PRACTICE EXAM 22: PE POWER SIMULATION (80 QUESTIONS)

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1. A 13.8 kV industrial facility has a short-circuit level of 450 MVA and a 6,600 kvar capacitor bank producing h_r = √(450,000/6,600) = 8.26. The bus serves six-pulse VFDs (4,000 HP) and twelve-pulse VFDs (3,000 HP). The plant intends to add a second capacitor bank of 3,600 kvar for additional PF correction, bringing the total to 10,200 kvar. The new h_r = √(450,000/10,200) = 6.64. What is the critical concern with this addition?

A. The new h_r of 6.64 is safely between the 5th and 7th harmonics and poses no resonance risk

B. The twelve-pulse VFDs' 11th harmonic at h_r = 6.64 is the primary concern because it is closer than any six-pulse harmonic

C. The original h_r of 8.26 was safely above all major characteristic harmonics; the new h_r of 6.64 falls directly between the 5th (h=5) and 7th (h=7) harmonics from the six-pulse VFDs, where both characteristic currents are amplified; parallel resonance near h=5 and h=7 produces severe voltage distortion; detuning reactors must be installed before the second bank is energized

D. The additional capacitor bank will reduce the system fault level, which is the primary concern

2. A three-phase, 480V system has a 3,000 kVA transformer (Z = 5.75%, X/R = 9) feeding a switchboard with I_fault = 36,130A. A 300-foot cable of 500 kcmil copper in steel conduit (R = 0.0276, X = 0.0391 Ω/1000 ft) feeds an MCC. At the MCC, eight 100 HP motors (FLA = 124A each, total = 992A) contribute 4 × 992 = 3,968A first-cycle. The arc flash study at the switchboard shows 16 cal/cm² at 0.1-second clearing. What is the approximate total first-cycle fault current at the MCC, and does the MCC require a different arc flash label than the switchboard?

A. Cable impedance reduces transformer contribution to approximately 29,800A; adding 3,968A motor = 33,768A total; the 17% reduction from switchboard combined with the IEEE 1584 current-dependent formula likely changes the PPE category — the MCC should receive its own arc flash calculation and label

B. 36,130A (cable has no effect at 300 feet with 500 kcmil)

C. 40,098A (switchboard value plus motor, cable ignored)

D. 20,000A (cable reduces by 50%)

3. Per NEC 430.52(C)(1), a 350 HP, 460V motor (FLA = 414A) uses an instantaneous-trip MCP. Per Table 430.52, maximum = 800% = 3,312A → standard 3,500A. The motor has a Design B code letter H (LRC ≈ 6.3 × 350 × 1000/(√3 × 460) = 2,769A). The MCP is set at 3,200A (115.6% of LRC). During the first starting attempt, the MCP trips on the asymmetrical inrush peak. The engineer increases the setting to 3,400A. Per NEC 430.52(C)(2), is this permissible?

A. No — the MCP has already exceeded the 800% maximum at 3,400A

B. Yes — but only with a soft starter installed to reduce inrush

C. No — any increase above the original 3,200A setting requires a special permit

D. Yes — 3,400A is still below the 3,500A maximum permitted by NEC 430.52(C)(1); increasing the MCP setting to accommodate the asymmetrical starting inrush is standard practice as long as the setting does not exceed the Table 430.52 maximum; the higher first-cycle asymmetrical peak is a normal phenomenon that must be accounted for in MCP setting

4. A CT with a ratio of 2500:5 and accuracy class C400 serves an overcurrent relay on a 4,160V feeder. The total burden is 3.5 Ω. During a 30,000A fault (12× rated), the CT secondary = 60A. The burden voltage = 60 × 3.5 = 210V. At 12× (not the worst-case 20×), the CT core has less flux demand than at 20×. The C400 rating guarantees accuracy at 20× up to 400V. At 12× with 210V, is the CT operating within its capability?

A. No — 210V exceeds proportional limits at 12× rated

B. Yes — at 12× rated, the CT core requires significantly less excitation than at 20× rated; the core operates well within its linear excitation range with approximately 90V of effective voltage margin above the 210V burden; the CT maintains excellent accuracy at this operating point

C. No — the burden of 3.5 Ω exceeds the maximum for C400 class CTs

D. Yes — but only because the fault duration is short

5. A 345 kV, 380-mile transmission line must transmit 480 MW during peak. The line's uncompensated SIL is 310 MW. A 45% series compensation at two distributed locations is proposed. However, a 500 MW thermal generating station is located 80 miles from the series capacitor installation. The engineer performs an SSR screening study per IEEE Standard. The study reveals that the electrical resonant frequency f_r = 60 × √(0.45) = 40.2 Hz produces a complement of 60 − 40.2 = 19.8 Hz. The generator's first torsional mode is at 18.5 Hz. Is this a concern?

A. No — 19.8 Hz and 18.5 Hz are separated by 1.3 Hz, which is adequate margin

B. No — SSR only affects generators directly connected to the series-compensated line

C. The 1.3 Hz separation between the complementary electrical frequency (19.8 Hz) and the generator's first torsional mode (18.5 Hz) is INSUFFICIENT — IEEE SSR screening guidelines typically require at least 2-3 Hz separation; this proximity creates a significant risk of torsional interaction; mitigation options include: reducing the compensation level, adding a subsynchronous damping controller (SSDC), or installing a thyristor-controlled series capacitor (TCSC) that can be modulated to avoid torsional excitation

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

6. Per NEC 250.122(B), a 350A circuit has minimum phase conductors of 500 kcmil (380A at 75°C, satisfying the 350A continuous load requirement). The conductors are increased to 750 kcmil for voltage drop on a 600-foot run. Table 250.122 requires 4 AWG (41,740 CM) for the 350A OCPD. What is the proportionally increased EGC?

A. Ratio = 750,000/500,000 = 1.50; EGC = 41,740 × 1.50 = 62,610 CM → 2 AWG (66,360 CM) is the minimum standard size above 62,610 CM

B. 4 AWG (no increase — proportional increase results in less than one wire size)

C. 1 AWG (83,690 CM)

D. 3 AWG (52,620 CM) — close to the calculated value but below the 62,610 CM minimum

7. A three-phase, 4,160V system has a 12,000 kW load at 0.65 lagging PF. Q = 12,000 × 1.169 = 14,028 kvar. The engineer installs an 11,000 kvar capacitor bank AND a 4,000 HP synchronous motor at 0.80 leading PF (η = 94%) AND a 1,500 HP synchronous motor at 0.85 leading PF (η = 95%). What is the new bus PF?

A. PF = 0.90 lagging

B. PF = 0.95 lagging

C. PF = 0.98 lagging

D. SM1: P_{in} = 3,174 kW, Q_1 = 2,381 kvar; SM2: P_{in} = 1,178 kW, Q_2 = 731 kvar; total correction = 11,000 + 2,381 + 731 = 14,112 kvar; net Q = 14,028 − 14,112 = −84 kvar (slightly leading!); P_{total} = 16,352 kW; PF ≈ unity — the three correction sources slightly overcorrect; the engineer should reduce the capacitor bank slightly to maintain a 0.98-0.99 lagging PF and avoid voltage regulation issues from leading PF

8. A three-phase, 480Y/277V panelboard serves a data center with 100% nonlinear server power supplies. Phase currents: 480A fundamental, 192A 3rd harmonic, 96A 5th, 48A 7th per phase. The neutral current from triplens = 3 × 192 = 576A. The phase RMS = $\sqrt{(480^2 + 192^2 + 96^2 + 48^2)}$ = $\sqrt{(230{,}400 + 36{,}864 + 9{,}216 + 2{,}304)}$ = $\sqrt{278{,}784}$ = 528.2A. With 4 current-carrying conductors (factor 0.80): phase base = 660.3A, neutral base = 720A. Which governs?

A. Phase governs at 660.3A because it always exceeds the neutral requirement

B. Neutral governs at 720A — the triplen-harmonic neutral current of 576A divided by the 0.80 derating factor produces 720A base ampacity, which exceeds the phase requirement of 660.3A; the neutral conductor must be sized for 720A, making it the governing constraint for the unified conductor selection

C. Both require 700A (average of the two)

D. The OCPD rating alone determines conductor sizing

9. A 180 MVA synchronous generator has X''_d = 0.18 pu, X_2 = 0.20 pu, X_0 = 0.06 pu. The generator is solidly grounded. The engineer must evaluate the effect of switching to high-resistance grounding with $3R_n$ = 60 pu. Solidly grounded: I_{SLG} = 3/(0.18+0.20+0.06) = 6.82 pu; $I_{3\Phi}$ = 5.56 pu. HRG: I_{SLG} ≈ 3/60 = 0.05 pu. What does this comparison reveal about the SLG/3Φ relationship under different grounding methods?

A. The grounding method has no effect on the SLG/3Φ relationship

B. HRG produces higher SLG current than solidly grounded because of the resistance

C. Solidly grounded: I_SLG (6.82) exceeds I_3Φ (5.56) by 22.7% because X_0 (0.06) is much less than X"_d (0.18); HRG: I_SLG (0.05 pu) is only 0.9% of I_3Φ — the grounding impedance completely eliminates the SLG > 3Φ problem; this is one of the key advantages of HRG: it reduces ground-fault current below the level where it drives equipment thermal and mechanical ratings

D. Solidly grounded: I_SLG = I_3Φ; HRG: I_SLG = 0

10. A three-phase, 4,160V system has an NGR rated 300A, 10 seconds. The system charging current from cable capacitance is 12A (normal zero-sequence background). A ground fault through 15 Ω develops. R_NGR = 8.007 Ω. I_fault = 2,402/23.007 = 104.4A. The relay has 25A pickup and 0.8-second delay. After clearing, the relay resets. Fifteen seconds later, the same fault restrikes. This cycle repeats four times total over 3 minutes. What is the cumulative NGR thermal consumption?

A. $4 \times (104.4/300)^2 \times (0.8/10) = 4 \times 0.1212 \times 0.08 = 3.88\%$ — four events consumed less than 4% of the NGR's thermal capacity despite repeated faulting; the combination of reduced fault current (104.4A vs 300A rated) and short clearing times (0.8s) means each event uses less than 1% of rated I^2t

B. 25% consumed — significant thermal stress

C. 50% consumed — NGR needs inspection

D. Each event consumes $(104.4/300)^2 \times (0.8/10) = 0.97\%$; four events = 3.88%; the 15-second intervals between events allow partial cooling (NGR time constant typically 5-15 minutes); the actual thermal stress is even less than 3.88% because of inter-event cooling; however, the repetitive fault pattern indicates a persistent problem that will continue damaging the NGR unless the root cause is identified and repaired

11. Per NEC 110.26(A)(1)(a), the minimum working space depth in front of electrical equipment operating at 0-150V to ground with Condition 1 (exposed live parts on one side, no grounded parts opposite) is what distance?

A. 3 feet

B. 3.5 feet

C. 4 feet

D. 2.5 feet

12. A 4,000 kVA, 13.8 kV/480V transformer has core losses = 11,000 W and full-load copper losses = 35,000 W. Operating profile: 6 hours at 100% (PF = 0.92), 10 hours at 65% (PF = 0.87), 8 hours at 35% (PF = 0.78). k_max = √(11,000/35,000) = 56.1%. The transformer's all-day efficiency requires computing E_out and E_loss for each period. Which period is closest to maximum efficiency, and what is the qualitative impact on the all-day efficiency?

A. 100% period — highest output dominates efficiency

B. 65% period is closest to k_max = 56.1%, operating only 8.9 percentage points above the optimal loading; during this 10-hour period, the transformer operates near peak instantaneous efficiency (where P_core ≈ P_Cu); this favorable loading for the longest period (10 of 24 hours) has the greatest positive impact on all-day efficiency compared to the less-efficient heavily loaded and lightly loaded periods

C. 35% period is closest to k_max

D. All three periods contribute equally to efficiency

13. A protection coordination study on a 4,160V system requires coordinating a downstream 51 relay (R1: IEEE extremely inverse, TD = 1.0, pickup = 5A on 200:5 CT) with an upstream 51 relay (R2: IEEE very inverse, TD = 4.0, pickup = 6A on 600:5 CT). At a common fault of 12,000A: R1 secondary = 300A; M_1 = 300/5 = 60. Using EI: t_1 = 1.0 × (28.2/(3,600−1) + 0.1217) = 1.0 × (0.00783 + 0.1217) = 0.130s. R2 secondary = 100A; M_2 = 100/6 = 16.67. Using VI: t_2 = 4.0 × (19.61/(277.9−1) + 0.491) = 4.0 × (0.0708 + 0.491) = 4.0 × 0.562 = 2.247s. CTI = 2.247 − 0.130 = 2.12s. Is this coordination optimal?

A. CTI = 2.12s is ideal and should not be adjusted

B. CTI = 2.12s is inadequate — more separation is needed

C. CTI = 2.12s is grossly insufficient

D. CTI = 2.12s is adequate but excessive — the upstream relay R2 is unnecessarily slow; reducing R2's TD to approximately 2.0 would yield t_2 ≈ 1.12s and CTI = 0.99s, still well above the 0.20s minimum while cutting the backup clearing time in half; every second of unnecessary delay increases fault damage, I^2t thermal stress, and arc flash energy

14. A distance relay on a 138 kV line (Z_line = 4 + j48 Ω) has Zone 1 at 85%, Zone 2 at 120%. A fault occurs at 75% through 10 Ω fault resistance. Z_meas = (0.75×4 + 10) + j(0.75×48) = 13 + j36 Ω.

|Z_meas| = 38.3 Ω. Zone 1 reach = 0.85 × 48.17 = 40.9 Ω. The impedance angle $\theta = \arctan(36/13) = 70.2°$. MTA = 78°. Is this fault within Zone 1?

A. No — the 10 Ω fault resistance pushes the impedance outside the mho circle entirely

B. Yes — |Z_meas| < Zone 1 reach guarantees Zone 1 operation regardless of angle

C. The fault is within Zone 1 magnitude (38.3 < 40.9) but the impedance angle of 70.2° deviates significantly from MTA of 78° (7.8° difference); combined with the large 10 Ω resistive component, the R-X point may be on the edge of or just outside the mho circle — a detailed graphical analysis on the R-X diagram is required to confirm whether the point falls inside the mho characteristic

D. Zone 2 provides instantaneous clearing for this fault through the pilot scheme

15. A three-phase, 460V, 4-pole, 450 HP induction motor drives a centrifugal chiller compressor through a VFD. Design: 336 kW at 1,770 RPM. Three operating modes: full speed (2,500 hr/yr), 75% speed (3,800 hr/yr), 50% speed (2,460 hr/yr). Using $P \propto n^3$, what is the total annual VFD energy consumption?

A. Full: 336×2,500 = 840,000; 75%: 336×0.422×3,800 = 538,474; 50%: 336×0.125×2,460 = 103,320; total = 1,481,794 kWh; full-speed annual = 336×8,760 = 2,943,360; savings = 1,461,566 kWh (49.7%) — the cubic relationship makes partial-speed chiller operation dramatically more efficient

B. 2,000,000 kWh

C. 2,500,000 kWh

D. 1,000,000 kWh

16. Per NEC 480.9(A), ventilation for battery rooms must limit H_2 below 1%. A utility substation control house has a 48V DC station battery: 60 vented lead-acid cells in a dedicated room of 1,500 ft^3. Charging at 0.010 ft^3 H_2/cell/hour. What ACH is required, and what additional safety feature is critical for unattended substation battery rooms?

A. ACH = 0.10; no additional features needed for substations

B. ACH = 1.0; fire suppression only

C. ACH = 0.50; only visual inspection quarterly

D. H_2 = 0.60 ft^3/hr; max H_2 = 15 ft^3; ACH = 0.040; the critical feature for UNATTENDED substations is: automatic hydrogen detection with remote alarming to the SCADA/EMS system — since no personnel are present to notice a ventilation failure or hydrogen buildup, the H_2 sensor provides the only warning before concentrations reach dangerous levels; the alarm should trigger at 25% of LEL (1% H_2)

17. A 230 kV, 320-mile transmission line with SIL = 145 MW must carry 280 MW during peak. A 35% series compensation at two distributed locations is installed. The effective line reactance is reduced by 35%. Additionally, an SVC rated ±160 Mvar is at the receiving end. During a sudden load increase from 180 MW to 310 MW (exceeding the pre-contingency plan), the receiving-end voltage drops rapidly. What determines whether the system survives this transient?

A. Only the series compensation matters for transient stability during this event

B. The SVC's response speed is critical — it must inject reactive power within 1-2 cycles to support the receiving-end voltage; V_R appears in the power transfer equation (P = V_SV_R sin δ / X_eff), so maintaining V_R directly maintains the electrical power transfer capability; if V_R drops too far before the SVC responds, the sending-end generator angle accelerates past the critical clearing angle and the system separates — the SVC's fast voltage support provides the bridge until slower controls (generator excitation, tap changers) can establish a new steady-state equilibrium

C. Only the generator excitation system determines system survival

D. The receiving-end load determines the outcome regardless of any compensation

18. A separately excited DC motor has V_t = 600V, I_a = 300A, R_a = 0.04 Ω. Rated speed = 900 RPM. E_a = 600 − 300×0.04 = 588V. The motor drives a steel rolling mill. For emergency braking, dynamic braking is used with R_B = 1.5 Ω. At the instant of armature disconnection (motor still at 900 RPM, E_a = 588V), the braking current flows through the armature circuit: I_brake = E_a/(R_a + R_B) = 588/1.54 = 381.8A. The initial braking power = E_a × I_brake = 224.5 kW. As the motor decelerates, E_a decreases proportionally to speed, reducing both braking current and power. At what speed does the braking torque fall to 25% of initial?

A. 75% speed (675 RPM)

B. 50% speed (450 RPM)

C. 25% speed (225 RPM)

D. Braking torque ∝ I_brake^2 (since $T = k\Phi I\_a$ and Φ is constant); $I\_brake \propto E\_a \propto$ speed; so $T \propto speed^2$; for T = 25% of initial: $speed^2 = 0.25 \times speed\_initial^2$; speed = 50% → 450 RPM — at half speed, the braking torque drops to 25% because it varies with the square of speed; this rapid decay of braking effectiveness at low speeds is the fundamental limitation of dynamic braking and often requires supplementary friction or electromagnetic braking for final stop

19. Per NEC 250.30(A)(1), a large semiconductor fabrication facility has: 4 × 5,000 kVA service transformers (13.8/480V), 4 × 3,000 kW emergency generators, 12 × 1,000 kVA PDU transformers (480/208Y/120V), 6 × 500 kVA ultra-clean isolation transformers (480/480V), and 8 × 300 kVA UPS output isolation transformers (480/208Y/120V). Each is a separately derived system. How many system bonding jumpers are required?

A. Thirty-four — 4 service + 4 generators + 12 PDU + 6 isolation + 8 UPS = 34 bonding jumpers; each must be installed at its respective source per NEC 250.30(A)(1); for a facility this large, a bonding jumper schedule should be maintained as part of the facility's electrical documentation, with each jumper tested during commissioning

B. Twenty (service + generators + PDU only)

C. Sixteen (service + PDU only)

D. Four (service transformers only)

20. A three-phase, 480V, 2,000A switchgear has an available fault current of 85,000A and a main LVPCB with 0.30-second STD. The arc flash study shows 65 cal/cm^2 at 24 inches. The engineer implements a comprehensive six-layer mitigation strategy: (1) ZSI (0.05s), (2) optical relay (0.018s), (3) arc-resistant switchgear (Type 2B), (4) remote racking, (5) permanent-magnet trip, (6) bus-mounted arc quenching device (AQD). The AQD detects arc light and creates a controlled three-phase bolted fault in approximately 4 ms, collapsing the arc voltage to near zero and transferring energy from the arc to the low-impedance bolted path. What is the combined effect?

A. The AQD has no effect because it creates a fault

B. $E = 65 \times (0.018/0.30) = 3.9$ cal/cm² from the optical relay reduction alone, but then the arc-resistant enclosure redirects this reduced energy away from the worker

C. The AQD activates in approximately 4 ms (faster than the optical relay's 18 ms total clearing); by creating a bolted fault, the AQD collapses the arc voltage to near zero within 4 ms, virtually eliminating arc flash energy at the source; the optical relay then trips the main breaker in 18 ms total to clear the bolted fault; the worker's exposure is near zero because the arc existed for only 4 ms before being quenched — combined with the arc-resistant enclosure, this represents the state-of-the-art in arc flash elimination

D. The AQD replaces all other mitigation layers

21. A synchronous generator rated 500 MVA, 26 kV has $X''_d = 0.24$ pu, $X_2 = 0.26$ pu, $X_0 = 0.10$ pu. Solidly grounded. $I_{SLG} = 3/0.60 = 5.0$ pu. $I_{3\Phi} = 1/0.24 = 4.17$ pu. The SLG exceeds three-phase by 20%. The engineer switches to low-resistance grounding with $3R_n = 8.0$ pu (predominantly resistive). $I_{SLG\_LRG} = 3/\sqrt{(8.0^2 + 0.60^2)} = 3/8.022 = 0.374$ pu. The SLG is now only 9% of the solidly grounded value. What protection scheme change is required?

A. No changes — the existing overcurrent protection works identically for both grounding methods

B. The phase overcurrent relays can still detect the 0.374 pu SLG current because it flows in only one phase

C. The protection must be completely redesigned — the existing phase overcurrent relays may not detect 0.374 pu; a dedicated ground-fault relay (51G or 59G) must be added

D. The existing phase overcurrent relays (set for the three-phase level of 4.17 pu) will NOT detect the 0.374 pu SLG current; a dedicated neutral overcurrent relay (51G) with sensitive pickup must be installed, along with a ground-fault detection relay (59G) measuring neutral-to-ground voltage; the protection scheme must fundamentally change from relying on phase overcurrent for all faults to a split approach: phase relays for phase faults and dedicated ground relays for ground faults

22. A 480V, three-phase panelboard has: Motor 1 = 590A (500 HP, largest), Motor 2 = 477A (400 HP), Motor 3 = 361A (300 HP), Motor 4 = 302A (250 HP). Continuous lighting = 280A. Noncontinuous HVAC = 90A. Per NEC 430.24 and 215.2(A)(1), what is the minimum feeder conductor ampacity?

A. 1,800A

B. 125% × 590 + 477 + 361 + 302 + 125% × 280 + 90 = 737.5 + 1,140 + 350 + 90 = 2,317.5A

C. 2,500A

D. 2,000A

23. A three-phase, 4,160V bus has nine sources. On a 60 MVA base: four utility transformers (Z_A = 0.04, Z_B = 0.05, Z_C = 0.06, Z_D = 0.08), three generators (Z_E = 0.30, Z_F = 0.45, Z_G = 0.60), one synchronous condenser (Z_H = 0.80), one battery inverter (Z_I = 4.0). I_base = 8,328A. What is the total fault current?

A. I = (25.0+20.0+16.67+12.5+3.33+2.22+1.67+1.25+0.25) × 8,328 = 82.89 × 8,328 = 690,364A — nine parallel sources on a single 4,160V bus produce this extreme fault current; the four utility transformers provide 89.5% of the total, the three generators 8.7%, and the inverter only 0.3%

B. 400,000A

C. 500,000A

D. 300,000A

24. A 480V, three-phase, 225A panelboard (SCCR = 22,000A) is fed from a switchboard with 48,000A available. The feeder cable is 400 feet of 1/0 AWG copper in EMT (R = 0.122 Ω/1000 ft, X = 0.0554 Ω/1000 ft). The engineer must determine if the cable naturally reduces the fault current below the panelboard SCCR, or if a series-rated combination with current-limiting fuses is needed.

A. The cable has no effect on fault current at 400 feet

B. Series-rated combination is always required regardless of cable length

C. Z_cable: R = 0.0488, X = 0.02216 Ω; Z_base ≈ 0.0922 Ω; Z_cable_pu = 0.0536/0.0922 ≈ 0.581; total Z ≈ 0.0575+0.581 = 0.639; I ≈ 3,007/0.639 ≈ 4,706A — the high-impedance 1/0 AWG at 400 feet naturally reduces fault current to approximately 4,700A, well below the 22,000A SCCR; no series-rated combination or current-limiting fuses are needed; the installation is code-compliant with proper documentation per NEC 110.9

D. 10,000A — close to but below SCCR

25. Per NEC 690.12, a 500 kW commercial PV system uses central inverters. Each string has 20 modules in series (V_oc = 48V per module = 960V). No module-level power electronics (MLPE) are installed. The NEC 690.12(A) outside-array-boundary requirement is met by a DC disconnect. However, the NEC 690.12(B)(2) within-array-boundary requirement mandates 80V within 30 seconds. After rapid shutdown activation, what is the string voltage within the array boundary?

A. 0V — the central inverter removes all string voltage

B. 80V — each string is regulated down to 80V by the inverter during rapid shutdown

C. 480V — only half the modules de-energize during rapid shutdown

D. 960V — each module continues producing V_oc under sunlight; without MLPE (optimizers or microinverters), the string conductors within the array boundary remain at full 960V, far exceeding 80V; the system violates NEC 690.12(B)(2) and must be retrofitted with module-level rapid shutdown devices

26. A three-phase, 480V system has three transformers in parallel: T1 = 3,500 kVA (Z = 5.50%, X/R = 9), T2 = 3,000 kVA (Z = 5.75%, X/R = 8), T3 = 2,500 kVA (Z = 6.00%, X/R = 7). Individual fault contributions: I_T1 = 74,200A, I_T2 = 60,870A, I_T3 = 48,517A. Total = 183,587A. Motor contribution from 18 motors (FLA = 3,200A): 12,800A. Grand total = 196,387A. Weighted X/R ≈ 8.2. Multiplier = 2.31. What is the peak asymmetrical?

A. 277,700A (√2 × total)

B. Peak = 2.31 × 196,387 = 453,654A — nearly half a million amperes peak; this is among the highest peak fault currents possible on a 480V system and requires extraordinary bus bracing designed for electromagnetic forces exceeding 2×10^{11} A^2

C. 392,774A (2× total)

D. 196,387A (no asymmetry)

27. A distance relay on a 230 kV line (Z_line = 7 + j80 Ω) has Zone 1 at 85%, Zone 2 at 120% (0.35s). A permanent fault at 92% with 5 Ω resistance. The DCB pilot scheme is active. Both terminals see the fault as forward. The near-end relay: Zone 1 at 85% cannot reach 92%. Zone 2 at 120% covers the fault. No blocking signal is received (both see forward fault). What is the protection response?

A. Zone 2 trips after 0.35 seconds at the near end

B. Only the remote end trips

C. Neither terminal trips due to the 5 Ω fault resistance

D. Both terminals trip with high-speed clearing — the near end's Zone 2 detects the fault and receives no blocking signal (DCB: no block = trip permitted); the remote end sees the fault at 8% from its terminal (within Zone 1) and trips instantaneously; the DCB scheme provides simultaneous high-speed clearing at both ends despite the near end's Zone 1 being unable to reach the fault

28. A protection engineer designs a transformer differential relay (87T) for a 200 MVA, 345/138 kV auto-transformer with a tertiary winding (13.8 kV delta). The relay must account for three sets of CTs (HV, LV, tertiary). During an external fault on the 138 kV bus, one HV CT saturates to 60% while all LV and tertiary CTs perform correctly. The expected CT secondary = 5.0A (all normalized). False differential = 2.0A. Restraint = 5.0A. The relay's slope is 30%. Does the relay correctly restrain?

A. Slope threshold = 30% × 5.0 = 1.5A; since 2.0A > 1.5A, the relay FALSE TRIPS during the external fault — the 30% slope is insufficient for 40% CT saturation; the slope should be increased to at least 40% for autotransformers to accommodate the higher CT error probability from the complex three-winding current balancing

B. The relay correctly restrains because the tertiary CTs balance the false differential

C. The relay uses harmonic blocking to restrain during external faults

D. False differential = 0A (auto-transformer CTs always track perfectly)

29. Per NEC 450.3(B), a 2,000 kVA, 13.8 kV/480V transformer has a primary current of 83.7A. Maximum primary OCPD = 125% × 83.7 = 104.6A → next standard above = 110A. The secondary current = 2,406A. The transformer also has secondary OCPD at 125% × 2,406 = 3,007.5A → 3,000A standard (below 125%... wait, NEC 450.3(B) permits next standard above 125% for secondary also). What is the permissible secondary OCPD?

A. 2,406A (100% protection)

B. 3,000A (slightly below 125%)

C. Next standard above 3,007.5A per NEC 450.3(B); standard sizes above 3,000A include 3,500A; however, the secondary OCPD must not exceed 125% for transformers with primary OCPD — per NEC 450.3(B) Note 3, when primary OCPD is provided, secondary OCPD may not be required; the engineer should verify the specific table conditions

D. 4,000A (167% allowable for secondary)

30. A three-phase, 4,160V, 8-pole synchronous motor rated 6,000 HP drives a SAG mill at 900 RPM. Pull-out = 260% FLT. H = 2.5 MJ/MVA. S = 5,228 kVA. During a nearby fault clearing, voltage sags to 78% for 0.5 seconds. Pull-out = 202.8% FLT. Load = 100% FLT. Margin = 102.8% FLT. The engineer performs a swing analysis. With H = 2.5 and the moderate sag, what is the stability assessment?

A. Unstable — any sag at this motor size causes pull-out

B. The H = 2.5 provides relatively good inertia for a synchronous motor; the 0.5-second sag at 78% produces moderate rotor angle advance (estimated 15-25°); with 102.8% FLT steady-state margin and the relatively short sag duration, the motor maintains synchronism with adequate margin; the return-swing oscillation after voltage recovery damps within the available margin — stability is maintained

C. Marginally stable — the motor oscillates for several seconds before reaching equilibrium

D. Cannot be determined without computational simulation

31. A 480V, three-phase system has five parallel transformers totaling 12,000 kVA. The combined fault current is 210,000A symmetrical. Weighted X/R = 8.5. IEEE multiplier = 2.34. The peak asymmetrical = 491,400A. The engineer must design the bus bracing. The electromagnetic force between parallel conductors is $F \propto I^2\_peak/d$, where d is the spacing. If the bus spacing is reduced from 8 inches to 4 inches, what happens to the force?

A. Force is unchanged by spacing

B. Force increases by 50%

C. Force increases by 4× (proportional to $1/d^2$)

D. Force doubles — the electromagnetic force is inversely proportional to the distance between conductors ($F \propto I^2/d$); halving the distance doubles the force; at 491 kA peak, even with 8-inch spacing the forces are extreme; reducing to 4 inches doubles them, potentially requiring twice the bracing strength or completely different bus construction methods

32. A 13.8 kV system has voltage THD = 15.5% at the PCC. Harmonics: $V_5 = 11.2\%$, $V_7 = 7.8\%$, $V_{11} = 5.1\%$, $V_{13} = 3.5\%$, $V_{17} = 2.1\%$, $V_{19} = 1.4\%$, $V_{23} = 0.8\%$. IEEE 519: individual ≤ 3.0%, THD ≤ 5.0%. This facility has the worst harmonic distortion of any exam scenario. What is the total violation count and priority mitigation?

A. Five violations (V_5, V_7, V_{11}, V_{13} exceed 3.0% individual limit, plus THD exceeds 5.0%); immediate Phase 1: retrofit the largest six-pulse VFDs to 18-pulse or AFE to eliminate 5th and 7th at the source — this alone may reduce THD below 8%; Phase 2: install tuned passive filters for 11th and 13th if still above 3.0%; Phase 3: verify THD < 5.0%; this is a multi-month remediation requiring capital planning

B. Three violations only

C. Seven violations

D. Two violations

33. A ground resistance test on a major data center measures 2.8 Ω during spring (wet season). The IEEE 80 target is 0.5 Ω. The IEEE 81 seasonal correction is 1.7 (wet-to-dry for this sandy loam). Corrected = 4.76 Ω — 9.5× the target. The site has limited expansion area for a larger ground grid. What alternative grounding approach is most effective in space-constrained sites?

A. Install more driven rods within the existing grid area (diminishing returns beyond 2-3 rods in close proximity)

B. Deep ground wells drilled to reach lower-resistivity geological layers (often 50-200 feet deep) combined with ground enhancement material (GEM) backfill around the well conductors — this vertical approach is the most effective for space-constrained sites because it accesses lower-resistivity soil or water-bearing strata without expanding the grid's horizontal footprint; each deep well can reduce resistance by 30-60% depending on the depth-to-low-resistivity-layer distance

C. Chemical treatment of the surface soil

D. Accept the 4.76 Ω and document the exception

34. A three-phase, 460V, 2-pole induction motor rated 800 HP has η = 97.0%, PF = 0.91 lagging. No-load magnetizing = 105 kvar. A 90 kvar capacitor is proposed (85.7% of no-load mag). Per NEC 460.9, the 90 kvar is below the self-excitation threshold. However, the motor operates on a VFD at speeds from 100% down to 60%. At 60% speed and 22% load (affinity law for centrifugal pump), the motor's no-load magnetizing drops to approximately 65% of full value = 68.3 kvar. Is the 90 kvar capacitor safe at this reduced speed?

A. Yes — the capacitor is always safe regardless of speed or loading

B. Yes — VFD operation actually improves capacitor safety

C. No — but only for speeds below 40%

D. No — at 60% speed with 68.3 kvar no-load magnetizing, the 90 kvar capacitor represents 132% of the motor's magnetizing requirement — well above the self-excitation threshold; if the VFD trips or is disconnected, the capacitor will sustain the motor's residual field and cause dangerous self-excitation voltage buildup; the capacitor must be interlocked with the VFD and disconnected during reduced-speed operation

35. A three-phase, 460V, 6-pole VFD-driven motor operates a centrifugal chilled water pump. Design: 280 kW at 1,170 RPM. Six operating modes: 100% (1,000 hr), 90% (1,500 hr), 80% (2,000 hr), 70% (1,800 hr), 60% (1,500 hr), 40% (960 hr). Using $P \propto n^3$, what is the total annual savings versus full speed at $0.082/kWh?

A. VFD total = 2,500,000 kWh; savings = $10,000

B. VFD total = 1,800,000 kWh; savings = $85,000

C. 100%: 280,000; 90%: 280×0.729×1,500 = 306,180; 80%: 280×0.512×2,000 = 286,720; 70%: 280×0.343×1,800 = 172,872; 60%: 280×0.216×1,500 = 90,720; 40%: 280×0.064×960 = 17,203; VFD = 1,153,695; full = 280×8,760 = 2,452,800; savings = 1,299,105 × $0.082 = $106,527/year — six operating modes with the cubic relationship produce 53% total energy reduction

D. VFD total = 1,153,695 kWh; savings = $106,527

36. A 480V, three-phase, 200A feeder uses 250 kcmil THHN copper in PVC conduit (R = 0.0541, X = 0.0489 Ω/1000 ft). The feeder is 750 feet long and serves a load at 0.85 lagging PF. What is the voltage drop?

A. V_drop = √3 × 200 × (0.0541×0.75×0.85 + 0.0489×0.75×0.527) = 346.4 × (0.03449 + 0.01933) = 346.4 × 0.05382 = 18.64V; 18.64/480 = 3.88% — significantly exceeds the NEC 3% recommendation; the engineer must upsize to at least 500 kcmil to bring the drop below 3% at this extreme 750-foot distance

B. 2.5%

C. 3.0% (exactly at the limit)

D. 1.5%

37. A 100 MVA, 230/69 kV autotransformer has Z = 10% on its own base. Three identical units in parallel. A 50 MVA generator (X"_d = 0.22 pu), a 35 MVA synchronous condenser (X"_d = 0.15 pu), a 25 MVA synchronous motor (X"_d = 0.20 pu), a 20 MVA solar array (effective X"_d = 1.0 pu), and a 10 MVA wind farm (effective X"_d = 1.2 pu) are on the 69 kV bus. On 100 MVA base, what is the total fault current?

A. 12,000A

B. Z_T_par = 0.0333; Z_gen = 0.44; Z_SC = 0.429; Z_SM = 0.80; Z_solar = 5.0; Z_wind = 12.0; I_pu = (30.0+2.273+2.331+1.25+0.20+0.083) × 418.4 = 36.14 × 418.4 = 15,121A — three autotransformers dominate at 83%; the two inverter-based resources (solar + wind) contribute less than 0.8% combined despite 30 MVA aggregate rating; their high effective impedance limits fault contribution to approximately 1.0-1.2× rated current

C. 20,000A

D. 8,000A

38. A three-phase, 480V system has a 4,000 kVA transformer (Z = 5.75%, X/R = 10) and a 3,000 kVA transformer (Z = 6.00%, X/R = 8) in parallel, plus 20 motors (combined FLA = 4,000A) contributing 16,000A first-cycle. I_T1 = 48,111/0.0575 = wait, I_T1 = I_rated_T1/Z = (4,000,000/(√3×480))/0.0575 = 4,811/0.0575 = 83,670A. I_T2 = 3,608/0.06 = 60,133A. Total transformers = 143,803A. Grand total = 159,803A. X/R ≈ 9.2. Multiplier = 2.36. What is the peak asymmetrical?

A. 226,000A

B. 319,606A (2× total)

C. 159,803A (no asymmetry)

D. Peak = 2.36 × 159,803 = 377,135A — the two large parallel transformers plus 20 motors produce over a third of a million amperes peak; bus bracing must withstand forces proportional to $(377\text{ kA})^2 = 1.42 \times 10^{11}\text{ A}^2$; this level approaches the physical design limits of standard 480V bus construction

39. Per NEC 250.53(A)(2), an engineer discovers that a large hospital facility has only two driven rods measuring 45 Ω — compliant with NEC (supplemental rod meets NEC minimum) but far from the IEEE 142 recommendation of ≤5 Ω. The building has a concrete-encased electrode (Ufer ground) in the foundation measuring 2.1 Ω. Additionally, the building's cold water pipe system (meeting NEC 250.52(A)(1) for 10 feet of underground metal water pipe) is available. The water pipe resistance is estimated at 1.5 Ω. All three electrode systems connected in parallel: what is the combined resistance?

A. 45 Ω (the rods dominate because they have the highest resistance)

B. 1/R_total = 1/45 + 1/2.1 + 1/1.5 = 0.0222 + 0.4762 + 0.6667 = 1.1651; R_total = 0.858 Ω — well below 5 Ω

C. R_total = 1/(1/45 + 1/2.1 + 1/1.5) = 0.858 Ω — the water pipe (1.5 Ω) and Ufer (2.1 Ω) dominate the parallel combination; the 45 Ω rod grid contributes negligibly; this demonstrates that existing building infrastructure (water pipe, Ufer) often provides far better grounding than driven rods, especially in high-resistivity soil

D. R_total = (45 + 2.1 + 1.5)/3 = 16.2 Ω (average)

40. A 480V, three-phase system has a 3,000 kVA transformer (Z = 5.75%) feeding a switchboard. A 900-foot cable of 4/0 AWG copper in PVC conduit (R = 0.0608, X = 0.0532 Ω/1000 ft) feeds a remote panelboard. What is the available fault current at the panelboard?

A. Cable: R = 0.05472, X = 0.04788 Ω; Z_base = 0.0768 Ω; Z_cable_pu = 0.0727/0.0768 = 0.946; total Z = 0.0575 + 0.946 = 1.004; I = 3,608/1.004 = 3,594A

B. Cable impedance ≈ 0.946 pu; total Z ≈ 1.004; I ≈ 3,594A — the extremely long 900-foot 4/0 cable reduces fault current to less than 10% of the switchboard value; the engineer must verify that downstream breakers can still clear faults at this very low current level, and that the protective device time-current curves provide adequate coordination at 3,594A

C. 20,000A (cable has minimal effect)

D. 36,130A (switchboard value unchanged)

41. A 60 MVA, 138/13.8 kV, delta-wye grounded transformer has Z_1 = j0.085 pu, Z_0 = j0.050 pu on its own base. The 138 kV source has Z_1_src = j0.045 pu on the transformer base. On a 100 MVA base: Z_1_total = (0.085+0.045)×100/60 = 0.2167 pu. Z_0_total = 0.050×100/60 = 0.0833 pu. I_3Φ = 4.615 pu. I_SLG = 3/(0.2167+0.2167+0.0833) = 3/0.5167 = 5.806 pu. The SLG exceeds 3Φ by 25.8%. The engineer considers adding 10 MVA of solar PV inverters to the 13.8 kV bus. How does the solar PV affect the I_SLG/I_3Φ ratio?

A. Solar inverters with very high effective impedance (approximately 1.0 pu on their own base = 10 pu on 100 MVA base) contribute negligible current to both SLG and 3Φ faults; their presence does not meaningfully change the I_SLG/I_3Φ ratio because the transformer and source dominate the fault calculation — the 25.8% SLG exceedance remains essentially unchanged with or without the solar addition

B. Solar PV increases the SLG to 50% above 3Φ

C. Solar PV eliminates the SLG > 3Φ problem

D. Solar PV reduces both SLG and 3Φ by 10%

42. A three-phase, 460V, 6-pole induction motor rated 500 HP has PF = 0.88, η = 95.8%. No-load magnetizing = 72 kvar. A 55 kvar capacitor is installed (76.4% of no-load mag — safe at full load). The motor is connected to a VFD and operates at variable speed. At full speed and full load, the corrected PF ≈ 0.95. At 65% speed and approximately 27% load (cubic law for centrifugal fan), the motor's no-load magnetizing drops to approximately 60% of full value = 43.2 kvar. Is the 55 kvar capacitor safe at this operating point?

A. Yes — the capacitor provides better PF correction at reduced speed

B. No — at full speed, 55 < 72 kvar is safe; but at 65% speed, 55 > 43.2 kvar — the capacitor exceeds the motor's reduced magnetizing requirement by 127%

C. No — 55 kvar exceeds the 43.2 kvar no-load magnetizing at reduced speed by 27%; this creates a self-excitation risk if the VFD trips while the capacitor remains connected; the capacitor must be switched off during reduced-speed operation or interlocked with the VFD output contactor to disconnect when the VFD de-energizes

D. Yes — VFD operation eliminates self-excitation risk because the VFD controls voltage

43. A CT with a ratio of 4000:5 and accuracy class C800 serves a line current differential relay on a 345 kV transmission line. During a 72,000A close-in fault with X/R = 32, the extreme DC offset produces an asymmetrical peak of approximately 2.8 × I_sym_peak = 2.8 × 101,823 = 285,104A in the primary. The CT must faithfully reproduce this waveform. At 18× rated (72,000/4,000 = 18), the symmetrical burden voltage is within the C800 rating. However, the DC component drives total flux to approximately 2.5× the symmetrical peak flux. What happens to the CT?

A. The CT handles the combined flux without difficulty because C800 provides ample margin

B. The CT core saturates deeply during the first 5-8 cycles as the combined AC and DC flux exceeds the core's saturation level by approximately 2.5×; the secondary current is severely distorted — reduced in magnitude and shifted in phase; the line differential relay may: (1) fail to detect internal faults during CT saturation, or (2) false trip on external faults if the remote CT performs correctly while the near CT is saturated; modern 87L relays use CT saturation detection algorithms and replica-current compensation to maintain security

C. DC offset has no effect on CT performance at the C800 rating level

D. The relay automatically compensates by increasing its internal gain during DC offset

44. A balanced three-phase, 208Y/120V panelboard in a hospital serves a combination: 40% imaging equipment (highly nonlinear, producing 3rd and 5th harmonics), 35% linear motor loads, 25% lighting (LED with 3rd harmonic). Phase current: 300A fundamental. Third harmonic: 0.40×300×0.35 + 0.25×300×0.30 = 42 + 22.5 = 64.5A. Fifth harmonic: 0.40×300×0.18 = 21.6A. Phase RMS = $\sqrt{(300^2+64.5^2+21.6^2)} = \sqrt{(90,000+4,160+467)} = \sqrt{94,627} = 307.6$A. Neutral = 3×64.5 = 193.5A. Does the neutral exceed the phase?

A. Yes — neutral is 63% of phase, which is significant but does not exceed phase

B. No — the neutral is larger in some scenarios but not this one

C. Yes — the neutral always exceeds the phase in hospital installations

D. No — the neutral of 193.5A is 63% of the phase RMS of 307.6A; the neutral does NOT exceed the phase in this mixed-load scenario because the nonlinear loads constitute only 65% of the total; however, the neutral carries significant current (193.5A) that is often overlooked in design — it must be counted as current-carrying per NEC 310.15(C)(1) and sized accordingly

45. Per NEC 517.17(A), a hospital's LIM alarms at 5 mA. During a complex surgery, 18 devices are connected to a single isolated power panel. Individual device leakage ranges from 0.1 to 0.5 mA. The total hazard current = 4.8 mA (within the 5 mA threshold but only 0.2 mA of margin). The surgeon requests one additional device with 0.15 mA leakage. Connecting it would bring the total to 4.95 mA — technically below the 5 mA alarm. Should the biomedical engineer approve this connection?

A. Technically compliant at 4.95 mA < 5.0 mA, but the engineer should NOT approve the connection because: the 0.05 mA margin (1%) is inadequate to account for (1) leakage current drift during the procedure as devices warm up, (2) measurement accuracy of the LIM (typically ±5%), (3) the possibility of any device developing slightly higher leakage during operation — a LIM alarm during active surgery is disruptive and dangerous; the device should be powered from a different panel or the highest-leakage device should be replaced first

B. Yes — 4.95 mA is below 5 mA, so connect the device immediately

C. Yes — the LIM has built-in tolerance above 5 mA

D. No — 18 devices exceeds the maximum count per panel

46. A 345 kV, three-phase line has V_S = 368 kV, V_R = 340 kV at 1,000 MW, 0.89 lagging PF. Line X = 52 Ω (with 35% series compensation already applied, X_original = 80 Ω). What are the power angle, voltage regulation, and stability fraction WITH the series compensation?

A. $\delta = 15°$; VR = 8.2%; at 26% of limit

B. $\delta = 30°$; VR = 8.2%; at 50% of limit

C. $\sin \delta = 1{,}000\times52/(368\times340) = 52{,}000/125{,}120 = 0.4156$; $\delta = 24.6°$; VR = $(368-340)/340 = 8.24\%$; stability fraction = 41.6%; WITHOUT series comp: $\sin \delta = 1{,}000\times80/125{,}120 = 0.6394$; $\delta = 39.7°$; stability = 63.9% → compare: series compensation reduced the stability fraction from 63.9% to 41.6%, INCREASING the available margin from 36.1% to 58.4%; this dramatically improved operating point provides far better resilience to contingencies

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

47. A recloser on a 12.47 kV feeder coordinates with a 200A lateral fuse. At 7,000A: fuse MM = 0.018s, fuse TC = 0.035s, recloser fast = 0.013s, recloser delayed = 0.08s. A temporary overhead fault occurs on the lateral. After the fast trip (0.013s < 0.018s MM → fuse saved), the recloser recloses and the fault has cleared. Three minutes later, a DIFFERENT temporary fault occurs on the same lateral. The recloser fast-trips again, recloses, and the fault clears. What is the cumulative effect on the fuse?

A. The fuse is progressively weakened by each fast-trip operation even though it didn't melt

B. The fuse is unaffected by the fast-trip operations because it did not reach minimum melting time during either event — the pre-damage curve shows that at 0.013 seconds (72% of the 0.018s MM time), the fuse element heats but does not sustain permanent damage; the 3-minute interval between events provides complete thermal recovery; however, repeated operations within a short time window without adequate cooling could cause cumulative damage

C. The fuse has melted during the first event but wasn't replaced

D. The fuse is permanently damaged after any fast-trip exposure

48. A 480V, three-phase, 800A switchboard with 800A bus. Load: 500A continuous motor + 120A continuous lighting + 80A noncontinuous = 700A. OCPD = 125%×620 + 80 = 855A → exceeds 800A bus. With 100%-rated 800A breaker: 700A ≤ 800A. Conductor at 75°C must handle 700A. Two parallel 350 kcmil = 2×310 = 620A (insufficient). Two parallel 500 kcmil = 2×380 = 760A. Is 760A adequate?

A. Two parallel 500 kcmil at 75°C = 760A ≥ 700A with 8.6% margin; this is code-compliant with the 100%-rated system; each set must be identical per NEC 310.10(G); while 8.6% margin is adequate, two parallel 600 kcmil (2×420 = 840A) would provide 20% margin for better thermal performance

B. No — 760A provides insufficient margin; three parallel sets are required

C. No — parallel conductors cannot be used with 100%-rated breakers

D. Yes — but 600 kcmil per phase (single conductor) provides better performance

49. A three-phase, 480V system has a 4,000 kVA transformer (Z = 5.75%, X/R = 10) and 16 motors (FLA = 3,200A). Transformer fault = 48,111A. Motor = 12,800A. Total = 60,911A. X/R = 10. Multiplier = 2.38. What is the peak asymmetrical?

A. Peak = 2.38 × 60,911 = 144,968A — this peak establishes the momentary withstand and close-and-latch rating for all equipment; the 12,800A motor contribution (21%) cannot be ignored in the peak calculation

B. 86,100A (√2 × total)

C. 121,822A (2× total)

D. 60,911A (no asymmetry)

50. 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 800 feet long and serves a load at 0.87 lagging PF. What is the voltage drop?

A. 2.5%

B. 3.0% (exactly at the NEC limit)

C. V_drop = √3 × 200 × (0.0367×0.8×0.87 + 0.0407×0.8×0.493) = 346.4 × (0.02554 + 0.01605) = 346.4 × 0.04159 = 14.41V; 14.41/480 = 3.00%; this is exactly at the NEC 3% recommendation — the engineer should consider upsizing to 500 kcmil for any margin, especially if load growth is anticipated

D. 4.0%

51. Per NEC 110.14(C)(1), a 1,600A switchboard has terminals marked "75°C/90°C." The continuous load = 1,280A. Required ampacity = 1,600A. At 75°C: four parallel 500 kcmil = 4×380 = 1,520A (inadequate). At 90°C: three parallel 750 kcmil = 3×535 = 1,605A (adequate). Four parallel 500 kcmil at 90°C = 4×430 = 1,720A (adequate). Which is the better engineering choice?

A. Three parallel 750 kcmil at 90°C provides only 0.3% margin above 1,600A — technically compliant but unacceptable for a 1,600A installation

B. Four parallel 500 kcmil at 90°C = 1,720A provides 7.5% margin; this is the better engineering choice because: (1) adequate margin for thermal variability, (2) uses standard conductor sizes readily available, (3) four identical sets comply with NEC 310.10(G); the 75°C column (1,520A) cannot meet the requirement regardless of conductor size increase, demonstrating the critical importance of 90°C-rated terminals for large switchboards

C. Three parallel 750 kcmil at 90°C — the smaller number of parallel sets is always preferred

D. Five parallel 350 kcmil at 75°C = 5×310 = 1,550A (inadequate)

52. A 250 MVA synchronous generator has H = 4.0 MJ/MVA, delivers 200 MW when a three-phase fault occurs. Critical clearing angle = 118°. Relay = 0.010s (optical), breaker = 0.025s (fast SF_6), total = 0.035s. What is the rotor angle advance?

A. Δδ = 30° — stable but marginal

B. Δδ = 118° — at critical clearing

C. Δδ = 60° — limited margin

D. Δδ = $(180\times60\times200\times0.035^2)/(4.0\times250)$ = (180×60×200×0.001225)/1,000 = 2,646/1,000 = 2.65° — stability maintained with 115.35° margin; the ultrafast 0.035-second clearing (optical relay + fast SF_6 breaker) produces negligible rotor advance even at 80% loading; this represents the state of the art in fast fault clearing for generator protection

53. A three-phase, 13.8 kV capacitor bank rated 14,400 kvar has six series groups of eight parallel units per phase (48 per phase, 144 total). Four units in one series group fail and their fuses blow. Each remaining unit sees 8/4 = 2.0× normal voltage (100% overvoltage). What is the expected timeline for cascading failure?

A. At 200% voltage, the dielectric stress is 4× rated (V^2); the remaining four units will fail within seconds to a few cycles — far faster than any manual intervention; the cascade is nearly instantaneous because each unit failure further increases voltage on survivors: after the next unit fails (3 remaining), each sees 8/3 = 2.67× (7.1× stress); the cascade accelerates exponentially to catastrophic bank failure; only automatic high-speed protection (sub-cycle unbalance relay) can prevent this scenario

B. Cascade takes approximately 30 minutes — adequate for manual intervention

C. The remaining units will survive indefinitely at 200% voltage

D. Cascade takes approximately 5 seconds — adequate for relay operation

54. A three-phase, 460V, 8-pole wound-rotor motor rated 1,800 HP drives a cement kiln at 873 RPM. Required breakaway = 340% FLT. Wound-rotor achieves 350% at 370% FLA. Design B: 150% at 600% FLA. Design D: 275% at 650% FLA. The kiln also has periodic 250% FLT overloads lasting 5 seconds during clinker buildup. Which motor type best serves this application?

A. Design D — provides 275% starting torque, adequate for the periodic overloads

B. Design B with a soft starter to boost starting torque above 340%

C. Only the wound-rotor meets the 340% breakaway requirement (350% > 340%); the wound-rotor also handles 250% periodic overloads because external resistance can be re-engaged to reduce current while maintaining torque; T/I = 350/370 = 0.946 vs Design D T/I = 275/650 = 0.423 (2.24× better); the wound-rotor's adjustable slip provides thermal absorption for intermittent severe-duty overloads that would trip overload relays on squirrel-cage motors

D. All three motor types meet the 340% requirement

55. Per NEC 310.15(C)(1), a cable tray contains: ten three-phase circuits (30 phase conductors) serving VFD loads, seven neutral conductors carrying triplen harmonics, three neutral conductors NOT carrying harmonics, and ten EGCs. How many current-carrying conductors and what adjustment factor?

A. 30 (phase only); factor = 0.30

B. 37 (30+7); factor = 0.30

C. 40 (30+7+3); factor = 0.25

D. 37 (30 phase + 7 harmonic-carrying 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 tray impractical — at least seven separate raceways with 5-6 conductors each are needed to restore the 0.80 factor

56. A 480V, three-phase LVPCB main has 0.30s STD. ZSI, optical relay, and a bus-mounted arc quenching device (AQD) are installed. During a bus fault, the AQD detects arc light in 1.5 ms and creates a controlled bolted fault in approximately 2.5 ms after detection (4 ms total). The optical relay detects the arc in 1.5 ms and sends a trip signal. The breaker begins opening approximately 20 ms after the optical trip signal. What is the total arc duration?

A. 0.30 seconds (the STD controls all clearing)

B. The arc exists for only approximately 4 ms — the AQD quenches the arc by creating a bolted fault at 4 ms, collapsing the arc voltage to near zero; the breaker then clears the bolted fault in approximately 22 ms total (1.5 ms optical detection + 0.5 ms signal + 20 ms mechanism); the worker is exposed to arc flash energy for only the 4 ms before the AQD activates — approximately 1/75th of the 0.30s STD

C. 22 ms (the breaker clearing time)

D. 1.5 ms (the detection time only)

57. A protection engineer must set a 51 overcurrent relay (IEEE extremely inverse) on a 13.8 kV main bus tie. CT = 1200:5 (ratio 240:1). Maximum load through the tie = 900A. Minimum tie-bus fault = 3,000A. The engineer sets pickup at 5A (1,200A primary — above maximum load of 900A). TD = 2.0. At the minimum fault of 3,000A: secondary = 12.5A; M = 2.5. Using $t = TD \times (28.2/(M^2-1) + 0.1217)$, what is the operating time, and is this acceptable for a bus-tie application?

A. t = 2.0 × (28.2/5.25 + 0.1217) = 2.0 × 5.493 = 10.99s — unacceptably slow for a bus tie relay

B. t = 5.5s — marginally acceptable

C. t = 10.99 seconds — grossly unacceptable for bus-tie protection; bus ties must clear quickly to prevent fault propagation between bus sections; at M = 2.5, the extremely inverse characteristic is essentially non-functional; the engineer should: (1) reduce pickup to increase M (but pickup must stay above max load), (2) use instantaneous elements (50) in addition to the time-overcurrent, or (3) use differential protection (87B) for bus-tie applications instead of time-overcurrent alone

D. t = 0.5s — fast and acceptable

58. A 345 kV, 480-mile line has $Z_1 = 38.4 + j360\ \Omega$ total, $Z_0 = 115.2 + j1{,}080\ \Omega$ total. Source: Z_1_src = j24 Ω, Z_0_src = j36 Ω. For a bolted SLG at the remote end: Z_1_total = 38.4+j384; Z_0_total = 115.2+j1,116. What is I_SLG?

A. $|Z_1$_total$| = \sqrt{(38.4^2+384^2)} = 385.9$; $|Z_0$_total$| = \sqrt{(115.2^2+1{,}116^2)} = 1{,}121.9$; Sum = 192+j1,884; |Sum| = 1,893.8; I_SLG = 3×199,186/1,893.8 = 315.6A ≈ 316A — this extremely low SLG current on a 480-mile line makes conventional distance protection virtually unreliable; line differential (87L) with fiber-optic communication is the only dependable primary protection

B. 800A

C. 500A

D. 100A

59. Per NEC 700.10(B)(1), emergency wiring must be independent from normal wiring. A manufacturing facility routes emergency conduit through the same cable tray as normal conduit. Each wiring system uses its own metal conduit. The cable tray serves only as a physical support structure. Is this installation compliant?

A. No — cable trays cannot support both emergency and normal conduit

B. Yes — but only if the cable tray is fire-rated

C. No — NEC 700.10(B)(1) requires complete separation, including physical supports

D. Yes — separate metallic conduits on a shared cable tray provide adequate independence because each wiring system is in its own dedicated raceway; the cable tray is merely a support structure, not part of either wiring system; NEC 700.10(B)(1) requires independence of the wiring systems themselves (conductors and raceways), not the physical support infrastructure

60. A three-phase, 480V, 225A panelboard has: Motor 1 = 180A (150 HP, largest), Motor 2 = 96A (75 HP). Continuous lighting = 100A. Noncontinuous = 40A. Bus = 225A. OCPD = 125%×180 + 96 + 125%×100 + 40 = 225 + 96 + 125 + 40 = 486A → 500A next standard → far exceeds 225A bus. With 100%-rated 225A breaker: load = 416A > 225A. Can this panelboard serve this load?

A. No — the 225A panelboard is inadequate

B. No — total load of 416A exceeds the 225A bus rating; even with a 100%-rated breaker (which eliminates the 125% adder), the physical bus cannot carry 416A; the panelboard must be upgraded to at least a 500A rating; this is a common design error where the load calculation reveals the initial panelboard selection was significantly undersized

C. Yes — with a 100%-rated breaker

D. Yes — the 125% adder artificially inflates the calculation

61. A balanced three-phase, 4,160V source feeds a 20,000 kW load at 0.65 lagging PF. Q = 20,000 × 1.169 = 23,380 kvar. Utility penalty = $6.00/kvar/month above 0.96 PF. Q_allowed = 20,000 × 0.292 = 5,840 kvar. Excess = 17,540 kvar. Penalty = $105,240/month = $1,262,880/year. What capacitor bank eliminates the penalty, and what is the approximate payback?

A. 17,540 kvar; bank cost at $25/kvar = $438,500; payback = $438,500/$105,240 = 4.2 months — less than one fiscal quarter; this is among the most compelling ROI cases in industrial power engineering

B. 10,000 kvar (partial correction); payback = 12 months

C. 23,380 kvar (corrects to unity); payback = 6 months

D. 5,840 kvar (only reduces to threshold); payback = 8 months

62. A 480V, three-phase MCC has 30 motors (FLA = 6,000A combined). Motor contribution = 24,000A. Two transformers (4,000 kVA each, Z = 5.75%) provide 83,670A each = 167,340A. Total = 191,340A. X/R = 10. Multiplier = 2.38. What is the peak asymmetrical?

A. 270,700A (√2 × total)

B. 382,680A (2× total)

C. 191,340A (no asymmetry)

D. Peak = 2.38 × 191,340 = 455,389A — nearly half a million amperes peak from two 4,000 kVA parallel transformers plus 30 motors; the electromagnetic forces at this peak level approach the physical design limits of standard bus construction and may require segregated-phase bus or metal-enclosed bus duct designs

63. A three-phase, 13.8 kV underground cable is 60 miles long with charging current of 7.0A per mile per phase. A zero-sequence CT with 8A relay pickup and 0.3-second delay is installed. The cable charging = 420A per phase. A high-impedance ground fault of 10A zero-sequence develops. The relay sees only the 10A fault (balanced charging cancels). Since 10A > 8A, the relay trips. However, the margin is only 25%. What sensitivity improvement is available?

A. No improvement is possible without reducing the pickup below the 8A system unbalance

B. The relay could use a percentage-based pickup that accounts for charging current variation

C. Installing a second zero-sequence CT with 5A pickup provides 100% margin; however, the normal system unbalance must be verified to be below 5A — if the cable charging has asymmetry due to different cable lengths per phase, the residual unbalance could be 3-5A, making a 5A pickup prone to false tripping; the engineer must measure the actual system zero-sequence background before reducing pickup

D. Replace the CT with a higher ratio to amplify the fault signal

64. Per NEC 430.24, a feeder serves: Motor A = 683A (600 HP), Motor B = 590A (500 HP), Motor C = 477A (400 HP), Motor D = 414A (350 HP), Motor E = 361A (300 HP), Motor F = 302A (250 HP), Motor G = 242A (200 HP). Continuous lighting = 200A. Noncontinuous HVAC = 120A. What is the minimum feeder conductor ampacity?

A. 3,500A

B. 125%×683 + 590 + 477 + 414 + 361 + 302 + 242 + 125%×200 + 120 = 853.75 + 2,386 + 250 + 120 = 3,609.75A

C. 4,000A

D. 3,000A

65. A distance relay on a 230 kV line (Z_line = 8 + j92 Ω) has Zone 1 at 85%, Zone 2 at 120%. A fault at 86% through 15 Ω resistance. Z_meas = (0.86×8 + 15) + j(0.86×92) = 21.88 + j79.12 Ω. |Z_meas| = 82.1 Ω. Zone 1 reach = 0.85×92.35 = 78.5 Ω. |Z_meas| = 82.1 > 78.5 Ω Zone 1 reach. The fault is OUTSIDE Zone 1. What protection operates?

A. Zone 1 may still reach — the mho circle geometry could include this point at the line angle

B. Zone 2 at 120% (0.35s) covers the fault; Zone 1 clearly cannot because |Z_meas| exceeds reach by 4.6%

C. Zone 3 at 1.0 second

D. Zone 2 detects the fault; with a pilot scheme active, both terminals can achieve high-speed clearing; without a pilot, Zone 2 operates after 0.35 seconds; the 15 Ω fault resistance combined with the 86%

location pushes the impedance clearly beyond Zone 1's reach — this scenario demonstrates why pilot schemes are essential for high-speed clearing of resistive faults in the last 15-20% of a protected line

66. A three-phase, 4,160V system has an NGR rated 400A, 10 seconds. The engineer must determine the maximum number of consecutive bolted ground faults ($R_f = 0\ \Omega$) the NGR can handle with 1.0-second clearing each, separated by 5-minute cooling intervals, before reaching 50% thermal capacity. Each event: $(400/400)^2 \times (1.0/10) = 10\%$. Without cooling adjustment, how many events to reach 50%?

A. 3 events (30%)

B. 5 events × 10% = 50% thermal capacity; however, the 5-minute cooling intervals between events allow partial thermal recovery (NGR time constant typically 5-15 minutes); with approximately 20-30% cooling per 5-minute interval, the actual number of events before reaching 50% is higher — approximately 6-8 events depending on the NGR's specific thermal time constant

C. 10 events (100% capacity reached at 10 events)

D. 2 events (20%)

67. Per NEC 480.9(A), a grid-scale BESS uses lithium-ion NMC cells in a utility-scale containerized installation. The container is sealed during normal operation. During a thermal runaway event, cells produce: hydrogen fluoride (HF), carbon monoxide (CO), hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), and other toxic/flammable gases. The off-gas mixture is both toxic AND potentially explosive. What is the comprehensive safety system design?

A. Standard HVAC ventilation is sufficient for all scenarios

B. Only fire suppression is required

C. The safety system must address both toxicity and explosibility: (1) early-warning gas detection (HF, CO, combustible gas sensors) inside the container, (2) emergency exhaust ventilation sized to prevent gas accumulation above 25% LEL, (3) deflagration venting panels on the container to safely relieve pressure if ignition occurs, (4) fire suppression (water mist or clean agent) to cool affected cells and slow thermal propagation, (5) exhaust ductwork directing toxic gases away from personnel and air intakes, (6) automatic HVAC shutdown of adjacent buildings upon alarm activation — this is the state of the art for utility-scale NMC BESS safety

D. The container is sealed and self-contained; no external safety systems needed

68. A three-phase, 480V, 400A panelboard has available fault current of 35,000A. IEEE 1584 shows 14 cal/cm^2 at 24 inches with 0.20-second clearing. An optical relay (0.010s), ZSI backup (0.05s), maintenance switch (0.04s), and arc-resistant enclosure are installed. With the optical relay: $E = 14 \times (0.010/0.20) = 0.70$ cal/cm^2. What is the significance of this sub-1.0 cal/cm^2 result?

A. At 0.70 cal/cm^2, the incident energy is below both the 1.2 cal/cm^2 arc flash boundary AND below the onset threshold for first-degree burn (approximately 1.0 cal/cm^2); combined with the arc-resistant enclosure redirecting energy, the worker has essentially zero exposure; this enables maintenance in normal work clothing without specific arc-rated PPE, dramatically improving worker comfort and productivity — though many facilities still require PPE as a conservative measure

B. 0.70 cal/cm^2 still requires Category 2 PPE

C. Sub-1.0 cal/cm^2 has no practical significance

D. 0.70 cal/cm^2 means the arc flash boundary distance is zero

69. A three-phase, 460V, 6-pole synchronous motor rated 4,000 HP drives a paper machine at 1,200 RPM. Pull-out = 250% FLT. H = 2.0 MJ/MVA. During a system fault clearing, voltage sags to 70% for 1.0 second. Pull-out = 175% FLT. Load = 90% FLT. Margin = 85% FLT. Using the swing equation concept with H = 2.0 and the 1.0-second sag at 70%, what is the stability assessment?

A. Stable with excellent margin — the high margin and moderate H ensure stability

B. Stable — but only if the load is reduced during the sag

C. The motor trips on undervoltage within 0.5 seconds regardless of stability

D. Despite the 85% FLT steady-state margin, the swing equation with H = 2.0 and t = 1.0 second at 70% voltage produces very large rotor angle advance ($\Delta\delta \propto t^2$); using the simplified formula with estimated P_accel: the 1.0-second duration is long enough that the accumulated angular momentum may push the rotor past the critical clearing angle; at H = 2.0, the motor has moderate inertia — insufficient for a 1.0-second deep sag; a detailed transient stability simulation is mandatory because the steady-state margin alone is misleading

70. A 230 kV, 400-mile line has Z_1_total = 32+j300 Ω, Z_0_total = 96+j900 Ω. $|Z_1|$ = 301.7 Ω. $|Z_0|$ = 905.1 Ω. |Sum| = |160+j1,500| = 1,508.5 Ω. I_SLG = 398,400/1,508.5 = 264A. This extremely low SLG fault current creates multiple protection challenges. A 87L line differential relay is proposed as primary

protection. What is the maximum communication channel latency acceptable for 87L on a 400-mile line?

A. 100 ms — any latency is acceptable for 87L

B. 10 ms — modern 87L relays can tolerate short communication delays

C. The maximum latency depends on the relay's sampling rate and stability algorithm; for a 400-mile line, the propagation delay of light through fiber is approximately 2 ms (400 miles × 5 μs/km × 1.6 km/mile); the relay must compensate for this propagation delay plus any channel jitter; modern 87L relays typically require total one-way channel latency ≤ 10 ms for reliable operation; the relay uses GPS time-stamping of current samples to align measurements from both terminals despite the propagation delay

D. 1 ms — any channel delay above this causes relay failure

71. Per NEC 250.122(B), a 1,200A circuit has two parallel 750 kcmil per phase (1,500,000 CM total), increased to two parallel 1,000 kcmil (2,000,000 CM) for voltage drop. The EGC from Table 250.122 for 1,200A = 3/0 AWG (167,800 CM). What is the proportionally increased EGC?

A. Ratio = 2,000,000/1,500,000 = 1.333; EGC = 167,800 × 1.333 = 223,767 CM → 4/0 AWG (211,600 CM) is below; 250 kcmil (250,000 CM) is the minimum standard size above 223,767 CM

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

C. 3/0 AWG (no increase needed)

D. 350 kcmil (350,000 CM)

72. A balanced three-phase, 4,160V source feeds a 25,000 kW load at 0.67 lagging PF. The engineer installs an 18,000 kvar capacitor bank, a 6,000 HP synchronous motor at 0.80 leading PF ($\eta = 94\%$), AND a 2,500 HP synchronous motor at 0.85 leading ($\eta = 95\%$). What is the new PF?

A. PF = 0.90

B. PF = 0.95

C. PF = 0.99 (near unity)

D. Original Q = 27,500 kvar; cap = −18,000; SM1: P = 4,762 kW, Q_1 = 3,571; SM2: P = 1,964 kW, Q_2 = 1,219; net Q = 27,500 − 18,000 − 3,571 − 1,219 = 4,710; P_total = 31,726 kW; PF = 31,726/32,074 = 0.989 ≈ 0.99

73. A 100 MVA, 230/69 kV autotransformer has Z = 10.5% on its own base. Two identical units in parallel. A 60 MVA generator (X"_d = 0.20), 50 MVA synchronous condenser (X"_d = 0.15), 30 MVA synchronous motor (X"_d = 0.22), 25 MVA solar (effective Z = 1.0), 15 MVA wind (effective Z = 1.2), and 10 MVA BESS (effective Z = 1.5) are on the 69 kV bus. On 100 MVA base, what is the total fault current?

A. 12,000A

B. Z_T_par = 0.0525; Z_gen = 0.333; Z_SC = 0.30; Z_SM = 0.733; Z_solar = 4.0; Z_wind = 8.0; Z_BESS = 15.0; I_pu = (19.05+3.003+3.333+1.364+0.25+0.125+0.0667) × 418.4 = 27.19 × 418.4 = 11,377A — two autotransformers dominate at 70%; three rotating machines contribute 28%; three inverter-based resources (solar+wind+BESS) contribute only 1.6% combined despite 50 MVA aggregate rating

C. 15,000A

D. 8,000A

74. A three-phase, 460V, 4-pole induction motor rated 350 HP operates at 1,770 RPM. A VFD reduces speed to 700 RPM for a centrifugal pump application. P_pump = 261 × $(700/1,770)^3$ = 261 × 0.0618 = 16.1 kW. VFD η = 95%, motor η at very light load = 78%. What is the total supply power, and what percentage of rated power does the motor consume?

A. P_supply = 16.1/(0.78 × 0.95) = 21.7 kW; this is only 8.3% of the 261 kW rated — the motor operates at extreme light load with significantly reduced efficiency (78% vs 96% at full load); at this operating point, the motor's iron and friction losses represent a larger percentage of total input power

B. P_supply = 16.1 kW (losses negligible)

C. P_supply = 50 kW

D. P_supply = 100 kW

75. Per NEC 430.32(A)(1), a motor with SF = 1.15 has maximum overload at 125% of FLA. A motor has FLA = 600A, SF = 1.15. Overload set at 750A (125%). The motor drives a large centrifugal compressor that requires 45 seconds to reach full speed during starting (high-inertia load). During acceleration, the motor draws 2× FLA (1,200A) for the first 20 seconds, then drops to 1.5× (900A) for 15 seconds, then settles to rated 600A. Does the overload relay trip during this extended start?

A. Yes — the overload trips within 15 seconds because 1,200A far exceeds the 750A setting

B. The overload relay's thermal model integrates I^2t throughout the starting sequence; the total thermal accumulation must be calculated: $(1{,}200^2\times20 + 900^2\times15)/(750^2)$ equivalent = (28,800,000 + 12,150,000)/562,500 = 72.8 equivalent seconds at the trip setting — this suggests the relay WILL trip during starting; the motor requires a separate overload with a longer thermal time constant or a motor-starting relay that temporarily raises the trip threshold during acceleration

C. The overload trips at exactly 750A, regardless of duration

D. No — overload relays never trip during starting

76. A 480V, three-phase system has a 3,500 kVA transformer (Z = 5.50%, X/R = 9) and a 3,000 kVA transformer (Z = 5.75%, X/R = 8) in parallel. I_{T1} = 3,608/0.055 = 65,600A; I_{T2} = 3,608/0.0575 = 62,748A. Total = 128,348A. Motor contribution (FLA = 3,500A) = 14,000A. Grand total = 142,348A. Weighted X/R ≈ 8.5. Multiplier = 2.34. Peak = ?

A. 201,300A ($\sqrt{2}$ × total)

B. 284,696A (2× total)

C. 142,348A (no asymmetry)

D. Peak = 2.34 × 142,348 = 333,094A — this exceeds a third of a million amperes peak; the electromagnetic forces on the paralleled 480V bus at this peak level require extraordinary mechanical bracing that may exceed the capability of standard bus construction methods

77. A three-phase, 4,160V, 10-pole synchronous motor rated 6,000 HP drives a ball mill at 720 RPM. Pull-out = 270% FLT. H = 1.8 MJ/MVA. During a catastrophic grid event, voltage drops to 58% for 2.5 seconds. Pull-out = 156.6% FLT. Load = 100% FLT. Margin = 56.6% FLT. What happens?

A. Stable — 56.6% margin is adequate for any event

B. Absolute instability — at H = 1.8 (very low) with 2.5 seconds at 58% voltage: $\Delta\delta \propto t^2 \rightarrow 2.5^2 = 6.25$ seconds^2 — producing rotor angle advance hundreds of times what a 0.1-second sag would cause; the motor will lose synchronism within 0.3-0.5 seconds of the sag onset despite the 56.6% steady-state margin; the UV relay should trip the motor within 0.3 seconds to prevent mechanical damage during pull-out; this is the most severe combination of parameters in the exam series

C. Marginally stable — depends on the ball mill inertia

D. The motor maintains synchronism through the entire 2.5-second event

78. Per NEC 110.24(A), a facility originally had a single 3,000 kVA transformer (Z = 5.75%) producing 36,130A. The facility adds a second 3,000 kVA transformer (Z = 5.75%) in parallel AND replaces the utility service cable, reducing source impedance from 5% to 2% on the transformer base. Original: Z_eff = 5.75% + 5% = 10.75%; I = 3,608/0.1075 = 33,563A. New: Z_eff per transformer = 5.75% + 2% = 7.75%; Z_parallel = 7.75%/2 = 3.875%; I = 3,608/0.03875 = 93,109A. What is the percentage increase?

A. New I = 93,109A; increase = (93,109 − 33,563)/33,563 = 177% — nearly tripling the fault current; this dramatic increase results from two compounding effects: parallel transformers (halving impedance) AND reduced source impedance (from 5% to 2%); all downstream equipment, SCCR ratings, series combinations, and arc flash studies must be comprehensively re-evaluated

B. 62,748A (simply doubled from original single-transformer value)

C. 50,000A

D. 75,000A

79. A 2,000 kVA, 480V/208Y/120V transformer has Z = 5.0% and X/R = 5. The symmetrical RMS fault current at 208V = 23,100A. Using the IEEE multiplier of 2.17 for X/R = 5, what is the peak asymmetrical?

A. 32,700A ($\sqrt{2}$ × symmetrical)

B. 46,200A (2× symmetrical)

C. 23,100A (no asymmetry)

D. Peak = 2.17 × 23,100 = 50,127A — this peak determines the momentary withstand for all 208V equipment; at 50 kA peak on a 208V system, many standard panelboards and switchboards may not have adequate momentary ratings, potentially requiring upgrades or current-limiting fuses

80. A 600 kW, three-phase, 480V resistance heater operates continuously 24/7/365. Electricity costs \$0.055/kWh. Per NEC 210.20(A), minimum OCPD = 125% of continuous. What is the load current, minimum OCPD, annual energy, and cost?

A. I = 601.4A; OCPD = 800A; E = 5,256,000 kWh; cost = \$289,080

B. I = 500A; OCPD = 700A; E = 5,256,000 kWh; cost = \$289,080

C. I = 600,000/(√3×480) = 721.7A; OCPD = 125% × 721.7 = 902.1A → next standard per NEC 240.6(A) = 1,000A; E = 600 × 24 × 365 = 5,256,000 kWh; cost = 5,256,000 × \$0.055 = \$289,080/year — this nearly \$300,000 annual energy cost for a single heater makes it one of the most expensive single loads in any industrial facility; waste heat recovery and insulation improvements should be primary engineering priorities

D. I = 721.7A; OCPD = 800A; E = 4,000,000 kWh; cost = \$220,000

Practice Exam 22: Answer Key and Explanations

1. C — The original h_r = 8.26 was safely above all major characteristic harmonics. Adding the second bank shifts h_r to 6.64, which falls directly between the 5th and 7th harmonics from the six-pulse VFDs. Both characteristic currents experience significant amplification near this resonant frequency. Detuning reactors must be installed before the second bank is energized.

2. A — Cable Z reduces the transformer's 36,130A to approximately 29,800A at the MCC. Adding 3,968A motor contribution = 33,768A total first-cycle. The 17% reduction from the switchboard value changes the IEEE 1584 calculation significantly — the MCC should receive its own arc flash study and label rather than inheriting the switchboard's higher PPE category.

3. D — 3,400A is below the NEC 430.52(C)(1) maximum of 3,500A. Adjusting the MCP upward to accommodate the asymmetrical starting inrush peak is standard practice. The first-cycle asymmetrical peak can exceed the symmetrical LRC by 50-80%, and the MCP must be set above this peak to avoid nuisance tripping during starting.

4. B — At 12× rated with 210V burden, the CT operates well within its C400 capability. The C400 guarantees accuracy at 20× up to 400V — at only 12×, the core requires significantly less excitation, providing approximately 90V of effective margin. The CT maintains excellent accuracy with ample headroom before saturation.

5. C — The 1.3 Hz separation between the 19.8 Hz complementary frequency and the 18.5 Hz first torsional mode is dangerously close. IEEE SSR guidelines typically require 2-3 Hz minimum separation. Mitigation options include reducing compensation, adding a subsynchronous damping controller, or using a TCSC that modulates to avoid torsional excitation.

6. A — Ratio = 750,000/500,000 = 1.50. EGC = 41,740 × 1.50 = 62,610 CM. From wire tables: 3 AWG = 52,620 CM (below — insufficient). 2 AWG = 66,360 CM (above — adequate). The minimum EGC is 2 AWG per NEC 250.122(B).

7. D — SM1: Q_1 = 2,381 kvar. SM2: Q_2 = 731 kvar. Total correction = 11,000 + 2,381 + 731 = 14,112 kvar. Net Q = 14,028 − 14,112 = −84 kvar (slightly leading). PF ≈ unity. The three sources slightly overcorrect — the engineer should reduce the capacitor bank to maintain 0.98-0.99 lagging and avoid voltage regulation issues from leading PF.

8. B — Phase base = 528.2/0.80 = 660.3A. Neutral base = 576/0.80 = 720A. The neutral governs at 720A because triplen-harmonic neutral current (576A) divided by the 0.80 factor produces 720A — exceeding the phase requirement. This is a critical scenario where the neutral conductor must be larger than the phase conductors.

9. C — Solidly grounded: I_SLG = 6.82 pu exceeds I_3Φ = 5.56 pu by 22.7% because X_0 (0.06) is much less than X"_d (0.18). HRG: I_SLG = 0.05 pu — only 0.9% of three-phase. The HRG completely eliminates the SLG > 3Φ problem and reduces ground-fault current below any level that drives equipment ratings or arc flash hazard.

10. D — Each event: $(104.4/300)^2$ × (0.8/10) = 0.97%. Four events = 3.88%. The 15-second intervals allow partial cooling. However, the repetitive fault pattern indicates a persistent root cause (likely damaged insulation or contamination) that will continue stressing the NGR unless the fault location is identified and repaired.

11. A — NEC 110.26(A)(1)(a) specifies 3 feet minimum working space depth for 0-150V to ground equipment under Condition 1 (exposed live parts on one side, no grounded parts opposite). This is the minimum clearance for safe access to electrical equipment at these lower voltage levels.

12. B — k_max = 56.1%. The 65% load period operates only 8.9 points above k_max — closest of the three. During this 10-hour period, core losses approximately equal copper losses, producing near-peak instantaneous efficiency. This favorable loading for the longest period has the greatest positive impact on all-day efficiency.

13. D — R1 at M = 60: $t_1 = 0.130$s (extremely inverse at very high multiple — ultra-fast). R2 at M = 16.67: $t_2 = 2.247$s (very inverse at moderate multiple). CTI = 2.12s — adequate but excessive. Reducing R2's TD to approximately 2.0 yields CTI ≈ 1.0s, still above 0.20s minimum while cutting backup clearing time in half and reducing fault damage.

14. C — |Z_meas| = 38.3 Ω is within Zone 1 magnitude (40.9 Ω), but the impedance angle of 70.2° deviates 7.8° from MTA of 78°. Combined with the large 10 Ω resistive component, the R-X point may be on the edge of the mho circle. A detailed graphical analysis on the R-X diagram is required to confirm Zone 1 coverage.

15. A — Full: 840,000. 75%: 336×0.422×3,800 = 538,474. 50%: 336×0.125×2,460 = 103,320. VFD total = 1,481,794 kWh. Full-speed = 2,943,360 kWh. Savings = 1,461,566 kWh (49.7%). The cubic relationship makes partial-speed chiller operation dramatically more efficient across three operating modes.

16. D — $H_2 = 0.60\ \text{ft}^3/\text{hr}$. Max $H_2 = 15\ \text{ft}^3$. ACH = 0.040. For unattended substations, the critical feature is automatic hydrogen detection with remote alarming to SCADA/EMS. Since no personnel are present, the H_2 sensor provides the only warning before dangerous concentrations develop. The alarm should trigger at 25% of LEL.

17. B — The SVC responds within 1-2 cycles, injecting reactive power to support V_R during the power surge. V_R appears in P = V_SV_R sinδ/X_eff — maintaining V_R directly maintains power transfer capability during the critical first-swing period. Without fast voltage support, the voltage dip could push the system toward angular instability before slower controls can act.

18. D — Braking torque $\propto I^2 \propto E\_a^2 \propto \text{speed}^2$. For T = 25% of initial: $\text{speed}^2 = 0.25 \rightarrow$ speed = 50% = 450 RPM. At half speed, braking torque drops to 25% because it varies with the square of speed. This

rapid decay at low speeds is the fundamental limitation of dynamic braking, often requiring supplementary braking for final stop.

19. A — Thirty-four separately derived systems: 4 service + 4 generators + 12 PDU + 6 isolation + 8 UPS = 34 bonding jumpers. Each installed at its respective source per NEC 250.30(A)(1). A bonding jumper schedule should be maintained as part of facility electrical documentation.

20. C — The AQD activates in approximately 4 ms — faster than the optical relay's 18 ms total clearing. By creating a bolted fault, the AQD collapses arc voltage to near zero within 4 ms, virtually eliminating arc flash energy at the source. The optical relay then clears the bolted fault. The arc existed for only 4 ms — combined with arc-resistant enclosure, this is state-of-the-art arc flash elimination.

21. D — Existing phase overcurrent relays (set for 4.17 pu three-phase) cannot detect the 0.374 pu SLG current under LRG. Dedicated neutral overcurrent (51G) with sensitive pickup must be installed, along with neutral-to-ground voltage detection (59G). The protection must fundamentally change from phase-overcurrent-for-all-faults to a split approach: phase relays for phase faults, ground relays for ground faults.

22. B — Per NEC 430.24: 125% × 590 = 737.5A. Other motors = 477+361+302 = 1,140A. Per NEC 215.2: 125% × 280 = 350A. Noncontinuous = 90A. Total = 737.5 + 1,140 + 350 + 90 = 2,317.5A. The 125% applies independently to the largest motor and the continuous non-motor load.

23. A — I = (25.0+20.0+16.67+12.5+3.33+2.22+1.67+1.25+0.25) × 8,328 = 82.89 × 8,328 = 690,364A. Nine parallel sources produce this extreme fault current. The four utility transformers provide 89.5%, generators 8.7%, and the battery inverter only 0.3% due to its inherently high effective impedance.

24. C — Cable Z_pu ≈ 0.581. Total Z ≈ 0.639. I_transformer ≈ 4,706A. Motor contribution = 3,200A. Total = 7,906A.

24. C — Cable impedance reduces transformer contribution to approximately 16,080A at the panelboard. Adding 3,200A motor contribution = 19,280A total. Since 19,280A < 22,000A SCCR, the cable naturally reduces fault current below the panelboard's rating. No series-rated combination or current-limiting fuses are needed — proper documentation per NEC 110.9 is sufficient.

25. D — Without module-level power electronics, each module continues producing V_oc (48V) under sunlight after the central inverter shuts down. String voltage = 24 × 48 = 1,152V at elevated temperature, 960V at STC — far exceeding 80V. The system violates NEC 690.12(B)(2) and must be retrofitted with module-level rapid shutdown devices.

26. B — Total symmetrical = 183,587 + 12,800 = 196,387A. Peak = 2.31 × 196,387 = 453,654A. Nearly half a million amperes peak from three parallel transformers plus 18 motors. Electromagnetic forces exceeding 2×10^{11} A^2 demand extraordinary bus bracing that dominates engineering cost.

27. D — Both terminals achieve high-speed clearing via DCB. The near end's Zone 2 detects the fault and receives no blocking signal (forward fault at both ends). The remote end's Zone 1 covers the fault at 8% from its terminal. DCB permits instantaneous tripping at the near end because no blocking signal was received — both ends clear simultaneously.

28. A — Slope threshold = 30% × 5.0 = 1.5A. False differential of 2.0A > 1.5A → FALSE TRIP. The 30% slope is insufficient for 40% CT saturation on autotransformers. Autotransformers require higher slopes (≥40%) due to the complex three-winding current balancing that increases CT error probability during external faults.

29. C — Maximum primary = 125% × 83.7 = 104.6A → next standard = 110A. Per NEC 450.3(B), when primary OCPD is provided at not more than the next standard above 125%, secondary OCPD may not be required depending on the specific table conditions. The engineer should verify against the NEC 450.3(B) table notes for the exact requirements.

30. B — H = 2.5 provides good inertia. The 0.5-second sag at 78% produces moderate angle advance (estimated 15-25°). With 102.8% FLT margin and relatively short duration, the motor maintains synchronism. The return-swing oscillation after voltage recovery damps within the available margin — stability is maintained.

31. D — Force $\propto$ I^2_peak/d. Halving the distance doubles the force. At 491 kA peak with 8-inch spacing, forces are already extreme. Reducing to 4 inches doubles them, potentially requiring twice the bracing strength or completely different bus construction methods such as segregated-phase or isolated-phase bus.

32. A — Five violations: V_5 (11.2%), V_7 (7.8%), V_{11} (5.1%), V_{13} (3.5%) exceed 3.0%, plus THD (15.5%) exceeds 5.0%. This is the worst harmonic scenario in the exam series. Priority: retrofit six-pulse

VFDs to eliminate 5th/7th, install tuned filters for 11th/13th, then verify THD. Multi-month remediation requiring capital planning.

33. B — Deep ground wells are most effective for space-constrained sites because they access lower-resistivity geological layers (often 50-200 feet deep) without expanding the grid's horizontal footprint. Each well can reduce resistance by 30-60%. Combined with GEM backfill, this vertical approach achieves low resistance even when surface area for a horizontal grid is limited.

34. D — At 60% speed, no-load magnetizing drops to 68.3 kvar. The 90 kvar capacitor at 132% of reduced magnetizing far exceeds the self-excitation threshold. If the VFD trips, the capacitor sustains the residual field and causes dangerous voltage buildup. The capacitor must be interlocked with the VFD.

35. C — Full: 280,000. 90%: 306,180. 80%: 286,720. 70%: 172,872. 60%: 90,720. 40%: 17,203. VFD = 1,153,695 kWh. Full-speed = 2,452,800 kWh. Savings = 1,299,105 × $0.082 = $106,527/year. Six operating modes with the cubic relationship produce 53% total energy reduction.

36. A — R = 0.0541 × 750/1000 = 0.04058. X = 0.0489 × 750/1000 = 0.03668. V_drop = 346.4 × (0.04058×0.85 + 0.03668×0.527) = 346.4 × (0.03449+0.01933) = 346.4 × 0.05382 = 18.64V. V_drop% = 3.88%. Significantly exceeds 3% — upsize to at least 500 kcmil for this extreme 750-foot distance.

37. B — Z_T_par = 0.0333. Z_gen = 0.44. Z_SC = 0.429. Z_SM = 0.80. Z_solar = 5.0. Z_wind = 12.0. I_pu = 30.0+2.273+2.331+1.25+0.20+0.083 = 36.14. I = 36.14 × 418.4 = 15,121A. Three autotransformers dominate at 83%. The two inverter-based resources contribute less than 0.8% combined despite 30 MVA aggregate rating.

38. D — I_T1 = 83,670A. I_T2 = 60,133A. Total transformers = 143,803A. Motors = 16,000A. Grand total = 159,803A. Peak = 2.36 × 159,803 = 377,135A. Over a third of a million amperes peak — approaching the physical design limits of standard 480V bus construction.

39. C — R_total = 1/(1/45 + 1/2.1 + 1/1.5) = 1/1.165 = 0.858 Ω. The water pipe (1.5 Ω) and Ufer (2.1 Ω) dominate the parallel combination. The 45 Ω rods contribute negligibly. This demonstrates that existing building infrastructure often provides far better grounding than driven rods in high-resistivity soil.

40. B — Cable: R = 0.05472, X = 0.04788 Ω. Z_cable_pu = 0.0727/0.0768 = 0.946. Total Z = 1.004. I = 3,608/1.004 = 3,594A. The 900-foot 4/0 cable reduces fault current to less than 10% of switchboard value. The engineer must verify that downstream breakers can clear faults at this very low current level.

41. A — Solar inverters with approximately 10 pu impedance on the 100 MVA base contribute negligible current to both SLG and three-phase faults. The I_SLG/I_3Φ ratio of 25.8% exceedance remains essentially unchanged because the transformer and source completely dominate the fault calculation. The solar addition does not meaningfully alter the asymmetric grounding behavior.

42. C — At 65% speed, no-load magnetizing drops to 43.2 kvar. The 55 kvar capacitor at 127% of reduced magnetizing exceeds the self-excitation threshold. If the VFD trips while the capacitor is connected, self-excitation is likely. The capacitor must be switched off during reduced-speed operation or interlocked with the VFD output contactor.

43. B — At X/R = 32, the DC offset drives total CT flux to approximately 2.5× the symmetrical peak. The core saturates deeply for 5-8 cycles, producing severely distorted secondary current. Modern 87L relays use CT saturation detection algorithms and replica-current compensation, but older relays may false trip or fail to detect faults during the saturation period.

44. D — Neutral = 3 × 64.5 = 193.5A (63% of phase RMS 307.6A). The neutral does NOT exceed the phase in this mixed-load scenario because nonlinear loads are only 65% of total. However, 193.5A is significant and must be counted as current-carrying per NEC 310.15(C)(1). Pure nonlinear loads produce neutral > phase; mixed loads typically do not.

45. A — At 4.95 mA, the 0.05 mA margin (1%) is inadequate to account for leakage drift, LIM accuracy (±5%), and device-level variations during the procedure. A LIM alarm during active surgery is dangerous and disruptive. The device should be powered from a different panel or the highest-leakage device replaced first.

46. C — With compensation: sin δ = 0.4156; δ = 24.6°; stability = 41.6%. Without: sin δ = 0.6394; δ = 39.7°; stability = 63.9%. Series compensation reduced the stability fraction from 63.9% to 41.6%, INCREASING available margin from 36.1% to 58.4%. The dramatically improved operating point provides far better resilience to contingencies.

47. B — The fuse did not reach minimum melting time (0.013s < 0.018s MM) during either fast-trip event. At 72% of MM time, the fuse element heats but does not sustain permanent damage. The 3-

minute interval provides complete thermal recovery. Repeated close-interval operations without adequate cooling could cause cumulative damage, but 3 minutes is sufficient.

48. A — With 100%-rated breaker: 700A ≤ 800A. Two parallel 500 kcmil at 75°C = 760A ≥ 700A with 8.6% margin. Code-compliant per NEC 310.10(G). While 8.6% margin is adequate, two parallel 600 kcmil (840A) would provide 20% margin for better thermal performance in high-ambient environments.

49. A — Total symmetrical = 48,111 + 12,800 = 60,911A. Peak = 2.38 × 60,911 = 144,968A. The 12,800A motor contribution (21%) cannot be ignored. All equipment momentary ratings, bus bracing, and close-and-latch specifications must account for this combined peak current.

50. C — R = 0.0367 × 800/1000 = 0.02936. X = 0.0407 × 800/1000 = 0.03256. V_drop = 346.4 × (0.02936×0.87 + 0.03256×0.493) = 346.4 × (0.02554+0.01605) = 346.4 × 0.04159 = 14.41V. V_drop% = 3.00%. Exactly at the NEC 3% limit — upsize to 500 kcmil for any margin, especially with anticipated load growth.

51. B — Four parallel 500 kcmil at 90°C = 1,720A with 7.5% margin. Three parallel 750 kcmil at 90°C = 1,605A provides only 0.3% margin — technically compliant but unacceptable for a 1,600A installation. The 75°C column cannot meet the requirement regardless of conductor size. The dual-rated terminal is essential for large switchboards.

52. D — $\Delta\delta$ = (180×60×200×0.001225)/1,000 = 2,646/1,000 = 2.65°. The ultrafast 0.035-second clearing (optical relay + fast SF_6 breaker) produces negligible rotor advance. The 115.35° margin demonstrates the extraordinary transient stability benefit of state-of-the-art fast-clearing protection systems.

53. A — At 200% voltage, dielectric stress = 4× rated (V^2). Failure occurs within seconds to a few cycles. As each unit fails, voltage on survivors increases further (8/3 = 2.67× for three remaining → 7.1× stress). The cascade accelerates exponentially. Only automatic high-speed unbalance protection can prevent catastrophic bank failure.

54. C — Only the wound-rotor meets 340% breakaway (350% > 340%). T/I = 0.946 vs Design D 0.423 (2.24× better). The wound-rotor also handles 250% periodic overloads through external resistance re-engagement — the adjustable slip provides thermal absorption for intermittent severe-duty overloads that would trip overload relays on squirrel-cage motors.

55. D — 30 phase + 7 harmonic-carrying neutrals = 37 current-carrying conductors (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 tray impractical — at least seven parallel raceways are needed to restore reasonable derating.

56. B — The AQD quenches the arc in approximately 4 ms by creating a bolted fault. The arc exists for only 4 ms — approximately 1/75th of the 0.30s STD. The breaker then clears the bolted fault in approximately 22 ms total. The worker is exposed to arc flash energy for only those 4 ms before the AQD activates.

57. C — At M = 2.5: t = 10.99 seconds — grossly unacceptable for bus-tie protection. Bus ties must clear quickly to prevent fault propagation. At this low multiple, the extremely inverse characteristic is essentially non-functional. The engineer should use instantaneous elements (50) or differential protection (87B) for bus-tie applications.

58. A — Z_1_total = 38.4+j384; |Z_1| = 385.9. Z_0_total = 115.2+j1,116; |Z_0| = 1,121.9. Sum = 192+j1,884; |Sum| = 1,893.8. I_SLG = 597,558/1,893.8 = 316A. This extremely low SLG on a 480-mile line makes conventional distance protection virtually unreliable. Line differential (87L) with fiber-optic communication is the only dependable primary protection.

59. D — NEC 700.10(B)(1) requires independence of wiring systems — conductors and raceways — not the physical support structure. Separate metallic conduits on a shared cable tray provide adequate independence because each wiring system is in its own dedicated raceway. The cable tray is merely a support structure.

60. B — Total load = 180 + 96 + 100 + 40 = 416A > 225A bus rating. Even with a 100%-rated breaker, the physical bus cannot carry 416A. The panelboard must be upgraded to at least 500A. This is a common design error where the load calculation reveals the initial panelboard selection was significantly undersized.

61. A — Excess = 17,540 kvar. Annual penalty = $1,262,880. Bank at $25/kvar = $438,500. Payback = 4.2 months — less than one fiscal quarter. This is among the most compelling ROI cases in industrial power engineering, where the annual penalty exceeds the capital cost nearly threefold.

62. D — Total = 167,340 + 24,000 = 191,340A. Peak = 2.38 × 191,340 = 455,389A. Nearly half a million amperes peak from two 4,000 kVA parallel transformers plus 30 motors. This approaches the physical design limits of standard bus construction and may require segregated-phase bus duct designs.

63. C — Relay sees 10A fault only (charging cancels). 10A > 8A → trips. But 25% margin is thin. Installing a second CT with 5A pickup provides 100% margin, but the engineer must verify actual system zero-sequence background is below 5A. Cable charging asymmetry from different cable lengths could produce 3-5A residual, making low pickup prone to false tripping.

64. B — 125% × 683 = 853.75A. Other motors = 590+477+414+361+302+242 = 2,386A. Motor subtotal = 3,239.75A. 125% × 200 = 250A. HVAC = 120A. Total = 3,239.75 + 250 + 120 = 3,609.75A. Multiple parallel conductor sets per phase are required at this extreme ampacity.

65. D — |Z_meas| = 82.1 > Zone 1 reach of 78.5 Ω. The fault is clearly outside Zone 1. Zone 2 at 120% covers the fault. With pilot scheme active, high-speed clearing occurs. Without pilot, Zone 2 operates after 0.35 seconds. The 15 Ω resistance combined with 86% location pushes impedance beyond Zone 1.

66. B — Without cooling: 5 events × 10% = 50%. With 5-minute cooling intervals (approximately 20-30% recovery per interval), approximately 6-8 events before reaching 50%. The cooling intervals allow partial thermal recovery, extending the NGR's effective capacity for repetitive fault events.

67. C — NMC thermal runaway produces toxic AND flammable gases (HF, CO, H_2, CH_4). The safety system must address both: gas detection, emergency exhaust below 25% LEL, deflagration venting, fire suppression (water mist or clean agent), toxic exhaust routing away from personnel, and automatic HVAC shutdown of adjacent buildings. This is state-of-the-art for utility-scale NMC BESS safety.

68. A — E = 14 × (0.010/0.20) = 0.70 cal/cm^2. Below both the 1.2 cal/cm^2 arc flash boundary AND the 1.0 cal/cm^2 first-degree burn threshold. Combined with arc-resistant enclosure, effective exposure is zero. This enables maintenance in normal clothing without specific arc-rated PPE, dramatically improving comfort and productivity.

69. D — Despite 85% FLT margin, H = 2.0 with t = 1.0 second at 70% produces very large rotor angle advance ($\Delta\delta \propto t^2$). The 1.0-second duration is long enough that accumulated angular momentum may exceed the critical clearing angle. At H = 2.0, the moderate inertia is insufficient for a 1.0-second deep sag. Detailed transient stability simulation is mandatory.

70. C — For a 400-mile line, fiber propagation delay ≈ 2 ms. Modern 87L relays require total one-way latency ≤ 10 ms. GPS time-stamping aligns current samples from both terminals despite propagation delay. The relay compensates for measured channel delay and jitter, maintaining accurate differential calculations across the extreme line length.

71. A — Ratio = 2,000,000/1,500,000 = 1.333. EGC = 167,800 × 1.333 = 223,767 CM. 4/0 AWG = 211,600 CM (below — insufficient). 250 kcmil = 250,000 CM (above — adequate). The minimum EGC is 250 kcmil per the proportional increase calculation.

72. D — Original Q = 27,500 kvar. Cap = −18,000. SM1: Q_1 = 3,571. SM2: Q_2 = 1,219. Net Q = 27,500 − 18,000 − 3,571 − 1,219 = 4,710 kvar. P_total = 31,726 kW. PF = 31,726/32,074 = 0.989 ≈ 0.99. Four correction sources reduce reactive demand by 83% while adding 8,500 HP of mechanical output.

73. B — I_pu = 19.05+3.003+3.333+1.364+0.25+0.125+0.067 = 27.19. I = 27.19 × 418.4 = 11,377A. Two autotransformers dominate at 70%. Three rotating machines contribute 28%. Three inverter-based resources (solar+wind+BESS) contribute only 1.6% combined despite 50 MVA aggregate rating — illustrating negligible fault contribution.

74. A — P_pump = 16.1 kW. P_supply = 16.1/(0.78 × 0.95) = 21.7 kW — only 8.3% of rated. Motor efficiency drops to 78% at this extreme light load. Iron and friction losses represent a larger percentage of total input. While absolute losses are small, the 35% loss ratio indicates diminishing returns on speed reduction below certain thresholds.

75. C — The thermal accumulation during the 45-second starting sequence: $(1{,}200^2 \times 20 + 900^2 \times 15)$ equivalent = 40,950,000 A^2s vs the relay's trip threshold of approximately $750^2 \times$thermal_constant. This suggests the relay WILL trip during starting. A motor-starting relay with longer thermal time constant or temporary threshold elevation is needed for high-inertia loads.

76. D — Total = 128,348 + 14,000 = 142,348A. Peak = 2.34 × 142,348 = 333,094A. Over a third of a million amperes peak. The electromagnetic forces at this peak level require extraordinary mechanical bracing that may exceed the capability of standard bus construction methods.

77. B — At H = 1.8 with 2.5 seconds at 58% voltage: $\Delta\delta \propto t^2 \rightarrow 2.5^2 = 6.25\times$ the advance of 1.0 seconds. The motor loses synchronism within 0.3-0.5 seconds despite the 56.6% margin. This is the most severe parameter combination in the exam series. UV relay should trip within 0.3 seconds to prevent mechanical damage during pull-out.

78. A — Original: Z_eff = 10.75%; I = 33,563A. New: Z_parallel = 3.875%; I = 93,109A. Increase = 177% — nearly tripling. Two compounding effects: parallel transformers AND reduced source impedance. All downstream equipment, SCCR, series combinations, and arc flash studies must be comprehensively re-evaluated.

79. D — Peak = 2.17 × 23,100 = 50,127A. At 50 kA peak on a 208V system, many standard panelboards may not have adequate momentary ratings. The moderate X/R of 5 produces moderate asymmetry. This demonstrates why even 208V systems require careful attention to available fault current and equipment ratings.

80. C — I = 600,000/(√3×480) = 721.7A. OCPD = 125% × 721.7 = 902.1A → next standard = 1,000A. E = 600 × 24 × 365 = 5,256,000 kWh. Cost = 5,256,000 × $0.055 = $289,080/year. This nearly $300,000 annual cost makes waste heat recovery and insulation improvements primary engineering priorities.