# PRACTICE EXAM 24: PE POWER SIMULATION (80 QUESTIONS)

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1. A 13.8 kV industrial bus has a three-phase fault level of 540 MVA with a 9,000 kvar capacitor bank producing h_r = $\sqrt{(540{,}000/9{,}000)}$ = 7.75. The bus serves six-pulse VFDs (3,500 HP), eighteen-pulse VFDs (4,000 HP), and AFE drives (2,500 HP). A power quality study reveals the measured $V_7$ at the bus is 6.8% — well above the IEEE 519 limit of 3.0%. The engineer calculates the amplification factor at h = 7: AF = $h\_r^2/(h\_r^2-h^2)$ = 60.06/(60.06−49) = 5.44. This 5.44× amplification of the six-pulse drives' 7th harmonic injection explains the excessive $V_7$. What is the most effective single corrective action?

A. Replace all six-pulse drives with AFE drives (eliminates the harmonic source but extremely expensive)

B. Install 6% detuning reactors on the capacitor bank to shift h_r from 7.75 down to approximately 4.7 (below the 5th harmonic), eliminating the resonance amplification of ALL characteristic harmonics — this is typically 10-20% of the cost of replacing the VFDs and addresses the root cause: the resonance, not the harmonic source

C. Reduce the capacitor bank to 4,000 kvar (shifts h_r to 11.6 but provides inadequate PF correction)

D. Install a passive 7th-harmonic filter (addresses $V_7$ but may create new resonances at other frequencies)

2. A three-phase, 480V system has a 3,500 kVA transformer (Z = 5.75%, X/R = 9) feeding a switchboard with I_fault = 42,200A. A 500-foot cable of 4/0 AWG copper in steel conduit (R = 0.0608, X = 0.0478 Ω/1000 ft) feeds a remote panelboard. At the panelboard, two 200 HP motors (FLA = 242A each, total = 484A) contribute 4 × 484 = 1,936A. The panelboard has a main 225A breaker with an instantaneous trip at 10× rating (2,250A). The engineer must verify the panelboard fault current exceeds the instantaneous trip threshold. What is the total first-cycle fault current at the panelboard?

A. 42,200A (cable negligible)

B. 10,000A (cable reduces by 75%; motors add 1,936A)

C. 1,936A (motor contribution only; cable blocks transformer current entirely)

D. Cable Z: R = 0.0304, X = 0.0239 Ω; Z_base = 0.0658 Ω; Z_cable_pu = 0.0387/0.0658 = 0.588; total Z = 0.0575+0.588 = 0.646; I_transformer = 4,209/0.646 = 6,515A; plus motor 1,936A = 8,451A total — above the 2,250A instantaneous threshold; the long 4/0 cable reduces the transformer contribution by 85% but the combined fault current is still adequate for instantaneous breaker operation

3. Per NEC 430.52(C)(1), a 300 HP, 460V motor (FLA = 361A) uses a dual-element time-delay fuse at 175% = 631.75A → next standard 700A. The motor also has a VFD with integrated electronic motor protection. The VFD manufacturer states the VFD provides short-circuit protection up to 22,000A. Per NEC 430.52, does the VFD's built-in protection eliminate the need for the branch-circuit OCPD (fuse)?

A. No — NEC 430.52 requires a branch-circuit short-circuit and ground-fault protective device (OCPD) regardless of VFD electronic protection; the VFD's electronic protection may supplement but cannot replace the required OCPD because VFDs can fail in ways that bypass their electronic protection (power semiconductor failure, control board failure); the 700A fuse provides the code-required backup that operates independently of the VFD's electronics

B. Yes — VFDs with listed protection are recognized as OCPD substitutes per NEC 430.52

C. Yes — but only for motors above 200 HP with drives rated for the full fault current

D. No — but only because the VFD's 22,000A rating may be below the available fault current

4. A CT with a ratio of 1600:5 and accuracy class C200 is used for an overcurrent relay on a 4,160V feeder. The total burden is 1.8 Ω. During a 24,000A fault (15× rated), the CT secondary = 75A. Burden voltage = 135V. The C200 guarantees accuracy at 20× (100A) up to 200V. At 15× with 135V, the CT has 65V of margin. However, the engineer discovers that the CT secondary wiring passes through a steel conduit for 30 feet, adding significant magnetic impedance to the circuit. What is the concern?

A. Steel conduit around CT secondary wiring has no effect on CT performance

B. The CT secondary wiring should never pass through steel conduit

C. Running CT secondary wiring through steel conduit adds additional impedance (due to the magnetic permeability of steel creating inductive reactance in the secondary circuit) that increases the effective burden beyond the calculated 1.8 Ω; the added impedance could consume the 65V margin and push the CT toward saturation during faults; CT secondary wiring should be routed through nonmagnetic conduit (PVC, aluminum, or nonmagnetic stainless steel) to avoid this hidden burden increase

D. Steel conduit only affects the CT during DC offset conditions, not steady-state AC faults

5. A 345 kV, 400-mile transmission line must transmit 550 MW. SIL = 315 MW. A 45% series compensation distributed at three locations is installed. The effective X_eff = 0.55 × X_line. A 300 MVA STATCOM is placed at the receiving end. During a contingency, the sending-end voltage drops to 0.92 pu while the receiving end must maintain 1.0 pu for critical industrial load. The STATCOM must inject reactive power to boost V_R. If the STATCOM operates at its maximum capacitive output of 300 Mvar at 1.0 pu voltage, what approximately is its output at the 0.92 pu sending-end condition?

A. 300 Mvar (unchanged — STATCOM output is independent of system voltage)

B. The STATCOM maintains its rated CURRENT at reduced voltage, but since Q = V × I, the reactive power output at 0.92 pu is approximately 0.92 × 300 = 276 Mvar; however, the STATCOM can temporarily exceed rated current (short-term overload capability) to compensate — a key advantage over SVCs where output drops with $V^2$ (at 0.92 pu, SVC output = 0.846 × 300 = 254 Mvar); the STATCOM provides 9% more reactive support than an equivalent SVC during this voltage depression

C. 150 Mvar (output drops with $V^2$)

D. 0 Mvar (STATCOM trips at voltages below 0.95 pu)

6. Per NEC 250.122(B), a 1,000A circuit has two parallel 500 kcmil per phase (1,000,000 CM total, providing 760A at 75°C per set × 2 = 1,520A — well above the 1,000A after 125% adjustment). The conductors are increased to two parallel 750 kcmil (1,500,000 CM total) for voltage drop on a 500-foot run. Table 250.122 requires 2/0 AWG (133,100 CM) for 1,000A. What is the proportionally increased EGC?

A. 2/0 AWG (no increase)

B. 3/0 AWG (167,800 CM)

C. 4/0 AWG (211,600 CM)

D. Ratio = 1,500,000/1,000,000 = 1.50; EGC = 133,100 × 1.50 = 199,650 CM → 4/0 AWG (211,600 CM) is the minimum standard size above 199,650 CM

7. A three-phase, 4,160V system has a 20,000 kW load at 0.63 lagging PF. Q = 20,000 × 1.233 = 24,660 kvar. The engineer installs a 18,000 kvar capacitor bank, a 6,000 HP synchronous motor at 0.80 leading PF ($\eta$ = 94%), AND a 3,000 HP synchronous motor at 0.85 leading ($\eta$ = 95%), AND a 1,000 HP synchronous motor at 0.90 leading ($\eta$ = 95%). What is the new bus PF?

A. SM1: P = 4,762 kW, $Q_1$ = 3,571 kvar; SM2: P = 2,357 kW, $Q_2$ = 1,463 kvar; SM3: P = 785 kW, $Q_3$ = 380 kvar; total correction = 18,000+3,571+1,463+380 = 23,414 kvar; net Q = 24,660−23,414 = 1,246 kvar; P_total = 27,904 kW; PF = 27,904/27,932 = 0.999 ≈ unity — four correction sources virtually eliminate reactive demand while adding 10,000 HP of production capacity

B. PF = 0.92 lagging

C. PF = 0.85 lagging

D. PF = 0.95 lagging

8. A three-phase, 480Y/277V panelboard serves a semiconductor fab cleanroom. Load: 60% nonlinear process power supplies (3rd at 45%, 5th at 20%, 7th at 10%), 30% linear HVAC blowers, 10% linear lighting. Each phase: 600A fundamental. Third = 0.45×0.60×600 = 162A. Fifth = 0.20×0.60×600 = 72A. Seventh = 0.10×0.60×600 = 36A. Neutral = 3×162 = 486A. Phase RMS = $\sqrt{(600^2+162^2+72^2+36^2)}$ = $\sqrt{(360{,}000+26{,}244+5{,}184+1{,}296)}$ = $\sqrt{392{,}724}$ = 626.7A. With 4 conductors (0.80): phase base = 783.4A; neutral base = 607.5A. Which governs?

A. Neutral governs at 607.5A because it carries the highest triplen current

B. Both require identical sizing at 700A

C. Phase governs at 783.4A — despite the very high 486A neutral, the phase requirement after derating (626.7/0.80 = 783.4A) exceeds the neutral requirement (486/0.80 = 607.5A); the phase conductors carry substantial harmonic current in addition to the fundamental, making their RMS-to-derating ratio the governing constraint

D. Neither governs — the OCPD determines all conductor sizing

9. A 280 MVA synchronous generator has X"_d = 0.20 pu, $X_2$ = 0.22 pu, $X_0$ = 0.08 pu. The generator is solidly grounded: I_SLG = 3/0.50 = 6.0 pu; I_3Φ = 5.0 pu. The SLG exceeds 3Φ by 20%. An engineer proposes switching to low-resistance grounding with R_n = 2.0 Ω. Z_base = $24^2/280$ = 2.057 Ω. R_n(pu) = 0.973. 3R_n = 2.918. I_SLG_LRG = $3/\sqrt{(2.918^2+0.50^2)}$ = 3/2.961 = 1.013 pu. This is 20.3%

of I_3Φ. The engineer then evaluates adding a neutral reactor (X_n = 2.0 Ω → 3X_n = 2.918 pu reactive) as an alternative. I_SLG_reactor = 3/j(0.50+2.918) = 3/j3.418 = 0.878 pu. How do the two alternatives compare?

A. Both produce identical SLG fault current magnitudes

B. LRG produces I_SLG = 1.013 pu (predominantly resistive, ~10° lag); reactor produces I_SLG = 0.878 pu (purely reactive, 90° lag); the LRG provides lower arc energy because resistive current passes through zero every half-cycle (facilitating arc extinction), while the reactive current from the reactor maintains the arc more persistently; LRG is preferred for generator grounding because it limits damage AND facilitates arc self-extinction

C. The reactor provides lower fault current and is always preferred

D. LRG is prohibited for generators above 200 MVA

10. A three-phase, 4,160V system has an NGR rated 400A, 10 seconds. The system has three feeders with different cable lengths creating different charging current contributions: Feeder 1 = 4A, Feeder 2 = 6A, Feeder 3 = 8A. Total system zero-sequence background = 4+6+8 = 18A (vector sum considering phase angles). The relay pickup is 30A with 0.5-second delay. A bolted ground fault on Feeder 2 produces 400A. The relay sees 400A and trips in 0.5 seconds. But the 18A background is SUBTRACTED from or ADDED to the fault current depending on the fault location relative to the CT. What is the actual relay current?

A. The relay current depends on the CT location: if the CT is at the source (measuring total zero-sequence), it sees I_fault + I_charging = 400 + 18 = 418A; if the CT is on the faulted feeder (measuring only that feeder's current), it sees I_fault − I_charging_other_feeders = 400 − (4+8) = 388A because the other feeders' charging current flows toward the fault through the source neutral, not through Feeder 2's CT; the 12A difference (3%) is negligible for a 30A pickup relay but becomes significant for sensitive ground-fault detection schemes

B. The relay always sees exactly 400A regardless of charging current

C. The relay sees 418A on all feeders simultaneously

D. Charging current has no effect on ground-fault relay measurement

11. Per NEC 110.26(A)(1)(c), the minimum working space depth for equipment rated 601-2,500V with Condition 3 (exposed live parts on both sides of the working space) is what distance?

A. 3 feet

B. 4 feet

C. 5 feet

D. 4 feet per NEC Table 110.26(A)(1) for 601-2,500V, Condition 3

12. A 6,000 kVA, 13.8 kV/480V transformer has core losses = 16,000 W and full-load copper losses = 50,000 W. k_max = √(16,000/50,000) = 56.6%. The transformer serves a smelting facility operating continuously at 95% load (PF = 0.91) for 20 hours, then at 10% load (PF = 0.70) for 4 hours during electrode maintenance. During the 10% load period, the transformer's copper losses drop to $(0.10)^2 \times$ 50,000 = 500 W, but core losses remain at 16,000 W. The core-to-total-loss ratio during the 10% period is 16,000/16,500 = 97%. What does this reveal about transformer efficiency at very light loads?

A. Very light loads produce the highest efficiency because copper losses are negligible

B. The transformer is most efficient at 10% load

C. At 10% load, the transformer's efficiency is dominated by core losses — the 16,000 W core loss compared to only 500 W copper loss means the transformer consumes 16,500 W to deliver approximately 0.10×6,000×0.70 = 420 kW of useful output; $\eta$ = 420,000/(420,000+16,500) = 96.2%; compare to 95% load: $\eta$ = 5,187,000/(5,187,000+61,250) = 98.8%; the 10% load efficiency (96.2%) is significantly lower than the 95% load (98.8%) because the fixed core losses represent a much larger fraction of the small output — this demonstrates why lightly loaded transformers should be de-energized when possible

D. Core losses decrease proportionally with load

13. A protection coordination study on a 4,160V system involves three coordinated devices: a downstream motor fuse (200E, TC = 0.005s at 12,000A), a mid-level 51 relay (R1: IEEE extremely inverse, TD = 1.5, pickup = 5A on 400:5 CT), and an upstream main relay (R2: IEEE very inverse, TD = 4.0, pickup = 8A on 1200:5 CT). At the maximum fault of 12,000A: R1 secondary = 150A, $M_1$ = 30, $t_1$ = 1.5×(28.2/899+0.1217) = 1.5×0.153 = 0.229s. R2 secondary = 50A, $M_2$ = 6.25, $t_2$ =

4.0×(19.61/38.06+0.491) = 4.0×(0.515+0.491) = 4.0×1.006 = 4.024s. CTI fuse-R1 = 0.224s. CTI R1-R2 = 3.795s. Is the coordination optimal?

A. CTI fuse-R1 at 0.224s barely exceeds the 0.20s minimum — acceptable but with zero engineering margin; any relay or fuse tolerance variation could cause miscoordination

B. CTI fuse-R1 = 0.224s is adequate with minimal margin; CTI R1-R2 = 3.795s is grossly excessive — R2 at 4.024s means the main breaker provides very slow backup; reducing R2's TD to 2.0 yields approximately 2.01s (CTI ≈ 1.78s — still well above 0.20s) while halving the backup clearing time

C. All CTIs are ideal and require no adjustment

D. The fuse-R1 CTI is inadequate; more separation needed

14. A distance relay on a 230 kV line (Z_line = 8+j92 Ω) has Zone 1 at 85%, Zone 2 at 120%. A fault at 83% through 5 Ω resistance. Z_meas = (0.83×8+5)+j(0.83×92) = 11.64+j76.36 Ω. |Z_meas| = 77.2 Ω. Zone 1 reach = 0.85×92.35 = 78.5 Ω. Margin = 78.5−77.2 = 1.3 Ω (1.7%). Combined CT/PT error = ±3.5%. At 3.5% error: apparent impedance could be 77.2×1.035 = 79.9 Ω. Does Zone 1 operate?

A. At 79.9 Ω apparent, the fault appears outside Zone 1 (78.5 Ω reach); the relay fails to trip on Zone 1 and reverts to Zone 2 (0.35s delay) or pilot-assisted tripping; this is the Zone 1 margin problem: the 5 Ω fault resistance plus CT/PT errors consume the 1.3 Ω margin; the pilot scheme is essential for reliable high-speed clearing of resistive faults near the Zone 1 boundary

B. Zone 1 always operates for faults below 85% regardless of resistance

C. The 5 Ω fault resistance has no effect on distance relay measurement

D. Zone 1 trips instantaneously with adequate margin

15. A three-phase, 460V, 4-pole, 500 HP induction motor drives a centrifugal chiller. Design: 373 kW at 1,770 RPM. The chiller operates at six conditions: 100% (1,000 hr), 90% (1,500 hr), 80% (2,000 hr), 70% (1,800 hr), 55% (1,500 hr), 35% (960 hr). VFD η varies: 97% at full, 96% at 90%, 96% at 80%, 95% at 70%, 93% at 55%, 88% at 35%. Motor η: 96.5%, 96%, 95%, 93%, 88%, 78%. What is the total supply energy including all losses?

A. Full: 373/(0.965×0.97)×1,000 = 398,574; 90%: 271.8/(0.96×0.96)×1,500 = 442,383; 80%: 191.0/(0.95×0.96)×2,000 = 418,779; 70%: 128.0/(0.93×0.95)×1,800 = 260,716; 55%: 62.0/(0.88×0.93)×1,500 = 113,636; 35%: 16.0/(0.78×0.88)×960 = 22,378; total ≈ 1,656,466 kWh

B. 2,500,000 kWh (full-speed estimate)

C. 1,200,000 kWh (ideal affinity law only)

D. The detailed calculation including speed-dependent VFD and motor efficiency at each point yields approximately 1,656,000 kWh; full-speed = 373×8,760 = 3,267,480 kWh; savings = 1,611,480 kWh (49.3%); the light-load efficiency penalty adds approximately 12% to the ideal affinity-law-only calculation of 1,478,000 kWh

16. Per NEC 480.9(A), a hospital critical-care UPS has 480 vented lead-acid cells in a dedicated room of 6,000 $ft^3$. Charging rate = 0.008 $ft^3$ $H_2$/cell/hour. The room also contains critical monitoring equipment for the UPS. What ventilation rate is required, and what design consideration applies to the monitoring equipment?

A. ACH = 0.064; no special considerations for room equipment

B. ACH = 5.0; all equipment must be explosion-proof

C. $H_2$ = 3.84 $ft^3$/hr; max $H_2$ = 60 $ft^3$; ACH = 0.064; the monitoring equipment (BMS controllers, annunciator panels, communication interfaces) must either be: (1) located outside the battery room with only sensors extending inside, or (2) rated for the potential hydrogen atmosphere if located inside; additionally, all electrical equipment inside the battery room should be evaluated against NEC 500 hazardous location criteria — while the ventilation normally keeps $H_2$ well below 1%, a ventilation failure during charging could create a hazardous atmosphere within hours

D. No ventilation required — VRLA cells produce no hydrogen

17. A 230 kV, 450-mile transmission line with SIL = 140 MW must transmit 350 MW during peak and only 20 MW during off-peak. The line has 45% distributed series compensation, two 150 Mvar switched shunt reactors at the receiving end, and a ±200 Mvar STATCOM at the midpoint. During the transition from peak to off-peak (load drops from 350 to 20 MW over 30 minutes), what is the reactive compensation switching sequence to prevent transient overvoltage?

A. All devices operate simultaneously at all times — no switching sequence needed

B. The switching sequence must be phased: (1) as load decreases through SIL (140 MW), the line transitions from reactive absorption to reactive generation — switch ON the first reactor at approximately 150 MW; (2) the STATCOM continuously absorbs reactive to smooth voltage transitions between discrete reactor switching steps; (3) switch ON the second reactor at approximately 80 MW; (4) at 20 MW, both reactors are on and the STATCOM fine-tunes to maintain receiving-end voltage; the STATCOM's fast continuous response bridges the discrete reactor switching steps, preventing the voltage spikes that occur during mechanical switching of large reactive devices

C. Only the STATCOM operates; the reactors remain off during all conditions

D. Both reactors switch on immediately when load drops below 200 MW

18. A separately excited DC motor (V_t = 550V, I_a = 200A, R_a = 0.10 Ω, rated speed = 1,200 RPM) drives a crane hoist. E_a = 530V. The crane must lower a heavy load at controlled speed. During regenerative lowering, the load drives the motor, making E_a > V_t. At 1,200 RPM lowering, E_a = 530V. To achieve regeneration, the field is strengthened to increase E_a above V_t. If the field is increased by 10% (E_a → 583V): I_regen = (583−550)/0.10 = 330A. P_regen = 550 × 330 = 181.5 kW returned to supply. What is the braking torque?

A. T = 0 (no braking during regeneration)

B. T = 181.5 kW / (2π × 1,200/60) = 181,500/125.7 = 1,444 N-m — but this is power at the electrical terminals

C. T_brake = E_a × I_regen / ω = 583 × 330 / (2π × 1,200/60) = 192,390/125.7 = 1,530 N-m; the braking torque is determined by E_a × I (mechanical power converted to electrical), not V_t × I (electrical power at terminals); the difference (192.4−181.5 = 10.9 kW) is dissipated as $I^2R$ loss in the armature resistance

D. T = 500 N-m (constant regardless of speed or current)

19. Per NEC 250.30(A)(1), a large university campus has: 8 × 5,000 kVA service transformers, 4 × 3,000 kW emergency generators, 6 × 2,000 kW CHP (combined heat and power) generators, 20 × 1,000 kVA building PDU transformers, 12 × 500 kVA laboratory isolation transformers, and 6 × 300 kVA UPS output transformers. Are CHP generators separately derived systems?

A. No — CHP generators are excluded because they provide heat as well as electricity

B. CHP generators connected in a configuration that isolates them from the utility (through a transfer switch) ARE separately derived systems, identical to emergency generators in this respect

C. Only half the CHP generators require bonding jumpers

D. Yes — all transformers and generators are separately derived systems: 8 service + 4 emergency + 6 CHP + 20 PDU + 12 isolation + 6 UPS = 56 bonding jumpers; the CHP generators are separately derived when configured to operate independently from the utility through transfer switching; each requires a bonding jumper sized per NEC 250.30(A)(2)

20. A three-phase, 480V, 3,200A main-tie-main switchgear configuration has Bus A (4,000 kVA transformer, Z = 5.50%) and Bus B (3,500 kVA transformer, Z = 5.75%). With the tie breaker closed: I_A = 87,473A; I_B = 73,200A; combined = 160,673A. Motor contribution = 16,000A. Total = 176,673A. With the tie open, Bus A alone = 87,473 + 8,000 = 95,473A and Bus B alone = 73,200 + 8,000 = 81,200A. What is the critical implication of the tie-open versus tie-closed fault current for protection and equipment ratings?

A. The tie position has no effect on fault current or protection

B. Equipment on both buses must be rated for the TIE-CLOSED fault level of 176,673A (plus peak asymmetrical), because the tie breaker may be closed at any time; protection must coordinate for BOTH conditions: tie-open provides faster clearing (lower current, single-source coordination) while tie-closed requires both mains to trip simultaneously for bus faults; the arc flash labels must reflect the WORST-CASE (tie-closed) condition unless administrative controls guarantee the tie position

C. Equipment only needs to be rated for the tie-open condition since the tie is normally open

D. The tie-closed fault current is always lower than tie-open because impedances add in parallel

21. A synchronous generator rated 500 MVA, 26 kV has X"_d = 0.24 pu, $X_2$ = 0.26 pu, $X_0$ = 0.10 pu, solidly grounded. I_SLG = 5.0 pu; I_3Φ = 4.17 pu. SLG exceeds 3Φ by 20%. The engineer installs a hybrid grounding system: reactor during normal (3X_n = 0.30 pu) → I_SLG = 3/j(0.60+0.30) = 3.33 pu. After 200 ms, auto-switches to HRG (3R_n = 50 pu) → I_SLG = 0.06 pu. During the 200 ms reactor period, what must the protection system accomplish?

A. Nothing — 200 ms is too short for any relay action

B. The protection system must merely ride through the 200 ms period without tripping

C. During the 200 ms reactor-grounded period (I_SLG = 3.33 pu), the protection must: (1) detect the ground fault, (2) determine the faulted feeder using directional ground overcurrent relays, (3) initiate the grounding system switch to HRG, and (4) store the fault location information for maintenance crew dispatch — all within 200 ms; modern microprocessor relays can accomplish this in approximately 50-100 ms, leaving adequate margin for the switching transient to settle before the system transitions to HRG

D. The 200 ms period is used solely for arc flash mitigation

22. A 480V, three-phase panelboard has: Motor 1 = 862A (750 HP, largest), Motor 2 = 683A (600 HP), Motor 3 = 590A (500 HP), Motor 4 = 477A (400 HP). Continuous lighting = 350A. Noncontinuous receptacles = 120A. Per NEC 430.24 and 215.2(A)(1), what is the minimum feeder conductor ampacity?

A. 125%×862 + 683+590+477 + 125%×350 + 120 = 1,077.5+1,750+437.5+120 = 3,385A

B. 3,000A

C. 3,500A

D. 2,800A

23. A three-phase, 4,160V bus has eight sources. On a 60 MVA base: five transformers (Z = 0.03, 0.04, 0.05, 0.06, 0.08), two generators (Z = 0.30, 0.50), one 50 MVA BESS inverter (effective Z = 3.0). I_base = 8,328A. What is the total fault current, and what percentage does the BESS contribute?

A. Total = 500,000A; BESS = 5%

B. Total = 700,000A; BESS = 1%

C. Total = 400,000A; BESS = 2%

D. I = (33.33+25.0+20.0+16.67+12.50+3.33+2.0+0.333) × 8,328 = 113.16 × 8,328 = 942,549A; BESS = 0.333/113.16 = 0.29% — the 50 MVA BESS contributes less than 0.3% despite its large rating because inverter-based resources have inherently high effective impedance limiting fault contribution to approximately 1.0-1.2× rated current; the five transformers provide 95% of the total

24. A 480V, three-phase, 400A panelboard (SCCR = 22,000A) is fed from a switchboard with 65,000A available. The cable is 350 feet of 350 kcmil copper in steel conduit (R = 0.0367, X = 0.0407 Ω/1000 ft). Ten motors at the panelboard (FLA = 800A total) contribute 3,200A first-cycle. Does the installation comply with NEC 110.10 regarding SCCR?

A. No — the cable cannot reduce 65,000A sufficiently at 350 feet with 350 kcmil

B. Cable Z: R = 0.01285, X = 0.01425 Ω; Z_base = 0.0658; Z_cable_pu = 0.01918/0.0658 = 0.291; total Z = 0.0575+0.291 = 0.349; I_transformer = 4,209/0.349 = 12,060A; motor = 3,200A; total = 15,260A — below the 22,000A SCCR; the installation complies without current-limiting fuses; proper documentation per NEC 110.9 is required

C. The motor contribution pushes the total above 22,000A

D. Only a series-rated combination can satisfy NEC 110.10

25. Per NEC 690.12, a 3 MW commercial PV system uses 40 string inverters. Each string has 20 modules (V_oc = 50V per module = 1,000V). Module-level rapid shutdown devices are installed on each module. At −25°C, V_oc per module = 57.5V. The temperature-corrected string voltage = 20 × 57.5 = 1,150V. The system is rated for 1,000V DC. What NEC violation exists, and what is the correction?

A. NEC 690.12(B)(2) violation — the RSDs don't reduce voltage fast enough

B. No violation — the RSDs reduce voltage below 80V during rapid shutdown regardless of temperature

C. NEC 690.7(A) violation — the maximum system voltage of 1,150V exceeds the 1,000V DC equipment rating regardless of rapid shutdown; correction: reduce string length to 17 modules (17×57.5 = 977.5V < 1,000V) or upgrade ALL system components (conductors, disconnects, inverters, combiner boxes) to 1,500V DC rating

D. The violation exists only during nighttime when modules are cold

26. A three-phase, 480V system has four parallel transformers: T1 = 3,500 kVA (Z = 5.50%), T2 = 3,000 kVA (Z = 5.75%), T3 = 2,500 kVA (Z = 6.00%), T4 = 2,000 kVA (Z = 6.25%). Individual contributions: I_T1 = 74,200A, I_T2 = 60,870A, I_T3 = 48,517A, I_T4 = 37,209A. Total = 220,796A. Motor (FLA = 5,000A) = 20,000A. Grand total = 240,796A. Weighted X/R ≈ 8.3. Multiplier = 2.32. What is the peak asymmetrical?

A. 340,500A (√2 × total)

B. 481,592A (2× total)

C. 240,796A (no asymmetry)

D. Peak = 2.32 × 240,796 = 558,647A — over half a million amperes peak from four parallel transformers plus motors; electromagnetic forces proportional to $I^2\_peak = 3.12 \times 10^{11}$ $A^2$ — this is the highest peak asymmetrical current in the exam series and represents the absolute physical design limit for any 480V bus system; custom-engineered bus structures with analysis comparable to structural/seismic engineering are required

27. A distance relay on a 138 kV line (Z_line = 3.5+j42 Ω) has Zone 1 at 80%, Zone 2 at 120% (0.35s). A fault at 95% through 8 Ω resistance. The DCB pilot scheme is active. Near-end: Zone 1 at 80% cannot reach 95%. Zone 2 covers it. Remote end sees 5% from its terminal (Zone 1). Both see forward. Neither sends blocking. What is the clearing time?

A. Both trip on Zone 2 after 0.35 seconds

B. Both terminals trip with high-speed clearing — the near-end Zone 2 trips instantaneously via DCB (no blocking received) and the remote end trips on Zone 1; the DCB logic: absence of blocking signal = permission to trip; high-speed clearing at both ends simultaneously despite the fault being beyond the near end's Zone 1 reach; the 8 Ω resistance does not prevent Zone 2 detection at either terminal

C. Only the remote end trips on Zone 1

D. Neither trips due to the 8 Ω resistance

28. A transformer differential relay (87T) for a 250 MVA, 345/69 kV, delta-wye grounded transformer experiences a magnetizing inrush during energization. The inrush current is 6× rated with 65% second-harmonic content. The relay's second-harmonic blocking threshold is 12%. Additionally, the relay has a fifth-harmonic blocking feature (threshold 25%) to prevent tripping during overexcitation. During energization, the fifth-harmonic content is approximately 8%. Does either harmonic blocking feature engage?

A. Second-harmonic blocking engages (65% >> 12% threshold); fifth-harmonic blocking does NOT engage (8% < 25% threshold); the second-harmonic blocking alone is sufficient to prevent false tripping during inrush; the fifth-harmonic feature is designed for overexcitation events (sustained overvoltage), not for energization inrush — the two harmonic blocking features address different operating conditions

B. Both features engage simultaneously

C. Neither feature engages — inrush is handled by a separate time delay

D. Only fifth-harmonic blocking engages during energization

29. Per NEC 450.3(B), a 2,500 kVA, 13.8 kV/480V transformer has primary current = 104.6A. At 125% = 130.75A. Next standard = 150A. The transformer also has a 250 kVA tertiary winding (13.8 kV delta) for station service. Per NEC 450.3(B), does the tertiary require its own overcurrent protection?

A. No — the primary OCPD protects the tertiary automatically

B. Yes — but only for transformers above 5,000 kVA

C. No — tertiary windings are never protected

D. Yes — per NEC 450.3(B), each winding of a multi-winding transformer must be considered for overcurrent protection; the tertiary winding has its own rated current (10.5A at 13.8 kV), and if it serves loads, those loads must be protected at not more than the tertiary's rated capacity; the 150A primary OCPD does NOT protect the 250 kVA tertiary — a separate OCPD sized for the tertiary's rated current is required

30. A three-phase, 4,160V, 6-pole synchronous motor rated 7,000 HP drives a large mine hoist at 1,200 RPM. Pull-out = 280% FLT. H = 3.5 MJ/MVA (high inertia — large flywheel on the hoist). S = 6,100 kVA. During a system fault clearing, voltage sags to 70% for 0.8 seconds. Pull-out = 196% FLT. Load = 95% FLT. Margin = 101% FLT. With H = 3.5 (the highest in the exam series), what is the stability assessment?

A. Unstable despite the high H — 0.8 seconds at 70% is too severe

B. Marginally stable — detailed simulation needed for this borderline case

C. H = 3.5 (highest in the exam series) provides exceptional resistance to angular acceleration; the large flywheel absorbs accelerating energy like a mechanical battery; the 101% FLT margin combined with the high inertia produces relatively small rotor angle advance (estimated 8-15° for the 0.8-second sag); stability is maintained with good margin — the flywheel is specifically engineered for this purpose in mine hoist applications where grid disturbances are common

D. Cannot be determined without the hoist's load torque curve

31. A 480V, three-phase system has five parallel transformers with a combined symmetrical fault of 225,000A. Weighted X/R = 8.5. Multiplier = 2.34. Peak = 526,500A. The engineer must design the bus bracing. Using $F = \mu_0 I^2\_peak/(2\pi d)$ with 8-inch (0.203 m) spacing: $F = (2\times10^{-7} \times 526{,}500^2)/0.203$. What is the approximate force per meter of bus, and what design approach is required?

A. $F = (2\times10^{-7} \times 2.77\times10^{11})/0.203 = 55{,}400/0.203 = 272{,}906$ N/m ≈ 273 kN/m (61,300 lbs/foot); at this force level, standard bus construction is completely inadequate; the bus requires: segregated-phase construction with reinforced concrete barriers between phases, high-strength composite insulators at 12-inch intervals, structural steel support frames designed by a structural engineer for dynamic loading, and potentially flexible bus connections to absorb mechanical shock

B. F = 5,000 N/m (standard bracing adequate)

C. F = 50,000 N/m (heavy-duty bracing required)

D. F = 500 N/m (minimal bracing needed)

32. A 13.8 kV system has a voltage THD of 16.8% at the PCC. Harmonics: $V_5 = 12.0\%$, $V_7 = 8.5\%$, $V_{11} = 5.8\%$, $V_{13} = 4.0\%$, $V_{17} = 2.5\%$, $V_{19} = 1.8\%$. IEEE 519: individual ≤ 3.0%, THD ≤ 5.0%. The facility has 40 six-pulse VFDs of various sizes totaling 12,000 HP. Replacing all VFDs is cost-prohibitive ($3M+). What is the most cost-effective comprehensive remediation strategy?

A. Replace all 40 VFDs with AFE drives

B. Install a single large active harmonic filter (AHF) at the 13.8 kV bus — the AHF dynamically measures harmonic currents in real-time and injects equal-and-opposite currents to cancel harmonics at the PCC; a properly sized AHF can address ALL individual harmonic violations AND the THD simultaneously without modifying any existing VFD; the cost is typically $500K-$800K — approximately 20-25% of full VFD replacement; the AHF can be installed while the VFDs continue operating, requiring no production downtime

C. Install passive filters for the 5th and 7th harmonics only

D. Accept the harmonic violations and pay IEEE 519 penalties

33. A ground resistance test on a large airport facility measures 1.8 Ω during spring. IEEE 80 target = 0.5 Ω. Seasonal correction = 1.6. Corrected = 2.88 Ω (5.76× target). The airport has extensive underground infrastructure: fuel piping (cathodically protected), water mains, storm drainage (metallic), building structural steel, and runway lighting conduit. Can any of this infrastructure supplement the ground grid?

A. None of the underground infrastructure can be used for grounding

B. Only the water mains per NEC 250.52(A)(1)

C. All metallic underground infrastructure can be bonded to the grid with appropriate engineering

D. The storm drainage (metallic), building structural steel, and runway lighting conduit can all be bonded to the ground grid to supplement resistance; however, the cathodically protected fuel piping CANNOT be directly bonded because it would disrupt the cathodic protection system — bonding would drain the protective current, accelerating corrosion of the fuel piping; the engineer must consult with the cathodic protection specialist before any connections near the fuel system; per NEC 250.52(B), the connections must not damage other systems

34. A three-phase, 460V, 4-pole induction motor rated 500 HP has $\eta$ = 96.5%, PF = 0.90. No-load magnetizing = 72 kvar. A 55 kvar capacitor is installed (76.4% of no-load — safe at full load). The motor operates on a VFD. The VFD's output voltage contains high-frequency PWM switching harmonics (typically 2-8 kHz carrier frequency). The capacitor bank presents very low impedance to these high-frequency harmonics. What operational concern does this create?

A. PWM harmonics have no effect on capacitors

B. The capacitor's impedance decreases with frequency (X_C = 1/2πfC); at the VFD's switching frequency (e.g., 4 kHz), the capacitor impedance is approximately 1/67th of its 60 Hz value; this creates a low-impedance path for high-frequency harmonic currents, causing: (1) excessive capacitor heating from $I^2R$ losses in the capacitor's ESR, (2) premature capacitor insulation degradation from dielectric stress cycling at kHz rates, (3) potential capacitor failure from thermal overload — capacitors installed at VFD motor terminals must be rated for the VFD's harmonic spectrum or an output line reactor must be installed between the VFD and the capacitor to attenuate the switching harmonics

C. The VFD output harmonics improve the capacitor's performance

D. Only oil-filled capacitors are affected; dry-film capacitors are immune

35. A three-phase, 460V, 8-pole VFD-driven motor operates a mine ventilation fan. Design: 400 kW at 877 RPM. Seven operating modes spanning full emergency ventilation to minimal monitoring: 100% (500 hr), 95% (800 hr), 85% (1,500 hr), 75% (2,200 hr), 60% (1,800 hr), 45% (1,200 hr), 30% (760 hr). Using $P \propto n^3$, what is the VFD annual energy versus full speed at $0.075/kWh?

A. VFD = 2,000,000 kWh; savings = $75,000

B. VFD = 1,800,000 kWh; savings = $93,150

C. 100%: 200,000; 95%: 400×0.857×800 = 274,304; 85%: 400×0.614×1,500 = 368,520; 75%: 400×0.422×2,200 = 371,360; 60%: 400×0.216×1,800 = 155,520; 45%: 400×0.091×1,200 = 43,740; 30%: 400×0.027×760 = 8,208; VFD = 1,421,652; full = 400×8,760 = 3,504,000; savings = 2,082,348 kWh × $0.075 = $156,176/year — seven operating modes with the cubic relationship produce 59.4% energy reduction; the lowest modes (45% and 30%) contribute only 3.7% of the annual VFD energy despite 22.4% of operating hours

D. VFD = 1,000,000 kWh; savings = $187,800

36. A 480V, three-phase, 200A feeder uses 500 kcmil THHN copper in PVC conduit (R = 0.0276, X = 0.0442 Ω/1000 ft). The feeder is 900 feet long and serves a load at 0.85 lagging PF. What is the voltage drop?

A. V_drop = $\sqrt{3}$ × 200 × (0.0276×0.9×0.85 + 0.0442×0.9×0.527) = 346.4 × (0.02111 + 0.02097) = 346.4 × 0.04208 = 14.58V; 14.58/480 = 3.04% — barely exceeds the NEC 3% recommendation despite using the large 500 kcmil conductor; the extreme 900-foot distance drives the voltage drop above 3% even with low-resistance conductor; upsizing to 750 kcmil would reduce the drop to approximately 2.4%

B. 2.0%

C. 4.5%

D. 1.5%

37. A 100 MVA, 345/138 kV autotransformer has Z = 10.5%. Three identical units in parallel. A 70 MVA generator (X"_d = 0.20), 50 MVA synchronous condenser (X"_d = 0.14), 30 MVA synchronous motor (X"_d = 0.22), and 50 MVA combined renewable generation (30 MVA solar at effective Z = 1.0, 20 MVA BESS at effective Z = 1.5) are on the 138 kV bus. On 100 MVA base: Z_T_par = 0.035. What is the total fault current?

A. 10,000A

B. 12,000A

C. 18,000A

D. Z_gen = 0.286; Z_SC = 0.28; Z_SM = 0.733; Z_solar = 3.333; Z_BESS = 7.50; I_pu = (28.57+3.497+3.571+1.364+0.30+0.133) × 418.4 = 37.44 × 418.4 = 15,661A; renewable contribution (solar+BESS) = 0.433/37.44 = 1.16%; despite 50 MVA of renewables (17% of connected capacity), they contribute only 1.16% of fault current — this demonstrates the fundamental grid protection challenge as renewable penetration increases: less fault current means less reliable conventional protection operation

38. A three-phase, 480V system has a 4,500 kVA transformer (Z = 5.50%, X/R = 10) and a 3,500 kVA transformer (Z = 5.75%, X/R = 9) in parallel. I_T1 = 5,413/0.055 = 98,418A. I_T2 = 4,209/0.0575 = 73,200A. Total = 171,618A. Motors (FLA = 4,000A) = 16,000A. Grand total = 187,618A. X/R ≈ 9.6. Multiplier = 2.37. Peak?

A. 265,300A (√2)

B. Peak = 2.37 × 187,618 = 444,755A — this extreme peak current from two very large parallel transformers plus motors approaches the physical design limits for 480V bus construction; the 4,500 kVA transformer alone produces nearly 100 kA symmetrical, demonstrating why transformers above 3,000 kVA on 480V systems create extraordinary fault current challenges

C. 375,236A (2×)

D. 187,618A (no asymmetry)

39. Per NEC 250.53(A)(2), an engineer designs grounding for a petrochemical refinery in coastal sandy soil (ρ = 1,500 Ω-m at surface, dropping to 50 Ω-m at the water table 25 feet below grade). The IEEE 80

design target is 1.0 Ω. The surface ground grid alone cannot achieve 1.0 Ω due to the extreme 1,500 Ω-m surface resistivity. What strategy exploits the soil stratification?

A. Install only driven rods to 10-foot depth in the sandy surface layer

B. Apply chemical treatment to the surface layer to reduce resistivity

C. Install deep ground wells (30-40 feet) that penetrate through the high-resistivity sandy surface layer to reach the low-resistivity (50 Ω-m) water-table stratum; these wells use bare copper conductors surrounded by ground enhancement material (GEM) backfill; each well effectively bypasses the 1,500 Ω-m surface layer and contacts the conductive water-bearing soil; combined with a surface ground grid (for step-and-touch potential control) and bonding to underground metal piping that also contacts the water table, this two-layer approach achieves resistance targets that surface grounding alone cannot

D. Accept the high resistance — 1.0 Ω is unachievable in sandy soil

40. A 480V, three-phase system has a 3,500 kVA transformer (Z = 5.75%) feeding a switchboard. A 1,200-foot cable of 3/0 AWG copper in PVC conduit (R = 0.0766, X = 0.0532 Ω/1000 ft) feeds a remote panelboard. At this extreme distance, what is the available fault current at the panelboard, and what protective device concern exists?

A. Cable: R = 0.0919, X = 0.0638 Ω; Z_base = 0.0658 Ω; Z_cable_pu = 0.1120/0.0658 = 1.702; total Z = 0.0575+1.702 = 1.760; I = 4,209/1.760 = 2,392A — only 5.7% of switchboard value

B. 15,000A

C. 25,000A

D. I = 2,392A; at this extremely low fault current, a 100A breaker sees 23.9× (adequate for instantaneous), but a 225A breaker sees only 10.6× — which may fall in the time-overcurrent region rather than the instantaneous region, significantly increasing the clearing time and arc flash energy; the engineer must plot the breaker's time-current curve to verify clearing time at 2,392A and may need to install a breaker with a lower instantaneous trip threshold

41. A 75 MVA, 138/13.8 kV, delta-wye grounded transformer has $Z_1$ = j0.09 pu, $Z_0$ = j0.04 pu on its own base. The 138 kV source has $Z_1$_src = j0.06 pu on the transformer base. On 100 MVA: $Z_1$_total = (0.09+0.06)×100/75 = 0.20 pu. $Z_0$_total = 0.04×100/75 = 0.0533 pu. I_3Φ = 5.0 pu. I_SLG =

3/(0.20+0.20+0.0533) = 3/0.4533 = 6.62 pu. SLG exceeds $3\Phi$ by 32.4% — the highest ratio in the exam series. What design parameter produces this extreme ratio?

A. The extremely low $Z_0$ (0.04 pu, less than half of $Z_1$) combined with delta blocking creates $Z_0$_total (0.0533) = only 26.7% of $Z_1$_total (0.20); this extreme disparity between $Z_0$ and $Z_1$ produces the 32.4% exceedance — the lowest $Z_0/Z_1$ ratio in the exam series; all equipment on the secondary must be rated for the SLG current (6.62 pu), and ground-fault relays must coordinate for this higher-than-three-phase current

B. The high source impedance $Z_1$_src creates the extreme ratio

C. The 100 MVA base conversion artificially inflates the ratio

D. The delta winding has no influence on SLG fault magnitude

42. A three-phase, 460V, 6-pole induction motor rated 700 HP (PF = 0.88, $\eta$ = 96.5%) has no-load magnetizing = 90 kvar. A 70 kvar capacitor is installed (77.8%). The motor operates on a VFD at variable speed. At constant V/f in the constant-torque region, magnetizing kvar remains approximately 90 kvar and the 70 kvar capacitor is safe. However, during field-weakening above base speed (V/f decreases), the motor's magnetizing kvar increases as the slip increases. At 120% of base speed with field weakening, the magnetizing kvar may actually increase to 105 kvar. Is the 70 kvar capacitor safe above base speed?

A. No — above base speed with field weakening, the capacitor becomes unsafe

B. Counterintuitively, the capacitor is SAFER above base speed; when V/f decreases (field weakening), the motor requires LESS magnetizing current, not more — the air-gap flux decreases proportionally with V/f ratio; at 120% speed with V/f reduced to 83%, the magnetizing kvar drops to approximately 75 kvar; the 70 kvar capacitor at 93% of reduced magnetizing is close to the limit but still below it

C. The capacitor is safe at all speeds because VFDs prevent self-excitation through active voltage control — even if the motor coasts after VFD trip, the 70 kvar at 77.8% of full-speed magnetizing is well below the self-excitation threshold at rated V/f; however, the critical moment remains the VFD trip event, where the capacitor and motor interact without VFD voltage control

D. Capacitors are prohibited above base speed per NEC 460.9

43. A CT with a ratio of 5000:5 (C800) serves a generator differential relay on a 500 MVA machine. During a 75,000A internal fault, the CT secondary = 75A (15×). With proper burden ($< 4.0\ \Omega$), the CT performs well. However, the generator has a grounding transformer that limits zero-sequence current to 200A. During a phase-to-ground fault, the zero-sequence component flowing through the neutral CT is 200A/5000 = 0.04A secondary. The phase differential CT sees 75A. What relay sensitivity challenge exists?

A. No challenge — the relay only uses phase CTs

B. The neutral CT output of 0.04A is below most differential relay minimum operating thresholds (typically 0.1-0.3A); for restricted earth-fault protection (REF), the relay must be extremely sensitive to detect the 200A ground-fault current through a 5000:5 CT; a lower-ratio CT (200:5 or 400:5) dedicated to the neutral ground connection provides adequate sensitivity — 200A through a 200:5 CT produces 5.0A secondary, well above any relay threshold

C. Both the phase and neutral CTs must be replaced with higher-ratio units

D. The relay automatically compensates for the low neutral CT output

44. A balanced three-phase, 208Y/120V panelboard serves a modern commercial office with 100% LED lighting and plug-load power supplies (all nonlinear). Each phase: 400A fundamental, 160A 3rd harmonic (40%), 80A 5th (20%), 40A 7th (10%), 20A 9th (5%), 12A 11th (3%). Phase RMS = $\sqrt{(400^2+160^2+80^2+40^2+20^2+12^2)} = \sqrt{(160{,}000+25{,}600+6{,}400+1{,}600+400+144)} = \sqrt{194{,}144} = 440.6$A. Neutral = 3×(160+20) = 540A (3rd and 9th are both triplens). Ratio = 540/440.6 = 1.226. The neutral exceeds phase by 22.6%.

A. The neutral exceeds the phase due to 9th-harmonic contribution

B. The 9th harmonic is a triplen and adds to the neutral along with the 3rd

C. Only the 3rd harmonic contributes to neutral current in balanced systems

D. Neutral = $3 \times (I_3 + I_9) = 3 \times (160 + 20) = 540$A because BOTH the 3rd and 9th harmonics are triplens ($h = 3n$, where $n = 1$ and 3); in balanced three-phase systems, only triplen harmonics add arithmetically in the neutral; the 5th, 7th, and 11th cancel; the 22.6% exceedance of neutral over phase is driven by the combined triplen content and requires the neutral to be sized significantly larger than the phase conductors

45. Per NEC 517.17(A), a hospital has 10 operating rooms served by 5 isolated power panels. During a mass-casualty event, all 10 rooms operate simultaneously with maximum device counts. Four panels are at 4.7-4.9 mA (near the 5.0 mA alarm threshold). One panel (Panel E) is at 3.5 mA. The clinical engineering team must connect 4 additional devices (0.3 mA each) that are needed for emergency procedures. The total additional leakage = 1.2 mA. What is the optimal distribution strategy?

A. Connect all 4 devices to Panel E: 3.5+1.2 = 4.7 mA; this concentrates the additions on the panel with the most headroom while keeping all five panels below 5.0 mA; alternatively, distribute 2 to Panel E (4.1 mA) and 1 each to the two panels with the most remaining margin — but during a mass-casualty event, speed of connection matters more than optimization, and Panel E can safely accept all four devices

B. Connect one device to each of the four highest panels (4.7+0.3 = 5.0 mA maximum)

C. Install emergency portable isolation transformers for the additional devices

D. The devices cannot be connected — all panels are at or near capacity

46. A 345 kV, three-phase line has V_S = 372 kV, V_R = 344 kV at 1,200 MW, 0.87 lagging PF. Line X_eff = 42 Ω (after 45% series compensation from X_original = 76.4 Ω). What is the power angle and stability fraction WITH compensation?

A. δ = 20°; stability = 34%

B. δ = 30°; stability = 50%

C. sin δ = 1,200×42/(372×344) = 50,400/127,968 = 0.394; δ = 23.2°; stability fraction = 39.4%; WITHOUT compensation: sin δ = 1,200×76.4/127,968 = 0.716; δ = 45.7°; stability = 71.6%; series compensation reduced δ from 45.7° to 23.2° and stability fraction from 71.6% to 39.4%, INCREASING margin from 28.4% to 60.6% — more than doubling the stability margin; this enables confident 1,200 MW transmission with 60.6% reserve for contingencies

D. δ = 50°; stability = 77%

47. A recloser on a 12.47 kV feeder coordinates with a 300A lateral fuse. At 10,000A: fuse MM = 0.012s, fuse TC = 0.024s, recloser fast = 0.008s, recloser delayed = 0.050s. A permanent underground cable fault occurs. Fast trip saves the fuse (0.008 < 0.012). After reclose, fault persists. During delayed trip: recloser (0.050s) vs fuse TC (0.024s). The fuse blows at 0.024s. Margin = 0.026s. The engineer

notes that at the minimum fault of 2,000A: fuse MM = 0.15s, fuse TC = 0.30s, recloser fast = 0.08s, recloser delayed = 0.50s. Does coordination hold at minimum fault?

A. No — at minimum fault, the recloser delayed trip (0.50s) exceeds the fuse TC (0.30s); coordination is maintained with 0.20s margin; the fuse blows before the recloser trips

B. Coordination holds at both fault levels: at 10,000A, the fuse clears 0.026s before the recloser; at 2,000A, the fuse clears 0.20s before the recloser; the margin actually IMPROVES at lower fault currents because the fuse TC-to-recloser delayed ratio increases — this is the characteristic behavior of properly coordinated fuse-saving schemes across the full fault current range

C. Coordination fails at minimum fault because the recloser fast trip exceeds fuse MM

D. Fuse-saving schemes only work at maximum fault current

48. A 480V, three-phase, 800A switchboard with 800A bus. Load: 550A continuous motor + 100A continuous lighting + 60A noncontinuous = 710A. OCPD = 125%×650 + 60 = 872.5A → exceeds 800A bus. With 100%-rated 800A breaker: 710A ≤ 800A. Conductor at 75°C must handle 710A. Two parallel 500 kcmil = 760A. The 50A margin (7%) is tight. The engineer discovers the ambient temperature in the electrical room reaches 40°C during summer. Per NEC Table 310.15(B)(1), the 40°C correction factor for 75°C conductors is 0.82. What is the corrected ampacity?

A. Two parallel 500 kcmil at 75°C × 0.82 = 760 × 0.82 = 623.2A — below the 710A requirement; the temperature derating renders the 500 kcmil inadequate; the engineer must upsize to two parallel 750 kcmil (2×475×0.82 = 779A) or install air conditioning in the electrical room to maintain ambient below 30°C

B. 760A (temperature derating does not apply to 100%-rated breaker circuits)

C. 710A (temperature derating is offset by the 100%-rated breaker allowance)

D. 623.2A (below requirement but within the 100%-rated breaker tolerance)

49. A three-phase, 480V system has a 3,500 kVA transformer (Z = 5.75%, X/R = 9) and 20 motors (FLA = 4,000A). Transformer fault = 42,200A. Motor = 16,000A. Total = 58,200A. X/R = 9. Multiplier = 2.35. Peak?

A. 82,300A (√2)

B. 116,400A (2×)

C. Peak = 2.35 × 58,200 = 136,770A — the 16,000A motor contribution (27.5%) adds significantly; this is one of the highest motor-contribution percentages in the exam series, demonstrating why motor fault contribution cannot be ignored even when transformer contribution dominates

D. 58,200A (no asymmetry)

50. A 480V, three-phase, 200A feeder uses 350 kcmil THHN copper in EMT (R = 0.0367, X = 0.0407 Ω/1000 ft). The feeder is 900 feet long, serving a load at 0.84 lagging PF. What is the voltage drop?

A. V_drop = √3 × 200 × (0.0367×0.9×0.84 + 0.0407×0.9×0.542) = 346.4 × (0.02774 + 0.01985) = 346.4 × 0.04759 = 16.49V; 16.49/480 = 3.44% — exceeds the 3% NEC recommendation; at 900 feet, even 350 kcmil is inadequate; the engineer must upsize to 500 kcmil (which would produce approximately 2.7%) or consider installing a step-down transformer closer to the load

B. 2.5%

C. 4.5%

D. 1.5%

51. Per NEC 110.14(C)(1), a 2,500A switchboard has terminals marked "90°C." Continuous load = 2,000A. Required ampacity = 2,500A. At 90°C: five parallel 750 kcmil = 5×535 = 2,675A (adequate with 7%). At 75°C: five parallel 750 kcmil = 5×475 = 2,375A (inadequate). Six parallel 500 kcmil at 90°C = 6×430 = 2,580A (adequate with 3.2%). Which is the better engineering choice?

A. Six parallel 500 kcmil at 90°C — more parallel sets with smaller conductors

B. Both are technically adequate

C. Five parallel 500 kcmil at 90°C = 5×430 = 2,150A (inadequate)

D. Five parallel 750 kcmil at 90°C = 2,675A with 7% margin is the better choice — five parallel sets is more manageable than six, with 7% margin providing adequate thermal headroom; the 75°C column cannot satisfy the requirement (2,375A < 2,500A), demonstrating that 90°C-rated terminals are absolutely essential for switchboards at this current level

52. A 350 MVA synchronous generator has $H = 5.5$ MJ/MVA and delivers 280 MW when a three-phase fault occurs. Critical clearing angle = 122°. Relay = 0.006s (optical with ultra-high-speed trip), breaker = 0.015s (ultra-fast vacuum), total = 0.021s. What is the angle advance?

A. $\Delta\delta = 10°$ — stable with good margin

B. $\Delta\delta = (180\times60\times280\times0.021^2)/(5.5\times350) = (180\times60\times280\times0.000441)/1{,}925 = 1{,}333.6/1{,}925 = 0.693° \approx 0.7°$ — the state-of-the-art 0.021-second clearing (fastest in the exam series) produces less than 1° of rotor advance; the 121.3° margin represents essentially zero transient stability risk at any loading level; this demonstrates the ultimate capability of modern ultra-fast protection systems

C. $\Delta\delta = 30°$ — marginally stable

D. $\Delta\delta = 122°$ — at critical clearing

53. A three-phase, 13.8 kV capacitor bank rated 18,000 kvar has six series groups of ten parallel units per phase (60 per phase, 180 total). Six units in one series group fail and their fuses blow. The remaining four units see 10/4 = 2.50× normal voltage (150% overvoltage). At $(2.50)^2 = 6.25\times$ rated dielectric stress, the cascade timeline is measured in individual power-frequency cycles. How many cycles until complete group failure?

A. The remaining four units experience 6.25× rated dielectric stress — far beyond any insulation design margin; failure occurs within 1-3 power-frequency cycles (approximately 17-50 ms at 60 Hz); each subsequent failure accelerates the cascade: 4→3 units (3.33×, 11.1× stress → sub-cycle failure), 3→2 (5.0×, 25× stress → instantaneous), 2→1 (10×, 100× stress → instantaneous); the entire cascade from the initial 6-unit failure to complete group destruction takes approximately 50-100 ms — no conventional protection can respond fast enough; the only prevention is ensuring the bank trips BEFORE the 6th unit fails

B. 60 cycles (1 second)

C. 600 cycles (10 seconds)

D. 3,600 cycles (1 minute)

54. A three-phase, 460V, 8-pole wound-rotor motor rated 2,500 HP drives a cement kiln requiring 360% breakaway torque. Wound-rotor: 370% at 390% FLA (T/I = 0.949). Design D: 280% at 680% FLA (T/I = 0.412). The kiln also requires 15-minute operation at 180% FLT during clinker buildup events occurring 3-4 times per shift. What unique advantage does the wound-rotor provide for the sustained 180% overload?

A. Design D handles sustained overloads better due to higher slip

B. The wound-rotor handles sustained overloads identically to squirrel-cage motors

C. During the 15-minute 180% overload, the wound-rotor's external resistance can be partially re-engaged, transferring $I^2R$ heating from the rotor windings to the external resistor bank; the external resistors are designed for high-duty-cycle thermal absorption with forced-air cooling, providing essentially unlimited thermal capacity for this overload level; in contrast, a squirrel-cage motor must absorb all rotor heating internally, and 180% FLT for 15 minutes would likely exceed the motor's thermal damage curve, causing insulation degradation or failure

D. Both motor types handle 180% overload for 15 minutes without concern

55. Per NEC 310.15(C)(1), a cable tray in a large data center contains: fifteen three-phase VFD circuits (45 phase conductors), ten neutral conductors carrying triplen harmonics (from server power supplies), five neutral conductors NOT carrying harmonics (from HVAC circuits), and fifteen EGCs. What is the count and adjustment factor?

A. 45 (phase only); factor = 0.30

B. 55 (45+10); factor = 0.25 for 41+ conductors

C. 60 (45+10+5); factor = 0.20

D. 55 (45 phase + 10 triplen-carrying neutrals); non-harmonic neutrals and EGCs excluded; for 41+ conductors: the NEC does not specify a factor — the authority having jurisdiction determines the derating; in practice, this installation is completely impractical in a single tray and MUST be split into at least eleven parallel raceways (5 conductors each) to achieve a 0.80 factor

56. A 480V, three-phase LVPCB main has 0.30s STD. The system has: ZSI, optical relay, AQD, arc-resistant switchgear, permanent-magnet trip coil, and a redundant fiber-optic trip path that bypasses all control wiring. During a bus fault, the AQD activates in 4 ms. Simultaneously, the optical relay sends a trip via both the standard copper control wiring AND the fiber-optic path. If electromagnetic interference (EMI) from the 200+ kA arc fault corrupts the copper trip signal, does the breaker still trip?

A. No — if the copper signal is corrupted, the breaker cannot trip

B. Yes — the fiber-optic trip path is completely immune to EMI because light signals in glass fibers are not affected by electromagnetic fields; the fiber signal reaches the breaker's trip coil driver (located at the breaker mechanism, beyond the EMI zone) and initiates tripping; this redundant communication path eliminates the last common-mode failure mechanism for arc flash protection in high-fault-current environments

C. The EMI concern is theoretical — copper wiring is never affected by arc faults

D. The AQD eliminates the need for the breaker to trip

57. A protection engineer must set a ground-fault relay (51G) on a 13.8 kV resistance-grounded system. The NGR is rated 400A. Normal system zero-sequence background = 12A (from cable charging asymmetry). The relay CT ratio = 50:5 (on the neutral). At rated fault: relay secondary = 400/10 = 40A. At the 12A background: relay secondary = 1.2A. The engineer sets pickup at 3.0A secondary (30A primary = 7.5% of NGR rating). What is the maximum detectable fault resistance?

A. R_max = V_LN/I_pickup − R_NGR = 2,402/30 − 6.005 = 80.1 − 6.005 = 74.1 Ω; the margin above background is (30−12)/12 = 150% — excellent sensitivity with robust security against false tripping from normal unbalance; this is a well-engineered relay setting that balances sensitivity and security for an LRG system

B. R_max = 50 Ω; margin above background = 100%

C. R_max = 150 Ω; margin above background = 500%

D. R_max = 20 Ω; margin = 50%

58. A 345 kV, 520-mile line has $Z_1$ = 41.6+j390 Ω, $Z_0$ = 124.8+j1,170 Ω. Source: $Z_1$_src = j26 Ω, $Z_0$_src = j39 Ω. SLG at remote end: $Z_1$_total = 41.6+j416; $Z_0$_total = 124.8+j1,209. |$Z_1$| = 418.1; |$Z_0$| = 1,215.4. Sum = 208+j2,041; |Sum| = 2,051.6. I_SLG = 597,558/2,051.6 = 291A. This is the lowest SLG fault

current in the entire exam series. What is the ONLY protection scheme that can reliably detect and clear this fault with high speed?

A. Zone 1 distance relay (21) with pilot scheme can clear this fault

B. Ground overcurrent relay (51G) with sensitive settings is adequate

C. Zone 2 distance with stepped timing provides adequate backup

D. Line current differential (87L) with fiber-optic communication is the ONLY scheme that provides reliable high-speed clearing at 291A — distance relays are at or beyond their accuracy limits at this impedance magnitude; ground overcurrent must use pickup settings so low they risk false operation on load unbalance; pilot-distance schemes inherit the distance relay accuracy problem; 87L measures DIFFERENCE in terminal currents (independent of magnitude), making it reliable even at a few hundred amperes

59. Per NEC 700.10(B)(1), a hospital routes emergency conduit through a dedicated chase within the building structure, while normal wiring runs through a common ceiling plenum. Both systems occasionally cross at penetration points where they share the same wall penetration (each in its own conduit). Is this compliant?

A. No — the systems cannot share wall penetration points

B. No — emergency wiring cannot use a dedicated chase if it is within the same building as normal wiring

C. Yes — each system maintains its own dedicated raceway throughout; at penetration points, the conduits pass through the same wall opening but remain physically separate — NEC 700.10(B)(1) requires independence of wiring systems (conductors and raceways), not absolute spatial separation at every point; fire-stopping of the shared penetration per NEC 300.21 ensures fire integrity

D. Yes — but only if the penetration has a 4-hour fire rating

60. A three-phase, 480V, 400A panelboard has: Motor 1 = 302A (250 HP, largest), Motor 2 = 242A (200 HP). Continuous lighting = 150A. Noncontinuous = 45A. Bus = 400A. OCPD = 125%×302 + 242 + 125%×150 + 45 = 377.5+242+187.5+45 = 852A → next standard = 1,000A → far exceeds 400A bus. With 100%-rated 400A breaker: load = 739A > 400A. Resolution?

A. Install a 100%-rated breaker to bring load within 400A rating

B. The 400A panelboard is grossly undersized — total load of 739A is 85% above the bus rating; a 100%-rated breaker cannot overcome the physical 400A bus limitation; the panelboard must be replaced with a minimum 800A unit, or the load must be split across two separate panelboards; this represents a significant design error requiring immediate correction

C. De-rate the lighting load

D. The 100%-rated breaker resolves the bus limitation

61. A balanced three-phase, 4,160V source feeds a 25,000 kW load at 0.63 lagging PF. Q = 25,000 × 1.233 = 30,825 kvar. Utility penalty = $7.00/kvar/month above 0.96 PF. Q_allowed = 25,000 × 0.292 = 7,300 kvar. Excess = 23,525 kvar. Penalty = $164,675/month = $1,976,100/year. Cap bank at $25/kvar = $588,125. Payback?

A. Payback = 12 months

B. Payback = 6 months

C. Payback = 24 months

D. Payback = $588,125/$164,675 = 3.57 months — the annual savings of $1,976,100 represent a 336% return on the $588,125 investment; this is the highest penalty value in the exam series and demonstrates why power factor correction is the single most impactful capital investment in large industrial facilities with poor power factor

62. A 480V, three-phase MCC has 30 motors (FLA = 6,500A combined). Motor contribution = 26,000A. Three parallel transformers (3,500 kVA each, Z = 5.75%) provide 74,200A each = 222,600A. Total = 248,600A. X/R = 9. Multiplier = 2.35. Peak?

A. Peak = 2.35 × 248,600 = 584,210A — this is the second-highest peak in the exam series; three parallel 3,500 kVA transformers plus 30 motors produce nearly 600 kA peak; the motor contribution of 26,000A (10.5%) adds measurably; custom segregated-phase bus construction is mandatory

B. 351,600A (√2)

C. 497,200A (2×)

D. 248,600A (no asymmetry)

63. A three-phase, 13.8 kV underground cable system is 70 miles long with charging current of 8.0A per mile per phase. A zero-sequence CT with 6A pickup and 0.2-second delay is installed. Total charging = 560A/phase. During cable energization at no-load, a pre-existing ground fault of 8A zero-sequence is present. The relay sees only 8A (balanced charging cancels). Since 8A > 6A, the relay trips 0.2 seconds after energization. However, this is the INTENDED behavior — the fault was present before energization. But the operator expected normal energization without a trip. What is the operational issue?

A. The relay should be blocked during energization to prevent nuisance trips

B. The relay is correctly detecting a pre-existing ground fault during energization — this is desired protective behavior, not a nuisance trip

C. The operator should be warned that energization may reveal pre-existing faults

D. The operational issue is communication: the relay correctly detected a pre-existing ground fault, but the operator didn't expect it because no fault existed before the cable was de-energized; the fault developed while the cable was de-energized (possibly from mechanical damage during adjacent work); the correct response is to investigate the fault before re-attempting energization, NOT to block the relay during energization — doing so would energize a faulted cable and potentially cause equipment damage or personnel injury

64. Per NEC 430.24, a feeder serves eight motors and continuous lighting. Motor A = 862A (750 HP, largest). Motors B through H = 683+590+477+414+361+302+242 = 3,069A. Continuous lighting = 300A. Noncontinuous HVAC = 180A. What is the minimum feeder conductor ampacity?

A. 4,000A

B. 4,500A

C. 125%×862 + 3,069 + 125%×300 + 180 = 1,077.5+3,069+375+180 = 4,701.5A — this extreme ampacity requires multiple parallel conductor sets per phase; at this level, bus duct may be more practical than individual conductors in raceways

D. 5,000A

65. A distance relay on a 345 kV line (Z_line = 12+j140 Ω) has Zone 1 at 85%, Zone 2 at 120%. A fault at 80% through 20 Ω resistance. Z_meas = (0.80×12+20)+j(0.80×140) = 29.6+j112 Ω. |Z_meas| = 115.8 Ω. Zone 1 = 0.85×140.5 = 119.4 Ω. |Z_meas| < Zone 1 reach. Impedance angle = arctan(112/29.6) = 75.2°. MTA = 82°. The 6.8° angular deviation combined with 20 Ω resistance: is this fault within the mho circle?

A. Yes — the magnitude margin (3.6 Ω, 3.0%) combined with 6.8° angular deviation keeps the R-X point within the mho circle because the mho geometry at 80% of reach accommodates moderate resistive shift

B. The fault is within Zone 1 magnitude but the mho circle analysis requires careful evaluation — the 20 Ω resistance creates a significant rightward shift on the R-X diagram, and the 6.8° angular deviation from MTA pushes the point toward the mho circle boundary; at 80% of reach (well within the magnitude), the mho circle is wider and accommodates more resistance; however, the specific mho circle geometry must be plotted to confirm — this is a borderline case where the pilot scheme provides essential backup

C. The 20 Ω resistance guarantees the fault is outside the mho circle

D. Distance relays do not consider fault resistance in their operating characteristic

66. A three-phase, 4,160V system has an NGR rated 300A, 10 seconds. A ground fault through 40 Ω develops. I = 2,402/48.007 = 50.0A. The relay (pickup 15A) detects this with 233% margin. The engineer asks: if this same fault were on a solidly grounded 4,160V system (zero-sequence impedance $Z_0$ = j2.0 Ω, $Z_1$ = $Z_2$ = j3.0 Ω), what would I_SLG be?

A. On the solidly grounded system: I_SLG = 3V_f/($Z_1$+$Z_2$+$Z_0$+3Z_f) where Z_f = 40+j0 Ω; I_SLG = 3×2,402/(j3+j3+j2+120) = 7,206/(120+j8) = 7,206/120.3 = 59.9A — essentially the same as the NGR system (50A) because the 40 Ω fault resistance dominates both systems; the NGR and solidly grounded systems converge in behavior when the fault resistance greatly exceeds the grounding impedance; this demonstrates that LRG provides minimal benefit for high-impedance faults — its primary advantage is limiting BOLTED ground-fault current

B. I_SLG = 400A (much higher on solidly grounded)

C. I_SLG = 50A (identical to the NGR system)

D. I_SLG = 1,000A (solidly grounded always produces maximum fault current)

67. Per NEC 480.9(A), a containerized BESS uses lithium-ion NMC cells. The container has an HVAC system maintaining cells at 25°C. During summer, ambient reaches 45°C. The HVAC system draws 25 kW continuously. If the HVAC fails, how long before cell temperatures reach the 60°C maximum operating limit (above which the BMS should begin load shedding)?

A. The container reaches 60°C in approximately 30 minutes (the thermal mass of the cells provides limited buffer)

B. The container reaches 60°C immediately — cells have no thermal mass

C. The time depends on the container's thermal insulation, cell thermal mass, and the charging/discharging state

D. The time to reach 60°C depends on: (1) the container's R-value (thermal insulation), (2) the total cell mass and specific heat (thermal capacitance), (3) the internal heat generation from charging/discharging ($I^2R$ losses), and (4) the 20°C ΔT between the 25°C operating point and 45°C ambient; for a typical 1 MWh container with moderate insulation, the time is approximately 30-60 minutes at idle and 15-30 minutes at full charge/discharge; the BMS must activate emergency cooling (opening louvers, activating backup fans) AND begin load shedding within this window to prevent cell degradation

68. A three-phase, 480V, 800A panelboard has available fault current of 45,000A. IEEE 1584: 18 cal/cm² at 24 inches with 0.20s clearing. Layered protection: optical relay (0.006s — the fastest in the exam series, using a solid-state trip unit), ZSI (0.05s), maintenance switch (0.04s), AQD (0.004s), and arc-resistant enclosure. With the AQD quenching the arc in 4 ms and the optical clearing in 6 ms, what is the worker's effective exposure?

A. 18 cal/cm² (unchanged)

B. E at optical clearing: 18×(0.006/0.20) = 0.54 cal/cm²; but the AQD quenches at 4 ms — BEFORE the optical clears at 6 ms

C. The AQD activates first (4 ms), collapsing arc voltage to near zero; the arc exists for only 4 ms; E_arc ≈ 18×(0.004/0.20) = 0.36 cal/cm² — the lowest calculated arc energy in the exam series; the optical relay then clears the remaining bolted fault at 6 ms; combined with the arc-resistant enclosure, the worker's effective exposure is essentially zero; this six-layer defense (AQD + optical + ZSI +

maintenance switch + arc-resistant + PM trip) represents the absolute pinnacle of arc flash protection engineering

D. E = 9.0 cal/cm² (50% reduction from arc-resistant alone)

69. A three-phase, 460V, 4-pole synchronous motor rated 5,000 HP drives a large compressor at 1,800 RPM. Pull-out = 260% FLT. H = 4.0 MJ/MVA (the highest synchronous motor H in the exam series — massive flywheel). During a severe grid event, voltage sags to 68% for 1.2 seconds. Pull-out = 176.8% FLT. Load = 88% FLT. Margin = 88.8% FLT. What is the stability assessment?

A. Unstable despite the high H and high margin — 1.2 seconds at 68% is too severe

B. H = 4.0 with 88.8% FLT margin: the massive flywheel (highest H in the exam series) provides extraordinary resistance to angular acceleration; even with the 1.2-second sag at 68%, the angle advance is moderate (estimated 15-25°); the combination of highest H, generous margin, and the flywheel's role as a mechanical energy buffer ensures stability; the motor maintains synchronism through the sag and the subsequent return-swing oscillation is well-damped by the large inertia

C. Marginally stable — requires detailed simulation

D. Cannot be determined without the exact pull-out curve

70. A 345 kV, 500-mile line has $Z_1$_total = 40+j375 Ω, $Z_0$_total = 120+j1,125 Ω. $|Z_1|$ = 377.1, $|Z_0|$ = 1,131.4. Sum = 200+j1,875; |Sum| = 1,885.6. I_SLG = 598,558/1,885.6 = 317A. The engineer evaluates pilot scheme options: (A) directional comparison blocking over PLC, (B) permissive overreaching transfer trip over fiber, (C) line current differential over fiber. Which provides the most reliable primary protection?

A. Line current differential (87L) over fiber provides the most reliable primary protection because: (1) it measures current difference, not impedance — reliable at any fault current; (2) fiber communication is immune to EMI from the fault arc; (3) 87L is immune to power swings and load encroachment that affect distance-based schemes at 317A; (4) PLC communication may be degraded by the fault arc on the same line; option (B) is the next best but inherits distance relay accuracy limitations at 317A

B. Directional comparison blocking over PLC is the most reliable

C. All three options provide identical reliability

D. None of the options can detect a 317A fault

71. Per NEC 250.122(B), a 2,000A circuit has two parallel 1,250 kcmil per phase (2,500,000 CM total), increased to two parallel 1,500 kcmil (3,000,000 CM total) for voltage drop. The EGC from Table 250.122 for 2,000A = 350 kcmil (350,000 CM). What is the proportionally increased EGC?

A. 350 kcmil (no increase)

B. 400 kcmil

C. 500 kcmil

D. Ratio = 3,000,000/2,500,000 = 1.20; EGC = 350,000 × 1.20 = 420,000 CM → 500 kcmil (500,000 CM) is the minimum standard size above 420,000 CM; 400 kcmil is not a standard conductor size in NEC Table 250.122

72. A balanced three-phase, 4,160V source feeds a 30,000 kW load at 0.65 lagging PF. The engineer installs a 22,000 kvar cap bank, a 7,000 HP sync motor at 0.80 leading ($\eta$ = 94%), a 3,500 HP sync motor at 0.85 leading ($\eta$ = 95%), AND a 1,500 HP sync motor at 0.90 leading ($\eta$ = 95%). What is the new PF?

A. PF = 0.90

B. PF = 0.95

C. SM1: P=5,558, $Q_1$=4,169; SM2: P=2,750, $Q_2$=1,707; SM3: P=1,179, $Q_3$=571; total correction=22,000+4,169+1,707+571=28,447; orig Q=35,070; net Q=6,623; P_total=39,487; PF=39,487/40,039=0.986 ≈ 0.99

D. PF = unity

73. A 100 MVA, 345/138 kV autotransformer (Z = 10%). Two units in parallel. A 70 MVA generator (X"_d = 0.18), 50 MVA sync condenser (X"_d = 0.12), 40 MVA sync motor (X"_d = 0.20), 35 MVA solar (eff Z = 1.0), 25 MVA wind (eff Z = 1.2), and 20 MVA BESS (eff Z = 1.5) are on the 138 kV bus. On 100 MVA base, what is the total fault current and the combined inverter-based contribution?

A. 10,000A; inverter = 5%

B. Z_T_par = 0.05; Z_gen = 0.257; Z_SC = 0.24; Z_SM = 0.50; Z_solar = 2.857; Z_wind = 4.80; Z_BESS = 7.50; I_pu = (20.0+3.891+4.167+2.0+0.35+0.208+0.133) × 418.4 = 30.75 × 418.4 = 12,866A; inverter contribution = (0.35+0.208+0.133)/30.75 = 2.25% — three inverter sources totaling 80 MVA (28% of connected capacity) contribute only 2.25% of fault current; this is the highest inverter penetration scenario in the exam series, demonstrating the profound protection challenge as grids transition to predominantly inverter-based generation

C. 15,000A; inverter = 10%

D. 8,000A; inverter = 15%

74. A three-phase, 460V, 4-pole induction motor rated 450 HP operates at 1,770 RPM. A VFD reduces speed to 500 RPM for a centrifugal pump. P = 336×(500/1,770)$^3$ = 336×0.0226 = 7.6 kW. VFD η = 92%, motor η at extreme light load = 65%. P_supply = 7.6/(0.65×0.92) = 12.7 kW. Losses = 5.1 kW = 67% of pump power. What does this extreme scenario reveal?

A. At 28% of rated speed, motor efficiency drops to 65% — the lowest in the exam series; the losses (67% of pump power) exceed the useful output; this represents the absolute bottom of the diminishing-returns curve for VFD speed reduction on centrifugal loads; below approximately 30% speed, the fixed motor losses (iron, friction, windage) dominate and the efficiency collapses; the economic crossover occurs where the VFD energy savings from speed reduction no longer exceed the increased percentage of losses — below this point, it may be more efficient to use a smaller, properly loaded motor

B. The motor operates efficiently at all VFD speeds

C. The losses are negligible at any speed

D. VFDs always save energy regardless of speed

75. Per NEC 430.32(A)(1), a motor with SF = 1.15 has maximum overload at 125% FLA. A 1,000 HP motor (FLA = 1,180A, SF = 1.15) drives a mine hoisting system with 90-second start time (extremely high inertia). During starting, the motor draws 4× FLA (4,720A) for 50 seconds, then 2.5× (2,950A) for 30 seconds, then settles to rated in 10 seconds. A standard Class 30 overload relay (30-second trip at 6× FLA) will trip during this start. What protection solution is needed?

A. The thermal accumulation during the 90-second start far exceeds any standard overload class; the motor requires: (1) a microprocessor-based motor protection relay with a programmable thermal model that includes a motor-starting mode with adjustable stall time and $I^2t$ curves matched to the specific motor's thermal damage characteristics; (2) during starting, the relay temporarily raises its effective trip threshold based on the known starting profile; (3) after the motor reaches full speed, normal thermal protection resumes; this is the most demanding motor protection scenario in the exam series

B. Remove the overload relay during starting and reinstall after the motor reaches speed

C. Use a Class 10 relay which will not trip during starting due to faster reset

D. Standard overload relays automatically accommodate starting regardless of duration

76. A 480V, three-phase system has a 5,000 kVA transformer (Z = 5.50%, X/R = 10) and a 4,000 kVA transformer (Z = 5.75%, X/R = 9) in parallel, plus 25 motors (FLA = 5,000A) = 20,000A. I_T1 = 6,014/0.055 = 109,345A. I_T2 = 4,811/0.0575 = 83,670A. Total = 193,015 + 20,000 = 213,015A. X/R ≈ 9.5. Multiplier = 2.37. Peak?

A. 301,200A (√2)

B. 426,030A (2×)

C. Peak = 2.37 × 213,015 = 504,846A — over half a million amperes peak; this is the highest combined fault current in the exam series; the 5,000 kVA + 4,000 kVA parallel combination with 25 motors produces forces that exceed any standard 480V bus construction capability; custom segregated-phase bus with structural engineering analysis is the ONLY viable approach

D. 213,015A (no asymmetry)

77. A three-phase, 4,160V, 12-pole synchronous motor rated 8,000 HP drives a ball mill at 600 RPM. Pull-out = 280% FLT. H = 1.4 MJ/MVA (the lowest H in the exam series). Voltage drops to 52% for 3.5 seconds during a catastrophic grid event. Pull-out = 145.6% FLT. Load = 100% FLT. Margin = 45.6% FLT. Despite the positive margin, what is the absolute outcome?

A. The motor maintains synchronism — 45.6% margin is adequate

B. Certain instability — H = 1.4 (lowest in the series) combined with the deepest sag (52%), longest duration (3.5 seconds), and extreme $t^2$ factor ($3.5^2 = 12.25$) produces rotor angle advance thousands of degrees; the motor loses synchronism within 0.2-0.3 seconds of sag onset — the fastest pull-out in the exam series; the UV relay MUST be set to trip within 0.2 seconds for this low-H motor; steady-state margin is completely irrelevant to transient stability at these extreme parameters

C. Marginally stable

D. Stable with reduced margin

78. Per NEC 110.24(A), a facility originally had three parallel 2,000 kVA transformers (Z = 5.75% each). Z_parallel = 1.917%. I_original = 3,007/0.01917 = 156,887A. A fourth identical transformer is added. Z_new = 5.75%/4 = 1.4375%. I_new = 3,007/0.014375 = 209,183A. What is the percentage increase?

A. I_new/I_original = $(3/4)^{-1}$ / $(3/3)^{-1}$ = (4/3)/(3/3) = 4/3 = 1.333 → 33.3% increase; I_new = 209,183A; this 33% increase (from 157 kA to 209 kA) pushes the system further into the realm where standard 480V equipment is inadequate; comprehensive reverification is mandatory for all equipment downstream of the paralleled bus

B. 25% increase (one-fourth additional capacity)

C. 50% increase

D. No increase — a fourth transformer in parallel has negligible effect

79. A 3,000 kVA, 480V/208Y/120V transformer has Z = 4.50% and X/R = 4. The symmetrical RMS fault current at 208V = 38,500A. Using the IEEE multiplier of 2.07 for X/R = 4, what is the peak asymmetrical?

A. 54,500A ($\sqrt{2}$ × symmetrical)

B. 77,000A (2× symmetrical)

C. 38,500A (no asymmetry)

D. Peak = 2.07 × 38,500 = 79,695A — at 80 kA peak on a 208V system, virtually ALL standard panelboards and switchboards at 208V are inadequately rated; this large, low-impedance transformer requires current-limiting fuses or specialized high-SCCR equipment throughout the 208V distribution system

80. A 1,000 kW, three-phase, 480V resistance heater operates continuously 24/7/365 at a steel mill. Electricity costs \$0.048/kWh. Per NEC 210.20(A), minimum OCPD = 125% of continuous. What is the load current, minimum OCPD, annual energy, and cost?

A. I = 800A; OCPD = 1,000A; E = 8,760,000 kWh; cost = \$420,480

B. I = 1,000A; OCPD = 1,200A; E = 8,760,000 kWh; cost = \$420,480

C. I = 1,000,000/(√3×480) = 1,202.8A; OCPD = 125%×1,202.8 = 1,503.5A → next standard per NEC 240.6(A) = 1,600A; E = 1,000×8,760 = 8,760,000 kWh; cost = 8,760,000×\$0.048 = \$420,480/year — this \$420,000 annual energy cost is the highest in the exam series and represents a transformative economic driver for waste heat recovery, process efficiency improvements, and alternative heating technologies; at this cost level, even a 5% efficiency improvement saves \$21,000/year

D. I = 1,202.8A; OCPD = 1,400A; E = 6,000,000 kWh; cost = \$288,000

## Practice Exam 24: Answer Key and Explanations

1. B — The amplification factor AF = 5.44× at h = 7 explains the 6.8% $V_7$. Installing 6% detuning reactors shifts h_r from 7.75 to approximately 4.7 (below the 5th harmonic), eliminating resonance amplification of ALL characteristic harmonics. This costs 10-20% of VFD replacement and addresses the root cause — the resonance, not the harmonic source.

2. D — Cable Z_pu = 0.588. Total Z = 0.646. I_transformer = 6,515A at the panelboard. Motor contribution = 1,936A. Total = 8,451A — above the 2,250A instantaneous threshold. The long 4/0 cable reduces transformer contribution by 85%, but the combined fault current remains adequate for instantaneous breaker operation.

3. A — NEC 430.52 requires a branch-circuit OCPD regardless of VFD electronic protection. VFDs can fail in ways that bypass their electronics (semiconductor failure, control board failure). The 700A fuse provides code-required backup that operates independently of the VFD's internal protection — this separation of protection layers is a fundamental safety principle.

4. C — Steel conduit around CT secondary wiring adds inductive impedance due to the magnetic permeability of steel. This hidden burden increase could consume the 65V margin and push the CT

toward saturation. CT secondary wiring must be routed through nonmagnetic conduit (PVC, aluminum, or nonmagnetic stainless steel) to avoid this effect.

5. B — The STATCOM maintains rated CURRENT at reduced voltage. At 0.92 pu: Q ≈ 0.92 × 300 = 276 Mvar. An SVC at 0.92 pu provides only $V^2$ × 300 = 254 Mvar. The STATCOM provides 9% more reactive support. Additionally, STATCOMs can temporarily exceed rated current for short-term overload capability — a critical advantage during voltage depressions.

6. D — Ratio = 1,500,000/1,000,000 = 1.50. EGC = 133,100 × 1.50 = 199,650 CM. 3/0 AWG = 167,800 (below). 4/0 AWG = 211,600 (above — adequate). The minimum EGC is 4/0 AWG per NEC 250.122(B).

7. A — Four correction sources: cap SM1 $Q_1$=3,571; SM2 $Q_2$=1,463; SM3 $Q_3$=380; total = 18,000+3,571+1,463+380 = 23,414. Net Q = 24,660−23,414 = 1,246. PF ≈ unity. Four sources virtually eliminate reactive demand while adding 10,000 HP of production capacity.

8. C — Phase base = 626.7/0.80 = 783.4A. Neutral base = 486/0.80 = 607.5A. Phase governs at 783.4A. Despite the very high 486A neutral, the phase carries substantial harmonic current (both triplens AND non-triplens) in addition to the fundamental, making its derating-adjusted requirement the governing constraint.

9. B — LRG: I_SLG = 1.013 pu (resistive, ~10° lag). Reactor: I_SLG = 0.878 pu (reactive, 90° lag). LRG provides lower arc energy because resistive current crosses zero every half-cycle, facilitating arc extinction. Reactive current from the reactor maintains the arc more persistently. LRG is preferred for generator grounding because it limits damage AND facilitates self-extinction.

10. A — CT location determines what current it measures. Source CT: I_fault + I_charging = 418A. Feeder CT: I_fault − other feeders' charging = 388A. The 12A difference (3%) is negligible for a 30A pickup relay but becomes significant for sensitive ground-fault schemes where pickup approaches the charging current magnitude.

11. D — NEC Table 110.26(A)(1) specifies 4 feet for 601-2,500V equipment under Condition 3 (exposed live parts on both sides). This increased depth reflects the greater hazard from exposed energized conductors on both sides of the working space, requiring more room for safe work and emergency egress.

12. C — At 10% load: η = 420,000/(420,000+16,500) = 96.2%. At 95%: η = 5,187,000/(5,187,000+61,250) = 98.8%. The 10% load efficiency (96.2%) is 2.6 points lower than 95% load because the fixed 16,000W core losses dominate the small output. This demonstrates why lightly loaded transformers should be de-energized when possible.

13. B — CTI fuse-R1 = 0.224s — barely above 0.20s minimum (zero engineering margin). CTI R1-R2 = 3.795s — grossly excessive (R2 at 4.024s). Reducing R2's TD to 2.0 yields approximately 2.01s (CTI ≈ 1.78s) while halving backup clearing time. Every second of unnecessary delay increases fault damage proportionally.

14. A — At 79.9 Ω apparent (with 3.5% CT/PT error), the fault appears outside Zone 1 (78.5 Ω). The relay fails Zone 1 and reverts to Zone 2 (0.35s). The 5 Ω resistance plus measurement errors consume the 1.3 Ω margin. Pilot schemes are essential for reliable clearing of resistive faults near Zone 1 boundaries.

15. D — Including speed-dependent motor and VFD efficiency at each point adds approximately 12% to the ideal affinity-law calculation. The light-load efficiency penalty (78% motor, 88% VFD at 35% speed) significantly impacts energy at reduced speeds. Total supply energy ≈ 1,656,000 kWh vs 3,267,480 full-speed = 49.3% savings.

16. C — $H_2$ = 3.84 ft$^3$/hr. Max $H_2$ = 60 ft$^3$. ACH = 0.064. Monitoring equipment inside the battery room must either be located outside with only sensors inside, or rated for the potential $H_2$ atmosphere. While ventilation normally keeps $H_2$ below 1%, a ventilation failure during charging creates a hazardous atmosphere within hours.

17. B — The switching sequence must be phased as load crosses SIL: switch first reactor ON at approximately 150 MW, STATCOM absorbs continuously to smooth transitions, second reactor ON at approximately 80 MW. The STATCOM's fast continuous response bridges the discrete reactor steps, preventing voltage spikes from mechanical switching of large reactive devices.

18. C — $T\_brake = E\_a \times I\_regen / \omega = 583 \times 330 / 125.7 = 1,530$ N-m. The braking torque is determined by $E\_a \times I$ (mechanical power converted to electrical), not $V\_t \times I$ (terminal power). The 10.9 kW difference (192.4 − 181.5) is dissipated as $I^2R$ loss in the armature resistance.

19. D — Fifty-six separately derived systems: 8 service + 4 emergency + 6 CHP + 20 PDU + 12 isolation + 6 UPS = 56. CHP generators configured to operate independently through transfer switching are separately derived systems, identical to emergency generators. Each requires a bonding jumper per NEC 250.30(A)(2).

20. B — Equipment must be rated for the TIE-CLOSED fault level (176,673A) because the tie may be closed at any time. Protection must coordinate for both conditions. Arc flash labels must reflect the worst case (tie-closed) unless administrative controls guarantee tie position. The 85% increase from tie-open to tie-closed dramatically affects equipment ratings.

21. C — During 200 ms reactor period: I_SLG = 3.33 pu — sufficient for relays to detect, locate (directional ground overcurrent), and initiate the grounding switch. Modern microprocessor relays accomplish this in 50-100 ms. After switching to HRG, fault damage is minimized while the faulted feeder is isolated based on the stored location data.

22. A — Per NEC 430.24: 125%×862 = 1,077.5. Other motors = 683+590+477 = 1,750. Per NEC 215.2: 125%×350 = 437.5. Noncontinuous = 120. Total = 1,077.5+1,750+437.5+120 = 3,385A. The 125% applies independently to the largest motor and continuous non-motor load.

23. D — I = 113.16 × 8,328 = 942,549A. The 50 MVA BESS contributes 0.333/113.16 = 0.29% despite its large rating. Inverter-based resources have inherently high effective impedance limiting fault contribution to approximately 1.0-1.2× rated. The five transformers provide 95% of total.

24. B — Cable Z_pu = 0.291. Total Z = 0.349. I_transformer = 12,060A. Motor = 3,200A. Total = 15,260A < 22,000A SCCR. The cable naturally reduces fault current below the panelboard rating without current-limiting fuses. Proper documentation per NEC 110.9 is required.

25. C — NEC 690.7(A): 20 × 57.5V = 1,150V > 1,000V DC rating. This violation exists during ALL cold-weather conditions. Reduce to 17 modules (977.5V) or upgrade all system components to 1,500V DC. This is separate from rapid shutdown compliance.

26. D — Total = 220,796 + 20,000 = 240,796A. Peak = 2.32 × 240,796 = 558,647A. Over half a million amperes peak — the highest in the exam series. Forces proportional to $3.12 \times 10^{11}$ A$^2$ represent the absolute physical design limit for 480V bus systems.

27. B — Both terminals trip with high-speed clearing via DCB. Near end: Zone 2 covers 95%; no blocking received → trips instantaneously. Remote end: Zone 1 covers 5% from its terminal → trips instantaneously. The 8 Ω resistance does not prevent Zone 2 detection. DCB: absence of blocking = permission to trip.

28. A — Second-harmonic blocking engages (65% >> 12% threshold), preventing false differential trip during inrush. Fifth-harmonic blocking does NOT engage (8% < 25% threshold) — this feature is designed for overexcitation (sustained overvoltage), not energization inrush. The two blocking features address different operating conditions.

29. D — Each winding of a multi-winding transformer must be considered for overcurrent protection. The 150A primary OCPD does NOT protect the 250 kVA tertiary (rated 10.5A). A separate OCPD sized for the tertiary's rated current is required if it serves loads. The tertiary needs its own dedicated protection.

30. C — H = 3.5 (highest in the exam series) provides exceptional inertia. The large flywheel absorbs accelerating energy. With 101% FLT margin and 0.8-second sag at 70%, the angle advance is estimated 8-15°. The flywheel is specifically engineered for mine hoist applications where grid disturbances are common. Stability is maintained with good margin.

31. A — $F = (2\times10^{-7} \times 526{,}500^2)/0.203 = 55{,}400/0.203 = 272{,}906$ N/m ≈ 273 kN/m (61,300 lbs/foot). Standard bus construction is completely inadequate. Segregated-phase construction with reinforced barriers, high-strength insulators at 12-inch intervals, and structural steel supports designed for dynamic loading are mandatory.

32. B — A single large active harmonic filter (AHF) at the 13.8 kV bus dynamically cancels ALL harmonics simultaneously without modifying any VFD. Cost: $500K-800K (20-25% of $3M VFD replacement). The AHF can be installed during normal operation with zero production downtime. This is the most cost-effective solution for existing installations.

33. D — Storm drainage, building steel, and runway lighting conduit can be bonded to the grid. However, cathodically protected fuel piping CANNOT be directly bonded — bonding would drain protective current and accelerate corrosion. The cathodic protection specialist must be consulted before any connections near fuel piping per NEC 250.52(B).

34. B — At 76.4% of no-load magnetizing (direct-line operation, no VFD), the capacitor presents low impedance to the VFD's PWM switching harmonics (2-8 kHz). The capacitor's impedance at 4 kHz is 1/67th of its 60 Hz value, creating excessive heating from high-frequency currents. A line reactor between VFD and capacitor is required to attenuate switching harmonics.

35. C — Full: 200,000. 95%: 274,304. 85%: 368,520. 75%: 371,360. 60%: 155,520. 45%: 43,740. 30%: 8,208. VFD = 1,421,652. Full = 3,504,000. Savings = 2,082,348 × \$0.075 = \$156,176/year. Seven modes produce 59.4% reduction. The lowest modes (45%, 30%) contribute only 3.7% of VFD energy despite 22.4% of hours.

36. A — R = 0.0276×0.9 = 0.02484. X = 0.0442×0.9 = 0.03978. V_drop = 346.4 × (0.02484×0.85 + 0.03978×0.527) = 346.4 × (0.02111+0.02096) = 346.4 × 0.04207 = 14.57V. V_drop% = 3.04%. Barely exceeds 3% despite 500 kcmil. The extreme 900-foot distance drives the drop above 3%. Upsize to 750 kcmil for 2.4%.

37. D — I_pu = 28.57+3.497+3.571+1.364+0.30+0.133 = 37.44. I = 15,661A. Renewable contribution = 0.433/37.44 = 1.16%. Despite 50 MVA of renewables (17% of connected capacity), they contribute only 1.16% of fault current — demonstrating the fundamental grid protection challenge as renewable penetration increases.

38. B — Total = 171,618 + 16,000 = 187,618A. Peak = 2.37 × 187,618 = 444,755A. The 4,500 kVA transformer alone produces nearly 100 kA symmetrical. Two very large transformers in parallel with motors approach the physical design limits for 480V bus construction.

39. C — Deep ground wells (30-40 feet) penetrate through the 1,500 Ω-m surface to the 50 Ω-m water table. Each well bypasses the high-resistivity surface and contacts conductive soil. Combined with a surface grid (for step-and-touch potential control) and underground piping connections, this two-layer approach achieves targets that surface grounding alone cannot.

40. D — Z_cable_pu = 1.702. Total Z = 1.760. I = 2,392A. At this extremely low current, a 225A breaker sees only 10.6× — which may fall in the time-overcurrent region rather than instantaneous, significantly increasing clearing time. The engineer must verify the breaker's TCC at 2,392A and may need a lower instantaneous threshold.

41. A — $Z_0$_total (0.0533) = only 26.7% of $Z_1$_total (0.20) — the most extreme $Z_0/Z_1$ ratio in the exam series. This produces the 32.4% SLG exceedance. The very low $Z_0$ (0.04 pu) is characteristic of some three-limb core-form designs. All equipment must be rated for the 6.62 pu SLG current.

42. C — At constant V/f, magnetizing kvar remains approximately 90 kvar and the 70 kvar capacitor is safe at all speeds. During field-weakening above base speed, V/f decreases, reducing flux and magnetizing kvar. The critical risk is during VFD trip when the motor coasts — at rated V/f, 70 kvar at 77.8% is below the self-excitation threshold.

43. B — The neutral CT produces only 0.04A secondary (200A through 5000:5) — below any differential relay threshold. A dedicated lower-ratio CT (200:5) on the neutral provides 5.0A secondary at rated ground-fault current, well above relay minimum. This is why separate neutral CTs are essential for restricted earth-fault protection on generators with limited ground-fault current.

44. D — Neutral = 3 × ($I_3 + I_9$) = 3 × (160+20) = 540A because BOTH the 3rd AND 9th harmonics are triplens (h = 3n). The 5th, 7th, and 11th cancel in balanced systems. The 22.6% neutral exceedance over phase is driven by the combined 3rd and 9th triplen content.

45. A — Connect all 4 to Panel E: 3.5+1.2 = 4.7 mA (0.3 mA margin). During mass-casualty events, speed of connection matters more than optimization. Panel E can safely accept all four devices while keeping all panels below 5 mA. This is the fastest path to getting critical devices connected.

46. C — With compensation: sin δ = 0.394; δ = 23.2°; stability = 39.4%; margin = 60.6%. Without: δ = 45.7°; stability = 71.6%; margin = 28.4%. Series compensation more than doubled the stability margin (from 28.4% to 60.6%), enabling confident 1,200 MW transmission.

47. B — At 10,000A: fuse clears 0.026s before recloser. At 2,000A: fuse clears 0.20s before recloser (0.50−0.30). The margin IMPROVES at lower fault currents because the fuse-to-recloser ratio increases. This is characteristic of properly coordinated fuse-saving schemes across the full fault current range.

48. A — At 40°C ambient, 75°C correction = 0.82. Corrected ampacity = 760 × 0.82 = 623.2A < 710A required. The temperature derating renders 500 kcmil inadequate. Upsize to two parallel 750 kcmil (2×475×0.82 = 779A) or install HVAC to maintain ambient below 30°C.

49. C — Total = 42,200 + 16,000 = 58,200A. Peak = 2.35 × 58,200 = 136,770A. The 27.5% motor contribution is one of the highest percentages in the exam series. This demonstrates why motor fault contribution must always be included in peak calculations.

50. A — R = 0.0367×0.9 = 0.03303. X = 0.0407×0.9 = 0.03663. V_drop = 346.4 × (0.03303×0.84 + 0.03663×0.542) = 346.4 × (0.02775+0.01985) = 346.4 × 0.04760 = 16.49V. V_drop% = 3.44%. At 900 feet, even 350 kcmil is inadequate. Upsize to 500 kcmil (≈2.7%) or install a closer transformer.

51. D — Five parallel 750 kcmil at 90°C = 2,675A with 7% margin. Five sets is more manageable than six parallel 500 kcmil. At 75°C (2,375A < 2,500A), the requirement cannot be met. The 90°C terminal rating is absolutely essential for switchboards at this current level.

52. B — $\Delta\delta$ = (180×60×280×0.000441)/1,925 = 1,334/1,925 = 0.693° ≈ 0.7°. The state-of-the-art 0.021-second clearing (fastest in the exam series) produces less than 1° of advance. The 121.3° margin represents essentially zero transient stability risk. This demonstrates the ultimate capability of modern protection systems.

53. A — At 6.25× rated stress, failure occurs in 1-3 cycles (17-50 ms). Each subsequent failure accelerates: 4→3 (11.1× stress), 3→2 (25× stress), 2→1 (100× stress). The entire cascade from the 6-unit failure to complete group destruction takes approximately 50-100 ms. Only sub-cycle protection can prevent propagation.

54. C — During 15-minute 180% overloads, the wound-rotor's external resistance transfers $I^2R$ heating from rotor windings to the external resistor bank. The external resistors have forced-air cooling with essentially unlimited thermal capacity for this level. A squirrel-cage motor must absorb all heating internally and would likely exceed its thermal damage curve.

55. D — 45 phase + 10 triplen neutrals = 55 current-carrying conductors. For 41+ conductors, the NEC does not specify a standard factor — the AHJ determines derating. This is completely impractical in a single tray. At least eleven parallel raceways are needed for a 0.80 factor.

56. B — The fiber-optic trip path is completely immune to EMI from the 200+ kA arc fault. Light signals in glass fibers are unaffected by electromagnetic fields. The fiber signal reaches the trip coil driver and initiates tripping. This redundant path eliminates the last common-mode failure mechanism in high-fault-current environments.

57. A — R_max = 2,402/30 − 6.005 = 74.1 Ω. Margin above 12A background = (30−12)/12 = 150%. The 3.0A secondary (30A primary) at 7.5% of NGR rating provides excellent sensitivity with robust security against false tripping. This is a well-engineered setting balancing sensitivity and security.

58. D — 87L with fiber is the ONLY reliable scheme at 291A. Distance relays are beyond their accuracy limits. Ground overcurrent requires dangerously low settings. Pilot-distance inherits accuracy problems. 87L measures current DIFFERENCE (independent of magnitude), providing reliable detection even at a few hundred amperes.

59. C — Each system maintains its own dedicated raceway. At penetration points, separate conduits pass through the same wall opening but remain physically separate. NEC 700.10(B)(1) requires independence of wiring systems, not absolute spatial separation at every point. Fire-stopping per NEC 300.21 ensures integrity.

60. B — Total load = 739A > 400A bus. The panelboard is grossly undersized — 85% above bus rating. A 100%-rated breaker cannot overcome the physical 400A limitation. Replace with minimum 800A panelboard or split loads across multiple panels.

61. D — Payback = $588,125/$164,675 = 3.57 months. Annual savings = $1,976,100 = 336% return. The highest penalty value in the exam series demonstrates why PF correction is the single most impactful capital investment for large industrial facilities with poor power factor.

62. A — Total = 222,600 + 26,000 = 248,600A. Peak = 2.35 × 248,600 = 584,210A. Second-highest peak in the series. Three parallel 3,500 kVA transformers plus 30 motors. Custom segregated-phase bus is mandatory — no standard 480V product is rated for this level.

63. D — The relay correctly detected a pre-existing ground fault that developed while the cable was de-energized. The correct response is to investigate, NOT block the relay during energization. Blocking would energize a faulted cable, risking equipment damage and personnel injury.

64. C — 125%×862 = 1,077.5. Other motors B-H = 3,069. Motor subtotal = 4,146.5. 125%×300 = 375. HVAC = 180. Total = 4,701.5A. Multiple parallel sets per phase required. At this level, bus duct may be more practical than conductors in raceways.

65. B — |Z_meas| = 115.8 < Zone 1 reach 119.4 (3.0% margin). But 20 Ω resistance creates significant rightward R-X shift. The 6.8° angular deviation from MTA pushes toward the mho boundary. At 80% reach, the mho circle is wider — the specific geometry must be plotted. Pilot scheme provides essential backup.

66. A — On the solidly grounded system: I_SLG = 7,206/(120+j8) = 59.9A — essentially the same as the NGR system (50A). When fault resistance (40 Ω) greatly exceeds grounding impedance, LRG and solidly grounded systems converge. LRG's primary advantage is limiting BOLTED ground-fault current, not high-impedance faults.

67. D — Time to 60°C depends on insulation R-value, cell thermal mass, internal heat generation, and the 20°C ΔT. For typical 1 MWh containers: 30-60 minutes at idle, 15-30 minutes at full charge/discharge. The BMS must activate emergency cooling AND load shedding within this window.

68. C — AQD activates first (4 ms), quenching the arc. E_arc ≈ 18×(0.004/0.20) = 0.36 cal/cm² — the lowest in the exam series. The optical relay clears the bolted fault at 6 ms. Combined with arc-resistant enclosure: effective exposure is zero. This six-layer defense represents the absolute pinnacle of arc flash protection.

69. B — H = 4.0 (highest motor H in the series) with 88.8% FLT margin. The massive flywheel provides extraordinary resistance to angular acceleration. Even with 1.2 seconds at 68%, angle advance is moderate (15-25°). The flywheel acts as a mechanical energy buffer ensuring stability through the sag and return-swing.

70. A — 87L over fiber provides the most reliable protection: measures current difference (reliable at any magnitude), fiber immune to EMI, immune to power swings and load encroachment. PLC may be degraded by fault arc on the same line. Option B inherits distance relay accuracy limitations at 317A.

71. D — Ratio = 3,000,000/2,500,000 = 1.20. EGC = 350,000 × 1.20 = 420,000 CM. 400 kcmil is not a standard NEC size. 500 kcmil = 500,000 CM (above — adequate). Minimum EGC = 500 kcmil.

72. C — Net Q = 35,070 − 28,447 = 6,623. P_total = 39,487. PF = 39,487/40,039 = 0.986 ≈ 0.99. Five correction sources reduce reactive demand by 81% while adding 12,000 HP of mechanical output.

73. B — I_pu = 20.0+3.891+4.167+2.0+0.35+0.208+0.133 = 30.75. I = 12,866A. Inverter contribution = 2.25%. Three inverter sources (80 MVA, 28% of capacity) contribute only 2.25% of fault current — the highest inverter penetration scenario in the exam series, demonstrating the profound protection challenge.

74. A — P_supply = 7.6/(0.65×0.92) = 12.7 kW. Losses = 5.1 kW = 67% of pump power. At 28% speed, motor efficiency collapses to 65%. Below approximately 30% speed, fixed losses dominate and the efficiency floor is reached — the economic crossover where a smaller, properly loaded motor may be more efficient.

75. D — The 90-second start with 4× FLA for 50 seconds far exceeds any standard overload class. A microprocessor relay with programmable thermal model and motor-starting mode is essential. The relay temporarily raises its trip threshold during the known starting profile, then resumes normal protection. This is the most demanding motor protection scenario in the exam series.

76. C — Total = 193,015 + 20,000 = 213,015A. Peak = 2.37 × 213,015 = 504,846A. Over half a million amperes peak — the highest in the exam series. The 5,000+4,000 kVA combination with 25 motors exceeds any standard 480V bus capability. Custom segregated-phase bus with structural analysis is the ONLY approach.

77. B — H = 1.4 (lowest), 52% voltage (deepest sag), 3.5 seconds (longest duration), $t^2 = 12.25$. The motor loses synchronism within 0.2-0.3 seconds — the fastest pull-out in the series. UV relay must trip within 0.2 seconds. Steady-state margin is completely irrelevant at these extreme parameters.

78. A — Adding a fourth parallel: Z changes from Z/3 to Z/4. I_new/I_old = $(3/4)^{-1}/(3/3)^{-1}$ = 4/3 = 33.3% increase. I_new = 209,183A. The 33% increase (not 25%) is a common misconception. All downstream equipment must be reverified.

79. D — Peak = 2.07 × 38,500 = 79,695A ≈ 80 kA peak on 208V. Virtually ALL standard 208V equipment is inadequately rated. The large 3,000 kVA transformer with low 4.50% impedance requires current-limiting fuses or high-SCCR equipment throughout the 208V distribution.

80. C — I = 1,202.8A. OCPD = 1,600A. E = 8,760,000 kWh. Cost = $420,480/year — the highest in the exam series. At this level, a 5% efficiency improvement saves $21,000/year. Waste heat recovery and alternative heating technologies are primary engineering priorities.