PRACTICE EXAM 21: PE POWER SIMULATION (80 QUESTIONS)

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1. A 13.8 kV industrial bus has a three-phase fault level of 520 MVA and currently hosts a 6,000 kvar capacitor bank with a measured resonant harmonic order of h_r = √(520,000/6,000) = 9.31. The bus serves primarily eighteen-pulse and AFE VFDs, but the facility plans to add a large six-pulse VFD-driven compressor (2,000 HP) next quarter. The existing system has no harmonic violations. After the six-pulse VFD is added, the engineer recalculates using the new total capacitor bank of 8,400 kvar: h_r_new = √(520,000/8,400) = 7.87. What is the primary concern with this change?

A. The existing eighteen-pulse drives will generate new harmonics due to the larger capacitor bank size

B. The AFE drives will lose their active filtering capability when the resonance shifts downward

C. The h_r of 9.31 was safely above all characteristic harmonics, but the new h_r of 7.87 is dangerously close to the 7th harmonic injected by the new six-pulse VFD

D. The resonant harmonic order has shifted from a safe position above the 9th harmonic down to near the 7th harmonic — precisely where the new six-pulse VFD injects its largest current (approximately 20% of fundamental); this creates a dual hazard: a new harmonic source AND a resonance tuned to amplify that source; detuning reactors are now mandatory despite the previous harmonic-clean installation

2. A three-phase, 480V system has a 3,000 kVA transformer (Z = 5.75%, X/R = 9). The switchboard feeds a remote MCC through 400 feet of 350 kcmil copper in EMT (R = 0.0367, X = 0.0407 Ω/1000 ft). The MCC has six 200 HP motors (FLA = 242A each, total = 1,452A). During a bolted three-phase fault at the MCC, the motor contribution is 4 × 1,452 = 5,808A. The engineer must calculate the TOTAL first-cycle fault current at the MCC including both the transformer contribution through the cable AND the local motor contribution. What is the approximate total?

A. 36,130A (transformer contribution at the switchboard, ignoring cable)

B. Transformer through cable: cable Z reduces transformer contribution to approximately 27,500A at the MCC; adding motor contribution of 5,808A = approximately 33,300A total first-cycle fault current — this value determines the MCC equipment SCCR rating, which must be verified against the combined utility and motor contributions

C. 5,808A (motor contribution only)

D. 42,000A (switchboard fault current plus motor contribution without cable reduction)

3. Per NEC 430.52(C)(1), a 400 HP, 460V motor (FLA = 477A) uses an instantaneous-trip circuit breaker (motor circuit protector). Per Table 430.52, the maximum for an instantaneous-trip breaker is 800% = 3,816A → next standard 4,000A. The motor has a Design B locked-rotor code letter G (5.6-6.29 kVA/HP). At 460V, LRC ≈ 6.0 × 400 × 1000/(√3 × 460) = 3,012A. The engineer wants the MCP set point at 3,500A (116% of LRC). Per NEC 430.52(C)(2), is this permissible?

A. Yes — NEC 430.52(C)(2) permits adjustable MCPs to be set at any value up to the 800% maximum as long as the setting exceeds the motor's locked-rotor current; the 3,500A setting provides margin above LRC for starting transients while staying well below the 4,000A maximum — this is the standard practice for motor circuit protectors

B. No — MCPs must be set at exactly 800% of FLA

C. No — instantaneous-trip breakers are not permitted above 200 HP

D. Yes — but only with reduced-voltage starting

4. A CT with a ratio of 2000:5 and accuracy class C400 serves a bus differential relay. The bus has five feeders, each with its own CT. During a 35,000A external through-fault on Feeder 3 (X/R = 18), the Feeder 3 CT saturates to 55% of expected output while all other CTs perform correctly. The expected secondary per CT = 87.5A. What is the false differential current, and what relay feature prevents false tripping?

A. False differential = 87.5A (100% error)

B. False differential = 39.4A (87.5 − 48.1); the relay uses a percentage restraint characteristic where the operating threshold increases with restraint current — at 87.5A restraint, a 40% slope threshold = 35.0A; since 39.4A > 35.0A, additional security features are needed

C. False differential = 87.5 − 48.1 = 39.4A; a high-impedance bus differential relay prevents false tripping by forcing all CT saturation voltage to appear across a high-impedance relay element — saturated CTs present low impedance and cannot drive significant current through the high-impedance element, providing inherent security against CT saturation

D. False differential = 0A (bus differential relays automatically compensate for CT saturation)

5. A 345 kV, 450-mile transmission line with $Z_c = 370\ \Omega$ and SIL = 322 MW must transmit 600 MW. The uncompensated stability limit $P_{max} = V^2/X_{total}$ is insufficient. A 50% series compensation

distributed at three locations AND a ±250 Mvar SVC at the receiving end are proposed. With 50% series compensation, the effective reactance is halved. However, at 50% compensation on a 450-mile line, subsynchronous resonance (SSR) is a significant concern for nearby thermal generating units. What is the SSR frequency and why is it dangerous?

A. SSR occurs at the fundamental frequency and is harmless

B. SSR occurs at exactly 60 Hz minus the electrical resonant frequency of the series LC circuit, typically in the 15-45 Hz range; this subsynchronous frequency can couple with the torsional natural frequencies of turbine-generator shaft sections, causing shaft fatigue and potentially catastrophic failure — this is the primary safety concern limiting the degree of series compensation on lines near thermal generators

C. SSR occurs at frequencies above 60 Hz and only affects electronic equipment

D. SSR occurs at the resonant frequency $f_r = f_{nom} \times \sqrt{(X_C/X_L)} \approx 60 \times \sqrt{(0.50)} = 42.4$ Hz; the complementary subsynchronous frequency is $60 - 42.4 = 17.6$ Hz; if this 17.6 Hz matches a torsional mode of a nearby turbine-generator shaft, energy transfer between the electrical system and the mechanical shaft can grow unstably, causing destructive torsional oscillations — this Phenomenon killed a generator shaft at the Mohave Generating Station in 1970 and led to IEEE SSR screening standards

6. Per NEC 250.122(B), a 400A circuit has minimum phase conductors of 500 kcmil (380A at 75°C, meeting the calculated ampacity after the continuous load 125% adjustment yields 400A from a 320A continuous load). The engineer increases to 750 kcmil for voltage drop. Table 250.122 requires 3 AWG (52,620 CM) for 400A. What is the proportionally increased EGC?

A. 3 AWG (no increase required because the OCPD hasn't changed)

B. Ratio = 750,000/500,000 = 1.50; EGC = 52,620 × 1.50 = 78,930 CM → 1 AWG (83,690 CM); the EGC must maintain the impedance ratio with the upsized phase conductors to ensure adequate fault current for OCPD operation

C. 2 AWG (66,360 CM)

D. 1/0 AWG (105,600 CM)

7. A three-phase, 4,160V system has a 10,000 kW load at 0.66 lagging PF. Q = 10,000 × 1.138 = 11,380 kvar. The engineer installs an 8,000 kvar capacitor bank, a 3,000 HP synchronous motor at 0.80 leading PF ($\eta = 94\%$), AND a 1,000 HP synchronous motor at 0.85 leading PF ($\eta = 95\%$). What is the new combined bus power factor?

A. PF = 0.90 lagging

B. PF = 0.95 lagging

C. Motor 1: P_in = 2,383 kW, Q_1 = 1,787 kvar; Motor 2: P_in = 785 kW, Q_2 = 487 kvar; total correction = 8,000 + 1,787 + 487 = 10,274 kvar; net Q = 11,380 − 10,274 = 1,106 kvar; P_total = 13,168 kW; PF = 13,168/13,214 = 0.997 ≈ 0.99 — three simultaneous correction sources nearly eliminate the entire reactive demand while adding 4,000 HP of mechanical output

D. PF = unity

8. A three-phase, 480Y/277V panelboard serves a 100% LED lighting installation in a large retail store. Each phase draws 350A fundamental. The LED drivers produce: 3rd harmonic at 38% of fundamental = 133A, 5th harmonic at 15% = 52.5A, 7th harmonic at 8% = 28A per phase. The neutral current = 3 × 133 = 399A (triplens only). With 4 current-carrying conductors (0.80 factor), what governs conductor selection?

A. I_phase_RMS = $\sqrt{(350^2+133^2+52.5^2+28^2)}$ = √(122,500+17,689+2,756+784) = √143,729 = 379.1A; phase base = 379.1/0.80 = 473.9A; neutral base = 399/0.80 = 498.8A — the NEUTRAL governs at 498.8A because it exceeds the phase requirement; this is the first scenario where triplen-harmonic neutral current dominates conductor sizing

B. Phase governs at 473.9A; neutral is automatically smaller

C. Both require identical ampacity of 475A

D. The OCPD rating alone determines conductor sizing

9. A 200 MVA synchronous generator has X"_d = 0.18 pu, X_2 = 0.20 pu, X_0 = 0.07 pu. The generator has dual grounding: a 1.0 Ω reactor for normal operation that can be switched to a 10 Ω resistor during maintenance. For a bolted SLG fault with the reactor: Z_0_network = j(0.07 + 3×0.207) = j0.691. I_SLG = 3/j(0.18+0.20+0.691) = 3/j1.071 = 2.80 pu. For the resistor: 3R_n(pu) = 3×(10/2.42) = 12.40. Z_0_network = 12.40 + j0.07. I_SLG = 3/(j0.38 + 12.40 + j0.07) = 3/(12.40+j0.45). What is the SLG current with the resistor, and how does the dual grounding provide operational flexibility?

A. I_SLG_reactor = 5.0 pu; I_SLG_resistor = 0.24 pu; no operational benefit

B. I_SLG_reactor = 2.80 pu (reactive); I_SLG_resistor = 3/12.41 = 0.242 pu (resistive); the dual system provides: normal operation with reactor grounding (moderate SLG current at 2.80 pu for fast relay operation with reactive character), and maintenance mode with resistance grounding (very low SLG current at 0.242 pu, predominantly resistive, limiting arc flash energy during maintenance)

C. Both grounding methods produce identical fault currents

D. I_SLG_resistor = 2.80 pu; the resistor has no effect on fault current

10. A three-phase, 4,160V system has an NGR rated 400A, 10 seconds. Three sequential ground faults occur through different fault resistances: Fault 1 (R_f = 5 Ω, cleared in 0.5s), Fault 2 (R_f = 12 Ω, cleared in 1.0s, occurs 3 minutes after Fault 1), Fault 3 (R_f = 20 Ω, cleared in 1.5s, occurs 8 minutes after Fault 2). R_NGR = 6.005 Ω. Calculate the cumulative thermal stress.

A. Fault 1: I = 2,402/11.005 = 218.3A, $(218.3/400)^2 \times (0.5/10)$ = 1.49%; Fault 2: I = 2,402/18.005 = 133.4A, $(133.4/400)^2 \times (1.0/10)$ = 1.11%; Fault 3: I = 2,402/26.005 = 92.4A, $(92.4/400)^2 \times (1.5/10)$ = 0.80%; cumulative = 3.40% — the NGR retains over 96% of its thermal capacity; the decreasing fault current with increasing fault resistance means each successive event poses less thermal stress despite longer clearing times

B. Cumulative = 50% (each fault consumes approximately 16.7%)

C. Cumulative = 100% (three faults always exhaust the NGR)

D. Cumulative = 25%

11. Per NEC 110.26(C)(2), for equipment rated 1,200A or more and over 6 feet wide that contains overcurrent devices or switching devices, a minimum of two entrance/exit doorways is required. The doorways must be located at opposite ends of the working space. What is the minimum width of each doorway?

A. 30 inches

B. 36 inches

C. 24 inches with a minimum height of 6.5 feet

D. 24 inches wide and 6.5 feet high per NEC 110.26(C)(2)

12. A 5,000 kVA, 13.8 kV/480V transformer has core losses of 12,000 W and full-load copper losses of 38,000 W. The facility has three distinct operating modes over a 24-hour cycle: 10 hours at 100% load (PF = 0.92), 8 hours at 60% load (PF = 0.85), and 6 hours at 25% load (PF = 0.75). k_max = $\sqrt{(12{,}000/38{,}000)}$ = 56.2%. The all-day efficiency computation requires energy input and output for each period. Which period operates closest to k_max, and what is the approximate all-day efficiency?

A. The 100% period is closest; all-day η ≈ 98.5%

B. The 25% period is closest; all-day η ≈ 96.5%

C. The 60% period operates closest to k_max (56.2%); at this loading, core losses approximately equal copper losses, maximizing instantaneous efficiency; all-day η calculation: E_out = (5,000×1.0×0.92×10) + (5,000×0.6×0.85×8) + (5,000×0.25×0.75×6) = 46,000 + 20,400 + 5,625 = 72,025 kWh; E_loss = 10×(12+38)/1000 + 8×(12+13.68)/1000 + 6×(12+2.375)/1000 = 0.50 + 0.205 + 0.086 = 0.791 MWh; η ≈ 72,025/(72,025+791) = 98.9%

D. All three periods operate at equal efficiency

13. A protection coordination study on a 4,160V system involves a 51 relay (IEEE extremely inverse, TD = 1.5, pickup = 4A on 400:5 CT) that must coordinate with both a downstream 200E fuse (total clearing = 0.006s at 10,000A) AND an upstream 51 bus relay. At the maximum downstream fault of 10,000A: relay secondary = 125A; M = 125/4 = 31.25. Using $t = TD \times (28.2/(M^2-1) + 0.1217)$, what is the relay operating time?

A. t = 1.5 × (28.2/976 + 0.1217) = 1.5 × (0.0289 + 0.1217) = 1.5 × 0.1506 = 0.226s; CTI with fuse = 0.220s — barely adequate; the extremely inverse characteristic provides excellent coordination at high fault levels

B. t = 0.226s; CTI = 0.220s — adequate but with minimal margin above the 0.20s minimum; at this high multiple of pickup (31.25×), the extremely inverse characteristic produces fast operation — this is exactly the scenario where extremely inverse relays excel

C. t = 0.50s; excessive margin

D. t = 0.10s; below minimum CTI

14. A distance relay on a 230 kV line has Zone 1 at 85% (Z_line = 7 + j80 Ω), Zone 2 at 120% (0.35s). A fault occurs at 78% of the line through 8 Ω fault resistance. Z_meas = (0.78×7 + 8) + j(0.78×80) = 13.46 + j62.4 Ω. |Z_meas| = 63.8 Ω. Zone 1 reach = 68.3 Ω. The fault is within Zone 1 magnitude. However, the mho relay MTA = 80°. The impedance angle θ = arctan(62.4/13.46) = 77.8°. Is the fault securely inside the mho circle?

A. No — the impedance is outside the mho circle because 77.8° < 80° MTA

B. Yes — but marginally; the 8 Ω resistance shifts the impedance rightward on the R-X diagram

C. No — any fault resistance above 5 Ω is outside the mho circle for this line impedance angle

D. Yes — the measured impedance angle of 77.8° is very close to the MTA of 80°, and the magnitude of 63.8 Ω is well within the 68.3 Ω reach; the fault is securely inside the mho circle because the R-X point falls within the circular characteristic defined by the MTA and reach; the small angular difference (2.2°) combined with the significant magnitude margin (6.6%) places this fault reliably within Zone 1

15. A three-phase, 460V, 6-pole, 500 HP induction motor drives a centrifugal compressor through a VFD. Design: 373 kW at 1,170 RPM. The facility operates at four load conditions: 100% speed (1,500 hr/yr), 85% speed (2,800 hr/yr), 70% speed (2,960 hr/yr), and 50% speed (1,500 hr/yr). Using $P \propto n^3$, what is the annual energy savings versus full-speed operation at $0.079/kWh?

A. VFD saves $50,000/year — minimal reduction

B. VFD saves $100,000/year — moderate reduction

C. 100%: 373×1,500 = 559,500; 85%: 373×0.614×2,800 = 641,546; 70%: 373×0.343×2,960 = 378,681; 50%: 373×0.125×1,500 = 69,938; VFD = 1,649,665; full = 373×8,760 = 3,267,480; savings = 1,617,815 × $0.079 = $127,807/year — the cubic relationship produces 49.5% energy reduction across the four operating modes

D. VFD saves $200,000/year — extreme reduction

16. Per NEC 480.9(A), ventilation for battery rooms must limit H_2 below 1%. A large hospital UPS uses 840 vented nickel-cadmium (NiCd) cells charging at 0.006 ft^3 H_2/cell/hour. Room = 10,000 ft^3. What is the required ACH, and what NiCd-specific corrosion concern must the ventilation system address?

A. H_2 = 840 × 0.006 = 5.04 ft^3/hr; max H_2 = 100 ft^3; ACH = 0.050; the critical NiCd concern is potassium hydroxide (KOH) mist generated during charging — KOH is highly corrosive to copper, aluminum, steel, and electronic components; the exhaust system must use corrosion-resistant materials (PVC, stainless steel, or coated ductwork) and the exhaust must be directed away from other equipment rooms, HVAC intakes, and occupied spaces

B. ACH = 0.050; no special concerns for NiCd cells

C. ACH = 5.0; NiCd cells produce excessive hydrogen requiring industrial-grade ventilation

D. No ventilation required — NiCd cells produce less hydrogen than lead-acid

17. A 230 kV, 380-mile transmission line with SIL = 140 MW must transmit 300 MW during peak and 25 MW during off-peak. A 40% series compensation is installed at two points, two 100 Mvar switchable shunt reactors at the receiving end, and a ±180 Mvar SVC at the receiving end. During a unit trip at a

nearby generating station, the line loading suddenly increases from 200 MW to 350 MW (above the series-compensated stability limit of 400 MW). What is the SVC's role during this post-contingency transient?

A. The SVC does nothing during transient events — it only operates in steady state

B. The SVC provides var support only, with no impact on transient stability

C. The SVC trips offline to protect itself from the transient overload condition

D. The SVC responds within 1-2 cycles, injecting up to +180 Mvar of reactive power to support the receiving-end voltage during the post-contingency power surge; this fast voltage support directly improves transient stability by maintaining the electrical power transfer capability (P ∝ V_SV_R/X) during the critical first-swing period — without the SVC's rapid response, the voltage dip from the sudden load increase could push the system toward angular instability before slower-responding devices (reactor switching, generator excitation) can act

18. A separately excited DC motor has V_t = 500V, I_a = 250A, R_a = 0.06 Ω. Rated speed = 1,200 RPM. E_a = 500 − 250×0.06 = 485V. The motor drives a mine hoist. For speed control below rated, the armature voltage is reduced by a thyristor converter. For speed control above rated (field weakening), the field current is reduced while V_t remains at 500V. At 150% speed (1,800 RPM) with field weakened to 67%: E_a_new = 0.67 × 485 × (1,800/1,200) = 487.5V. I_a = (500 − 487.5)/0.06 = 208.3A. What is the motor's power output at this operating point?

A. P = E_a × I_a = 487.5 × 208.3 = 101,546W = 101.5 kW — but this exceeds rated power

B. P = E_a_new × I_a = 487.5 × 208.3 = 101,546W ≈ 101.5 kW; this is 83.7% of rated power (121.3 kW); in the field-weakened region, although speed increases, the available torque decreases proportionally (constant-power region) — the motor operates at reduced torque (T = P/ω) but with nearly equal armature current, maintaining near-rated thermal loading

C. P = 121.3 kW (always rated power in field-weakened region)

D. P = 50 kW (power decreases linearly with field weakening)

19. Per NEC 250.30(A)(1) and 250.36, a large data center uses a high-resistance grounded (HRG) 480V system derived from delta-wye isolation transformers. Each isolation transformer creates a separately derived system. The HRG system uses a neutral grounding resistor that limits ground-fault current to 5A. Per NEC 250.36(A), each HRG system must have a ground-fault detection system (GFD). How many GFD systems are required for 10 isolation transformers?

A. One — a single GFD monitors the entire 480V system

B. Five — one GFD per two transformers

C. Ten — each isolation transformer creates an independent HRG separately derived system requiring its own GFD per NEC 250.36(A); each GFD must be capable of detecting a ground fault on its associated derived system and alarming to maintenance personnel within one second

D. Zero — HRG systems do not require ground-fault detection

20. A three-phase, 480V, 1,600A switchgear has an available fault current of 75,000A and a main LVPCB with 0.30-second STD. The arc flash study shows 58 cal/cm^2 at 24 inches. The engineer designs a five-layer mitigation strategy: (1) ZSI (0.05s for bus faults), (2) optical relay (0.020s), (3) arc-resistant switchgear (Type 2B), (4) remote racking, (5) permanent-magnet trip with an energy-reducing maintenance switch (ERMS) at 0.04s. For a bus fault with the optical relay AND ERMS active, what is the fastest achievable clearing time?

A. 0.04s (ERMS controls)

B. 0.05s (ZSI controls)

C. 0.30s (normal STD always controls)

D. The optical relay provides the fastest clearing at approximately 0.020-0.025 seconds; the ERMS (0.04s) provides backup if the optical relay fails; ZSI (0.05s) provides tertiary backup; the calculated energy at 0.022s: $E = 58 \times (0.022/0.30) = 4.25$ cal/cm^2; with the arc-resistant enclosure redirecting energy, the worker's effective exposure is near zero

21. A synchronous generator rated 400 MVA, 26 kV has X"_d = 0.25 pu, $X_2 = 0.27$ pu, $X_0 = 0.12$ pu. The generator is solidly grounded. I_3Φ = 4.0 pu. I_SLG = 3/(0.25+0.27+0.12) = 4.69 pu. The SLG exceeds three-phase by 17.2%. The generator is then switched to high-resistance grounding (3R_n = 50 pu). I_SLG_HRG = 3/(j0.64 + 50 + j0.12) = 3/|50.004| = 0.060 pu. What does this comparison reveal about grounding system selection?

A. Solidly grounded: I_SLG = 4.69 pu exceeds I_3Φ = 4.0 pu by 17%, producing the highest faulted-phase current of any fault type — this drives equipment ratings upward; HRG: I_SLG = 0.060 pu (1.3% of solidly grounded value), virtually eliminating arc flash hazard during ground faults but requiring ground-fault detection and alarm systems since overcurrent relays cannot detect 0.060 pu; the trade-off is between fast, reliable overcurrent clearing (solidly grounded) and minimal ground-fault damage (HRG)

B. Both grounding systems produce identical SLG fault currents

C. HRG always produces higher fault current than solidly grounded systems

D. The solidly grounded system is always superior for all applications

22. A 480V, three-phase panelboard has: Motor 1 = 477A (400 HP, largest), Motor 2 = 361A (300 HP), Motor 3 = 302A (250 HP). Continuous lighting = 250A. Noncontinuous receptacles = 75A. Per NEC 430.24 and 215.2(A)(1), what is the minimum feeder conductor ampacity?

A. 1,500A

B. 125% × 477 + 361 + 302 + 125% × 250 + 75 = 596.25 + 663 + 312.5 + 75 = 1,646.75A

C. 1,800A

D. 1,250A

23. A three-phase, 4,160V industrial bus has eight sources. On a 40 MVA base: Transformer A (Z = 0.04 pu), Transformer B (Z = 0.06 pu), Transformer C (Z = 0.08 pu), Transformer D (Z = 0.10 pu), Generator E (X"_d = 0.35 pu), Generator F (X"_d = 0.50 pu), Synchronous Condenser G (X"_d = 0.80 pu), Battery Inverter H (effective Z = 5.0 pu). I_base = 5,552A. What is the total fault current?

A. I = (25.0 + 16.67 + 12.5 + 10.0 + 2.857 + 2.0 + 1.25 + 0.20) × 5,552 = 70.477 × 5,552 = 391,369A — eight sources produce this extreme fault current; the battery inverter contributes only 0.3% despite its large kVA rating because inverter-based sources have inherently high effective impedance limiting fault contribution to 1.0-1.2× rated current

B. 200,000A

C. 500,000A

D. 300,000A

24. A 480V, three-phase, 600A switchboard has an available fault current of 60,000A. The switchboard SCCR is 65,000A (adequate). A downstream 400A panelboard has SCCR of 22,000A. The feeder cable is 250 feet of 500 kcmil copper in steel conduit (R = 0.0276, X = 0.0391 Ω/1000 ft). Does the cable reduce the fault current below the panelboard's SCCR? Additionally, 4 motors at the panelboard (FLA = 200A each) add 3,200A motor contribution. What is the total fault current at the panelboard?

A. 60,000A (cable has no effect)

B. Transformer contribution through cable ≈ 45,000A; motor = 3,200A; total = 48,200A; exceeds 22,000A SCCR

C. Cable reduces transformer contribution: Z_cable = $\sqrt{((0.0276\times0.25)^2 + (0.0391\times0.25)^2)}$ = 0.01197 Ω; Z_base ≈ 0.0922; Z_cable_pu = 0.130; total Z ≈ 0.0575 + 0.130 = 0.187; I_transformer = 3,007/0.187 ≈ 16,080A; add 3,200A motor = 19,280A — below the 22,000A SCCR; the installation is code-compliant WITHOUT a series-rated combination

D. 10,000A (cable dramatically reduces fault current)

25. Per NEC 690.12, a large commercial rooftop PV system uses central inverters with 24 modules per string in series (V_oc = 44V per module = 1,056V). Module-level rapid shutdown devices compliant with UL 1741 are installed. During rapid shutdown, each device reduces module output to 1V per module. What is the string voltage after rapid shutdown, and is the system compliant with NEC 690.12(B)(2)?

A. String voltage = 24 × 44 = 1,056V — rapid shutdown devices are non-functional

B. String voltage = 24 × 1V = 24V — well below the 80V threshold; the system is compliant with NEC 690.12(B)(2) because each module-level device reduces its output to 1V, and the series string of 24 × 1V = 24V is within the 80V array-boundary voltage limit within 30 seconds of rapid shutdown initiation

C. String voltage = 80V exactly (devices regulate to the limit)

D. String voltage = 528V (only half the devices activate)

26. A three-phase, 480V system has three transformers in parallel: T1 = 3,000 kVA (Z = 5.50%), T2 = 2,500 kVA (Z = 5.75%), T3 = 2,000 kVA (Z = 6.00%). Individual contributions: I_T1 = 65,600A, I_T2 = 52,296A, I_T3 = 38,849A. Total = 156,745A. Additionally, 20 motors (FLA = 3,500A) contribute 14,000A first-cycle. Grand total = 170,745A. Weighted X/R ≈ 8.5. IEEE multiplier = 2.34. What is the peak asymmetrical current?

A. 241,500A ($\sqrt{2}$ × total)

B. 341,490A (2× total)

C. 170,745A (no asymmetry)

D. Peak = 2.34 × 170,745 = 399,543A — nearly 400,000 amperes peak; the electromagnetic forces on bus structures are proportional to I^2_peak = 1.60×10^{11} A^2; this requires extreme mechanical bracing design that dominates the engineering cost and physical size of the paralleled 480V bus system

27. A distance relay on a 138 kV line (Z_line = 3.5 + j42 Ω) has Zone 1 at 85% and Zone 2 at 120% (0.35s). A bolted three-phase fault occurs at 90% of the line. The DCB pilot scheme is active with a healthy channel. The near end detects the fault in Zone 2 (90% > 85%). The remote end detects the fault at 10% from its terminal (within its Zone 1). Neither terminal sends a blocking signal because both see the fault as forward. What happens at both terminals?

A. Both terminals trip with high-speed clearing via the DCB scheme — the near end's Zone 2 trips instantaneously (no blocking signal received) and the remote end's Zone 1 trips instantaneously; the DCB scheme enables high-speed fault clearing at BOTH ends even though the fault exceeds the near end's Zone 1 reach, because the absence of a blocking signal permits immediate tripping

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

C. Both trip on Zone 2 after 0.35 seconds

D. Neither trips — DCB requires positive permission, not absence of blocking

28. A protection engineer designs a generator differential relay (87G) for a 250 MVA, 18 kV machine. The relay has a dual-slope characteristic: 10% below 1.0 pu restraint and 40% above 2.0 pu restraint (linear interpolation between). During an internal turn-to-turn fault, the differential current is only 0.15 pu with a restraint current of 0.8 pu. At this low restraint, the 10% slope applies: threshold = 10% × 0.8 = 0.08 pu. Since 0.15 > 0.08, the relay correctly detects the internal fault. If the slope were set at 25% (a common setting for transformer differential), what would happen?

A. The relay would still detect the fault (0.15 > 0.08 regardless of slope)

B. Threshold at 25% = 25% × 0.8 = 0.20 pu; since 0.15 < 0.20, the relay FAILS to detect the internal turn-to-turn fault — this is why generator differential relays use a much lower minimum slope than transformer differential relays; generators have no inrush or tap changes, so the lower slope provides the sensitivity needed to detect low-magnitude internal faults

C. The slope setting has no effect on relay sensitivity for internal faults

D. The 25% slope provides better security and should always be used

29. Per NEC 450.3(B), a 1,500 kVA, 480V/208Y/120V transformer has primary current of 1,804A. At 125% = 2,255A. The next standard above 2,255A per NEC 240.6(A) is 2,500A. The secondary current = 4,164A. Per NEC 450.3(B), if primary protection is provided at the next standard above 125% (2,500A), is secondary protection required?

A. Yes — secondary protection is always required regardless of primary protection

B. Per NEC 450.3(B), when primary overcurrent protection is provided at not more than 125% (or the next higher standard size), secondary protection is NOT required for transformers 600V and below; the 2,500A primary OCPD satisfies the requirement and no secondary OCPD is needed

C. Yes — but only for transformers above 1,000 kVA

D. No — but only because the transformer is below 2,000 kVA

30. A three-phase, 4,160V, 6-pole synchronous motor rated 5,000 HP drives a cement kiln at 1,200 RPM. Pull-out = 250% FLT. H = 2.2 MJ/MVA. S_rated = 4,357 kVA. During a system disturbance, voltage sags to 73% for 0.8 seconds. Pull-out = 182.5% FLT. Kiln = 100% FLT. Margin = 82.5% FLT. The engineer must perform a simplified swing analysis. During the sag, the electrical power output capability is reduced. If the motor was delivering 100% FLT and the available power transfer drops to approximately 73% × P_rated (simplified estimate), then P_accel ≈ P_mech − P_elec = 1.0 − 0.73 = 0.27 × P_rated. Using P_rated = 3.73 MW: $\Delta\delta = (180 \times 60 \times 0.27 \times 3.73 \times 0.8^2)/(2.2 \times 4.357)$. What is the approximate angle advance?

A. $\Delta\delta \approx 10°$ — easily stable

B. $\Delta\delta \approx 25°$ — stable with good margin

C. $\Delta\delta \approx 60°$ — marginally stable; detailed analysis required

D. $\Delta\delta = (180 \times 60 \times 1.007 \times 0.64)/(9.585) = (180 \times 60 \times 0.6445)/9.585 = 6{,}960.6/9.585 = 726°$... clearly the simplified formula must use per-unit or consistent units; using P_a = 0.27 per unit of S_rated = 0.27 × 4.357 = 1.176 MVA: $\Delta\delta = (180\times60\times1.176\times0.64)/(2.2\times4.357) = 8{,}145/9.585 = 849°$... still unrealistic; the formula Δδ(degrees) = 180f×P_a(MW)×t^2/(H×S_MVA) with f=60, P_a=1.007MW, $t^2=0.64$, H=2.2, S=4.357: = 180×60×1.007×0.64/(2.2×4.357) = 6,960/9.59 = 726°; this enormous angle confirms certain loss of synchronism — the 0.8-second sag at 73% with moderate H = 2.2 produces catastrophic instability

31. A 480V, three-phase system has five parallel transformers: T1 = 3,000 kVA (Z = 5.50%), T2 = 2,500 kVA (Z = 5.75%), T3 = 2,000 kVA (Z = 6.00%), T4 = 1,500 kVA (Z = 6.25%), T5 = 1,000 kVA (Z = 6.50%). On a 3,000 kVA common base: Z_T1 = 0.055, Z_T2 = 0.069, Z_T3 = 0.09, Z_T4 = 0.125, Z_T5 = 0.195. What percentage of a combined load does T1 carry, and what is the total fault current?

A. 1/Z_T1 = 18.18; 1/Z_T2 = 14.49; 1/Z_T3 = 11.11; 1/Z_T4 = 8.0; 1/Z_T5 = 5.13; sum = 56.91; T1 share = 18.18/56.91 = 31.9%; individual fault contributions: I_T1 = 65,600, I_T2 = 52,296, I_T3 = 38,849, I_T4 = 27,972, I_T5 = 17,939; total = 202,656A — five parallel transformers produce over 200 kA symmetrical, requiring a bus rated for approximately 470 kA peak asymmetrical

B. T1 carries 20% (equal shares); total = 150,000A

C. T1 carries 40%; total = 250,000A

D. T1 carries 50%; total = 100,000A

32. A 13.8 kV system has voltage THD = 14.2% at the PCC. Harmonics: V_5 = 10.8%, V_7 = 7.1%, V_{11} = 4.5%, V_{13} = 3.2%, V_{17} = 1.9%, V_{19} = 1.2%. IEEE 519: individual ≤ 3.0%, THD ≤ 5.0%. How many individual harmonic violations exist, and what is the recommended multi-phase remediation strategy?

A. Two violations (V_5 and V_7 only)

B. Three violations

C. Five individual violations (V_5, V_7, V_{11}, V_{13} all exceed 3.0%) plus THD violation — wait, V_{17} = 1.9% < 3.0% and V_{19} = 1.2% < 3.0%; so four individual violations (V_5, V_7, V_{11}, V_{13}) plus THD; Phase 1: retrofit six-pulse VFDs to 18-pulse/AFE (eliminates 5th, 7th); Phase 2: verify V_{11} and V_{13} after source mitigation; Phase 3: install tuned passive filters for remaining violations; Phase 4: verify THD < 5.0% after all corrections

D. Six violations

33. A ground resistance test on a nuclear power plant site measures 0.3 Ω during fall conditions. The IEEE 80 design target is 0.1 Ω. The IEEE 81 seasonal correction is 1.4 for this clay soil. Corrected = 0.42 Ω — 4.2× the target. The plant's grounding system consists of a ground grid, deep wells, and connections to all underground infrastructure. What additional measures might achieve the 0.1 Ω target?

A. No additional measures possible — 0.1 Ω is unachievable

B. Install chemical ground rods around the perimeter

C. Replace the existing grid with a new design

D. The 0.42 Ω corrected value is 4.2× the 0.1 Ω target; potential measures: (1) expand the grid beyond the plant footprint ($R \propto 1/\sqrt{A}$), (2) increase grid conductor density (closer spacing), (3) add more deep ground wells to reach lower-resistivity layers, (4) apply GEM around all conductors and wells, (5) install counterpoise conductors radiating outward from the grid — nuclear plants may also use continuously wetted ground systems or hybrid approaches combining all methods to achieve ultra-low resistance targets required for nuclear safety analysis

34. A three-phase, 460V, 2-pole induction motor rated 700 HP has $\eta = 96.8\%$, PF = 0.91 lagging. No-load magnetizing kvar = 95 kvar. An 80 kvar capacitor is proposed. Per NEC 460.9, is 80 kvar safe? What is the corrected PF?

A. Unsafe — 80 kvar is too close to the 95 kvar limit for safe operation

B. Safe — 80 kvar is 84% of the 95 kvar no-load magnetizing, below the self-excitation threshold; however, 84% is well above manufacturers' typical 67% recommendation; P_in = 540 kW; Q_orig = $\sqrt{(540/0.91)^2 - 540^2} = 246$ kvar; Q_new = 166 kvar; PF_new = $540/\sqrt{540^2+166^2} = 540/565 = 0.956$; the engineer should obtain the motor manufacturer's explicit approval before installing at 84% of no-load magnetizing

C. Unsafe — exceeds the IEEE standard maximum

D. Safe — no manufacturer approval needed below 90%

35. A three-phase, 460V, 8-pole VFD-driven motor operates a cooling tower fan at design: 300 kW at 877 RPM. Five operating modes: full (1,800 hr/yr), 90% (2,000 hr/yr), 75% (2,200 hr/yr), 60% (1,500 hr/yr), 40% (1,260 hr/yr). Using $P \propto n^3$, what is the total annual VFD energy, full-speed energy, and savings at $0.078/kWh?

A. 90%: 300×0.729×2,000 = 437,400; 75%: 300×0.422×2,200 = 278,520; 60%: 300×0.216×1,500 = 97,200; 40%: 300×0.064×1,260 = 24,192; full: 300×1,800 = 540,000; VFD = 1,377,312; full-speed = 300×8,760 = 2,628,000; savings = 1,250,688 × $0.078 = $97,554/year

B. Savings = $50,000/year

C. Savings = $150,000/year

D. Savings = $200,000/year

36. A 480V, three-phase, 200A feeder uses 350 kcmil THHN copper in steel conduit (R = 0.0367, X = 0.0407 Ω/1000 ft). The feeder is 700 feet long and serves a load at 0.82 lagging PF. What is the voltage drop percentage?

A. 2.0%

B. 2.5%

C. V_drop = √3 × 200 × (0.0367×0.7×0.82 + 0.0407×0.7×0.572) = 346.4 × (0.02106 + 0.01629) = 346.4 × 0.03735 = 12.94V; 12.94/480 = 2.69% ≈ 2.7% — within the NEC 3% feeder recommendation but with limited margin at this very long run

D. 4.0%

37. A 100 MVA, 345/138 kV autotransformer has Z = 11% on its own base. Three identical units in parallel. A 60 MVA generator (X"_d = 0.20 pu), a 40 MVA synchronous condenser (X"_d = 0.15 pu), a 25 MVA synchronous motor (X"_d = 0.22 pu), and a 15 MVA solar inverter array (effective X"_d = 1.0 pu) are on the 138 kV bus. On 100 MVA base, what is the total fault current?

A. I = (27.27 + 2.50 + 2.667 + 1.136 + 0.15) × 418.4 = 33.72 × 418.4 = 14,107A

B. 10,000A

C. 20,000A

D. Z_T_par = 0.11/3 = 0.0367; Z_gen = 0.333; Z_SC = 0.375; Z_SM = 0.88; Z_solar = 6.667; I = (27.27+3.003+2.667+1.136+0.15) × 418.4 = 34.23 × 418.4 = 14,320A — the three autotransformers dominate at 80%, while the solar inverter's high impedance limits its contribution to only 0.4% of total despite its 15 MVA rating

38. A 480V, three-phase system has a 3,500 kVA transformer (Z = 5.75%, X/R = 9) and a 2,500 kVA transformer (Z = 6.00%, X/R = 8) in parallel. I_T1 = 42,200A; I_T2 = 48,517A. Wait — I_T2 = 3,007/0.06 = 50,117A with infinite source. Total = 92,317A plus 15 motors (FLA = 3,000A) contributing 12,000A first-cycle. Grand total = 104,317A. Weighted X/R ≈ 8.5. Multiplier = 2.34. What is the peak asymmetrical?

A. 147,500A (√2 × total)

B. Peak = 2.34 × 104,317 = 244,102A — this extreme peak current determines the close-and-latch rating for all switching equipment and the mechanical bracing for the paralleled bus structure

C. 208,634A (2× total)

D. 104,317A (no asymmetry)

39. Per NEC 250.53(A)(2), an engineer tests a new telecommunications facility's grounding and finds 35 Ω with two driven rods. The facility requires IEEE 142-recommended ≤5 Ω. The soil resistivity measures 800 Ω-m (high clay content). A concrete-encased electrode (Ufer ground) exists per NEC 250.52(A)(3) in the building foundation. The engineer measures the Ufer ground alone at 3.2 Ω. When

the Ufer ground is connected in parallel with the two driven rods, what is the approximate combined resistance?

A. R_combined ≈ (3.2 × 35)/(3.2 + 35) = 112/38.2 = 2.93 Ω — below the 5 Ω target; the Ufer ground dominates the parallel combination because its resistance (3.2 Ω) is much lower than the rod grid (35 Ω); the combined resistance is always less than the lowest individual element; this demonstrates why Ufer grounds are extremely effective in high-resistivity soil

B. R_combined = 35 Ω (the rods dominate)

C. R_combined = 38.2 Ω (resistances add in parallel... incorrectly stated as adding)

D. R_combined = 3.2 Ω (the Ufer ground alone, rods have no effect)

40. A 480V, three-phase system has a 3,000 kVA transformer (Z = 5.75%) feeding a switchboard. A 800-foot cable of 4/0 AWG copper in PVC conduit (R = 0.0608, X = 0.0532 Ω/1000 ft) feeds a remote panelboard. At the remote panelboard, the engineer needs to verify that the available fault current is still adequate for the 100A main breaker to clear faults within its rated time. What is the available fault current?

A. Cable Z: R = 0.04864, X = 0.04256 Ω; Z_base = 0.0768 Ω; Z_cable_pu = 0.0647/0.0768 = 0.842; Total Z = 0.0575 + 0.842 = 0.900; I = 3,608/0.900 = 4,009A

B. 25,000A

C. I = 3,608/0.900 = 4,009A — the extremely long 4/0 cable run reduces fault current to only 11% of the switchboard value; while this dramatically reduces arc flash energy, the engineer must verify that the 100A breaker's instantaneous trip setting can still operate at this reduced current level and that the breaker can clear faults within its rated interrupting time

D. 36,130A (unchanged by cable)

41. A 60 MVA, 138/13.8 kV, delta-wye grounded transformer has Z_1 = j0.09 pu, Z_0 = j0.06 pu on its own base. The 138 kV source has Z_1_src = j0.05 pu and Z_0_src = j0.15 pu on the transformer base. On a 100 MVA base: Z_1_total = (0.09+0.05)×100/60 = 0.2333 pu. But the delta BLOCKS source Z_0, so Z_0_total = 0.06×100/60 = 0.10 pu. The engineer incorrectly includes source Z_0: Z_0_wrong = (0.06+0.15)×100/60 = 0.35 pu. What is the error in the SLG fault calculation if source Z_0 is incorrectly included?

A. I_SLG_correct = 3/(0.2333+0.2333+0.10) = 5.29 pu; I_SLG_wrong = 3/(0.2333+0.2333+0.35) = 4.18 pu — the incorrect calculation understates the SLG by 21%

B. I_SLG_correct = 4.18 pu; I_SLG_wrong = 5.29 pu (error overstates the fault)

C. No error — source Z_0 always flows through the delta

D. I_SLG_correct = 5.29 pu; I_SLG_wrong = 4.18 pu; the error is 21% understated; failing to recognize that the delta blocks source Z_0 causes the engineer to include impedance that does not exist in the zero-sequence circuit, making the calculated SLG 21% lower than reality — this means equipment may be underrated and protection settings too insensitive for the actual fault current

42. A three-phase, 460V, 4-pole induction motor rated 400 HP has PF = 0.89, $\eta = 96.2\%$. No-load magnetizing = 68 kvar. A 50 kvar capacitor is installed (73.5% of no-load mag — safe). The motor operates a centrifugal pump through a VFD. When the VFD reduces speed to 70%, the motor draws approximately 35% of rated power (affinity law). At reduced load, the motor's no-load magnetizing kvar drops to approximately 75% of full value (51 kvar). Is the 50 kvar capacitor still safe at reduced load?

A. Yes — 50 kvar is always safe regardless of operating speed or load

B. At reduced load with VFD operation, the motor's no-load magnetizing kvar drops to approximately 51 kvar; the 50 kvar capacitor now represents 98% of no-load magnetizing — dangerously close to self-excitation; if the VFD trips and the motor coasts with the capacitor still connected, self-excitation is likely; the capacitor should be switched off during reduced-speed operation or interlocked with the VFD

C. No — 50 kvar is never safe for VFD-driven motors

D. No — but only at speeds below 50% of rated

43. A CT with a ratio of 1200:5 (C200) and a total burden of 1.8 Ω is used for overcurrent protection. At a 20× rated fault (24,000A), the CT produces 100A secondary. The burden voltage = 100 × 1.8 = 180V. The C200 rating guarantees accuracy at 20× up to 200V. With 20V margin, the CT is adequate. However, during a motor starting event, the CT sees 6× rated (7,200A) with 60% second harmonic content in the inrush waveform. How does the second harmonic affect the CT?

A. Second harmonic causes the CT core to saturate faster because the combined fundamental and second harmonic flux peaks exceed the fundamental-alone flux peak by approximately 60% — the core may temporarily saturate during the harmonic peaks even though the fundamental current is well within the C200 rating; this can cause the overcurrent relay to see distorted, reduced secondary current, potentially delaying trip decisions during motor-starting fault scenarios

B. Second harmonic has no effect on CT performance

C. Second harmonic improves CT accuracy by reducing core flux

D. CT is only affected by harmonics above the 5th order

44. A balanced three-phase, 208Y/120V panelboard serves a large office building. Phase A draws 350A fundamental + 105A 3rd harmonic + 42A 5th. Phase B draws 320A fundamental + 96A 3rd + 38A 5th. Phase C draws 380A fundamental + 114A 3rd + 46A 5th. The system is UNBALANCED. The neutral current is NOT simply 3 × I_3rd. For unbalanced systems, neutral current = $\sqrt{((I\_A3 - I\_B3)^2 + (I\_B3 - I\_C3)^2 + (I\_A3 - I\_C3)^2)}$ for fundamental unbalance PLUS 3 × average I_3rd for triplens. What is the dominant neutral current component?

A. The fundamental unbalance produces negligible neutral current (phases nearly balanced)

B. The 5th harmonic dominates neutral current because it doesn't cancel in balanced systems

C. The neutral carries the vector sum of all harmonic and fundamental currents from each phase

D. The dominant component is the triplen (3rd harmonic) sum: I_neutral_3rd = I_A3 + I_B3 + I_C3 = 105 + 96 + 114 = 315A; the fundamental unbalance contribution is I_neutral_fund ≈ |380−320| ≈ 60A peak-to-peak ≈ 35A RMS; the 5th harmonic cancels in a three-phase system (even unbalanced, the residual 5th is small); total neutral ≈ $\sqrt{(315^2 + 35^2)}$ = 317A — triplens overwhelmingly dominate

45. Per NEC Article 517.17(A), a hospital's LIM alarms at 5 mA. A surgical suite is planning a complex multi-room procedure using 5 operating rooms simultaneously, each with 12-15 devices. The total hazard current across five panels is: Panel A = 4.5 mA, Panel B = 4.7 mA, Panel C = 4.1 mA, Panel D = 3.8 mA, Panel E = 4.3 mA. A new imaging device (0.6 mA) must be added to one panel. Only Panel D can accept it (3.8 + 0.6 = 4.4 mA < 5.0). However, the imaging device is physically located in Room A (Panel A territory). Is it acceptable to power a Room A device from Panel D?

A. No — each device must be powered by the panel serving that room

B. Yes — but only during emergency procedures

C. Yes — cross-panel connections within the same surgical suite are acceptable when the originating panel cannot accept the device without exceeding the 5 mA threshold; Panel D (Room D) can supply the imaging device in Room A through properly installed permanent wiring; this is standard biomedical engineering practice to distribute hazard current across available isolated power systems

D. No — but a portable isolation transformer can be used instead

46. A 345 kV, three-phase transmission line has V_S = 365 kV, V_R = 338 kV at 950 MW, 0.90 lagging PF. Line X = 55 Ω. The line also has a 40% series capacitor (X_C = 22 Ω). What is the effective line reactance, the power angle, voltage regulation, and stability fraction with and without the series compensation?

A. Without: X_eff = 55; sin δ = 950×55/(365×338) = 52,250/123,370 = 0.424; δ = 25.1°; VR = 7.99%; stability = 42.4%. With: X_eff = 33; sin δ = 950×33/(365×338) = 31,350/123,370 = 0.254; δ = 14.7°; stability = 25.4% — the series compensation reduces the power angle from 25.1° to 14.7° and the stability fraction from 42.4% to 25.4%, INCREASING the stability margin from 57.6% to 74.6%; this demonstrates how series compensation improves stability by reducing the effective electrical length of the line

B. Both cases produce identical stability margins

C. Series compensation worsens stability

D. The line cannot transmit 950 MW with or without compensation

47. A recloser on a 12.47 kV feeder coordinates with a 250A lateral fuse. At 8,000A: fuse MM = 0.015s, fuse TC = 0.03s, recloser fast = 0.012s, recloser delayed = 0.10s. A permanent cable fault occurs. The recloser fast-trips (0.012s < 0.015s MM → fuse saved). After reclosure, the fault persists. On the delayed trip, the recloser time (0.10s) exceeds the fuse TC (0.03s). What is the sequence?

A. The recloser locks out before the fuse can blow

B. The fuse blows at 0.03 seconds during the delayed trip, the recloser holds, and service is restored to unfaulted sections — this is the designed fuse-clearing sequence for permanent faults under fuse-saving coordination

C. Both the recloser and fuse operate simultaneously at 0.03 seconds

D. The fuse blows during the fast trip despite the fuse-saving attempt

48. A 480V, three-phase, 600A panelboard with 600A bus. Load: 400A continuous motor + 80A continuous lighting + 60A noncontinuous = 540A. Per NEC 215.2(A)(1): OCPD = 125% × 480 + 60 = 660A → exceeds 600A bus. With a 100%-rated 600A breaker: 540A ≤ 600A. Conductor at 75°C must carry 540A. Two parallel 350 kcmil = 2 × 310 = 620A. Is this adequate?

A. No — 620A provides only 14.8% margin above 540A; while code-compliant, the thermal margin is thin

B. Yes — but two parallel 500 kcmil = 2 × 380 = 760A provides better margin

C. No — parallel conductors are not permitted for 600A circuits

D. Yes — two parallel 350 kcmil at 75°C = 620A ≥ 540A; the installation is code-compliant with the 100%-rated breaker; each parallel set must be identical per NEC 310.10(G); the 14.8% margin (80A above required) provides adequate thermal headroom for the continuous load

49. A three-phase, 480V system has a 3,500 kVA transformer (Z = 5.75%, X/R = 9) and 14 motors (FLA = 2,800A). Transformer fault = 42,200A. Motor = 11,200A. Total = 53,400A. X/R = 9, multiplier = 2.35. What is the peak asymmetrical?

A. 75,500A (√2 × total)

B. 106,800A (2× total)

C. Peak = 2.35 × 53,400 = 125,490A — the 11,200A motor contribution (21%) significantly increases the peak; all equipment momentary ratings, bus bracing, and close-and-latch specifications must account for this combined peak

D. 53,400A (no asymmetry)

50. A 480V, three-phase, 200A feeder uses 4/0 THHN copper in EMT (R = 0.0608, X = 0.0478 Ω/1000 ft). The feeder is 600 feet long and serves a load at 0.80 lagging PF. What is the voltage drop, and does it comply with NEC 3% recommendation?

A. 2.5% — within limits

B. V_drop = √3 × 200 × (0.0608×0.6×0.80 + 0.0478×0.6×0.60) = 346.4 × (0.02918 + 0.01721) = 346.4 × 0.04639 = 16.07V; 16.07/480 = 3.35% — exceeds the NEC 3% recommendation; the engineer must upsize to 250 kcmil or 350 kcmil to bring the voltage drop into compliance

C. 1.5% — well within limits

D. 5.0% — grossly exceeds limits

51. Per NEC 110.14(C)(1), a 1,200A switchboard has terminals marked "75°C/90°C." The continuous load = 960A. Required ampacity = 125% × 960 = 1,200A. At 75°C: two parallel 600 kcmil = 2 × 420 = 840A (inadequate); two parallel 750 kcmil = 2 × 475 = 950A (inadequate). At 90°C: two parallel 600 kcmil = 2 × 490 = 980A (inadequate); two parallel 750 kcmil = 2 × 535 = 1,070A (inadequate); three parallel 500 kcmil = 3 × 430 = 1,290A (adequate). What is the minimum conductor configuration?

A. Three parallel 500 kcmil per phase at 90°C = 1,290A ≥ 1,200A; the dual-rated terminal permits using the 90°C column; at 75°C, three parallel 500 kcmil = 3 × 380 = 1,140A < 1,200A (inadequate), demonstrating the significant sizing advantage of 90°C-rated terminals; each parallel set must comply with NEC 310.10(G) requirements

B. Two parallel 750 kcmil at 90°C (1,070A) — close enough

C. Two parallel 1,000 kcmil at 75°C = 2 × 545 = 1,090A (inadequate)

D. Four parallel 350 kcmil at 90°C = 4 × 350 = 1,400A

52. A 300 MVA synchronous generator has H = 5.0 MJ/MVA and delivers 240 MW when a three-phase fault occurs. Critical clearing angle = 120°. Relay = 0.012s, breaker = 0.030s, total = 0.042s. What is the rotor angle advance?

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

B. $\Delta\delta \approx 30°$ — marginally stable

C. $\Delta\delta = 120°$ — at critical clearing angle

D. $\Delta\delta = (180 \times 60 \times 240 \times 0.042^2)/(5.0 \times 300) = (180 \times 60 \times 240 \times 0.001764)/1{,}500 = 4{,}572/1{,}500 = 3.05°$ — stability maintained with 116.95° of margin; the ultrafast 0.042-second clearing (modern optical relay + fast SF_6 breaker) produces negligible rotor advance even at 80% loading

53. A three-phase, 13.8 kV capacitor bank rated 12,000 kvar has five series groups of six parallel units per phase (30 per phase, 90 total). Three units in one series group fail. Each remaining unit in that group sees 6/3 = 2.0× normal voltage (100% overvoltage). This far exceeds the 110% IEEE limit. How quickly will cascading failure occur, and what protection must operate?

A. Cascading takes several hours — adequate time for manual intervention

B. The remaining units will survive at 200% voltage because capacitors are overbuilt

C. At 200% voltage, the remaining three units experience dielectric stress proportional to V^2, meaning the insulation is stressed to 4× its rated level; failure will occur within seconds to a few cycles; the neutral unbalance relay and backup bank overcurrent protection must trip the bank within these few seconds or faster to prevent catastrophic failure including tank ruptures, dielectric fluid fire, and potential arc blast — this scenario demonstrates why banks with many parallel units per series group are inherently more vulnerable to cascading failures

D. The bank automatically rebalances when units fail

54. A three-phase, 460V, 8-pole wound-rotor motor rated 1,500 HP (FLS = 873 RPM) drives a crusher requiring 330% breakaway torque. With external resistance: wound-rotor achieves 340% starting torque at 360% FLA. A Design D squirrel-cage: 280% starting torque at 650% FLA. A Design B: 150% at 600% FLA. Additionally, the crusher has periodic overloads reaching 200% FLT during rock jamming events lasting 3-5 seconds. Which motor type is the best choice?

A. Only the wound-rotor meets the 330% breakaway (340% > 330%); T/I = 340/360 = 0.944 vs Design D T/I = 280/650 = 0.431; the wound-rotor also handles the periodic 200% FLT overloads because its external resistance can be re-engaged during jamming events to increase slip and reduce current while maintaining high torque — the external resistance provides thermal capacity that absorbs the intermittent overloads

B. Design D is the best choice despite not meeting breakaway requirements

C. Design B with soft starter

D. All three motor types are equally suitable

55. Per NEC 310.15(C)(1), a large cable tray contains: nine three-phase VFD circuits (27 phase conductors), six neutral conductors carrying triplen harmonics, three neutral conductors NOT carrying harmonics, and nine equipment grounding conductors. How many current-carrying conductors and what adjustment factor?

A. 27 phase + 9 neutrals = 36; factor = 0.30

B. 33 (27 phase + 6 triplen neutrals); non-harmonic neutrals and EGCs excluded; per NEC Table 310.15(C)(1) for 31-40 conductors: factor = 0.30 — this extreme 70% derating makes a single cable tray completely impractical; the installation must be split into at least six parallel raceways (approximately 5-6 conductors each) to restore the 0.80 adjustment factor

C. 27 (phase only); factor = 0.35

D. 45 (all conductors); factor = 0.25

56. A 480V, three-phase LVPCB main breaker has 0.30s STD. ZSI, optical relay, and arc-resistant switchgear are installed. During a bus fault, the ZSI system detects no restraint signal (confirming bus fault) and the optical relay detects arc light. Both signals are processed through separate logic paths that arrive at the breaker trip coil. The optical signal arrives in 2 ms, the ZSI signal in 8 ms. After receiving

the first signal, the breaker mechanism requires 28 ms to open and interrupt. What determines the total clearing time?

A. The ZSI signal at 8 ms (slower signal controls)

B. Both signals must be received before the breaker can trip

C. The 0.30s STD overrides all other trip signals

D. The optical signal arrives first (2 ms) and initiates the breaker trip; the breaker does not wait for the ZSI signal — it begins opening upon the first valid trip signal; total clearing = 2 ms + 28 ms = 30 ms = 0.030 seconds; the ZSI signal at 8 ms provides redundancy but does not affect clearing time because the trip was already initiated

57. A protection engineer coordinates two 51 relays on a 13.8 kV system. The downstream relay (R1) uses IEEE extremely inverse with TD = 1.0, pickup = 5A on a 400:5 CT. The upstream relay (R2) uses IEEE very inverse with TD = 3.5, pickup = 6A on a 800:5 CT. At a common fault of 8,000A: R1 secondary = 100A, M_1 = 20, t_1 = 1.0 × (28.2/399 + 0.1217) = 0.192s. R2 secondary = 50A, M_2 = 50/6 = 8.33, t_2 = 3.5 × (19.61/68.39 + 0.491) = 3.5 × (0.2867 + 0.491) = 3.5 × 0.778 = 2.72s. CTI = 2.72 − 0.192 = 2.53s. Is this coordination adequate or excessive?

A. CTI = 2.53s is both adequate AND excessive — while it exceeds the 0.20s minimum, the upstream relay R2 is unnecessarily slow at this fault level; the TD of R2 should be reduced to approximately 1.5-2.0 to bring the CTI to 0.30-0.50s, providing adequate margin while significantly improving upstream clearing speed for backup protection

B. CTI = 2.53s is ideal and should not be changed

C. CTI = 2.53s is inadequate — more separation needed

D. CTI = 2.53s indicates a coordination conflict that must be resolved

58. A 345 kV, 430-mile line has Z_1 = 34.4 + j322.5 Ω total and Z_0 = 103.2 + j967.5 Ω total. Source: Z_1_src = j21.5 Ω, Z_0_src = j32.25 Ω. For a bolted SLG fault at the remote end: Z_1_total = 34.4 + j344; Z_0_total = 103.2 + j999.75. What is I_SLG?

A. I_SLG = 600A

B. I_SLG = 200A

C. $|Z_1\_total| = \sqrt{(34.4^2 + 344^2)} = 345.7$; $|Z_0\_total| = \sqrt{(103.2^2 + 999.75^2)} = 1{,}005.1$; |Sum| = |172 + j1687.75| = 1,696.5; V_f = 199,186V; I_SLG = 3 × 199,186/1,696.5 = 352A — the extreme 430-mile length limits SLG current to only 352A; the $|Z_0|/|Z_1|$ ratio of 2.91 causes significant voltage elevation on unfaulted phases; pilot protection is mandatory for reliable high-speed clearing at this low current

D. I_SLG = 1,000A

59. Per NEC 700.10(D)(1), emergency luminaires that are supplied from a branch circuit also serving non-emergency loads must be connected to the emergency branch circuit through a transfer switch. A hospital corridor has six emergency luminaires on a branch circuit that also serves twelve normal luminaires. The ATS provides emergency power to the circuit. During a power failure, do ALL eighteen luminaires operate on emergency power?

A. No — only the six emergency luminaires receive emergency power; the twelve normal luminaires do not

B. Yes — the entire branch circuit is energized through the ATS, so all eighteen luminaires receive emergency power; the ATS transfers the entire circuit to emergency power, not just the emergency luminaires; the six luminaires designated as "emergency" must meet the performance requirements of NEC 700, but all loads on the transferred circuit receive power

C. Only nine luminaires operate (50% of total)

D. No luminaires operate — the circuit must be dedicated to emergency loads only

60. A three-phase, 480V, 225A panelboard has: Motor 1 = 124A (100 HP, largest), Motor 2 = 65A (50 HP), Motor 3 = 34A (25 HP). Continuous lighting = 90A. Noncontinuous receptacles = 30A. Per NEC 430.24 and 215.2(A)(1): OCPD = 125% × 124 + 65 + 34 + 125% × 90 + 30 = 155 + 99 + 112.5 + 30 = 396.5A → next standard = 400A. Bus = 225A. With 100%-rated 225A breaker: total load = 124 + 65 + 34 + 90 + 30 = 343A. But 343A > 225A. What is the resolution?

A. The panelboard must be upgraded to a minimum 400A bus to accommodate the 343A total load; even with a 100%-rated breaker, the physical bus rating of 225A cannot carry 343A — the bus is the hard constraint; the engineer must specify a panelboard with adequate bus rating for the actual load

B. Install a 300A panelboard

C. Reduce lighting to 45A

D. Use a 400A breaker with the 225A panelboard

61. A balanced three-phase, 4,160V source feeds a 18,000 kW load at 0.66 lagging PF. Q = 18,000 × 1.138 = 20,484 kvar. The utility penalty is $5.50/kvar/month for excess above 0.95 PF. Q_allowed = 18,000 × 0.329 = 5,922 kvar. Excess = 14,562 kvar. Penalty = $80,091/month. What is the annual penalty and the payback period for a 14,562 kvar capacitor bank at $25/kvar installed?

A. Annual penalty = $961,092; cap bank cost = $364,050; payback = 4.5 months

B. Annual penalty = $500,000; payback = 8 months

C. Annual penalty = $100,000; payback = 4 years

D. Annual penalty = $961,092; payback = 4.5 months — however, the correction slightly exceeds the threshold

62. A 480V, three-phase MCC has 25 motors (FLA = 5,000A combined). Motor contribution = 20,000A. Two transformers (3,000 kVA each, Z = 5.75%) provide 65,600A each = 131,200A combined. Total = 151,200A. X/R = 9. Multiplier = 2.35. What is the peak asymmetrical?

A. 213,700A (√2 × total)

B. 302,400A (2× total)

C. Peak = 2.35 × 151,200 = 355,320A — this extreme peak from two parallel transformers plus 25 motors demands bus bracing designed for forces proportional to $(355{,}320)^2 = 1.26 \times 10^{11}$ A^2; the motor contribution of 20,000A (13%) is significant and must be included

D. 151,200A (no asymmetry)

63. A three-phase, 13.8 kV underground cable is 55 miles long with charging current of 6.5A per mile per phase. A zero-sequence CT with 10A relay pickup and 0.3-second delay is installed. During energization, charging = 357.5A/phase. A 12A ground fault develops simultaneously. What does the relay detect, and is the margin adequate?

A. Relay sees 357.5A total charging plus 12A fault

B. Relay sees 12A fault only (charging cancels); 12A > 10A pickup → trips; but the margin is only 20% (12/10 = 1.2) — marginal; voltage variations or CT accuracy tolerance could push the effective relay current below pickup

C. Relay sees 0A (fault cancels the charging)

D. Relay sees 12A fault only; the balanced charging cancels in the zero-sequence CT; since 12A > 10A pickup, the relay trips after 0.3s; however, the 20% margin above pickup is quite thin — a 15% system voltage reduction (reducing fault current to approximately 10.2A) combined with CT accuracy tolerance could result in relay failure to operate; the engineer should consider reducing the pickup to 8A for better sensitivity margin

64. Per NEC 430.24, a feeder serves: Motor A = 590A (500 HP), Motor B = 477A (400 HP), Motor C = 414A (350 HP), Motor D = 361A (300 HP), Motor E = 302A (250 HP), Motor F = 242A (200 HP). Continuous lighting = 180A. Noncontinuous HVAC = 100A. What is the minimum feeder ampacity?

A. 2,200A

B. 125% × 590 + 477 + 414 + 361 + 302 + 242 + 125% × 180 + 100 = 737.5 + 1,796 + 225 + 100 = 2,858.5A

C. 2,500A

D. 3,000A

65. A distance relay on a 230 kV line (Z_line = 8 + j90 Ω) has Zone 1 at 85%, Zone 2 at 120%. A fault occurs at 80% through 12 Ω fault resistance. Z_meas = (0.80×8 + 12) + j(0.80×90) = 18.4 + j72 Ω. |Z_meas| = 74.3 Ω. Zone 1 reach = 0.85 × 90.4 = 76.8 Ω. The magnitude is within Zone 1 (74.3 < 76.8). However, the impedance angle θ = arctan(72/18.4) = 75.7° versus MTA = 80°. Is this fault within the mho circle?

A. The R-X point (18.4, 72) must be tested against the mho circle centered on the Zone 1 reach at MTA = 80°; the moderate fault resistance of 12 Ω shifts the impedance rightward but the point remains within the mho circle because: (1) the magnitude is 3.3% below reach, (2) the angular deviation is only 4.3° from MTA, and (3) the mho circle geometry accommodates moderate resistive shift at impedances well within the reach magnitude — the fault is within Zone 1

B. The fault is outside the mho circle due to the 12 Ω resistance

C. Zone 2 detects the fault after 0.35 seconds

D. The mho circle does not consider fault resistance

66. A three-phase, 4,160V system has an NGR rated 300A, 10 seconds. The system has 8A of normal zero-sequence unbalance from cable charging asymmetry. A relay pickup of 20A provides (20−8)/20 = 60% margin above unbalance. The maximum detectable fault resistance is R_max = 2,402/20 − 8.007 =

112.1 Ω. If the engineer reduces pickup to 15A for better sensitivity: R_max_new = 2,402/15 − 8.007 = 152.1 Ω. What is the trade-off?

A. Pickup of 15A provides 40% margin above normal unbalance; 20A provides 60% margin

B. Pickup of 15A provides zero margin and will false-trip on normal unbalance

C. The 15A pickup increases the detectable fault resistance from 112 Ω to 152 Ω (36% improvement) but reduces the margin above normal 8A unbalance from 60% to (15−8)/15 = 47%; the engineer must balance sensitivity improvement against false-trip risk — if cable charging unbalance increases (due to cable aging, additions, or switching), the 47% margin may be insufficient; typical practice is to set pickup at 2-3× the normal unbalance current

D. There is no trade-off — lower pickup is always better

67. Per NEC 480.9(A), a grid-scale battery energy storage system uses sodium-sulfur (NaS) batteries operating at 300°C. During normal operation, the hermetically sealed cells produce no gases. However, a cell failure can release liquid sodium and molten sulfur. What is the primary safety system requirement beyond ventilation?

A. Standard fire suppression (water sprinkler) is adequate

B. No safety systems needed — the cells are sealed

C. Only gas detection is needed

D. The primary requirement is a Class D fire suppression system rated for alkali metal fires (sodium) — water, foam, and CO_2 suppressants are PROHIBITED because they react violently with molten sodium; dry chemical agents (Na_2CO_3 or NaCl based) or sand are required; additionally, the containment system must prevent molten sodium from contacting moisture, structural steel, or other reactive materials; the high 300°C operating temperature means any breach can immediately ignite sodium in ambient air

68. A three-phase, 480V, 400A panelboard has an available fault current of 30,000A. IEEE 1584 shows 12 cal/cm² at 24 inches with 0.20-second clearing. An optical relay (0.012s), ZSI (0.05s), maintenance switch (0.04s), and arc-resistant enclosure are installed. What is the calculated energy with the optical relay?

A. 12 × (0.012/0.20) = 0.72 cal/cm² — below 1.2 threshold

B. E = 0.72 cal/cm²; with the arc-resistant enclosure, the worker's effective exposure is near zero; this three-layer approach (optical + ZSI backup + arc-resistant enclosure) provides redundant protection — if the optical relay fails, the maintenance switch provides 0.04s (2.4 cal/cm²), then ZSI at 0.05s (3.0 cal/cm²), with the arc-resistant enclosure redirecting energy in all cases

C. 6.0 cal/cm² (50% reduction from arc-resistant only)

D. 12.0 cal/cm² (unchanged)

69. A three-phase, 460V, 4-pole synchronous motor rated 3,500 HP drives a paper machine at 1,800 RPM. Pull-out = 240% FLT. H = 2.8 MJ/MVA. Voltage sags to 80% for 0.5 seconds. Pull-out = 192% FLT. Load = 88% FLT. Margin = 104% FLT. With H = 2.8 (relatively high for a synchronous motor), the inertia provides significant resistance to angular acceleration. What is the stability assessment?

A. Stable with good margin — the 104% FLT steady-state margin combined with H = 2.8 provides excellent stability performance; the 0.5-second sag at 80% with high inertia produces relatively small rotor angle advance (approximately 10-20°); the high H slows rotor acceleration, and the generous steady-state margin ensures the power angle never approaches the pull-out angle during the sag or the subsequent return swing

B. Marginally stable — detailed swing analysis required

C. Unstable — any voltage sag causes synchronism loss

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

70. A 230 kV, 350-mile line has Z_1_total = 28 + j262.5 Ω and Z_0_total = 84 + j787.5 Ω. V_f = 132.8 kV. $|Z_1|$ = 264.0. $|Z_0|$ = 792.0. Sum = 140 + j1,312.5. |Sum| = 1,320. I_SLG = 398,400/1,320 = 302A. This extremely low SLG current creates a severe protection sensitivity challenge. A line differential relay (87L) is proposed as primary protection. What advantage does 87L provide over distance protection for this application?

A. 87L has no advantage over distance protection

B. 87L provides faster clearing time only

C. 87L provides only backup protection, not primary

D. The 87L relay compares current magnitude and phase at both ends of the line — it detects internal faults regardless of fault current magnitude because it measures the DIFFERENCE between terminal currents, not the absolute current value; at 302A, distance relays operate near their accuracy limits and may not reliably detect end-of-line faults, but 87L can detect even a 50A differential with high reliability; 87L also provides immunity to power swings and load encroachment that plague distance relays on long, heavily loaded lines

71. Per NEC 250.122(B), a 1,000A circuit has two parallel 750 kcmil per phase (1,500,000 CM total), increased to two parallel 1,000 kcmil (2,000,000 CM). The EGC from Table 250.122 for 1,000A = 2/0 AWG (133,100 CM). What is the proportionally increased EGC?

A. 2/0 AWG (no increase)

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

C. Ratio = 2,000,000/1,500,000 = 1.333; EGC = 133,100 × 1.333 = 177,422 CM → 4/0 AWG (211,600 CM) is the minimum standard size above 177,422 CM

D. 250 kcmil

72. A balanced three-phase, 4,160V source feeds a 20,000 kW load at 0.67 lagging PF. The engineer installs a 16,000 kvar capacitor bank AND a 5,000 HP synchronous motor at 0.80 leading PF (η = 94%) AND a 2,000 HP synchronous motor at 0.85 leading (η = 95%). What is the new bus PF?

A. PF = 0.95

B. Original Q = 20,000 × 1.100 = 22,000 kvar; cap = −16,000; SM1: P_in = 3,968 kW, Q_1 = 2,976 kvar; SM2: P_in = 1,571 kW, Q_2 = 975 kvar; net Q = 22,000 − 16,000 − 2,976 − 975 = 2,049 kvar; P_total = 25,539 kW; PF = 25,539/25,621 = 0.997 ≈ 0.99

C. PF = 0.90

D. PF = unity

73. A 100 MVA, 345/138 kV autotransformer has Z = 10% on its own base. Two identical units in parallel. A 60 MVA generator (X"_d = 0.22 pu), a 40 MVA synchronous condenser (X"_d = 0.16 pu), a 30 MVA synchronous motor (X"_d = 0.20 pu), a 20 MVA distributed solar array (effective Z = 1.0 pu), and a 10 MVA BESS inverter (effective Z = 1.5 pu) are on the 138 kV bus. On 100 MVA base, what is the total fault current?

A. Z_T_par = 0.05; Z_gen = 0.367; Z_SC = 0.40; Z_SM = 0.667; Z_solar = 5.0; Z_BESS = 15.0; I = (20.0 + 2.725 + 2.50 + 1.50 + 0.20 + 0.0667) × 418.4 = 26.99 × 418.4 = 11,293A — the two autotransformers dominate at 74%, the three rotating machines contribute 25%, and the two inverter-based resources contribute only 1% combined; this illustrates the negligible fault contribution of inverter-based generation

B. 15,000A

C. 8,000A

D. 20,000A

74. A three-phase, 460V, 4-pole induction motor rated 300 HP operates at 1,770 RPM. A VFD reduces speed to 800 RPM for a centrifugal pump. P_pump = 224 × $(800/1{,}770)^3$ = 224 × 0.0921 = 20.6 kW. VFD efficiency = 96%, motor efficiency at this very light load = 82%. What is the total supply power?

A. 20.6 kW (pump only — ignoring losses)

B. P_supply = 26.2 kW (P/(η_motor × η_VFD) = 20.6/(0.82 × 0.96) = 26.2 kW)

C. P_supply = 20.6/(0.82 × 0.96) = 20.6/0.787 = 26.2 kW — the cascade of significantly reduced motor efficiency at very light load (82% vs 96% at full load) and VFD losses adds 5.6 kW; at this operating point, losses are 27% of the useful pump power — while the absolute losses are small, the percentage is high, indicating diminishing returns on VFD speed reduction below a certain threshold

D. P_supply = 50 kW

75. Per NEC 430.32(A)(1), a motor with SF = 1.0 has maximum overload = 115% of FLA. A motor has FLA = 500A, SF = 1.0. The overload is set at 575A (115%). The motor drives a conveyor that experiences periodic jamming. During a jam, the motor draws locked-rotor current of 3,000A (6× FLA). The overload relay's thermal model at 6× FLA produces a trip in approximately 10-12 seconds. Is this stall protection time acceptable for the motor?

A. 10-12 seconds at LRC is acceptable for most motor designs

B. 10-12 seconds may be adequate for the overload relay but NOT for the motor — at 6× FLA (3,000A), the motor's rotor heats rapidly; the safe stall time depends on the motor's thermal damage curve, which is typically 10-15 seconds for large TEFC motors; the overload trip at 10-12 seconds is near the thermal damage limit and may not provide adequate margin

C. 10-12 seconds is always too long — the motor is damaged instantly at LRC

D. 10-12 seconds is always acceptable — motors can withstand locked rotor indefinitely

76. A 480V, three-phase system has a 3,000 kVA transformer (Z = 5.75%, X/R = 9) and a 2,000 kVA transformer (Z = 6.50%, X/R = 7) in parallel. I_T1 = 62,748A; I_T2 = 35,840A. Total = 98,588A. Motor

contribution (FLA = 2,500A) = 10,000A. Grand total = 108,588A. Weighted X/R ≈ 8.3. Multiplier = 2.32. What is the peak asymmetrical?

A. 153,500A (√2 × total)

B. Peak = 2.32 × 108,588 = 251,924A — this peak current determines the close-and-latch rating and mechanical bracing for the entire paralleled bus system

C. 217,176A (2× total)

D. 108,588A (no asymmetry)

77. A three-phase, 4,160V, 10-pole synchronous motor rated 5,000 HP drives a ball mill at 720 RPM. Pull-out = 260% FLT. H = 1.6 MJ/MVA (low inertia). Voltage sags to 62% for 1.8 seconds. Pull-out = 0.62 × 260 = 161.2% FLT. Load = 100% FLT. Margin = 61.2% FLT. What happens?

A. At H = 1.6 (very low inertia) with a 1.8-second sag at 62% voltage, the rotor accelerates rapidly; $\Delta\delta \propto t^2$ means 1.8 seconds produces 324× the advance of 0.1 seconds; the motor will almost certainly lose synchronism within the first 0.5-1.0 seconds despite the 61.2% steady-state margin — the combination of low H, deep sag, and extremely long duration makes stability virtually impossible; the motor should be tripped by undervoltage protection within 0.5 seconds to prevent damage during pull-out

B. Stable — 61.2% margin is always adequate

C. Marginally stable — requires detailed analysis

D. The motor maintains synchronism but with reduced speed

78. Per NEC 110.24(A), a facility originally had three parallel 1,500 kVA transformers (Z = 5.75% each), producing combined I_fault = 3 × 31,374 = 94,122A... wait — for parallel transformers with identical Z, combined Z = 5.75%/3 = 1.917%. I_fault = 1,804/(0.01917) = 94,106A. One transformer is replaced with a 2,500 kVA unit (Z = 4.50%). The system now has: two 1,500 kVA (Z = 5.75%) and one 2,500 kVA (Z = 4.5%). What is the new fault current?

A. 94,106A (unchanged)

B. 80,000A (the new transformer reduces total fault current)

C. I_T1 = I_T2 = 1,804/0.0575 = 31,374A each; I_T3 = 3,007/0.045 = 66,822A; Total = 129,570A — a 38% increase over the original 94,106A; the combination of larger kVA AND lower impedance of the replacement transformer dramatically increases the combined fault level; comprehensive downstream equipment reverification is required

D. 150,000A

79. A 1,500 kVA, 480V/208Y/120V transformer has Z = 5.25% and X/R = 5.5. The symmetrical fault current at 208V secondary = 16,500A. Using the IEEE multiplier of 2.19 for X/R = 5.5, what is the peak asymmetrical?

A. 23,300A (√2 × symmetrical)

B. 33,000A (2× symmetrical)

C. Peak = 2.19 × 16,500 = 36,135A — this determines the momentary withstand rating for all 208V equipment; the moderate X/R of 5.5 produces moderate asymmetry typical of distribution transformers serving commercial buildings

D. 16,500A (no asymmetry)

80. A 500 kW, three-phase, 480V resistance heater operates as a continuous load, running 24 hours/day, 7 days/week, 52 weeks/year. Electricity costs $0.058/kWh. Per NEC 210.20(A), minimum OCPD = 125% of continuous. What is the load current, minimum OCPD, annual energy consumption, and annual cost?

A. I = 601.4A; OCPD = 800A (next standard above 751.75A); E = 4,368,000 kWh; cost = $253,344

B. I = 500,000/(√3 × 480) = 601.4A; OCPD = 125% × 601.4 = 751.8A → next standard per NEC 240.6(A) = 800A; E = 500 × 24 × 7 × 52 = 4,368,000 kWh; cost = 4,368,000 × $0.058 = $253,344/year — this quarter-million-dollar annual energy cost for a single heater underscores the critical importance of process heating efficiency and waste heat recovery

C. I = 601.4A; OCPD = 700A; E = 3,000,000 kWh; cost = $174,000

D. I = 500A; OCPD = 700A; E = 4,368,000 kWh; cost = $253,344

Practice Exam 21: Answer Key and Explanations

1. D — The resonant harmonic order shifted from h_r = 9.31 (safely above all characteristic harmonics) to h_r = 7.87, directly adjacent to the 7th harmonic that the new six-pulse VFD injects at approximately 20% of fundamental. This creates a dual hazard: a new harmonic source AND a resonance tuned to

amplify that specific source. Detuning reactors are now mandatory despite the previously clean installation.

2. B — Cable Z reduces the transformer's 36,130A switchboard contribution to approximately 27,500A at the remote MCC. The six local motors contribute 4 × 1,452 = 5,808A first-cycle. The total MCC fault current ≈ 33,300A determines equipment SCCR requirements. Both utility-through-cable and local motor contributions must be included in MCC fault calculations.

3. A — NEC 430.52(C)(2) permits adjustable MCPs to be set at any value up to the Table 430.52 maximum (800% for instantaneous-trip breakers). The 3,500A setting (116% of LRC) provides adequate margin above the 3,012A locked-rotor current for starting transients while remaining well below the 4,000A maximum. This is standard MCP sizing practice.

4. C — A high-impedance bus differential relay forces all CT saturation voltage across a high-impedance element. Saturated CTs present very low impedance and cannot drive significant current through the high-impedance relay element, providing inherent security against CT saturation-induced false tripping. This eliminates the false differential concern regardless of the degree of individual CT saturation.

5. D — The electrical resonant frequency of the series LC circuit is f_r = 60 × √(0.50) = 42.4 Hz. The complementary subsynchronous frequency is 60 − 42.4 = 17.6 Hz. If this matches a turbine-generator shaft torsional mode, destructive mechanical oscillations can result. The Mohave Generating Station incident in 1970 validated this concern and led to IEEE SSR screening standards for all series-compensated lines near thermal generators.

6. B — Ratio = 750,000/500,000 = 1.50. EGC = 52,620 × 1.50 = 78,930 CM. From wire tables: 2 AWG = 66,360 CM (below — insufficient). 1 AWG = 83,690 CM (above — adequate). The minimum EGC is 1 AWG per NEC 250.122(B), maintaining the impedance ratio with the upsized phase conductors.

7. C — Motor 1: P_in = 2,383 kW, Q_1 = 1,787 kvar. Motor 2: P_in = 785 kW, Q_2 = 487 kvar. Total correction = 8,000 + 1,787 + 487 = 10,274 kvar. Net Q = 11,380 − 10,274 = 1,106 kvar. P_total = 13,168 kW. PF = 13,168/13,214 = 0.997 ≈ 0.99. Three simultaneous correction sources nearly eliminate the entire reactive demand while adding 4,000 HP of mechanical output.

8. A — I_phase_RMS = 379.1A; phase base = 379.1/0.80 = 473.9A. I_neutral = 3 × 133 = 399A; neutral base = 399/0.80 = 498.8A. The NEUTRAL governs at 498.8A because it exceeds the phase

requirement of 473.9A. This is the critical scenario where triplen-harmonic neutral current, amplified by the 0.80 derating factor, drives conductor selection above the phase requirement.

9. B — Reactor: I_SLG = 2.80 pu (reactive, 90° lag). Resistor: I_SLG = 3/12.41 = 0.242 pu (resistive, ~2° lag). The dual system provides operational flexibility: reactor grounding during normal operation enables fast relay detection with moderate fault current, while resistance grounding during maintenance limits arc flash energy to minimal levels. Switching between modes adapts the grounding system to the operational risk profile.

10. A — Fault 1: $(218.3/400)^2 \times (0.5/10) = 1.49\%$. Fault 2: $(133.4/400)^2 \times (1.0/10) = 1.11\%$. Fault 3: $(92.4/400)^2 \times (1.5/10) = 0.80\%$. Cumulative = 3.40%. The NGR retains over 96% capacity. Each successive fault has lower current (higher R_f) but longer clearing time — the decreasing I^2 effect outweighs the increasing t, reducing thermal stress per event.

11. D — NEC 110.26(C)(2) requires doorways at least 24 inches wide and 6.5 feet high for equipment rated 1,200A or more and over 6 feet wide. Two doorways at opposite ends of the working space provide safe egress during an arc flash or other emergency. This requirement ensures personnel can escape in either direction.

12. C — k_max = 56.2%. The 60% load period operates closest (3.8 points above k_max). All-day efficiency: E_out = 46,000 + 20,400 + 5,625 = 72,025 kWh. Losses at each period include constant core losses plus load-dependent copper losses. The near-optimal second period contributes significantly to the overall high all-day efficiency.

13. B — M = 31.25. t = 1.5 × (28.2/976.56 + 0.1217) = 1.5 × (0.0289 + 0.1217) = 1.5 × 0.1506 = 0.226s. CTI = 0.226 − 0.006 = 0.220s — adequate with minimal margin above the 0.20s minimum. At M = 31.25, the extremely inverse characteristic provides excellent speed — this is the high-multiple scenario where extremely inverse relays excel.

14. D — |Z_meas| = 63.8 Ω is well within Zone 1 reach of 68.3 Ω (6.6% margin). The impedance angle of 77.8° is very close to MTA of 80° (only 2.2° deviation). The R-X point falls securely inside the mho circle because the combination of adequate magnitude margin and minimal angular deviation places the fault reliably within the Zone 1 characteristic.

15. C — 100%: 559,500. 85%: 373×0.614×2,800 = 641,546. 70%: 373×0.343×2,960 = 378,681. 50%: 373×0.125×1,500 = 69,938. VFD = 1,649,665 kWh. Full-speed = 3,267,480 kWh. Savings = 1,617,815

kWh × \$0.079 = \$127,807/year. The cubic relationship produces 49.5% energy reduction across four operating modes.

16. A — H_2 = 5.04 ft^3/hr. Max H_2 = 100 ft^3. ACH = 0.050. The critical NiCd concern is KOH mist — highly corrosive to metals and electronics. Exhaust ductwork must be PVC, stainless steel, or coated. Exhaust must be directed away from equipment rooms, HVAC intakes, and occupied spaces to prevent corrosion damage and personnel exposure.

17. D — The SVC responds within 1-2 cycles, injecting up to +180 Mvar to support receiving-end voltage during the post-contingency power surge. This fast voltage support directly improves transient stability by maintaining P ∝ V_SV_R/X during the critical first-swing period. Without the SVC's rapid response, the voltage dip could trigger angular instability before slower devices can react.

18. B — P = E_a × I_a = 487.5 × 208.3 = 101.5 kW (83.7% of rated 121.3 kW). In the field-weakened region, torque decreases proportionally with speed increase (constant-power region). The motor operates at approximately T = 101,500/(2π × 1,800/60) = 538.5 N-m compared to rated torque of 693 N-m — reduced torque at increased speed with near-rated thermal loading.

19. C — Each isolation transformer creates an independent HRG separately derived system. NEC 250.36(A) requires each HRG system to have its own ground-fault detection system. Ten transformers = ten GFD systems. Each must detect and alarm within one second because HRG systems are designed to continue operating on the first ground fault while alerting maintenance.

20. D — The optical relay clears in approximately 0.022s. E = 58 × (0.022/0.30) = 4.25 cal/cm^2. The ERMS (0.04s) and ZSI (0.05s) provide progressive backup layers. The Type 2B arc-resistant switchgear redirects energy from the front. The permanent-magnet trip ensures breaker opening even if control power is destroyed by the arc event.

21. A — Solidly grounded: I_SLG = 4.69 pu exceeds I_3Φ = 4.0 pu by 17%. Equipment on the faulted phase must withstand 4.69 pu. HRG: I_SLG = 0.060 pu — virtually eliminates arc flash during ground faults but requires GFD systems. The fundamental trade-off: fast overcurrent clearing with high damage potential (solidly grounded) versus minimal damage with alarm-only response (HRG).

22. B — Per NEC 430.24: 125% × 477 = 596.25A. Other motors = 361 + 302 = 663A. Per NEC 215.2: 125% × 250 = 312.5A. Noncontinuous = 75A. Total = 596.25 + 663 + 312.5 + 75 = 1,646.75A. The 125% applies independently to the largest motor and the continuous non-motor load.

23. A — I = (25.0+16.67+12.5+10.0+2.857+2.0+1.25+0.20) × 5,552 = 70.477 × 5,552 = 391,369A. Eight parallel sources produce this extreme fault current. The battery inverter contributes only 0.3% because inverter-based sources have inherently high effective impedance. All equipment must have extraordinarily high SCCR ratings.

24. C — Cable Z_pu ≈ 0.130. Total Z = 0.0575 + 0.130 = 0.187. I_transformer = 3,007/0.187 ≈ 16,080A. Motor contribution = 3,200A. Total = 19,280A — below the 22,000A panelboard SCCR. The cable impedance naturally reduces the transformer contribution enough that the total (including motors) stays below the SCCR without requiring a series-rated combination.

25. B — Each module-level rapid shutdown device reduces its output to 1V per module. String voltage = 24 × 1V = 24V — well below the 80V threshold. The system complies with NEC 690.12(B)(2). The optimizers control the module output voltage, not the internal V_oc, so the string conductors see only 24V total.

26. D — Total symmetrical = 156,745 + 14,000 = 170,745A. Peak = 2.34 × 170,745 = 399,543A. Nearly 400 kA peak produces electromagnetic forces proportional to I^2_peak = 1.60 × 10^{11} A^2, demanding extraordinary mechanical bracing that dominates engineering cost and physical size.

27. A — Both terminals achieve high-speed clearing. The near end detects in Zone 2 and receives no blocking signal (DCB logic: no block = trip permitted). The remote end trips on Zone 1 instantaneously (5% from its terminal). Neither sends blocking because both see forward faults. The DCB scheme enables simultaneous high-speed clearing at both ends.

28. C — At 0.8 pu restraint, the 10% low slope applies. Threshold = 0.08 pu. Since 0.15 > 0.08, the relay correctly detects the fault. At 25% slope: threshold = 0.20 pu; since 0.15 < 0.20, the relay FAILS. Generator differential relays use lower minimum slopes than transformer relays because generators have no inrush — the low slope provides sensitivity for turn-to-turn faults.

29. B — Per NEC 450.3(B), when primary OCPD is provided at not more than 125% (or the next higher standard size), secondary protection is NOT required for transformers rated 600V and below. The 2,500A primary OCPD at the next standard above 125% satisfies the requirement. No secondary OCPD is needed.

30. D — The swing equation yields an enormous angle advance (hundreds of degrees), confirming certain loss of synchronism. With H = 2.2 and a 0.8-second sag at 73%, the motor cannot maintain synchronism. The simplified formula confirms catastrophic instability — the motor must be tripped by undervoltage protection before mechanical damage occurs during pull-out.

31. A — T1 share = 18.18/56.91 = 31.9%. Individual contributions: I_T1 = 65,600, I_T2 = 52,296, I_T3 = 38,849, I_T4 = 27,972, I_T5 = 17,939. Total = 202,656A. Five parallel transformers produce over 200 kA symmetrical. At X/R ≈ 8, the peak asymmetrical approaches 470 kA, requiring extraordinary bus bracing.

32. C — Four individual violations: V_5 (10.8%), V_7 (7.1%), V_{11} (4.5%), V_{13} (3.2%) all exceed 3.0%, plus THD (14.2%) exceeds 5.0%. V_{17} and V_{19} are within limits. The phased approach: retrofit six-pulse VFDs to eliminate 5th/7th at source, verify remaining harmonics, install tuned filters for residual violations, then confirm THD compliance.

33. D — Corrected = 0.42 Ω, exceeding the 0.1 Ω target by 4.2×. Nuclear plants may require: grid expansion, increased conductor density, deep ground wells, GEM, counterpoise conductors radiating outward, and potentially continuously wetted systems. The ultra-low 0.1 Ω target reflects nuclear safety analysis requirements for step-and-touch potential compliance during the maximum fault.

34. B — 80 kvar is 84% of 95 kvar no-load magnetizing — below the absolute self-excitation threshold but above the typical 67% manufacturer recommendation. P_in = 540 kW; Q_orig = 246 kvar; Q_new = 166 kvar; PF_new = 0.956. Manufacturer approval is essential because the 84% level leaves minimal margin against self-excitation under voltage or temperature variations.

35. A — Full: 540,000. 90%: 437,400. 75%: 278,520. 60%: 97,200. 40%: 24,192. VFD = 1,377,312 kWh. Full-speed = 2,628,000 kWh. Savings = 1,250,688 kWh × $0.078 = $97,554/year. Five operating modes with the cubic relationship produce nearly 48% energy reduction.

36. C — R = 0.0367 × 700/1000 = 0.02569. X = 0.0407 × 700/1000 = 0.02849. V_drop = 346.4 × (0.02569×0.82 + 0.02849×0.572) = 346.4 × (0.02107+0.01630) = 346.4 × 0.03737 = 12.94V. V_drop% = 2.70%. Within the NEC 3% limit but with limited margin on this very long 700-foot run.

37. D — Z_T_par = 0.11/3 = 0.0367. Z_gen = 0.333. Z_SC = 0.375. Z_SM = 0.88. Z_solar = 6.667. I_pu = 27.27+3.003+2.667+1.136+0.15 = 34.23. I = 34.23 × 418.4 = 14,320A. Three autotransformers dominate at 80%. The 15 MVA solar inverter contributes only 0.4% due to its high effective impedance.

38. B — Total symmetrical ≈ 104,317A. Peak = 2.34 × 104,317 = 244,102A. This extreme peak determines close-and-latch ratings and mechanical bracing for the paralleled bus. The electromagnetic forces at 244 kA peak are approximately 400× those of a standard 42 kA single-transformer installation.

39. A — R_combined = (3.2 × 35)/(3.2 + 35) = 112/38.2 = 2.93 Ω — below the 5 Ω target. The Ufer ground dominates because its 3.2 Ω is much lower than the rod grid's 35 Ω. In parallel, the combined resistance is always less than the lowest element. Ufer grounds excel in high-resistivity soil because concrete retains moisture regardless of soil conditions.

40. C — Cable: R = 0.04864, X = 0.04256 Ω. Z_base = 480^2/3,000,000 = 0.0768 Ω. Z_cable_pu = 0.0647/0.0768 = 0.842. Total Z = 0.900. I = 3,608/0.900 = 4,009A. The 800-foot 4/0 cable reduces fault current to only 11%. The engineer must verify the 100A breaker can still clear faults at this reduced level.

41. D — I_SLG_correct = 3/(0.2333+0.2333+0.10) = 5.29 pu (delta blocks source Z_0). I_SLG_wrong = 3/(0.2333+0.2333+0.35) = 4.18 pu (incorrectly includes source Z_0). The error understates SLG by 21%. Equipment may be underrated and protection settings too insensitive for the actual fault current. This is one of the most common symmetrical component calculation errors.

42. B — At reduced VFD speed (70%), the motor's no-load magnetizing kvar drops to approximately 51 kvar. The 50 kvar capacitor now represents 98% of no-load magnetizing — dangerously close to self-excitation. If the VFD trips while the capacitor remains connected, self-excitation is likely. The capacitor must be interlocked with the VFD or switched off during reduced-speed operation.

43. A — Second harmonic from motor inrush causes the CT core flux to peak at approximately 160% of fundamental-alone values. At 6× rated with 60% second harmonic, the combined flux exceeds the core's saturation level during harmonic peaks, causing temporary saturation even though the fundamental current is well within the C200 rating. This distorts the secondary current and can delay relay trip decisions.

44. D — The dominant neutral component is the triplen sum: I_neutral_3rd = 105 + 96 + 114 = 315A (triplens ADD in the neutral regardless of phase balance). The fundamental unbalance contributes approximately 35A RMS. The 5th harmonic cancels in three-phase systems. Total neutral ≈ $\sqrt{(315^2 + 35^2)}$ = 317A. Triplens overwhelmingly dominate at 99.4% of the total.

45. C — Panel D can accept the device (3.8 + 0.6 = 4.4 mA < 5.0). Cross-panel connections within the same surgical suite are acceptable practice when the originating panel cannot accept the additional device. This distributes hazard current optimally while maintaining all panels below the 5 mA alarm threshold.

46. A — Without compensation: sin δ = 0.424; δ = 25.1°; stability fraction = 42.4%. With 40% series cap: X_eff = 33 Ω; sin δ = 0.254; δ = 14.7°; stability fraction = 25.4%. The reduced stability FRACTION means the line operates further from the stability LIMIT — increasing margin from 57.6% to 74.6%. Series compensation improves stability by reducing the effective electrical length.

47. B — During the delayed trip, the recloser curve (0.10s) is slower than the fuse TC (0.03s). The fuse blows at 0.03 seconds, isolating the faulted lateral. The recloser holds closed and restores service to unfaulted sections. This is the designed sequence: fast trip saves the fuse for temporary faults; delayed trip allows the fuse to isolate permanent faults.

48. D — With 100%-rated breaker: 540A ≤ 600A. Conductor: two parallel 350 kcmil = 620A ≥ 540A with 14.8% margin. The installation is code-compliant. Each parallel set must be identical per NEC 310.10(G). The 80A margin above the 540A requirement provides adequate thermal headroom.

49. C — Total symmetrical = 42,200 + 11,200 = 53,400A. Peak = 2.35 × 53,400 = 125,490A. The 11,200A motor contribution (21%) significantly increases the peak. All equipment momentary ratings and bus bracing must account for this combined peak.

50. B — R = 0.03344, X = 0.02868 Ω. V_drop = 346.4 × (0.03344×0.80 + 0.02868×0.60) = 346.4 × (0.02675+0.01721) = 346.4 × 0.04396 = 15.22V. V_drop% = 3.17% → 3.35% with precise calculation. Exceeds the NEC 3% recommendation. Upsize to 250 kcmil or 350 kcmil for compliance.

51. A — With dual-rated "75°C/90°C" terminals: three parallel 500 kcmil at 90°C = 3 × 430 = 1,290A ≥ 1,200A. At 75°C: 3 × 380 = 1,140A < 1,200A (inadequate). The 90°C terminal rating saves the cost and complexity of larger conductors. Each parallel set must comply with NEC 310.10(G).

52. A — Δδ = (180 × 60 × 240 × 0.001764)/1,500 = 4,572/1,500 = 3.05°. The ultrafast 0.042-second clearing produces negligible rotor advance — far below the 120° critical clearing angle. The 116.95° margin demonstrates the extraordinary transient stability benefit of modern fast-clearing protection systems.

53. C — 6/3 = 2.0× voltage (100% overvoltage). At 200% voltage, insulation stress is proportional to V^2 = 4× rated. Failure occurs within seconds to a few cycles. The neutral unbalance relay must trip immediately. Banks with many parallel units per series group are inherently more vulnerable because each unit failure dramatically increases voltage on survivors.

54. A — Only the wound-rotor meets 330% breakaway (340% > 330%). T/I = 0.944 vs Design D 0.431 — 2.19× better. The wound-rotor also handles 200% FLT periodic overloads because external resistance can be re-engaged during jamming events, increasing slip and providing thermal absorption capacity. The external resistance is the key advantage for intermittent severe-duty applications.

55. B — 27 phase + 6 triplen-carrying neutrals = 33 current-carrying conductors (non-harmonic neutrals and EGCs excluded). Per NEC Table 310.15(C)(1) for 31-40 conductors: factor = 0.30. This 70% derating makes a single cable tray completely impractical — at least six parallel raceways are needed.

56. D — Optical signal arrives at 2 ms and initiates the trip. The breaker does not wait for the 8 ms ZSI signal — it begins opening immediately. Total = 2 + 28 = 30 ms = 0.030 seconds. The ZSI signal at 8 ms provides redundancy but is irrelevant to clearing time because the trip was already initiated by the faster optical signal.

57. A — R1 at M = 20: t = 0.192s (extremely inverse at high multiple — fast). R2 at M = 8.33: t = 2.72s (very inverse at moderate multiple — slow). CTI = 2.53s — adequate but excessive. The upstream relay R2 is unnecessarily slow. Reducing R2's TD to 1.5-2.0 would improve backup clearing speed while maintaining adequate CTI of 0.30-0.50 seconds.

58. C — Z_1_total = 34.4+j344; $|Z_1|$ = 345.7. Z_0_total = 103.2+j999.75; $|Z_0|$ = 1,005.1. |Sum| = 1,696.5 Ω. I_SLG = 597,558/1,696.5 = 352A. The extreme 430-mile length limits SLG to only 352A. Pilot protection is mandatory for reliable high-speed clearing at this low current level.

59. B — The ATS transfers the entire branch circuit to emergency power. All eighteen luminaires (both emergency and normal) receive power. The six designated emergency luminaires must meet NEC 700 performance requirements, but the twelve normal luminaires also operate since they share the transferred circuit.

60. A — Total load = 343A > 225A bus. Even with a 100%-rated breaker, the bus cannot carry 343A. The panelboard must be upgraded to a minimum 400A bus. The bus is the physical constraint — no breaker selection overcomes an undersized bus.

61. D — Excess = 14,562 kvar. Penalty = $80,091/month = $961,092/year. Capacitor bank at $25/kvar = $364,050. Payback = $364,050/$80,091 = 4.5 months. This is one of the highest-ROI investments available — the penalty alone exceeds the capital cost within five months.

62. C — Total = 131,200 + 20,000 = 151,200A. Peak = 2.35 × 151,200 = 355,320A. The motor contribution of 20,000A (13%) is significant. Forces proportional to $(355\ \text{kA})^2$ demand extreme bus bracing. The dual-transformer plus 25-motor system produces extraordinary fault levels.

63. D — Relay sees 12A fault only (charging cancels). 12A > 10A → trips. But the 20% margin is thin. Voltage variations and CT accuracy could push effective current below pickup. Reducing pickup to 8A improves sensitivity margin to 50% while maintaining adequate margin above normal zero-sequence unbalance.

64. B — 125% × 590 = 737.5A. Other motors = 477+414+361+302+242 = 1,796A. Motor subtotal = 2,533.5A. 125% × 180 = 225A. Noncontinuous = 100A. Total = 2,533.5 + 225 + 100 = 2,858.5A. Multiple parallel conductor sets per phase are required at this extreme ampacity.

65. A — $|Z_{meas}| = 74.3\ \Omega$ is 3.3% below Zone 1 reach of 76.8 Ω. Impedance angle 75.7° deviates only 4.3° from MTA 80°. The moderate 12 Ω resistance shifts the impedance rightward but the point remains within the mho circle due to adequate magnitude margin and minimal angular deviation. The fault is securely within Zone 1.

66. C — At 15A pickup: $R_{max} = 152.1\ \Omega$ (36% better than 112.1 Ω at 20A). Margin above 8A unbalance = 47% (vs 60% at 20A). The trade-off is improved sensitivity versus reduced security margin. Typical practice sets pickup at 2-3× normal unbalance to balance these competing requirements.

67. D — Sodium fires require Class D suppression — water, foam, and CO_2 react violently with molten sodium. Dry chemical agents (Na_2CO_3 or NaCl based) or sand are required. The 300°C operating temperature means any breach immediately ignites sodium in ambient air. Containment must prevent molten sodium from contacting moisture, structural steel, or other reactive materials.

68. B — E = 12 × (0.012/0.20) = 0.72 cal/cm^2 — below 1.2 threshold. The arc-resistant enclosure provides physical redirection. If optical fails: ERMS at 0.04s → 2.4 cal/cm^2; if both fail: ZSI at 0.05s → 3.0 cal/cm^2. Arc-resistant enclosure redirects energy in all cases. Three independent layers provide redundant protection.

69. A — The 104% FLT margin combined with H = 2.8 provides excellent stability. At H = 2.8, the high inertia significantly slows rotor acceleration during the 0.5-second sag. The angle advance is approximately 10-20° — well below the critical clearing angle. The generous margin and high inertia together ensure reliable synchronism maintenance.

70. D — 87L compares terminal currents and detects faults by the DIFFERENCE, not absolute magnitude. At 302A, distance relays operate near accuracy limits, but 87L can detect even 50A differential with high reliability. 87L also provides immunity to power swings and load encroachment that plague distance relays on long, heavily loaded lines — making it the ideal primary protection for very long lines.

71. C — Ratio = 2,000,000/1,500,000 = 1.333. EGC = 133,100 × 1.333 = 177,422 CM. 3/0 AWG = 167,800 (below). 4/0 AWG = 211,600 (above — adequate). The minimum EGC is 4/0 AWG per the proportional increase calculation.

72. B — Original Q = 22,000 kvar. Cap = −16,000. SM1: Q_1 = 2,976 kvar. SM2: Q_2 = 975 kvar. Net Q = 22,000 − 16,000 − 2,976 − 975 = 2,049 kvar. P_total = 25,539 kW. PF = 25,539/25,621 = 0.997 ≈ 0.99. Four correction sources nearly eliminate the reactive demand while adding 7,000 HP of mechanical output.

73. A — I_pu = 20.0 + 2.725 + 2.50 + 1.50 + 0.20 + 0.067 = 26.99. I = 26.99 × 418.4 = 11,293A. Two autotransformers dominate at 74%. Three rotating machines contribute 25%. The two inverter-based resources (solar + BESS) contribute only 1% combined — illustrating the negligible fault contribution of inverter-based generation.

74. C — P_pump = 20.6 kW. P_supply = 20.6/(0.82 × 0.96) = 26.2 kW. At this very light loading, motor efficiency drops to 82%, making losses 27% of useful pump power. While absolute losses are small (5.6 kW), the high percentage indicates diminishing returns on speed reduction below a certain threshold.

75. D — At 6× FLA, the overload relay's thermal model trips in approximately 10-12 seconds. The motor's safe stall time is typically 10-15 seconds. The relay trip at 10-12 seconds provides minimal margin against the motor's thermal damage limit. For crusher applications with frequent jamming, a separate stall-protection relay set at a shorter time (5-8 seconds) should supplement the standard overload.

76. B — Total = 98,588 + 10,000 = 108,588A. Peak = 2.32 × 108,588 = 251,924A. This peak determines close-and-latch ratings and mechanical bracing for the entire paralleled bus system. The motor contribution of 10,000A (9.2%) adds measurably to the peak.

77. A — At H = 1.6 with 1.8 seconds at 62% voltage, the rotor accelerates rapidly. $\Delta\delta \propto t^2$ means 1.8 seconds produces 324× the advance of 0.1 seconds. The motor will lose synchronism within the first 0.5-1.0 seconds. The combination of very low H, deep sag, and extreme duration makes stability impossible. Undervoltage protection should trip within 0.5 seconds.

78. C — I_T1 = I_T2 = 31,374A each. I_T3 = 3,007/0.045 = 66,822A (new 2,500 kVA). Total = 129,570A — a 38% increase. The combination of larger kVA and lower Z of the replacement transformer dramatically increases the combined fault level. Comprehensive downstream equipment reverification and new arc flash study are mandatory.

79. C — Peak = 2.19 × 16,500 = 36,135A. The X/R = 5.5 produces moderate asymmetry at 2.19× symmetrical RMS. This peak determines momentary withstand ratings for all 208V equipment downstream of the transformer — typical for commercial building distribution.

80. B — I = 500,000/(√3 × 480) = 601.4A. OCPD = 125% × 601.4 = 751.8A → next standard = 800A. E = 500 × 24 × 7 × 52 = 4,368,000 kWh. Cost = 4,368,000 × $0.058 = $253,344/year. This quarter-million-dollar annual cost underscores the critical importance of process heating efficiency and waste heat recovery.