PRACTICE EXAM 19: PE POWER SIMULATION (80 QUESTIONS)

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1. A 13.8 kV industrial facility has a three-phase fault level of 600 MVA and proposes installing a 10,800 kvar capacitor bank on a bus that serves a mix of six-pulse VFDs (5,000 HP), eighteen-pulse VFDs (3,000 HP), and active front-end (AFE) drives (2,000 HP). The resonant harmonic order is h_r = √(600,000/10,800) = 7.45. The engineer must determine which drive type creates the dominant resonance risk and whether the eighteen-pulse drives' residual 5th and 7th harmonics (typically 2-3% of fundamental vs 20% for six-pulse) contribute meaningfully. What is the correct assessment?

A. The eighteen-pulse drives dominate because their residual harmonics are closer to h_r than the six-pulse harmonics

B. All three drive types contribute equally to resonance risk at h_r = 7.45

C. The six-pulse VFDs dominate overwhelmingly — their 7th harmonic current (20% of fundamental at h = 7) is very close to h_r = 7.45; the eighteen-pulse residual 7th (2-3%) is one-tenth the magnitude; the AFE drives inject negligible low-order harmonics; detuning reactors (6%) must be installed

D. No concern exists because h_r = 7.45 is exactly between the 7th and 8th harmonics

2. A three-phase, 480V system has a 4,000 kVA service transformer (Z = 5.75%, X/R = 10) feeding a main switchboard. The switchboard has an available fault current of 48,300A. Two remote MCCs are fed from the switchboard: MCC-A through 250 feet of 500 kcmil copper in steel conduit, and MCC-B through 600 feet of 3/0 AWG copper in EMT. An arc flash study at the switchboard shows 18 cal/cm² at 0.1-second clearing. The engineer must determine which MCC requires the LOWER PPE category. Which MCC has significantly lower arc flash energy?

A. MCC-B — the much longer cable with smaller conductor produces dramatically higher impedance, reducing the fault current and arc flash energy far more than MCC-A's shorter run of larger conductor

B. MCC-A — the larger conductor provides lower impedance and therefore lower arc flash energy

C. Both MCCs have approximately equal arc flash energy because they share the same clearing time

D. Neither — cable impedance has no meaningful effect on arc flash energy at these distances

3. Per NEC 430.52(C)(1), a 750 HP, 460V motor has Table 430.250 FLA = 862A. The maximum inverse-time breaker at 250% = 2,155A → next standard 2,500A. Exception 1 permits 400% = 3,448A → next standard not exceeding 3,448A. Per NEC 240.6(A), standard sizes include 2,500A, 3,000A, and 3,500A. What is the maximum breaker size per Exception 1?

A. 3,500A (exceeds 3,448A — non-compliant)

B. 2,500A (the original 250% value — no increase permitted for motors above 500 HP)

C. 4,000A

D. 3,000A — the largest standard size not exceeding 3,448A

4. A CT with a ratio of 3000:5 and accuracy class C800 is connected to a generator differential relay. During a 45,000A internal fault, the CT secondary is 75A (15× rated). The total burden is 8.0 Ω. The voltage across the burden is 600V. At the 20× rated operating point, C800 guarantees 800V. At the actual 15× point with 600V, is the CT performing adequately, and what additional concern exists for this high-burden application?

A. Yes — 600V is within the C800 capability at 15× rated with substantial margin

B. The CT is within its rating at 15× for steady-state AC; however, the 8.0 Ω burden is very high and during the first few cycles of a fault with significant DC offset (high X/R), the combined AC and DC flux may drive the CT into momentary saturation, causing false differential current — the burden should be reduced or a higher-class CT specified

C. No — 600V exceeds the proportional limit at 15× rated

D. No — 8.0 Ω exceeds the maximum burden for any CT accuracy class

5. A 345 kV, 380-mile transmission line has $Z_c = 370\ \Omega$ and SIL = 322 MW. The line must transmit 500 MW during summer peak. A 50% series capacitor compensation is installed at two locations (25% at the one-third point and 25% at the two-thirds point). What is the effective line reactance, the new stability limit, and why is distributed compensation preferred over a single midpoint installation?

A. X_eff = 0.50 × X_line; P_max doubles; distributed compensation reduces the peak voltage across each capacitor bank during faults (subsynchronous resonance concern) and provides more uniform voltage profile along the line than a single midpoint installation

B. X_eff = 0.75 × X_line; P_max increases by 33%; single midpoint is always preferred

C. X_eff = X_line (series capacitors have no effect on lines above 300 miles)

D. X_eff = 0.50 × X_line; P_max increases by 100%; but single midpoint installation is simpler and equivalent

6. Per NEC 250.122(B), a 500A circuit has minimum phase conductors of 700 kcmil copper (475A at 75°C — meeting the 500A continuous requirement after the 125% adder). The conductors are increased to 1,000 kcmil for voltage drop. The minimum EGC from Table 250.122 for a 500A OCPD is 2/0 AWG (133,100 CM). What is the proportionally increased EGC?

A. 2/0 AWG (no increase needed)

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

C. Ratio = 1,000,000/700,000 = 1.429; EGC = 133,100 × 1.429 = 190,199 CM → 4/0 AWG (211,600 CM) is the minimum standard size above 190,199 CM

D. 250 kcmil (must exceed 200,000 CM by at least 10%)

7. A three-phase, 4,160V system has a 9,000 kW load at 0.66 lagging PF through a feeder with Z = 0.60 + j3.50 Ω per phase. The original reactive demand is Q = 9,000 × tan(arccos 0.66) = 9,000 × 1.138 = 10,242 kvar. The engineer evaluates installing a 7,500 kvar capacitor bank AND a 3,000 HP synchronous motor at 0.80 leading PF (η = 94%). What is the new combined bus power factor after both are energized?

A. PF = 0.85 lagging

B. PF = 0.92 lagging

C. PF = 0.95 lagging

D. Sync motor: P_in = 3,000×0.746/0.94 = 2,381 kW; S = 2,381/0.80 = 2,976 kVA; Q_sync = $\sqrt{(2{,}976^2 - 2{,}381^2)}$ = 1,786 kvar; total correction = 7,500 + 1,786 = 9,286 kvar; net Q = 10,242 − 9,286 = 956 kvar; P_total = 11,381 kW; PF = 11,381/$\sqrt{(11{,}381^2+956^2)}$ = 11,381/11,421 = 0.997 ≈ 0.99

8. A three-phase, 480Y/277V panelboard serves a large warehouse with 70% LED high-bay lighting (nonlinear, producing 3rd harmonic at 35% of fundamental), 20% motor loads (linear), and 10% resistance heating (linear). Each phase draws 320A total fundamental. The LED drivers produce 3rd harmonic current of 0.35 × 0.70 × 320 = 78.4A per phase. The neutral current = 3 × 78.4 = 235.2A. With 4 current-carrying conductors (0.80 factor), what are the minimum base ampacities for phase and neutral?

A. Phase = 320A; neutral = 235.2A; phase governs at 320/0.80 = 400A base ampacity

B. Phase = 320/0.80 = 400A; neutral = 235.2/0.80 = 294A; phase governs at 400A

C. Neutral governs at 294A because the neutral carries the highest harmonic current

D. Both require 400A base ampacity (must be sized identically)

9. A 200 MVA synchronous generator has X"_d = 0.19 pu, X_2 = 0.21 pu, X_0 = 0.08 pu on its own base. The generator is grounded through a 0.6 Ω reactor. Z_base = $(22)^2$/200 = 2.42 Ω. X_n(pu) = 0.6/2.42 = 0.248 pu. In the zero-sequence network, 3X_n = 0.744 pu. For a bolted SLG fault, the total impedance Z_total = j(X"_d + X_2 + X_0 + 3X_n) = j(0.19 + 0.21 + 0.08 + 0.744) = j1.224 pu. What is the SLG fault current and how does it compare to the three-phase fault?

A. I_SLG = 3/1.224 = 2.45 pu; I_3Φ = 1/0.19 = 5.26 pu; the reactor grounding reduces SLG current to 47% of three-phase — unlike resistance grounding, the current remains purely reactive (90° lag), maintaining the same phase angle as a solidly grounded system but at reduced magnitude

B. I_SLG = 5.26 pu (same as three-phase)

C. I_SLG = 2.45 pu with a predominantly resistive character

D. I_SLG = 1.0 pu (reduced to the reactor's rated current)

10. A three-phase, 4,160V system has a neutral grounding resistor rated 300A, 10 seconds. A ground fault through 10 Ω fault resistance develops. R_NGR = 2,402/300 = 8.007 Ω. I_fault = 2,402/(8.007 + 10) = 133.4A. The ground-fault relay has a pickup of 30A with 1.5-second delay. After clearing, the engineer discovers that the same fault re-strikes 5 minutes later and the relay clears it again in 1.5 seconds. What is the cumulative I^2t consumption after both fault events?

A. $2 \times (133.4^2 \times 1.5) = 53{,}337$ A^2s; rated = 900,000 A^2s; consumed = 5.93% — the NGR retains 94% of its capacity despite two consecutive fault events

B. 100% — two faults always exhaust the NGR

C. Approximately 6% total — but the 5-minute gap between faults allowed significant cooling, so the actual thermal stress is even lower than the simple I^2t calculation suggests

D. 50% consumed after the first fault

11. Per NEC 110.34(C), outdoor electrical installations operating at over 600V must have a fence or other barrier that limits access to qualified persons. For a 34.5 kV substation, the minimum fence height is what distance?

A. 6 feet

B. 8 feet

C. 10 feet

D. 7 feet with an additional 1 foot of barbed wire or equivalent for a total of 8 feet per typical utility practice, although NEC 110.34(C) specifies a minimum of 7 feet

12. A 3,000 kVA, 13.8 kV/480V transformer has core losses of 8,200 W and full-load copper losses of 26,000 W. The facility operates two shifts: Shift 1 (12 hours at 85% load, PF = 0.90) and Shift 2 (12 hours at 45% load, PF = 0.80). The maximum efficiency loading is $k_{max} = \sqrt{(8{,}200/26{,}000)} = 56.2\%$. The transformer's all-day efficiency involves computing output energy and loss energy for each period. Which shift operates closer to maximum efficiency?

A. Shift 1 (85%) — although farther from k_{max}, the higher PF produces better overall efficiency

B. Shift 2 (45%) — closest to k_max = 56.2%, operating only 11.2 percentage points below optimal; this shift operates near the point where core losses equal copper losses, producing the highest instantaneous efficiency despite lower output power

C. Both shifts operate at identical efficiency because transformer efficiency is constant

D. Neither — maximum efficiency only occurs at 100% loading

13. A protection coordination study on a 4,160V system requires coordinating a 350E current-limiting fuse on a large motor feeder with an upstream 51 bus relay (IEEE extremely inverse, TD = 2.0, pickup = 8A on 1000:5 CT). At the maximum bus fault of 20,000A: fuse total clearing = 0.003 seconds. Relay secondary = 20,000/200 = 100A. M = 100/8 = 12.5. Using $t = TD \times (28.2/(M^2-1) + 0.1217)$, what is the relay operating time and CTI?

A. t = 0.39s; CTI = 0.387s — adequate coordination with generous margin

B. t = 0.15s; CTI = 0.147s — below the 0.20s minimum

C. t = 1.0s; CTI = 0.997s — excessive

D. t = 0.25s; CTI = 0.247s — adequate

14. A distance relay on a 230 kV line has Zone 1 at 85% reach (Z_line = 7 + j80 Ω). A bolted three-phase fault occurs at exactly 85% of the line. The relay measures Z_meas = 0.85 × (7 + j80) = 5.95 + j68 Ω. |Z_meas| = 68.3 Ω. Zone 1 reach = 0.85 × 80.3 = 68.3 Ω. The fault is at the exact boundary of Zone 1. What is the reliability concern?

A. No concern — the relay trips instantaneously at its rated reach

B. The relay may not operate reliably at exactly 85% reach due to CT/PT measurement errors

C. At exactly the Zone 1 boundary, the relay is on the edge of its operating characteristic — CT errors (±3%), PT errors (±3%), relay tolerance (±5%), and transient measurement uncertainty mean the relay may or may not trip for this fault; this is why Zone 1 is set at 80-85% rather than 100%, creating a margin for measurement uncertainty that still leaves faults in the last 15-20% to be cleared by pilot schemes or Zone 2

D. The relay over-reaches at the boundary and trips for faults beyond 85%

15. A three-phase, 460V, 4-pole, 350 HP induction motor drives a centrifugal chiller compressor. At design speed (1,770 RPM, 60 Hz), the compressor requires 261 kW. During shoulder-season operation (4,200 hours/year), the chiller needs 60% capacity. Using the affinity laws for centrifugal compressors (capacity ∝ speed; power ∝ speed^3), the speed for 60% capacity is 60% of rated = 1,062 RPM. What is the compressor power and annual energy savings compared to full-speed operation at $0.088/kWh?

A. P = 56.4 kW; savings = (261 − 56.4) × 4,200 × $0.088 = $75,700/year

B. P = 156.6 kW; savings = $38,650/year (linear reduction — incorrect)

C. P = 56.4 kW; savings = $75,700/year... but the actual number: P = 261 × 0.6^3 = 261 × 0.216 = 56.4; savings = (261-56.4) × 4,200 × 0.088 = 204.6 × 4,200 × 0.088 = $75,659

D. P = 261 × 0.6 = 156.6 kW; savings per hour = 104.4 kW; annual = $38,583

16. Per NEC 480.9(A), ventilation for battery rooms must limit hydrogen below 1% by volume. A data center has a massive VRLA battery system: 960 cells in floor-standing racks within a dedicated 12,000 ft^3 room. The manufacturer states worst-case H_2 emission during equalize charging is 0.0015 ft^3/cell/hour. What ventilation rate is required, and what battery management system (BMS) features help prevent the worst-case charging condition from occurring?

A. ACH = 0.50; BMS has no role in hydrogen management

B. H_2 = 960 × 0.0015 = 1.44 ft^3/hr; max H_2 at 1% = 120 ft^3; ACH = 1.44/120 = 0.012; the BMS should include: temperature-compensated charging to prevent overcharging (the primary cause of H_2 emission), individual cell voltage monitoring to detect thermal runaway early, and automatic charge termination when cell voltages exceed limits — proper BMS management dramatically reduces actual H_2 production below worst-case values

C. No ventilation needed for VRLA — sealed cells produce zero hydrogen

D. ACH = 5.0; forced ventilation with explosion-proof fans required

17. A 230 kV, 400-mile transmission line has Z_c = 380 Ω, SIL = 139 MW. The line must transmit 280 MW during peak and operates at only 30 MW during off-peak. The Ferranti effect at 400 miles with the line open is approximately 22% voltage rise. An engineer proposes: (1) 40% series compensation at two

distributed locations, (2) two 120 Mvar switched shunt reactors at the receiving end, and (3) an SVC rated ±150 Mvar at the receiving end. During peak loading (280 MW > SIL), what is the primary function of each device?

A. Series capacitors improve voltage regulation and stability by reducing effective line reactance; shunt reactors are OFF during peak (above SIL, the line absorbs reactive power — turning on reactors would worsen voltage drop); the SVC operates in generating mode to support voltage by supplying reactive power to compensate for the line's reactive absorption

B. All three devices operate simultaneously in absorbing mode

C. Only the SVC operates during peak; the other devices are for emergencies only

D. The shunt reactors support voltage during peak by generating reactive power

18. A separately excited DC motor has V_t = 500V, I_a = 200A, R_a = 0.08 Ω, rated speed = 1,800 RPM. The back-EMF E_a = V_t − I_aR_a = 484V. The motor drives a winder that requires dynamic braking during deceleration. For dynamic braking, the armature is disconnected from the supply and connected to a braking resistor R_B. At the instant of switching (motor still at 1,800 RPM), the initial braking current is I_brake = E_a/(R_a + R_B). If R_B = 2.0 Ω, what is the initial braking current and power dissipated?

A. I_brake = 100A; P = 20 kW

B. I_brake = 484/(0.08 + 2.0) = 232.7A; P = 232.7 × 484 = 112,627W — but this is E × I, not I^2R; the power dissipated IN THE BRAKING RESISTOR = I^2×R_B = 232.7^2 × 2.0 = 108,299W ≈ 108 kW; the total braking power = I^2 × (R_a+R_B) = 232.7^2 × 2.08 = 112.6 kW

C. I_brake = 484/2.0 = 242A; P_brake = 242^2 × 2.0 = 117.1 kW

D. I_brake = 200A; P = 80 kW (same as motoring)

19. Per NEC 250.30(A)(1), each separately derived system requires a system bonding jumper. A large hospital campus has: 4 × 2,000 kVA service transformers (13.8/480V), 2 × 1,500 kW emergency generators, 6 × 500 kVA PDU transformers (480/208Y/120V), and 3 × 225 kVA isolation transformers (480/480V for sensitive equipment). How many total system bonding jumpers are required?

A. Four (service transformers only)

B. Fifteen — each transformer and generator is a separately derived system: 4 service transformers + 2 generators + 6 PDU transformers + 3 isolation transformers = 15 bonding jumpers, each installed at its respective source

C. Six (PDU transformers only)

D. Ten (service + generators + PDU)

20. A three-phase, 480V, 800A switchboard has an available fault current of 58,000A and a main LVPCB with 0.30-second short-time delay. The arc flash study shows 42 cal/cm^2 at 24 inches. The engineer implements a comprehensive strategy: (1) ZSI (bus fault → 0.05s), (2) optical relay (0.025s), (3) arc-resistant switchgear, (4) remote racking, (5) permanent magnet trip on the main breaker (eliminates dependency on control power for tripping). For a bus fault, what is the calculated incident energy with the optical relay, and why is the permanent magnet trip important?

A. $E = 42 \times (0.025/0.30) = 3.5$ cal/cm^2; permanent magnet trip is irrelevant

B. $E = 42$ cal/cm^2 (unchanged by any mitigation)

C. $E = 21$ cal/cm^2 (halved by arc-resistant switchgear)

D. $E = 3.5$ cal/cm^2; the permanent magnet trip mechanism ensures the breaker can trip even if the control power supply is lost during the arc flash event — a stored-energy mechanism that does not depend on external power, providing the last-resort tripping capability that electronic trip units alone cannot guarantee during a catastrophic arc event

21. A synchronous generator rated 300 MVA, 24 kV has X"_d = 0.21 pu, $X_2 = 0.23$ pu, $X_0 = 0.10$ pu. The generator is solidly grounded. For all four bolted fault types (3Φ, LL, SLG, DLG), calculate the subtransient fault currents in per-unit and rank them from highest to lowest.

A. I_3Φ > I_SLG > I_DLG > I_LL

B. I_SLG (5.56 pu) > I_DLG (5.33 pu) > I_3Φ (4.76 pu) > I_LL (4.13 pu) — the SLG exceeds all other fault types because X_0 (0.10) is much less than X"_d (0.21); the DLG fault also exceeds three-phase for the same reason

C. I_3Φ > I_DLG > I_SLG > I_LL always

D. All four produce identical fault current in solidly grounded systems

22. A 480V, three-phase panelboard has: Motor 1 = 302A (250 HP, largest), Motor 2 = 242A (200 HP), Motor 3 = 180A (150 HP). Continuous lighting = 200A. Noncontinuous receptacles = 60A. Per NEC 430.24 and 215.2(A)(1), what is the minimum feeder conductor ampacity?

A. 125% × 302 + 242 + 180 + 125% × 200 + 60 = 377.5 + 422 + 250 + 60 = 1,109.5A

B. 900A

C. 1,200A

D. 1,109.5A

23. A three-phase, 4,160V system has six sources on a common bus. On a 50 MVA system base: Transformer A (Z = 0.06 pu), Transformer B (Z = 0.08 pu), Transformer C (Z = 0.10 pu), Generator D (X"_d = 0.50 pu), Generator E (X"_d = 0.80 pu), Synchronous Condenser F (X"_d = 1.0 pu). I_base = 6,940A. What is the total three-phase fault current?

A. 100,000A

B. 200,000A

C. I = (1/0.06 + 1/0.08 + 1/0.10 + 1/0.50 + 1/0.80 + 1/1.0) × 6,940 = (16.67 + 12.50 + 10.0 + 2.0 + 1.25 + 1.0) × 6,940 = 43.42 × 6,940 = 301,335A — this extraordinarily high combined fault current from six parallel sources demonstrates why large industrial facilities require very high SCCR equipment and comprehensive fault current studies

D. 150,000A

24. A 480V, three-phase, 225A panelboard has an available fault current of 42,000A. The panelboard SCCR is 22,000A. An upstream 225A Class J current-limiting fuse limits let-through to 9,500A peak (6,200A RMS) at 42,000A available. Per NEC 240.86 and 110.10, the fuse-panelboard combination

must be tested, listed, and documented as a series-rated system. The let-through of 6,200A is well below the 22,000A SCCR. If the combination IS listed, what additional requirement must be met?

A. No additional requirements beyond the listing documentation

B. The panelboard must be physically upgraded with higher-rated bus bars

C. The series combination must be re-tested annually

D. The equipment must be field-marked with the series combination rating per NEC 240.86, including: the available fault current, the type and ampere rating of the upstream current-limiting device, and a statement that the series combination has been evaluated and found to be in compliance — without this permanent field marking, the installation is non-compliant even if the listed combination is correct

25. Per NEC 690.12, a residential PV system on a single-family dwelling uses string inverters with 16 modules per string (V_oc = 50V per module = 800V). No module-level power electronics are installed. The homeowner asks if the system complies with NEC 690.12(B)(2) for the within-array-boundary requirement of 80V within 30 seconds. After rapid shutdown initiation, what voltage exists on the rooftop string conductors?

A. 0V — the string inverter removes all voltage when it shuts down

B. 800V — each module continues producing V_oc under sunlight; without module-level shutdown devices, the string conductors within the array boundary remain at full string voltage (800V) far exceeding the 80V threshold; the system is NON-COMPLIANT and requires module-level optimizers or microinverters

C. 50V — only one module remains energized after rapid shutdown

D. 80V — the inverter regulates each module to 5V output during rapid shutdown

26. A three-phase, 480V system has two transformers in parallel: T1 = 3,000 kVA (Z = 5.75%, X/R = 9) and T2 = 2,000 kVA (Z = 6.00%, X/R = 8). Both have identical ratios and configurations. The engineer must determine the total fault current for equipment rating and the individual transformer contributions for protection coordination. On a 3,000 kVA base: Z_T1 = 0.0575 pu, Z_T2 = 0.06 × (3,000/2,000) = 0.09 pu. What is the total fault current?

A. I_T1 = 3,608/0.0575 = 62,748A; I_T2 = 2,406/0.06 = 40,100A; Total = 102,848A — this extremely high combined fault current requires all downstream equipment to have SCCR ratings exceeding 100 kA, which is above the rating of most standard 480V equipment

B. 62,748A (T1 alone)

C. 50,000A

D. 80,000A

27. A balanced three-phase, 4,160V source feeds a 10,000 kW load at 0.68 lagging PF. Q = 10,000 × 1.078 = 10,780 kvar. The engineer installs an 8,000 kvar capacitor bank AND a 3,500 HP synchronous motor at 0.80 leading PF ($\eta = 94\%$). What is the new bus PF?

A. PF = 0.88 lagging

B. PF = 0.95 lagging

C. Sync motor: P_in = 2,760 kW; Q_sync = 2,070 kvar; total correction = 8,000 + 2,070 = 10,070 kvar; net Q = 10,780 − 10,070 = 710 kvar; P_total = 12,760 kW; PF = 12,760/12,780 = 0.998 ≈ 0.99

D. PF = unity

28. A protection engineer designs a transformer differential relay (87T) for a 100 MVA, 230/69 kV, wye-grounded/delta transformer. The relay uses restraint slope of 25% and a minimum pickup of 0.3A. During an external fault, one HV-side CT saturates to 55% of expected output (X/R = 22 system). The expected CT secondary for both sides is 4.5A. What is the false differential and does the relay trip?

A. False differential = 0A (equal saturation on both sides)

B. False differential = 4.5 − 2.475 = 2.025A; restraint = 4.5A; slope threshold = 25% × 4.5 = 1.125A; since 2.025A > 1.125A AND > 0.3A pickup, the relay FALSE TRIPS

C. False differential = 0.45A; relay correctly restrains

D. False differential = 2.025A; but the relay restrains because the slope threshold is 2.25A

29. Per NEC 450.3(B), a 5,000 kVA, 480V/208Y/120V transformer has a primary current of 6,014A. Maximum primary OCPD at 125% = 7,517.5A. Standard sizes include 7,000A and 8,000A. NEC 450.3(B) permits the next higher standard above 125%. What is the maximum primary OCPD?

A. 7,000A — must not exceed 125%

B. 8,000A — the next standard size above 7,517.5A

C. 6,014A — 100% protection required above 5,000 kVA

D. 10,000A — transformers above 3,000 kVA may use 167%

30. A three-phase, 4,160V, 6-pole synchronous motor rated 4,000 HP drives a SAG mill at 1,200 RPM. Pull-out torque = 260% FLT. Field current = 420A. During a system disturbance, the voltage sags to 72% for 0.9 seconds (fixed field, E_a constant). Pull-out = 0.72 × 260% = 187.2% FLT. Mill load = 100% FLT. Margin = 87.2% FLT. The motor has H = 1.8 MJ/MVA and S_rated = 3,482 kVA. Using the swing equation, what is the approximate rotor angle advance during the sag?

A. Δδ ≈ (180 × 60 × P_accel × t^2)/(H × S) where P_accel depends on the reduced electrical output during the sag; the net accelerating torque is the difference between the mechanical load and the electrical output capability at 72% voltage; for a simplified analysis assuming P_accel ≈ 0.28 × P_rated (28% reduction in electrical capability), Δδ ≈ (180 × 60 × 0.28 × 2,984 × 0.81)/(1.8 × 3,482) — this calculation yields approximately 35-50° of angular advance, suggesting stability is maintained but with reduced margin compared to the steady-state analysis

B. Δδ = 0° — synchronous motors do not experience angular displacement

C. Δδ = 180° — the motor immediately pulls out

D. Δδ = 5° — negligible advance

31. A 480V, three-phase system has four parallel transformers: T1 = 2,500 kVA (Z = 5.50%), T2 = 2,000 kVA (Z = 5.75%), T3 = 1,500 kVA (Z = 6.00%), T4 = 1,000 kVA (Z = 6.25%). On a 2,500 kVA common base: Z_T1 = 0.055, Z_T2 = 0.0719, Z_T3 = 0.10, Z_T4 = 0.1563. What percentage of a combined 5,000 kVA load does T1 carry?

A. 25% (equal shares among four transformers)

B. 35%

C. 1/Z_T1 = 18.18; 1/Z_T2 = 13.91; 1/Z_T3 = 10.0; 1/Z_T4 = 6.40; sum = 48.49; T1 share = 18.18/48.49 = 37.5% — T1 carries the most because it has the lowest per-unit impedance on the common base

D. 50% (T1 is the largest and carries half)

32. A 13.8 kV, three-phase system has a voltage THD of 12.8% at the PCC. Individual harmonics: V_5 = 9.5%, V_7 = 6.2%, V_{11} = 3.8%, V_{13} = 2.6%, V_{17} = 1.5%. IEEE 519 limits: THD_V ≤ 5.0%, individual ≤ 3.0%. The facility has predominantly old six-pulse VFDs on large compressors. What is the total violation count and the recommended phased mitigation approach?

A. Three violations

B. Four violations (V_5, V_7, V_{11}, THD)

C. Two violations only

D. Five violations — V_5 (9.5%), V_7 (6.2%), V_{11} (3.8%) all exceed 3.0%, and THD (12.8%) exceeds 5.0%; the fifth violation doesn't exist but four violations require a phased approach: Phase 1 — retrofit the largest six-pulse VFDs to 18-pulse or AFE to eliminate 5th and 7th at source; Phase 2 — verify V_{11} compliance after Phase 1; Phase 3 — if V_{11} still exceeds 3.0%, install an 11th-harmonic passive filter; Phase 4 — verify THD < 5.0%

33. A ground resistance test on a semiconductor fabrication facility measures 3.5 Ω during wet spring conditions. The IEEE 80 design target is 0.5 Ω. IEEE 81 seasonal correction factor is 1.8 (wet-to-dry for this sandy soil). What is the estimated worst-case resistance, and what comprehensive grounding strategy is required?

A. Corrected = 3.5 × 1.8 = 6.3 Ω; the ground grid is catastrophically inadequate at 12.6× the 0.5 Ω target

B. Corrected = 3.5 Ω (seasonal correction not applicable in sandy soil)

C. Corrected = 1.94 Ω (dividing by the correction factor)

D. Corrected = 6.3 Ω; remediation requires: (1) expanding the ground grid to maximum practical extent under and around the facility, (2) deep ground wells drilled to reach water table or lower-resistivity geology, (3) ground enhancement material (GEM) backfill around all grid conductors and wells, (4) chemical ground electrodes for persistent low-resistivity zones, (5) bonding to all underground utilities and building steel — achieving 0.5 Ω in sandy soil (typical resistivity 500-3,000 Ω-m) requires an aggressive, multi-method approach

34. A three-phase, 460V, 2-pole induction motor rated 500 HP has full-load speed 3,555 RPM, efficiency 96.5%, PF 0.90 lagging. The motor's no-load magnetizing kvar is approximately 75 kvar. A 60 kvar capacitor is proposed at the motor terminals. Per NEC 460.9, is this installation safe, and what corrected PF results?

A. Unsafe — 60 kvar exceeds the recommended 67% of no-load magnetizing kvar (67% × 75 = 50.25 kvar)

B. Safe — 60 kvar is 80% of 75 kvar, within the self-excitation limit; however, 80% is above some manufacturers' recommended maximum of 67%; PF calculation: P_in = 386.8 kW; Q_orig = $\sqrt{((386.8/0.90)^2 - 386.8^2)} = 187.3$ kvar; Q_new = 127.3 kvar; PF_new = $386.8/\sqrt{(386.8^2 + 127.3^2)} = 0.950$; the engineer should consult the motor manufacturer regarding the 80% level

C. Unsafe — any capacitor above 50 kvar causes self-excitation on 500 HP motors

D. Safe — 60 kvar is well within all limits for a motor this size

35. A three-phase, 460V, 8-pole VFD-driven induction motor operates a centrifugal cooling tower fan at design speed of 877 RPM (60 Hz), consuming 200 kW. The facility requires three operating modes: full speed (2,500 hr/yr), 75% speed (3,500 hr/yr), and 50% speed (2,760 hr/yr). Using the affinity laws, what is the total annual energy consumption with the VFD versus full-speed operation?

A. VFD: full = 500,000 + 75% = 200×0.422×3,500 + 50% = 200×0.125×2,760 = 500,000 + 295,312 + 69,000 = 864,312 kWh; full-speed = 200 × 8,760 = 1,752,000 kWh; savings = 887,688 kWh (50.7% reduction)

B. VFD total = 1,200,000 kWh; savings = 552,000 kWh

C. VFD total = 864,312 kWh; savings = 887,688 kWh

D. VFD total = 1,500,000 kWh; savings = 252,000 kWh

36. A 480V, three-phase, 200A feeder uses 250 kcmil THHN copper in steel conduit (R = 0.0541 Ω/1000 ft, X = 0.0442 Ω/1000 ft). The feeder is 600 feet long and serves a load at 0.84 lagging PF. What is the voltage drop percentage?

A. 2.0%

B. 2.5%

C. V_drop = √3 × 200 × (0.0541×0.6×0.84 + 0.0442×0.6×0.542) = 346.4 × (0.02727 + 0.01438) = 346.4 × 0.04165 = 14.42V; 14.42/480 = 3.00% — exactly at the NEC recommended 3% feeder maximum; the engineer should consider upsizing to 350 kcmil to provide margin

D. 4.5%

37. A 100 MVA, 345/138 kV autotransformer has series impedance 10% on its own base. Three identical units operate in parallel. A 50 MVA generator (X"_d = 0.22 pu), a 30 MVA synchronous condenser (X"_d = 0.18 pu), and a 20 MVA synchronous motor (X"_d = 0.25 pu) are connected to the 138 kV bus. On a 100 MVA base: Z_T_par = 0.10/3 = 0.0333; Z_gen = 0.44; Z_SC = 0.60; Z_SM = 1.25. What is the total fault current?

A. I_base = 418.4A; I = (30.0 + 2.273 + 1.667 + 0.80) × 418.4 = 34.74 × 418.4 = 14,535A

B. 10,000A

C. 20,000A

D. I = 34.74 × 418.4 = 14,535A — the three parallel transformers dominate at 86%, with the three rotating machines contributing only 14% of the total; the synchronous motor's relatively high impedance (1.25 pu on 100 MVA base) produces minimal fault contribution

38. A 480V, three-phase system has a 3,000 kVA transformer (Z = 5.75%, X/R = 9) and a 2,000 kVA transformer (Z = 6.25%, X/R = 8) in parallel. I_T1 = 62,748A; I_T2 = 37,209A; Total = 99,957A. Additionally, 12 motors with combined FLA of 2,400A contribute 4 × 2,400 = 9,600A first-cycle. The grand total symmetrical first-cycle = 109,557A. Using a weighted X/R of approximately 8.6 and an IEEE multiplier of 2.33, what is the peak asymmetrical current?

A. 155,000A

B. Peak = 2.33 × 109,557 = 255,268A — this quarter-million-ampere peak current produces massive electromagnetic forces on bus structures; the paralleled 480V system requires extreme mechanical bracing designed to withstand forces proportional to I^2_peak

C. 219,114A (2× symmetrical)

D. 109,557A (no asymmetry for parallel sources)

39. Per NEC 250.53(A)(2), only one supplemental electrode is required when a single rod fails 25 Ω. IEEE 142 recommends ≤5 Ω for industrial facilities. A new data center facility's two-rod installation measures 42 Ω. The engineer proposes an alternative: a concrete-encased electrode (Ufer ground) per NEC 250.52(A)(3) — the building's reinforced concrete foundation with a minimum of 20 feet of bare copper conductor encased in the footer. What advantage does the Ufer ground provide?

A. A concrete-encased electrode (Ufer ground) provides excellent long-term ground resistance because concrete absorbs moisture from surrounding soil and maintains relatively stable resistivity over seasons; the large surface area of the encased conductor in contact with moist concrete provides significantly lower resistance than driven rods in high-resistivity soil — often achieving 5 Ω or less even in poor soil conditions

B. The Ufer ground provides no advantage over driven rods

C. The Ufer ground is only effective in wet climates

D. The Ufer ground is prohibited for data centers by NEC

40. A 480V, three-phase system has a 2,500 kVA transformer (Z = 5.75%) feeding a switchboard. A 600-foot cable of 3/0 AWG copper in PVC conduit (R = 0.0766 Ω/1000 ft, X = 0.0532 Ω/1000 ft) feeds a remote panelboard. What is the approximate available fault current at the remote panelboard?

A. 42,700A (switchboard value — cable negligible)

B. 22,000A

C. Cable: R = 0.04596, X = 0.03192 Ω/phase; Z_base = 0.0922 Ω; Z_cable_pu = $\sqrt{(0.04596^2 + 0.03192^2)}$/0.0922 = 0.05596/0.0922 = 0.607 pu; Total = 0.0575 + 0.607 = 0.664 pu; I = 3,007/0.664 =

4,528A — the very long run of 3/0 conductor reduces the fault current to approximately 11% of the switchboard value, dramatically lowering arc flash energy

D. 15,000A

41. A 60 MVA, 138/13.8 kV, delta-wye grounded transformer has $Z_1 = Z_2 = j0.085$ pu and $Z_0 = j0.055$ pu on its own base. The 138 kV source has Z_1_src = j0.04 pu on the transformer base. On a 100 MVA system base: Z_1_total = 0.085×100/60 + 0.04×100/60 = 0.1417 + 0.0667 = 0.2083 pu. Z_0_total = 0.055×100/60 = 0.0917 pu (delta blocks source Z_0). Compare I_SLG and I_3Φ and calculate the percentage by which the larger exceeds the smaller.

A. I_SLG = I_3Φ (equal)

B. I_3Φ > I_SLG by 10%

C. I_SLG > I_3Φ by 25%

D. I_3Φ = 1/0.2083 = 4.80 pu; I_SLG = 3/(0.2083+0.2083+0.0917) = 3/0.5083 = 5.90 pu; I_SLG > I_3Φ by (5.90−4.80)/4.80 = 22.9% — the delta blocking source Z_0 creates a zero-sequence impedance (0.0917) dramatically lower than Z_1_total (0.2083), producing SLG current 23% above three-phase

42. A three-phase, 460V, 4-pole induction motor rated 300 HP has PF = 0.88 lagging, efficiency = 95.8%. Two capacitor options: 40 kvar and 65 kvar. The motor's no-load magnetizing kvar is 55 kvar. Per NEC 460.9, which option(s) are safe?

A. Both are safe because both are below 65 kvar

B. Only the 40 kvar is safe (40 < 55 kvar limit); the 65 kvar exceeds the no-load magnetizing kvar (65 > 55) and will cause self-excitation after disconnection — the capacitor provides more reactive power than the motor needs to maintain its magnetic field, causing voltage to build up dangerously

C. Neither is safe for motors above 250 HP

D. Both are safe — NEC 460.9 applies only to motors below 200 HP

43. A CT with a ratio of 2000:5 and accuracy class C400 serves a bus differential relay. During an external through-fault of 50,000A with X/R = 24, one of five CTs saturates to 50% of expected output during the first four cycles. The expected secondary per CT = 125A. The false differential = 125 − 62.5 = 62.5A. The restraint current = 125A. The relay slope is set at 35%. Does the relay correctly restrain?

A. Slope threshold = 35% × 125 = 43.75A; since 62.5A > 43.75A, the relay FALSE TRIPS — the 35% slope is insufficient to accommodate the 50% CT saturation caused by the very high X/R = 24 DC offset; the slope must be increased to at least 50% to maintain security for this level of CT saturation

B. The relay correctly restrains because the differential current is within tolerance

C. The relay trips correctly because 62.5A indicates a real internal fault

D. The relay restrains because the fixed pickup is 100A

44. A balanced three-phase, 208Y/120V panelboard serves a data center with 100% nonlinear server loads. Each phase draws 380A fundamental, 152A 3rd harmonic, 76A 5th harmonic, and 38A 7th harmonic. Calculate the true-RMS phase current, neutral current, and the neutral-to-phase ratio.

A. I_phase = 380A; I_neutral = 456A; ratio = 1.20

B. I_phase = 435A; I_neutral = 456A; ratio = 1.05

C. I_phase = $\sqrt{(380^2 + 152^2 + 76^2 + 38^2)} = \sqrt{(144,400 + 23,104 + 5,776 + 1,444)} = \sqrt{174,724}$ = 417.8A; I_neutral = 3 × 152 = 456A (only triplens — 5th and 7th cancel balanced); ratio = 456/417.8 = 1.091 — the neutral exceeds the phase by 9.1%, requiring larger neutral conductors

D. I_phase = 646A; I_neutral = 456A; ratio = 0.71

45. Per NEC Article 517.17(A), a hospital's LIM alarms at 5 mA. An operating suite has three operating rooms sharing two isolated power panels. Panel A serves Rooms 1 and 2 (total hazard current = 4.6 mA with 16 devices). Panel B serves Room 3 (total hazard current = 3.1 mA with 9 devices). A surgeon in Room 1 needs two additional devices (0.3 mA each). Connecting both to Panel A would bring it to 5.2 mA (alarm). The engineer proposes connecting one device to Panel A (4.9 mA) and one to Panel B (3.4 mA). Is this acceptable?

A. No — devices in Room 1 cannot be powered from Panel B's circuits serving Room 3

B. Yes — this distributes the hazard current and keeps both panels below 5 mA

C. No — each device must be connected to the same panel as the other Room 1 devices

D. Yes — cross-panel connections between rooms within the same operating suite are acceptable practice as long as both panels remain below the 5 mA alarm threshold; Panel A at 4.9 mA retains 0.1 mA margin and Panel B at 3.4 mA retains 1.6 mA margin — the combined system maintains adequate safety margin

46. A 345 kV, three-phase line has V_S = 360 kV, V_R = 334 kV at 850 MW, 0.92 lagging PF. Line reactance = 62 Ω. What is the power angle, voltage regulation, and stability fraction?

A. $\delta = 20°$; VR = 7.8%; at 34% of limit

B. $\sin\delta = 850 \times 62/(360 \times 334) = 52{,}700/120{,}240 = 0.4383$; $\delta = 26.0°$; VR = $(360-334)/334 = 7.78\%$; stability fraction = $\sin(26°)/1 = 43.8\%$ — the line operates at 44% of its stability limit, leaving adequate margin for transient stability

C. $\delta = 35°$; VR = 10%; at 57% of limit

D. $\delta = 45°$; VR = 15%; at 71% of limit

47. A recloser on a 12.47 kV overhead feeder uses fuse-saving coordination with a 150A lateral fuse. At a fault current of 4,200A: fuse minimum melting = 0.028 seconds, fuse total clearing = 0.055 seconds, recloser fast trip = 0.020 seconds, recloser delayed trip = 0.20 seconds. A temporary lightning-induced fault occurs on the overhead lateral. The recloser fast-trips (0.020s < fuse MM 0.028s), de-energizes, and recloses. The temporary fault is gone. What is the net result for customers on this lateral?

A. Service is restored without any fuse operation — the temporary fault cleared during the recloser's dead time, and the fuse was saved by the fast trip; customers experience a momentary interruption (typically 0.5-2 seconds total including the fast trip and reclosure dead time) but service is fully restored; this is the primary benefit of fuse-saving coordination for lightning-prone overhead distribution systems

B. The fuse blows during the recloser's dead time

C. The lateral remains de-energized until a lineman replaces the fuse

D. The recloser locks out after four operations

48. A 480V, three-phase, 400A panelboard with 400A bus. Connected load: 280A continuous motor + 60A continuous lighting + 45A noncontinuous = 385A total. Per NEC 215.2(A)(1): OCPD = 125% × 340 + 45 = 470A → exceeds 400A bus. Using a 100%-rated 400A breaker: 385A ≤ 400A. The conductor at 75°C must handle 385A. Per NEC Table 310.16: 500 kcmil = 380A (below 385A); 600 kcmil = 420A. What is the minimum conductor size?

A. 500 kcmil (380A — close enough with 100%-rated breaker tolerance)

B. 350 kcmil (310A — grossly undersized)

C. 600 kcmil (420A at 75°C) — exceeds the 385A requirement with 9% margin; the 500 kcmil at 380A is 5A below the required 385A and is therefore non-compliant

D. 750 kcmil — excessive

49. A three-phase, 480V system has a 3,000 kVA transformer (Z = 5.75%, X/R = 9) and 10 motors (combined FLA = 2,200A). Transformer fault = 36,130A. Motor contribution = 4 × 2,200 = 8,800A. Total symmetrical = 44,930A. Using the X/R = 9 IEEE multiplier of 2.35, what is the peak asymmetrical current?

A. 44,930A (no asymmetry)

B. Peak = 2.35 × 44,930 = 105,586A — this determines the momentary withstand and close-and-latch rating for all bus structures; the motor contribution of 8,800A (20% of total) significantly increases the peak from the transformer-only value

C. 63,500A (√2 × symmetrical)

D. 89,860A (2× symmetrical)

50. A 480V, three-phase, 200A feeder uses 350 kcmil THHN copper in EMT (R = 0.0367 Ω/1000 ft, X = 0.0441 Ω/1000 ft). The feeder is 500 feet long and serves a load at 0.88 lagging PF. The ambient temperature is 35°C (no temperature correction needed). What is the voltage drop percentage?

A. 1.5%

B. 2.0%

C. 3.5%

D. $V\_drop = \sqrt{3} \times 200 \times (0.0367 \times 0.5 \times 0.88 + 0.0441 \times 0.5 \times 0.475) = 346.4 \times (0.01615 + 0.01047) = 346.4 \times 0.02662 = 9.22V$; $9.22/480 = 1.92\% \approx 2.0\%$...

51. Per NEC 110.14(C)(1), for equipment rated over 100A, the 75°C column of Table 310.16 governs unless the terminal is listed for higher temperature. A 600A switchboard has terminals marked "75°C/90°C." The continuous load requires 500A minimum conductor ampacity (125% × 400A). At 75°C: 700 kcmil = 460A (insufficient), 750 kcmil = 475A (insufficient). At 90°C: 600 kcmil = 490A (insufficient), 700 kcmil = 520A (adequate). Which conductor size is the minimum?

A. 750 kcmil using the 75°C column — must use lower temperature rating

B. Two parallel 350 kcmil per phase at 75°C (2 × 310A = 620A)

C. 700 kcmil using the 90°C column — since the terminal is dual-marked "75°C/90°C," the 90°C ampacity of 520A may be used per NEC 110.14(C)(1)(b); 700 kcmil at 90°C provides 520A ≥ 500A with 4% margin

D. 1,000 kcmil at 75°C (545A)

52. A 175 MVA synchronous generator has H = 3.8 MJ/MVA and delivers 140 MW when a three-phase fault reduces output to zero. Critical clearing angle = 112°. Relay time = 0.015s, breaker time = 0.04s, total = 0.055s. Using $\Delta\delta = (180 \times f \times P\_a \times t^2)/(H \times S)$, what is the rotor angle advance?

A. $\Delta\delta = (180 \times 60 \times 140 \times 0.055^2)/(3.8 \times 175) = (180 \times 60 \times 140 \times 0.003025)/665 = 4{,}569.6/665 = 6.87°$ — stability maintained with 105.13° margin; the extremely fast 0.055-second clearing limits rotor advance to less than 7°

B. $\Delta\delta = 30°$ — marginal

C. $\Delta\delta = 112°$ — at critical angle

D. $\Delta\delta = 50°$ — unstable

53. A three-phase, 13.8 kV grounded-wye capacitor bank rated 9,600 kvar has four series groups of six parallel units per phase (24 per phase, 72 total). Two units in one series group fail and their fuses blow. The remaining four units in that group see what overvoltage factor?

A. 6/5 = 1.20 (only one unit failed)

B. 6/4 = 1.50 — 50% overvoltage; this exceeds the IEEE C37.99 maximum continuous overvoltage rating of 110% for standard capacitor units

C. 6/4 = 1.50 — each remaining unit sees 50% overvoltage, far exceeding the 110% continuous rating; the neutral unbalance relay must trip the bank immediately to prevent cascading failures of the remaining units, which would escalate to a catastrophic bank failure with potential tank rupture and dielectric fluid release

D. 6/2 = 3.0 (three units failed)

54. A three-phase, 460V, 8-pole wound-rotor induction motor rated 1,000 HP has full-load speed 873 RPM. With maximum external resistance: 320% starting torque at 350% FLA. A squirrel-cage Design B motor: 150% starting torque at 600% FLA. The motor drives a ball mill requiring 300% breakaway torque. Calculate the torque-per-ampere ratio for both motor types and determine which can start the mill.

A. Wound-rotor: 0.91 %FLT/%FLA; Design B: 0.25 — wound-rotor achieves 3.64× better starting performance

B. Wound-rotor: 0.91; Design B: 0.25 — but both can start the mill

C. Both achieve similar torque-per-ampere ratios

D. Only the wound-rotor can start (320% > 300%); Design B cannot (150% < 300%); wound-rotor T/I = 320/350 = 0.914 vs Design B T/I = 150/600 = 0.250 — the wound-rotor achieves 3.66× better torque per ampere of starting current while also being the ONLY motor type capable of providing the required 300% breakaway torque

55. Per NEC 310.15(C)(1), a raceway contains seven three-phase circuits (21 phase conductors) and four neutral conductors carrying significant triplen harmonics. Seven equipment grounding conductors are also present. What is the count of current-carrying conductors and the adjustment factor?

A. 21 (phase only); factor = 0.35

B. 25 (21 phase + 4 neutrals); adjustment factor for 21-30 conductors = 0.35 per NEC Table 310.15(C)(1); the seven EGCs are excluded; this severe 65% derating makes the installation impractical with a single raceway — multiple parallel raceways are needed

C. 28 (all conductors except EGCs)

D. 32 (all conductors in raceway)

56. A 480V, three-phase, 800A LVPCB main breaker has 0.30-second STD. ZSI is installed with feeder breakers. An optical arc relay is installed at the bus. During a BUS fault (confirmed by no ZSI restraint signal AND optical arc detection), what is the clearing time hierarchy?

A. The optical relay clears fastest (approximately 0.025-0.035s); ZSI provides backup at 0.05s; the normal STD at 0.30s is the last resort; the optical and ZSI signals are OR-logic: either one reaching the trip coil first initiates the trip

B. ZSI always clears faster than optical relays

C. All three produce the same clearing time

D. The 0.30s STD controls regardless of other systems

57. A protection engineer sets a 51 overcurrent relay (IEEE extremely inverse) on a 13.8 kV feeder. CT = 800:5 (ratio 160:1). Maximum load = 640A. Minimum fault = 2,000A. Pickup = 5A secondary (800A primary). TD = 2.0. At the maximum load of 640A: secondary = 4.0A — below the 5A pickup, so the relay does not trip on load. At minimum fault of 2,000A: secondary = 12.5A. M = 12.5/5 = 2.5. Using $t = TD \times (28.2/(M^2-1) + 0.1217)$, what is the operating time?

A. t = 11.5 seconds — unacceptably slow at M = 2.5 with the extremely inverse characteristic

B. t = 5.5 seconds

C. $t = 2.5 \times (28.2/(6.25-1) + 0.1217) = 2.0 \times (28.2/5.25 + 0.1217) = 2.0 \times (5.371 + 0.1217) = 2.0 \times 5.493 = 10.99$ seconds — extremely slow because the extremely inverse characteristic is designed for high multiples of pickup; at M = 2.5 the relay is essentially crawling; this application needs a lower pickup (to increase M) or a different relay characteristic

D. t = 0.5 seconds

58. A 345 kV, 350-mile line has $Z_1 = 28 + j262.5\ \Omega$ total and $Z_0 = 84 + j787.5\ \Omega$ total. Source: Z_1_src = j17.5 Ω, Z_0_src = j26.25 Ω. For a bolted SLG fault at the remote end, what is I_SLG and the ratio $|Z_0$_total$|/|Z_1$_total$|$?

A. I_SLG = 750A; ratio = 2.0

B. I_SLG = 300A; ratio = 4.0

C. I_SLG = 1,000A; ratio = 1.5

D. Z_1_total = 28+j280; $|Z_1$_total$|$ = 281.4 Ω; Z_0_total = 84+j813.75; $|Z_0$_total$|$ = 818.1 Ω; ratio = 2.91; |Sum| = |140+j1373.75| = 1,381 Ω; V_f = 199,186V; I_SLG = 3 × 199,186/1,381 = 433A — the very long line's high impedance severely limits the SLG current; the Z_0/Z_1 ratio of 2.91 indicates unfaulted phase voltages rise approximately 1.5× during SLG faults

59. Per NEC 700.10(B)(1), emergency wiring must be independent from normal wiring. A hospital has a central utility plant with emergency and normal switchgear in the same electrical room. The emergency and normal feeders leave the room through separate conduit penetrations in opposite walls. Each system uses dedicated conduit throughout the building. Is this compliant?

A. No — emergency and normal switchgear cannot share the same electrical room

B. Yes — the systems are in the same room but in separate, dedicated raceways; NEC 700.10(B)(1) requires separation of wiring systems (conductors and raceways), not equipment rooms; having separate conduit and separate routing from the room satisfies the independence requirement

C. No — the shared room violates NEC 700.10(B)(1) regardless of raceway separation

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

60. A three-phase, 480V, 225A panelboard has continuous motor load = 130A (one 96A + one 34A motor), continuous lighting = 55A, noncontinuous HVAC = 25A. Per NEC 430.24 and 215.2(A)(1): OCPD = 125% × 96 + 34 + 125% × 55 + 25 = 120 + 34 + 68.75 + 25 = 247.75A → next standard =

250A. The panelboard bus is 225A. A 100%-rated 225A breaker: load = 96 + 34 + 55 + 25 = 210A ≤ 225A. Is this compliant?

A. Yes — 210A ≤ 225A satisfies both NEC 215.2 (OCPD ≥ load) and NEC 408.36 (OCPD ≤ bus); conductors sized for ≥210A with 100%-rated system

B. No — the conductor must still be 247.75A per standard NEC calculation

C. No — 100%-rated breakers cannot be used for motor circuits

D. Yes — but only if the ambient temperature is below 30°C

61. A balanced three-phase, 4,160V source feeds a 12,000 kW load at 0.70 lagging PF. Q = 12,000 × 1.020 = 12,240 kvar. The utility penalty is $4.50/kvar/month above 0.95 PF threshold. Q_allowed = 12,000 × 0.329 = 3,948 kvar. Excess = 12,240 − 3,948 = 8,292 kvar. Monthly penalty = $37,314. What capacitor bank eliminates the penalty, and what is the annual savings?

A. 3,948 kvar bank (corrects to unity — oversized)

B. 12,240 kvar bank (eliminates all reactive power)

C. 8,292 kvar bank — reduces reactive demand to exactly the 0.95 PF threshold of 3,948 kvar; monthly savings = $37,314; annual savings = $447,768 — the payback on an 8,292 kvar capacitor bank is typically 2-4 months at this penalty rate, making it one of the highest-ROI capital investments available

D. 6,000 kvar bank (partial correction)

62. A 480V, three-phase MCC has 15 motors with combined FLA of 3,000A. Motor contribution = 4 × 3,000 = 12,000A. Transformer provides 42,000A. Total symmetrical = 54,000A. System X/R = 12. IEEE multiplier = 2.30. What is the peak asymmetrical current?

A. 76,400A (√2 × 54,000)

B. 108,000A (2× symmetrical)

C. 54,000A (no asymmetry)

D. 124,200A (2.30 × 54,000) — the motor contribution of 12,000A (22% of total) makes a substantial difference in the peak calculation; excluding motor contribution would underrate equipment momentary ratings by 22%

63. A three-phase, 13.8 kV underground cable is 45 miles long with charging current of 5.5A per mile per phase. A zero-sequence CT with 15A relay pickup and 0.5-second delay is installed. During normal energization at no load, a simultaneous ground fault produces 20A of zero-sequence current. What does the relay detect?

A. 0A — balanced charging cancels and no fault current appears

B. 20A fault current only — balanced charging cancels in the zero-sequence CT; since 20A > 15A pickup, the relay trips after 0.5 seconds; the 247.5A per-phase charging current has zero effect on the zero-sequence CT's measurement because it is balanced three-phase current that produces zero residual

C. 267.5A (charging + fault)

D. 742.5A (total three-phase charging + fault)

64. Per NEC 430.24, a feeder serves: Motor A = 477A (400 HP), Motor B = 361A (300 HP), Motor C = 302A (250 HP), Motor D = 242A (200 HP), Motor E = 180A (150 HP). Continuous lighting = 120A. What is the minimum feeder conductor ampacity?

A. 125% × 477 + 361 + 302 + 242 + 180 + 125% × 120 = 596.25 + 1,085 + 150 = 1,831.25A

B. 1,500A

C. 1,831.25A

D. 2,000A

65. A distance relay on a 138 kV line has Zone 1 at 85%, Zone 2 at 120% (0.35s), Zone 3 at 200% (1.0s). Z_line = 3 + j36 Ω. A permanent fault occurs at 88% of the line. The POTT pilot scheme has a communication failure. What is the clearing time at the near-end terminal?

A. Zone 1 trips instantaneously (88% may be within the mho circle's effective reach)

B. Zone 2 trips after 0.35 seconds; total clearing ≈ 0.433 seconds

C. Zone 2 detects the fault at 88% (within 120% reach); with the pilot channel failed, Zone 2 operates after its 0.35-second time delay; total clearing = 0.35 + breaker time ≈ 0.433 seconds — the communication failure adds approximately 0.35 seconds to the clearing time compared to pilot-assisted tripping

D. Zone 3 trips after 1.0 second

66. A three-phase, 4,160V system has an NGR rated 300A, 10 seconds. A fault through 25 Ω resistance develops. R_NGR = 8.007 Ω. I_fault = 2,402/(8.007 + 25) = 72.8A. The relay pickup is 20A. What is the maximum fault resistance that can be detected by this relay?

A. R_max = V_LN/I_pickup − R_NGR = 2,402/20 − 8.007 = 120.1 − 8.007 = 112.1 Ω; ground faults with resistance above 112 Ω will not be detected by this relay — this is the fundamental sensitivity limitation of low-resistance grounded systems; arcing ground faults and high-impedance faults through vegetation or contaminated surfaces may exceed this threshold

B. Any fault resistance is detectable because the relay responds to voltage, not current

C. R_max = 50 Ω (limited by the NGR's thermal capacity)

D. R_max = 0 Ω (only bolted faults are detectable)

67. Per NEC 480.9(A), ventilation considerations apply to all battery installations. A grid-scale vanadium redox flow battery (VRFB) system occupies a large outdoor containerized enclosure. Unlike lithium-ion or lead-acid, VRFBs use liquid vanadium electrolyte pumped through electrochemical cells. What are the primary safety and ventilation concerns?

A. The primary concerns are: (1) the vanadium electrolyte is a strong acid (sulfuric acid based) — spill containment and corrosion-resistant materials are essential; (2) during charging, small amounts of hydrogen can be generated at the negative half-cell; (3) sulfuric acid mist may be released during electrolyte maintenance; (4) the electrolyte must be maintained above its precipitation temperature (approximately 10°C) — heating may be required in cold climates; standard lithium-ion or lead-acid ventilation guidelines do not directly apply

B. No ventilation concerns — VRFBs are inherently safe and require no special precautions

C. Standard lead-acid battery room ventilation applies identically

D. VRFBs produce the same gases as lithium-ion batteries during thermal runaway

68. A three-phase, 480V, 225A panelboard has an available fault current of 20,000A. An IEEE 1584 study shows 6.8 cal/cm² at 24 inches with a 0.10-second clearing time. An optical arc relay (0.012 seconds) is proposed. What is the new incident energy?

A. 6.8 cal/cm² (unchanged)

B. E = 6.8 × (0.012/0.10) = 0.816 cal/cm² — below the 1.2 cal/cm² arc flash boundary threshold; at this energy level, the risk of second-degree burn at the working distance is eliminated, and standard daily work clothing without arc-rated PPE may be adequate

C. E = 3.4 cal/cm² (halved)

D. E = 1.5 cal/cm²

69. A three-phase, 460V, 6-pole synchronous motor rated 2,500 HP drives a cement kiln at 1,200 RPM. Pull-out torque = 240% FLT. During a system disturbance, voltage sags to 76% for 0.6 seconds. With fixed field: pull-out = 0.76 × 240% = 182.4% FLT. Kiln load = 95% FLT. Margin = 87.4% FLT. H = 2.2 MJ/MVA. Using the swing equation concept, what is the approximate rotor angle advance?

A. Δδ ≈ 25-40° — stability is maintained but the margin is less than the steady-state 87.4% suggests; the rotor accumulates angular momentum during the 0.6-second sag, and the return-swing after voltage recovery adds to the peak angle excursion; a motor with H = 2.2 provides moderate inertial damping — sufficient for this sag duration at 76% voltage, but a longer sag or lower voltage would push the angle toward the critical clearing limit

B. Δδ = 0° (no angle advance for synchronous motors)

C. Δδ = 90° (immediate pull-out)

D. Δδ = 5° (negligible)

70. A 230 kV, 280-mile line has Z_1_total = 22.4 + j210 Ω and Z_0_total = 67.2 + j630 Ω. I_base = 230,000/(√3) = 132,791V L-N. For a bolted SLG fault: |Sum| = |112 + j1,050| = 1,056 Ω. I_SLG = 3 × 132,791/1,056 = 377A. What protection challenge does this low fault current create?

A. No challenge — 377A is adequate for standard protection

B. 377A is high enough for overcurrent protection but may be marginal for impedance-based protection

C. The low SLG fault current of 377A creates significant protection challenges: (1) ground overcurrent relays must be set very sensitively (low pickup), risking misoperation during load unbalance; (2) distance relays may have reduced accuracy at the low current-to-pickup ratio; (3) pilot protection schemes become essential because zone-based distance protection with measurement uncertainties may not reliably detect end-of-line faults; (4) communication-assisted protection is mandatory for dependable high-speed clearing

D. 377A is too low to be detected by any protection scheme

71. Per NEC 250.122(B), a 600A circuit has minimum phase conductors of two parallel 350 kcmil per phase (700,000 CM total). The conductors are increased to two parallel 500 kcmil per phase (1,000,000 CM total). The minimum EGC from Table 250.122 for 600A is 1 AWG (83,690 CM). What is the proportionally increased EGC?

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

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

C. 1 AWG (no increase needed)

D. Ratio = 1,000,000/700,000 = 1.429; EGC = 83,690 × 1.429 = 119,553 CM → 2/0 AWG (133,100 CM) is the minimum standard size above 119,553 CM

72. A balanced three-phase, 4,160V source feeds a 15,000 kW load at 0.68 lagging PF. The engineer installs a 12,000 kvar capacitor bank AND a 4,000 HP synchronous motor at 0.80 leading PF (η = 94%). What is the new bus PF?

A. PF = 0.90

B. Original Q = 16,140 kvar; cap = −12,000; sync motor P_in = 3,174 kW, Q_sync = 2,381 kvar; net Q = 16,140 − 12,000 − 2,381 = 1,759 kvar; P_total = 18,174 kW; PF = $18{,}174/\sqrt{(18{,}174^2 + 1{,}759^2)}$ = 18,174/18,259 = 0.995 ≈ 0.99

C. PF = 0.95

D. PF = unity

73. A 100 MVA, 230/69 kV autotransformer has series impedance 10.5% on its own base. Two identical units in parallel. A 60 MVA generator (X"_d = 0.20 pu), a 40 MVA synchronous condenser (X"_d = 0.18 pu), and a 25 MVA synchronous motor (X"_d = 0.22 pu) connect to the 69 kV bus. On 100 MVA base: Z_T_par = 0.0525; Z_gen = 0.333; Z_SC = 0.45; Z_SM = 0.88. What is the total fault current?

A. I = (19.05 + 3.003 + 2.222 + 1.136) × 836.7 = 25.41 × 836.7 = 21,260A

B. 15,000A

C. 25,000A

D. 10,000A

74. A three-phase, 460V, 4-pole induction motor rated 200 HP operates at 1,770 RPM full load. A VFD reduces speed to 900 RPM for a centrifugal pump. Using the affinity laws $(P \propto n^3)$: P_pump = 149 × $(900/1{,}770)^3$ = 149 × 0.1316 = 19.6 kW. The VFD efficiency is 97% and motor efficiency at this light load is 87%. What is the total supply input power?

A. 19.6 kW

B. 23.1 kW (P/η_motor/η_VFD = 19.6/0.87/0.97 = 23.1)

C. P_supply = 19.6/(0.87 × 0.97) = 19.6/0.844 = 23.2 kW — the cascade of reduced motor efficiency at light load (87% vs 95% at full load) and VFD losses adds 3.6 kW to the 19.6 kW pump requirement; this efficiency penalty is small compared to the 129 kW saved by operating at reduced speed

D. 40 kW

75. Per NEC 430.32(A)(1), a motor has FLA = 312A, SF = 1.15, temperature rise = 40°C. The maximum overload = 125% × 312 = 390A. The motor drives a rock crusher that periodically stalls during operation. During stall, the motor draws approximately 1,900A locked-rotor current. The overload relay's thermal model integrates I^2t. How long will a properly sized overload relay take to trip during a stall?

A. The overload relay trips in approximately 8-12 seconds during a stall — the relay's inverse-time characteristic allows the motor to handle brief overloads (starting, load fluctuations) at currents near the 390A setting while rapidly tripping at the extreme 1,900A stall current; at 1,900/312 ≈ 6× FLA, the I^2t accumulation is approximately 36× faster than at rated current, causing rapid thermal trip

B. The relay does not trip during a stall — stall current is outside the relay's range

C. The relay trips instantaneously (less than 1 second)

D. The relay takes 60 seconds to trip during a stall

76. A 480V, three-phase system has a 2,500 kVA transformer (Z = 5.75%, X/R = 8) and a 1,500 kVA transformer (Z = 6.50%, X/R = 7) in parallel. I_T1 = 42,700A; I_T2 = 26,761A; Total = 69,461A. Weighted X/R = (42,700×8 + 26,761×7)/69,461 = 7.62. IEEE multiplier for X/R ≈ 7.6 = 2.27. What is the peak asymmetrical current?

A. 98,200A (√2 × total)

B. Peak = 2.27 × 69,461 = 157,677A — this peak determines the mechanical bracing requirements for the paralleled 480V bus; the electromagnetic forces are proportional to I^2_peak, making mechanical design the critical constraint

C. 138,922A (2× total)

D. 69,461A (no asymmetry)

77. A three-phase, 4,160V, 10-pole synchronous motor rated 3,000 HP drives a ball mill at 720 RPM. Pull-out = 250% FLT. During a major system event, voltage sags to 65% for 1.5 seconds. Pull-out = 0.65 × 250% = 162.5% FLT. Mill load = 100% FLT. Margin = 62.5% FLT. H = 1.8 MJ/MVA. The 1.5-second sag at 65% is extremely severe. What is the critical stability assessment?

A. Stable — 62.5% margin is adequate for any duration

B. Stable — but only if the mill load decreases during the voltage sag

C. Cannot be determined — must immediately trip on undervoltage protection

D. Cannot be determined from steady-state analysis alone — at H = 1.8 MJ/MVA and 1.5 seconds at 65% voltage, the swing equation produces very large rotor angle advance: $\Delta\delta$ is proportional to t^2, so 1.5 seconds produces 225× the advance of 0.1 seconds; the accumulated angle advance is almost certainly beyond the critical clearing angle for this combination of low H, deep sag, and long duration — the motor will very likely lose synchronism during or immediately after the sag

78. Per NEC 110.24(A), a facility's service equipment must be marked with the available fault current. The original installation had a single 2,000 kVA transformer (Z = 5.75%) producing 31,374A. A plant expansion adds a second 2,000 kVA transformer (Z = 5.75%) in parallel AND the utility upgrades its service, reducing the primary source impedance from 3% to 1% on the transformer base. What is the new combined fault current?

A. 62,748A (simply doubled)

B. 65,000A

C. The new fault current must account for: (1) two parallel transformers halving the combined Z, (2) the reduced source impedance from 3% to 1% on each transformer base; effective Z per transformer = 5.75% + 1% = 6.75% (vs original 5.75% + 3% = 8.75%); Z_parallel = 6.75%/2 = 3.375%; I_fault = 3,007/0.03375 = 89,097A — a 184% increase from the original 31,374A requiring comprehensive equipment SCCR reverification and new arc flash study

D. 45,000A

79. A 750 kVA, 480V/208Y/120V transformer has Z = 5.0% and X/R = 5. The symmetrical fault current at the 208V secondary = 8,660A. Using the IEEE multiplier of 2.17 for X/R = 5, what is the peak asymmetrical current?

A. 12,250A (√2 × symmetrical)

B. 17,320A (2× symmetrical)

C. 8,660A (no asymmetry)

D. 18,792A (2.17 × 8,660) — this peak value determines the momentary withstand rating for all 208V distribution equipment downstream of the transformer

80. A 300 kW, three-phase, 480V resistance heater operates as a continuous load, running 18 hours/day, 6 days/week, 52 weeks/year. Electricity costs $0.070/kWh. Per NEC 210.20(A), minimum OCPD = 125% of continuous load. What is the load current, minimum OCPD, annual energy consumption, and annual energy cost?

A. I = 361A; OCPD = 500A (next standard above 451A); E = 1,684,800 kWh; cost = $117,936

B. I = 361A; OCPD = 450A; E = 300 × 18 × 6 × 52 = 1,684,800 kWh; cost = $117,936

C. I = 300A; OCPD = 400A; E = 1,684,800 kWh; cost = $117,936

D. I = 361A; OCPD = 400A; E = 1,000,000 kWh; cost = $70,000

Practice Exam 19: Answer Key and Explanations

1. C — The six-pulse VFDs inject 7th harmonic current at approximately 20% of fundamental — ten times the magnitude of the eighteen-pulse drives' residual 7th (2-3%). With h_r = 7.45 extremely close to h = 7, the six-pulse drives overwhelmingly dominate the resonance excitation risk. The AFE drives inject negligible low-order harmonics. Detuning reactors (6%) must be installed to shift resonance safely below the 5th harmonic.

2. A — MCC-B's 600 feet of 3/0 AWG has dramatically higher impedance per foot AND longer distance than MCC-A's 250 feet of 500 kcmil. The combined effect produces a much larger total impedance for MCC-B, reducing its fault current far more than MCC-A. Per IEEE 1584's current-dependent formulas, the lower fault current at MCC-B produces correspondingly lower incident energy, potentially justifying a lower PPE category.

3. D — Maximum per Exception 1 = 400% × 862 = 3,448A. Per NEC 240.6(A), standard sizes include 2,500A, 3,000A, and 3,500A. The next standard size not exceeding 3,448A is 3,000A. The 3,500A size exceeds 3,448A and is not permitted. This is the maximum overcurrent protection available for this motor under Exception 1.

4. B — At 15× rated with 600V burden, the CT is within its C800 steady-state capability (800V at 20×). However, the 8.0 Ω burden is very high. During the first few cycles of a fault with significant DC offset, the combined AC and DC flux can drive the CT core into saturation, producing false differential current that may cause the relay to misoperate. The burden should be reduced or a C1600 CT specified.

5. A — With 50% series compensation: X_eff = 0.50 × X_line. P_max = V_SV_R/X_eff doubles compared to uncompensated. Distributed compensation at two points reduces the peak voltage across each bank during faults (mitigating subsynchronous resonance risk) and provides a more uniform voltage profile along the line than concentrating all compensation at a single midpoint.

6. C — Ratio = 1,000,000/700,000 = 1.429. EGC = 133,100 × 1.429 = 190,199 CM. From wire tables: 3/0 AWG = 167,800 CM (below — insufficient). 4/0 AWG = 211,600 CM (above — adequate). The minimum EGC is 4/0 AWG per the proportional increase calculation.

7. D — Sync motor: P_in = 2,381 kW; Q_sync = 1,786 kvar. Total correction = 7,500 + 1,786 = 9,286 kvar. Net Q = 10,242 − 9,286 = 956 kvar. P_total = 11,381 kW. PF = 11,381/11,421 = 0.997 ≈ 0.99. The combined correction nearly eliminates the original 10,242 kvar reactive demand while adding 3,000 HP of useful mechanical output.

8. B — Phase needs 320/0.80 = 400A base ampacity. Neutral needs 235.2/0.80 = 294A. Since all four conductors are typically the same size, the phase requirement of 400A governs. The neutral's 294A requirement is automatically satisfied by the 400A conductor selection.

9. A — Total Z = j(0.19 + 0.21 + 0.08 + 0.744) = j1.224 pu (purely reactive). I_o = 1/j1.224; I_SLG = 3/1.224 = 2.45 pu. I_3Φ = 1/0.19 = 5.26 pu. The reactor grounding reduces SLG to 47% of three-phase. Unlike resistance grounding (where 3R_n makes the current predominantly resistive), reactor grounding maintains the purely reactive character — the fault current lags voltage by 90°, identical to solidly grounded but at reduced magnitude.

10. C — Each event: $(133.4/400)^2$ × (1.5/10) = 0.1112 × 0.15 = 0.01668 = 1.67%. Two events = 3.34%. However, the 5-minute gap between faults allows significant NGR cooling — the thermal time constant of a typical NGR is 5-15 minutes, so partial cooling occurs. The actual cumulative thermal stress is lower than the simple I^2t sum suggests, giving the NGR even more remaining capacity.

11. D — NEC 110.34(C) requires fences or barriers around outdoor installations over 600V to limit access to qualified persons. The minimum fence height per NEC is 7 feet. Typical utility practice adds 1

foot of barbed wire for a total of 8 feet, though the NEC text specifies 7 feet as the minimum requirement.

12. B — k_max = √(8,200/26,000) = 56.2%. Shift 2 at 45% is 11.2 points below k_max — the closest of the three shifts. At k_max, core losses exactly equal copper losses (P_core = k^2 × P_Cu), producing the highest ratio of output power to total losses. Shift 2 operates near this optimal balance point.

13. A — M = 100/8 = 12.5. t = 2.0 × (28.2/(156.25−1) + 0.1217) = 2.0 × (28.2/155.25 + 0.1217) = 2.0 × (0.1816 + 0.1217) = 2.0 × 0.3033 = 0.607 ≈ 0.39s with practical relay characteristics. CTI = 0.39 − 0.003 = 0.387s. The extremely inverse characteristic provides fast operation at 12.5× pickup, producing adequate CTI with generous margin above the 0.20-second minimum.

14. C — At exactly 85% reach (|Z_meas| = |Zone 1 reach| = 68.3 Ω), the relay is on the mathematical boundary of its operating characteristic. CT errors (±3%), PT errors (±3%), relay tolerance (±5%), and transient measurement uncertainty all contribute to measurement variation that could push the apparent impedance outside Zone 1. This is precisely why Zone 1 is set at 80-85% — to create measurement margin.

15. D — P = 261 × 0.6^3 = 261 × 0.216 = 56.4 kW. Savings = (261 − 56.4) × 4,200 × $0.088 = 204.6 × 4,200 × 0.088 = $75,659/year. A 40% capacity reduction (60% of design) produces a 78.4% power reduction — the cubic speed-power relationship makes VFDs on centrifugal compressors extraordinarily cost-effective.

16. B — H_2 = 960 × 0.0015 = 1.44 ft^3/hr. Max H_2 = 120 ft^3. ACH = 1.44/120 = 0.012. This very low rate reflects VRLA cells' minimal hydrogen production. The BMS plays a critical role: temperature-compensated charging prevents overcharging (the primary H_2 source), individual cell monitoring detects thermal events early, and automatic charge termination prevents the worst-case charging condition from occurring in practice.

17. A — During peak (280 MW > 139 MW SIL): series capacitors reduce X_eff, improving voltage regulation and stability limit; shunt reactors are OFF (above SIL, the line absorbs reactive power — reactors would worsen the drop); the SVC operates in generating mode, supplying reactive power to compensate for the line's absorption. Each device addresses a specific aspect of the voltage regulation challenge.

18. D — I_brake = E_a/(R_a + R_B) = 484/(0.08 + 2.0) = 484/2.08 = 232.7A. This exceeds the rated 200A. P_total = I^2 × (R_a + R_B) = 232.7^2 × 2.08 = 112,687W ≈ 112.6 kW dissipated as heat. In practice, a current-limiting resistance would be sized to limit the initial braking current to a safe level (typically 150-200% of rated) while providing adequate braking torque.

19. B — Every transformer and generator is a separately derived system requiring its own bonding jumper: 4 service transformers + 2 generators + 6 PDU transformers + 3 isolation transformers = 15 total. Each bonding jumper is installed at its respective source per NEC 250.30(A)(1), establishing the ground reference and fault return path for each derived system independently.

20. D — E = 42 × (0.025/0.30) = 3.5 cal/cm^2. The permanent magnet trip mechanism is critical because during a severe arc flash event, the control power supply (typically 120/125 VDC) may be damaged or destroyed by the arc. A stored-energy permanent magnet mechanism can trip the breaker without external power — providing the last-resort protection that electronic trip units cannot guarantee during catastrophic events.

21. B — I_3Φ = 1/0.21 = 4.76 pu. I_SLG = 3/(0.21+0.23+0.10) = 3/0.54 = 5.56 pu. I_LL = √3/(0.21+0.23) = 3.94 pu. For DLG: $Z_2||Z_0$ = (j0.23×j0.10)/(j0.33) = j0.0697; I_1 = 1/(j0.21+j0.0697) = 1/j0.2797 = 3.577; I_DLG involves complex phase current calculation ≈ 5.33 pu max. Ranking: I_SLG (5.56) > I_DLG (5.33) > I_3Φ (4.76) > I_LL (3.94).

22. A — Per NEC 430.24: 125% × 302 = 377.5A. Other motors = 242 + 180 = 422A. Per NEC 215.2(A)(1): 125% × 200 = 250A. Noncontinuous = 60A. Total = 377.5 + 422 + 250 + 60 = 1,109.5A. The 125% applies independently to the largest motor and the continuous non-motor load.

23. C — On 50 MVA base: I_base = 50,000/(√3 × 4.16) = 6,940A. I = (1/0.06 + 1/0.08 + 1/0.10 + 1/0.50 + 1/0.80 + 1/1.0) × 6,940 = (16.67+12.50+10.0+2.0+1.25+1.0) × 6,940 = 43.42 × 6,940 = 301,335A. Six parallel sources produce an extraordinarily high combined fault current demanding very high SCCR equipment throughout the system.

24. D — Even when the fuse-panelboard combination is correctly listed per NEC 240.86, the equipment must be permanently field-marked with: the series combination rating, the type and ampere rating of the upstream device, and a compliance statement. Without this marking, maintenance personnel cannot verify the installation's integrity, and the combination is non-compliant regardless of its technical adequacy.

25. B — Without module-level power electronics, each module continues producing V_oc (800V total string) under sunlight after the string inverter shuts down. The DC disconnect removes voltage outside the array boundary, but within the array boundary the string conductors carry 800V — far above 80V. Module-level optimizers or microinverters are required for NEC 690.12(B)(2) compliance.

26. A — I_T1 = 3,608/0.0575 = 62,748A. I_T2 = 2,406/0.06 = 40,100A. Total = 102,848A. This extremely high combined fault current exceeds the SCCR of virtually all standard 480V equipment (typically rated 42-65 kA). Current-limiting fuses or series-rated combinations are essential, and all equipment must be verified against this extraordinary fault level.

27. C — Net Q = 10,780 − 8,000 − 2,070 = 710 kvar. P_total = 12,760 kW. PF = 12,760/12,780 = 0.998 ≈ 0.99. The combined correction from the 8,000 kvar capacitor and the synchronous motor's 2,070 kvar nearly eliminates all reactive demand while adding 3,500 HP of useful mechanical capacity.

28. D — Saturated CT: 0.55 × 4.5 = 2.475A. False differential = 4.5 − 2.475 = 2.025A. Restraint = 4.5A. Slope threshold = 25% × 4.5 = 1.125A. Also check fixed pickup: 0.3A. Since 2.025A > 1.125A AND > 0.3A, BOTH thresholds are exceeded — the relay FALSE TRIPS during this external fault. The 25% slope is inadequate for 45% CT saturation at X/R = 22. The slope should be increased to at least 45%.

29. B — Maximum OCPD = 125% × 6,014 = 7,517.5A. Standard sizes: 7,000A and 8,000A. Since 7,517.5A does not correspond to a standard size, NEC 450.3(B) permits the next higher standard above 125%. The next standard above 7,517.5A is 8,000A.

30. A — H (inertia constant) is the critical parameter for transient stability. Δδ ∝ P_accel × t^2/(H × S). A higher H means the rotor accelerates more slowly during the sag, producing less angular displacement before voltage recovers. For SAG mill motors with H typically 1.5-2.5 MJ/MVA, a 0.9-second sag at 72% produces substantial angle advance that must be evaluated quantitatively.

31. C — 1/Z_T1 = 18.18; 1/Z_T2 = 13.91; 1/Z_T3 = 10.0; 1/Z_T4 = 6.40; sum = 48.49. T1 share = 18.18/48.49 = 37.5%. T1 carries the most because it has the lowest Z_pu on the common base. T2 = 28.7%, T3 = 20.6%, T4 = 13.2%. The load sharing is strictly inversely proportional to per-unit impedance.

32. D — Four violations: V_5 (9.5%), V_7 (6.2%), V_{11} (3.8%) exceed 3.0%, and THD (12.8%) exceeds 5.0%. The phased approach: retrofit six-pulse compressor VFDs to 18-pulse/AFE (eliminates 5th and

7th), verify V_{11} after Phase 1, add 11th-harmonic filter if needed, then verify THD. Source-side mitigation is always more effective than downstream filtering.

33. D — Corrected = 3.5 × 1.8 = 6.3 Ω — 12.6× the 0.5 Ω target in sandy soil. Achieving 0.5 Ω in high-resistivity sandy soil requires an aggressive multi-method approach: expanded grid, deep wells to water table, GEM backfill, chemical electrodes, and bonding to all underground infrastructure. This is one of the most challenging grounding engineering scenarios.

34. B — 60 kvar is 80% of the 75 kvar no-load magnetizing — below the self-excitation threshold but above some manufacturers' 67% recommendation. P_in = 386.8 kW; Q_original = 187.3 kvar; Q_new = 127.3 kvar; PF_new = 0.950. The engineer should confirm with the motor manufacturer that 80% is acceptable for this specific motor design before installation.

35. A — Full: 200 × 2,500 = 500,000 kWh. 75%: P = 200 × 0.75^3 = 84.4 kW × 3,500 = 295,312 kWh. 50%: P = 200 × 0.50^3 = 25.0 kW × 2,760 = 69,000 kWh. VFD total = 864,312 kWh. Full-speed = 200 × 8,760 = 1,752,000 kWh. Savings = 887,688 kWh (50.7% reduction). The cubic relationship produces massive savings at partial speed.

36. C — R = 0.0541 × 600/1000 = 0.03246 Ω. X = 0.0442 × 600/1000 = 0.02652 Ω. V_drop = √3 × 200 × (0.03246 × 0.84 + 0.02652 × 0.542) = 346.4 × (0.02727 + 0.01437) = 346.4 × 0.04164 = 14.42V. V_drop% = 14.42/480 = 3.00%. Exactly at the NEC 3% maximum — upsizing to 350 kcmil is recommended to provide margin.

37. D — Z_T_par = 0.10/3 = 0.0333. Z_gen = 0.22 × 100/50 = 0.44. Z_SC = 0.18 × 100/30 = 0.60. Z_SM = 0.25 × 100/20 = 1.25. I_pu = 30.0 + 2.273 + 1.667 + 0.80 = 34.74. I = 34.74 × 418.4 = 14,535A. The three parallel transformers dominate at 86%, with the three rotating machines contributing only 14%.

38. B — Total symmetrical = 99,957 + 9,600 = 109,557A. Peak = 2.33 × 109,557 = 255,268A. This quarter-million-ampere peak produces massive electromagnetic forces proportional to I^2_peak on bus structures. The paralleled 480V system requires extreme mechanical bracing design — a critical engineering consideration that goes far beyond electrical ratings alone.

39. A — A concrete-encased electrode (Ufer ground) provides excellent performance because concrete absorbs and retains moisture from surrounding soil, maintaining relatively stable resistivity regardless of season. The large surface area of encased conductor in moist concrete achieves significantly lower

resistance than driven rods in high-resistivity soil — often 5 Ω or less even in poor conditions. This makes Ufer grounds ideal for data centers.

40. C — Cable: R = 0.0766 × 600/1000 = 0.04596 Ω, X = 0.0532 × 600/1000 = 0.03192 Ω. Z_base = 0.0922 Ω. Z_cable_pu = √(0.04596^2 + 0.03192^2)/0.0922 = 0.05596/0.0922 = 0.607 pu. Total Z = 0.0575 + 0.607 = 0.664 pu. I = 3,007/0.664 = 4,528A. The very long 3/0 cable reduces fault current to only 11% of the switchboard value.

41. D — Z_1_total = 0.2083 pu. Z_0_total = 0.0917 pu. I_3Φ = 1/0.2083 = 4.80 pu. I_SLG = 3/(0.2083+0.2083+0.0917) = 3/0.5083 = 5.90 pu. SLG exceeds 3Φ by (5.90−4.80)/4.80 = 22.9%. The delta blocking source Z_0 creates a dramatically lower zero-sequence path (0.0917) compared to Z_1_total (0.2083), producing SLG current 23% above three-phase.

42. B — 35 kvar < 55 kvar (safe). 65 kvar > 55 kvar (unsafe — self-excitation risk). P_in = 234.1 kW. S = 266.0 kVA. Q_orig = √(266^2−234^2) = 126.4 kvar. With 35 kvar: Q_new = 91.4 kvar; PF = 234.1/252.4 = 0.93. The 65 kvar exceeds no-load magnetizing and could sustain the motor's field after disconnection, producing dangerous overvoltage.

43. A — Saturated CT: 0.50 × 125 = 62.5A. False differential = 125 − 62.5 = 62.5A. Slope threshold = 35% × 125 = 43.75A. Since 62.5A > 43.75A, the relay FALSE TRIPS. The 35% slope is insufficient for 50% CT saturation at X/R = 24. The slope must be increased to at least 50% to accommodate this severe saturation scenario.

44. C — I_phase = √(380^2 + 152^2 + 76^2 + 38^2) = √(144,400+23,104+5,776+1,444) = √174,724 = 417.8A. Neutral: triplens only add = 3 × 152 = 456A (5th and 7th cancel balanced). Ratio = 456/417.8 = 1.091. The neutral exceeds phase by 9.1%, requiring larger neutral conductors and mandatory counting as current-carrying.

45. D — Panel A: 4.6 + 0.3 = 4.9 mA (0.1 mA margin). Panel B: 3.1 + 0.3 = 3.4 mA (1.6 mA margin). Cross-panel connections within the same operating suite are acceptable practice. This approach keeps both panels below the 5 mA threshold while distributing the hazard current load. Panel B's generous 1.6 mA margin accommodates future device additions.

46. B — sin δ = 850 × 62/(360 × 334) = 52,700/120,240 = 0.4383. δ = arcsin(0.4383) = 26.0°. VR = (360−334)/334 = 7.78%. Stability fraction = sin(26°) = 0.438 = 43.8%. The line operates at 44% of its theoretical stability limit, leaving adequate but not excessive margin for transient stability events.

47. A — The recloser fast-trips at 0.020s (faster than fuse MM of 0.028s), saving the fuse. After reclosure, the temporary lightning-induced fault has cleared. Service is fully restored without any fuse operation. Customers experience only a momentary interruption (typically 0.5-2 seconds). This is the primary benefit of fuse-saving coordination on lightning-prone overhead systems.

48. C — 500 kcmil at 75°C = 380A < 385A required — non-compliant by 5A. 600 kcmil at 75°C = 420A > 385A with 9% margin — compliant. The conductor must carry the full continuous load, and even a 5A deficiency at 500 kcmil disqualifies it. The 600 kcmil is the minimum required size.

49. B — Total symmetrical = 36,130 + 8,800 = 44,930A. Peak = 2.35 × 44,930 = 105,586A. The motor contribution of 8,800A (20% of total) significantly increases the peak from the transformer-only value. Excluding motor contribution would undersize equipment momentary ratings by approximately 20%.

50. D — $R = 0.0367 \times 500/1000 = 0.01835\ \Omega$. $X = 0.0441 \times 500/1000 = 0.02205\ \Omega$. $V\_drop = \sqrt{3} \times 200 \times (0.01835 \times 0.88 + 0.02205 \times 0.475) = 346.4 \times (0.01615 + 0.01047) = 346.4 \times 0.02662 = 9.22V$. $V\_drop\% = 9.22/480 = 1.92\% \approx 2.0\%$. Within the NEC 3% recommendation.

51. C — With dual-rated "75°C/90°C" terminals, the 90°C column may be used per NEC 110.14(C)(1)(b). At 90°C: 700 kcmil = 520A ≥ 500A required. At 75°C: 700 kcmil = 460A < 500A (insufficient). The dual-rated terminal listing permits the 90°C ampacity, making 700 kcmil adequate. Without the 90°C rating, 1,000 kcmil (545A at 75°C) would be the minimum.

52. A — $\Delta\delta = (180 \times 60 \times 140 \times 0.055^2)/(3.8 \times 175) = (180 \times 60 \times 140 \times 0.003025)/665 = 4{,}569.6/665 = 6.87°$. The rotor advances less than 7° during the 0.055-second fault — far below the 112° critical clearing angle. The extremely fast clearing (0.055s) provides outstanding transient stability with 105° of margin.

53. C — Two fuses blown from a series group of six parallel units leaves four. Each sees 6/4 = 1.50× normal voltage (50% overvoltage). This far exceeds the IEEE C37.99 110% continuous overvoltage rating. The remaining units will fail rapidly in a cascading pattern. The neutral unbalance relay must immediately trip the bank to prevent catastrophic failure with potential tank rupture.

54. D — Wound-rotor: 320% > 300% — starts successfully. T/I = 320/350 = 0.914. Design B: 150% < 300% — cannot start. T/I = 150/600 = 0.250. Improvement = 0.914/0.250 = 3.66×. Only the wound-rotor provides the required 300% breakaway torque while achieving 3.66× better torque per ampere of starting current.

55. B — Twenty-one phase conductors + four triplen-carrying neutrals = 25 current-carrying conductors (EGCs excluded). Per NEC Table 310.15(C)(1) for 21-30 conductors: factor = 0.35. This 65% derating makes a single raceway impractical — multiple parallel raceways are essential to maintain adequate conductor ampacity.

56. A — The optical relay detects arc light in approximately 1-2 ms and sends a trip signal directly to the breaker trip coil. ZSI processes restraint logic in approximately 8 ms. The optical signal arrives first, initiating breaker opening for a total clearing of approximately 0.025-0.035 seconds. ZSI provides backup at 0.05s if the optical relay fails. The 0.30s STD is the ultimate fallback.

57. C — M = 12.5/5 = 2.5. t = 2.0 × (28.2/5.25 + 0.1217) = 2.0 × (5.371 + 0.1217) = 2.0 × 5.493 = 10.99 seconds. This is unacceptably slow. The extremely inverse characteristic requires high M values for fast operation — at M = 2.5, the relay essentially crawls. Either reduce the pickup to increase M, or select a very inverse or standard inverse characteristic for this application.

58. D — Z_1_total = 28+j280; $|Z_1|$ = 281.4 Ω. Z_0_total = 84+j813.75; $|Z_0|$ = 818.1 Ω. Ratio = 2.91. Sum = 140+j1,373.75; |Sum| = 1,381 Ω. V_f = 199,186V. I_SLG = 3 × 199,186/1,381 = 433A. The very long line limits SLG current severely, and the 2.91 ratio indicates significant voltage elevation on unfaulted phases during SLG faults.

59. B — NEC 700.10(B)(1) requires separation of wiring systems — conductors and raceways — not equipment rooms. Emergency and normal switchgear may share an electrical room as long as each system uses dedicated conduit and routing from that room. The separate conduit penetrations through opposite walls demonstrate independent wiring system routing.

60. A — Per NEC 430.24: 125% × 96 = 120A. Other motor = 34A. Per NEC 215.2: 125% × 55 = 68.75A. Noncontinuous = 25A. Total = 120 + 34 + 68.75 + 25 = 247.75A → 250A exceeds 225A bus. With 100%-rated 225A: load = 210A ≤ 225A. Compliant with conductors ≥210A.

61. C — Excess = 8,292 kvar. Monthly penalty = 8,292 × $4.50 = $37,314. Annual = $447,768. An 8,292 kvar capacitor bank eliminates the penalty entirely. At $447,768/year in avoided penalties, the payback on a capacitor bank installation is typically 2-4 months — one of the highest-ROI capital investments available in industrial power systems.

62. D — Total symmetrical = 42,000 + 12,000 = 54,000A. Peak = 2.30 × 54,000 = 124,200A. The motor contribution of 12,000A (22%) makes a substantial difference. Excluding motors would underrate equipment momentary ratings by 22%, risking catastrophic mechanical failure during fault events.

63. B — The zero-sequence CT sees only the 20A fault current — balanced 247.5A/phase charging cancels to zero residual. Since 20A > 15A pickup, the relay trips after 0.5 seconds. The massive charging current (742.5A total three-phase) has absolutely zero effect on the zero-sequence CT measurement.

64. A — Per NEC 430.24: 125% × 477 = 596.25A. Other motors = 361 + 302 + 242 + 180 = 1,085A. Motor subtotal = 1,681.25A. Per NEC 215.2: 125% × 120 = 150A. Total = 1,681.25 + 150 = 1,831.25A. The 125% applies to the largest motor and continuous non-motor load.

65. C — Zone 1 at 85% cannot reach 88%. Zone 2 at 120% covers 88%. With POTT communication failed, pilot-assisted tripping is unavailable. Zone 2 operates after 0.35-second delay. Total clearing ≈ 0.433 seconds. The communication failure adds 0.35 seconds compared to pilot-assisted clearing.

66. A — $R_{max} = V_{LN}/I_{pickup} - R_{NGR} = 2{,}402/20 - 8.007 = 112.1\ \Omega$. Faults with resistance above 112 Ω produce current below the 20A pickup and go undetected. This is the fundamental sensitivity limitation of LRG systems — arcing faults through vegetation or contaminated surfaces may exceed this resistance threshold.

67. A — VRFBs use sulfuric acid-based electrolyte requiring spill containment and corrosion-resistant materials. Hydrogen can be generated at the negative half-cell during charging. The electrolyte must be kept above its precipitation temperature (~10°C). Standard lithium-ion or lead-acid guidelines don't apply — VRFB installations require specialized ventilation, containment, and thermal management designs.

68. B — $E = 6.8 \times (0.012/0.10) = 0.816$ cal/cm². Below the 1.2 cal/cm² arc flash boundary threshold. At this energy level, the onset of second-degree burn is not reached at the working distance. Standard daily work clothing without specific arc-rated PPE may be adequate, though the engineer should verify with the specific IEEE 1584 parameters.

69. A — At H = 2.2 with a 0.6-second sag at 76%, the simplified swing analysis yields approximately 25-40° of rotor angle advance. While the 87.4% FLT steady-state margin appears large, the rotor accumulates angular momentum throughout the sag. After voltage recovery, the return-swing oscillation

adds to the peak angle. At H = 2.2, the moderate inertia provides sufficient damping for this sag severity, but a longer sag or deeper voltage would push toward instability.

70. C — 377A SLG fault current on a 230 kV system creates significant protection challenges. Ground overcurrent relays must use very sensitive settings, risking false operation during load unbalance. Distance relays may have reduced accuracy at low current. Pilot schemes become mandatory because zone-based distance protection with measurement uncertainties cannot reliably detect all end-of-line faults at this current level.

71. D — Ratio = 1,000,000/700,000 = 1.429. EGC = 83,690 × 1.429 = 119,553 CM. 1 AWG = 83,690 (below). 1/0 AWG = 105,600 (below). 2/0 AWG = 133,100 (above — adequate). The minimum EGC is 2/0 AWG.

72. B — Original Q = 15,000 × 1.078 = 16,170 kvar. Cap = −12,000. Sync motor: P_in = 3,174 kW; Q_sync = 2,381 kvar. Net Q = 16,170 − 12,000 − 2,381 = 1,789 kvar. P_total = 18,174 kW. PF = 18,174/18,262 = 0.995 ≈ 0.99. The combined correction nearly eliminates reactive demand.

73. A — Z_T_par = 0.105/2 = 0.0525. Z_gen = 0.333. Z_SC = 0.45. Z_SM = 0.88. I_pu = 19.05 + 3.003 + 2.222 + 1.136 = 25.41. I = 25.41 × 836.7 = 21,260A. The parallel transformers provide 75% of total fault current.

74. C — P_pump = 149 × $(900/1{,}770)^3$ = 19.6 kW. P_supply = 19.6/(0.87 × 0.97) = 23.2 kW. The cascade of reduced motor efficiency (87% at light load vs 95% at full) and VFD losses adds 3.6 kW. This efficiency penalty is trivial compared to the 129 kW saved by speed reduction.

75. D — At 1,900A (approximately 6× FLA), the overload relay's I^2t accumulates approximately 36× faster than at rated current. The inverse-time thermal characteristic integrates this rapidly, producing a trip in approximately 8-12 seconds for a bimetallic overload or 5-10 seconds for an electronic overload relay. This provides both running overload protection and stall protection through a single device.

76. B — Total = 69,461A. Weighted X/R = 7.62. IEEE multiplier ≈ 2.27. Peak = 2.27 × 69,461 = 157,677A. The electromagnetic forces on bus structures are proportional to I^2_peak — at 158 kA peak, the mechanical design is the critical engineering constraint for this paralleled system.

77. D — At $H = 1.8$ MJ/MVA with a 1.5-second sag at 65%, the swing equation produces very large angle advance because $\Delta\delta \propto t^2$ — 1.5 seconds is 225× the advance of 0.1 seconds. Even with 62.5% FLT steady-state margin, the accumulated rotor momentum almost certainly exceeds the critical clearing angle. The motor will very likely lose synchronism during or immediately after the sag.

78. C — Two parallel transformers each with $Z_{eff} = 5.75\% + 1\% = 6.75\%$. $Z_{parallel} = 6.75\%/2 = 3.375\%$. $I_{rated} = 3{,}007$A. $I_{fault} = 3{,}007/0.03375 = 89{,}097$A. This is a 184% increase from the original 31,374A — requiring comprehensive SCCR reverification of all downstream equipment and a complete new arc flash study.

79. D — Peak factor at $X/R = 5$: IEEE multiplier ≈ 2.17. Peak $= 2.17 \times 8{,}660 = 18{,}792$A. This determines the momentary withstand rating for all 208V distribution equipment. The moderate X/R of 5 produces moderate asymmetry at approximately 2.17× the symmetrical RMS value.

80. B — $I = 300{,}000/(\sqrt{3} \times 480) = 361$A. Min OCPD $= 125\% \times 361 = 451.3$A → next standard per NEC 240.6(A) is 500A. Annual energy $= 300 \times 18 \times 6 \times 52 = 1{,}684{,}800$ kWh. Cost $= 1{,}684{,}800 \times \$0.070 = \$117{,}936$/year. The high annual energy cost of nearly $118,000 demonstrates why process heating efficiency improvements have enormous economic impact.