

PRACTICE PAPER – SET 3
NATIONAL CERTIFICATION EXAMINATION FOR
ENERGY MANAGERS & ENERGY AUDITORS
PAPER – 3: ENERGY EFFICIENCY IN ELECTRICAL UTILITIES
ANSWER KEY, EXPLANATIONS AND MODEL ANSWERS

Duration: 3 HRS Max. Marks: 150

General instructions:

- Please check that this question paper contains 64 questions
- The question paper is divided into three sections
- All questions in all three sections are compulsory
- All parts of a question should be answered at one place
- Use of a non-programmable scientific calculator is permitted

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Section – I: OBJECTIVE TYPE Marks: 50 x 1 = 50

1. Answer all 50 questions
2. Each question carries one mark
3. Choose the most appropriate option (a, b, c or d)

1 A Class F motor with an expected insulation life of 20 years runs continuously 15 °C above its permissible winding temperature because of a choked cooling fan cowl. Using the common rule that insulation life halves for every 10 °C rise, its expected insulation life becomes about:

[3P3CEM001 | Chapter 2: Electrical Motors | 2.4 Factors affecting motor life – winding temperature]

- a) 10.0 years
- b) 5.0 years
- c) 13.3 years
- d) 7.1 years**

Answer & explanation

Correct answer: (d) ≈ 7.1 years.

Given: base life $L_0 = 20$ years; excess temperature $\Delta T = 15$ °C; life halves per 10 °C.

Formula: $L = L_0 \times 0.5^{(\Delta T / 10)}$.

Substitution: $0.5^{1.5} = 0.354$; $L = 20 \times 0.354$.

Result: **expected life ≈ 7.1 years**, about one-third of design life.

Why the others are wrong: (a) applies only one halving step; (b) rounds up to two halving steps (20 °C); (c) reduces life in simple proportion, but insulation ageing is exponential with temperature. High winding temperature also raises stator resistance and copper loss, lowering efficiency. Causes include dirty fins, blocked

cowls, overload, low or unbalanced voltage and high ambient temperature. Keeping motors clean and correctly loaded protects both efficiency and life, and avoids early rewinding, which itself lowers efficiency.

Ref: BEE Guidebook Paper 3, Ch. 2 (Factors affecting motor performance; maintenance).

2 A 625 kVA DG set (500 kW at 0.8 PF) supplies a 440 kW load at 0.70 PF. If capacitors at the load raise the PF to 0.90, the DG kVA loading changes from about:

[3P3CEM002 | Chapter 9: Diesel / Natural Gas Power Generating System | 9.3 DG operation – kVA loading and the effect of load PF]

- a) 101 % to 78 %
- b) 88 % to 88 %
- c) 70 % to 90 %
- d) 101 % to 70 %

Answer & explanation

Correct answer: (a) $\approx$ 101 % to 78 %.

Given: rating 625 kVA; load 440 kW; $PF_1 = 0.70$; $PF_2 = 0.90$.

Formula: $kVA = kW / PF$; loading = $kVA / \text{rated } kVA \times 100$.

Substitution: $kVA_1 = 440 / 0.70 = 628.6$ kVA, i.e. 100.6 %; $kVA_2 = 440 / 0.90 = 488.9$ kVA, i.e. 78.2 %.

Result: **kVA loading falls from $\approx$ 101 % to $\approx$ 78 %**; about 122 kW of extra load could then be carried at 0.9 PF within 625 kVA.

Why the others are wrong: (b) compares kW with 500 kW only, but alternator heating depends on current (kVA); (c) mistakes the PF values for loading; (d) divides kW by kVA rating. At 0.70 PF the alternator is at its current limit, although the engine is only 88 % loaded. Load PF correction frees alternator capacity, cuts copper losses and may avoid running a second set at poor loading.

Ref: BEE Guidebook Paper 3, Ch. 9 (Operational factors – load and power factor).

3 Eco-Niwas Samhita (ECBC for residential buildings) Part 1 limits the RETV of the building envelope. RETV is the:

[3P3CEM003 | Chapter 10: Energy Conservation in Buildings and ECBC | 10.6 Eco-Niwas Samhita – RETV for residential envelopes]

- a) Visible light transmitted through the windows per unit carpet area
- b) Ventilation air changes per hour required in the habitable rooms
- c) Embodied carbon of the walling material per square metre of wall
- d) **Heat gain through the envelope, excluding the roof, per unit envelope area**

Answer & explanation

Correct answer: (d).

Residential Envelope Transmittance Value (RETV), in W/m^2 , is the net heat gain rate through the building envelope excluding the roof (opaque walls and non-opaque elements such as windows) divided by the area of that envelope. It accounts for conduction through walls and windows and solar radiation through glazing, weighted by climate-zone coefficients. Eco-Niwas Samhita 2018 Part 1 caps RETV at $15 W/m^2$ for the composite, hot-dry, warm-humid and temperate zones. Separate limits apply to roof transmittance (U_{roof}), openable window-to-floor area ratio and, for the cold zone, wall and window transmittance.

Why the others are wrong: (a) describes a daylighting measure; (b) is a ventilation requirement; (c) concerns embodied carbon, which RETV does not cover. Lower RETV reduces cooling demand and improves comfort in non-air-conditioned homes, which matters because residential AC demand is growing rapidly.

Ref: BEE Guidebook Paper 3, Ch. 10 (Energy conservation in buildings – residential code).

4 An LED high-bay datasheet states 'L70 at 50,000 h'. For lighting design and replacement planning, this means:

[3P3CEM004 | Chapter 8: Lighting System | 8.3 LED luminaires – rated life (L70) and lumen maintenance]

- a) Seventy per cent of the luminaires will have failed by 50,000 hours
- b) The luminaire's efficacy rises to 70 lm/W after 50,000 hours of use
- c) Light output falls to 70 % of initial lumens at 50,000 h**
- d) The driver will operate at 70 % power for the first 50,000 hours

Answer & explanation

Correct answer: (c).

LEDs rarely fail abruptly; instead their light output slowly falls as phosphor and chip performance degrade, largely driven by junction temperature. L70 is the operating time at which lumen output is expected to fall to 70 % of the initial value, which is the commonly accepted end of useful life. A design must therefore use a lumen maintenance (depreciation) factor so that maintained illuminance is still met near the end of the rated period.

Why the others are wrong: (a) confuses lumen maintenance with a failure rate (failure statistics are quoted separately, for example B10 or B50); (b) efficacy does not rise with age; it falls along with output; (d) L70 has nothing to do with driver power level. Good thermal design (heat sinks, ambient temperature) extends L70 life, and constant-lumen drivers can start at lower power and raise it with age, saving energy in early years.

Ref: BEE Guidebook Paper 3, Ch. 8 (Light sources – LED characteristics; maintenance factor).

5 A centrifugal chiller's tested specific power is 0.62 kW/TR at 100 % load, 0.55 at 75 %, 0.50 at 50 % and 0.58 at 25 %. Using the AHRI weighting (1 %, 42 %, 45 %, 12 %) applied to kW/TR as $IPLV = 1 / (0.01/A + 0.42/B + 0.45/C + 0.12/D)$, its IPLV is about:

[3P3CEM005 | Chapter 4: HVAC and Refrigeration System | 4.7 Chiller part-load rating – IPLV]

- a) 0.563 kW/TR
- b) 0.620 kW/TR
- c) 0.530 kW/TR**
- d) 0.500 kW/TR

Answer & explanation

Correct answer: (c) ≈ 0.530 kW/TR.

Given: A = 0.62, B = 0.55, C = 0.50, D = 0.58 kW/TR at 100/75/50/25 % load; weights 0.01, 0.42, 0.45, 0.12.

Formula: $IPLV (kW/TR) = 1 / (0.01/A + 0.42/B + 0.45/C + 0.12/D)$.

Substitution: $0.01/0.62 = 0.0161$; $0.42/0.55 = 0.7636$; $0.45/0.50 = 0.9000$; $0.12/0.58 = 0.2069$; sum = 1.8867.

Result: **$IPLV \approx 1 / 1.8867 \approx 0.530$ kW/TR.**

Why the others are wrong: (a) is a simple average of the four points, ignoring that chillers run mostly at 50–75 % load; (b) is the full-load rating, which the machine sees for only about 1 % of hours; (d) is the single best point at 50 % load, not a weighted value. Comparing chillers on IPLV, or on site-specific load hours, gives a truer picture of annual energy than full-load kW/TR alone. ECBC specifies both full-load and IPLV limits.

Ref: BEE Guidebook Paper 3, Ch. 4 (Performance assessment of refrigeration plants) and Ch. 10 (ECBC HVAC requirements).

6 A thermographic survey of a 3-phase LT bus duct carrying 800 A per phase finds one hot tap-off joint in each phase, each with about 0.5 mΩ of extra contact resistance. If the joints are left unattended for 8,000 operating hours a year, the energy wasted in them is about:

- a) **7,680 kWh**
- b) 2,560 kWh
- c) 13,302 kWh
- d) 4,434 kWh

Answer & explanation

Correct answer: (a) $\approx 7,680$ kWh per year.

Given: $I = 800$ A per phase; extra resistance $R = 0.5 \text{ m}\Omega = 0.0005 \Omega$ per joint; three joints (one per phase); 8,000 h/year.

Formula: loss per joint $= I^2 \times R$; annual energy = number of joints $\times I^2 R \times \text{hours} / 1,000$.

Substitution: $800^2 \times 0.0005 = 320$ W per joint; $3 \times 320 = 960$ W; $0.96 \text{ kW} \times 8,000 \text{ h}$.

Result: $\approx 7,680 \text{ kWh per year}$ ($\approx ₹ 61,440$ at $₹ 8/\text{kWh}$).

Why the others are wrong: (b) counts only one phase's joint; (c) multiplies the three-joint loss again by $\sqrt{3}$, which applies to line voltage, not to I^2R of individual conductors; (d) divides by $\sqrt{3}$ for the same reason. Beyond the energy loss, a hot joint heats up further as oxidation increases its resistance, and can fail and cause a fire.

Periodic thermography, re-torquing and cleaning of joints are cheap, high-value maintenance measures in distribution systems.

Ref: BEE Guidebook Paper 3, Ch. 1 (Distribution losses; electrical system maintenance).

7 A chiller has an evaporating temperature of 5°C . Cleaning its condenser tubes lowers the condensing temperature from 45°C to 38°C . The theoretical (Carnot) cooling COP changes from:

- a) 7.95 to 9.43
- b) 0.13 to 0.15
- c) **6.95 to 8.43**
- d) 8.43 to 6.95

Answer & explanation

Correct answer: (c) 6.95 to 8.43.

Given: $T_e = 5^\circ\text{C} = 278.15 \text{ K}$; $T_c = 45^\circ\text{C} (318.15 \text{ K})$, then $38^\circ\text{C} (311.15 \text{ K})$.

Formula: Carnot cooling $\text{COP} = T_e / (T_c - T_e)$, with absolute temperatures.

Substitution: before $= 278.15 / 40 = 6.95$; after $= 278.15 / 33 = 8.43$.

Result: **theoretical COP rises from ≈ 6.95 to ≈ 8.43 (+21 %).**

Why the others are wrong: (a) is the heat-pump (heating) COP, $T_c / (T_c - T_e)$; (b) uses Celsius values, which is not valid; (d) reverses the direction of change. Real machines reach only about half the Carnot value, but the trend holds: every reduction in temperature lift (condensing minus evaporating temperature) cuts compressor work. Fouled condenser tubes, high condenser water temperature and non-condensables raise the condensing temperature and specific power, so tube cleaning and good cooling tower performance give direct savings.

Ref: BEE Guidebook Paper 3, Ch. 4 (Vapour compression refrigeration; factors affecting performance).

8 The charge air cooler (after-cooler) of a turbocharged DG set is badly fouled, so intake manifold air temperature rises by about 20°C at the same load. The main consequence is:

- a) Higher air density, so the set can carry more than its rated load
- b) Lower exhaust temperature, so the waste-heat recovery potential falls
- c) No change in fuel use, since only lube oil temperature is affected
- d) Lower air density and mass, so SFC and exhaust temperature rise**

Answer & explanation

Correct answer: (d).

The turbocharger compresses intake air, which heats it. The after-cooler then cools it so that more air mass fits into each cylinder charge. If the cooler is fouled, warmer and less dense air enters. Air mass per cycle falls and combustion becomes air-starved (richer mixture), so combustion efficiency drops, specific fuel consumption rises, and exhaust temperature and smoke increase. Thermal stress on valves and turbocharger also rises, and the set may need derating.

Why the others are wrong: (a) hotter air is less dense, not more, and lower density reduces, not raises, output capability; (b) exhaust temperature rises, not falls; (c) charge air temperature directly affects combustion and fuel use. Logging charge air temperature, exhaust temperature per cylinder and kWh per litre helps detect such faults early. Cleaning coolers, air filters and turbochargers is a basic DG energy-saving measure.

Ref: BEE Guidebook Paper 3, Ch. 9 (Energy saving measures for DG sets – air intake and turbocharging).

9 A raw-water transfer system has a static head of 25 m and a friction head of 15 m at 300 m³/h. Flow is reduced to 210 m³/h by a VFD, with no throttling, so the pump follows the system curve. Assuming constant pump efficiency, the hydraulic power at reduced flow as a percentage of the original is about:

[3P3CEM009 | Chapter 6: Pumps and Pumping System | 6.6 VFD savings in systems with static head]

- a) 34.3 %
- b) 56.6 %**
- c) 49.0 %
- d) 70.0 %

Answer & explanation

Correct answer: (b) ≈ 56.6 %.

Given: $H_{\text{static}} = 25 \text{ m}$; $H_{\text{friction}} = 15 \text{ m}$ at $Q_1 = 300 \text{ m}^3/\text{h}$; $Q_2 = 210 \text{ m}^3/\text{h}$.

Formula: system head $H = H_{\text{static}} + H_{\text{friction}} \times (Q_2/Q_1)^2$; hydraulic power $\propto Q \times H$.

Substitution: $H_2 = 25 + 15 \times 0.49 = 32.35 \text{ m}$; power ratio = $(210 \times 32.35) / (300 \times 40) = 6,793.5 / 12,000$.

Result: **hydraulic power ≈ 56.6 % of original.**

Why the others are wrong: (a) applies the cube law (0.7^3), valid only when the system has no static head; (c) uses the square of the flow ratio; (d) scales power linearly with flow, ignoring the head reduction. With high static head, the affinity laws overstate VFD savings. Pump efficiency may also fall if speed is reduced too far. The savings estimate must come from the intersection of the pump curve at reduced speed with the actual system curve.

Ref: BEE Guidebook Paper 3, Ch. 6 (System characteristics; flow control by variable speed drives).

10 Air enters a chilled water cooling coil at 32 °C DBT and leaves at 15 °C DBT. The coil's apparatus dew point (ADP) is 11 °C. The bypass factor of the coil is about:

[3P3CEM010 | Chapter 4: HVAC and Refrigeration System | 4.2 Cooling coil performance – bypass factor]

- a) 0.81
- b) 0.19**

- c) 0.27
- d) 0.24

Answer & explanation

Correct answer: (b) ≈ 0.19 .

Given: $t_{in} = 32\text{ }^{\circ}\text{C}$; $t_{out} = 15\text{ }^{\circ}\text{C}$; $ADP = 11\text{ }^{\circ}\text{C}$.

Formula: bypass factor $BF = (t_{out} - ADP) / (t_{in} - ADP)$; contact factor $= 1 - BF$.

Substitution: $BF = (15 - 11) / (32 - 11) = 4 / 21$.

Result: **bypass factor ≈ 0.19 ; contact factor ≈ 0.81 .**

Why the others are wrong: (a) is the contact factor, the fraction of air that effectively touches the coil surface; (c) divides by the leaving temperature (4 / 15); (d) divides by the temperature drop (4 / 17) instead of the difference between inlet temperature and ADP. Bypass factor rises with face velocity and fewer coil rows. A high bypass factor forces a lower ADP, and hence a lower chilled water temperature, for the same leaving air condition. That lowers chiller evaporator temperature and raises kW/TR, so coil selection and cleanliness affect plant efficiency.

Ref: BEE Guidebook Paper 3, Ch. 4 (Air-conditioning processes – cooling coil, ADP and bypass factor).

11 Select the CORRECT comparison of induced-draft counterflow and crossflow cooling towers:

[3P3CEM011 | Chapter 7: Cooling Towers | 7.1 Cooling tower types – counterflow and crossflow]

- a) Counterflow towers move air horizontally across the falling water
- b) Crossflow towers need higher pump head because of pressurised sprays
- c) Counterflow towers need less plan area for the same thermal duty**
- d) Counterflow fill can only be splash bars, never film packs

Answer & explanation

Correct answer: (c).

In a counterflow tower, air moves vertically upward against water falling through the fill. The coldest air meets the coldest water, so heat-transfer driving force is used well, and the tower is compact in plan for a given duty. Water is distributed by pressurised spray nozzles above the fill, which needs a little more pump head.

Why the others are wrong: (a) horizontal air flow across the falling water describes the crossflow tower; (b) crossflow towers usually use open gravity hot-water basins with low-pressure nozzles, so they need less pump head, not more; (d) counterflow towers commonly use high-efficiency film fill, while splash fill is chosen only where water is dirty. Crossflow towers are easier to inspect and maintain and have low pumping head.

Counterflow towers save space and usually reach a closer approach. The auditor should account for both fan and pump energy when comparing options.

Ref: BEE Guidebook Paper 3, Ch. 7 (Types of cooling towers; components).

12 Three identical pumps work in parallel on a header: one has a VFD and two run at fixed speed. When the VFD pump is slowed well below full speed, the most likely problem is:

[3P3CEM012 | Chapter 6: Pumps and Pumping System | 6.5 Parallel pumps with mixed fixed and variable speed]

- a) It takes a larger share of the flow and overloads its own motor
- b) Its shut-off head drops below header pressure, so its flow nearly stops**
- c) The fixed-speed pumps move towards shut-off and begin to overheat
- d) System head rises sharply because friction grows with pump speed

Answer & explanation

Correct answer: (b).

In parallel operation all pumps discharge against the same header pressure. Shut-off head varies with the square of speed, so at 75 % speed the VFD pump's shut-off head is only about 56 % of the fixed-speed pumps' value. Once its shut-off head falls below the header pressure set by the fixed-speed pumps, it delivers little or no flow. It then churns water near shut-off, heating up at very low efficiency while still drawing power.

Why the others are wrong: (a) a slower pump takes a smaller share, not a larger one; (c) the fixed-speed pumps pick up the lost flow and move towards run-out (higher flow), not shut-off; (d) system friction depends on total flow, not on one pump's speed. Good practice is to run all parallel pumps at the same speed through a common VFD control, with pump staging, and to check minimum-flow limits.

Ref: BEE Guidebook Paper 3, Ch. 6 (Pumps in parallel; flow control by variable speed).

13 Heat radiated into a DG room from the engine, alternator and exhaust piping is 90 kW. The room temperature rise over ambient must not exceed 7 °C. Taking air density 1.2 kg/m³ and cp 1.005 kJ/kg·K, the ventilation air required (excluding combustion air) is about:

[3P3CEM013 | Chapter 9: Diesel / Natural Gas Power Generating System | 9.4 DG installation – ventilation air for the DG room]

- a) 46,055 m³/h
- b) 9,212 m³/h
- c) 38,380 m³/h**
- d) 55,267 m³/h

Answer & explanation

Correct answer: (c) $\approx 38,380 \text{ m}^3/\text{h}$.

Given: heat radiated $Q = 90 \text{ kW}$; permitted rise $\Delta T = 7 \text{ K}$; $\rho = 1.2 \text{ kg/m}^3$; $c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$.

Formula: mass flow $m = Q / (c_p \times \Delta T)$; volume flow $= m / \rho \times 3,600$.

Substitution: $m = 90 / (1.005 \times 7) = 12.79 \text{ kg/s}$; $V = 12.79 / 1.2 \times 3,600$.

Result: $\approx 38,380 \text{ m}^3/\text{h}$ ($\approx 10.7 \text{ m}^3/\text{s}$) of ventilation air.

Why the others are wrong: (a) treats kg/h as m³/h by ignoring density; (b) uses the specific heat of water (4.187 kJ/kg·K) instead of air; (d) multiplies by density instead of dividing. Poor ventilation raises the temperature of the engine's intake air. Hotter, thinner air reduces the air mass per cycle, which raises specific fuel consumption and forces derating, as with a high-ambient site. Combustion air should preferably be drawn from outside through a short, low-resistance duct, and the hot air exhausted high on the opposite wall.

Ref: BEE Guidebook Paper 3, Ch. 9 (DG installation and operational factors – air intake and ventilation).

14 In a four-cell tower, cells 1 and 2 give cold water 2.5 °C warmer than cells 3 and 4 at the same fan current. The hot-water basins of cells 1–2 overflow, while those of cells 3–4 are half dry. The best first action is:

[3P3CEM014 | Chapter 7: Cooling Towers | 7.4 Water distribution – hydraulic imbalance between cells]

- a) Raise blade pitch on cells 1 and 2 to boost their air flow
- b) Raise blowdown so the cycles of concentration in the basin rise
- c) Balance hot-water flow between cells with riser valves and clean nozzles**
- d) Add a fifth cell, as the tower is thermally undersized

Answer & explanation

Correct answer: (c).

The symptoms show hydraulic imbalance. Cells 1–2 receive more water than their fill and air flow can cool, so water overflows the basins and bypasses part of the fill. Meanwhile, cells 3–4 are under-loaded with dry patches,

so their air passes through partly unused fill. Balancing flow with riser valves and clearing choked nozzles restores even loading and lowers the mixed cold-water temperature without extra fan power.

Why the others are wrong: (a) more air on overloaded cells raises fan power (roughly with the cube of air flow) while the real cause stays; (b) increasing blowdown lowers, not raises, cycles of concentration, and water chemistry is not the cause; (d) capacity cannot be judged until flow is evenly distributed. Each 1 °C of colder water typically cuts chiller power by 2–3 %, so balancing gives a quick, low-cost gain.

Ref: BEE Guidebook Paper 3, Ch. 7 (Cooling tower performance; energy saving opportunities – water distribution).

15 An office AHU takes 10,000 m³/h of fresh air at 40 °C. A heat recovery wheel exchanges heat with the 24 °C exhaust air, and the fresh air leaves the wheel at 28 °C. Taking $\rho = 1.2 \text{ kg/m}^3$ and $c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$, the wheel's sensible effectiveness and the cooling load it saves are:

[3P3CEM015 | Chapter 4: HVAC and Refrigeration System | 4.8 Energy recovery wheel – sensible effectiveness and load saved]

- a) 25 % and 3.8 TR
- b) 75 % and 11.4 TR**
- c) 75 % and 40.2 TR
- d) 30 % and 11.4 TR

Answer & explanation

Correct answer: (b) 75 % and $\approx 11.4 \text{ TR}$.

Given: fresh air 10,000 m³/h at 40 °C; exhaust 24 °C; leaving wheel 28 °C; $\rho = 1.2 \text{ kg/m}^3$; $c_p = 1.005 \text{ kJ/kg}\cdot\text{K}$; 1 TR = 3.517 kW.

Formula: $\epsilon = (t_{\text{oa}} - t_{\text{sa}}) / (t_{\text{oa}} - t_{\text{ra}})$; load saved = $m \times c_p \times (t_{\text{oa}} - t_{\text{sa}})$.

Substitution: $\epsilon = (40 - 28) / (40 - 24) = 12 / 16$; $m = 10,000 \times 1.2 / 3,600 = 3.333 \text{ kg/s}$; $Q = 3.333 \times 1.005 \times 12 = 40.2 \text{ kW}$; $40.2 / 3.517$.

Result: $\epsilon = 75 \%$; **sensible load saved $\approx 40.2 \text{ kW} \approx 11.4 \text{ TR}$.**

Why the others are wrong: (a) uses the remaining 4 °C approach instead of the 12 °C drop; (c) reports kW as TR; (d) divides the drop by outdoor temperature instead of the available difference. Enthalpy wheels also recover latent heat, so savings are larger in humid climates.

Ref: BEE Guidebook Paper 3, Ch. 4 (Energy saving opportunities – heat recovery in HVAC).

16 A wall consists of 230 mm brick ($k = 0.81 \text{ W/m}\cdot\text{K}$) with 12 mm cement plaster on each side ($k = 0.72 \text{ W/m}\cdot\text{K}$). Inside and outside surface film resistances are 0.13 and 0.04 m²·K/W. Its U-value, and the U-value after adding 50 mm of EPS insulation ($k = 0.035 \text{ W/m}\cdot\text{K}$), are about:

[3P3CEM016 | Chapter 10: Energy Conservation in Buildings and ECBC | 10.3 Building envelope – U-value of a composite wall]

- a) 3.15 and 0.57 W/m²·K
- b) 0.49 and 1.92 W/m²·K
- c) 2.05 and 0.84 W/m²·K
- d) 2.05 and 0.52 W/m²·K**

Answer & explanation

Correct answer: (d) ≈ 2.05 and 0.52 W/m²·K.

Given: brick 0.230 m, k 0.81; plaster $2 \times 0.012 \text{ m}$, k 0.72; $R_{\text{si}} = 0.13$, $R_{\text{so}} = 0.04 \text{ m}^2\cdot\text{K/W}$; EPS 0.050 m, k 0.035.

Formula: $R_{\text{total}} = R_{\text{si}} + R_{\text{so}} + \Sigma(L / k)$; $U = 1 / R_{\text{total}}$.

Substitution: $R = 0.13 + 0.04 + 0.284 + 0.033 = 0.487 \text{ m}^2\cdot\text{K}/\text{W}$, so $U = 2.05$; with EPS, $R = 0.487 + 1.429 = 1.916$, so $U = 0.52$.

Result: **$U \approx 2.05 \text{ W}/\text{m}^2\cdot\text{K}$, falling to $\approx 0.52 \text{ W}/\text{m}^2\cdot\text{K}$ with insulation.**

Why the others are wrong: (a) omits the surface film resistances; (b) reports the resistances (R) instead of U-values; (c) adds k/L (0.7) instead of L/k for the insulation. The insulated wall conducts about a quarter of the heat. ECBC sets maximum wall and roof U-factors by climate zone.

Ref: BEE Guidebook Paper 3, Ch. 10 (Building envelope – thermal transmittance).

17 Select the CORRECT statement about centrifugal air compressors:

[3P3CEM017 | Chapter 3: Compressed Air System | 3.2 Compressor types – centrifugal compressors]

- a) Their efficiency improves when they are turned down below surge
- b) They are positive-displacement machines with fixed output per revolution
- c) They give the lowest specific power at flows below $10 \text{ m}^3/\text{min}$
- d) They deliver oil-free air and suit large, steady base-load demand**

Answer & explanation

Correct answer: (d).

Centrifugal compressors are dynamic machines: high-speed impellers raise air velocity, which diffusers convert to pressure. With no oil in the compression chamber they deliver oil-free air. They are most efficient in large sizes, typically above about $100 \text{ m}^3/\text{min}$, and are best run as steady base-load machines near design flow.

Why the others are wrong: (a) below the surge line, flow reverses and becomes unstable, so the machine must blow off air, which wastes energy; turndown is limited, typically to about 70–80 % with inlet guide vanes; (b) positive-displacement machines are reciprocating, screw and vane types, while centrifugal output varies with system pressure; (c) at small flows, screw or reciprocating machines are more efficient. In multi-compressor plants, centrifugals carry base load while a VSD screw trims the varying load.

Ref: BEE Guidebook Paper 3, Ch. 3 (Types of compressors and their selection).

18 A conveyor motor develops a starting torque of 180 % of full-load torque at its rated 415 V. When it is started at the end of a long cable, the terminal voltage dips to 360 V. The starting torque actually available is about:

[3P3CEM018 | Chapter 2: Electrical Motors | 2.3 Motor characteristics – torque at reduced terminal voltage]

- a) 156 % of full-load torque
- b) 118 % of full-load torque
- c) 135 % of full-load torque**
- d) 239 % of full-load torque

Answer & explanation

Correct answer: (c) ≈ 135 % of full-load torque.

Given: $T_{st} = 180$ % at 415 V; actual voltage 360 V.

Formula: induction motor torque at a given slip $\propto V^2$, so $T_2 = T_1 \times (V_2 / V_1)^2$.

Substitution: $(360 / 415)^2 = 0.8675^2 = 0.7525$; $T_2 = 180 \times 0.7525$.

Result: **starting torque ≈ 135 % of full-load torque.**

Why the others are wrong: (a) scales torque linearly with voltage; (b) uses the cube of the voltage ratio; (d) inverts the ratio, as if torque rose at lower voltage. A 13 % voltage dip removes a quarter of the starting torque, so a loaded conveyor needing about 140 % breakaway torque may fail to start, overheat and trip. Low voltage

also raises running current and copper loss at the same load. Remedies include a larger cable, a transformer tap change, or a soft starter matched to the load.

Ref: BEE Guidebook Paper 3, Ch. 2 (Motor characteristics; effect of voltage variation).

19 A lux survey on a 3 × 3 grid in a machine shop gives 420, 380, 310, 450, 470, 360, 290, 400 and 430 lux. The average illuminance and the uniformity ratio ($E_{\min} / E_{\text{avg}}$) are:

[3P3CEM019 | Chapter 8: Lighting System | 8.5 Lighting survey – average illuminance and uniformity]

- a) 390 lux and 0.62
- b) 390 lux and 0.74**
- c) 400 lux and 0.73
- d) 390 lux and 1.34

Answer & explanation

Correct answer: (b) 390 lux and 0.74.

Given: nine grid readings; sum = 3,510 lux; minimum = 290 lux; maximum = 470 lux.

Formula: $E_{\text{avg}} = \Sigma \text{ readings} / \text{number of points}$; uniformity $U_o = E_{\min} / E_{\text{avg}}$.

Substitution: $E_{\text{avg}} = 3,510 / 9 = 390 \text{ lux}$; $U_o = 290 / 390$.

Result: **average ≈ 390 lux; uniformity ≈ 0.74.**

Why the others are wrong: (a) uses $E_{\min} / E_{\max}$ (0.62), a different, stricter ratio; (c) uses the median reading (400 lux) instead of the mean; (d) inverts the ratio, giving a value above 1, which uniformity cannot exceed. Good grid measurement, with points evenly spaced and away from the walls, comes before any retrofit. Low uniformity shows uneven spacing or failed lamps. Users then tend to demand higher average illuminance, so improving uniformity can allow lower installed wattage for the same visual comfort.

Ref: BEE Guidebook Paper 3, Ch. 8 (Assessment of lighting systems – illuminance measurement).

20 A 600 kW drive is converted from a 6-pulse rectifier to a 12-pulse rectifier fed by a three-winding (star and delta secondary) transformer. Which characteristic harmonics are largely cancelled at the supply side?

[3P3CEM020 | Chapter 1: Electrical Systems | 1.10 Harmonics – multi-pulse rectifiers]

- a) 3rd and 9th, leaving 5th and 7th as the lowest
- b) 5th and 7th, leaving 11th and 13th as the lowest**
- c) 11th and 13th, leaving 5th and 7th as the lowest
- d) All odd orders, leaving only even harmonics in the supply

Answer & explanation

Correct answer: (b).

A p-pulse converter produces characteristic harmonics of order $h = kp \pm 1$ ($k = 1, 2, 3 \dots$). A 6-pulse bridge therefore produces the 5th, 7th, 11th, 13th and so on, with the 5th and 7th the largest. In a 12-pulse arrangement the two 6-pulse bridges are supplied 30° apart by the star and delta secondaries. The 5th, 7th, 17th and 19th currents of the two bridges are in antiphase on the primary side and cancel, leaving the 11th, 13th, 23rd and 25th.

Why the others are wrong: (a) triplen harmonics come mainly from single-phase non-linear loads, not 3-phase bridges; (c) reverses the cancellation; (d) balanced converters do not generate even harmonics, and not all odd orders cancel. Lower THD means lower transformer and cable losses and less risk of capacitor resonance.

Ref: BEE Guidebook Paper 3, Ch. 1 (Harmonics – sources, effects and mitigation).

21 Replacing a thermostatic expansion valve (TXV) with an electronic expansion valve (EEV) on an air-cooled chiller saves energy mainly because it:

[3P3CEM021 | Chapter 4: HVAC and Refrigeration System | 4.8 Expansion devices – electronic expansion valve]

- a) Raises the condensing temperature to improve compressor oil return
- b) Removes the need for compressor capacity control at part load
- c) Increases suction superheat, raising compressor volumetric efficiency
- d) Allows floating (lower) head pressure at low ambient temperatures**

Answer & explanation

Correct answer: (d).

A TXV needs a minimum pressure difference across it to feed the evaporator properly. Plants with TXVs therefore often hold condensing pressure artificially high (head-pressure control) even on cool days or nights. An EEV with electronic superheat control works over a wide pressure difference, so condensing pressure can float down with ambient temperature. Each degree of lower lift reduces compressor power, so annual savings can be significant in seasons or regions with cool ambient air.

Why the others are wrong: (a) a higher condensing temperature increases compressor work; (b) the EEV controls refrigerant feed, not compressor capacity, which is still needed at part load; (c) higher superheat lowers suction density and evaporator effectiveness, which reduces capacity and efficiency; the EEV actually allows lower, stable superheat. EEVs are now standard on inverter and VRF equipment for these reasons.

Ref: BEE Guidebook Paper 3, Ch. 4 (Refrigeration system components; energy saving opportunities).

22 A plant at 7 kg/cm²(g) ($\approx$ 6.86 bar(g)) supplies a general workshop (indoors, always above 15 °C) and an instrument air line that runs outdoors where winter nights reach 0 °C. Which drying arrangement is energy-sensible?

[3P3CEM022 | Chapter 3: Compressed Air System | 3.4 Dryer selection – matching dew point to end use]

- a) Refrigerated dryer for all air; small desiccant dryer only for instrument air**
- b) Heatless desiccant dryer to –40 °C dew point for the entire plant flow
- c) No dryer, since the after-cooler removes all moisture from compressed air
- d) Refrigerated dryer only, as a +3 °C dew point suits the outdoor line

Answer & explanation

Correct answer: (a).

A refrigerated dryer gives a pressure dew point of about +3 °C at low energy cost (roughly 2–3 % of compressor power), which is enough for indoor air that never cools below 15 °C. The outdoor instrument line can fall to 0 °C, below +3 °C, so water would condense and freeze. Only that small flow needs a desiccant dryer (dew point –20 to –40 °C).

Why the others are wrong: (b) heatless desiccant dryers use about 15 % of the dried air for purge, so drying all the air this way wastes a lot of compressor energy; (c) an after-cooler removes only part of the moisture, and the air leaves saturated; (d) a +3 °C dew point is above the 0 °C pipe temperature outdoors, so condensation will occur. Matching air quality to each end use, rather than to the strictest use, is a basic compressed air energy principle.

Ref: BEE Guidebook Paper 3, Ch. 3 (Compressed air treatment – dryers).

23 A motor nameplate reads 30 kW, continuous duty, service factor 1.15. Which interpretation is correct?

[3P3CEM023 | Chapter 2: Electrical Motors | 2.3 Motor nameplate – service factor]

- a) It may carry up to 34.5 kW, but with higher winding temperature
- b) Its efficiency at 34.5 kW output is 15 % above nameplate value
- c) It should be loaded to 26 kW only, i.e. rated kW ÷ 1.15
- d) Its starting current is limited to 1.15 times full-load current

Answer & explanation

Correct answer: (a).

Service factor is a multiplier showing the permissible continuous overload when the motor runs at rated voltage and frequency. With SF 1.15, a 30 kW motor can deliver up to $1.15 \times 30 = 34.5$ kW, but at higher current, higher winding temperature and reduced insulation life. Operation in the service-factor zone is meant for occasional margin, not as normal duty.

Why the others are wrong: (b) efficiency normally peaks around 75–100 % load and does not rise by 15 % in overload; (c) inverts the meaning, since SF permits overload rather than requiring derating; (d) starting current of a DOL motor is typically 6–7 times full-load current and is not related to service factor. In energy audits, a motor found running in its service-factor range is a reliability concern. A motor found running at 30–40 % load is the commoner efficiency concern.

Ref: BEE Guidebook Paper 3, Ch. 2 (Motor selection and rating).

24 A conditioned laboratory has a room sensible heat load of 42 kW and a latent load of 14 kW. Supply air enters 10 °C below room temperature. Taking air density 1.2 kg/m³ and cp 1.005 kJ/kg·K, the supply air quantity required is about:

[3P3CEM024 | Chapter 4: HVAC and Refrigeration System | 4.2 Psychrometrics – supply air quantity from room sensible load]

- a) 16,716 m³/h
- b) 12,537 m³/h**
- c) 15,045 m³/h
- d) 18,054 m³/h

Answer & explanation

Correct answer: (b) $\approx 12,537$ m³/h.

Given: room sensible heat (RSH) = 42 kW; latent = 14 kW; supply-to-room $\Delta T = 10$ K; $\rho = 1.2$ kg/m³; cp = 1.005 kJ/kg·K.

Formula: $m = \text{RSH} / (cp \times \Delta T)$; volume flow = $m / \rho \times 3,600$.

Substitution: $m = 42 / (1.005 \times 10) = 4.179$ kg/s; $V = 4.179 / 1.2 \times 3,600$.

Result: **supply air $\approx 12,537$ m³/h**; room sensible heat factor = $42 / 56 = 0.75$.

Why the others are wrong: (a) sizes air on the total (sensible + latent) load, but latent load is removed by condensation at the coil and does not set the air quantity; (c) treats kg/h as m³/h by omitting density; (d) multiplies by density instead of dividing. Over-sized air quantities raise AHU fan power and can leave humidity uncontrolled, so the air quantity should be set from the sensible load and the permissible supply temperature difference.

Ref: BEE Guidebook Paper 3, Ch. 4 (Psychrometrics and air-conditioning processes).

25 During a fan test the readings are: inlet static pressure –165 mmWC ($\approx -1,618$ Pa), inlet velocity pressure 18 mmWC (≈ 177 Pa), outlet static pressure +45 mmWC (≈ 441 Pa) and outlet velocity pressure 12 mmWC (≈ 118 Pa). The fan total pressure is:

[3P3CEM025 | Chapter 5: Fans and Blowers | 5.6 Fan performance testing – fan total pressure from measurements]

- a) 204 mmWC
- b) 210 mmWC
- c) 240 mmWC
- d) 192 mmWC

Answer & explanation

Correct answer: (a) 204 mmWC.

Given: inlet SP = -165 mmWC ($\approx -1,618$ Pa), inlet VP = 18 mmWC (≈ 177 Pa); outlet SP = +45 mmWC (≈ 441 Pa), outlet VP = 12 mmWC (≈ 118 Pa).

Formula: total pressure = static + velocity pressure at each plane; fan total pressure = TP_outlet – TP_inlet.

Substitution: TP_out = 45 + 12 = 57 mmWC; TP_in = -165 + 18 = -147 mmWC; FTP = 57 – (-147).

Result: **fan total pressure = 204 mmWC (≈ 2.00 kPa).**

Why the others are wrong: (b) is the static pressure difference only (45 + 165), ignoring velocity pressures; (c) adds both velocity pressures to the static difference, treating inlet velocity pressure as an extra rise; (d) is the fan static pressure (FTP minus outlet velocity pressure), a different quantity. Signs matter: inlet static pressure on an induced-draft or suction-side fan is negative. Using the correct pressure term is essential when computing fan total or static efficiency.

Ref: BEE Guidebook Paper 3, Ch. 5 (Fan performance assessment – static and total pressure).

26 A fan is driven by a 1,476 rpm motor through V-belts; the motor pulley is 180 mm and the fan pulley 450 mm. A stroboscope shows the fan shaft at 562 rpm. The belt slip is about:

[3P3CEM026 | Chapter 2: Electrical Motors | 2.5 Belt drives – measuring belt slip]

- a) 5.1 %
- b) 1.6 %
- c) **4.8 %**
- d) 6.4 %

Answer & explanation

Correct answer: (c) ≈ 4.8 %.

Given: N_motor = 1,476 rpm; D_motor = 180 mm; D_fan = 450 mm; measured N_fan = 562 rpm.

Formula: theoretical fan speed = N_motor $\times$ D_motor / D_fan; belt slip = (theoretical – measured) / theoretical $\times$ 100.

Substitution: $1,476 \times 180 / 450 = 590.4$ rpm; $(590.4 - 562) / 590.4 \times 100$.

Result: **belt slip ≈ 4.8 %.**

Why the others are wrong: (a) divides by the measured speed instead of the theoretical speed; (b) is the motor's own slip from 1,500 rpm synchronous speed, not belt slip; (d) adds motor slip to belt slip. Well-tensioned V-belts normally slip about 1–2 %. Slip near 5 % points to loose or worn belts or worn pulley grooves, which waste energy as heat and reduce fan speed, so the fan delivers less air. Re-tensioning, matched belt sets or cogged and synchronous belts restore speed and efficiency.

Ref: BEE Guidebook Paper 3, Ch. 2 (Transmission – belt drives).

27 A packaging line's rotameter shows a compressed-air flow of 0.45 m³/min measured at line conditions of 6.0 kg/cm²(g) (≈ 5.88 bar(g)), at the same temperature as intake air (atmosphere 1.033 kg/cm²(a) (≈ 1.01 bar(a))). With a plant specific power of 6.5 kW per m³/min of free air, the free-air equivalent and the compressor power it represents are:

- a) 2.61 m³/min and 17.0 kW
- b) 3.16 m³/min and 20.6 kW
- c) 0.45 m³/min and 2.9 kW
- d) 3.06 m³/min and 19.9 kW**

Answer & explanation

Correct answer: (d) 3.06 m³/min free air, 19.9 kW.

Given: V_line = 0.45 m³/min at 6.0 kg/cm²(g) ($\approx$ 5.88 bar(g)); P_atm = 1.033 kg/cm²(a) ($\approx$ 1.01 bar(a)); same temperature; specific power 6.5 kW/(m³/min).

Formula: free air = V_line $\times$ (P_gauge + P_atm) / P_atm (Boyle's law); power = free air $\times$ specific power.

Substitution: $0.45 \times 7.033 / 1.033 = 0.45 \times 6.808 = 3.06$ m³/min; 3.06×6.5 .

Result: $\approx$ **3.06 m³/min free air, needing $\approx$ 19.9 kW of compressor power.**

Why the others are wrong: (a) uses gauge instead of absolute pressure; (b) multiplies by absolute pressure but forgets to divide by atmospheric pressure; (c) compares line volume directly with free-air specific power. Specific power is always quoted per unit of free air, so line flows must be converted before costing an end use or comparing it with compressor FAD.

Ref: BEE Guidebook Paper 3, Ch. 3 (Compressor capacity – free air delivery).

28 A cooling water system circulates 2,400 m³/h. Replacing the tower's high-pressure spray headers with a low-pressure distribution system reduces the head needed at the tower inlet by 5.5 m. The pump impeller is trimmed to match at the same flow, with pump efficiency 78 % and motor efficiency 93 % unchanged. The reduction in motor input is about:

- a) 49.6 kW**
- b) 36.0 kW
- c) 46.1 kW
- d) 38.7 kW

Answer & explanation

Correct answer: (a) $\approx$ 49.6 kW.

Given: Q = 2,400 m³/h = 0.667 m³/s; ΔH = 5.5 m; η_{pump} = 0.78; η_{motor} = 0.93.

Formula: hydraulic power = $\rho g Q \Delta H$; motor input = hydraulic power / ($\eta_{\text{pump}} \times \eta_{\text{motor}}$).

Substitution: hydraulic = $1,000 \times 9.81 \times 0.667 \times 5.5 = 35.97$ kW; input = $35.97 / (0.78 \times 0.93) = 35.97 / 0.7254$.

Result: **reduction $\approx$ 49.6 kW ($\approx$ 3.97 lakh kWh over 8,000 h).**

Why the others are wrong: (b) is the hydraulic power only; (c) divides by pump efficiency but omits motor efficiency; (d) divides by motor efficiency only. Head at the tower inlet is often forgotten in condenser-water audits, yet it acts all year. Lowering it only saves energy if the pump is re-matched by trimming or speed reduction; otherwise the pump simply delivers more flow.

Ref: BEE Guidebook Paper 3, Ch. 7 (Cooling tower components and energy saving opportunities) and Ch. 6 (pumping).

29 ECBC 2017 defines three levels of energy performance for commercial buildings. Which list is correct, in increasing order of efficiency?

- a) Super ECBC, ECBC Plus and ECBC
- b) ECBC, ECBC Plus and Super ECBC**
- c) ECBC Basic, ECBC Gold and ECBC Platinum
- d) ECBC Plus, ECBC and Super ECBC

Answer & explanation

Correct answer: (b).

ECBC 2017 sets three voluntary-to-mandatory tiers. ECBC-compliant buildings meet the mandatory and prescriptive (or whole-building performance) requirements, giving roughly 25 % savings against a conventional reference building. ECBC Plus requires about 35 % savings, and Super ECBC about 50 %, through tighter envelope, lighting, HVAC and electrical requirements. Super ECBC buildings typically combine high-performance glazing and shading, very low lighting power density with controls, high-efficiency chillers or radiant systems, and on-site renewable energy.

Why the others are wrong: (a) reverses the order; (c) uses names from green-rating systems, not ECBC; (d) wrongly puts ECBC Plus below the base ECBC level. Each level has its own set of prescriptive tables and EPI ratios for compliance. States notify the code with any local amendments, and the Energy Conservation (Amendment) Act 2022 extends coverage through the Energy Conservation and Sustainable Building Code, including large residential buildings.

Ref: BEE Guidebook Paper 3, Ch. 10 (Energy Conservation Building Code).

30 Which sequence correctly arranges these sources in DECREASING order of colour rendering index: halogen, good-quality white LED, high-pressure sodium vapour (HPSV) and low-pressure sodium vapour (LPSV)?

[3P3CEM030 | Chapter 8: Lighting System | 8.3 Light sources – colour rendering index (CRI)]

- a) LED > Halogen > LPSV > HPSV
- b) HPSV > LED > Halogen > LPSV
- c) LPSV > HPSV > LED > Halogen
- d) Halogen > LED > HPSV > LPSV**

Answer & explanation

Correct answer: (d).

CRI measures how faithfully a source renders colours compared with a reference source, on a scale up to 100. Incandescent and halogen lamps have a continuous spectrum and a CRI of about 100. Good-quality white LEDs typically reach 80–90. HPSV lamps have a CRI of about 20–25, giving a golden-yellow light. LPSV lamps are almost monochromatic at 589 nm, with CRI close to 0, although they have very high efficacy.

Why the others are wrong: (a) places LPSV above HPSV and LED above halogen; (b) ranks HPSV first, though its colour rendering is poor; (c) reverses the true order. Efficacy (lm/W) and CRI must both be considered: high-efficacy sodium lamps suit roads and yards, while LEDs now combine high efficacy with good CRI. That is why LEDs replace both halogen and sodium lamps in most energy-efficiency retrofits.

Ref: BEE Guidebook Paper 3, Ch. 8 (Light source characteristics – efficacy and colour rendering).

31 An old standard motor is fed from a new PWM variable frequency drive through a 150 m cable. Which risk and remedy is correct?

[3P3CEM031 | Chapter 2: Electrical Motors | 2.6 VFD retrofit – motor insulation stress]

- a) Voltage spikes stress insulation; use an inverter-duty motor or dv/dt filter**
- b) Rotor copper loss falls to zero; downsize the motor by one frame size

- c) Supply PF drops sharply; fit a capacitor bank at the motor terminals
- d) Motor speed becomes fixed; add a gearbox for the speed range needed

Answer & explanation

Correct answer: (a).

PWM inverters switch the DC bus voltage with very fast rise times. On long cables, reflected waves can almost double the peak voltage at the motor terminals. These steep, repetitive spikes stress turn-to-turn insulation of older motors, and common-mode voltages can drive bearing currents. Inverter-duty motors (reinforced insulation, insulated bearings) or output dv/dt and sine filters address this.

Why the others are wrong: (b) rotor losses do not disappear on a VFD; harmonic currents actually add a little loss, and the motor may need derating at low speed for cooling, not downsizing; (c) capacitors must never be connected on the drive output, as they draw damaging current pulses, and the input displacement PF of a VFD is already near unity; (d) the whole purpose of the drive is variable speed. Proper specification avoids premature motor failure after VFD retrofits.

Ref: BEE Guidebook Paper 3, Ch. 2 (Speed control of AC induction motors – VFDs).

32 A trivector meter integrates demand over 30-minute blocks. In the peak block a rolling mill draws 1,800 kVA for 12 min, 2,600 kVA for 6 min while two furnaces overlap, and 1,500 kVA for 12 min. Staggering the furnaces cuts the 6-minute overlap to 2,000 kVA, with other periods unchanged. At ₹ 450 per kVA per month, the monthly demand-charge saving is:

[3P3CEM032 | Chapter 1: Electrical Systems | 1.3 Maximum demand – integrated demand over the metering interval]

- a) ₹ 90,000
- b) ₹ 1,08,000
- c) ₹ 54,000**
- d) ₹ 2,70,000

Answer & explanation

Correct answer: (c) ₹ 54,000 per month.

Given: 30-min block; 1,800 kVA × 12 min, 2,600 kVA × 6 min, 1,500 kVA × 12 min; overlap reduced to 2,000 kVA; demand rate ₹ 450/kVA/month.

Formula: recorded MD = $\Sigma(\text{kVA} \times \text{minutes}) / 30$; saving = $(\text{MD}_1 - \text{MD}_2) \times \text{rate}$.

Substitution: $\text{MD}_1 = (21,600 + 15,600 + 18,000) / 30 = 1,840 \text{ kVA}$; $\text{MD}_2 = (21,600 + 12,000 + 18,000) / 30 = 1,720 \text{ kVA}$; saving = 120×450 .

Result: **MD falls by 120 kVA; saving ≈ ₹ 54,000 per month (₹ 6.48 lakh per year).**

Why the others are wrong: (a) averages the three kVA values without time weighting; (b) wrongly assumes a 15-minute integration window around the peak; (d) takes the whole 600 kVA instantaneous reduction, but the meter records only the 30-minute average. Because short peaks are diluted by the integration period, MD control should target sustained overlaps of large loads.

Ref: BEE Guidebook Paper 3, Ch. 1 (Electrical load management and maximum demand control).

33 Input to a balanced 3-phase motor is measured by the two-wattmeter method. The readings are $W_1 = 28.4 \text{ kW}$ and $W_2 = 11.6 \text{ kW}$, both positive. The motor input power and power factor are:

[3P3CEM033 | Chapter 2: Electrical Motors | 2.4 Motor input measurement – two-wattmeter method]

- a) 16.8 kW at 0.81 PF
- b) 40.0 kW at 0.92 PF

- c) 69.3 kW at 0.81 PF
d) 40.0 kW at 0.81 PF

Answer & explanation

Correct answer: (d) 40.0 kW at 0.81 PF.

Given: $W_1 = 28.4$ kW; $W_2 = 11.6$ kW; balanced load.

Formula: $P = W_1 + W_2$; $\tan \phi = \sqrt{3} \times (W_1 - W_2) / (W_1 + W_2)$; $PF = \cos \phi$.

Substitution: $P = 40.0$ kW; $\tan \phi = 1.732 \times 16.8 / 40.0 = 0.7275$; $\phi = 36.0^\circ$.

Result: **input = 40.0 kW, PF $\approx$ 0.81 lagging.**

Why the others are wrong: (a) takes the difference of the readings as power; (b) leaves out $\sqrt{3}$ in the $\tan \phi$ expression; (c) multiplies the total by $\sqrt{3}$ as if the readings were per-phase values. The method needs no neutral, which makes it handy for delta motors. If one wattmeter reads negative (PF below 0.5), its reading must be subtracted. Accurate input measurement is the starting point for estimating motor loading, efficiency and capacitor requirement in a motor survey.

Ref: BEE Guidebook Paper 3, Ch. 2 (Motor performance assessment – input power measurement).

34 A 15 kW pump fills an overhead tank whose bottom is 18 m above the sump water level. The tank is 4 m deep, and the delivery pipe discharges freely 1 m above the tank top. Friction head is 5 m. If the inlet is moved to the tank bottom (non-return valve fitted), the average static head becomes the mid-level of the tank. At the same flow and efficiency, for 10 h/day, 365 days, the annual saving is about:

[3P3CEM034 | Chapter 6: Pumps and Pumping System | 6.6 Reducing static head – bottom inlet to overhead tanks]

- a) 9,777 kWh
 b) 7,141 kWh
 c) 1,955 kWh
d) 5,866 kWh

Answer & explanation

Correct answer: (d) $\approx$ 5,866 kWh per year.

Given: discharge at $18 + 4 + 1 = 23$ m; friction 5 m, so total head 28 m; bottom inlet means average static head is mid-level = 20 m, so new total head 25 m; input 15 kW; 3,650 h/year.

Formula: at constant flow and efficiency, power $\propto$ total head; saving = input $\times \Delta H / H \times$ hours.

Substitution: $\Delta H = 23 - 20 = 3$ m; $3 / 28 = 10.7\%$; $15 \times 0.107 \times 3,650$.

Result: **saving $\approx$ 1.61 kW, i.e. $\approx$ 5,866 kWh per year.**

Why the others are wrong: (a) assumes the tank stays empty (head 18 m); (b) divides the reduction by static head only, not total head; (c) assumes discharge at the tank top (only 1 m saved). Free discharge above a tank wastes head throughout filling.

Ref: BEE Guidebook Paper 3, Ch. 6 (Energy conservation opportunities in pumping systems).

35 A plant has a connected load of 2,000 kW. The individual maximum demands of its four sections are 420, 360, 300 and 270 kW, but the plant's simultaneous maximum demand is only 1,080 kW. Its diversity factor and demand factor are respectively:

[3P3CEM035 | Chapter 1: Electrical Systems | 1.3 Load management – diversity factor and demand factor]

- a) 1.25 and 0.54**
 b) 0.80 and 0.54
 c) 1.25 and 0.68

d) 0.80 and 1.85

Answer & explanation

Correct answer: (a) 1.25 and 0.54.

Given: connected load = 2,000 kW; section MDs = 420 + 360 + 300 + 270 = 1,350 kW; plant MD = 1,080 kW.

Formula: diversity factor = sum of individual MDs / plant MD (always ≥ 1); demand factor = plant MD / connected load (≤ 1).

Substitution: $1,350 / 1,080 = 1.25$; $1,080 / 2,000 = 0.54$.

Result: **diversity factor = 1.25; demand factor = 0.54.**

Why the others are wrong: (b) inverts the diversity ratio, giving a value below 1, which is not possible; (c) divides the sum of section MDs, not the plant MD, by connected load; (d) inverts both ratios. A higher diversity factor means section peaks do not coincide, which lets the transformer and contract demand be sized well below the sum of section peaks. Scheduling large batch loads so they do not overlap raises diversity and reduces MD charges.

Ref: BEE Guidebook Paper 3, Ch. 1 (Electrical load management – load curve, demand and diversity).

36 Electronic 'energy savers' that lower the terminal voltage of an induction motor when it is lightly loaded give meaningful savings mainly when:

[3P3CEM036 | Chapter 2: Electrical Motors | 2.6 Voltage-reduction energy savers on lightly loaded motors]

a) The motor runs below about 40 % load for long periods

b) The motor runs near full load for most operating hours

c) The motor drives a fan at rated speed and full flow

d) The supply voltage is already below the motor's rating

Answer & explanation

Correct answer: (a).

At light load, an induction motor's iron (core) loss and magnetising current form a large part of its input.

Lowering the voltage reduces flux, so core loss falls roughly with V^2 , while the higher current at the reduced voltage still stays small. This gives a net gain only when the load is low for long periods, typically below about 40 % of rating, for example presses, granulators or conveyors idling between batches.

Why the others are wrong: (b) near full load, any voltage reduction raises current and copper loss and can overheat the motor; (c) a fan at full flow is heavily loaded, and the right tool for flow reduction is a VFD, not voltage reduction; (d) undervoltage already raises current, so reducing voltage further worsens losses. Such devices also generate harmonics, so measured trials should precede any purchase.

Ref: BEE Guidebook Paper 3, Ch. 2 (Energy saving opportunities in motors; soft starters).

37 A plant's receiver and piping total 6 m³. During a short demand surge, consumption exceeds compressor output by 3.5 m³/min of free air, and header pressure may fall from 7.5 kg/cm²(g) (≈ 7.35 bar(g)) to 6.0 kg/cm²(g) (≈ 5.88 bar(g)) (atmosphere 1.033 kg/cm²(a) (≈ 1.01 bar(a)), constant temperature). How long can the stored air cover the surge before pressure falls to 6.0 kg/cm²(g) (≈ 5.88 bar(g))?

[3P3CEM037 | Chapter 3: Compressed Air System | 3.6 Air receivers – storage as a buffer for peak demand]

a) 1.7 min

b) 2.5 min

c) 14.2 min

d) 11.7 min

Answer & explanation

Correct answer: (b) ≈ 2.5 min.

Given: $V = 6 \text{ m}^3$; $P_1 = 7.5 \text{ kg/cm}^2(\text{g}) (\approx 7.35 \text{ bar}(\text{g}))$; $P_2 = 6.0 \text{ kg/cm}^2(\text{g}) (\approx 5.88 \text{ bar}(\text{g}))$; $P_{\text{atm}} = 1.033 \text{ kg/cm}^2(\text{a}) (\approx 1.01 \text{ bar}(\text{a}))$; deficit = $3.5 \text{ m}^3/\text{min}$ free air.

Formula: usable free air = $V \times (P_1 - P_2) / P_{\text{atm}}$; time = usable free air / deficit.

Substitution: $6 \times 1.5 / 1.033 = 8.71 \text{ m}^3$ free air; $8.71 / 3.5$.

Result: ≈ 2.5 minutes of cover.

Why the others are wrong: (a) divides the geometric volume by the deficit, ignoring pressure; (c) counts all the air stored down to atmospheric pressure, which is not usable; (d) counts the air stored at $6.0 \text{ kg/cm}^2(\text{g})$, which must remain. Adequate storage lets short peaks be met without starting another compressor or raising the generation pressure for everyone. This is cheaper than running an extra machine part-loaded and is a key point when sizing receivers near large intermittent users.

Ref: BEE Guidebook Paper 3, Ch. 3 (Compressed air system components – receivers).

38 A rural feeder's 630 kVA CRGO distribution transformer (no-load loss 1.10 kW) is replaced by an amorphous-core unit with a no-load loss of 0.35 kW and the same load loss. The transformer stays energised all year, but it is loaded only about 12 hours a day. At ₹ 8/kWh, the annual saving is about:

[3P3CEM038 | Chapter 1: Electrical Systems | 1.5 Energy-efficient transformers – amorphous core replacement]

a) ₹ 26,280

b) ₹ 77,088

c) ₹ 24,528

d) ₹ 52,560

Answer & explanation

Correct answer: (d) $\approx ₹ 52,560$ per year.

Given: no-load loss: CRGO 1.10 kW, amorphous 0.35 kW; load loss unchanged; energised 8,760 h/year; ₹ 8/kWh.

Formula: saving = (no-load loss₁ – no-load loss₂) $\times$ energised hours $\times$ tariff.

Substitution: $1.10 - 0.35 = 0.75 \text{ kW}$; $0.75 \times 8,760 = 6,570 \text{ kWh}$; $6,570 \times 8$.

Result: $\approx 6,570 \text{ kWh}$, i.e. $\approx ₹ 52,560$ per year.

Why the others are wrong: (a) counts only the 12 loaded hours a day, but core loss occurs whenever the transformer is energised, loaded or not; (b) assumes the amorphous core has no core loss at all; (c) is the amorphous unit's own remaining no-load loss cost, not the saving. Amorphous metal is a thin, high-resistivity, non-crystalline ribbon with very low hysteresis and eddy-current loss. That is why amorphous transformers pay back fastest on lightly loaded, always-energised distribution transformers.

Ref: BEE Guidebook Paper 3, Ch. 1 (Transformers – losses and energy-efficient transformers).

39 A matt desk surface with reflectance 0.65 receives an illuminance of 400 lux. Treating it as a perfectly diffuse reflector, its luminance is about:

[3P3CEM039 | Chapter 8: Lighting System | 8.2 Lighting terms – luminance of a diffuse surface]

a) 260 cd/m^2

b) 817 cd/m^2

c) 82.8 cd/m^2

d) 127 cd/m^2

Answer & explanation

Correct answer: (c) $\approx 82.8 \text{ cd/m}^2$.

Given: reflectance $\rho = 0.65$; illuminance $E = 400 \text{ lux (lm/m}^2\text{)}$.

Formula: for a perfectly diffuse (Lambertian) surface, $L = \rho \times E / \pi$, in cd/m^2 .

Substitution: $L = 0.65 \times 400 / 3.1416 = 260 / 3.1416$.

Result: **luminance $\approx 82.8 \text{ cd/m}^2$.**

Why the others are wrong: (a) gives the luminous exitance ρE in lm/m^2 , which is not the same as luminance and lacks the division by π ; (b) multiplies by π instead of dividing; (d) omits the reflectance. Illuminance is the light falling on a surface, measured with a lux meter. Luminance is the brightness seen by the eye, so it depends on the surface's reflectance. Light-coloured walls, ceilings and work surfaces raise luminance and inter-reflections, which raises the utilisation factor and lets the same visual task be met with fewer watts, a no-cost lighting measure.

Ref: BEE Guidebook Paper 3, Ch. 8 (Basic terms in lighting; illuminance and luminance).

40 A 3-phase, 4-wire lighting distribution board feeds single-phase resistive loads drawing 120 A on R, 90 A on Y and 60 A on B, all at unity power factor. The current in the neutral conductor is about:

[3P3CEM040 | Chapter 1: Electrical Systems | 1.6 Distribution – neutral current from unbalanced single-phase loads]

a) 52.0 A

b) 60.0 A

c) 0 A

d) 270 A

Answer & explanation

Correct answer: (a) $\approx 52.0 \text{ A}$.

Given: $I_R = 120 \text{ A}$, $I_Y = 90 \text{ A}$, $I_B = 60 \text{ A}$, all in phase with their own voltages (120° apart).

Formula: for unity-PF phase currents, $I_N = \sqrt{(I_R^2 + I_Y^2 + I_B^2 - I_R I_Y - I_Y I_B - I_B I_R)}$.

Substitution: $\sqrt{(14,400 + 8,100 + 3,600 - 10,800 - 5,400 - 7,200)} = \sqrt{2,700}$.

Result: **$I_N \approx 52.0 \text{ A}$.**

Why the others are wrong: (b) simply subtracts the smallest from the largest current, ignoring phasor addition; (c) holds only for a balanced load; (d) adds the currents arithmetically as if all were in phase. Neutral current causes extra I^2R loss in the neutral and voltage unbalance at the loads. Redistributing circuits to about 90 A per phase would bring the neutral current close to zero and cut feeder losses, which is a no-cost measure in building and lighting boards.

Ref: BEE Guidebook Paper 3, Ch. 1 (Distribution losses and load balancing).

41 A pump is to deliver $0.12 \text{ m}^3/\text{s}$ against 36 m head at 1,450 rpm. Its specific speed, $N_s = N\sqrt{Q} / H^{0.75}$ (N in rpm, Q in m^3/s , H in m), is about:

[3P3CEM041 | Chapter 6: Pumps and Pumping System | 6.2 Pump selection – specific speed]

a) 83.7

b) 34.2

c) 14.0

d) 11.8

Answer & explanation

Correct answer: (b) ≈ 34.2 .

Given: $N = 1,450 \text{ rpm}$; $Q = 0.12 \text{ m}^3/\text{s}$; $H = 36 \text{ m}$.

Formula: $N_s = N \times \sqrt{Q} / H^{0.75}$.

Substitution: $\sqrt{0.12} = 0.3464$; $36^{0.75} = 14.70$; $N_s = 1,450 \times 0.3464 / 14.70$.

Result: **$N_s \approx 34.2$ (metric units), i.e. a radial-flow centrifugal impeller.**

Why the others are wrong: (a) uses $H^{0.5}$ instead of $H^{0.75}$; (c) uses H to the first power; (d) uses Q instead of $\sqrt{Q}$. Specific speed characterises impeller geometry independent of size. In these units, low values (about 10–80) indicate radial impellers suited to high head and low flow, mid values mixed-flow impellers, and high values axial impellers for large flow at low head. Each type has its best efficiency in its own range, so choosing a pump type that matches the duty's specific speed is the first step towards high operating efficiency.

Ref: BEE Guidebook Paper 3, Ch. 6 (Pump types and selection).

42 Select the WRONG statement about variable refrigerant flow (VRF) air-conditioning systems:

[3P3CEM042 | Chapter 4: HVAC and Refrigeration System | 4.10 Variable refrigerant flow (VRF) systems]

- a) **They circulate chilled water to fan-coil units in each zone**
- b) Inverter compressors vary refrigerant flow to match zone loads
- c) Heat-recovery versions heat some zones while cooling others
- d) Long refrigerant piping and many joints make leak checks important

Answer & explanation

Correct answer: (a) is the wrong statement.

A VRF system is a direct-expansion system: refrigerant itself is piped from the outdoor units to many indoor evaporator units, and each indoor unit has an electronic expansion valve. Chilled water fan-coil systems use a chiller plant with water distribution, which is a different arrangement.

Why the other statements are true: (b) inverter-driven compressors modulate refrigerant flow, so part-load efficiency is high, and part load is where buildings operate most of the time; (c) three-pipe heat-recovery VRF can move heat rejected by zones in cooling to zones needing heating, such as a core and perimeter in winter, which saves energy; (d) VRF systems hold a large refrigerant charge in long pipe runs with many brazed joints, so leak testing and refrigerant management are important for both efficiency and environment. VRF suits buildings with diverse zone loads and part-time occupancy.

Ref: BEE Guidebook Paper 3, Ch. 4 (Types of air-conditioning systems).

43 An axial-flow ID fan shows pulsating flow, vibration and noise when the system resistance rises and flow falls well below design. The most probable cause is:

[3P3CEM043 | Chapter 5: Fans and Blowers | 5.4 Fan curve – stall and unstable operation]

- a) Operation at the best-efficiency point of the fan curve
- b) Excess motor capacity relative to the fan's absorbed power
- c) **Operation left of the pressure peak, in the stall region**
- d) Low gas temperature that raises density at the fan inlet

Answer & explanation

Correct answer: (c).

Axial fans, and to a lesser extent forward-curved fans, have a pressure curve with a peak followed by a dip at low flow. When the system resistance pushes the operating point to the left of this peak, air separates from the blades (aerodynamic stall). Flow then becomes unstable and can surge back and forth, causing pulsation, vibration, noise and poor efficiency. Remedies include reducing system resistance, using variable-pitch blades or speed control to move the curve, or reselecting the fan so the duty lies safely right of the peak.

Why the others are wrong: (a) operation at the best-efficiency point is smooth and stable; (b) an oversized motor only lowers motor efficiency and PF, without causing aerodynamic pulsation; (d) higher density raises pressure and power at the same volume flow, but does not by itself create stall. Checking where the operating point sits on the fan curve is the first step in any fan audit.

Ref: BEE Guidebook Paper 3, Ch. 5 (Fan performance and system curves).

44 A data centre's IT equipment draws 800 kW. At the same time, cooling uses 360 kW, UPS and distribution losses are 60 kW, and lighting and miscellaneous loads are 20 kW. Its power usage effectiveness (PUE) is:

[3P3CEM044 | Chapter 10: Energy Conservation in Buildings and ECBC | 10.5 Data centres – power usage effectiveness (PUE)]

- a) 0.65
- b) 1.48
- c) 0.55
- d) **1.55**

Answer & explanation

Correct answer: (d) 1.55.

Given: IT load = 800 kW; cooling = 360 kW; UPS and distribution losses = 60 kW; lighting and others = 20 kW.

Formula: $PUE = \text{total facility power} / \text{IT equipment power}$.

Substitution: $\text{total} = 800 + 360 + 60 + 20 = 1,240 \text{ kW}$; $PUE = 1,240 / 800$.

Result: **PUE = 1.55** (overhead of 0.55 kW per kW of IT load).

Why the others are wrong: (a) is the inverse ratio (data centre infrastructure efficiency, DCiE ≈ 0.65 or 65 %); (b) leaves out UPS and distribution losses, which are part of facility overhead; (c) is the overhead-to-IT ratio, not PUE. An ideal data centre would approach PUE 1.0. Raising supply air temperature within the allowable range, using hot and cold aisle containment, free cooling and high-efficiency modular UPS all reduce the overhead, and each kW saved in IT load also cuts cooling and UPS losses.

Ref: BEE Guidebook Paper 3, Ch. 10 (Energy efficiency in buildings – data centres and UPS).

45 A 110 kW compressor's intake filter shows a pressure drop of 625 mmWC ($\approx 6.13 \text{ kPa}$) against 125 mmWC ($\approx 1.23 \text{ kPa}$) when clean. Using the guidebook thumb rule for suction-side pressure drop, the annual cost of the choked filter at 8,000 h/year and ₹ 8/kWh is about:

[3P3CEM045 | Chapter 3: Compressed Air System | 3.5 Intake filter pressure drop – effect on compressor power]

- a) **₹ 2,81,600**
- b) ₹ 3,52,000
- c) ₹ 1,40,800
- d) ₹ 70,400

Answer & explanation

Correct answer: (a) $\approx ₹ 2,81,600$ per year.

Given: extra drop = $625 - 125 = 500 \text{ mmWC}$ ($\approx 4.90 \text{ kPa}$); compressor 110 kW; 8,000 h/year; ₹ 8/kWh; thumb rule: about 2 % more power for every 250 mmWC ($\approx 2.45 \text{ kPa}$) of suction pressure drop.

Formula: $\text{extra power} = 110 \times 2 \% \times (\text{extra drop} / 250)$; $\text{annual cost} = \text{extra kW} \times \text{hours} \times \text{tariff}$.

Substitution: $500 / 250 = 2$ steps, so 4 %; $\text{extra power} = 0.04 \times 110 = 4.4 \text{ kW}$; $4.4 \times 8,000 \times 8$.

Result: $\approx 35,200 \text{ kWh/year}$, costing $\approx ₹ 2,81,600$.

Why the others are wrong: (b) charges the full 625 mmWC, though a clean filter's 125 mmWC is unavoidable; (c) applies 2 % to the whole 500 mmWC instead of per 250 mmWC; (d) uses 1 % per 250 mmWC. A differential-pressure gauge across the filter and condition-based cleaning are cheap ways to hold this loss down.

Ref: BEE Guidebook Paper 3, Ch. 3 (Efficient operation – pressure drops in air filter).

46 An FD fan runs at 70–80 % of design flow most of the time. Why do inlet guide vanes consume less power than an outlet damper for the same reduction in flow?

[3P3CEM046 | Chapter 5: Fans and Blowers | 5.5 Flow control – inlet guide vanes compared with outlet dampers]

- a) They raise fan speed slightly, moving operation to peak efficiency
- b) They pre-swirl the inlet air, reducing work input at part flow**
- c) They lower system resistance by enlarging the duct cross-section
- d) They convert the fan into a positive-displacement blower at low flow

Answer & explanation

Correct answer: (b).

Inlet guide vanes (IGVs) give the air a swirl in the direction of impeller rotation before it enters the fan. This reduces the tangential velocity change across the impeller and therefore the work, and hence the pressure and power, at reduced flow. An outlet damper simply adds resistance: the fan rides up its own curve and the extra pressure is throttled away. Between about 80 % and 100 % flow IGVs save noticeably; at lower flows their advantage shrinks, and a VFD saves most because power then falls almost with the cube of speed.

Why the others are wrong: (a) IGVs do not change speed; (c) vanes add some resistance rather than enlarging the duct; (d) a centrifugal fan remains a dynamic machine at any vane setting. For fans that run long hours at reduced flow, a VFD is normally the best retrofit, with IGVs as a lower-cost middle option.

Ref: BEE Guidebook Paper 3, Ch. 5 (Flow control strategies).

47 Only two of four chillers run, so condenser water flow falls to half. For the least fan energy at the same cold-water temperature, the cooling tower should be operated by:

[3P3CEM047 | Chapter 7: Cooling Towers | 7.5 Part-flow operation of multi-cell towers]

- a) Isolating two cells completely and running the other two fans at full speed
- b) Spreading the flow over all cells within nozzle limits and running fans on VFD**
- c) Running all four fans at full speed to obtain the lowest possible cold water
- d) Bypassing half the flow around the tower and straight back to the basin

Answer & explanation

Correct answer: (b).

Fan power varies roughly with the cube of air flow, while heat transfer depends on fill area wetted and on total air flow. Spreading the reduced water flow over all cells, provided the nozzles still give even coverage at the lower flow, puts all the fill to work. The needed air flow can then come from all fans at reduced speed. For example, four fans at 50 % speed use about $4 \times 0.125 = 0.5$ of one fan's full power. Two fans at full speed use 2.0, i.e. four times as much.

Why the others are wrong: (a) wastes half the fill and needs full-speed fans; (c) over-cools at high fan power, and the chillers may not benefit below their minimum condenser water temperature; (d) bypassing raises the mixed condenser water temperature and wastes tower capacity. Control by cold-water set point with VFD fans gives the best result.

Ref: BEE Guidebook Paper 3, Ch. 7 (Cooling tower fan control; energy saving opportunities).

48 A pump draws condensate at 70 °C from a vented tank whose water level is 2.0 m below the pump centreline. Atmospheric pressure head at site is 10.2 m, suction pipe friction is 0.8 m, the vapour pressure of water at 70 °C is 31.2 kPa and its density is 978 kg/m³. The NPSH available is about:

[3P3CEM048 | Chapter 6: Pumps and Pumping System | 6.4 Suction conditions – NPSH available for hot water]

- a) 7.40 m
- b) 8.15 m
- c) 4.15 m**
- d) 4.95 m

Answer & explanation

Correct answer: (c) $\approx$ 4.15 m.

Given: $H_{\text{atm}} = 10.2$ m; suction lift = 2.0 m; friction = 0.8 m; $P_v = 31.2$ kPa; $\rho = 978$ kg/m³.

Formula: $\text{NPSH}_a = H_{\text{atm}} - \text{suction lift} - \text{suction friction} - H_v$, where $H_v = P_v / (\rho g)$.

Substitution: $H_v = 31,200 / (978 \times 9.81) = 3.25$ m; $\text{NPSH}_a = 10.2 - 2.0 - 0.8 - 3.25$.

Result: **$\text{NPSH}_a \approx 4.15$ m.**

Why the others are wrong: (a) ignores the vapour pressure, which is large for hot water; (b) adds the suction lift as if the tank were above the pump; (d) omits suction friction. If the pump needs, say, 4.5 m NPSH_r, it will cavitate, losing head and efficiency and eroding the impeller. Remedies are to raise the tank, lower the pump, enlarge the suction line or cool the liquid.

Ref: BEE Guidebook Paper 3, Ch. 6 (Factors affecting pump performance – suction head and NPSH).

49 An old radial-blade process fan (fan efficiency 52 %) draws 64 kW from its motor. It is replaced by a backward-curved aerofoil fan of 80 % efficiency at the same flow and pressure, with the same motor efficiency. At 7,500 h/year, the annual energy saving is about:

[3P3CEM049 | Chapter 5: Fans and Blowers | 5.2 Fan selection – replacing an inefficient impeller]

- a) 1,68,000 kWh**
- b) 1,34,400 kWh
- c) 2,58,462 kWh
- d) 3,12,000 kWh

Answer & explanation

Correct answer: (a) $\approx$ 1,68,000 kWh per year.

Given: $\eta_{\text{old}} = 52$ %; $\eta_{\text{new}} = 80$ %; old input = 64 kW; same duty and motor efficiency; 7,500 h/year.

Formula: input $\propto$ air power / fan efficiency, so $P_{\text{new}} = P_{\text{old}} \times \eta_{\text{old}} / \eta_{\text{new}}$.

Substitution: $P_{\text{new}} = 64 \times 0.52 / 0.80 = 41.6$ kW; saving = $64 - 41.6 = 22.4$ kW; $22.4 \times 7,500$.

Result: **saving ≈ 22.4 kW, i.e. $\approx 1,68,000$ kWh per year (35 %).**

Why the others are wrong: (b) multiplies the old power by the 28-point efficiency difference; (c) uses $(80 - 52) / 52$, the fractional rise in efficiency, as if it were the fractional power saving; (d) is the new fan's annual consumption, not the saving. Radial blades are rugged for dust-laden gas, but where gas is clean, backward-curved or aerofoil fans give much higher efficiency. Fan selection near the best-efficiency point matters as much as motor efficiency.

Ref: BEE Guidebook Paper 3, Ch. 5 (Fan types and their selection).

50 A 75 kW, 415 V induction motor on a crusher draws a no-load current of 32 A at very low PF. A fixed capacitor is to be connected directly across its terminals, switched with the motor. Following the guidebook caution on self-excitation, the largest capacitor rating that should be fitted is about:

[3P3CEM050 | Chapter 1: Electrical Systems | 1.4 Capacitor at motor terminals – limit set by no-load kVAr]

- a) 23.0 kVAr
- b) 20.7 kVAr**
- c) 35.9 kVAr
- d) 12.0 kVAr

Answer & explanation

Correct answer: (b) ≈ 20.7 kVAr.

Given: $V = 415$ V; no-load current $I_0 = 32$ A; no-load PF very low, so no-load kVA $\approx$ magnetising kVAr; limit $\approx 90\%$ of no-load kVAr.

Formula: no-load kVAr $\approx \sqrt{3} \times V \times I_0 / 1,000$; maximum capacitor $\approx 0.9 \times$ no-load kVAr.

Substitution: $\sqrt{3} \times 415 \times 32 / 1,000 = 23.0$ kVAr; 0.9×23.0 .

Result: **maximum capacitor ≈ 20.7 kVAr.**

Why the others are wrong: (a) equals the full magnetising kVAr, which risks self-excitation; (c) uses 3 instead of $\sqrt{3}$; (d) omits $\sqrt{3}$, treating the motor as single-phase. If the capacitor exceeds the magnetising requirement, the motor can self-excite after disconnection while still coasting, producing dangerous overvoltages and transient torques on reclosure. Any larger correction should be provided at the bus through switched APFC steps.

Ref: BEE Guidebook Paper 3, Ch. 1 (Power factor improvement – location and sizing of capacitors).

..... End of Section I

Section – II: SHORT DESCRIPTIVE QUESTIONS Marks: 8 x 5 = 40

- 4. Answer all Eight questions
- 5. Each question carries Five marks

S-1 A compressor house is fed from the main LT panel by a 180 m long 3½-core 240 mm² aluminium cable. Data:

Parameter	Value
Load	220 kW at 0.90 PF, 415 V, 3-phase
Cable AC resistance (operating temperature)	0.161 Ω /km per conductor
Cable reactance	0.072 Ω /km per conductor
Operating hours	7,200 h/year
Tariff	₹ 8/kWh
Cost of a second identical cable laid in parallel	₹ 4,20,000

- (a) Line current. (0.5 Mark)
- (b) Present I^2R loss in the cable, in kW and as % of load. (1.5 Marks)
- (c) Present voltage drop in volts and as % of 415 V. (1 Mark)
- (d) Loss, voltage drop, annual saving and simple payback if the second cable is laid in parallel. (1.5 Marks)
- (e) State one further benefit to the compressors. (0.5 Mark)

S-1 – Model answer (5 marks)

Given: $P = 220 \text{ kW}$; $\text{PF} = 0.90$ ($\sin \phi = 0.436$); $V = 415 \text{ V}$; $L = 0.18 \text{ km}$; $r = 0.161 \text{ } \Omega/\text{km}$; $x = 0.072 \text{ } \Omega/\text{km}$; 7,200 h/year; ₹ 8/kWh; second cable ₹ 4,20,000.

(a) Line current (0.5 Mark)

Formula: $I = P / (\sqrt{3} \times V \times \text{PF})$

Substitution: $2,20,000 / (1.732 \times 415 \times 0.90)$

Result: **$I \approx 340.1 \text{ A}$**

(b) Present cable loss (1.5 Marks)

Formula: $R = r \times L$; $\text{loss} = 3 I^2 R$

Substitution: $R = 0.161 \times 0.18 = 0.02898 \text{ } \Omega$ per conductor; $\text{loss} = 3 \times 340.1^2 \times 0.02898$ (1 Mark)

Result: **Cable loss $\approx 10.05 \text{ kW}$, i.e. 4.6 % of the 220 kW load** (0.5 Mark)

(c) Present voltage drop (1 Mark)

Formula: $\Delta V = \sqrt{3} \times I \times (R \cos \phi + X \sin \phi)$

Substitution: $X = 0.072 \times 0.18 = 0.01296 \text{ } \Omega$; $\Delta V = 1.732 \times 340.1 \times (0.02898 \times 0.90 + 0.01296 \times 0.436)$

Result: **$\Delta V \approx 18.7 \text{ V}$, i.e. 4.5 % of 415 V**

(d) With a second cable in parallel (1.5 Marks)

Paralleling halves R and X , so loss and drop halve: new loss = $10.05 / 2 = 5.03 \text{ kW}$; new drop $\approx 9.3 \text{ V}$ (2.25 %) (0.5 Mark)

Formula: $\text{annual saving} = \Delta \text{loss} \times \text{hours} \times \text{tariff}$; $\text{payback} = \text{cost} / \text{annual saving}$

Substitution: $5.027 \times 7,200 = 36,196 \text{ kWh}$; $36,196 \times 8 = ₹ 2,89,571$ (0.5 Mark)

Result: **Annual saving $\approx 36,196 \text{ kWh}$ (₹ 2,89,571); simple payback $\approx 4,20,000 / 2,89,571 \approx 1.45 \text{ years}$** (0.5 Mark)

(e) Further benefit (0.5 Mark)

Motor terminal voltage rises by about 9 V, which lowers motor current and copper loss, raises available starting torque and cuts cable temperature, extending cable life. A loss of more than 4 % in one feeder also shows that the cable was undersized for its load.

Marking: (a) 0.5; (b) 1 for R and formula + 0.5 result; (c) 1; (d) 0.5×3 ; (e) 0.5.

S-2 A brine-circulation pump in a dairy runs 8,400 h/year and needs 50 kW shaft power. Two 55 kW motors are offered:

Motor	Efficiency at 50 kW output	Price (installed)
IE2	93.0 %	₹ 2,10,000
IE4	95.4 %	₹ 3,40,000

Electricity costs ₹ 8/kWh. Use a 10-year life and a 10 % discount rate (no escalation, no salvage).

(a) Input power of each motor. (1 Mark)

(b) Annual energy and cost saving with the IE4 motor. (1 Mark)

(c) Simple payback of the extra price. (0.5 Mark)

(d) Present value of the savings and net present value of choosing IE4. (1.5 Marks)

(e) 10-year life-cycle cost of each motor and the share of energy in it. (1 Mark)

S-2 – Model answer (5 marks)

Given: shaft power 50 kW; $\eta_{IE2} = 0.930$, $\eta_{IE4} = 0.954$; 8,400 h/year; ₹ 8/kWh; prices ₹ 2,10,000 and ₹ 3,40,000 (extra ₹ 1,30,000); $n = 10$ years; $i = 10\%$.

(a) Input power (1 Mark)

Formula: input = shaft output / efficiency

Substitution: $50 / 0.930$; $50 / 0.954$

Result: **IE2 $\approx$ 53.76 kW; IE4 $\approx$ 52.41 kW** (0.5 Mark each)

(b) Annual saving (1 Mark)

Formula: saving = Δ input $\times$ hours $\times$ tariff

Substitution: $\Delta = 53.763 - 52.411 = 1.3525$ kW; $1.3525 \times 8,400 = 11,361$ kWh

Result: **$\approx$ 11,361 kWh/year, i.e. $\approx$ ₹ 90,891 per year**

(c) Simple payback (0.5 Mark)

Result: **1,30,000 / 90,891 $\approx$ 1.43 years**

(d) Present value and NPV (1.5 Marks)

Formula: PV factor (annuity) = $[1 - (1 + i)^{-n}] / i$; NPV = annual saving $\times$ PV factor – extra investment

Substitution: PV factor = $(1 - 1.1^{-10}) / 0.1 = 6.1446$; PV of savings = $90,891 \times 6.1446 = ₹ 5,58,484$ (1 Mark)

Result: **NPV $\approx$ 5,58,484 – 1,30,000 = ₹ 4,28,484 (positive, so IE4 is justified)** (0.5 Mark)

(e) Life-cycle cost (1 Mark)

Annual energy cost: IE2 = $53.76 \times 8,400 \times 8 = ₹ 36,12,903$; IE4 = $52.41 \times 8,400 \times 8 = ₹ 35,22,013$

Formula: LCC = price + annual energy cost $\times$ PV factor

Result: **LCC (IE2) $\approx$ ₹ 2,24,09,726; LCC (IE4) $\approx$ ₹ 2,19,81,243; energy is about 99 % of LCC** (0.5 + 0.5)

Comment: the purchase price is about 1 % of a continuously running motor's life-cycle cost, so motors must be bought on efficiency (LCC), not first cost.

Marking: (a) 1; (b) 1; (c) 0.5; (d) 1 + 0.5; (e) 1.

S-3 A forging plant's compressed air header is held at 7.5 kg/cm²(g) ($\approx$ 7.35 bar(g)) although all end uses work well at 5.5 kg/cm²(g) ($\approx$ 5.39 bar(g)). Measured free-air demand is 28 m³/min. A survey shows that 40 % of this demand goes to unregulated uses (blow-guns, air motors and cylinders without regulators, and leaks downstream of the user drops), whose free-air consumption is proportional to the absolute pressure at which they are supplied. Point-of-use regulators set at 5.5 kg/cm²(g) ($\approx$ 5.39 bar(g)) are proposed; header pressure stays unchanged. Atmospheric pressure is 1.033 kg/cm²(a) ($\approx$ 1.01 bar(a)). The compressor plant's specific power is 6.8 kW per m³/min of free air; the plant runs 7,000 h/year at ₹ 8/kWh.

(a) Free-air demand of the unregulated uses before and after regulation, and the reduction. (2 Marks)

(b) Compressor power and annual energy and cost saving. (2 Marks)

(c) Explain the term 'artificial demand' and give two other measures that reduce it. (1 Mark)

S-3 – Model answer (5 marks)

Given: header 7.5 kg/cm²(g) ($\approx$ 7.35 bar(g)), i.e. 8.533 kg/cm²(a) ($\approx$ 8.37 bar(a)); regulated pressure 5.5 kg/cm²(g) ($\approx$ 5.39 bar(g)), i.e. 6.533 kg/cm²(a) ($\approx$ 6.41 bar(a)); demand 28 m³/min, of which 40 % unregulated; specific power 6.8 kW/(m³/min); 7,000 h/year; ₹ 8/kWh.

(a) Unregulated demand (2 Marks)

Before: $0.40 \times 28 = 11.2 \text{ m}^3/\text{min}$ (0.5 Mark)

Formula: $Q_2 = Q_1 \times P_2(\text{abs}) / P_1(\text{abs})$

Substitution: $11.2 \times 6.533 / 8.533 = 11.2 \times 0.7656$ (1 Mark)

Result: **After regulation $\approx 8.57 \text{ m}^3/\text{min}$; reduction $\approx 2.63 \text{ m}^3/\text{min}$ (9.4 % of total demand)** (0.5 Mark)

(b) Power and savings (2 Marks)

Formula: power saving = reduction $\times$ specific power

Substitution: $2.625 \times 6.8 = 17.85 \text{ kW}$ (1 Mark)

Annual energy = $17.851 \times 7,000 = 1,24,955 \text{ kWh}$ (0.5 Mark)

Result: **Annual cost saving $\approx ₹ 9,99,639$ ($\approx ₹ 10.0$ lakh)** (0.5 Mark)

(c) Artificial demand (1 Mark)

Artificial demand is the extra air consumed by unregulated end uses and leaks only because they are supplied at a higher pressure than they need. Their flow rises with absolute supply pressure, so the excess pressure is paid for twice: more air and more compression power per unit of air. (0.5 Mark)

Other measures (any two, 0.25 each): lower the header set point once distribution pressure drops are fixed; use pressure/flow controllers downstream of the receiver; fit zero-loss drains and repair leaks; replace open blowing with engineered nozzles or blowers.

Marking: (a) 0.5 + 1 + 0.5; (b) 1 + 0.5 + 0.5; (c) 0.5 + 0.5.

S-4 An effluent treatment plant aerates its tank with two identical Roots (positive displacement) blowers, each delivering $1,500 \text{ m}^3/\text{h}$ of free air at $0.55 \text{ kg}/\text{cm}^2(\text{g})$ ($\approx 0.539 \text{ bar}(\text{g})$) discharge pressure, with intake at atmospheric pressure of $1.033 \text{ kg}/\text{cm}^2(\text{a})$ ($\approx 1.01 \text{ bar}(\text{a})$). Each blower motor draws 38 kW and they run $8,760 \text{ h}/\text{year}$. Dissolved-oxygen (DO) logging shows that only $2,100 \text{ m}^3/\text{h}$ of air is needed on average. It is proposed to run one blower at full speed and fit a VFD (97 % efficient) to the second, controlled by DO. Assume blower power is proportional to flow at constant discharge pressure. Tariff $₹ 7.50/\text{kWh}$; $\gamma = 1.4$.

(a) Theoretical adiabatic power per blower and its overall (wire-to-air) efficiency. (2 Marks)

(b) Power with the proposed scheme and the annual energy and cost saving. (2 Marks)

(c) Why must the air flow of a Roots blower not be reduced by throttling its discharge valve? (1 Mark)

[3P3CEM054 | Chapter 5: Fans and Blowers | 5.8 Roots blowers in aeration – adiabatic power, efficiency and VFD with DO control]

S-4 – Model answer (5 marks)

Given: $V_1 = 1,500 \text{ m}^3/\text{h} = 0.4167 \text{ m}^3/\text{s}$ per blower; $P_1 = 1.033 \text{ kg}/\text{cm}^2(\text{a}) = 101.3 \text{ kPa}$; $P_2 = 1.583 \text{ kg}/\text{cm}^2(\text{a}) = 155.2 \text{ kPa}$; $\gamma = 1.4$; input 38 kW per blower; required air $2,100 \text{ m}^3/\text{h}$; VFD 97 %; $8,760 \text{ h}/\text{year}$; $₹ 7.50/\text{kWh}$.

(a) Adiabatic power and efficiency (2 Marks)

Formula: $P_{\text{ad}} = [\gamma / (\gamma - 1)] \times P_1 \times V_1 \times [(P_2/P_1)^{(\gamma-1)/\gamma} - 1]$

Substitution: pressure ratio = $155.2 / 101.3 = 1.532$; $1.532^{0.2857} = 1.1297$; $P_{\text{ad}} = 3.5 \times 101.3 \times 0.4167 \times 0.1297$ (1 Mark)

Result: **$P_{\text{ad}} \approx 19.2 \text{ kW}$ per blower; wire-to-air efficiency = $19.2 / 38 \approx 50.4 \%$** (1 Mark)

(b) Proposed scheme (2 Marks)

Blower 1 full flow $1,500 \text{ m}^3/\text{h}$ at 38 kW ; blower 2 on VFD supplies $600 \text{ m}^3/\text{h}$.

Formula: $P_2 = 38 \times (600 / 1,500) / 0.97$

Substitution: $38 \times 0.40 / 0.97 = 15.67 \text{ kW}$; total = $38 + 15.67 = 53.67 \text{ kW}$ (1 Mark)

Saving = $76 - 53.67 = 22.33 \text{ kW}$; annual energy = $22.33 \times 8,760 = 1,95,610 \text{ kWh}$ (0.5 Mark)

Result: **Annual cost saving $\approx$ ₹ 14,67,074 ($\approx$ ₹ 14.7 lakh)** (0.5 Mark)

(c) No discharge throttling (1 Mark)

A Roots blower is a positive displacement machine: it delivers a fixed volume per revolution. Closing a discharge valve does not reduce flow much but raises discharge pressure, power and temperature sharply and can overload the motor or damage the blower. Flow must be reduced by speed (VFD or pulley change), by switching machines, or by venting through a blow-off, which wastes energy.

Marking: (a) 1 + 1; (b) 1 + 0.5 + 0.5; (c) 1.

S-5 A 60 m $\times$ 40 m warehouse is lit by 96 LED high-bay luminaires of 150 W each (including driver), operated 12 h/day (07:00–19:00) for 360 days/year. The required illuminance is 200 lux. Thirty tubular daylight devices are installed. On a design overcast day, an outdoor horizontal illuminance of 12,000 lux gives an average indoor daylight illuminance of 216 lux at floor level. Climate data show that, averaged over the year, outdoor illuminance is high enough for the daylight alone to meet 200 lux for 8 of the 12 operating hours, and the lights can be dimmed to 50 % for another 2 hours. Photo-sensor control switches the lights off or dims them accordingly. Cost: daylight devices ₹ 45,000 each installed plus controls ₹ 1,00,000; tariff ₹ 9/kWh.

(a) Daylight factor, and the minimum outdoor illuminance at which daylight alone meets 200 lux. (1.5 Marks)

(b) Present annual lighting energy. (0.5 Mark)

(c) Annual energy and cost saving. (1.5 Marks)

(d) Simple payback. (1 Mark)

(e) One design precaution with roof daylighting. (0.5 Mark)

[3P3CEM055 | Chapter 8: Lighting System | 8.6 Daylight harvesting in a warehouse – daylight factor and photo-sensor savings]

S-5 – Model answer (5 marks)

Given: 96 $\times$ 150 W = 14.4 kW; 12 h/day $\times$ 360 days = 4,320 h/year; E_{in} = 216 lux at E_{out} = 12,000 lux; target 200 lux; lights off for 8 h/day and at 50 % for 2 h/day; cost 30 $\times$ 45,000 + 1,00,000 = ₹ 14,50,000; ₹ 9/kWh.

(a) Daylight factor (1.5 Marks)

Formula: $DF = E_{indoor} / E_{outdoor} \times 100$; $E_{out(min)} = E_{required} / DF$

Substitution: $216 / 12,000 \times 100 = 1.8 \%$; $200 / 0.018$

Result: **DF = 1.8 %; daylight alone suffices when outdoor illuminance $\geq \approx$ 11,111 lux** (0.75 + 0.75)

(b) Present energy (0.5 Mark)

Result: **14.4 kW $\times$ 4,320 h = 62,208 kWh/year**

(c) Savings (1.5 Marks)

Formula: saving = load $\times$ hours off + load $\times$ dimming fraction $\times$ hours dimmed

Substitution: off: $14.4 \times 8 \times 360 = 41,472$ kWh; dimmed: $14.4 \times 0.5 \times 2 \times 360 = 5,184$ kWh (1 Mark)

Result: **Saving = 46,656 kWh/year (75 %), i.e. ₹ 4,19,904 per year** (0.5 Mark)

(d) Payback (1 Mark)

Result: **14,50,000 / 4,19,904 $\approx$ 3.45 years**

(e) Precaution (0.5 Mark)

Limit the daylight aperture area and use diffusing, UV-filtering domes so that solar heat gain and glare stay low (keep skylight area to about 3–5 % of roof); orient and space devices for uniformity, and commission sensors with time delays to avoid frequent switching.

Marking: (a) 0.75 $\times$ 2; (b) 0.5; (c) 1 + 0.5; (d) 1; (e) 0.5.

S-6 An office building in the composite climate zone has a total built-up area of 24,000 m², including a 6,000 m² basement car park. Annual electricity use: grid 23,40,000 kWh, DG 1,20,000 kWh, rooftop solar generated and used on site 1,80,000 kWh. For this exercise use these programme rules: EPI = total electricity used from all sources ÷ built-up area excluding the car park; and the following star bands (kWh/m²·year):

Star level	1 Star	2 Star	3 Star	4 Star	5 Star
EPI band	190–165	165–140	140–115	115–90	below 90

Two measures are evaluated: an LED and lighting-controls retrofit saving 1,10,000 kWh/year, and VFDs on AHUs and secondary pumps saving 1,60,000 kWh/year. Average electricity cost ₹ 9.50/kWh.

- (a) EPI area and present EPI. (2 Marks)
- (b) Present star band and the annual reduction needed to reach 3 Star. (1 Mark)
- (c) EPI and band after both measures, and the annual cost saving. (1.5 Marks)
- (d) Why is EPI used rather than total kWh for comparing buildings? (0.5 Mark)

[3P3CEM056 | Chapter 10: Energy Conservation in Buildings and ECBC | 10.7 Building energy performance index (EPI) and star-band benchmarking]

S-6 – Model answer (5 marks)

Given: built-up area 24,000 m²; car park 6,000 m²; grid 23,40,000 kWh, DG 1,20,000 kWh, solar 1,80,000 kWh; measures 1,10,000 + 1,60,000 kWh; ₹ 9.50/kWh.

(a) EPI (2 Marks)

EPI area = 24,000 – 6,000 = 18,000 m² (0.5 Mark)

Total use = 23,40,000 + 1,20,000 + 1,80,000 = 26,40,000 kWh (0.5 Mark)

Formula: EPI = annual energy / EPI area

Substitution: 26,40,000 / 18,000

Result: **EPI ≈ 146.7 kWh/m²·year** (1 Mark). (Using gross area would wrongly give 110 kWh/m²·year.)

(b) Band and gap (1 Mark)

Result: **146.7 lies in 165–140, i.e. 2 Star**. For 3 Star, EPI must be ≤ 140: 140 × 18,000 = 25,20,000 kWh, so **reduction needed = 1,20,000 kWh/year (4.5 %)**

(c) After measures (1.5 Marks)

New use = 26,40,000 – 2,70,000 = 23,70,000 kWh

Substitution: EPI = 23,70,000 / 18,000

Result: **EPI ≈ 131.7 kWh/m²·year, i.e. 3 Star; cost saving = 2,70,000 × 9.50 = ₹ 25,65,000 per year (1 + 0.5)**

(d) Why EPI (0.5 Mark)

EPI normalises consumption by floor area, so buildings of different sizes can be compared and tracked year on year; benchmarks are set per climate zone, building type and operating hours, which a total kWh figure cannot reflect.

Marking: (a) 0.5 + 0.5 + 1; (b) 0.5 + 0.5; (c) 1 + 0.5; (d) 0.5.

S-7 A water works must run on a standby DG set during grid failures. Loads:

Load	Details
Base load (already running)	120 kW at 0.85 PF
Largest pump motor (started last)	75 kW output, efficiency 93 %, running PF 0.86

Starting current of pump motor	DOL: $6.5 \times$ full-load current; star-delta: one-third of DOL value
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Manufacturer's data: the DG can accept a sudden motor starting kVA of up to 2.0 times its rating (for $\leq 15\%$ voltage dip), and its running rating is kVA at 0.8 PF. Available sizes: 250, 320, 400 and 500 kVA. Take the base load and starting kVA as adding arithmetically during starting.

- (a) Running kW, kVA and kVA of the total load. (2 Marks)
- (b) DG size needed with DOL starting. (1.5 Marks)
- (c) DG size needed with star-delta starting. (1 Mark)
- (d) Energy implication of the choice. (0.5 Mark)

[3P3CEM057 | Chapter 9: Diesel / Natural Gas Power Generating System | 9.4 DG set sizing – running kVA and motor starting kVA]

S-7 – Model answer (5 marks)

Given: base 120 kW at 0.85 PF; motor 75 kW output, η 0.93, PF 0.86; DOL starting $6.5 \times$ FLC; star-delta $1/3$ of DOL; starting capability $2.0 \times$ rating; running rating at 0.8 PF.

(a) Running load (2 Marks)

Formula: $kW_{in} = \text{output} / \eta$; $kVA = kW / PF$; $kVA_r = kVA \times \sin \phi$; total $kVA = \sqrt{\sum kW^2 + \sum kVA_r^2}$

Substitution: motor: $75 / 0.93 = 80.65$ kW; $80.65 / 0.86 = 93.77$ kVA; $kVA_r = 93.77 \times 0.510 = 47.85$ (0.75 Mark)

Base: $120 / 0.85 = 141.18$ kVA; $kVA_r = 141.18 \times 0.527 = 74.37$ (0.5 Mark)

Result: **Total = 200.65 kW, 122.22 kVA, $\sqrt{(200.65^2 + 122.22^2)} \approx 234.9$ kVA (PF 0.854)** (0.75 Mark)

(b) DOL starting (1.5 Marks)

Starting kVA = $6.5 \times 93.77 = 609.5$ kVA; with base load = $609.5 + 141.2 = 750.7$ kVA (0.75 Mark)

Formula: required rating = starting kVA / 2.0

Result: **750.7 / 2.0 = 375.4 kVA, so a 400 kVA set is needed** (0.75 Mark)

(c) Star-delta starting (1 Mark)

Starting kVA = $609.5 / 3 = 203.2$ kVA; with base load 344.4 kVA; $344.4 / 2.0 = 172.2$ kVA. Running load now governs: 234.9 kVA and 200.65 kW ($\leq 0.8 \times 320 = 256$ kW).

Result: **A 320 kVA set suffices (about 73 % kVA and 78 % kW loading)**

(d) Energy implication (0.5 Mark)

With DOL the 400 kVA set would carry only $200.65 / 320 = 63\%$ of its kW rating continuously, at poorer kWh per litre, and costs more. Reduced-voltage starting (star-delta, soft starter) or VFD starting allows a smaller, better-loaded DG set.

Marking: (a) $0.75 + 0.5 + 0.75$; (b) $0.75 + 0.75$; (c) 1; (d) 0.5.

S-8 A bank's regional office has 24 old fixed-speed split air conditioners of 1.5 TR (5.28 kW) each, with a rated EER of 2.75 W/W; because of on–off cycling their seasonal EER is estimated at 2.6 W/W. They are to be replaced by BEE 5-star inverter split units with an ISEER of 5.2 W/W. Each unit meets an annual cooling seasonal total load (CSTL) of $5.28 \text{ kW} \times 1,600$ equivalent full-load hours. A new unit costs ₹ 52,000 installed and the old unit has a buy-back value of ₹ 6,000. Tariff ₹ 10/kWh.

- (a) Specific power (kW/TR) of the old unit at rated EER and of the new unit at its ISEER. (1 Mark)
- (b) Annual electricity consumption per unit, old and new. (2 Marks)

(c) Annual saving for 24 units and simple payback. (1.5 Marks)

(d) Two operational measures to reduce room AC energy. (0.5 Mark)

[3P3CEM058 | Chapter 4: HVAC and Refrigeration System | 4.9 Room air conditioners – EER, ISEER and replacement economics]

S-8 – Model answer (5 marks)

Given: capacity 1.5 TR = 5.28 kW per unit (1 TR = 3.517 kW); EER_{rated} = 2.75; SEER_{old} = 2.6; ISEER_{new} = 5.2; CSTL = $5.28 \times 1,600 = 8,448$ kWh per unit; net cost ₹ 46,000 per unit; ₹ 10/kWh.

(a) kW/TR (1 Mark)

Formula: $\text{kW/TR} = 3.517 / \text{EER}$

Substitution: $3.517 / 2.75$; $3.517 / 5.2$

Result: **Old ≈ 1.28 kW/TR; new ≈ 0.68 kW/TR (seasonal)** (0.5 + 0.5)

(b) Annual consumption (2 Marks)

Formula: annual energy (CSEC) = CSTL / seasonal efficiency

Substitution: old: $8,448 / 2.6$; new: $8,448 / 5.2$

Result: **Old $\approx 3,249$ kWh/year; new $\approx 1,625$ kWh/year per unit** (1 + 1)

(c) Savings and payback (1.5 Marks)

Saving = $(3,249.2 - 1,624.6) \times 24 = 38,991$ kWh/year; $\times ₹ 10 = ₹ 3,89,908$ per year (0.75 Mark)

Investment = $24 \times (52,000 - 6,000) = ₹ 11,04,000$

Result: **Simple payback = $11,04,000 / 3,89,908 \approx 2.83$ years** (0.75 Mark)

(d) Operational measures (0.5 Mark; any two)

Set thermostats at 24–26 °C (default 24 °C as per BEE advisory); clean filters and condenser coils regularly; shade outdoor units and keep their air path clear; close doors and windows and switch units off through occupancy or timers after office hours.

Marking: (a) 0.5×2 ; (b) 1×2 ; (c) $0.75 + 0.75$; (d) 0.5.

..... End of Section II

Section – III: LONG DESCRIPTIVE QUESTIONS Marks: 6 x 10 = 60

6. Answer all Six questions

7. Each question carries Ten marks

L-1 A plant is fed by a 2,000 kVA, 11/0.433 kV transformer with 6.25 % impedance (take the LT bus fault level as transformer-limited). The LT load is 1,600 kW at a displacement PF of 0.82; 1,200 kW of it is six-pulse VFD load, and the current THD at the LT bus is 32 %. The demand charge is ₹ 450 per kVA per month on recorded kVA.

A vendor offers a 700 kVAR plain (non-detuned) APFC panel in two equal steps to raise the displacement PF to 0.97.

(a) Calculate the kVAR needed to raise the displacement PF from 0.82 to 0.97, and comment on the 700 kVAR offer. (2 Marks)

(b) Calculate the LT fault level and the parallel resonance harmonic order with the full 700 kVAR and with one 350 kVAR step in service. Comment on the risk. (2.5 Marks)

(c) A detuned bank with 7 % series reactors is proposed instead. Calculate its tuning frequency and the voltage across the capacitors, and the rated kVAR of 480 V capacitors needed to deliver 700 kVAR effective at 433 V. (2.5 Marks)

- (d) Calculate the true power factor before correction and after correction to 0.97 displacement PF (THD unchanged), and with an active harmonic filter reducing THD to 8 %. (2 Marks)
- (e) Estimate the annual demand-charge saving from (d) without the active filter. (1 Mark)

[3P3CEM059 | Chapter 1: Electrical Systems | 1.10 Harmonics – capacitor resonance, detuned bank design and true power factor]

L-1 – Model answer (10 marks)

Given: $S_{tr} = 2,000$ kVA; $Z = 6.25$ %; $P = 1,600$ kW; $PF_1 = 0.82$; $PF_2 = 0.97$; $THD_i = 32$ %; bank 700 kVAr (2×350); 7 % reactor; capacitors rated 480 V; bus 433 V; ₹ 450/kVA/month.

(a) Capacitor requirement (2 Marks)

Formula: $kVAr = kW \times (\tan \phi_1 - \tan \phi_2)$

Substitution: $\tan \phi_1 = 0.698$, $\tan \phi_2 = 0.251$; $1,600 \times (0.698 - 0.251)$ (1 Mark)

Result: ≈ 716 kVAr, so **700 kVAr is the right size in kVAr terms** (0.5 Mark); but with 75 % of the load on VFDs, a plain bank is risky, as (b) shows. (0.5 Mark)

(b) Fault level and resonance (2.5 Marks)

Formula: $S_{sc} = S_{tr} / Z$; resonance order $h = \sqrt{S_{sc} / Q_c}$

Substitution: $S_{sc} = 2,000 / 0.0625 = 32,000$ kVA (32 MVA) (0.5 Mark)

700 kVAr: $h = \sqrt{32,000 / 700} = \sqrt{45.7}$ (0.75 Mark)

Result: **$h \approx 6.76$ (≈ 338 Hz), close to the 7th harmonic (350 Hz)**

350 kVAr: $h = \sqrt{32,000 / 350} = \sqrt{91.4}$

Result: **$h \approx 9.56$ (≈ 478 Hz)** (0.5 Mark)

Comment: as steps switch, the resonance sweeps between about the 7th and 10th orders. With the 7th (and 5th) harmonic currents injected by six-pulse drives, the full bank operates almost at resonance, so harmonic currents and voltage distortion will be amplified, capacitors will overheat and fuses blow. A plain bank must not be used. (0.75 Mark)

(c) Detuned bank (2.5 Marks)

Formula: tuning order $h_t = 1 / \sqrt{p}$

Substitution: $1 / \sqrt{0.07} = 3.78$

Result: **tuning frequency $\approx 3.78 \times 50 \approx 189$ Hz, below the 5th harmonic, so the bank is inductive at all characteristic harmonics and cannot resonate with them** (1 Mark)

Capacitor voltage = $V / (1 - p) = 433 / 0.93$

Result: **≈ 466 V, so 480 V (or higher) rated capacitors are needed** (0.5 Mark)

Formula: $Q_{eff} = Q_{rated} \times (V / V_{rated})^2 / (1 - p)$, so $Q_{rated} = Q_{eff} \times (1 - p) / (V / V_{rated})^2$

Substitution: $700 \times 0.93 / (433 / 480)^2 = 651 / 0.8138$

Result: **Rated capacity ≈ 800 kVAr at 480 V (with 7 % reactors) to give 700 kVAr effective** (1 Mark)

(d) True power factor (2 Marks)

Formula: distortion factor = $1 / \sqrt{1 + THD^2}$; true PF = displacement PF $\times$ distortion factor

Substitution: $1 / \sqrt{1 + 0.32^2} = 0.952$

Result: **Before: $0.82 \times 0.952 \approx 0.781$; after: $0.97 \times 0.952 \approx 0.924$; with active filter: $0.97 / \sqrt{1 + 0.08^2} \approx 0.967$** (0.5 + 0.75 + 0.75)

(e) Demand saving (1 Mark)

kVA before = $1,600 / 0.781 = 2,049$ kVA (above the transformer rating); after = $1,600 / 0.924 = 1,732$ kVA

Result: **Reduction ≈ 317 kVA; saving $\approx 316.8 \times 450 \times 12 \approx ₹ 17,10,760$ per year** (the transformer is also relieved from overload)

Marking: (a) 1 + 0.5 + 0.5; (b) 0.5 + 0.75 + 0.5 + 0.75; (c) 1 + 0.5 + 1; (d) 0.5 + 0.75 + 0.75; (e) 1.

L-2 A process plant needs 500 TR ($\approx 1,758$ kW) of chilled water for 6,000 h/year. Two options are compared:

Item	Option A: water-cooled screw chiller	Option B: double-effect steam VAM
Compressor / generator	0.65 kW/TR	Steam 4.5 kg/h per TR at 8 kg/cm ² (g) (≈ 7.85 bar(g))
Solution pumps	–	8 kW
Condenser water pump	45 kW	75 kW
Cooling tower fans	22 kW	37 kW

For Option B, steam would come from a natural-gas-fired boiler: heat added per kg of steam 620 kcal/kg ($\approx 2,596$ kJ/kg), boiler efficiency 85 %, gas GCV 9,000 kcal/Sm³ (≈ 37.7 MJ/Sm³) at ₹ 45/Sm³. Electricity costs ₹ 8.50/kWh. Take 1 TR = 3,024 kcal/h (≈ 3.52 kW).

(a) Annual electricity use and cost of Option A. (2 Marks)

(b) Annual steam, gas and auxiliary power costs of Option B. (3 Marks)

(c) Thermal COP of the VAM, and the heat rejected to the cooling tower by each option. Explain why Option B needs bigger pumps and fans. (2.5 Marks)

(d) Compare annual operating costs; then compare again if the steam were free waste-heat steam. (1.5 Marks)

(e) State two conditions under which a VAM is preferred. (1 Mark)

[3P3CEM060 | Chapter 4: HVAC and Refrigeration System | 4.5 Electric screw chiller vs steam-fired double-effect absorption chiller – operating economics]

L-2 – Model answer (10 marks)

Given: 500 TR ($\approx 1,758$ kW); 6,000 h/year; A: 0.65 kW/TR + 45 + 22 kW; B: 4.5 kg steam/h/TR, aux 8 + 75 + 37 = 120 kW; 620 kcal/kg steam ($\approx 2,596$ kJ/kg steam); $\eta_{\text{boiler}} = 0.85$; GCV 9,000 kcal/Sm³ (≈ 37.7 MJ/Sm³); ₹ 45/Sm³; ₹ 8.50/kWh.

(a) Option A (2 Marks)

Formula: total power = TR $\times$ kW/TR + auxiliaries

Substitution: $500 \times 0.65 + 45 + 22 = 392$ kW; $392 \times 6,000 = 23,52,000$ kWh (1 Mark)

Result: **Annual cost (A) = $23,52,000 \times 8.50 = ₹ 1,99,92,000$ ($\approx ₹ 2.0$ crore)** (1 Mark)

(b) Option B (3 Marks)

Steam = $500 \times 4.5 = 2,250$ kg/h; heat in steam = $2,250 \times 620 = 13,95,000$ kcal/h ($\approx 1,622$ kW) (0.5 Mark)

Formula: gas (Sm³/h) = steam heat / ($\eta_{\text{boiler}} \times \text{GCV}$)

Substitution: $13,95,000 / (0.85 \times 9,000) = 182.35$ Sm³/h; annual gas = $182.35 \times 6,000 = 10,94,118$ Sm³ (1 Mark)

Gas cost = $10,94,118 \times 45 = ₹ 4,92,35,294$ (0.5 Mark)

Auxiliary power = $120 \times 6,000 = 7,20,000$ kWh, i.e. ₹ 61,20,000 (0.5 Mark)

Result: **Annual cost (B) $\approx ₹ 5,53,55,294$ ($\approx ₹ 5.54$ crore)** (0.5 Mark)

(c) COP and heat rejection (2.5 Marks)

Formula: COP_{thermal} = cooling output / heat input

Substitution: $500 \times 3,024 / 13,95,000 = 15,12,000 / 13,95,000$

Result: **VAM COP ≈ 1.08** (0.5 Mark)

Heat rejected (A) = cooling + compressor heat = $15,12,000 + 325 \times 860 = 15,12,000 + 2,79,500$

Result: **(A) $\approx 17,91,500$ kcal/h ($\approx 2,083$ kW)** (0.75 Mark)

Heat rejected (B) = cooling + generator heat = 15,12,000 + 13,95,000

Result: **(B) $\approx 29,07,000$ kcal/h ($\approx 3,380$ kW), about 1.62 times Option A** (0.75 Mark)

Hence Option B needs more condenser water flow, a larger cooling tower and more pump and fan power, and loses more make-up water by evaporation. (0.5 Mark)

(d) Comparison (1.5 Marks)

Result: **Option A is cheaper by ₹ 5,53,55,294 – ₹ 1,99,92,000 = ₹ 3,53,63,294 per year** (0.75 Mark)

If steam is free waste heat, B costs only its auxiliaries:

Result: **B = ₹ 61,20,000 against A = ₹ 1,99,92,000, so B saves ₹ 1,38,72,000 per year** (0.75 Mark)

(e) VAM preferred when (1 Mark; any two)

Waste heat (exhaust gas, low-pressure steam, hot water from cogeneration) is available at little or no cost; electrical supply is limited or demand charges are high; the site already has a gas engine or turbine for trigeneration; noise and vibration must be low, or refrigerants with high GWP must be avoided.

Marking: (a) 1 + 1; (b) 0.5 + 1 + 0.5 + 0.5 + 0.5; (c) 0.5 + 0.75 + 0.75 + 0.5; (d) 0.75 + 0.75; (e) 0.5 $\times$ 2.

L-3 A chemical plant's cooling water system has two identical centrifugal pumps in parallel. The curves (Q in m³/h, H in m) are:

Curve	Equation
One pump at full speed (1,480 rpm, 50 Hz)	$H = 50 - 8 \times 10^{-5} Q^2$
System	$H = 20 + 4 \times 10^{-5} Q^2$
Pump efficiency at full speed	$\eta = 0.0034 Q - 3.4 \times 10^{-6} Q^2$ (per pump, Q per pump)

Process demand is now steady at 600 m³/h. At present both pumps run at full speed and the common delivery valve is throttled to give 600 m³/h. Motor efficiency is 92 %, VFD efficiency 97 %. The plant runs 8,000 h/year; tariff ₹ 7/kWh. Water density 1,000 kg/m³.

(a) Find the operating flow and head with one pump, and with two pumps in parallel with the valve fully open. (2.5 Marks)

(b) For the present throttled operation, find the pump head, the head lost across the valve, the pump efficiency and the total motor input. (2.5 Marks)

(c) With the valve fully open, both pumps are put on VFDs running at equal speed to give 600 m³/h. Find the speed ratio and frequency, pump efficiency, total input power, and annual energy and cost saving. (3.5 Marks)

(d) Trimming both impellers is an alternative. Estimate its input (assume efficiency 2 points lower than in (c), no VFD loss) and state when a VFD is still preferable. (1.5 Marks)

[3P3CEM061 | Chapter 6: Pumps and Pumping System | 6.5 Parallel pump operating points, throttling loss and VFD speed from pump and system curves]

L-3 – Model answer (10 marks)

Given: pump $H = 50 - 8 \times 10^{-5} Q^2$; system $H = 20 + 4 \times 10^{-5} Q^2$; $\eta = 0.0034 Q - 3.4 \times 10^{-6} Q^2$; demand 600 m³/h (300 m³/h per pump); $\eta_{\text{motor}} = 0.92$; $\eta_{\text{VFD}} = 0.97$; 8,000 h/year; ₹ 7/kWh.

(a) Operating points (2.5 Marks)

One pump: $50 - 8 \times 10^{-5} Q^2 = 20 + 4 \times 10^{-5} Q^2$, so $1.2 \times 10^{-4} Q^2 = 30$

Result: **Q = 500 m³/h at H = 30 m ($\eta = 85$ %, the BEP)** (1 Mark)

Two pumps in parallel (each Q/2): $50 - 2 \times 10^{-5} Q^2 = 20 + 4 \times 10^{-5} Q^2$, so $6 \times 10^{-5} Q^2 = 30$

Result: **$Q \approx 707 \text{ m}^3/\text{h}$ at $H = 40 \text{ m}$ (each pump $354 \text{ m}^3/\text{h}$, $\eta \approx 77.7 \%$)** (1 Mark)

The second pump adds only 41 % more flow because the system curve rises. (0.5 Mark)

(b) Present throttled operation (2.5 Marks)

System head needed at $600 \text{ m}^3/\text{h} = 20 + 4 \times 10^{-5} \times 600^2 = 34.4 \text{ m}$ (0.5 Mark)

Pump head at $300 \text{ m}^3/\text{h}$ each $= 50 - 8 \times 10^{-5} \times 300^2 = 42.8 \text{ m}$; head lost in valve $= 8.4 \text{ m}$ (0.5 Mark)

η at $300 \text{ m}^3/\text{h} = 0.0034 \times 300 - 3.4 \times 10^{-6} \times 300^2 = 71.4 \%$ (0.5 Mark)

Formula: shaft power per pump $= \rho g Q H / \eta$; input $= \Sigma \text{ shaft} / \eta_{\text{motor}}$

Substitution: $1,000 \times 9.81 \times (300 / 3,600) \times 42.8 / 0.714 = 49.0 \text{ kW}$ per pump

Result: **Total input $\approx 2 \times 49.0 / 0.92 \approx 106.5 \text{ kW}$, of which about 13.7 kW of hydraulic power is destroyed in the valve** (1 Mark)

(c) VFD operation (3.5 Marks)

Formula: at speed ratio r , pump curve $H = 50 r^2 - 8 \times 10^{-5} Q^2$; similar points keep efficiency at Q / r

Substitution: $34.4 = 50 r^2 - 8 \times 10^{-5} \times 300^2$, so $r^2 = 41.6 / 50 = 0.832$

Result: **$r \approx 0.912$, i.e. $\approx 1,350 \text{ rpm}$ or 45.6 Hz** (1 Mark)

Equivalent full-speed flow $= 300 / 0.912 = 328.9 \text{ m}^3/\text{h}$; $\eta = 0.0034 \times 328.9 - 3.4 \times 10^{-6} \times 328.9^2 = 75.0 \%$ (0.75 Mark)

Shaft power per pump $= 9.81 \times (300 / 3,600) \times 34.4 / 0.750 = 37.5 \text{ kW}$; input $= 2 \times 37.5 / (0.92 \times 0.97)$

Result: **Input $\approx 84.0 \text{ kW}$** (0.75 Mark)

Result: **Saving $\approx 106.5 - 84.0 = 22.5 \text{ kW}$, i.e. $\approx 1,80,387 \text{ kWh/year}$, $\approx ₹ 12,62,709$ per year** (1 Mark)

(d) Impeller trimming (1.5 Marks)

Input $= 2 \times 28.12 / (0.730 \times 0.92)$

Result: **$\approx 83.7 \text{ kW}$, about the same as the VFD at this fixed duty** (0.75 Mark)

A VFD remains preferable when demand varies with season or process (it can track each flow with no throttling), when future growth may need full speed again, and to give soft starting; trimming is permanent and suits a steady, well-defined duty. (0.75 Mark)

Marking: (a) $1 + 1 + 0.5$; (b) $0.5 + 0.5 + 0.5 + 1$; (c) $1 + 0.75 + 0.75 + 1$; (d) $0.75 + 0.75$.

L-4 An auditor tests one cell of a four-cell induced-draft cooling tower at a fertiliser plant (all cells identical and similarly loaded):

Parameter	Value
Fan stack throat diameter / hub diameter	8.0 m / 1.6 m
Average air velocity at fan throat (anemometer traverse)	7.5 m/s
Density of exit air (saturated, 36°C)	1.12 kg/m^3
Static pressure across the fan (plenum to atmosphere)	12 mmWC ($\approx 118 \text{ Pa}$)
Fan motor input	100 kW
Motor efficiency / gearbox efficiency	93 % / 96 %
Water flow per cell	$2,000 \text{ m}^3/\text{h}$
Hot / cold water temperature	$40^\circ\text{C} / 32^\circ\text{C}$

Proposal: replace the existing aluminium blades with FRP aerofoil blades of 82 % fan efficiency, giving the same air flow and pressure. Cost ₹ 9 lakh per cell. Operating hours 7,500 h/year; tariff ₹ 8/kWh.

(a) Air volume flow and mass flow through the cell. (2 Marks)

(b) Liquid-to-gas (L/G) ratio and heat load of the cell. (1 Mark)

(c) Fan velocity pressure, total pressure and air power. (2 Marks)

- (d) Fan shaft power and present fan efficiency. (1.5 Marks)
- (e) Power and annual saving for four cells with FRP blades, and payback. (2 Marks)
- (f) List three other checks that improve cooling tower fan efficiency. (1.5 Marks)

[3P3CEM062 | Chapter 7: Cooling Towers | 7.3 Cooling tower fan performance – air flow, L/G, fan efficiency and FRP aerofoil blade retrofit]

L-4 – Model answer (10 marks)

Given: $D = 8.0$ m, $d_{\text{hub}} = 1.6$ m; $v = 7.5$ m/s; $\rho = 1.12$ kg/m³; $SP = 12$ mmWC (≈ 118 Pa); motor input 100 kW; $\eta_{\text{motor}} = 0.93$; $\eta_{\text{gear}} = 0.96$; water 2,000 m³/h per cell; range 8 °C; $\eta_{\text{new fan}} = 0.82$; ₹ 9 lakh per cell; 7,500 h/year; ₹ 8/kWh.

(a) Air flow (2 Marks)

Formula: net area $A = (\pi/4)(D^2 - d^2)$; $Q = v \times A$; $m = \rho \times Q$

Substitution: $A = 0.7854 \times (64 - 2.56) = 48.25$ m²; $Q = 7.5 \times 48.25$ (1 Mark)

Result: **$Q \approx 361.9$ m³/s; $m \approx 361.9 \times 1.12 \approx 405.3$ kg/s** (0.5 + 0.5)

(b) L/G and heat load (1 Mark)

$L = 2,000 \times 1,000 / 3,600 = 555.6$ kg/s

Result: **$L/G \approx 555.6 / 405.3 \approx 1.37$; heat load = $2,000 \times 1,000 \times 8 = 1,60,00,000$ kcal/h (≈ 18.6 MW) per cell** (0.5 + 0.5)

(c) Pressures and air power (2 Marks)

Formula: $VP = \rho v^2 / 2$; $TP = SP + VP$; air power = $Q \times TP$

Substitution: $VP = 1.12 \times 7.5^2 / 2 = 31.5$ Pa (≈ 3.2 mmWC); $SP = 12 \times 9.807 = 117.7$ Pa; $TP = 149.2$ Pa (1 Mark)

Result: **Air power $\approx 361.9 \times 149.2 \approx 54.0$ kW** (1 Mark)

(d) Fan efficiency (1.5 Marks)

Formula: shaft power = motor input $\times \eta_{\text{motor}} \times \eta_{\text{gear}}$; fan efficiency = air power / shaft power

Substitution: $100 \times 0.93 \times 0.96 = 89.3$ kW; $54.0 / 89.3$ (0.75 Mark)

Result: **Present fan efficiency ≈ 60.5 %** (0.75 Mark)

(e) FRP blade retrofit (2 Marks)

New shaft power = $54.0 / 0.82 = 65.8$ kW; new motor input = $65.8 / (0.93 \times 0.96) = 73.7$ kW (0.75 Mark)

Saving = $100 - 73.7 = 26.3$ kW per cell; four cells = 105.0 kW; $105.0 \times 7,500 = 7,87,590$ kWh (0.5 Mark)

Result: **Annual saving $\approx$ ₹ 63,00,721; payback = $36,00,000 / 63,00,721 \approx 0.57$ year (≈ 7 months)** (0.75 Mark)

(f) Other checks (1.5 Marks; 0.5 each, any three)

Set all blades to the same correct pitch angle using a protractor, matched to the motor load at design air flow; reduce blade tip clearance with the fan stack and fit a velocity-recovery (flared) stack; keep drift eliminators and fill clean so that static pressure stays low; balance water distribution to avoid dry and flooded zones; control fans on cold-water temperature with VFDs.

Marking: (a) 1 + 0.5 + 0.5; (b) 0.5 + 0.5; (c) 1 + 1; (d) 0.75 + 0.75; (e) 0.75 + 0.5 + 0.75; (f) 0.5 $\times$ 3.

L-5 A tyre plant runs two oil-injected screw compressors with a combined average electrical input of 290 kW for 7,500 h/year. Their oil coolers are air-cooled, with two cooler fans of 5.5 kW each. It is proposed to fit plate heat exchangers on the oil circuits that can recover 72 % of the compressor electrical input as hot water, heating boiler make-up water from 30 °C to 65 °C. The plant's furnace oil-fired boiler needs 6,000 kg/h of make-up water at all times. With heat recovery, the oil-cooler fans will be switched off. Data: boiler efficiency 84 %; furnace oil GCV 10,200 kcal/kg ($\approx 42,705$ kJ/kg) at ₹ 52/kg; electricity ₹ 8/kWh; specific heat of water 4.187 kJ/kg·K; project cost ₹ 28 lakh.

- (a) Heat recoverable in kW and kcal/h. (1.5 Marks)
- (b) Quantity of water that can be heated from 30 °C to 65 °C, and whether the boiler can use all of it. (1.5 Marks)
- (c) Furnace oil saved per hour and per year, and its value. (2.5 Marks)
- (d) Electricity saving from the oil-cooler fans and the total annual saving. (1.5 Marks)
- (e) Simple payback. (1 Mark)
- (f) State four precautions for compressor heat recovery systems. (2 Marks)

[3P3CEM063 | Chapter 3: Compressed Air System | 3.9 Heat recovery from oil-injected screw compressors for boiler feed water]

L-5 – Model answer (10 marks)

Given: compressor input 290 kW; recovery 72 %; water 30 → 65 °C (ΔT 35 K); boiler make-up 6,000 kg/h; η_{boiler} = 0.84; GCV = 10,200 kcal/kg ($\approx$ 42,705 kJ/kg); ₹ 52/kg FO; fans 2 × 5.5 kW; 7,500 h/year; ₹ 8/kWh; cost ₹ 28,00,000.

(a) Recoverable heat (1.5 Marks)

Formula: $Q = \text{recovery fraction} \times \text{electrical input}; \text{kcal/h} = \text{kW} \times 860$

Substitution: 0.72×290

Result: **$Q \approx 208.8 \text{ kW} = 1,79,568 \text{ kcal/h}$** (1 + 0.5)

(b) Water heated (1.5 Marks)

Formula: $m = Q / (c_p \times \Delta T)$

Substitution: $208.8 / (4.187 \times 35) = 1.425 \text{ kg/s}$ (1 Mark)

Result: **$\approx 5,129 \text{ kg/h}$, less than the 6,000 kg/h make-up, so all recovered heat is usable year-round** (0.5 Mark)

(c) Fuel saving (2.5 Marks)

Formula: $\text{FO saved} = \text{heat recovered} / (\eta_{\text{boiler}} \times \text{GCV})$

Substitution: $1,79,568 / (0.84 \times 10,200)$ (1 Mark)

Result: **$\approx 20.96 \text{ kg/h of furnace oil}$** (0.5 Mark)

Annual FO = $20.958 \times 7,500 = 1,57,185 \text{ kg}$ (0.5 Mark)

Result: **Value $\approx 1,57,185 \times 52 \approx ₹ 81,73,613$ per year** (0.5 Mark)

(d) Fan saving and total (1.5 Marks)

Fan saving = $11 \times 7,500 = 82,500 \text{ kWh}$, i.e. ₹ 6,60,000 per year (0.75 Mark)

Result: **Total annual saving $\approx ₹ 88,33,613$** (0.75 Mark)

(e) Payback (1 Mark)

Result: **$28,00,000 / 88,33,613 \approx 0.32 \text{ year}$ (about 4 months)**

(f) Precautions (2 Marks; 0.5 each, any four)

Keep a thermostatic bypass and the original air coolers (or a back-up water cooler) so that oil temperature stays within limits when hot-water demand falls; use treated, soft water and a strainer to prevent scaling of plate exchangers; monitor oil and water temperatures with alarms and interlocks to trip compressors on high oil temperature; ensure no cross-contamination of oil into boiler feed (double-wall or intermediate loop); match recovery to a steady heat sink, as here, and insulate hot-water lines.

Marking: (a) 1 + 0.5; (b) 1 + 0.5; (c) 1 + 0.5 + 0.5 + 0.5; (d) 0.75 + 0.75; (e) 1; (f) 0.5 × 4.

L-6 An engineering plant on an HT TOD tariff considers running its existing 1,000 kVA DG set in parallel with the grid during the evening peak to cut energy and demand charges. Data:

Item	Value
Base energy charge	₹ 7.20/kWh
Peak-hour surcharge (18:00–22:00)	₹ 2.00/kWh
Demand charge	₹ 480 per kVA per month on recorded MD
Plant load during peak hours	2,400 kW at 0.95 PF
Highest load outside peak hours	2,000 kW at 0.95 PF
Proposed DG output during peak hours	700 kW, 4 h/day, 26 days/month
DG specific energy generation at 700 kW (70 % load)	3.6 kWh/litre
DG specific energy generation at 400 kW (40 % load)	3.1 kWh/litre
Diesel price	₹ 92/litre
Lube oil, spares and maintenance	₹ 1.40 per kWh generated

- (a) Cost of DG power per kWh at 700 kW output. (1.5 Marks)
- (b) Monthly extra energy cost of replacing peak grid energy with DG energy. (2 Marks)
- (c) New maximum demand and monthly demand-charge saving. (2.5 Marks)
- (d) Net monthly result. Find the DG cost per kWh at which peak lopping would break even, and the kWh/litre this implies. Also evaluate running the DG at only 400 kW. (2.5 Marks)
- (e) Suggest better ways to reduce the peak-period cost. (1.5 Marks)

[3P3CEM064 | Chapter 9: Diesel / Natural Gas Power Generating System | 9.6 Peak lopping with a grid-synchronised DG set – TOD and demand economics]

L-6 – Model answer (10 marks)

Given: grid peak rate = 7.20 + 2.00 = ₹ 9.20/kWh; demand ₹ 480/kVA/month; peak load 2,400 kW, off-peak maximum 2,000 kW, PF 0.95; DG 700 kW × 4 h × 26 days; SEG 3.6 kWh/L at 700 kW and 3.1 kWh/L at 400 kW; diesel ₹ 92/L; O&M ₹ 1.40/kWh.

(a) DG cost per kWh (1.5 Marks)

Formula: DG cost = diesel price / SEG + O&M

Substitution: $92 / 3.6 = ₹ 25.56/\text{kWh fuel}$; + 1.40 (1 Mark)

Result: **≈ ₹ 26.96 per kWh** (0.5 Mark)

(b) Extra energy cost (2 Marks)

DG energy = $700 \times 4 \times 26 = 72,800 \text{ kWh/month}$ (0.5 Mark)

Formula: extra cost = DG kWh × (DG cost – grid peak rate)

Substitution: $72,800 \times (26.96 - 9.20)$ (1 Mark)

Result: **≈ ₹ 12,92,604 per month extra** (0.5 Mark)

(c) Demand saving (2.5 Marks)

Present MD = $2,400 / 0.95 = 2,526 \text{ kVA}$ (0.5 Mark)

Grid peak load with DG = $2,400 - 700 = 1,700 \text{ kW}$, but the off-peak load of 2,000 kW now sets the MD (1 Mark)

New MD = $2,000 / 0.95 = 2,105 \text{ kVA}$; reduction = 421 kVA (0.5 Mark)

Result: **Demand saving = $421.05 \times 480 \approx ₹ 2,02,105 \text{ per month}$** (0.5 Mark); only 400 kW of the 700 kW actually reduces MD.

(d) Net result and break-even (2.5 Marks)

Result: **Net loss $\approx 12,92,604 - 2,02,105 \approx ₹ 10,90,499 \text{ per month}$** (**≈ ₹ 1.31 crore per year**), so peak lopping at **700 kW is not viable** (0.75 Mark)

Formula: break-even DG cost = grid peak rate + demand saving / DG kWh

Substitution: $9.20 + 2,02,105 / 72,800 = 9.20 + 2.78$

Result: $\approx ₹ 11.98/\text{kWh}$, which needs $92 / (11.98 - 1.40) \approx 8.7 \text{ kWh/litre}$, far above any diesel engine (3.5–4.0) (1 Mark)

At 400 kW (just enough to cap MD at 2,105 kVA): DG cost = $92 / 3.1 + 1.40 = ₹ 31.08/\text{kWh}$; DG energy 41,600 kWh; extra energy cost = $41,600 \times (31.08 - 9.20) = ₹ 9,10,101$; net loss $\approx ₹ 7,07,995$ per month.

Result: **Still a loss, and the poorer part-load SEG makes each kWh dearer** (0.75 Mark)

(e) Better options (1.5 Marks; 0.5 each, any three)

Shift deferrable loads (batch furnaces, pumping, charging, compressed-air filling) out of 18:00–22:00 using TOD rebates; reduce the 2,000 kW off-peak peak through load scheduling and a demand controller, so contract demand can also be lowered; use thermal storage (ice/chilled water) for process cooling; improve PF to near unity to cut kVA; consider grid-connected solar with storage. Keep the DG for emergencies, where its reliability value justifies its cost.

Marking: (a) $1 + 0.5$; (b) $0.5 + 1 + 0.5$; (c) $0.5 + 1 + 0.5 + 0.5$; (d) $0.75 + 1 + 0.75$; (e) 0.5×3 .

..... End of Section III

Section I – Answer key

Q	Ans	Q	Ans	Q	Ans	Q	Ans	Q	Ans
1	d	11	c	21	d	31	a	41	b
2	a	12	b	22	a	32	c	42	a
3	d	13	c	23	a	33	d	43	c
4	c	14	c	24	b	34	d	44	d
5	c	15	b	25	a	35	a	45	a
6	a	16	d	26	c	36	a	46	b
7	c	17	d	27	d	37	b	47	b
8	d	18	c	28	a	38	d	48	c
9	b	19	b	29	b	39	c	49	a
10	b	20	b	30	d	40	a	50	b