

PRACTICE EXAM 23: PE POWER SIMULATION (80 QUESTIONS)

1. A 13.8 kV industrial facility has a short-circuit level of 480 MVA with a 7,200 kvar capacitor bank producing $h_r = \sqrt{(480,000/7,200)} = 8.16$. The bus currently serves only eighteen-pulse and AFE VFDs with negligible 5th and 7th harmonic injection. A planned expansion will add a large six-pulse rectifier furnace (2,500 kW) that injects 5th harmonic at 25% and 7th at 14% of fundamental. The engineer must determine if the existing capacitor bank creates a resonance hazard after the furnace is added. Does $h_r = 8.16$ pose a risk with the new harmonic source?

A. Yes — although $h_r = 8.16$ is above $h = 7$, the proximity (only 1.16 harmonic orders away) means the 7th harmonic from the furnace rectifier will experience significant amplification; the amplification factor at $h = 7$ is approximately $h_r^2/(h_r^2 - h^2) = 66.6/(66.6 - 49) = 3.78\times$; this nearly $4\times$ voltage amplification of the furnace's 14% seventh-harmonic current injection could produce V_7 exceeding the 3% IEEE 519 limit even though h_r is not exactly at $h = 7$

B. No — $h_r = 8.16$ is sufficiently above $h = 7$ to prevent any amplification

C. No — six-pulse rectifier furnaces do not produce harmonics because they operate at DC

D. Yes — but only if the furnace operates above 80% capacity

2. A three-phase, 480V system has a 3,000 kVA transformer ($Z = 5.75\%$, $X/R = 9$) feeding a switchboard. A 450-foot cable of 350 kcmil copper in EMT ($R = 0.0367$, $X = 0.0407 \Omega/1000$ ft) feeds a remote MCC. At the MCC, ten 75 HP motors (FLA = 96A each, total = 960A) contribute $4 \times 960 = 3,840$ A first-cycle. The arc flash study at the switchboard shows 14 cal/cm² at 0.10-second clearing. The engineer must calculate the total first-cycle MCC fault current and determine if a separate arc flash study is warranted. What is the approximate total?

A. 42,000A (switchboard value unchanged plus motors)

B. 3,840A (motor contribution only — cable blocks all transformer current)

C. 30,000A (cable reduces to approximately 26,500A; motors add 3,840A; total $\approx 30,340$ A)

D. Cable Z reduces transformer contribution to approximately 26,500A; adding 3,840A motor = approximately 30,340A total; the 16% reduction from the switchboard value, combined with the IEEE

1584 current-dependent formula, changes the calculated incident energy — a separate arc flash study at the MCC is warranted and will likely produce a lower PPE category label

3. Per NEC 430.52(C)(1), a 500 HP, 460V motor (FLA = 590A) uses a dual-element time-delay fuse. Maximum per Table 430.52 = $175\% \times 590 = 1,032.5A$ → next standard 1,100A. The motor starts but the fuse blows during the third consecutive cold start within 10 minutes. Per NEC 430.52(C)(1) Exception 2, the fuse may be increased to $225\% = 1,327.5A$ → next standard 1,400A. Under what condition does Exception 2 apply?

A. Exception 2 is not applicable — it only applies to motors that won't start, not fuses that blow during repetitive starts

B. Exception 2 applies when the motor cannot start with the maximum standard-size OCPD from the table; the repeated cold starts cause cumulative I^2t heating in the fuse element that exceeds its damage curve — increasing to 225% (1,400A) provides the thermal margin for repetitive starting while maintaining branch-circuit protection

C. Exception 2 applies only to motors above 1,000 HP

D. Exception 2 permits any fuse size as long as the motor starts successfully

4. A CT with a ratio of 3000:5 and accuracy class C400 is used for a feeder overcurrent relay on a 13.8 kV circuit. The relay has a burden of 0.5Ω and the lead wire burden is 2.5Ω , totaling 3.0Ω . During a 48,000A fault ($16\times$ rated), the CT secondary = 80A. Burden voltage = 240V. The C400 guarantees accuracy at $20\times$ up to 400V. At $16\times$ with 240V, is the margin adequate, and what is the significance of the lead wire burden being 83% of the total?

A. The CT is within its rating at $16\times$ with 160V of margin ($400V - 240V = 40\%$ headroom)

B. The lead wire burden is irrelevant to CT performance

C. The CT operates within its C400 capability with 40% voltage margin; however, the lead wire burden (2.5Ω out of 3.0Ω total = 83%) is the dominant burden component — this indicates the CT leads are excessively long or undersized; reducing lead wire resistance by increasing wire size or shortening the run would provide additional margin and improve CT performance during high-fault conditions with DC offset

D. The 240V burden exceeds the C400 rating because the rating only applies at exactly $20\times$ rated

5. A 345 kV, 350-mile transmission line has SIL = 320 MW and must transmit 500 MW. A 40% series capacitor is installed at two locations. The effective reactance $X_{\text{eff}} = 0.60 \times X_{\text{line}}$. Additionally, a STATCOM rated ± 300 Mvar is installed at the midpoint of the line. Compared to an SVC of the same rating at the same location, what advantage does the STATCOM provide during a severe voltage sag (V drops to 60% at the midpoint)?

A. The STATCOM maintains full reactive current output capability at reduced voltage because it is a voltage-source converter; at 60% voltage, the STATCOM can still inject its rated current (300 Mvar/V), actually providing MORE reactive power per ampere at reduced voltage; an SVC's reactive output drops with V^2 (thyristor-controlled reactor/capacitor output is proportional to V^2), providing only 36% of its rated capability at 60% voltage — the STATCOM provides approximately 2.8× more effective voltage support during the critical period

B. The STATCOM and SVC provide identical performance at all voltage levels

C. The SVC provides better performance than the STATCOM during voltage sags

D. The STATCOM can only operate at rated voltage and shuts down during sags

6. Per NEC 250.122(B), a 800A circuit has phase conductors of two parallel 500 kcmil (1,000,000 CM total, providing 760A at 75°C — meeting the 800A ampacity after 125% continuous adjustment from 640A load). The conductors are increased to two parallel 750 kcmil (1,500,000 CM total) for voltage drop. Table 250.122 requires 1/0 AWG (105,600 CM) for 800A. What is the proportionally increased EGC?

A. 1/0 AWG (no increase needed)

B. 2/0 AWG (133,100 CM)

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

D. Ratio = $1,500,000/1,000,000 = 1.50$; EGC = $105,600 \times 1.50 = 158,400$ CM → 3/0 AWG (167,800 CM) is the minimum standard size above 158,400 CM

7. A three-phase, 4,160V system has a 15,000 kW load at 0.64 lagging PF. $Q = 15,000 \times 1.201 = 18,015$ kvar. The engineer installs a 13,000 kvar capacitor bank AND a 5,000 HP synchronous motor at 0.80 leading PF ($\eta = 94\%$) AND a 2,000 HP synchronous motor at 0.85 leading PF ($\eta = 95\%$). What is the new bus PF?

A. PF = 0.90

B. SM1: $P_{in} = 3,968$ kW, $Q_1 = 2,976$ kvar; SM2: $P_{in} = 1,571$ kW, $Q_2 = 975$ kvar; total correction = $13,000 + 2,976 + 975 = 16,951$ kvar; net $Q = 18,015 - 16,951 = 1,064$ kvar; $P_{total} = 20,539$ kW; $PF = 20,539/20,567 = 0.999 \approx \text{unity}$ — the three correction sources virtually eliminate the reactive demand; the engineer should slightly reduce the capacitor bank to maintain 0.98 lagging PF

C. PF = 0.95

D. PF = 0.85

8. A three-phase, 480Y/277V panelboard serves a data center with a mix: 75% nonlinear server loads (producing 3rd harmonic at 42% of server fundamental, 5th at 18%) and 25% linear UPS bypass loads. Each phase: 500A total fundamental. Third harmonic = $0.42 \times 0.75 \times 500 = 157.5$ A per phase. Fifth = $0.18 \times 0.75 \times 500 = 67.5$ A. Neutral = $3 \times 157.5 = 472.5$ A. Phase RMS = $\sqrt{(500^2 + 157.5^2 + 67.5^2)} = \sqrt{(250,000 + 24,806 + 4,556)} = \sqrt{279,362} = 528.7$ A. With 4 conductors (0.80 factor): phase base = 660.9A; neutral base = 590.6A. Which governs?

A. Neutral governs at 590.6A — the triplen current drives the neutral sizing

B. Both require identical sizing at 625A

C. Phase governs at 660.9A — the phase RMS of 528.7A, divided by the 0.80 factor, produces 660.9A base ampacity; this exceeds the neutral requirement of 590.6A; despite the very high neutral current (472.5A), the phase requirement still governs because the phase carries significant harmonic current in addition to the fundamental

D. The OCPD alone determines sizing

9. A 220 MVA synchronous generator has $X''_d = 0.19$ pu, $X_2 = 0.21$ pu, $X_0 = 0.07$ pu. The generator currently uses solidly grounding ($I_{SLG} = 6.12$ pu, exceeding $I_{3\Phi} = 5.26$ pu by 16.3%). The engineer evaluates three alternative grounding options: (A) reactor grounding with $3X_n = 0.50$ pu, (B) low-resistance grounding with $3R_n = 5.0$ pu, (C) high-resistance grounding with $3R_n = 50$ pu. For each option, what is the approximate I_{SLG} ?

A. (A) Reactor: $I_{SLG} = 3/j(0.40+0.50+0.07) = 3/j0.97 = 3.09$ pu (reactive, still above $I_{3\Phi}$ but closer); (B) LRG: $I_{SLG} \approx 3/5.0 = 0.60$ pu (resistive); (C) HRG: $I_{SLG} \approx 3/50 = 0.06$ pu (resistive) — each

step from solidly grounded through reactor to LRG to HRG progressively reduces SLG current and transitions from reactive to resistive character

B. All three options produce the same I_{SLG} as solidly grounded

C. Only HRG reduces I_{SLG} ; reactor and LRG have no effect

D. Reactor grounding increases I_{SLG} above the solidly grounded value

10. A three-phase, 4,160V system has an NGR rated 400A, 10 seconds. A bolted ground fault ($R_f = 0 \Omega$) occurs and the relay (pickup 30A, time delay 0.5s) clears in 0.5 seconds. Thirty seconds later, a second bolted fault occurs at the same location (the repair crew inadvertently re-energized the circuit) and is cleared in 0.5 seconds. What is the cumulative I^2t consumption?

A. First: $(400/400)^2 \times (0.5/10) = 5.0\%$. Second at 30 seconds later: same = 5.0%. Cumulative = 10.0% — the two bolted faults consumed 10% of capacity

B. 100% — two bolted faults always exhaust the NGR

C. 50% consumed

D. Each bolted fault at rated current for 0.5 seconds consumes 5% of the NGR's thermal capacity; cumulative = 10%; the 30-second interval provides minimal cooling (NGR thermal time constant typically 5-15 minutes); the NGR retains approximately 90% capacity — but the inadvertent re-energization indicates a serious lockout/tagout (LOTO) violation that must be addressed immediately before any further work

11. Per NEC 110.26(A)(2), the width of the working space in front of electrical equipment must be at least what dimension?

A. The width of the equipment or 30 inches, whichever is greater; this ensures adequate space for the worker to safely operate, maintain, and escape from the equipment regardless of the equipment's physical width

B. 30 inches regardless of equipment width

C. 36 inches for equipment rated above 600V

D. The width of the equipment plus 6 inches on each side

12. A 5,000 kVA, 13.8 kV/480V transformer has core losses = 13,000 W, full-load copper losses = 42,000 W. Operating profile: 8 hours at 100% (PF = 0.93), 8 hours at 50% (PF = 0.85), 8 hours at no-load (0% output). $k_{max} = \sqrt{(13,000/42,000)} = 55.6\%$. During the no-load period, the transformer consumes only core losses ($13,000W \times 8h = 104 \text{ kWh}$) with zero useful output. How does the no-load period affect all-day efficiency?

A. The no-load period improves efficiency because the transformer cools down

B. The no-load period has no effect — zero output means zero losses

C. The no-load period degrades the all-day efficiency because the transformer still consumes 104 kWh of core losses while producing zero output — these losses are 100% waste; the all-day efficiency = total output/(total output + total losses); adding 104 kWh to the denominator without adding anything to the numerator reduces the ratio; this is why unloaded transformers should be de-energized if possible to save core loss energy

D. The no-load period produces negative efficiency

13. A protection coordination study on a 4,160V system requires coordinating two 51 relays: downstream R1 (IEEE extremely inverse, TD = 1.5, pickup = 5A on 300:5 CT) and upstream R2 (IEEE very inverse, TD = 3.0, pickup = 8A on 800:5 CT). At the maximum downstream fault of 15,000A: R1 secondary = 250A; $M_1 = 50$. $t_1 = 1.5 \times (28.2/(2,500-1) + 0.1217) = 1.5 \times (0.01128 + 0.1217) = 1.5 \times 0.133 = 0.200s$. R2 secondary = 93.75A; $M_2 = 93.75/8 = 11.72$. $t_2 = 3.0 \times (19.61/(137.4-1) + 0.491) = 3.0 \times (0.1438 + 0.491) = 3.0 \times 0.635 = 1.905s$. CTI = 1.705s. Is this optimal?

A. CTI = 1.705s is adequate but the upstream relay R2 is unnecessarily slow at this high fault current; reducing R2's TD to 1.5 yields approximately 0.95s, producing CTI $\approx 0.75s$ — still well above the 0.20s minimum while halving R2's clearing time for backup protection

B. CTI = 1.705s is ideal and should not be adjusted

C. CTI = 1.705s is inadequate — more separation needed

D. The relays are mis-coordinated because R1 is too fast

14. A distance relay on a 230 kV line ($Z_{\text{line}} = 8 + j90 \Omega$) has Zone 1 at 85%. A three-phase bolted fault occurs at 84% of the line. $Z_{\text{meas}} = 0.84 \times (8 + j90) = 6.72 + j75.6 \Omega$. $|Z_{\text{meas}}| = 75.9 \Omega$. Zone 1 reach = $0.85 \times 90.35 = 76.8 \Omega$. The impedance is 0.9Ω (1.2%) below Zone 1 reach. CT accuracy is $\pm 2\%$, PT accuracy is $\pm 1.5\%$. The combined worst-case error is $\pm 3.5\%$. At 3.5% error, the measured impedance could appear as $75.9 \times 1.035 = 78.6 \Omega$. Is Zone 1 reliable for this fault?

- A. Yes — 1.2% margin is adequate for all measurement conditions
- B. Yes — digital relays automatically compensate for CT/PT errors
- C. No — CT/PT errors only affect the current magnitude, not impedance measurement
- D. No — the 1.2% margin is consumed by the 3.5% worst-case measurement error; at 78.6Ω apparent, the fault appears outside Zone 1 (76.8Ω); the relay may fail to trip on Zone 1 and revert to Zone 2 (0.35s delay); this validates the Zone 1 setting at 85% — it creates margin for measurement uncertainty, but faults near the reach boundary are inherently unreliable and depend on pilot schemes for high-speed clearing

15. A three-phase, 460V, 4-pole, 350 HP induction motor drives a centrifugal chilled-water pump via VFD. Design: 261 kW at 1,770 RPM. The facility has five seasonal operating modes: 100% (1,200 hr/yr), 90% (1,800 hr/yr), 75% (2,400 hr/yr), 60% (1,800 hr/yr), 40% (1,560 hr/yr). The VFD efficiency is 97% across all speeds. Motor efficiency varies: 96% at full, 95% at 90%, 93% at 75%, 88% at 60%, 80% at 40%. What is the total annual SUPPLY energy (including VFD and motor losses)?

- A. Full: $261 / (0.96 \times 0.97) \times 1,200 = 336,289$; 90%: $261 \times 0.729 / (0.95 \times 0.97) \times 1,800 = 371,883$; other modes calculated similarly; total $\approx 1,650,000$ kWh
- B. Full: $261 / 0.931 \times 1,200 = 336,306$; 90%: $190.3 / 0.922 \times 1,800 = 371,383$; 75%: $110.0 / 0.902 \times 2,400 = 292,683$; 60%: $56.4 / 0.854 \times 1,800 = 118,829$; 40%: $16.7 / 0.776 \times 1,560 = 33,519$; total = 1,152,720 kWh — including motor and VFD losses at each operating point gives a more accurate picture than the simple $P \propto n^3$ calculation alone; the light-load efficiency penalty adds approximately 8% to the total compared to the ideal affinity-law-only calculation
- C. 2,000,000 kWh (full-speed equivalent)
- D. 900,000 kWh (ideal affinity law only)

16. Per NEC 480.9(A), ventilation must limit H₂ below 1%. A remote oil pumping station has a 120V DC battery system: 80 vented lead-acid cells in a small enclosure of 800 ft³, charging at 0.012 ft³ H₂/cell/hour. The station is unmanned and located in an area classified as a hazardous location (Class I, Division 2 per NEC 500). What ventilation and safety requirements apply?

A. Standard ventilation only — no special requirements for unmanned locations

B. ACH = 0.12; explosion-proof ventilation fans only

C. $H_2 = 80 \times 0.012 = 0.96 \text{ ft}^3/\text{hr}$; max $H_2 = 8.0 \text{ ft}^3$; ACH = 0.12; for a Class I, Division 2 hazardous location: all ventilation equipment (fans, dampers, controls) must be rated for the hazardous classification; electrical components in the battery room must meet Class I, Div 2 requirements; H₂ detection with remote alarming to the SCADA system is mandatory because no personnel are present; backup ventilation (N+1) is recommended because ventilation failure in this small space reaches 1% H₂ in approximately 8.3 hours

D. No ventilation needed — 80 cells produce insufficient hydrogen for concern

17. A 230 kV, 400-mile transmission line with SIL = 140 MW must transmit 320 MW during peak. A 40% series compensation is installed at three distributed locations. During an N-2 contingency (loss of two parallel circuits), the remaining line must carry the entire 320 MW load. The voltage at the midpoint drops to 0.88 pu due to the sudden load transfer. The SVC ($\pm 200 \text{ Mvar}$) and STATCOM ($\pm 150 \text{ Mvar}$) at the receiving end both respond. The STATCOM at the midpoint provides better voltage support than the receiving-end SVC for this midpoint voltage depression. Why?

A. The STATCOM and SVC provide identical performance regardless of location

B. The SVC provides better voltage support because it has higher Mvar rating

C. Neither device can respond to N-2 contingencies

D. The midpoint STATCOM provides superior support because: (1) it is electrically closer to the voltage depression (midpoint), providing direct local voltage injection rather than trying to pull up midpoint voltage from the receiving end; (2) the STATCOM maintains full current capability at the depressed 0.88 pu voltage, while the SVC's output drops proportionally to V²; (3) voltage support at the midpoint directly maximizes $P_{\text{max}} = V_1 V_2 / X$ for both halves of the line, whereas receiving-end compensation only supports one half

18. A separately excited DC motor ($V_t = 480\text{V}$, $I_a = 250\text{A}$, $R_a = 0.08\ \Omega$, rated speed 1,500 RPM) drives a winder. $E_a = 480 - 20 = 460\text{V}$. The winder requires constant tension, which means constant torque regardless of speed. For speed control from 750 RPM to 1,500 RPM at constant torque, the armature voltage is varied (V_a control region). At 750 RPM (50% speed), $E_a = 230\text{V}$. I_a remains 250A (constant torque). $V_t = E_a + I_a R_a = 230 + 20 = 250\text{V}$. What is the motor output power at 750 RPM compared to rated?

A. $P_{750} = E_a \times I_a = 230 \times 250 = 57,500\text{W} = 57.5\ \text{kW}$; this is exactly 50% of rated (115 kW) because at constant torque, power is directly proportional to speed; the motor current remains at rated 250A throughout the speed range — this means the motor operates at rated thermal loading at all speeds in the constant-torque region

B. $P_{750} = 115\ \text{kW}$ (same as rated — constant torque means constant power)

C. $P_{750} = 28.75\ \text{kW}$ (25% of rated — power proportional to speed²)

D. $P_{750} = 86.25\ \text{kW}$ (75% of rated)

19. Per NEC 250.30(A)(1), a petrochemical facility has: $6 \times 5,000\ \text{kVA}$ service transformers, $6 \times 3,000\ \text{kW}$ emergency generators, $4 \times 2,000\ \text{kW}$ fire pump generators, $16 \times 1,000\ \text{kVA}$ PDU transformers, $8 \times 500\ \text{kVA}$ isolation transformers, and $4 \times 250\ \text{kVA}$ UPS isolation transformers. How many total bonding jumpers?

A. Twelve (service transformers and emergency generators only)

B. Twenty-eight ($6+6+16$ — excluding fire pump generators and isolation transformers)

C. Forty-four — every transformer and generator: 6 service + 6 emergency generators + 4 fire pump generators + 16 PDU + 8 isolation + 4 UPS = 44 bonding jumpers; fire pump generators are separately derived systems just like emergency generators; each bonding jumper must be sized per NEC 250.30(A)(2) and installed at the source

D. Thirty-eight (excluding fire pump generators)

20. A three-phase, 480V, 2,000A main-tie-main switchgear has bus-A and bus-B each with 75,000A available fault current. With the tie breaker closed and both mains on, the total available at the tie point is 150,000A. The arc flash study shows $72\ \text{cal/cm}^2$ at 24 inches with 0.30-second STD. Each bus has: optical relay, ZSI, arc-resistant enclosure, and a bus-mounted AQD. During a tie-bus fault, the AQD

activates in 4 ms, quenching the arc. Both main breakers receive trip signals from the optical relays. What is the unique challenge of a tie-bus fault compared to a single-bus fault?

A. A tie-bus fault is fed from BOTH transformers simultaneously — the fault current is the sum of both sources (150,000A), producing approximately 4× the electromagnetic force of a single-bus fault (force $\propto I^2$); both main breakers must trip to clear the fault; if one breaker fails to trip, the fault continues to be fed by that source; the AQD is critical because it quenches the arc in 4 ms before the extreme 150 kA fault current can cause catastrophic mechanical damage to the bus structure

B. Tie-bus faults produce lower fault current than single-bus faults

C. No unique challenge — all bus faults are identical

D. The tie breaker automatically clears all tie-bus faults without involving the mains

21. A synchronous generator rated 400 MVA, 24 kV has $X''_d = 0.22$ pu, $X_2 = 0.24$ pu, $X_0 = 0.10$ pu. Solidly grounded: $I_{SLG} = 5.36$ pu, $I_{3\Phi} = 4.55$ pu. The SLG exceeds 3 Φ by 17.8%. The generator is then switched to a hybrid grounding scheme: reactor grounding ($3X_n = 0.20$ pu) for normal operation, automatically switching to high-resistance grounding ($3R_n = 40$ pu) within 100 ms upon detection of a ground fault. What does this provide?

A. No benefit — any grounding switching introduces transients that are worse than the fault

B. The reactor provides moderate fault current while the relay detects the fault location

C. Both reactor and HRG produce the same fault current

D. During the first 100 ms (reactor grounding): $I_{SLG} = 3/(j0.22+j0.24+j0.10+j0.20) = 3/j0.76 = 3.95$ pu — sufficient for the relay to detect, identify, and locate the fault with directional overcurrent; after 100 ms, the system switches to HRG ($I_{SLG} \approx 0.075$ pu), dramatically reducing arc flash energy and equipment damage for the duration of the fault until the affected feeder is isolated — this provides the best of both worlds: reliable fault detection AND minimal fault damage

22. A 480V, three-phase panelboard has: Motor 1 = 683A (600 HP, largest), Motor 2 = 515A (450 HP), Motor 3 = 414A (350 HP). Continuous lighting = 300A. Noncontinuous receptacles = 100A. Per NEC 430.24 and 215.2(A)(1), what is the minimum feeder conductor ampacity?

A. 2,200A

B. $125\% \times 683 + 515 + 414 + 125\% \times 300 + 100 = 853.75 + 929 + 375 + 100 = 2,257.75A$

C. 2,500A

D. 1,800A

23. A three-phase, 4,160V bus has ten sources. On a 50 MVA base: five transformers ($Z = 0.03, 0.04, 0.05, 0.06, 0.08$), three generators ($Z = 0.25, 0.40, 0.60$), one synchronous condenser ($Z = 0.75$), one 20 MVA battery inverter ($Z = 5.0$). $I_{base} = 6,940A$. What is the total fault current?

A. $I = (33.33+25.0+20.0+16.67+12.50+4.0+2.50+1.67+1.33+0.20) \times 6,940 = 117.20 \times 6,940 = 813,368A$ — ten parallel sources on a single bus produce over 800 kA symmetrical; the five utility transformers contribute 92.1% of the total; this extreme fault level is physically unrealistic for a single 4,160V bus and indicates the need for bus-section splitting with current-limiting reactors or separate bus configurations to reduce the combined fault level

B. 500,000A

C. 600,000A

D. 400,000A

24. A 480V, three-phase, 225A panelboard (SCCR = 14,000A) is fed from a switchboard with 55,000A. The cable is 500 feet of 2 AWG copper in EMT ($R = 0.194 \Omega/1000 \text{ ft}$, $X = 0.0573 \Omega/1000 \text{ ft}$). The engineer needs to know if the very high cable impedance of this small conductor at long distance naturally protects the panelboard without current-limiting fuses.

A. Cable Z is negligible for 2 AWG at 500 feet

B. The cable cannot reduce fault current below 14,000A at any practical distance

C. $Z_{cable} = \sqrt{((0.194 \times 0.5)^2 + (0.0573 \times 0.5)^2)} = \sqrt{(0.097^2 + 0.02865^2)} = 0.1011 \Omega$; $Z_{base} = 0.0922$; $Z_{cable_pu} = 1.097$; total $Z = 0.0575 + 1.097 = 1.154$; $I = 3,007/1.154 = 2,605A$ — the small conductor dramatically reduces the fault to only 2,605A; this might seem to solve the SCCR problem, but the engineer must also verify the 225A breaker trips fast enough at 2,605A (only 11.6× rating), and check that voltage drop at 500 feet with 2 AWG is acceptable

D. Z_{cable} : too complex to estimate without a computer simulation

25. Per NEC 690.12, a 1 MW commercial PV system uses central inverters. Each string has 28 modules ($V_{\text{oc}} = 42\text{V}$ per module = 1,176V). Module-level rapid shutdown devices (RSD) are installed. The RSD reduces each module output to near zero upon activation. At -30°C , V_{oc} per module increases to 49.1V (temperature coefficient $-0.32\%/^{\circ}\text{C}$). The maximum system voltage at $-30^{\circ}\text{C} = 28 \times 49.1 = 1,374.8\text{V}$. This exceeds the NEC 690.7(A) maximum of 1,000V (or 1,500V if the system is rated for it). Assuming the system is rated for 1,000V DC, what code violation exists?

A. NEC 690.7 is violated ($1,374.8\text{V} > 1,000\text{V}$ maximum) — this is a DESIGN ERROR separate from rapid shutdown compliance

B. No violation — the RSDs reduce voltage below 1,000V during operation

C. The string length of 28 modules with temperature-corrected V_{oc} of 1,374.8V exceeds the 1,000V system maximum per NEC 690.7(A); this violation exists during ALL cold-weather open-circuit conditions, not just during rapid shutdown; the strings must be shortened to a maximum of 20 modules ($20 \times 49.1 = 982\text{V} < 1,000\text{V}$) or the entire system must be re-rated for 1,500V DC with all equipment, conductors, and disconnects rated accordingly

D. The violation only exists during rapid shutdown conditions

26. A three-phase, 480V system has three transformers and motors in parallel. T1 = 3,000 kVA ($Z = 5.50\%$), T2 = 2,500 kVA ($Z = 5.75\%$), T3 = 2,000 kVA ($Z = 6.00\%$). $I_{\text{T1}} = 65,600\text{A}$, $I_{\text{T2}} = 52,296\text{A}$, $I_{\text{T3}} = 38,849\text{A}$. Motor contribution (FLA = 4,000A) = 16,000A. Grand total = 172,745A. Weighted $X/R \approx 8.3$. Multiplier = 2.32. What is the peak asymmetrical?

A. 244,200A ($\sqrt{2} \times \text{total}$)

B. Peak = $2.32 \times 172,745 = 400,768\text{A}$ — this 400 kA peak current from three parallel transformers plus motors creates extreme electromagnetic forces on the bus; at $F \propto I^2_{\text{peak}} = 1.61 \times 10^{11} \text{A}^2$, the bus bracing must withstand forces that exceed standard construction capabilities and may require specialized segregated-phase bus designs

C. 345,490A ($2 \times \text{total}$)

D. 172,745A (no asymmetry)

27. A distance relay on a 138 kV line ($Z_{\text{line}} = 3 + j36 \Omega$) has Zone 1 at 80%, Zone 2 at 120% (0.35s). A fault at 92% through 6Ω resistance. The POTT scheme is active with a healthy channel. Near-end: Zone 1 at 80% cannot reach 92%. Zone 2 at 120% covers it. Remote end: 92% from near = 8% from far end (within Zone 1). Both terminals see forward faults. What is the clearing sequence?

- A. Both terminals trip with high-speed clearing — the near end detects in Zone 2 and sends a permissive signal; the remote end detects in Zone 1, trips instantaneously, and sends a reciprocal signal; upon receiving the remote end's permissive, the near-end relay overrides its Zone 2 timer and trips instantaneously; both breakers open simultaneously within 0.05-0.08 seconds total
- B. Only the remote end trips; the near end waits 0.35 seconds
- C. Both trip on Zone 2 after 0.35 seconds
- D. The fault resistance prevents both relays from detecting the fault

28. A transformer differential relay (87T) for a 300 MVA, 345/138/13.8 kV three-winding transformer must handle CT connections from three voltage levels. The HV winding is wye-grounded, LV is wye-grounded, and tertiary is delta. During zero-sequence current flow (SLG fault on the HV side), the delta tertiary circulates zero-sequence current internally but does not present it to the tertiary CTs. How does this affect the differential relay?

- A. The relay sees zero-sequence current from HV CTs but not from tertiary CTs — this creates a false differential unless the relay is configured to filter zero-sequence from the HV CT inputs
- B. All CTs see identical zero-sequence current
- C. Zero-sequence current has no effect on differential relays
- D. The relay must compensate for zero-sequence current that appears in the HV (wye-grounded) CTs but NOT in the tertiary (delta) CTs; modern numerical relays accomplish this through internal zero-sequence filtering or by using delta-connected CT configurations on the wye-grounded sides; without proper compensation, every SLG fault on the HV system would cause a false differential trip — this is one of the most critical relay configuration details for three-winding transformer protection

29. Per NEC 450.3(B), a 750 kVA, 480V/208Y/120V transformer has a primary current of 903A. At 125% = 1,128.75A. Next standard = 1,200A. Secondary current = 2,082A. The transformer also has a secondary OCPD. Per NEC 450.3(B), if the primary OCPD is at the next standard above 125%, what is the maximum secondary OCPD?

A. $125\% \times 2,082 = 2,602.5A \rightarrow$ next standard size above 2,602.5A

B. Per NEC 450.3(B), when primary protection is provided at the next standard above 125% (1,200A), secondary protection at not more than 125% (or next standard above) is the corresponding table requirement; secondary max = $125\% \times 2,082 = 2,602.5A \rightarrow$ next standard = 2,500A (below 2,602.5A — acceptable) or 3,000A (next above — acceptable per NEC)

C. 100% of secondary rated current (2,082A)

D. No secondary OCPD is required because the primary provides adequate protection

30. A three-phase, 4,160V, 8-pole synchronous motor rated 6,000 HP drives a cement kiln at 900 RPM. Pull-out = 260% FLT. $H = 2.0$ MJ/MVA. $S = 5,228$ kVA. Voltage sags to 72% for 0.6 seconds. Pull-out = 187.2% FLT. Load = 100% FLT. Margin = 87.2% FLT. The engineer uses the swing equation: $P_{\text{accel}} \approx (1.0 - 0.72) \times P_{\text{rated}} = 0.28 \times 4.476 \text{ MW} = 1.253 \text{ MW}$. $\Delta\delta = (180 \times 60 \times 1.253 \times 0.36)/(2.0 \times 5.228)$. What is the approximate result?

A. $\Delta\delta = 5^\circ$ — easily stable

B. $\Delta\delta = 25^\circ$ — stable with margin

C. $\Delta\delta = (180 \times 60 \times 1.253 \times 0.36)/(10.456) = 4,883/10.456 = 467^\circ$ — this enormous angle advance indicates certain loss of synchronism; the formula yields hundreds of degrees because P_{accel} in MW divided by $(H \times S_{\text{MVA}})$ produces a very large ratio for this motor size; the motor cannot maintain synchronism during a 0.6-second sag at 72% with $H = 2.0$

D. $\Delta\delta = 90^\circ$ — at critical angle

31. A 480V, three-phase system has four parallel transformers totaling 10,000 kVA. Combined symmetrical fault = 190,000A. Weighted X/R = 8.4. IEEE multiplier = 2.33. Peak = 442,700A. The bus conductor spacing is 6 inches (0.15 m). The electromagnetic force per unit length between parallel conductors is $F = \mu_0 I_{\text{peak}}^2 / (2\pi d)$. With $\mu_0 = 4\pi \times 10^{-7}$, $I_{\text{peak}} = 442,700A$, $d = 0.15m$: $F = (4\pi \times 10^{-7} \times 442,700^2) / (2\pi \times 0.15)$. What is the approximate force?

A. $F = (2 \times 10^{-7} \times 1.96 \times 10^{11}) / 0.15 = 39,200 / 0.15 = 261,333 \text{ N/m} \approx 261 \text{ kN/m}$ — this is approximately 60,000 lbs/foot of bus length; such extreme forces require bus structures engineered with specialized high-strength insulators, bracing at close intervals, and potentially flexible connections to absorb mechanical shock; standard bus construction cannot withstand these forces

B. $F = 500 \text{ N/m}$ (approximately 100 lbs/foot) — manageable with standard bracing

C. $F = 5,000 \text{ N/m}$ (approximately 1,100 lbs/foot) — moderate bracing needed

D. $F = 50,000 \text{ N/m}$ (approximately 11,000 lbs/foot) — heavy-duty bracing required

32. A 13.8 kV system has measured harmonic spectrum: $V_5 = 12.5\%$, $V_7 = 8.3\%$, $V_{11} = 5.5\%$, $V_{13} = 3.8\%$, $V_{17} = 2.2\%$, $V_{19} = 1.6\%$, $V_{23} = 1.0\%$, $V_{25} = 0.7\%$. THD = 17.2%. IEEE 519: individual $\leq 3.0\%$, THD $\leq 5.0\%$. How many total violations exist, and what is the significance of this being the most severe harmonic scenario in the exam series?

A. Four violations (V_5 , V_7 , V_{11} , V_{13} , and THD = five total)

B. Three violations only

C. Six total violations including THD

D. Five total violations: V_5 (12.5%), V_7 (8.3%), V_{11} (5.5%), V_{13} (3.8%) each exceed the 3.0% individual limit, plus THD (17.2%) exceeds 5.0%; this represents a catastrophic harmonic environment that will cause: premature transformer failure from eddy current heating, capacitor bank resonance failures, sensitive equipment malfunctions, and excessive neutral currents; remediation requires a comprehensive, multi-phase capital project costing potentially hundreds of thousands of dollars

33. A ground resistance test on an oil refinery measures 1.2Ω during wet season. IEEE 80 target = 1.0Ω for the main substation. IEEE 81 correction = 1.5. Corrected = 1.80Ω (80% above target). The refinery is classified as a hazardous location (Class I, Division 2) per NEC 500. What additional consideration does the hazardous classification create for the grounding system?

A. No additional considerations — grounding is identical in hazardous and non-hazardous locations

B. The hazardous classification has no effect on the ground grid design itself

C. In a hazardous (classified) area, the grounding system must not only meet IEEE 80 step-and-touch potential requirements but also provide a low-impedance bonding path for all metallic structures to prevent static charge accumulation and spark generation; every metallic surface that could accumulate charge must be bonded to the ground grid; the 1.80Ω resistance may be acceptable for step-and-touch potentials but the bonding conductors must have sufficiently low impedance to prevent voltage differences between bonded objects that could create ignition-capable sparks in the hazardous atmosphere

D. Hazardous locations require ground resistance below 0.1Ω regardless of IEEE 80 analysis

34. A three-phase, 460V, 2-pole induction motor rated 900 HP has $\eta = 97.0\%$, PF = 0.91 lagging. No-load magnetizing = 115 kvar. A 100 kvar capacitor is proposed (87% of no-load mag — below the absolute self-excitation threshold but above the typical 67% manufacturer recommendation). The motor operates at rated speed on direct-line (no VFD). Is the 100 kvar installation safe?

A. At direct-line operation (no VFD), the motor always operates at rated speed with full magnetizing current; the 100 kvar at 87% of no-load magnetizing is below the self-excitation threshold — after disconnection, the capacitor cannot sustain the field at full voltage because $100 < 115$; however, the 87% level is close enough that voltage and frequency variations could push the effective ratio above 100%; the engineer should obtain explicit manufacturer approval and consider installing a capacitor-switching contactor that opens before or simultaneously with the motor contactor

B. Unsafe at any percentage above 67%

C. Safe without any special considerations

D. Unsafe because 900 HP motors have lower self-excitation thresholds

35. A three-phase, 460V, 8-pole VFD-driven motor operates a mine ventilation fan. Design: 350 kW at 877 RPM. Six operating modes: 100% (800 hr), 95% (1,200 hr), 85% (2,000 hr), 70% (2,400 hr), 55% (1,500 hr), 35% (860 hr). Using $P \propto n^3$, what is the VFD energy versus full-speed?

A. VFD total = 2,000,000 kWh; full = 3,066,000 kWh; savings = 1,066,000 kWh

B. VFD = 1,500,000 kWh; savings = 1,566,000 kWh

C. VFD = 2,500,000 kWh; savings = 566,000 kWh

D. 100%: 280,000; 95%: $350 \times 0.857 \times 1,200 = 359,940$; 85%: $350 \times 0.614 \times 2,000 = 429,800$; 70%: $350 \times 0.343 \times 2,400 = 288,120$; 55%: $350 \times 0.166 \times 1,500 = 87,150$; 35%: $350 \times 0.0429 \times 860 = 12,911$; VFD = 1,457,921; full = $350 \times 8,760 = 3,066,000$; savings = 1,608,079 kWh (52.4%) — the six operating modes with the cubic relationship produce over 52% energy reduction

36. A 480V, three-phase, 200A feeder uses 500 kcmil THHN copper in EMT ($R = 0.0276$, $X = 0.0391 \Omega/1000$ ft). The feeder is 800 feet long and serves a load at 0.86 lagging PF. What is the voltage drop?

A. 3.5%

B. $V_{\text{drop}} = \sqrt{3} \times 200 \times (0.0276 \times 0.8 \times 0.86 + 0.0391 \times 0.8 \times 0.510) = 346.4 \times (0.01899 + 0.01595) = 346.4 \times 0.03494 = 12.10\text{V}$; $12.10/480 = 2.52\%$ — within the NEC 3% recommendation despite the very long 800-foot run, because the 500 kcmil conductor provides low resistance per foot

C. 4.0%

D. 1.5%

37. A 100 MVA, 345/138 kV autotransformer has $Z = 10\%$ on its own base. Three units in parallel. A 70 MVA generator ($X''_d = 0.20$ pu), a 50 MVA synchronous condenser ($X''_d = 0.14$ pu), a 30 MVA synchronous motor ($X''_d = 0.22$ pu), and a 40 MVA combined solar+wind farm (effective $X''_d = 1.0$ pu) are on the 138 kV bus. On 100 MVA base, what is the total fault current, and what percentage do the inverter-based resources contribute?

A. 15,000A; inverters contribute 5%

B. 10,000A; inverters contribute 10%

C. $Z_{T_{\text{par}}} = 0.0333$; $Z_{\text{gen}} = 0.286$; $Z_{SC} = 0.28$; $Z_{SM} = 0.733$; $Z_{\text{inv}} = 2.50$; $I_{\text{pu}} = (30.0 + 3.497 + 3.571 + 1.364 + 0.40) \times 418.4 = 38.83 \times 418.4 = 16,247\text{A}$; inverter contribution = $0.40/38.83 = 1.0\%$ — the 40 MVA inverter farm contributes only 1% of total fault current despite representing 15% of the connected generation capacity; this has profound implications for protection design as the grid transitions to higher percentages of inverter-based resources

D. 20,000A; inverters contribute 15%

38. A three-phase, 480V system has a 4,000 kVA transformer ($Z = 5.50\%$, $X/R = 10$) and a 3,500 kVA transformer ($Z = 5.75\%$, $X/R = 9$) in parallel. $I_{T1} = 4,811/0.055 = 87,473\text{A}$. $I_{T2} = 4,209/0.0575 = 73,200\text{A}$. Total = 160,673A. Motors (FLA = 3,500A) add 14,000A. Grand total = 174,673A. $X/R \approx 9.5$. Multiplier = 2.37. Peak?

A. Peak = $2.37 \times 174,673 = 414,175\text{A}$ — over 400 kA peak from two very large parallel transformers plus motors; this exceeds the close-and-latch rating of virtually all standard 480V switchgear (typically rated 85-200 kA) and requires either bus splitting with current-limiting reactors or specialized high-fault-capacity equipment

B. 247,000A ($\sqrt{2} \times \text{total}$)

C. 349,346A ($2 \times \text{total}$)

D. 174,673A (no asymmetry)

39. Per NEC 250.53(A)(2), an engineer designs the grounding system for a new hospital. The IEEE 80 analysis requires $\leq 0.5 \Omega$. The site has variable soil: topsoil ($200 \Omega\text{-m}$, 3 feet deep), clay ($80 \Omega\text{-m}$, 10-30 feet), and bedrock ($5,000 \Omega\text{-m}$ below 30 feet). The engineer installs driven ground rods (10 feet each) into the clay layer, a concrete-encased Ufer electrode in the foundation, and a ground ring around the building. Using the Sverak formula with the clay layer as the effective soil for the rods and Ufer, and a building footprint of $80\text{m} \times 40\text{m}$: what is the most effective electrode combination?

A. Ground rods alone — they reach the low-resistivity clay layer

B. Ufer electrode alone — it provides the lowest single-electrode resistance

C. Ground ring alone — it has the largest soil contact area

D. The combination of all three provides the lowest resistance because: the ground ring (largest area, contacts topsoil and upper clay) provides the base resistance; the Ufer electrode (concrete retains moisture in contact with clay) provides a stable low-resistance supplement; driven rods reaching deep into the clay layer ($80 \Omega\text{-m}$ — the lowest-resistivity layer) add vertical contact; in parallel, the combined resistance is significantly lower than any single electrode; the bedrock at 30 feet limits the effectiveness of deeper electrodes, so the 10-foot rods optimally target the clay layer

40. A 480V, three-phase system has a 3,000 kVA transformer ($Z = 5.75\%$) feeding a switchboard. A 1,000-foot cable of 3/0 AWG copper ($R = 0.0766$, $X = 0.0532 \Omega/1000 \text{ft}$) feeds a remote panelboard.

The engineer discovers the available fault current at the panelboard and realizes it may be too low for the protective devices to operate correctly. What is the approximate fault current?

A. 36,130A (switchboard value)

B. Cable: $R = 0.0766$, $X = 0.0532 \Omega$; $Z_{\text{base}} = 0.0768$; $Z_{\text{cable_pu}} = \sqrt{(0.0766^2 + 0.0532^2)} / 0.0768 = 0.0933 / 0.0768 = 1.215$; total $Z = 0.0575 + 1.215 = 1.272$; $I = 3,608 / 1.272 = 2,836\text{A}$ — the extreme 1,000-foot run reduces fault current to only 7.9% of the switchboard value; at 2,836A, a 100A breaker has an I/I_{trip} ratio of 28.4 — adequate for instantaneous trip; however, a 225A breaker at $12.6\times$ may not reach its instantaneous region, potentially relying on the time-overcurrent curve for clearing

C. 15,000A

D. 25,000A

41. A 60 MVA, 138/13.8 kV, delta-wye grounded transformer has $Z_1 = j0.085 \text{ pu}$, $Z_0 = j0.045 \text{ pu}$ on its own base. The 138 kV source has $Z_{1_src} = j0.05 \text{ pu}$ on the transformer base. On a 100 MVA base: $Z_{1_total} = (0.085 + 0.05) \times 100 / 60 = 0.225 \text{ pu}$. $Z_{0_total} = 0.045 \times 100 / 60 = 0.075 \text{ pu}$ (delta blocks source Z_0). $I_{3\Phi} = 4.44 \text{ pu}$. $I_{\text{SLG}} = 3 / (0.225 + 0.225 + 0.075) = 5.71 \text{ pu}$. The SLG exceeds 3Φ by 28.6%. This is one of the highest $\text{SLG}/3\Phi$ ratios in the exam series. What design parameter drives this extreme ratio?

A. The very low Z_0 (0.045 pu on transformer base) combined with the delta blocking the relatively high source Z_0 creates the extreme ratio; Z_{0_total} (0.075 pu on 100 MVA base) is only 33% of Z_{1_total} (0.225 pu) — the larger the gap between Z_0 and Z_1 , the more the SLG exceeds three-phase; this transformer has an unusually low Z_0 relative to Z_1 , which is characteristic of some three-limb core-form designs

B. The source impedance drives the ratio — lower source impedance would eliminate the $\text{SLG} > 3\Phi$ problem

C. The 100 MVA base conversion creates the extreme ratio artificially

D. The delta winding has no effect on the $\text{SLG}/3\Phi$ ratio

42. A three-phase, 460V, 6-pole induction motor rated 600 HP has $\text{PF} = 0.88$, $\eta = 96.2\%$. No-load magnetizing = 82 kvar. A 60 kvar capacitor is installed (73.2% of no-load — safe at full load). The motor operates on a VFD at five speeds: 100%, 85%, 70%, 55%, 40%. At each speed, the motor's no-load magnetizing kvar changes approximately proportionally to V/f ratio (which the VFD holds constant in the constant-torque region). In the constant-torque region, magnetizing kvar remains approximately

constant. In the reduced-flux region (if V/f is reduced), magnetizing kvar drops. At what speed does the 60 kvar capacitor first exceed the motor's magnetizing kvar if the VFD maintains constant V/f?

- A. The capacitor remains safe at all speeds because V/f is constant and magnetizing kvar stays at approximately 82 kvar regardless of speed
- B. The capacitor exceeds magnetizing at 70% speed because V/f cannot be maintained below 75% of rated
- C. At constant V/f, the motor's magnetizing reactance remains approximately the same, and the magnetizing kvar remains near 82 kvar throughout the speed range; the 60 kvar capacitor at 73.2% stays below the limit at all speeds — HOWEVER, the critical risk occurs during VFD trip or loss of power when the motor coasts; at that moment, the VFD output collapses but the capacitor remains connected, and the decelerating motor with 60 kvar may self-excite depending on the coast-down speed
- D. The capacitor is never safe at any speed with a VFD

43. A CT with a ratio of 2000:5 and accuracy class C800 serves a bus differential relay. During a 60,000A external through-fault with $X/R = 35$ (extremely high), the DC time constant $\tau = X/(2\pi fR) = 35/(377) = 0.093$ seconds ≈ 5.6 cycles. The DC offset persists for approximately $3\tau = 16.8$ cycles before decaying to 5%. During these 17 cycles, the CT's total flux (AC + DC) exceeds the saturation level by approximately 3 \times . What is the expected CT behavior and the relay response?

- A. The CT handles the combined flux without saturation because C800 provides unlimited margin
- B. The CT provides accurate output throughout the DC offset period
- C. The relay trips correctly because the bus differential relay does not use the affected CT
- D. The CT saturates severely for approximately 17 cycles (0.28 seconds); during saturation, the CT output is a severely distorted, reduced-magnitude waveform; the bus differential relay sees false differential current from the saturated CT; a high-impedance bus differential relay provides security because the saturated CT presents low impedance that cannot drive current through the high-impedance element — this is why high-impedance differential is preferred for bus protection in high X/R systems

44. A balanced three-phase, 208Y/120V panelboard serves a research laboratory with: 50% variable-speed centrifuge drives (nonlinear, producing 3rd at 38%, 5th at 16%), 30% precision linear instruments, and 20% LED lighting (3rd at 32%). Phase current = 260A fundamental. Third harmonic:

$0.50 \times 260 \times 0.38 + 0.20 \times 260 \times 0.32 = 49.4 + 16.6 = 66.0\text{A}$. Fifth: $0.50 \times 260 \times 0.16 = 20.8\text{A}$. Phase RMS = $\sqrt{(260^2 + 66^2 + 20.8^2)} = \sqrt{(67,600 + 4,356 + 433)} = \sqrt{72,389} = 269.1\text{A}$. Neutral = $3 \times 66 = 198\text{A}$. Ratio = $198/269.1 = 0.736$. The neutral is 73.6% of phase. Does NEC 310.15(C)(1) require counting the neutral as current-carrying?

- A. No — the neutral only needs to be counted when it exceeds the phase current
- B. Yes — per NEC 310.15(C)(1), neutrals carrying predominantly harmonic currents must be counted as current-carrying conductors regardless of whether they exceed the phase current; the 198A neutral carries predominantly triplen harmonics (not fundamental unbalance) and must be counted, resulting in 4 current-carrying conductors with a 0.80 adjustment factor
- C. No — NEC 310.15(C)(1) only applies to circuits above 200A
- D. Yes — but only if the neutral carries more than 50% of the phase current

45. Per NEC 517.17(A), a hospital's LIM alarms at 5 mA. During a complex procedure, the LIM alarm activates at 5.1 mA. Per NEC 517.17(B), the alarm must alert personnel but does NOT automatically disconnect power. The surgical team must decide whether to continue or halt the procedure. What factors should influence this decision?

- A. The decision depends on: (1) the criticality of the ongoing procedure (life-threatening surgery cannot be interrupted), (2) whether the fault can be isolated by unplugging non-essential devices to reduce hazard current below 5 mA, (3) whether a second fault could create a shock hazard to the patient (the first fault on an isolated system does not create a shock path, but a second fault on the other conductor would), (4) the biomedical engineer's assessment of which device caused the alarm — a systematic approach of unplugging devices one at a time can identify and isolate the faulty equipment without interrupting the procedure
- B. The procedure must be immediately halted — 5.1 mA is dangerous to the patient
- C. The alarm should be ignored — it has no clinical significance
- D. Only the surgeon can make this decision — the biomedical engineer has no role

46. A 345 kV, three-phase line has $V_S = 370\text{ kV}$, $V_R = 342\text{ kV}$ at 1,100 MW, 0.88 lagging PF. Line $X = 48\ \Omega$ (with 40% series compensation already applied; $X_{\text{original}} = 80\ \Omega$). What is the power angle and stability fraction?

A. $\delta = 20^\circ$; stability = 34%

B. $\delta = 35^\circ$; stability = 57%

C. $\sin \delta = 1,100 \times 48 / (370 \times 342) = 52,800 / 126,540 = 0.4173$; $\delta = 24.7^\circ$; VR = 8.19%; stability fraction = 41.7%; WITHOUT compensation: $\sin \delta = 1,100 \times 80 / 126,540 = 0.695$; $\delta = 44.0^\circ$; stability = 69.5%; the series compensation reduced the stability fraction from 69.5% to 41.7%, INCREASING the available margin from 30.5% to 58.3% — a dramatic 91% improvement in stability margin that enables the line to transmit 1,100 MW with confidence

D. $\delta = 50^\circ$; stability = 77%

47. A recloser on a 12.47 kV feeder coordinates with a 250A lateral fuse. At 8,500A: fuse MM = 0.014s, fuse TC = 0.028s, recloser fast = 0.010s, recloser delayed = 0.065s. A permanent underground cable fault occurs. The recloser fast-trips ($0.010s < 0.014s \rightarrow$ fuse saved). After reclose, the fault persists. On delayed trip: recloser (0.065s) vs fuse TC (0.028s). The fuse blows at 0.028 seconds. However, the engineer notes that 0.065s is more than $2\times$ the fuse TC of 0.028s. What is the coordination margin during the delayed trip?

A. The fuse TC must be verified at the actual fault current because published fuse curves have manufacturing tolerances

B. The coordination is adequate — the fuse has ample time to clear before the recloser

C. The recloser and fuse will race — 0.065s and 0.028s are too close

D. The fuse clears at 0.028s with a 0.037s margin before the recloser would have tripped at 0.065s; this 132% margin ($0.037 / 0.028 = 1.32$) ensures the fuse blows cleanly before the recloser trips; the fuse-saving sequence works correctly: fast trip saves the fuse for temporary faults; during the delayed trip for permanent faults, the fuse isolates the lateral while the recloser holds and restores service to unfaulted sections

48. A 480V, three-phase, 600A switchboard with 600A bus. Load: 400A continuous motor + 80A continuous lighting + 50A noncontinuous = 530A. OCPD = $125\% \times 480 + 50 = 650A \rightarrow$ exceeds 600A bus. With 100%-rated 600A breaker: $530A \leq 600A$. Conductor at $75^\circ C$ must handle 530A. Two parallel 350 kcmil = 620A. Two parallel 500 kcmil = 760A. The 620A option provides 17% margin. Is 17% adequate?

A. Two parallel 500 kcmil is preferred for thermal headroom despite higher cost

B. Two parallel 350 kcmil at 620A provides 17% margin above 530A — this is code-compliant and provides adequate thermal performance for most installations; however, if the ambient temperature frequently exceeds 30°C or the conduit fill is high, the 500 kcmil option (43% margin) is the better engineering choice; the decision depends on installation conditions and anticipated load growth

C. 17% margin is insufficient — minimum 25% required

D. Neither option is adequate — three parallel sets are required

49. A three-phase, 480V system has a 4,000 kVA transformer ($Z = 5.75\%$, $X/R = 10$) and 18 motors (FLA = 3,600A). Transformer fault = 48,111A. Motor = 14,400A. Total = 62,511A. $X/R = 10$. Multiplier = 2.38. Peak?

A. 88,400A ($\sqrt{2} \times \text{total}$)

B. Peak = $2.38 \times 62,511 = 148,776\text{A}$ — the 14,400A motor contribution (23%) adds substantially to the peak; at 149 kA peak, the bus must be designed for electromagnetic forces proportional to $(148,776)^2 = 2.21 \times 10^{10} \text{A}^2$

C. 125,022A ($2 \times \text{total}$)

D. 62,511A (no asymmetry)

50. A 480V, three-phase, 200A feeder uses 4/0 AWG THHN copper in steel conduit ($R = 0.0608$, $X = 0.0478 \Omega/1000 \text{ft}$). The feeder is 700 feet long and serves a load at 0.82 lagging PF. What is the voltage drop?

A. 2.5%

B. 3.0%

C. $V_{\text{drop}} = \sqrt{3} \times 200 \times (0.0608 \times 0.7 \times 0.82 + 0.0478 \times 0.7 \times 0.572) = 346.4 \times (0.03490 + 0.01914) = 346.4 \times 0.05404 = 18.72\text{V}$; $18.72/480 = 3.90\%$ — significantly exceeds the NEC 3% recommendation; 4/0 AWG is inadequate for 700 feet at 200A; upsize to 250 kcmil or 350 kcmil

D. $V_{\text{drop}} = 346.4 \times 0.05404 = 18.72\text{V}$; $18.72/480 = 3.90\%$ — exceeds 3%; the high resistance of 4/0 AWG at this extreme distance produces unacceptable voltage drop; the engineer must upsize to at least 350 kcmil ($R = 0.0367$) which would produce approximately 2.7%

51. Per NEC 110.14(C)(1), a 2,000A switchboard has terminals marked "90°C." The continuous load = 1,600A. Required ampacity = 2,000A. At 75°C: four parallel 750 kcmil = $4 \times 475 = 1,900\text{A}$ (inadequate). At 90°C: four parallel 600 kcmil = $4 \times 490 = 1,960\text{A}$ (inadequate). Four parallel 750 kcmil at 90°C = $4 \times 535 = 2,140\text{A}$ (adequate). Five parallel 500 kcmil at 90°C = $5 \times 430 = 2,150\text{A}$ (adequate). Which is the better choice?

A. Five parallel 500 kcmil — too many parallel sets increases installation complexity

B. Both are technically adequate, but the determining factor is NEC 310.10(G) practicality

C. Four parallel 750 kcmil at 90°C = 2,140A with 7% margin is the better engineering choice — fewer parallel sets means: fewer terminations to maintain, lower probability of unequal current sharing, simpler installation, and reduced chance of parallel conductor violations; five parallel 500 kcmil provides nearly identical ampacity (2,150A) but with one additional parallel set per phase, adding complexity and potential failure points

D. Both options are inadequate — a higher switchboard rating is needed

52. A 300 MVA synchronous generator has $H = 4.5 \text{ MJ/MVA}$, delivers 240 MW when a three-phase fault occurs. Critical clearing angle = 120°. Relay = 0.008s (ultra-fast optical), breaker = 0.020s (ultra-fast vacuum), total = 0.028s. What is the angle advance?

A. $\Delta\delta = (180 \times 60 \times 240 \times 0.028^2) / (4.5 \times 300) = (180 \times 60 \times 240 \times 0.000784) / 1,350 = 2,032.1 / 1,350 = 1.505^\circ \approx 1.5^\circ$ — the state-of-the-art 0.028-second clearing produces negligible rotor advance; the 118.5° margin demonstrates that modern ultra-fast protection makes generator transient stability virtually guaranteed for any reasonable loading level

B. $\Delta\delta = 15^\circ$ — good margin

C. $\Delta\delta = 60^\circ$ — limited margin

D. $\Delta\delta = 120^\circ$ — at critical clearing

53. A three-phase, 13.8 kV capacitor bank rated 16,200 kvar has six series groups of nine parallel units per phase (54 per phase, 162 total). Five units in one series group fail and their fuses blow. The remaining four units each see $9/4 = 2.25\times$ normal voltage (125% overvoltage). At 225% voltage, the dielectric stress is $(2.25)^2 = 5.06\times$ rated. How fast does cascading failure occur?

A. The cascade takes minutes — adequate for manual intervention

B. The remaining units will survive at 225% voltage indefinitely

C. At 225% voltage, the insulation is stressed to $5.06\times$ its rated level — failure is virtually instantaneous (within 1-2 cycles); as the first surviving unit fails, the remaining three see $9/3 = 3.0\times$ voltage ($9\times$ stress), guaranteeing instantaneous failure; the entire cascade from 5-unit failure to complete series-group failure takes less than 0.1 seconds — far faster than any electromechanical relay

D. At $5.06\times$ rated dielectric stress, the remaining four units fail within cycles to fractions of a second; each subsequent failure accelerates the cascade exponentially ($4\rightarrow 3\rightarrow 2\rightarrow 1$ units, with voltage multipliers of $2.25\rightarrow 3.0\rightarrow 4.5\rightarrow 9.0\times$); the entire series group fails in less than 100 ms; only ultra-high-speed electronic unbalance detection with sub-cycle trip capability can prevent this cascade from propagating to other series groups and causing catastrophic bank failure

54. A three-phase, 460V, 8-pole wound-rotor motor rated 2,000 HP (FLS = 873 RPM) drives a SAG mill requiring 350% breakaway torque and periodic 280% overloads lasting 8 seconds during ore jamming. Wound-rotor: 360% starting torque at 380% FLA ($T/I = 0.947$). Design D: 280% at 650% FLA ($T/I = 0.431$). No squirrel-cage motor meets the 350% requirement. What additional wound-rotor advantage applies to the SAG mill application?

A. Design D is actually superior due to higher slip operation

B. Only the wound-rotor meets 350% breakaway; additionally, the wound-rotor provides: (1) adjustable starting torque curve for different ore hardness conditions by varying external resistance, (2) thermal management during the 8-second 280% overloads by shifting I^2t heating to the external resistors (which are designed for high-duty-cycle thermal absorption) rather than the rotor windings, (3) speed control through slip power recovery for energy-efficient reduced-speed operation

C. Both motor types are equally suitable for SAG mill service

D. The wound-rotor provides no advantages beyond higher starting torque

55. Per NEC 310.15(C)(1), a large industrial cable tray contains: twelve three-phase circuits (36 phase conductors), eight neutral conductors carrying triplen harmonics, four neutral conductors NOT carrying harmonics, and twelve EGCs. What is the count and adjustment factor?

A. 36 (phase only); factor = 0.30

B. 44 (36+8); factor 0.30

C. 44 (36 phase + 8 harmonic-carrying neutrals); non-harmonic neutrals and EGCs excluded; per NEC Table 310.15(C)(1) for 41+ conductors: factor = 0.25 — wait, 44 exceeds 40; checking the table: for 41 and above, the factor is determined by the authority having jurisdiction; however, NEC Table 310.15(C)(1) goes to "41 and above" with factor to be determined; practically, 44 conductors at 0.25 derating means conductors must be 4× their normal size — completely impractical; the installation MUST be split into at least nine parallel raceways

D. 60 (all conductors); factor = 0.20

56. A 480V, three-phase LVPCB main has 0.30s STD. ZSI, optical relay, AQD, and arc-resistant switchgear are installed. The system also has redundant trip coils (Trip Coil A powered by station battery, Trip Coil B powered by a permanent-magnet mechanism). During a bus fault, the AQD activates in 4 ms. Simultaneously, the optical relay sends a trip signal. If the station battery has failed (unknown to the operator), Trip Coil A receives no power. What happens?

A. The breaker cannot trip because Trip Coil A is the only trip mechanism; the AQD has quenched the arc, but the bolted fault continues indefinitely until the upstream utility protection clears — this is a catastrophic single-point-of-failure scenario

B. The optical signal arrives at both trip coils; Trip Coil A fails due to dead battery, but Trip Coil B (permanent magnet) operates using stored mechanical energy, opening the breaker; the AQD quenched the arc in 4 ms, and the breaker clears the resulting bolted fault in approximately 22 ms via Trip Coil B — the redundant trip mechanism prevented the single-point-of-failure scenario

C. The AQD clears the fault without needing the breaker to trip

D. Both trip coils require station battery power

57. A protection engineer coordinates three 51 relays on a 13.8 kV system. R1 (downstream feeder): EI, TD = 1.0, pickup = 4A. R2 (bus section): VI, TD = 2.5, pickup = 6A. R3 (main incoming): VI, TD =

5.0, pickup = 8A. At the maximum feeder fault of 10,000A (CT ratios: R1 = 200:5, R2 = 600:5, R3 = 1200:5): R1: $M = 250/4 = 62.5$; $t_1 = 1.0 \times (28.2/3,906 + 0.1217) = 0.129s$. R2: $M = 83.3/6 = 13.89$; $t_2 = 2.5 \times (19.61/192 - 1 + 0.491) = 2.5 \times (0.1027 + 0.491) = 1.485s$. R3: $M = 41.67/8 = 5.21$; $t_3 = 5.0 \times (19.61/26.1 + 0.491) = 5.0 \times (0.751 + 0.491) = 5.0 \times 1.242 = 6.21s$. $CTI_{12} = 1.356s$. $CTI_{23} = 4.725s$. What is the assessment?

A. All CTIs are adequate but both R2 and R3 are excessively slow; the 6.21-second clearing time for R3 at maximum fault is unacceptable for backup protection

B. All three relays are optimally coordinated

C. CTI_{23} is inadequate

D. R1 (0.129s) is fast and appropriate; R2 (1.485s) is slow but acceptable as bus section backup; R3 (6.21s) is grossly excessive — reducing R3's TD to 2.5 would yield approximately 3.1s, still maintaining $CTI_{23} > 0.20s$ while cutting the backup clearing time nearly in half; the 6.21-second clearing time means fault damage and arc flash energy increase by approximately 4× compared to a 1.5-second clearing

58. A 345 kV, 500-mile line has $Z_1 = 40 + j375 \Omega$ and $Z_0 = 120 + j1,125 \Omega$. Source: $Z_{1_src} = j25 \Omega$, $Z_{0_src} = j37.5 \Omega$. SLG fault at remote end: $Z_{1_total} = 40 + j400$; $Z_{0_total} = 120 + j1,162.5$. $|Z_1| = 402.0$; $|Z_0| = 1,168.7$; $Sum = 200 + j1,962.5$; $|Sum| = 1,972.7$. $I_{SLG} = 3 \times 199,186 / 1,972.7 = 303A$. At 303A on a 345 kV system, what additional protection challenge exists beyond the standard low-fault-current concerns?

A. 303A is adequate for all protection methods

B. At 303A, the fault current is: (1) below the typical CT accuracy threshold for distance relays on this line, (2) comparable in magnitude to the line's charging current (500 miles \times 6A/mile = 3,000A per phase — no, that's not comparable); the additional challenge is that at 303A, the ground overcurrent relay must be set well below load unbalance, and the power swing blocking function may not correctly discriminate between a real SLG fault and a power swing because the fault current's impact on impedance measurement is minimal at this level; 87L with fiber communication is essential

C. No additional challenges beyond standard low-current protection

D. 303A exceeds all protection thresholds and requires no special consideration

59. Per NEC 700.10(B)(1), emergency wiring must be independent. A large hospital has emergency and normal feeders routed through the same underground duct bank. The emergency feeders are in dedicated PVC conduit, and the normal feeders are in separate PVC conduit. Both sets of conduit are encased in a common concrete envelope. Is this compliant?

A. No — the common concrete envelope creates a thermal coupling that could cause simultaneous failure of both systems

B. No — underground duct banks cannot contain both emergency and normal wiring regardless of separate conduit

C. Yes — separate conduits within a common concrete-encased duct bank provide adequate independence; the concrete envelope provides fire protection and physical separation; NEC 700.10(B)(1) requires independence of wiring systems (conductors and raceways), and separate dedicated conduits within the duct bank satisfy this requirement

D. Yes — but only if the duct bank has a 2-hour fire rating

60. A three-phase, 480V, 400A panelboard has: Motor 1 = 242A (200 HP, largest), Motor 2 = 180A (150 HP), Motor 3 = 124A (100 HP). Continuous lighting = 110A. Noncontinuous receptacles = 35A. Bus = 400A. OCPD = $125\% \times 242 + 180 + 124 + 125\% \times 110 + 35 = 302.5 + 304 + 137.5 + 35 = 779A \rightarrow$ next standard = 800A \rightarrow far exceeds 400A bus. With 100%-rated 400A breaker: total load = 691A > 400A. What is the resolution?

A. Install a 100%-rated 400A breaker — the 125% adder artificially inflates the calculation

B. De-rate the motors to reduce total load below 400A

C. Install load-shedding controls to keep instantaneous load below 400A

D. The panelboard must be upgraded to a minimum 800A bus to accommodate 691A total load; the 400A bus cannot carry 691A regardless of breaker type; this is a significant undersizing error that requires either replacing the panelboard or splitting the load across multiple panels

61. A balanced three-phase, 4,160V source feeds a 22,000 kW load at 0.64 lagging PF. $Q = 22,000 \times 1.201 = 26,422$ kvar. Utility penalty = \$6.50/kvar/month above 0.96 PF. $Q_{\text{allowed}} = 22,000 \times 0.292 = 6,424$ kvar. Excess = 19,998 kvar. Monthly penalty = \$129,987. Annual = \$1,559,844. Capacitor bank at \$25/kvar = \$499,950. What is the payback?

A. Payback = $\$499,950/\$129,987 = 3.85$ months — less than one fiscal quarter; the annual savings of $\$1,559,844$ represent a 312% annual return on the $\$499,950$ investment; this is the highest-value PF correction investment in the exam series

B. Payback = 12 months

C. Payback = 6 months

D. Payback = 24 months

62. A 480V, three-phase MCC has 25 motors (FLA = 5,500A combined). Motor contribution = 22,000A. Three parallel transformers (3,000 kVA each, $Z = 5.75\%$) provide 62,748A each = 188,244A combined. Total = 210,244A. X/R = 9. Multiplier = 2.35. Peak?

A. Peak = 494,073A — nearly half a million amperes peak

B. Peak = $2.35 \times 210,244 = 494,073$ A — three parallel 3,000 kVA transformers plus 25 motors produce this extraordinary peak; the 22,000A motor contribution (10.5% of total) adds measurably; at nearly 500 kA peak, the bus requires custom-engineered segregated-phase bus construction that far exceeds any standard product rating

C. 297,300A ($\sqrt{2} \times$ total)

D. 420,488A ($2 \times$ total)

63. A three-phase, 13.8 kV cable system is 65 miles long with 7.5A charging per mile per phase. A zero-sequence CT with 8A pickup and 0.3s delay is installed. Charging = 487.5A/phase. A high-impedance ground fault of 9A develops. The relay sees 9A fault (charging cancels). Since $9A > 8A$, the relay trips. But the margin is only 12.5%. If the system voltage drops to 95% during a contingency, the fault current drops proportionally to approximately 8.55A. Does the relay still trip?

A. At 8.55A, the relay still exceeds the 8A pickup, but with only 6.9% margin

B. The relay may not trip — 6.9% margin is within the relay's pickup accuracy tolerance (typically $\pm 5\%$), meaning the relay might or might not operate

C. At 95% voltage: $I_{\text{fault}} \approx 0.95 \times 9 = 8.55\text{A}$; this still exceeds 8A pickup, but the margin is only 6.9%; relay pickup accuracy is typically $\pm 5\%$, and CT accuracy adds another $\pm 1\text{-}3\%$; at 8.55A with these combined tolerances, the relay's actual trip current could range from 7.6A to 8.4A (at 8A $\pm 5\%$); since $8.55\text{A} > 8.4\text{A}$ upper tolerance, the relay should trip — but with essentially zero engineering margin; the pickup should be reduced to 6A for this critical application

D. The relay trips reliably with adequate margin at 8.55A

64. Per NEC 430.24, a feeder serves: Motor A = 862A (750 HP), Motor B = 683A (600 HP), Motor C = 590A (500 HP), Motor D = 515A (450 HP), Motor E = 477A (400 HP), Motor F = 414A (350 HP), Motor G = 361A (300 HP), Motor H = 302A (250 HP). Continuous lighting = 250A. Noncontinuous HVAC = 150A. What is the minimum feeder conductor ampacity?

A. $125\% \times 862 + 683 + 590 + 515 + 477 + 414 + 361 + 302 + 125\% \times 250 + 150 = 1,077.5 + 3,342 + 312.5 + 150 = 4,882\text{A}$

B. 4,000A

C. 5,000A

D. 3,500A

65. A distance relay on a 230 kV line ($Z_{\text{line}} = 9 + j100 \Omega$) has Zone 1 at 85%, Zone 2 at 120%. A permanent fault at 84% with 20Ω fault resistance. $Z_{\text{meas}} = (0.84 \times 9 + 20) + j(0.84 \times 100) = 27.56 + j84.0 \Omega$. $|Z_{\text{meas}}| = 88.4 \Omega$. Zone 1 reach = 85.3Ω . $|Z_{\text{meas}}| > \text{Zone 1}$. The fault is outside Zone 1. Zone 2 reach = 120.4Ω covers it. The pilot scheme (POTT) is active. Both terminals see forward faults. What happens?

A. The near end detects in Zone 2, sends a permissive signal, receives one from the remote end (which sees the fault within its Zone 1 at 16% from its terminal), and trips instantaneously via POTT — high-speed clearing is achieved at both ends despite the near end's Zone 1 inability to reach through the 20Ω resistance; this demonstrates the critical importance of pilot schemes for resistive faults near the end of protected lines

B. Zone 2 trips after 0.35 seconds — pilot scheme cannot help with resistive faults

C. Neither relay detects the fault because of the 20Ω resistance

D. Only the remote end trips; the near end waits for Zone 2 delay

66. A three-phase, 4,160V system has an NGR rated 300A, 10 seconds. The ground-fault relay has 15A pickup. The engineer must calculate the maximum detectable fault resistance AND the fault current at that maximum resistance to assess whether the relay can reliably detect it.

A. $R_{\text{max}} = 2,402/15 - 8.007 = 152.1 \Omega$; at this resistance, $I_{\text{fault}} = 15\text{A}$ exactly — but relay accuracy of $\pm 5\%$ means the relay might see 14.25-15.75A; at the lower end (14.25A), the relay would NOT trip; the practical maximum detectable resistance is lower: $R_{\text{practical}} = 2,402/(15 \times 1.05) - 8.007 = 2,402/15.75 - 8.007 = 144.5 \Omega$, providing 5% margin

B. $R_{\text{max}} = 100 \Omega$; the relay trips reliably at this resistance

C. R_{max} is unlimited — the relay detects any fault resistance

D. $R_{\text{max}} = 152.1 \Omega$; the relay trips reliably at exactly 15A with no margin concerns

67. Per NEC 480.9(A), a container-mounted BESS uses lithium-ion LFP cells. The BMS monitors cell-level voltage, temperature, and current. During a thermal event, one cell reaches 150°C — the onset of thermal runaway for LFP chemistry. The BMS triggers the emergency response sequence. What is the correct sequence?

A. Standard HVAC increases cooling to maximum capacity

B. The emergency sequence should be: (1) BMS disconnects the affected battery string from the DC bus via contactors, (2) gas detection sensors activate emergency ventilation, (3) fire suppression (water mist or clean agent) activates to cool the affected cells and slow thermal propagation to adjacent cells, (4) emergency exhaust fans evacuate any off-gases (primarily electrolyte vapors and CO₂ for LFP — less HF than NMC), (5) SCADA/EMS alarm notifies operators, (6) the container remains sealed on non-ventilation sides to contain any fire — this sequence prioritizes electrical isolation, then thermal management, then gas management

C. Nothing — LFP cells cannot undergo thermal runaway

D. Immediately flood the container with water to cool all cells

68. A three-phase, 480V, 600A panelboard has an available fault current of 40,000A. IEEE 1584: 16 cal/cm² at 24 inches with 0.20s clearing. An optical relay (0.008s clearing with high-speed solid-state trip), ZSI (0.05s), maintenance switch (0.04s), and arc-resistant enclosure are installed. With the optical relay at 0.008s, what is the incident energy?

A. $16 \times (0.008/0.20) = 0.64$ cal/cm² — the fastest achievable clearing in the exam series

B. $E = 0.64$ cal/cm²; combined with arc-resistant enclosure, effective exposure is near zero

C. $E = 0.64$ cal/cm²; this represents a 96% reduction from the unmitigated 16 cal/cm²; at 0.64 cal/cm², the energy is well below the 1.2 cal/cm² arc flash boundary; the three backup layers (ZSI at 0.05s → 4.0 cal/cm²; maintenance switch at 0.04s → 3.2 cal/cm²; normal STD at 0.20s → 16 cal/cm²) provide progressive fallback; the arc-resistant enclosure adds physical protection regardless of which layer operates — this four-layer defense with the fastest optical clearing in the exam series represents the absolute state of the art

D. 8 cal/cm² (50% reduction from arc-resistant enclosure)

69. A three-phase, 460V, 4-pole synchronous motor rated 4,500 HP drives a large compressor at 1,800 RPM. Pull-out = 250% FLT. $H = 3.0$ MJ/MVA (high inertia due to a large flywheel). During a system event, voltage sags to 75% for 0.8 seconds. Pull-out = 187.5% FLT. Load = 85% FLT. Margin = 102.5% FLT. What is the stability assessment with $H = 3.0$?

A. With $H = 3.0$ (high inertia from the flywheel), the rotor accelerates slowly during the 0.8-second sag; the large margin (102.5% FLT) combined with the high inertia produces relatively small rotor angle advance (estimated 10-20°); the flywheel acts as an energy buffer, absorbing the accelerating power and limiting the angular displacement; stability is maintained with excellent margin — the flywheel's inertia is specifically designed to ride through voltage sags

B. Unstable — any sag above 0.5 seconds causes pull-out

C. Marginally stable — the flywheel provides no stability benefit

D. Cannot be determined without the exact compressor torque-speed curve

70. A 230 kV, 450-mile line has $Z_{1_total} = 36 + j337.5 \Omega$, $Z_{0_total} = 108 + j1,012.5 \Omega$. $|Z_1| = 339.4$, $|Z_0| = 1,018.2$. Sum = $180 + j1,687.5$; $|\text{Sum}| = 1,697.1$. $I_{SLG} = 398,400/1,697.1 = 235\text{A}$. This is the lowest SLG fault current in the exam series. A conventional pilot scheme using Power Line Carrier (PLC)

communication operates at a carrier frequency of approximately 30-300 kHz over the same 345 kV line. What reliability concern exists for the pilot scheme during this fault?

- A. No concern — PLC is perfectly reliable during all fault conditions
- B. PLC is unaffected by fault conditions on the line it uses for communication
- C. During a fault, the PLC signal can be attenuated or blocked by the low impedance at the fault point
- D. During a fault, the arc at the fault point acts as a high-frequency noise source that can interfere with PLC reception; additionally, fault-related voltage collapse at the fault point can attenuate the PLC carrier signal; for a 450-mile line where PLC signal strength is already at its limits, this interference could cause communication failure exactly when the pilot scheme is most needed; modern fiber-optic communication (dedicated OPGW or ADSS cable) provides a communication path completely independent of the power line and is immune to these concerns — this is why long lines increasingly use fiber-based pilot protection

71. Per NEC 250.122(B), a 1,600A circuit has two parallel 1,000 kcmil per phase (2,000,000 CM total), increased to two parallel 1,250 kcmil (2,500,000 CM). The EGC from Table 250.122 for 1,600A: the table goes up to 6,000A OCPD (with 400 kcmil EGC). For 1,600A: EGC = 250 kcmil (250,000 CM) from NEC Table 250.122 interpolation. What is the proportionally increased EGC?

- A. 250 kcmil (no increase needed)
- B. Ratio = $2,500,000/2,000,000 = 1.25$; EGC = $250,000 \times 1.25 = 312,500$ CM \rightarrow 350 kcmil (350,000 CM) is the minimum standard size above 312,500 CM
- C. 300 kcmil (300,000 CM)
- D. 500 kcmil

72. A balanced three-phase, 4,160V source feeds a 28,000 kW load at 0.66 lagging PF. $Q = 28,000 \times 1.138 = 31,864$ kvar. The engineer installs a 24,000 kvar capacitor bank, a 6,000 HP synchronous motor at 0.80 leading ($\eta = 94\%$), AND a 3,000 HP synchronous motor at 0.85 leading ($\eta = 95\%$). What is the new PF?

A. PF = 0.90

B. PF = 0.95

C. SM1: $P = 4,762$ kW, $Q_1 = 3,571$; SM2: $P = 2,357$ kW, $Q_2 = 1,463$; total correction = $24,000+3,571+1,463 = 29,034$; net $Q = 31,864-29,034 = 2,830$; $P_{total} = 35,119$; $PF = 35,119/35,233 = 0.997 \approx 0.99$

D. PF = unity

73. A 100 MVA, 345/138 kV autotransformer has $Z = 10.5\%$ on its own base. Two identical units in parallel. A 70 MVA generator ($X''_d = 0.18$ pu), a 50 MVA synchronous condenser ($X''_d = 0.12$ pu), a 35 MVA synchronous motor ($X''_d = 0.20$ pu), a 30 MVA solar farm (effective $Z = 1.0$ pu), a 20 MVA wind farm (effective $Z = 1.2$ pu), and a 15 MVA BESS (effective $Z = 1.5$ pu) are on the 138 kV bus. On 100 MVA base, what is the total fault current and the combined inverter-based contribution?

A. $Z_{T_par} = 0.0525$; $Z_{gen} = 0.257$; $Z_{SC} = 0.24$; $Z_{SM} = 0.571$; $Z_{solar} = 3.333$; $Z_{wind} = 6.0$; $Z_{BESS} = 10.0$; $I_{pu} = (19.05+3.891+4.167+1.751+0.30+0.167+0.10) \times 418.4 = 29.43 \times 418.4 = 12,309A$; inverter contribution = $(0.30+0.167+0.10)/29.43 = 1.93\%$ — three inverter-based sources totaling 65 MVA contribute less than 2% despite representing 23% of connected capacity; as grid penetration of renewables increases, fault current available for protection operation decreases — this fundamental challenge drives the need for new protection paradigms

B. 15,000A; inverter contribution = 5%

C. 10,000A; inverter contribution = 10%

D. 20,000A; inverter contribution = 15%

74. A three-phase, 460V, 4-pole induction motor rated 400 HP operates at 1,770 RPM. A VFD reduces speed to 600 RPM for a centrifugal pump. $P = 298 \times (600/1,770)^3 = 298 \times 0.0388 = 11.6$ kW. VFD $\eta = 94\%$, motor η at this extreme light load = 72%. What is the supply power, and what percentage of pump power is consumed by losses?

A. $P_{supply} = 11.6/(0.72 \times 0.94) = 17.1$ kW; losses = 5.5 kW = 47.4% of pump power

B. $P_{supply} = 11.6$ kW (losses negligible at low power)

C. $P_{\text{supply}} = 50 \text{ kW}$

D. $P_{\text{supply}} = 11.6 / (0.72 \times 0.94) = 17.1 \text{ kW}$; losses = $17.1 - 11.6 = 5.5 \text{ kW} = 47.4\%$ of pump power — at this extreme speed reduction (34% of rated), nearly half the electrical input is consumed by motor and VFD losses rather than useful pump work; motor efficiency drops dramatically to 72% because iron losses, friction, and windage are relatively constant while useful output drops to only 3.9% of rated; this represents the economic floor for VFD speed reduction on centrifugal loads

75. Per NEC 430.32(A)(1), a motor with SF = 1.15 has maximum overload at 125% of FLA. A 750 HP motor has FLA = 862A, SF = 1.15. Overload set at 1,077.5A (125%). The motor drives a large centrifugal compressor with a 60-second starting time (very high-inertia load). During starting, the motor draws $3.5 \times \text{FLA}$ (3,017A) for the first 30 seconds, then $2 \times \text{FLA}$ (1,724A) for the next 20 seconds, then settles to rated in the final 10 seconds. The standard overload relay has a Class 20 thermal time constant. Will the relay trip during this extended start?

A. The thermal accumulation is less than the Class 20 trip threshold — the relay rides through the start

B. The Class 20 relay WILL trip during this 60-second start because the I^2t accumulation at $3.5 \times$ for 30 seconds alone exceeds the relay's thermal capacity: $(3.5)^2 \times 30 = 367.5$ equivalent seconds at rated — far exceeding the Class 20 trip time of 20 seconds at $6 \times \text{FLA}$; this motor requires a Class 30 or Class 40 overload relay, or a microprocessor-based relay with adjustable thermal model and motor-starting bypass capability; high-inertia compressor starting is one of the most challenging motor protection scenarios

C. No relay trips during starting — overload relays are inactive for the first 60 seconds

D. The relay trips in exactly 20 seconds regardless of the starting current profile

76. A 480V, three-phase system has a 4,000 kVA transformer ($Z = 5.50\%$, $X/R = 10$) and a 3,000 kVA transformer ($Z = 5.75\%$, $X/R = 8$) in parallel, plus 16 motors (FLA = 3,200A) contributing 12,800A. $I_{T1} = 87,473\text{A}$. $I_{T2} = 62,748\text{A}$. Total transformers = 150,221A. Grand total = 163,021A. Weighted $X/R \approx 9.2$. Multiplier = 2.36. Peak?

A. 230,500A ($\sqrt{2} \times \text{total}$)

B. 326,042A ($2 \times \text{total}$)

C. Peak = $2.36 \times 163,021 = 384,730\text{A}$ — approaching 400 kA peak from two large parallel transformers plus 16 motors; at this peak level, the electromagnetic forces produce structural loads comparable to seismic events, requiring bus designs with specialized engineering analysis beyond standard electrical ratings

D. 163,021A (no asymmetry)

77. A three-phase, 4,160V, 12-pole synchronous motor rated 7,000 HP drives a ball mill at 600 RPM. Pull-out = 280% FLT. $H = 1.5$ MJ/MVA (very low inertia). Voltage sags to 55% for 3.0 seconds. Pull-out = 154% FLT. Load = 100% FLT. Margin = 54% FLT. Despite the apparently adequate steady-state margin, what happens?

A. At $H = 1.5$ (the lowest in the exam series) with 3.0 seconds at 55% (the deepest and longest sag): $\Delta\delta \propto t^2 \rightarrow 3.0^2 = 9.0 \times$ the advance of 1.0 seconds; the motor loses synchronism within the first 0.3-0.5 seconds, well before the 3.0-second sag ends; the 54% FLT margin is completely irrelevant to transient stability at these extreme parameters; the UV relay MUST trip the motor within 0.3 seconds to prevent catastrophic mechanical damage from out-of-step operation

B. Stable — 54% margin is barely adequate for the 3.0-second duration

C. The motor maintains synchronism through the sag due to the ball mill's high inertia

D. Cannot be determined without exact motor parameters

78. Per NEC 110.24(A), a facility originally had two parallel 2,500 kVA transformers ($Z = 5.75\%$ each). Original $Z_{\text{parallel}} = 5.75\%/2 = 2.875\%$. $I_{\text{original}} = 3,007/0.02875 = 104,591\text{A}$. A third identical transformer is added in parallel. New $Z_{\text{parallel}} = 5.75\%/3 = 1.917\%$. $I_{\text{new}} = 3,007/0.01917 = 156,887\text{A}$. What is the percentage increase, and what is the practical implication?

A. $I_{\text{new}} = 156,887\text{A}$; increase = 50% — adding one transformer to two increases the fault current by 50%, not 33%; this is because $Z_{\text{parallel}} = Z/n$, so going from $n=2$ to $n=3$: $Z_{\text{new}}/Z_{\text{old}} = (2/3)$, meaning $I_{\text{new}}/I_{\text{old}} = 3/2 = 1.50$

B. 33% increase (one-third additional capacity = one-third additional fault current)

C. 100% increase

D. 50% increase: $I = 3,007/0.01917 = 156,887\text{A}$; this 50% increase from 104,591A is critical because many 480V equipment items rated for the original 105 kA are now inadequately rated for 157 kA; all SCCR ratings, series combinations, and arc flash studies must be reverified; the 50% increase (not 33%) is a common design misconception — adding one transformer to two existing parallel units increases fault current by 50%, not the intuitive 33%

79. A 2,500 kVA, 480V/208Y/120V transformer has $Z = 4.75\%$ and $X/R = 4.5$. The symmetrical fault current at 208V = 30,500A. Using IEEE multiplier of 2.10 for $X/R = 4.5$, what is the peak asymmetrical?

A. 43,100A ($\sqrt{2} \times$ symmetrical)

B. Peak = $2.10 \times 30,500 = 64,050\text{A}$ — at 64 kA peak on a 208V system, this exceeds the momentary rating of many standard 208V panelboards (typically rated 22-42 kA SCCR); the low transformer impedance (4.75%) combined with the large kVA produces extremely high fault current that requires careful equipment selection and potentially current-limiting protection

C. 61,000A ($2 \times$ symmetrical)

D. 30,500A (no asymmetry)

80. A 750 kW, three-phase, 480V resistance heater operates continuously 24/7/365. Electricity costs \$0.052/kWh. Per NEC 210.20(A), minimum OCPD = 125% of continuous. What is the load current, minimum OCPD, annual energy, and cost?

A. $I = 750,000/(\sqrt{3} \times 480) = 902.1\text{A}$; OCPD = $125\% \times 902.1 = 1,127.6\text{A}$ → next standard per NEC 240.6(A) = 1,200A; $E = 750 \times 8,760 = 6,570,000$ kWh; cost = \$341,640

B. $I = 902.1\text{A}$; OCPD = 1,000A; $E = 6,570,000$ kWh; cost = \$341,640

C. $I = 902.1\text{A}$; OCPD = 1,200A; $E = 6,570,000$ kWh; cost = $6,570,000 \times \$0.052 = \$341,640/\text{year}$ — this \$342,000 annual energy cost for a single heater is the highest single-load energy cost in the exam series; at this level, every 1% improvement in heating efficiency saves \$3,416/year; waste heat recovery, improved insulation, and process optimization are essential engineering priorities

D. $I = 750\text{A}$; OCPD = 1,000A; $E = 5,000,000$ kWh; cost = \$260,000

Practice Exam 23: Answer Key and Explanations

1. A — Although $h_r = 8.16$ is above $h = 7$, the amplification factor at $h = 7$ is $h_r^2/(h_r^2 - h^2) = 66.6/17.6 = 3.78\times$. The furnace rectifier injects 7th harmonic at 14% of fundamental; amplified by $3.78\times$, the resulting voltage harmonic V_7 could reach $53\% \times$ (system impedance factor), potentially exceeding IEEE 519's 3% individual limit. Near-resonance amplification is dangerous even when h_r doesn't exactly match a characteristic harmonic.
2. D — Cable Z reduces transformer contribution from 36,130A to approximately 26,500A at the MCC. Adding 3,840A motor contribution = 30,340A total. The 16% reduction from switchboard value changes the IEEE 1584 calculation — the MCC warrants its own arc flash study and will likely receive a lower PPE category label than the switchboard.
3. B — NEC 430.52(C)(1) Exception 2 permits increasing the OCPD when the motor cannot start with the standard-size maximum. Repetitive cold starts cause cumulative I^2t in the fuse element exceeding its damage curve — even though a single start succeeds, consecutive starts without adequate cooling overwhelm the fuse. The 225% (1,400A) provides thermal margin for this repetitive duty.
4. C — At $16\times$ with 240V, the CT has 160V margin (40% headroom) below the 400V C400 rating. However, the lead wire burden (2.5Ω of 3.0Ω total = 83%) is the dominant component — indicating excessively long or undersized leads. Reducing lead resistance by upsizing wire or shortening the run provides additional margin during high-fault conditions with DC offset.
5. A — The STATCOM maintains full current output at reduced voltage because it is a voltage-source converter. At 60% voltage: STATCOM provides rated current (effectively more Mvar per ampere), while the SVC's output drops to $V^2 = 36\%$ of rated. The STATCOM provides approximately $2.8\times$ more effective voltage support during the critical sag period.
6. D — Ratio = $1,500,000/1,000,000 = 1.50$. EGC = $105,600 \times 1.50 = 158,400$ CM. 2/0 AWG = 133,100 (below). 3/0 AWG = 167,800 (above — adequate). The minimum EGC is 3/0 AWG per NEC 250.122(B).

7. B — SM2 $P_{in} = 1,571$ kW, $Q_2 = 975$ kvar. Total = $13,000 + 2,976 + 975 = 16,951$. Net $Q = 18,015 - 16,951 = 1,064$ kvar. $PF \approx$ unity. The three sources virtually eliminate reactive demand. The engineer should reduce the cap bank slightly to maintain 0.98 lagging.

8. C — Phase base = $528.7/0.80 = 660.9A$. Neutral base = $472.5/0.80 = 590.6A$. Phase governs at 660.9A because the phase carries significant harmonic current (both triplens AND non-triplens) in addition to the fundamental, making its RMS higher relative to its derating requirement. Despite the high 472.5A neutral, the phase requirement exceeds it after derating.

9. A — Reactor: $I_{SLG} = 3.09$ pu (reactive, still exceeds $I_{3\Phi}$ but reduced). LRG: $I_{SLG} = 0.60$ pu (predominantly resistive). HRG: $I_{SLG} = 0.06$ pu (resistive). Each step progressively reduces SLG current and transitions from reactive to resistive character — the fundamental trade-off is between fault detection capability (higher current) and fault damage limitation (lower current).

10. D — Each event: $(400/400)^2 \times (0.5/10) = 5.0\%$. Cumulative = 10.0%. The 30-second interval provides minimal cooling. The NGR retains 90% capacity. However, the inadvertent re-energization indicates a serious LOTO violation — the immediate safety concern is the work practice failure, not the NGR thermal status.

11. B — NEC 110.26(A)(2) requires the working space width to be at least the width of the equipment or 30 inches, whichever is greater. This ensures adequate space for safe operation, maintenance, and emergency egress regardless of equipment physical dimensions.

12. C — The no-load period consumes 104 kWh of core losses with zero useful output. These losses add to the denominator (total input) without adding to the numerator (useful output), degrading the all-day efficiency ratio. Unloaded transformers should be de-energized when possible to eliminate this pure waste.

13. A — R1 at $M = 50$: $t_1 = 0.200s$. R2 at $M = 11.72$: $t_2 = 1.905s$. CTI = 1.705s — adequate but R2 is unnecessarily slow. Reducing R2's TD to 1.5 yields approximately 0.95s with $CTI \approx 0.75s$ — still well above 0.20s minimum while halving backup clearing time and reducing fault damage proportionally.

14. D — The 1.2% margin is consumed by 3.5% worst-case CT/PT error. At 78.6 Ω apparent, the fault appears outside Zone 1 (76.8 Ω). The relay reverts to Zone 2. This validates the 85% Zone 1 setting — it creates margin for measurement uncertainty, but faults near the reach boundary are inherently unreliable and depend on pilot schemes.

15. B — Including motor and VFD efficiency at each operating point: losses add approximately 8% to the total compared to ideal affinity-law calculation. The light-load efficiency penalty (80% motor efficiency at 40% speed vs 96% at full) significantly impacts the energy calculation at reduced speeds, providing a more realistic picture than the simple $P \propto n^3$ alone.

16. C — $H_2 = 0.96 \text{ ft}^3/\text{hr}$. Max $H_2 = 8.0 \text{ ft}^3$. ACH = 0.12. In a Class I, Div 2 location: ventilation equipment must be rated for the hazardous classification. Remote H_2 detection with SCADA alarming is mandatory for unmanned stations. Backup ventilation is recommended because the small space reaches 1% H_2 in approximately 8.3 hours during ventilation failure.

17. D — The midpoint STATCOM provides superior support because: it is electrically closer to the voltage depression (direct local injection); it maintains full current at 0.88 pu voltage (STATCOM advantage over SVC); and midpoint compensation maximizes P_{max} for both halves of the line. Receiving-end SVC only supports one half and loses output proportional to V^2 .

18. A — $P_{750} = E_a \times I_a = 230 \times 250 = 57.5 \text{ kW} = 50\%$ of rated power. At constant torque, power is directly proportional to speed. The motor current remains at rated 250A throughout the constant-torque speed range, meaning the motor operates at rated thermal loading at all speeds — a critical design consideration for continuous-duty applications.

19. C — Forty-four separately derived systems: 6 service + 6 emergency generators + 4 fire pump generators + 16 PDU + 8 isolation + 4 UPS = 44. Fire pump generators are separately derived systems per NEC 250.30, identical to emergency generators. Each requires a bonding jumper sized per NEC 250.30(A)(2).

20. A — A tie-bus fault is fed from BOTH transformers (150,000A total = 4× the force of single-bus). Both mains must trip. If one fails, fault continues from that source. The AQD quenches the arc in 4 ms before the extreme 150 kA can cause catastrophic bus damage — it is most critical at the tie point where combined fault current is highest.

21. D — During the first 100 ms (reactor grounding): $I_{\text{SLG}} = 3.95 \text{ pu}$ — sufficient for relays to detect and locate the fault. After 100 ms, automatic switching to HRG reduces I_{SLG} to 0.075 pu, limiting arc flash and equipment damage. This hybrid approach provides reliable detection AND minimal damage — the best of both worlds.

22. B — Per NEC 430.24: $125\% \times 683 = 853.75\text{A}$. Other motors = $515+414 = 929\text{A}$. Per NEC 215.2: $125\% \times 300 = 375\text{A}$. Noncontinuous = 100A . Total = $853.75 + 929 + 375 + 100 = 2,257.75\text{A}$. The 125% applies independently to the largest motor and continuous non-motor load.

23. A — $I = (33.33+25.0+20.0+16.67+12.50+4.0+2.50+1.67+1.33+0.20) \times 6,940 = 117.20 \times 6,940 = 813,368\text{A}$. Ten sources produce over 800 kA. This extreme level is physically unrealistic for a single bus — bus-section splitting with current-limiting reactors is mandatory to reduce combined fault levels to manageable ranges.

24. D — $Z_{\text{cable_pu}} \approx 1.097$. Total $Z \approx 1.154$. $I \approx 2,605\text{A}$. The small 2 AWG at 500 feet dramatically reduces fault current well below 14,000A SCCR. However, the engineer must verify breaker trip speed at 2,605A (only 11.6× for a 225A breaker) and confirm that voltage drop is acceptable at this conductor size and distance.

25. C — NEC 690.7(A) maximum system voltage = 1,000V DC. At -30°C : $28 \times 49.1 = 1,374.8\text{V} > 1,000\text{V}$. This violation exists during ALL cold-weather conditions, not just rapid shutdown. Strings must be shortened to 20 modules (982V) or the entire system re-rated for 1,500V with all components upgraded accordingly.

26. B — Total = $156,745 + 16,000 = 172,745\text{A}$. Peak = $2.32 \times 172,745 = 400,768\text{A}$. This 400 kA peak from three transformers plus motors creates forces exceeding $1.61 \times 10^{11} \text{A}^2$. Standard bus construction cannot withstand these forces — specialized segregated-phase bus designs are required.

27. A — Both terminals trip with high-speed clearing via POTT. The near end detects in Zone 2, sends a permissive signal, and receives one from the remote end (which sees the fault within Zone 1 at 8% from its terminal). Upon receiving the permissive, the near end overrides its Zone 2 timer and trips instantaneously. Both breakers open simultaneously.

28. D — The relay must compensate for zero-sequence current appearing in HV (wye-grounded) CTs but NOT in tertiary (delta) CTs. Without proper compensation (zero-sequence filtering or delta CT connections on wye sides), every SLG fault would cause a false differential trip. This is one of the most critical configuration details for three-winding transformer protection.

29. B — Primary OCPD = 1,200A (next standard above 125%). Per NEC 450.3(B), secondary OCPD at not more than 125% (or next standard above) = $125\% \times 2,082 = 2,602.5\text{A}$. Standard sizes: 2,500A

(below — acceptable) or 3,000A (next above — per NEC table conditions). The exact permissible size depends on the specific NEC 450.3(B) table conditions.

30. C — $\Delta\delta = (180 \times 60 \times 1.253 \times 0.36) / (2.0 \times 5.228) = 4,883 / 10.456 = 467^\circ$. This enormous angle confirms certain loss of synchronism. The 0.6-second sag at 72% with $H = 2.0$ produces catastrophic instability despite the 87.2% steady-state margin. The motor must be tripped by UV protection.

31. A — $F = (2 \times 10^{-7} \times 442,700^2) / 0.15 = (2 \times 10^{-7} \times 1.96 \times 10^{11}) / 0.15 = 39,200 / 0.15 = 261,333 \text{ N/m} \approx 261 \text{ kN/m}$ (60,000 lbs/foot). These extreme forces require specialized high-strength bus construction far beyond standard designs. Halving the conductor spacing doubles the force, making spacing a critical design variable.

32. D — Five violations: V_5 (12.5%), V_7 (8.3%), V_{11} (5.5%), V_{13} (3.8%) exceed 3.0% individual, plus THD (17.2%) exceeds 5.0%. This catastrophic harmonic environment causes premature transformer failure, capacitor resonance, equipment malfunctions, and excessive neutral currents. Multi-phase capital remediation costing hundreds of thousands of dollars is required.

33. C — In hazardous areas, the grounding system must prevent static charge accumulation and spark generation in addition to IEEE 80 step-and-touch requirements. Every metallic surface must be bonded to the grid. The bonding conductors must maintain sufficiently low impedance to prevent voltage differences that could create ignition-capable sparks in the hazardous atmosphere.

34. A — At 87% of no-load magnetizing on direct-line operation: $100 < 115 \text{ kvar}$, so self-excitation cannot sustain full voltage after disconnection. However, 87% leaves minimal margin for voltage/frequency variations. The engineer should obtain manufacturer approval and install a capacitor-switching contactor that opens before or with the motor contactor to eliminate any self-excitation risk.

35. D — Full: 280,000. 95%: 359,940. 85%: 429,800. 70%: 288,120. 55%: 87,150. 35%: 12,911. VFD = 1,457,921 kWh. Full-speed = 3,066,000 kWh. Savings = 1,608,079 kWh (52.4%). Six operating modes with the cubic relationship produce over 52% energy reduction.

36. B — $R = 0.0276 \times 0.8 = 0.02208$. $X = 0.0391 \times 0.8 = 0.03128$. $V_{\text{drop}} = 346.4 \times (0.02208 \times 0.86 + 0.03128 \times 0.510) = 346.4 \times (0.01899 + 0.01595) = 346.4 \times 0.03494 = 12.10\text{V}$. $V_{\text{drop}}\% = 2.52\%$. Within 3% despite the extreme 800-foot run because 500 kcmil provides very low resistance per foot.

37. C — $I_{pu} = 30.0 + 3.497 + 3.571 + 1.364 + 0.40 = 38.83$. $I = 38.83 \times 418.4 = 16,247A$. Inverter contribution = $0.40/38.83 = 1.0\%$. The 40 MVA inverter farm (15% of connected capacity) contributes only 1% of fault current — a profound implication as grids transition to higher renewable penetration.

38. A — Total = $160,673 + 14,000 = 174,673A$. Peak = $2.37 \times 174,673 = 414,175A$. Over 400 kA peak exceeds the close-and-latch rating of virtually all standard 480V switchgear. Bus splitting with current-limiting reactors or specialized high-fault-capacity equipment is mandatory.

39. D — The combination of ground ring (largest area), Ufer electrode (stable moisture), and driven rods (reaching clay layer) provides the lowest resistance because they contact different soil layers and provide maximum total electrode surface area. In parallel, the combined resistance is significantly lower than any single electrode type.

40. B — Cable $Z_{pu} \approx 1.215$. Total $Z = 1.272$. $I = 3,608/1.272 = 2,836A$. The extreme 1,000-foot 3/0 cable reduces fault current to only 7.9% of switchboard value. Downstream breakers must be verified for adequate trip speed at this very low current level.

41. A — The very low Z_0 (0.045 pu) combined with delta blocking the source Z_0 creates Z_{0_total} (0.075) = only 33% of Z_{1_total} (0.225). This extreme ratio produces the 28.6% SLG exceedance — characteristic of some three-limb core-form transformer designs with unusually low zero-sequence impedance.

42. C — At 65% speed, magnetizing drops to 43.2 kvar. The 55 kvar at 127% of reduced magnetizing exceeds the self-excitation threshold. If the VFD trips, the capacitor sustains the residual field. The capacitor must be interlocked with the VFD — this is a critical safety issue specific to VFD-driven motors with terminal capacitors.

43. D — At $X/R = 35$, the DC time constant = 5.6 cycles; the CT saturates severely for approximately 17 cycles. A high-impedance bus differential relay provides security because the saturated CT presents low impedance that cannot drive current through the high-impedance element. This is why high-impedance differential is preferred for bus protection in high-X/R systems.

44. B — Per NEC 310.15(C)(1), neutrals carrying predominantly harmonic currents must be counted as current-carrying regardless of whether they exceed the phase. The 198A neutral carries predominantly triplen harmonics (not fundamental unbalance) and must be counted, resulting in 4 current-carrying conductors with the 0.80 adjustment factor.

45. A — The decision involves: procedure criticality, ability to isolate the fault by unplugging non-essential devices, risk of a second fault creating a shock path, and the biomedical engineer's device-by-device assessment. A systematic approach of unplugging devices can identify the faulty equipment without interrupting life-critical surgery.

46. C — With compensation: $\sin \delta = 0.4173$; $\delta = 24.7^\circ$; stability = 41.7%; margin = 58.3%. Without: $\sin \delta = 0.695$; $\delta = 44.0^\circ$; stability = 69.5%; margin = 30.5%. Series compensation improved margin from 30.5% to 58.3% — a 91% improvement enabling confident 1,100 MW transmission.

47. D — Fuse TC = 0.028s. Recloser delayed = 0.065s. The fuse clears at 0.028s with 0.037s margin (132%) before the recloser would trip. This clean margin ensures the fuse isolates the lateral while the recloser holds and restores unfaulted sections — the designed fuse-clearing sequence for permanent faults.

48. B — Two parallel 350 kcmil = 620A provides 17% margin above 530A — code-compliant. However, for high-ambient installations or anticipated load growth, two parallel 500 kcmil (760A, 43% margin) is the better engineering choice. The decision depends on installation conditions and future load expectations.

49. B — Total = 48,111 + 14,400 = 62,511A. Peak = $2.38 \times 62,511 = 148,776$ A. The 14,400A motor contribution (23%) adds substantially to the peak. All equipment momentary ratings and bus bracing must account for this combined 149 kA peak.

50. D — $R = 0.04256$, $X = 0.03346 \Omega$. $V_{\text{drop}} = 346.4 \times (0.04256 \times 0.82 + 0.03346 \times 0.572) = 346.4 \times (0.03490 + 0.01914) = 346.4 \times 0.05404 = 18.72$ V. $V_{\text{drop}\%} = 3.90\%$. Significantly exceeds 3% — upsize to 250 kcmil or 350 kcmil for this 700-foot distance.

51. C — Four parallel 750 kcmil at $90^\circ\text{C} = 2,140$ A with 7% margin. Fewer parallel sets means fewer terminations, lower probability of unequal current sharing, and simpler installation. Five parallel 500 kcmil provides similar ampacity but adds complexity. The four-set option is the better engineering choice.

52. A — $\Delta\delta = (180 \times 60 \times 240 \times 0.000784) / 1,350 = 2,032 / 1,350 = 1.5^\circ$. The state-of-the-art 0.028-second clearing produces negligible advance. The 118.5° margin demonstrates that ultra-fast protection makes transient stability virtually guaranteed at any reasonable loading.

53. D — At 225% voltage ($5.06\times$ stress), the four remaining units fail within cycles. Each failure accelerates the cascade: $4\rightarrow 3\rightarrow 2\rightarrow 1$ units with multipliers $2.25\rightarrow 3.0\rightarrow 4.5\rightarrow 9.0\times$. The entire series group fails in under 100 ms. Only ultra-high-speed electronic unbalance detection with sub-cycle trip can prevent propagation.

54. B — Only the wound-rotor meets 350% breakaway. Additional advantages: adjustable torque curve for varying ore conditions, thermal management during 8-second overloads by shifting I^2t to external resistors, and speed control through slip power recovery for energy-efficient reduced-speed operation.

55. C — 36 phase + 8 harmonic neutrals = 44 current-carrying conductors. For 41+ conductors, the derating factor approaches 0.25 — conductors must be approximately $4\times$ normal size. This is completely impractical in a single tray. At least nine parallel raceways are needed.

56. B — Trip Coil A fails (dead battery). Trip Coil B (permanent magnet) operates using stored mechanical energy — no external power needed. The breaker opens via Trip Coil B. The AQD quenched the arc in 4 ms, and the breaker clears the bolted fault in approximately 22 ms. Redundant trip mechanisms prevent the single-point-of-failure scenario.

57. A — $R1 = 0.129s$; $R2 = 1.485s$; $R3 = 6.21s$. $R3$ is grossly excessive — 6.21 seconds of fault damage and arc flash energy is unacceptable for backup. Reducing $R3$'s TD to 2.5 yields approximately 3.1s while maintaining CTI_{23} above 0.20s. Every second of unnecessary delay increases fault damage proportionally.

58. B — At 303A on a 500-mile line, the ground overcurrent relay must be set below load unbalance (risking false trips). Power swing blocking may not discriminate between SLG faults and power swings at this low current. PLC communication can be degraded by fault-point noise. 87L with fiber communication is the only dependable primary protection.

59. C — Separate conduits within a common concrete-encased duct bank provide adequate independence. The concrete provides fire protection and physical separation. NEC 700.10(B)(1) requires independence of wiring systems (conductors and raceways), and dedicated conduits within the duct bank satisfy this.

60. D — Total load = 691A > 400A bus. The panelboard must be upgraded to minimum 800A bus. The 400A bus cannot carry 691A regardless of breaker type. This significant undersizing error requires either replacing the panelboard or splitting the load across multiple panels.

61. A — Excess = 19,998 kvar. Annual penalty = \$1,559,844. Bank at \$25/kvar = \$499,950. Payback = 3.85 months. The annual savings represent a 312% return — the highest-value PF correction in the exam series.

62. B — Total = 188,244 + 22,000 = 210,244A. Peak = $2.35 \times 210,244 = 494,073$ A. Nearly 500 kA peak from three parallel transformers plus 25 motors. Custom segregated-phase bus construction is required — no standard 480V product is rated for this level.

63. C — At 95% voltage: $I = 8.55$ A vs 8A pickup. Margin = 6.9%. Relay accuracy $\pm 5\%$ means actual trip could range from 7.6A to 8.4A. Since $8.55\text{A} > 8.4\text{A}$ (upper tolerance), the relay should trip — but with essentially zero engineering margin. Reducing pickup to 6A provides robust margin for this critical application.

64. A — $125\% \times 862 = 1,077.5$ A. Other motors = $683+590+515+477+414+361+302 = 3,342$ A. Motor subtotal = 4,419.5A. $125\% \times 250 = 312.5$ A. HVAC = 150A. Total = 4,882A. Multiple parallel conductor sets per phase with individual EGCs required.

65. A — $|Z_{\text{meas}}| = 88.4 > \text{Zone 1 reach } 85.3 \Omega$ — outside Zone 1. Zone 2 covers it. With POTT active, the near end sends permissive signal, receives one from the remote end (16% from its terminal = Zone 1), and trips instantaneously. Pilot schemes are critical for resistive faults near the end of protected lines.

66. D — $R_{\text{max}} = 152.1 \Omega$ at exactly 15A. But relay accuracy $\pm 5\%$ means actual trip range is 14.25-15.75A. The practical maximum with 5% margin: $R_{\text{practical}} = 2,402/15.75 - 8.007 = 144.5 \Omega$. This 5% margin accounts for relay calibration tolerance and prevents unreliable detection at the boundary.

67. B — The emergency sequence: (1) BMS disconnects affected string, (2) gas detection activates ventilation, (3) fire suppression cools cells, (4) exhaust evacuates gases, (5) SCADA alarm, (6) container sealed on non-ventilation sides. This prioritizes electrical isolation → thermal management → gas management, the correct hierarchy for LFP thermal events.

68. C — $E = 16 \times (0.008/0.20) = 0.64 \text{ cal/cm}^2$ — 96% reduction and the fastest clearing in the exam series. The four-layer defense (optical → ZSI → maintenance switch → STD) with progressive backup and arc-resistant physical protection represents the absolute state of the art in arc flash mitigation.

69. A — $H = 3.0$ (high inertia from flywheel) with 102.5% FLT margin produces small angle advance during the 0.8-second sag. The flywheel absorbs accelerating power and limits angular displacement. Stability is maintained with excellent margin — the flywheel is specifically designed for voltage sag ride-through.

70. D — During a fault on a 450-mile line, the arc at the fault point produces high-frequency noise that interferes with PLC reception, and voltage collapse attenuates the carrier signal. For a line at PLC signal-strength limits, this causes communication failure when the pilot scheme is most needed. Fiber-optic communication (OPGW/ADSS) is immune to these concerns.

71. B — Ratio = $2,500,000/2,000,000 = 1.25$. EGC = $250,000 \times 1.25 = 312,500$ CM. 300 kcmil = 300,000 (below). 350 kcmil = 350,000 (above — adequate). Minimum EGC = 350 kcmil.

72. C — Net Q = $31,864 - 24,000 - 3,571 - 1,463 = 2,830$ kvar. $P_{\text{total}} = 35,119$ kW. PF = $35,119/35,233 = 0.997 \approx 0.99$. Four correction sources reduce reactive demand by 91% while adding 9,000 HP of mechanical output.

73. A — $I_{\text{pu}} = 19.05 + 3.891 + 4.167 + 1.751 + 0.30 + 0.167 + 0.10 = 29.43$. $I = 12,309$ A. Inverter contribution = 1.93%. Three inverter sources totaling 65 MVA contribute less than 2% despite 23% of connected capacity. This drives the need for new protection paradigms as renewable penetration increases.

74. D — $P_{\text{supply}} = 11.6 / (0.72 \times 0.94) = 17.1$ kW. Losses = 5.5 kW = 47.4% of pump power. At 34% of rated speed, motor efficiency drops to 72% and nearly half the input is losses. This represents the economic floor for VFD speed reduction on centrifugal loads.

75. B — At $3.5 \times \text{FLA}$ for 30 seconds: $(3.5)^2 \times 30 = 367.5$ equivalent A^2 -seconds at rated — far exceeding a Class 20 relay's capacity. The motor requires a Class 30/40 relay or a microprocessor relay with adjustable thermal model and motor-starting bypass. High-inertia compressor starting is one of the most challenging motor protection scenarios.

76. C — Total = $150,221 + 12,800 = 163,021$ A. Peak = $2.36 \times 163,021 = 384,730$ A. Approaching 400 kA peak — electromagnetic forces at this level produce structural loads comparable to seismic events, requiring specialized engineering analysis beyond standard electrical ratings.

77. A — At $H = 1.5$ with 3.0 seconds at 55%: the motor loses synchronism within 0.3-0.5 seconds. The combination of lowest H , deepest sag, and longest duration in the exam series makes stability impossible. UV relay MUST trip within 0.3 seconds to prevent catastrophic mechanical damage.

78. D — Adding a third parallel transformer: Z goes from $Z/2$ to $Z/3$. $I_{\text{new}}/I_{\text{old}} = (Z/2)/(Z/3) = 3/2 = 1.50 = 50\%$ increase. $I = 156,887\text{A}$. This 50% increase (not the intuitive 33%) is a common misconception. All downstream equipment must be reverified for the significantly higher fault level.

79. B — Peak = $2.10 \times 30,500 = 64,050\text{A}$. At 64 kA peak on 208V, many standard panelboards (22-42 kA SCCR) are inadequate. The low 4.75% impedance combined with 2,500 kVA produces extremely high fault current requiring careful equipment selection.

80. C — $I = 902.1\text{A}$. OCPD = $125\% \times 902.1 = 1,127.6\text{A} \rightarrow$ next standard = 1,200A. $E = 750 \times 8,760 = 6,570,000 \text{ kWh}$. Cost = \$341,640/year. This \$342,000 annual cost — the highest single-load energy cost in the exam series — makes process optimization and waste heat recovery essential engineering priorities.