

ENERGY CONSERVATION AND AUDIT

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MODULE 2: ENERGY EFFICIENCY IN ELECTRICAL SYSTEMS

2.1 Electricity Billing

Electricity billing is the basis on which an industrial or commercial consumer is charged by the utility (DISCOM/ELECTRICITY BOARD). Understanding the tariff structure is the first step of any energy audit, since a large fraction of savings often comes purely from optimizing billing parameters without any technical modification to the plant.

2.1.1 Components of an Electricity Bill

Component	Description
Maximum Demand (MD) Charges	Charged on the highest average kVA/kW recorded during any demand interval (usually 15/30 minutes) in the billing month, irrespective of total energy consumed.
Energy Charges (kWh)	Charged on the basis of total active energy (kWh) consumed during the billing period, often with slab-wise or time-of-day (ToD) rates.
Power Factor (PF) Penalty/Incentive	Penalty for low PF (below 0.85-0.90 lag) and incentive/rebate for maintaining high PF (above 0.95-0.98).
Fuel Surcharge / FAC	Fuel Adjustment Charge to compensate the utility for variation in fuel cost.
Electricity Duty / Tax	Statutory duty levied by the State Government as a percentage of the energy charge.
ToD (Time of Day) Tariff	Differential tariff with higher rates during peak hours and lower/rebate rates during off-peak hours to encourage load shifting.
Minimum Charges	Minimum amount payable even if actual consumption/demand is lower (based on contract demand).
Meter Rent / Service Charges	Fixed monthly charge for metering equipment and administrative service.

2.1.2 Important Terms and Definitions

- **Connected Load:** Sum of the rated capacities (kW) of all electrical equipment installed in the premises.
- **Contract Demand (CD):** The maximum demand that a consumer is permitted to draw as agreed with the utility, expressed in kVA.
- **Maximum Demand (MD):** The highest average kVA/kW drawn by the consumer over a fixed demand interval, recorded by the demand meter.
- **Load Factor (LF):** Ratio of average load to the maximum demand over a given period.
- **Plant Load Factor (PLF):** Ratio of actual energy generated/consumed to the energy that would be generated/consumed if the plant operated at full installed capacity for the same period.

2.1.3 Important Formulae

Quantity	Formula
Load Factor (LF)	$LF = \text{Average Load} / \text{Maximum Demand} = (\text{Energy consumed in kWh} / (\text{MD in kW} \times \text{Hours})) \times 100 \%$
Average Demand	$\text{Average Demand (kW)} = \text{Total kWh consumed} / \text{Total hours in the billing period}$
Plant Load Factor (PLF)	$PLF (\%) = (\text{Average load} / \text{Rated capacity}) \times 100$
kVA Demand	$kVA = kW / \text{Power Factor (cos phi)}$
Power Factor Penalty (typical slab)	For every 1% drop in PF below 0.90 (lag), a surcharge of about 1% on the demand and energy charges is levied (rates vary by state).
Power Factor Incentive (typical slab)	For every 1% rise in PF above 0.95 (up to 1.0), a rebate of about 0.5% on the demand/energy charges is given (rates vary by state).

2.1.4 Sample Tariff Structure (Illustrative, HT Industrial Consumer)

Tariff Component	Normal Hours	Peak Hours (ToD)	Off-Peak Hours (ToD)
Energy Charge (Rs/kWh)	Rs 7.50	Rs 7.50 + 20% surcharge = Rs 9.00	Rs 7.50 - 20% rebate = Rs 6.00
Demand Charge (Rs/kVA/month)	Rs 450	-	-
PF Incentive/Penalty	+/- as per slab above PF 0.90	Same	Same
Electricity Duty	9% of energy charge	Same	Same

Note: The above figures are illustrative for academic purposes; actual rates vary across DISCOMs and should be obtained from the latest tariff order of the respective State Electricity Regulatory Commission (SERC).

2.2 Electrical Load Management and Maximum Demand Control

2.2.1 Need for Load Management

Load management refers to a set of techniques used by an industrial/commercial consumer to control the pattern and magnitude of electricity demand so as to minimize the maximum demand (MD) charges, avoid penalties for exceeding contract demand, improve load factor, and shift loads from peak to off-peak periods to take advantage of ToD tariffs.

2.2.2 Objectives of Maximum Demand Control

1. Avoid penalty charges for exceeding the sanctioned/contract demand.
2. Reduce the billing demand and hence the fixed demand charges.
3. Achieve a high and uniform load factor.
4. Shift non-critical loads to off-peak hours to benefit from ToD rebates.
5. Improve the overall utilization of the electrical distribution infrastructure.

2.2.3 Methods/Strategies of Load Management

- Staggering of operation times of large loads (e.g., starting heavy motors/compressors at different times).
- Rescheduling of non-critical, energy-intensive operations (e.g., batch processes, water pumping) to off-peak hours.
- Shedding of non-essential loads (HVAC, lighting in unoccupied areas, water heaters) during anticipated demand peaks.
- Operation of standby diesel generators (DG sets) during peak demand periods to limit grid drawal (peak shaving).
- Use of energy storage systems (batteries, thermal storage - ice/chilled water storage for HVAC) to shift load from peak to off-peak periods.
- Installation of automatic Maximum Demand Controllers to monitor and control demand in real time.

2.2.4 Maximum Demand Controllers (MDC)

A Maximum Demand Controller is an electronic instrument that continuously monitors the kW/kVA demand of an installation over a sliding or fixed demand interval (commonly 15 or 30 minutes, as fixed by the utility) and gives a warning or automatically sheds pre-selected loads if the demand is likely to exceed a preset value.

Principle of Operation

6. The controller continuously integrates the load (kW) over the demand interval and predicts the likely demand at the end of the interval based on the present rate of rise.
7. If the projected demand is likely to exceed the set/target demand, the controller first gives an audio-visual alarm.
8. If the operator does not take corrective action, the controller automatically trips (sheds) pre-ranked, non-essential loads in a programmed sequence (load shedding priority list).
9. Once the demand falls below the set point, the controller automatically restores the shed loads in reverse order (load restoration).

Features of a Modern MDC

- Programmable target demand and demand interval (synchronized with the utility's pulse).
- Multiple load-shedding priority levels (critical, semi-critical, non-critical).
- Trend/graphic display of instantaneous demand, predicted demand, and historical demand profile.
- Data logging, alarm annunciation, and communication (RS-485/Modbus, SCADA integration) for remote monitoring.
- Integration with Building Management Systems (BMS) and Energy Management Systems (EMS).

Benefits of MDC Installation

Benefit	Typical Impact
Avoidance of penalty for demand excess	Penalty avoidance, typically Rs 200-500 per kVA per excess instance (varies by utility)
Reduction in contract demand	Allows downward revision of CD, reducing monthly fixed/demand charges by 5-15%
Improved load factor	Better utilization of sanctioned capacity, improved billing efficiency
Avoidance of transformer/feeder overload	Extends equipment life, reduces unplanned outages

2.3 Power Factor Improvement

2.3.1 Definition and Significance

Power factor (PF) is the ratio of active power (kW) to apparent power (kVA) drawn by an electrical load: $PF = \cos(\phi) = kW / kVA$. A low power factor (typically due to inductive loads such as motors, transformers, and welding equipment) results in higher current drawn for the same active power, leading to increased line losses (I^2R), higher kVA demand, voltage drop, and reduced system capacity.

2.3.2 Causes of Low Power Factor

- Large number of induction motors operating at light/no load.
- Old and oversized transformers operating at low loading.
- Arc and induction furnaces, welding transformers, and discharge lighting (older fluorescent fittings with magnetic ballasts).
- Variable and fluctuating loads (cranes, lifts, compressors with intermittent duty).

2.3.3 Disadvantages of Low Power Factor

10. Increased kVA demand for the same kW load, leading to higher demand charges.
11. Increased copper losses (I^2R) in cables, transformers, and switchgear.
12. Greater voltage drop and poor voltage regulation.
13. Reduced effective capacity of generators, transformers, and distribution lines.
14. PF penalty levied by the utility on the electricity bill.

2.3.4 Methods of Power Factor Improvement

Method	Description
Static Capacitors (Shunt Capacitors)	Most common and economical method; capacitors supply leading reactive power (kVAR) to compensate for the lagging kVAR drawn by inductive loads, thereby reducing the net reactive power drawn from the supply.
Synchronous Condensers	An over-excited synchronous motor running with no mechanical load, supplying reactive power to the system; used in large industrial/utility installations.

Phase Advancers	Used with large induction motors (especially slip-ring/wound rotor motors) to improve PF of the motor itself by supplying excitation mmf at slip frequency.
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2.3.5 Capacitor Sizing - Worked Formula

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

$$\text{Required kVAR} = \text{kW} \times (\tan(\phi_1) - \tan(\phi_2))$$

Example: A load of 100 kW operates at PF = 0.75 ($\phi_1 = 41.4^\circ$, $\tan = 0.882$). To improve PF to 0.95 ($\phi_2 = 18.2^\circ$, $\tan = 0.329$):

$$\text{Required kVAR} = 100 \times (0.882 - 0.329) = 100 \times 0.553 = 55.3 \text{ kVAR (approx)}$$

2.3.6 Levels of Compensation

Type	Location	Remarks
Individual / Local Compensation	Capacitor connected directly across the terminals of each inductive load (motor)	Most effective; reduces losses in cables feeding that load; capacitor switches with the motor
Group Compensation	Capacitor bank connected to a group of loads on a common distribution board/MCC	Reduces number of capacitor units; loses some loss-reduction benefit on individual feeders
Central / Bulk Compensation	Large capacitor bank installed at the main incoming supply (HT/LT panel)	Useful for overall plant PF correction and avoiding utility penalty; does not reduce losses in internal distribution

2.4 Automatic Power Factor Controllers (APFC)

An Automatic Power Factor Controller (APFC) panel is a microprocessor/relay-based control system that automatically switches capacitor banks (in steps) in and out of circuit to maintain the plant power factor close to a desired set value (commonly 0.99 lagging to slightly leading), compensating for continuously varying inductive loads.

2.4.1 Components of an APFC Panel

- Power Factor Controller Relay (PFC relay): Continuously measures the system PF/kVAR and decides which capacitor steps to switch ON/OFF.
- Capacitor Banks: Arranged in multiple steps (e.g., 25 + 25 + 50 + 50 kVAR) to provide fine control of reactive power.
- Contactors (preferably capacitor-duty contactors): Switch individual capacitor steps.
- Detuned/Tuned Reactors (Series Reactors): Protect capacitors from harmonic resonance and amplification, especially where VFDs/non-linear loads are present.
- Current Transformer (CT): Senses load current for the relay's PF calculation.
- Protection devices: HRC fuses/MCCBs for short-circuit and overload protection of each capacitor step.

2.4.2 Working Principle

15. CT senses load current; the PFC relay computes the existing PF using voltage and current phasor information.
16. If the measured PF is below the set target, the relay switches IN one or more capacitor steps (in a sequence that equalizes switching cycles among steps).
17. If the PF rises above the target (e.g., load reduces and PF becomes leading), the relay switches OUT capacitor steps.
18. A time delay is built in between successive switching operations to avoid hunting and to allow capacitor discharge before re-switching.

2.4.3 Advantages of APFC

- Maintains near-unity PF under varying load conditions, eliminating PF penalty and maximizing PF incentive/rebate.
- Reduces line losses, improves voltage profile, and frees up kVA capacity of transformers and cables.
- Reduces manual intervention and risk of over-compensation (leading PF) which can also attract penalties in some tariffs.

2.5 Efficient Operation of Transformers

2.5.1 Transformer Losses

Loss Type	Nature and Dependence
No-load (Core/Iron) Losses	Hysteresis and eddy current losses in the core; present as long as the transformer is energized, essentially independent of load; depend on core material and flux density.
Load (Copper) Losses	I^2R losses in primary and secondary windings; vary as the square of the load current (load factor squared).
Stray Losses	Losses due to leakage flux in tank, structural parts, and winding conductors (eddy currents), increase with load.
Dielectric Losses	Losses in the insulation, generally small.

2.5.2 Transformer Efficiency

$$\text{Efficiency} = \text{Output Power} / (\text{Output Power} + \text{Core Loss} + \text{Copper Loss}) \times 100$$

Maximum efficiency of a transformer occurs when copper loss equals iron (core) loss, i.e., at a load corresponding to:

$$\text{Load (fraction of full load) at max. efficiency} = \sqrt{\text{Core Loss} / \text{Full-Load Copper Loss}}$$

2.5.3 Measures for Efficient Transformer Operation

19. Operate transformers close to their maximum-efficiency loading point (typically 50-70% of rated capacity for distribution transformers); avoid prolonged operation at very low load factors.
20. Use Star-rated / energy-efficient transformers (e.g., BEE 5-star transformers, amorphous-core transformers) which have substantially lower no-load losses.

21. Avoid running transformers in parallel unnecessarily during light-load periods; switch off one transformer and operate the other near its optimum loading.
22. Maintain correct tap settings to ensure rated voltage and avoid excess flux (and hence excess core loss) due to over-voltage.
23. Improve load power factor (see Sections 2.3-2.4) so that transformer kVA capacity is used predominantly for active power.
24. Ensure proper cooling (oil level, radiators, fans) to keep operating temperature within limits, since losses and insulation life are temperature-dependent.
25. Balance loads across the three phases to avoid additional unbalance losses and neutral current.

2.5.4 Illustrative Comparison: Conventional vs Energy-Efficient (Amorphous Core) Distribution Transformer (100 kVA)

Parameter	Conventional (CRGO) Transformer	Amorphous Core (Energy-Efficient)
No-load loss (Watts)	180 - 200	60 - 90
Load loss at full load (Watts)	1500 - 1750	1500 - 1750 (similar)
Annual energy saving (approx, at 24x7 energization)	Reference	Approx. 1000-1200 kWh per year per transformer

2.6 Energy Efficient Motors (EEM)

2.6.1 Losses in Induction Motors

Loss Component	Approx. Share of Total Losses	Reduction Approach
Stator I^2R (Copper) Loss	30-35%	More copper, larger conductor cross-section, improved slot fill
Rotor I^2R Loss	15-20%	Higher conductivity rotor bars (copper rotor in some designs)
Core (Iron) Loss	20-25%	Low-loss silicon steel laminations, optimized flux density, thinner laminations
Friction & Windage Loss	5-10%	Improved bearings, optimized fan design
Stray Load Loss	10-15%	Optimized winding design and slot geometry

Note: Header row formatting kept consistent; the third column header was added for clarity of remedial measures.

2.6.2 Energy Efficient Motors - Key Features

- Use of low-loss, high-grade silicon steel laminations with reduced thickness to minimize hysteresis and eddy current losses.
- Increased quantity of copper/aluminum in stator and rotor windings to reduce I^2R losses (larger slot area, optimized winding factor).

- Optimized air-gap length and improved rotor design to reduce stray losses.
- Improved cooling fan design and high-efficiency bearings to reduce mechanical (friction and windage) losses.
- Better quality manufacturing and tighter tolerances reducing stray losses and improving power factor.

2.6.3 IS 12615 / IE Efficiency Classes (BIS Standard for Induction Motors)

Efficiency Class	Description
IE1 (Standard Efficiency)	Basic/standard efficiency motors as per older norms; being phased out.
IE2 (High Efficiency)	Improved efficiency over IE1; common minimum requirement in many markets.
IE3 (Premium Efficiency)	Significantly higher efficiency than IE2; increasingly mandated for new motors.
IE4 (Super Premium Efficiency)	Highest efficiency class for induction motors, often using improved materials/designs (e.g., copper rotor, premium electrical steel).

2.6.4 Illustrative Efficiency Comparison (Typical 3-Phase Induction Motor, 11 kW, 4-pole)

Motor Class	Full-Load Efficiency (%)	Annual Energy Saving vs IE1 (8000 hrs/yr, 75% load)
IE1 (Standard)	~88.0	Reference
IE2 (High Efficiency)	~89.8	~1500-2000 kWh/year
IE3 (Premium)	~91.2	~3000-3500 kWh/year

2.6.5 Considerations for Replacement / Retrofit

26. Energy efficient motors generally have a higher initial cost (10-30% more than standard motors); payback should be evaluated based on annual running hours and load factor.
27. Replacement is most beneficial for motors that run continuously (high duty cycle, e.g., > 4000 hours/year) at moderate-to-high loading (50-100%).
28. For motors with very low utilization, rewinding/replacement of standard motors with EEMs may not be economically justified - 'Energy Efficient Motors at the time of purchase/replacement, not necessarily by retrofitting' is the general guideline.

2.7 Soft Starters

2.7.1 Need for Soft Starting

Direct-on-line (DOL) starting of induction motors causes a high starting current (typically 6-8 times the rated current) and a high starting torque transient, leading to mechanical stress on couplings/belts, voltage dips in the supply system, and nuisance tripping. Reduced-voltage starting methods (star-delta, autotransformer) only provide fixed-step reduction; soft starters provide a smooth, controlled, stepless starting and stopping.

2.7.2 Construction and Working Principle

A soft starter consists of pairs of thyristors (SCRs) connected in anti-parallel (back-to-back) in each of the three phases, in series with the motor supply. By controlling the firing angle of the thyristors, the RMS voltage applied to the motor is gradually ramped up from a low initial value to full voltage over a programmable 'ramp-up time', and similarly ramped down during stopping ('soft stop').

2.7.3 Key Features and Benefits

- Reduced starting current (typically limited to 2-4 times rated current, adjustable).
- Smooth acceleration and deceleration, reducing mechanical shock to couplings, gearboxes, belts, and the driven load (pumps, conveyors, fans).
- Reduced voltage dip on the supply network during starting, beneficial where multiple motors share a common feeder.
- Built-in protection features: overload, phase loss, current imbalance, and stall protection.
- 'Soft stop' feature is particularly valuable for pumping applications to prevent water hammer.

2.7.4 Soft Starter vs Other Starting Methods

Parameter	DOL Starter	Star-Delta Starter	Soft Starter
Starting Current	6-8 x FLC	2-3 x FLC (step change)	2-4 x FLC (smooth, adjustable)
Starting Torque Profile	High transient, fixed	Step change at transition	Smooth, controllable ramp
Mechanical Stress	High	Moderate (transition shock)	Low
Cost	Lowest	Low-Moderate	Moderate-High

Note: Soft starters control voltage/current during start and stop but do NOT provide continuous speed control during running (the motor runs at near-synchronous speed once fully ramped up, by-passed via a bypass contactor in most installations).

2.8 Variable Speed Drives (VSD/VFD)

2.8.1 Concept

A Variable Speed Drive (commonly a Variable Frequency Drive, VFD, for AC induction motors) varies the speed of a motor by varying the frequency and voltage of the supply to the motor, using power electronic converters (typically a rectifier-DC link-inverter, i.e., a Voltage Source Inverter with PWM control).

2.8.2 Why VSDs Save Energy: The Affinity Laws (Fan/Pump Laws)

For centrifugal fans and pumps, the relationship between speed (N), flow (Q), head/pressure (H), and power (P) is governed by the affinity laws:

Relationship	Expression
Flow vs Speed	$Q_2/Q_1 = N_2/N_1$ (flow is directly proportional to speed)

Head/Pressure vs Speed	$H_2/H_1 = (N_2/N_1)^2$ (head is proportional to square of speed)
Power vs Speed	$P_2/P_1 = (N_2/N_1)^3$ (power is proportional to cube of speed)

Because power varies as the CUBE of speed, even a small reduction in speed (and hence flow) produces a large reduction in power consumption. For example, reducing flow to 80% of design flow (by reducing speed to 80%) reduces power requirement to approximately $0.8^3 = 0.512$, i.e., about 51% of full-speed power - a saving of nearly 49%.

2.8.3 VFD Construction (Block Diagram Description)

29. Rectifier Stage: Converts incoming 3-phase AC supply to DC using a diode or thyristor bridge.
30. DC Link: Smoothens the rectified DC using capacitors (voltage source inverter) or inductors (current source inverter).
31. Inverter Stage: Uses IGBTs (Insulated Gate Bipolar Transistors) with Pulse Width Modulation (PWM) to convert DC back to a variable-voltage, variable-frequency AC output for the motor.
32. Control Section: Microprocessor-based controller implementing V/f control, vector control, or direct torque control (DTC) algorithms, with feedback from speed/current sensors.

2.8.4 Comparison of VSD with Conventional Flow Control (Throttling/Damper)

Aspect	Conventional (Throttle Valve / Damper)	VFD-based Speed Control
Method of flow reduction	Increases system resistance; motor still runs at full speed/power	Reduces motor speed to match required flow
Energy consumption at reduced flow	Power reduces only marginally (system curve shifts, pump operates at lower efficiency)	Power reduces approximately as cube of speed (affinity laws)
Wear and tear	High wear on valves/dampers due to throttling	Reduced mechanical stress; smoother operation
Typical energy saving potential	Reference (baseline)	20-50% depending on duty cycle and flow variation

2.8.5 Applications of VSDs

- Centrifugal pumps (water supply, cooling water, boiler feed pumps with variable demand).
- Fans and blowers (HVAC supply/return air fans, cooling tower fans, ID/FD fans in boilers).
- Compressors with variable air demand.
- Conveyors, mixers, and extruders requiring process speed control.

2.8.6 Limitations / Precautions

- Higher initial cost compared to fixed-speed drives with throttling/damper control.
- Generation of harmonics on the supply side; may require input filters/reactors.
- Operation below approximately 20-30% speed for fans/pumps may not be efficient or may risk overheating of the motor due to reduced cooling at low speed - minimum speed limits should be set.
- Not economical for constant, fully-loaded, continuously running applications with no flow/pressure variation.

2.9 Performance Evaluation of Fans and Pumps

2.9.1 Key Performance Parameters

Parameter	Definition / Significance
Flow Rate (Q)	Volume of fluid (air/water) handled per unit time (m ³ /hr, m ³ /s, LPM, CFM).
Head (H) / Static Pressure (SP)	Energy imparted to the fluid per unit weight (pumps - meters of fluid; fans - mm WC or Pascals).
Shaft/Brake Power (BP)	Mechanical power delivered to the pump/fan shaft by the driver (kW).
Hydraulic/Air Power (HP/AP)	Useful power actually imparted to the fluid: HP = $(\rho \times g \times Q \times H) / 1000$ (kW) for pumps; AP = SP x Q for fans.
Overall Efficiency	$\text{Eta_overall} = (\text{Hydraulic/Air Power}) / (\text{Electrical Input Power}) = \text{Eta_motor} \times \text{Eta_pump_or_fan} \times \text{Eta_transmission}$
Specific Energy Consumption (SEC)	Energy consumed per unit volume of fluid delivered (kWh/m ³ or kWh/1000 m ³); a key benchmarking indicator.

2.9.2 Pump Performance Evaluation - Formula

Hydraulic Power (kW) = $(\rho \times g \times Q \times H) / 1000$ where ρ = density (kg/m³), g = 9.81 m/s², Q = flow (m³/s), H = total head (m)

Pump Efficiency (%) = $(\text{Hydraulic Power} / \text{Shaft Power Input to Pump}) \times 100$

Overall (Wire-to-Water) Efficiency (%) = $(\text{Hydraulic Power} / \text{Electrical Input Power to Motor}) \times 100$

2.9.3 Fan Performance Evaluation - Formula

Air Power (kW) = $(\text{Total Pressure (Pa)} \times \text{Flow Rate (m}^3/\text{s)}) / 1000$

Fan Efficiency (%) = $(\text{Air Power} / \text{Shaft Power Input to Fan}) \times 100$

2.9.4 Typical Performance Benchmarks (Illustrative)

Equipment Type	Typical Achievable Efficiency	Common As-Found Efficiency
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Centrifugal Pump (well-maintained)	70-80%	40-60% (due to wear, oversizing, throttling)
Centrifugal Fan (well-maintained, AF/BC blades)	75-85%	50-70%
Overall (Wire-to-Water/Air) System Efficiency	60-70%	30-50%

2.10 Flow Control Strategies and Energy Conservation Opportunities in Fans and Pumps

2.10.1 Flow Control Strategies

Strategy	Description	Relative Efficiency
On-Off Control	Equipment switched on/off to match average demand; suitable for storage-type systems (tanks, reservoirs)	Moderate
Throttling (Valve/Damper Control)	Restricting flow by increasing resistance using a control valve or damper while the driver runs at constant speed	Low (wastes energy as pressure drop across the valve/damper)
Bypass Control	Excess flow diverted back to source/suction; driver continues to deliver full flow	Low
Speed Control (VFD)	Driver speed varied to match the required flow/head as per affinity laws	High
Multiple Units with Sequencing	Several smaller pumps/fans operated in parallel, switched in/out to match demand, often combined with one VFD-controlled 'trim' unit	High
Impeller/Blade Trimming or Pulley Change	Permanent reduction of impeller diameter or pulley ratio where the system is permanently oversized	High (one-time correction)

2.10.2 Energy Conservation Opportunities (ECOs) - Checklist

33. Avoid over-sizing of pumps/fans at the design stage; select equipment matching actual system requirements rather than applying excessive safety margins.
34. Replace throttling/damper-based flow control with VFDs wherever flow demand varies significantly with time.
35. Trim impellers or replace with correctly sized impellers where the pump consistently operates against a throttled valve/significant bypass.
36. Reduce system resistance: clean/replace clogged filters, strainers, and pipelines; minimize unnecessary bends and fittings; use larger diameter pipes/ducts where economically justified to reduce friction losses.

37. Operate multiple pumps/fans in parallel rather than one large oversized unit, switching units in/out to track load (improves part-load efficiency).
38. Replace old, low-efficiency pumps/fans with modern high-efficiency models (e.g., as per IS 5120, IS 5312, or relevant fan efficiency standards).
39. Ensure proper alignment, belt tensioning, and bearing maintenance to minimize transmission losses.
40. Eliminate leaks in compressed air, water, or process fluid systems that increase the effective flow demand on pumps/fans.
41. Use Energy Efficient Motors (Section 2.6) and ensure correct motor sizing (avoid significant under-loading).
42. Recover energy where possible - e.g., using Pump-As-Turbine (PAT) for energy recovery in high-pressure-drop applications.

2.11 Electronic Ballast

2.11.1 Function of a Ballast

A ballast is a device used with discharge lamps (fluorescent tubes, CFLs, HID lamps) to provide the necessary starting voltage surge, and to limit and regulate the lamp current during steady-state operation, since discharge lamps have a negative resistance characteristic and cannot be connected directly across the supply.

2.11.2 Conventional (Electromagnetic/Copper) Ballast vs Electronic Ballast

Parameter	Conventional (Electromagnetic) Ballast	Electronic (High-Frequency) Ballast
Operating Frequency	50 Hz (line frequency)	20-50 kHz (high frequency)
Ballast Losses	High (10-15 W for a 40W tube light)	Low (1-3 W for a 40W tube light)
Lamp Efficacy (lm/W)	Lower (visible flicker at 100 Hz, stroboscopic effect)	Higher (lamp operates more efficiently at high frequency; flicker-free)
Power Factor	Low (0.3-0.5) unless a separate PF capacitor is used	High (typically > 0.95, built-in PF correction)
Starting	Requires a starter (glow-tube type); slow start, flicker	Instant/rapid start, no separate starter required
Weight and Size	Heavy (iron core and copper winding)	Light (compact electronic circuit)
Lamp Life	Reference	Extended (10-15% longer due to soft start and high-frequency operation)
Energy Saving (overall, vs conventional)	Reference (baseline)	Approximately 15-25% reduction in input power for the same light output

2.11.3 Working Principle of Electronic Ballast

43. AC supply (230V, 50 Hz) is rectified to DC using a bridge rectifier and filter capacitor.
44. A high-frequency inverter (using switching transistors, typically MOSFETs) converts the DC into a high-frequency AC output (20-50 kHz).
45. This high-frequency output is fed to the lamp through a small, low-loss inductor/capacitor network that provides the required pre-heating, ignition voltage, and current limiting.
46. Operating the lamp at high frequency reduces the 're-ignition' losses inherent in 50 Hz operation, improving luminous efficacy by approximately 8-10% for the same lamp.

2.12 Energy Efficient Lighting and Measures of Energy Efficiency in Lighting Systems

2.12.1 Basic Lighting Terminology

Term	Definition / Unit
Luminous Flux	Total quantity of light emitted by a source; unit - lumen (lm).
Illuminance (Illumination Level)	Luminous flux incident per unit area; unit - lux (lm/m ²). Determines adequacy of lighting for a task.
Luminous Efficacy	Ratio of luminous flux output to electrical power input; unit - lumens per watt (lm/W). Primary measure of lamp energy efficiency.
Color Rendering Index (CRI)	A measure (0-100) of how accurately a light source renders colors compared to a reference (natural daylight).
Color Temperature (CCT)	Measure of the 'warmth' or 'coolness' of light, expressed in Kelvin (K); e.g., 2700K (warm white) to 6500K (cool daylight).
Glare	Excessive and uncontrolled brightness causing visual discomfort.
Utilization Factor (UF) / Coefficient of Utilization (CU)	Ratio of luminous flux reaching the working plane to the total flux emitted by the lamps.
Maintenance Factor (MF)	A factor (< 1) accounting for the reduction in light output over time due to dirt accumulation, lamp depreciation, etc.

2.12.2 Comparison of Lamp Types (Luminous Efficacy)

Lamp Type	Luminous Efficacy (lm/W) - Approx.	Typical Lamp Life (hours)
Incandescent (GLS) Lamp	10-15	1,000
Halogen Lamp	15-25	2,000 - 4,000
Compact Fluorescent Lamp (CFL)	50-70	8,000 - 10,000
Tube Light (T8/T5) with Electronic Ballast	85-100	12,000 - 20,000
High Pressure Sodium Vapour (HPSV)	90-120	16,000 - 24,000

Metal Halide	70-100	10,000 - 15,000
LED (current generation)	100-150+	25,000 - 50,000+

2.12.3 Lighting Power Density (LPD) - Benchmarking Indicator

Lighting Power Density (W/m²) = Total connected lighting load (W) / Illuminated floor area (m²)

LPD is a key benchmark used in energy codes (e.g., Energy Conservation Building Code - ECBC) to set maximum allowable lighting power for different space types (offices, corridors, retail, etc.). Lower LPD for the same illuminance level indicates a more energy-efficient lighting system.

2.12.4 Measures of Energy Efficiency / Energy Conservation in Lighting Systems

47. Replace incandescent and conventional fluorescent (T12/magnetic ballast) lamps with LED lamps/luminaires, which offer the highest luminous efficacy and longest life.
48. Use electronic ballasts in place of conventional electromagnetic ballasts for any remaining discharge lamps (Section 2.11).
49. Adopt task/zone-based lighting design (illuminate only the work area to the required lux level, rather than uniform high illumination over the entire space).
50. Maximize use of daylighting through skylights, light shelves, and light pipes, combined with daylight-linked dimming/switching controls.
51. Install occupancy/motion sensors in intermittently used areas (toilets, stores, corridors, stairwells) to automatically switch off lighting when unoccupied.
52. Use timer-based or photo-sensor-based controls for outdoor/street lighting to avoid daytime operation.
53. Group switching/zoning of lighting circuits to allow selective switching based on occupancy and daylight availability.
54. Regular cleaning of luminaires, lamps, and reflectors, and repainting of walls/ceilings with light colors to maintain the Maintenance Factor and Utilization Factor close to design values.
55. Use of high-efficiency luminaires (e.g., parabolic/mirror-optic reflectors) that direct a higher proportion of lamp output to the working plane, allowing fewer fittings for the same illuminance.
56. Conduct periodic lux-level surveys and benchmark against recommended illuminance levels (as per IS 3646 / National Lighting Code) to identify both under-lit (productivity/safety concern) and over-lit (energy waste) areas.

2.12.5 Recommended Illuminance Levels (Illustrative, as per IS/National Lighting Code)

Area / Activity	Recommended Illuminance (lux)	Typical LPD Benchmark (W/m ²)
General Office Work	300 - 500	8 - 11
Corridors / Circulation Areas	100 - 150	3 - 5
Fine Assembly / Inspection Work	750 - 1000	12 - 15

Storage Areas / Warehouses	100 - 200	3 - 6
Classrooms	300 - 500	8 - 11

Summary of Module 2

Module 2 addresses energy efficiency improvement opportunities across the principal electrical loads found in industrial and commercial establishments. It begins with the structure of electricity billing and tariffs (energy charges, demand charges, power factor incentives/penalties, ToD tariffs), which forms the financial basis for evaluating savings. It then covers load management and maximum demand control (including MD controllers) to minimize demand-related charges. Power factor improvement (capacitors, synchronous condensers, phase advancers) and automatic power factor controllers are discussed as means of reducing reactive power drawal and associated penalties/losses. Efficient operation of transformers and the use of energy-efficient motors target the reduction of no-load and load-dependent losses in the two most common pieces of electrical equipment. Soft starters and variable speed drives address starting transients and, more importantly (for VSDs), the cube-law relationship between speed and power for fans/pumps, offering large energy-saving potential. Performance evaluation of fans and pumps, along with flow control strategies, provide the methodology to identify and quantify energy conservation opportunities. Finally, electronic ballasts and energy-efficient lighting measures (LEDs, daylighting, controls, LPD benchmarking) complete the module by addressing the lighting load, which is often a significant and easily improvable component of the electrical energy bill.