tension Power II):

- Specifically for water works and pumping stations operated by local authorities.
- Similar structure to HTP-I but often with concessional rates.

HTP-I & HTP-II: Demand and Energy Charges

Charge Component	Billing Slab / Condition	Indicative Rate
Demand Charge	First 500 kVA	Rs. 150 / kVA / month
Demand Charge	Next 500 kVA	Rs. 260 / kVA / month
Demand Charge	Above 1000 kVA	Rs. 475 / kVA / month
Energy Charge	Up to 500 kVA billing demand	435 Paise / Unit
Energy Charge	Above 500 kVA billing demand	455 Paise / Unit

Table: Sample Tariff Structure for HTP Consumers

Billing Demand, Minimum Bill & Time of Use

Definition

Key Tariff Terms

Billing Demand: The demand on which the monthly demand charge is calculated. It is the highest of:

- Actual maximum demand recorded during the month.
- 85% of the contract demand.
- 100 kVA.

Minimum Bill: The absolute minimum amount a consumer must pay, usually equal to the Demand Charge on the Billing Demand. **Time of Use (ToU) Charges:** Additional charges (e.g.,

85 Paise/Unit) applied during peak grid hours to discourage heavy loading.

Power Factor Adjustments and Rebates

Key Facts

PF Penalty and Rebate Mechanism

Power Factor Penalty: If PF falls below 0.90, a penalty is levied (e.g., 1% of energy charges for every 0.01 drop). **Power Factor**

Rebate: If PF is maintained above 0.95, a rebate is provided (e.g., 0.5% of energy charges for every 0.01 improvement up to 0.99). **Night Usage Rebate:** Consumers using electricity strictly during

off-peak night hours (e.g., 10 PM to 6 AM) receive a special concession on energy charges.

Tariffs for EV Charging Stations (LT & HT)

Overview of EV Tariffs:

- Special, subsidized tariff category introduced to accelerate e-mobility adoption.
- Applies to both Public and Captive charging stations.

LT (Low Tension) EV Charging:

- For smaller charging setups connected at 230V or 400V.
- Fixed charges are kept extremely low (e.g., Rs. 25/month/kW).

HT (High Tension) EV Charging:

- For bulk charging hubs connected at 11 kV or above.
- Energy charges are flat and highly competitive (e.g., Rs. 4.00 per kWh).

Case Study: HT EV Charging Station Bill

Example

Scenario: An HT EV charging hub has a contract demand of 200 kVA and consumes 15,000 units (kWh) in a month. **Tariff Rates:**

- **Fixed Charge:** Rs. 25 per kVA per month
- **Energy Charge:** Rs. 4.00 per Unit

Calculation:

$$\text{Total Fixed Charges} = 200 \text{ kVA} \times \text{Rs. } 25 = \text{Rs. } 5,000$$
$$\text{Total Energy Charges} = 15,000 \text{ Units} \times \text{Rs. } 4.00 = \text{Rs. } 60,000$$
$$\text{Total Bill (Excl. Tax)} = 5,000 + 60,000 = \textbf{Rs. 65,000}$$

Note: Time of Use (ToU) charges would be added if charging occurred during peak hours.

Components of an Electricity Bill

- An electricity bill comprises various charges based on the consumer category and tariff structure.
- **1. Fixed Charges:** Based on sanctioned load or maximum demand (kW or kVA).
- **2. Energy Charges:** Based on actual units consumed (kWh) with slab-wise or flat rates.
- **3. FPPPA Charges:** Fuel and Power Purchase Price Adjustment, applied per unit to cover fluctuating fuel costs.
- **4. Electricity Duty (ED):** A government tax calculated as a percentage of the total energy and fixed charges.
- **5. Other Charges:** Meter rent, delayed payment charges, power factor penalty/rebate (for industrial users).

Government Charges & FPPPA

Definition

FPPPA (Fuel and Power Purchase Price Adjustment): A mechanism to pass on the variations in the cost of fuel and power purchase to the consumer. It is charged on a per-unit basis (e.g., Rs. 2.50/kWh).
Electricity Duty (ED): A state government tax levied on electricity

consumption. It varies by category:

- **RGP (Residential):** Typically around 15%
- **LTMD / HTP-1 (Industrial/Commercial):** Varies between 10% to 20% depending on state policies and usage type.

Case Study: RGP (Residential General Purpose)

Example

Scenario: Sanctioned Load: 2 kW, Monthly Consumption: 250 units (kWh). **Tariff Rates:** Fixed Charge: Rs. 15/month per kW. Energy Charge: First 50 units @ Rs. 3.05, Next 50 @ Rs. 3.50, Next 150 @ Rs. 4.15. FPPPA: Rs. 2.50/unit, Electricity Duty: 15%, Meter Rent: Rs. 15.
Calculation:

- Fixed Charge $= 2 \times 15 =$ Rs. 30
- Energy Charge $= (50\times3.05)+(50\times3.50)+(150\times4.15) = 152.5+175+622.5 =$ Rs. 950
- FPPPA Charge $= 250 \times 2.50 =$ Rs. 625
- Subtotal $= 30 + 950 + 625 =$ Rs. 1605
- Electricity Duty (15% on subtotal) $= 0.15 \times 1605 =$ Rs. 240.75
- Total Bill $= 1605 + 240.75 + 15 =$ **Rs.** 1860.75

LTMD Tariff Structure Overview

Parameter	**Rate/Details**
Applicability	Commercial/Industrial up to 100 kW
Billing Demand	Actual Max Demand or 85% of Sanctioned (whichever is higher)
Demand Charges	First 40 kW @ Rs. 150/kW/month Above 40 kW @ Rs. 260/kW/month
Energy Charges	Flat rate (e.g., Rs. 4.60 per kWh)
Reactive Power	Penalty for low Power Factor (kVARh charges)

Table: Typical LTMD Tariff Elements

Case Study: HTP-1 (High Tension Power)

Example

Scenario: Contract Demand: 500 kVA, Max Demand: 450 kVA, Energy: 100,000 kWh, PF: 0.95 Lag. **Rates:** Demand: Rs. 150/kVA, Energy: Rs. 4.20/kWh, FPPPA: Rs. 2.50/kWh, ED: 10%. **Calculation:**

- Billing Demand = Max (450, 0.85*500=425) = 450 kVA
- Demand Charge $= 450 \times 150 =$ Rs. $67,500$
- Energy Charge $= 100,000 \times 4.20 =$ Rs. $420,000$
- FPPPA $= 100,000 \times 2.50 =$ Rs. $250,000$
- Subtotal $= 67,500 + 420,000 + 250,000 =$ Rs. $737,500$
- Electricity Duty (10% on subtotal) $= 0.10 \times 737,500 =$ Rs. $73,750$
- Total Bill $= 737,500 + 73,750 =$ **Rs.** 811,250

Importance of Power Factor in HTP/LTMD Billing

Key Facts

Why Power Factor Matters: Industrial loads (LTMD and HTP-1) are largely inductive, drawing reactive power (kVAR). Utilities penalize poor power factor (usually below 0.90) and reward good power factor (above 0.95) to encourage efficiency. **Financial Impact:**

- **Penalty:** Often charged at Rs. 3.00 per kVARh for PF ¡ 0.90, significantly increasing the bill.
- **Rebate:** Usually 0.5% of Energy Charges for every 0.01 unit improvement above 0.95.
- **Conclusion:** Installing capacitor banks reduces kVA demand and avoids kVARh penalties, leading to substantial savings.