PRACTICE EXAM 20: PE POWER SIMULATION (80 QUESTIONS)

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1. A 13.8 kV industrial facility has a three-phase fault level of 500 MVA and proposes installing a 7,800 kvar capacitor bank on a bus serving a mix of six-pulse VFDs (4,000 HP), eighteen-pulse VFDs (3,500 HP), and PWM active front-end drives (2,500 HP). The resonant harmonic order is h_r = √(500,000/7,800) = 8.01. The engineer notes that the 18-pulse VFDs still produce residual 5th and 7th harmonics at approximately 2% of fundamental due to supply voltage unbalance. Should these residual harmonics be considered in the resonance risk assessment?

A. No — residual harmonics at 2% are below the IEEE 519 limit and can be ignored

B. Yes — although the 18-pulse residual 7th is only 2% of fundamental (versus 20% from six-pulse), the proximity of h_r = 8.01 to h = 7 means even small harmonic currents experience significant amplification; the six-pulse drives dominate, but the residual from 18-pulse drives adds to the total 7th harmonic injection; detuning is still primarily driven by the six-pulse contribution

C. No — the PWM AFE drives cancel all residual harmonics from the 18-pulse drives through active filtering

D. Yes — but only for the 5th harmonic; the 7th harmonic residual from 18-pulse is too small to matter

2. A three-phase, 480V system has a 3,500 kVA service transformer (Z = 5.75%, X/R = 9) with a switchboard fault current of 42,200A. Three remote panelboards are fed through different cable configurations. Panel A: 200 ft of 500 kcmil copper. Panel B: 350 ft of 350 kcmil copper. Panel C: 500 ft of 4/0 AWG copper. The engineer must rank the panelboards from highest to lowest available fault current for arc flash labeling purposes. What is the correct ranking?

A. A > B > C (shortest distance, largest conductor first)

B. C > B > A (longest cable always has lowest fault current)

C. A = B = C (cable impedance has no effect at these distances)

D. A > B > C — Panel A has the shortest run with the largest conductor (lowest impedance), Panel B has moderate length with moderate conductor, and Panel C has the longest run with the smallest conductor (highest impedance); the fault current decreases in this order, and each panel may require different PPE category labels

3. Per NEC 430.52(C)(1), a 200 HP, 460V motor has FLA = 242A. A dual-element time-delay fuse is selected. Per Table 430.52, the maximum is 175% = 423.5A → next standard 450A. The motor starts successfully with this fuse. However, a plant engineer asks whether installing a smaller 300A fuse would be permissible for tighter branch-circuit protection. Per NEC 430.52, is this permissible?

A. No — the fuse must be set at exactly 175% of FLA

B. Yes — but only if a reduced-voltage starter is installed

C. Yes — NEC 430.52 establishes maximum OCPD sizes, not minimums; a 300A fuse that permits the motor to start is compliant and provides significantly better short-circuit protection with lower let-through energy

D. No — any fuse below 400A is too small for a 200 HP motor

4. A CT with a ratio of 4000:5 and accuracy class C800 serves a line differential relay on a 345 kV circuit. During a 60,000A external through-fault with X/R = 28, one CT saturates to 40% of expected output during the first five cycles due to extreme DC offset. The expected secondary per CT is 75A. What is the maximum false differential current, and what does the relay's dual-slope characteristic provide?

A. False differential = 75 − 30 = 45A; a dual-slope relay uses a lower slope (e.g., 20%) at low restraint currents for sensitivity and a higher slope (e.g., 60%) at high restraint currents to accommodate severe CT saturation during external through-faults — this adaptive characteristic provides both dependability for internal faults and security against CT saturation-induced false tripping

B. False differential = 7.5A; a single 25% slope is adequate for all conditions

C. False differential = 45A; but dual-slope relays are only used for transformer differential protection

D. False differential = 0A; external faults never cause CT saturation

5. A 345 kV, 420-mile transmission line must transmit 550 MW during summer peak. The uncompensated SIL is 320 MW. A 45% series capacitor compensation is installed at three distributed locations (15% each at the one-quarter, midpoint, and three-quarter points). Additionally, two 150 Mvar switched shunt reactors are installed at the receiving end. During off-peak (40 MW), both reactors are switched on. During peak (550 MW), both are off and the series capacitors improve voltage regulation and stability. What is the approximate new stability limit with 45% series compensation?

A. P_max_new = P_max_old / (1 − 0.45) = 1.82 × P_max_old — approximately 82% increase in the theoretical stability limit; the distributed three-point compensation provides superior voltage profile and reduced individual bank voltage stress compared to single-point midpoint compensation

B. P_max increases by only 10% with series compensation

C. P_max doubles with any series compensation above 25%

D. P_max_new = P_max_old × 0.55 — series compensation reduces the stability limit

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

A. 1 AWG (no increase needed for parallel conductor circuits)

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

C. 3/0 AWG (167,800 CM) — must provide 25% margin above the calculated value

D. 4/0 AWG (211,600 CM) — must match the phase conductor size increase

7. A three-phase, 4,160V system has an 8,000 kW load at 0.65 lagging PF through a feeder with $Z = 0.55 + j3.50\ \Omega$ per phase. The original reactive demand is Q = 8,000 × tan(arccos 0.65) = 8,000 × 1.169 = 9,352 kvar. The engineer installs a 7,000 kvar capacitor bank AND a 2,500 HP synchronous motor at 0.80 leading PF ($\eta = 94\%$). What is the new combined bus power factor?

A. Sync motor: P_in = 1,984 kW; Q_sync = 1,488 kvar; total correction = 8,488 kvar; net Q = 864 kvar; P_total = 9,984 kW; PF = $9{,}984/\sqrt{(9{,}984^2+864^2)}$ = 9,984/10,021 = 0.996 ≈ 0.99 — the combined correction eliminates 91% of the original reactive demand while adding 2,500 HP of mechanical output

B. PF = 0.85 lagging

C. PF = 0.92 lagging

D. PF = unity

8. A three-phase, 480Y/277V panelboard serves a large warehouse with 80% LED high-bay lighting (producing 3rd harmonic at 40% of LED fundamental) and 20% linear motor loads. Each phase draws 400A total fundamental. The LED drivers produce 3rd harmonic = 0.40 × 0.80 × 400 = 128A per phase. The neutral current = 3 × 128 = 384A. The true-RMS phase current = $\sqrt{(400^2 + 128^2)}$ = 420A. With 4 current-carrying conductors (0.80 factor), what base ampacity is required for the phase conductors?

A. 400A (fundamental only)

B. 420A (true RMS, no derating)

C. Phase RMS of 420A / 0.80 = 525A base ampacity; the neutral needs 384/0.80 = 480A; the phase requirement of 525A governs — this is significantly larger than the 400A fundamental would suggest, demonstrating how harmonic loading combined with conduit fill derating dramatically increases conductor sizing requirements

D. 480A (neutral governs)

9. A 250 MVA synchronous generator has $X''_d = 0.20$ pu, $X_2 = 0.22$ pu, $X_0 = 0.09$ pu on its own base. The generator is grounded through a 0.4 Ω reactor. $Z\_base = (24)^2/250 = 2.304$ Ω. $X\_n(pu) = 0.4/2.304 = 0.174$ pu. $3X\_n = 0.521$ pu. Total $Z_0\_network = j(0.09 + 0.521) = j0.611$ pu. For a bolted SLG fault: $I\_SLG = 3/j(X''\_d + X_2 + Z_0\_network) = 3/j(0.20 + 0.22 + 0.611) = 3/j1.031$. Compare this to a solidly grounded case where $Z_0 = j0.09$ and $I\_SLG = 3/j(0.20+0.22+0.09) = 3/j0.51 = 5.88$ pu.

A. Reactor-grounded: I_SLG = 2.91 pu (49.5% of solidly grounded); both are purely reactive at 90° lag — the reactor maintains the reactive character while reducing magnitude to below three-phase fault level (I_3Φ = 5.0 pu), which simplifies protection coordination

B. Reactor-grounded I_SLG = 5.88 pu (same as solidly grounded)

C. Reactor-grounded I_SLG = 2.91 pu with predominantly resistive character

D. Reactor-grounded I_SLG = 2.91 pu; this is 49.5% of the solidly grounded value; both currents are purely reactive (90° lag); the reactor reduces SLG below the three-phase level (5.0 pu), which is significant because it means the SLG no longer exceeds three-phase — simplifying equipment ratings and protection coordination compared to the solidly grounded case where I_SLG (5.88) exceeds I_3Φ (5.0)

10. A three-phase, 4,160V system has a neutral grounding resistor rated 400A, 10 seconds. A ground fault through 5 Ω fault resistance develops. R_NGR = 6.005 Ω. I_fault = 2,402/11.005 = 218.3A. The relay (pickup 35A, 1.0s delay) clears the fault. Five minutes later, a second fault at the same location (same fault resistance) restrikes and is cleared in 1.0 second. Ten minutes after the second event, a third fault occurs and is cleared in 1.0 second. What is the cumulative I^2t as a percentage of the NGR rating?

A. 3 × $(218.3/400)^2$ × (1.0/10) = 3 × 0.298 × 0.10 = 8.93% — the NGR retains 91% of its capacity despite three consecutive fault events; the 5-minute and 10-minute gaps provide partial cooling

B. 100% — three faults always exhaust the NGR

C. 50% — each fault consumes approximately 16.7%

D. 30% — significant thermal stress requiring NGR inspection

11. Per NEC 110.34(F), metal-enclosed equipment operating at over 600V must be marked with a warning sign reading "DANGER — HIGH VOLTAGE — KEEP OUT." The minimum letter height for this warning sign is what dimension?

A. 0.5 inches (12.7 mm)

B. 0.75 inches

C. 1.0 inch

D. No minimum height is specified by NEC 110.34(F)

12. A 3,500 kVA, 13.8 kV/480V transformer has core losses of 9,500 W and full-load copper losses of 30,000 W. The transformer serves a smelter with two operating modes: 16 hours at 90% load (PF = 0.90) and 8 hours at idle (20% load, PF = 0.70). The maximum efficiency loading is k_max = √(9,500/30,000) = 56.3%. Neither operating mode is near k_max. What is the all-day efficiency?

A. 96.0%

B. 97.5%

C. 16 hrs at 90%: P_Cu = 0.81×30,000 = 24,300W; E_out = 0.90×3,500×0.90×16 = 45,360 kWh; E_loss = (9,500+24,300)×16/1000 = 540.8 kWh. 8 hrs at 20%: P_Cu = 0.04×30,000 = 1,200W; E_out = 0.20×3,500×0.70×8 = 3,920 kWh; E_loss = (9,500+1,200)×8/1000 = 85.6 kWh. Total: η = 49,280/(49,280+626.4) = 98.7%. Answer 97.2% includes stray losses

D. 95.0%

13. A protection coordination study on a 13.8 kV system requires coordinating a 300E fuse on a transformer primary with an upstream 51 bus relay (IEEE very inverse, TD = 3.0, pickup = 5A on 600:5 CT). At the maximum fault of 18,000A, the fuse total clearing = 0.005 seconds. The relay secondary = 150A. M = 150/5 = 30. Using t = TD × (19.61/(M^2−1) + 0.491), what is the relay operating time?

A. t = 0.50s; CTI = 0.495s — adequate

B. t = 1.50s; CTI = 1.495s — coordination maintained but relay is slow

C. t = 0.25s; CTI = 0.245s — adequate

D. t = 3.0 × (19.61/(900−1) + 0.491) = 3.0 × (0.0218 + 0.491) = 3.0 × 0.5128 = 1.538s; CTI = 1.533s — adequate coordination but the relay is unnecessarily slow at this high fault level; reducing the TD to 1.5 would halve the operating time while maintaining CTI above 0.20s

14. A distance relay on a 230 kV line has Zone 1 at 85% reach (Z_line = 6 + j72 Ω). A three-phase fault occurs at 82% of the line. Z_meas = 0.82 × (6+j72) = 4.92 + j59.04 Ω. |Z_meas| = 59.2 Ω. Zone 1 reach = 0.85 × 72.25 = 61.4 Ω. The fault is 2.2 Ω below Zone 1 boundary (3.6% margin). A CT accuracy of ±3% and PT accuracy of ±3% could cause the relay to measure the impedance as high as 59.2 × 1.06 = 62.8 Ω. What is the consequence?

A. No consequence — 3.6% margin is adequate for all measurement errors

B. The combined CT/PT error of 6% could push the measured impedance to 62.8 Ω, which exceeds the Zone 1 reach of 61.4 Ω — the relay would fail to trip on Zone 1 and revert to Zone 2 (0.35-second delay); this demonstrates why Zone 1 is set at 80-85% rather than higher, providing margin for measurement instrument errors

C. CT/PT errors only affect current magnitude, not impedance measurement

D. The relay automatically compensates for CT/PT errors through digital signal processing

15. A three-phase, 460V, 4-pole, 400 HP induction motor drives a centrifugal pump. At design speed (1,770 RPM), the pump requires 298 kW. A VFD is installed. During off-peak (5,200 hours/year), the pump operates at 72% speed (1,274 RPM). The remaining hours are at full speed. Using $P \propto n^3$, what is the annual energy savings at $0.085/kWh?

A. $P_{reduced} = 298 \times 0.72^3 = 298 \times 0.3732 = 111.2$ kW; savings = $(298-111.2) \times 5{,}200 \times \$0.085 = 186.8 \times 5{,}200 \times 0.085 = \$82{,}534$/year — a 28% speed reduction produces a 62.7% power reduction

B. Savings = $40,000/year (linear speed-power assumed)

C. Savings = $150,000/year

D. Savings = $25,000/year

16. Per NEC 480.9(A), ventilation for battery rooms must limit hydrogen below 1%. A mission-critical data center has a massive vented lead-acid UPS: 1,200 cells charging at 0.007 ft^3 H_2/cell/hour. The room is 15,000 ft^3. What ventilation ACH is required, and what redundancy feature is recommended for mission-critical installations?

A. ACH = 0.056; no redundancy needed

B. ACH = 1.0; backup ventilation fan only

C. $H_2 = 1{,}200 \times 0.007 = 8.4$ ft^3/hr; max $H_2 = 150$ ft^3; ACH = 8.4/150 = 0.056; for mission-critical facilities, the ventilation system should include: redundant fans (N+1 configuration), hydrogen detection with automatic fan start, UPS-powered ventilation to maintain airflow during utility outages, and alarming to the building management system — a ventilation failure during an extended utility outage while batteries are charging is a catastrophic scenario

D. ACH = 5.0; explosion-proof fans mandatory

17. A 230 kV, 350-mile transmission line has Z_c = 375 Ω, SIL = 141 MW. The line must transmit 320 MW during peak. A 40% series compensation is installed at two points plus a ±200 Mvar SVC at the receiving end. During a sudden load rejection (load drops from 320 MW to 50 MW in 2 seconds), what transient condition occurs and how do the compensation devices respond?

A. Nothing happens — the series capacitors absorb all transient energy

B. The SVC cannot respond fast enough to prevent any voltage transient

C. The sudden load reduction causes the line to transition from above-SIL to below-SIL operation; the line's shunt capacitance now generates excess reactive power, causing rapid voltage rise at the receiving end; the SVC responds within 1-2 cycles by switching to maximum absorbing mode (−200 Mvar), and the shunt reactors (if installed) should be switched on — the SVC's fast response prevents transient overvoltage while the slower mechanical switching of the reactors provides sustained correction

D. Load rejection always causes voltage collapse, not voltage rise

18. A separately excited DC motor has V_t = 480V, I_a = 160A, R_a = 0.12 Ω. Rated speed = 1,750 RPM. E_a = 480 − 160×0.12 = 460.8V. The motor drives a press that requires plugging (reversal) for emergency stop. During plugging, the armature voltage is reversed to −480V while the motor runs at rated speed (E_a = 460.8V). What is the initial plugging current without a limiting resistor, and what resistor value limits the current to 200% of rated (320A)?

A. I_plug = (480 + 460.8)/0.12 = 7,840A without limiting; R_limit = (480+460.8)/320 − 0.12 = 2.94 − 0.12 = 2.82 Ω to limit to 320A

B. I_plug = 480/0.12 = 4,000A without limiting; R_limit = 1.38 Ω

C. I_plug = 160A (same as motoring); no resistor needed

D. I_plug = 320A (2× rated); no resistor needed because plugging automatically limits current

19. Per NEC 250.30(A)(1), each separately derived system requires a system bonding jumper. A campus-style pharmaceutical facility has: 3 × 3,000 kVA service transformers (13.8/480V), 3 × 2,000 kW emergency generators, 8 × 750 kVA PDU transformers (480/208Y/120V), 4 × 300 kVA isolation transformers (480/480V for sensitive labs), and 2 × 150 kVA UPS isolation transformers (480/208Y/120V). How many total system bonding jumpers are required?

A. Six (service transformers + generators only)

B. Fourteen (3 + 3 + 8 = 14, excluding isolation transformers)

C. Eleven (3 + 8 = 11, excluding generators and isolation transformers)

D. Twenty — every transformer and generator is a separately derived system: 3 service + 3 generators + 8 PDU + 4 lab isolation + 2 UPS isolation = 20 bonding jumpers, each at its respective source

20. A three-phase, 480V, 1,200A switchgear has an available fault current of 65,000A and a main LVPCB with 0.30-second short-time delay. The arc flash study shows 48 cal/cm^2 at 24 inches. The engineer implements a layered strategy: (1) ZSI (bus fault → 0.05s), (2) optical relay (0.022s), (3) arc-resistant switchgear (Type 2B — accessible from front), (4) remote racking, (5) permanent-magnet trip mechanism. For a bus fault during maintenance, what is the calculated incident energy with the optical relay, and what is the worker's exposure?

A. E = 48 cal/cm^2; arc-resistant has no effect on calculations

B. E = 48 × (0.022/0.30) = 3.5 cal/cm^2; the worker's effective exposure at the front is near zero because the Type 2B arc-resistant switchgear redirects all arc energy through top-mounted exhaust plenums away from the front; the permanent-magnet trip ensures the breaker can open even if control power is destroyed by the arc event

C. E = 3.5 cal/cm^2; the worker still needs full PPE Category 2

D. E = 0 cal/cm^2; arc-resistant switchgear prevents arcing entirely

21. A synchronous generator rated 350 MVA, 26 kV has X"_d = 0.23 pu, X_2 = 0.25 pu, X_0 = 0.11 pu. The generator is solidly grounded. For the four fault types, I_3Φ = 1/0.23 = 4.35 pu, I_SLG = 3/(0.23+0.25+0.11) = 5.08 pu, I_LL = √3/(0.23+0.25) = 3.61 pu. For the DLG fault: $Z_2||Z_0$ = (j0.25×j0.11)/(j0.36) = j0.0764; I_1_DLG = 1/(j0.23+j0.0764) = 1/j0.306 = 3.27 pu. The I_SLG exceeds I_3Φ by 17%. What equipment rating implication does this create?

A. All equipment must be rated for the SLG fault level, which exceeds three-phase

B. No implication — equipment is always rated for three-phase fault only

C. Equipment on the faulted phase must withstand 5.08 pu (SLG), while the three-phase rating of 4.35 pu is used for symmetrical interrupting calculations; ground-fault protection relays (51G, 87GN) must be coordinated for the higher SLG current, and the neutral conductor/bus must be rated for $3I_0 = 3 \times (5.08/3) = 5.08$ pu of neutral current during the SLG fault

D. The DLG fault is the critical case at 3.27 pu

22. A 480V, three-phase panelboard has: Motor 1 = 414A (350 HP, largest), Motor 2 = 302A (250 HP), Motor 3 = 242A (200 HP), Motor 4 = 180A (150 HP). Continuous lighting = 220A. Noncontinuous receptacles = 65A. Per NEC 430.24 and 215.2(A)(1), what is the minimum feeder conductor ampacity?

A. 1,244.5A

B. 1,100A

C. 125% × 414 + 302 + 242 + 180 + 125% × 220 + 65 = 517.5 + 724 + 275 + 65 = 1,581.5A

D. 1,400A

23. A three-phase, 4,160V system has seven sources on a common bus. On a 50 MVA base: Z_A = 0.05, Z_B = 0.07, Z_C = 0.09, Z_D = 0.12, Z_E_gen = 0.40, Z_F_gen = 0.60, Z_G_SC = 1.0. I_base = 6,940A. What is the total fault current?

A. 100,000A

B. 200,000A

C. 250,000A

D. I = (1/0.05 + 1/0.07 + 1/0.09 + 1/0.12 + 1/0.40 + 1/0.60 + 1/1.0) × 6,940 = (20.0+14.29+11.11+8.33+2.50+1.67+1.0) × 6,940 = 58.90 × 6,940 = 408,766A — this extreme combined fault current from seven parallel sources demonstrates the critical importance of detailed fault current studies for large industrial power systems with multiple utility ties and on-site generation

24. A 480V, three-phase, 400A panelboard has an available fault current of 55,000A. The panelboard SCCR is 22,000A. An upstream 400A Class L current-limiting fuse limits let-through to 18,000A peak (11,500A RMS) at 55,000A available. Per NEC 240.86, the specific fuse-panelboard combination must be tested and listed as a series-rated system. The let-through of 11,500A is below the 22,000A SCCR. After the combination is listed and the equipment is field-marked, what ongoing verification is required?

A. Annual re-testing of the fuse-panelboard combination

B. Whenever modifications are made that could affect the available fault current (per NEC 110.24(B)), the series-rated combination must be re-evaluated: if the available fault current changes, the fuse let-through at the new available current must be verified to still fall below the panelboard SCCR; additionally, fuse replacements must use the identical type and rating specified in the series combination listing

C. No ongoing verification — the initial listing is permanent

D. Monthly visual inspection of the fuse and panelboard

25. Per NEC 690.12, a commercial building PV system uses string inverters with 22 modules per string (V_oc = 46V = 1,012V per string). DC-DC power optimizers with rapid shutdown capability are installed on each module. The building is in a climate zone where temperatures reach −25°C. At −25°C, V_oc per module increases to 52.9V (temperature coefficient = −0.30%/°C). With optimizers shut down during rapid shutdown, each module's output drops to near zero. The engineer must verify that the maximum system voltage at −25°C (22 × 52.9 = 1,163.8V) does not exceed the inverter and conductor voltage rating of 1,000V DC. Is there a code violation?

A. Yes — the maximum system voltage of 1,163.8V exceeds the 1,000V DC rating of the conductors and inverter; the system must either reduce string length to 18 modules (18 × 52.9 = 952.2V < 1,000V) or use equipment rated for 1,500V DC; this is a NEC 690.7 voltage rating issue, separate from the rapid shutdown compliance

B. No — the optimizers reduce the voltage to zero during rapid shutdown

C. No — the 1,000V limit applies only during rapid shutdown, not during normal operation

D. Yes — but only for residential installations

26. A three-phase, 480V system has two transformers in parallel: T1 = 3,000 kVA (Z = 5.50%, X/R = 9) and T2 = 2,500 kVA (Z = 5.75%, X/R = 8). I_T1 = 3,608/0.055 = 65,600A; I_T2 = 3,007/0.0575 = 52,296A; Total = 117,896A. The weighted X/R = (65,600×9 + 52,296×8)/117,896 = 8.56. Using IEEE multiplier of 2.33, what is the peak asymmetrical current?

A. 166,830A (√2 × total)

B. 235,792A (2× total)

C. 117,896A (no asymmetry for parallel sources)

D. Peak = 2.33 × 117,896 = 274,698A — this quarter-million-ampere-plus peak current creates extraordinary electromagnetic forces on the paralleled 480V bus; the force is proportional to I^2_peak, making mechanical bracing design the dominant engineering challenge for this installation

27. A distance relay on a 138 kV line has Zone 1 at 85%, Zone 2 at 120% (0.35s), Zone 3 at 200% (1.0s). Z_line = 4 + j46 Ω. A bolted three-phase fault occurs at 95% of the line. The POTT pilot scheme is active with a healthy communication channel. The near-end relay sees the fault in Zone 2 (95% > 85%) and sends a permissive signal. The remote end sees the fault at 5% from its terminal (within its Zone 1) and trips instantaneously while also sending a permissive signal. What happens at the near end?

A. Zone 2 trips after 0.35 seconds because the pilot scheme only benefits the remote end

B. The near-end relay receives the permissive signal from the remote end, and since it has also detected the fault in its overreaching Zone 2, the POTT logic enables instantaneous tripping — both ends achieve high-speed clearing; the near end does NOT wait for its Zone 2 delay because the permissive trip overrides the timer

C. Zone 3 trips after 1.0 second

D. No trip occurs at the near end

28. A protection engineer designs a transformer differential relay (87T) for a 150 MVA, 345/69 kV, wye-grounded/delta transformer. The relay uses a dual-slope characteristic: 20% slope below the

breakpoint and 60% slope above. During an external through-fault at 120% of rated, one HV CT saturates to 70% output. The expected CT secondary = 5.0A. Saturated output = 3.5A. False differential = 1.5A. Restraint = 5.0A. At this low restraint level, which slope applies?

A. The 20% low slope applies; threshold = 20% × 5.0 = 1.0A; since 1.5A > 1.0A, the relay trips — a FALSE TRIP; this demonstrates that even moderate CT saturation (30%) at modest fault levels can defeat the low-slope characteristic; the breakpoint should be set below this restraint level so the high slope (60%) applies during through-faults

B. The 60% high slope applies; threshold = 3.0A; relay correctly restrains

C. Both slopes apply simultaneously

D. Neither slope matters — the relay always trips for any differential above 0.5A

29. Per NEC 450.3(B), a 4,000 kVA, 480V/208Y/120V transformer has a primary current of 4,811A. At 125% = 6,013.75A. Standard sizes: 5,000A and 6,000A... actually NEC 240.6(A) goes 5,000 and 6,000. Since 6,013.75A exceeds 6,000A, the next standard above 6,013.75A would be whatever is next (perhaps a custom size or 7,000A depends on manufacturer). For the purpose of this question, what is the correct maximum primary OCPD?

A. 5,000A — must not exceed 125%

B. 6,000A — close enough to 6,013.75A

C. The next standard size above 6,013.75A per NEC 240.6(A); NEC 450.3(B) permits the next higher standard when 125% doesn't correspond to a standard rating; the engineer must consult available fuse/breaker sizes to identify the exact next standard above 6,013.75A

D. 4,811A — 100% protection required for transformers above 3,000 kVA

30. A three-phase, 4,160V, 8-pole synchronous motor rated 5,000 HP drives a SAG mill at 900 RPM. Pull-out torque = 240% FLT. H = 2.0 MJ/MVA. During a severe system disturbance, voltage sags to 70% for 1.0 second (fixed field). Pull-out = 0.70 × 240% = 168% FLT. Mill = 100% FLT. Steady-state margin = 68% FLT. Using the swing equation with estimated P_accel ≈ 0.30 × P_rated: $\Delta\delta \approx (180 \times 60 \times 0.30 \times P_{rated} \times 1.0^2)/(H \times S_{rated})$. For a 5,000 HP motor with S ≈ 4,400 kVA: $\Delta\delta \approx (180 \times 60 \times 0.30 \times 3{,}730 \times 1.0)/(2.0 \times 4{,}400)$. What is the approximate angle advance?

A. Δδ ≈ 5° — negligible; stability is not a concern

B. Δδ ≈ 25° — stability maintained with good margin

C. Δδ ≈ 90° — at the critical angle; stability uncertain

D. Δδ ≈ (180 × 60 × 1,119)/(8,800) = 12,085,200/8,800 ≈ 1,373°... this is clearly wrong; the formula requires careful unit handling; with P_a in MW and S in MVA: P_a = 0.30 × 3.73 = 1.119 MW; Δδ = (180 × 60 × 1.119 × 1.0)/(2.0 × 4.4) = 12,085.2/8.8 = 1,373°... still wrong; the issue is the formula should use S_rated in MVA correctly; Δδ = (180f × P_a)/(H × S) × t^2 = (180×60×1.119)/(2.0×4.4) × 1.0 = 12,085/8.8 = 1,373°; this enormous angle indicates the motor WILL lose synchronism — the simplified formula confirms that 1.0 second at 70% voltage with H = 2.0 produces catastrophic instability

31. A 480V, three-phase system has four parallel transformers: T1 = 3,000 kVA (Z = 5.50%), T2 = 2,500 kVA (Z = 5.75%), T3 = 2,000 kVA (Z = 6.00%), T4 = 1,500 kVA (Z = 6.25%). The engineer must determine the total combined fault current. Individual contributions: I_T1 = 65,600A, I_T2 = 52,296A, I_T3 = 38,849A, I_T4 = 27,972A. What is the total?

A. 100,000A (estimate)

B. Total = 65,600 + 52,296 + 38,849 + 27,972 = 184,717A — four parallel large transformers on a common 480V bus produce this staggering fault current; the mechanical bracing for this bus must withstand electromagnetic forces proportional to the square of the peak asymmetrical current, which at X/R ≈ 8 produces approximately 430,000A peak

C. 150,000A

D. 200,000A

32. A 13.8 kV, three-phase system has a measured voltage THD of 13.5% at the PCC. Individual: V_5 = 10.1%, V_7 = 6.8%, V_{11} = 4.2%, V_{13} = 2.8%, V_{17} = 1.8%. IEEE 519 limits: THD ≤ 5.0%, individual ≤ 3.0%. The facility operates aging six-pulse VFDs on critical process compressors that cannot be shut down for replacement. What is the violation count, and what interim mitigation can be implemented without shutting down the VFDs?

A. Three violations; install passive filters only

B. Four violations; nothing can be done without shutting down the VFDs

C. Two violations only (V_5 and THD)

D. Five violations: V_5, V_7, V_{11} all exceed 3.0%, and V_{13} approaches the limit, plus THD exceeds 5.0%; wait — $V_{13} = 2.8\% < 3.0\%$, so four violations (V_5, V_7, V_{11}, THD); interim measures WITHOUT VFD shutdown: install tuned passive harmonic filters (5th, 7th, 11th) on the 13.8 kV bus — these filters sink harmonic current without modifying the VFDs themselves; alternatively, install an active harmonic filter that can be connected to the bus while VFDs continue operating

33. A ground resistance test on a military communication facility measures 0.6 Ω during fall conditions. The design target per MIL-STD-188-124B is 10 Ω or less (much less stringent than IEEE 80's 0.5 Ω). The IEEE 81 seasonal correction factor is 1.3 for this site. What is the corrected resistance, and does the system meet both the military and IEEE 80 standards?

A. Corrected = $0.6 \times 1.3 = 0.78$ Ω; meets MIL-STD ($0.78 < 10$ Ω) with enormous margin; marginally meets IEEE 80 ($0.78 > 0.5$ Ω target if that applies) — the installation exceeds military requirements by a factor of 12.8× but may not meet IEEE 80 substation requirements; the appropriate standard depends on the facility's classification

B. Corrected = 0.6 Ω; both standards met easily

C. Corrected = 0.78 Ω; fails both standards

D. Cannot be assessed without soil resistivity data

34. A three-phase, 460V, 2-pole induction motor rated 600 HP has full-load speed 3,555 RPM, efficiency 96.8%, PF 0.90 lagging. The motor's no-load magnetizing kvar is approximately 85 kvar. Two capacitor options: 70 kvar and 90 kvar. Per NEC 460.9, which is safe?

A. Both are safe — both are below the no-load magnetizing limit

B. Neither is safe for 2-pole motors above 500 HP

C. 70 kvar is safe ($70 < 85$, or 82% of no-load magnetizing — below the self-excitation limit but above the typical 67% manufacturer recommendation); 90 kvar is UNSAFE ($90 > 85$, exceeding the no-load magnetizing kvar and risking self-excitation after disconnection); PF with 70 kvar: P_in = 456 kW; Q_orig = 221 kvar; Q_new = 151 kvar; PF_new = 456/479 = 0.952

D. Only 90 kvar is safe — larger capacitors provide better correction

35. A three-phase, 460V, 6-pole VFD-driven motor operates a centrifugal cooling tower fan. Design: 250 kW at 1,170 RPM. Four operating modes: full speed (2,000 hr/yr), 85% (2,500 hr/yr), 65% (2,800 hr/yr), 40% speed (1,460 hr/yr). Using $P \propto n^3$, what is the total annual VFD energy consumption and savings versus full-speed year-round?

A. VFD = 250×2,000 + 250×0.614×2,500 + 250×0.274×2,800 + 250×0.064×1,460 = 500,000+383,750+192,080+23,360 = 1,099,190 kWh; full = 250×8,760 = 2,190,000; savings = 1,090,810 kWh (49.8%)

B. VFD = 1,500,000 kWh; savings = 690,000 kWh

C. VFD = 800,000 kWh; savings = 1,390,000 kWh

D. Full: 500,000; 85%: $250\times0.85^3\times2{,}500$ = 250×0.6141×2,500 = 383,813; 65%: $250\times0.65^3\times2{,}800$ = 250×0.2746×2,800 = 192,220; 40%: $250\times0.40^3\times1{,}460$ = 250×0.064×1,460 = 23,360; total VFD = 1,099,393 kWh; savings = 2,190,000 − 1,099,393 = 1,090,607 kWh × $0.082/kWh = $89,430/year savings

36. A 480V, three-phase, 200A feeder uses 4/0 AWG THHN copper in EMT (R = 0.0608 Ω/1000 ft, X = 0.0478 Ω/1000 ft). The feeder is 550 feet long and serves a load at 0.83 lagging PF. What is the voltage drop percentage?

A. 2.0%

B. V_drop = $\sqrt{3}$ × 200 × (0.0608×0.55×0.83 + 0.0478×0.55×0.558) = 346.4 × (0.02775 + 0.01468) = 346.4 × 0.04243 = 14.7V; 14.7/480 = 3.06% — exceeds the NEC 3% recommendation; the engineer should upsize to 250 kcmil or 350 kcmil to bring the voltage drop below 3%

C. 4.0%

D. 1.5%

37. A 100 MVA, 230/69 kV autotransformer has series impedance 10% on its own base. Three identical units operate in parallel. A 50 MVA generator (X"_d = 0.22 pu), a 35 MVA synchronous condenser (X"_d = 0.16 pu), and a 20 MVA synchronous motor (X"_d = 0.25 pu) are on the 69 kV bus. On a 100 MVA base: Z_T_par = 0.10/3 = 0.0333; Z_gen = 0.44; Z_SC = 0.457; Z_SM = 1.25. What is the total fault current?

A. I_base = 836.7A; I = (30.0 + 2.273 + 2.188 + 0.80) × 836.7 = 35.26 × 836.7 = 29,502A — the three parallel transformers provide 85% of the total, with the three rotating machines contributing 15%; the synchronous motor's high impedance (1.25 pu) produces minimal fault contribution

B. 20,000A

C. 40,000A

D. 15,000A

38. A three-phase, 480V system has a 3,000 kVA transformer (Z = 5.75%, X/R = 9) and a 2,500 kVA transformer (Z = 6.00%, X/R = 8) in parallel. Combined fault = 62,748 + 48,517 = 111,265A symmetrical. Motor contribution from 15 motors (FLA = 2,800A) adds 11,200A first-cycle. Grand total = 122,465A. What is the peak asymmetrical current at weighted X/R ≈ 8.5?

A. 173,200A (√2 × total)

B. 244,930A (2 × total)

C. Peak = 2.34 × 122,465 = 286,568A — over a quarter million amperes peak; the electromagnetic forces on bus structures are proportional to I^2_peak; at 287 kA peak, the forces are approximately 1,000× those of a typical 42 kA bus fault, demanding extraordinary mechanical bracing design

D. 122,465A (no asymmetry)

39. Per NEC 250.53(A)(2), only one supplemental rod is required. IEEE 80 grounding design for an HV substation requires ≤1 Ω ground resistance to maintain safe step-and-touch potentials. The substation ground grid is designed using the Sverak formula: R_g ≈ ρ/(4√A) + ρ/L, where ρ = soil resistivity (Ω-m), A = grid area (m^2), L = total buried conductor length (m). For ρ = 200 Ω-m and a 50m × 50m grid (A = 2,500 m^2) with L = 1,000m of buried conductor, what is the approximate grid resistance?

A. R_g ≈ 200/(4×50) + 200/1000 = 200/200 + 0.20 = 1.0 + 0.20 = 1.20 Ω — exceeds the 1.0 Ω target; the engineer must either expand the grid area, add more conductor length, or reduce effective soil resistivity with ground enhancement material to achieve the design target

B. R_g = 0.2 Ω (the second term only)

C. R_g = 5.0 Ω (first term only)

D. R_g = 0.5 Ω

40. A 480V, three-phase system has a 2,500 kVA transformer (Z = 5.75%) feeding a switchboard. A 700-foot cable of 3/0 AWG copper in PVC conduit (R = 0.0766, X = 0.0532 Ω/1000 ft) feeds a remote panelboard. What is the approximate available fault current at the panelboard?

A. Cable: R = 0.05362, X = 0.03724 Ω/phase; Z_base = 0.0922 Ω; Z_cable_pu = $\sqrt{(0.05362^2+0.03724^2)}$/0.0922 = 0.06530/0.0922 = 0.708 pu; Total Z = 0.0575 + 0.708 = 0.766; I = 3,007/0.766 = 3,926A — the extremely long 700-foot run of 3/0 reduces fault current to only 9.2% of the switchboard value; this dramatically reduces arc flash energy but also raises the question of whether overcurrent protective devices can clear faults quickly enough at this low current level

B. 15,000A

C. 42,700A (unchanged)

D. 25,000A

41. A 60 MVA, 138/13.8 kV, delta-wye grounded transformer has $Z_1 = Z_2 = j0.08$ pu and $Z_0 = j0.05$ 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 = 0.08×100/60 + 0.045×100/60 = 0.1333 + 0.075 = 0.2083 pu. Z_0_total = 0.05×100/60 = 0.0833 pu (delta blocks source Z_0). I_3Φ = 1/0.2083 = 4.80 pu. I_SLG = 3/(0.2083+0.2083+0.0833) = 3/0.5 = 6.0 pu. By what percentage does the SLG exceed three-phase?

A. I_3Φ > I_SLG

B. They are equal

C. I_SLG exceeds I_3Φ by (6.0−4.80)/4.80 = 25% — the delta blocking source Z_0 creates a dramatically lower zero-sequence impedance (0.0833) versus Z_1_total (0.2083); this 25% exceedance means the faulted-phase current during SLG faults is 25% higher than during three-phase faults, with significant implications for CT sizing, bus rating, and relay coordination

D. I_SLG exceeds I_3Φ by 10%

42. A three-phase, 460V, 4-pole induction motor rated 350 HP has PF = 0.89 lagging, η = 96%. Two capacitor options: 45 kvar and 70 kvar. No-load magnetizing kvar = 60 kvar. Per NEC 460.9, which is safe, and what are the corrected power factors?

A. Both are safe — both are below 60 kvar

B. Only 45 kvar is safe (75% of no-load magnetizing); corrected PF ≈ 0.95; the 70 kvar exceeds the 60 kvar no-load magnetizing limit (117%) and will cause self-excitation — after disconnection, the capacitor can sustain and amplify the motor's residual magnetic field, producing dangerous overvoltage that may damage connected equipment

C. Neither is safe

D. Only 70 kvar provides adequate correction

43. A CT with a ratio of 3000:5 and accuracy class C800 serves a generator differential relay on a 300 MVA machine. During a 55,000A external through-fault with X/R = 30, one CT saturates to 35% of expected output during the first six cycles. Expected secondary = 91.7A. Saturated output = 32.1A. False differential = 59.6A. Restraint = 91.7A. The relay has a dual-slope characteristic: 25% below 3× rated (15A) and 60% above 3× rated. At 91.7A restraint (above breakpoint), which slope applies, and does the relay restrain?

A. 25% slope applies; threshold = 22.9A; 59.6 > 22.9 → FALSE TRIP

B. 60% slope applies; threshold = 55.0A; 59.6 > 55.0 → FALSE TRIP; even the high slope is insufficient for 65% CT saturation at X/R = 30

C. 60% slope applies; threshold = 91.7A; relay restrains because the operate must exceed 91.7A

D. The 60% high slope applies at this restraint level; threshold = 60% × 91.7 = 55.0A; since 59.6A > 55.0A, the relay FALSE TRIPS — this extreme CT saturation (65% error) from X/R = 30 DC offset defeats even the 60% high slope; the CT must be upgraded to a higher class or the relay must use additional security features such as cross-blocking or waveshape analysis

44. A balanced three-phase, 208Y/120V panelboard serves a data center with 100% nonlinear server loads. Each phase draws 450A fundamental, 180A 3rd harmonic, 90A 5th harmonic, and 45A 7th harmonic. Calculate the true-RMS phase current, neutral current, neutral-to-phase ratio, and the THD of the phase current.

A. I_phase = $\sqrt{(450^2+180^2+90^2+45^2)}$ = $\sqrt{(202{,}500+32{,}400+8{,}100+2{,}025)}$ = $\sqrt{245{,}025}$ = 495.0A; I_neutral = 3×180 = 540A (5th and 7th cancel balanced); ratio = 540/495 = 1.091; THD = $\sqrt{(180^2+90^2+45^2)}/450$ = $\sqrt{(32{,}400+8{,}100+2{,}025)}/450$ = $\sqrt{42{,}525}/450$ = 206.3/450 = 45.8% — the neutral exceeds the phase by 9.1% and the THD of 45.8% indicates severe harmonic distortion requiring de-rated conductors and oversized neutral

B. I_phase = 765A; I_neutral = 540A; ratio = 0.71

C. I_phase = 450A; I_neutral = 0A

D. I_phase = 495A; I_neutral = 270A

45. Per NEC Article 517.17(A), a hospital's LIM alarms at 5 mA. An operating suite has three isolated power panels: Panel A (Room 1, 4.3 mA, 14 devices), Panel B (Room 2, 3.8 mA, 12 devices), Panel C (Room 3, 2.9 mA, 9 devices). A new surgical procedure in Room 1 requires connecting 3 additional devices totaling 1.2 mA. Panel A cannot accept them (4.3 + 1.2 = 5.5 mA > 5.0). The engineer evaluates three options: (1) connect all 3 to Panel C (2.9 + 1.2 = 4.1 mA), (2) split: 2 devices to Panel C and 1 to Panel B, (3) install a fourth panel. What is the best engineering solution?

A. Option 2 — distributing across panels maximizes future headroom

B. Option 1 — simplest to implement

C. Option 2 — splitting the devices maximizes headroom: Panel B goes to 3.8 + 0.4 = 4.2 mA; Panel C goes to 2.9 + 0.8 = 3.7 mA; all three panels remain below 5.0 mA with margins of 0.7, 0.8, and 1.3 mA respectively; this provides the most balanced distribution while avoiding the cost of Option 3

D. Option 3 — a new panel is always the best solution

46. A 345 kV, three-phase line has V_S = 362 kV, V_R = 336 kV at 900 MW, 0.91 lagging PF. Line reactance = 58 Ω. What is the power angle, voltage regulation, and the stability fraction?

A. δ = 20°; VR = 7.7%; at 34% of limit

B. sin δ = 900 × 58/(362 × 336) = 52,200/121,632 = 0.4292; δ = 25.4°; VR = (362−336)/336 = 7.74%; stability fraction = sin(25.4°) = 42.9%; the line operates at 43% of its theoretical stability limit with adequate but not excessive margin — a contingency that reduces V_R further or increases load could push toward the stability boundary

C. δ = 35°; VR = 10%; at 57% of limit

D. δ = 45°; VR = 15%; at 71% of limit

47. A recloser on a 12.47 kV overhead feeder uses fuse-saving coordination with a 200A lateral fuse. At a fault current of 6,000A: fuse minimum melting = 0.02 seconds, fuse total clearing = 0.04 seconds, recloser fast trip = 0.015 seconds, recloser delayed trip = 0.12 seconds. A permanent underground cable fault occurs on the lateral. The recloser fast-trips, recloses into the permanent fault, then operates on its delayed curve. During the delayed trip, does the fuse blow before the recloser trips?

A. No — the recloser's delayed trip (0.12s) is faster than the fuse total clearing (0.04s)

B. No — fuse-saving means the fuse never operates

C. Yes — the delayed trip time exceeds the fuse total clearing; but 0.12s > 0.04s means the recloser has NOT tripped yet when the fuse blows

D. Yes — the recloser's delayed curve at 0.12 seconds is slower than the fuse's total clearing time of 0.04 seconds; the fuse blows at 0.04 seconds, isolating the faulted underground lateral; the recloser sees no more fault current and holds closed, restoring service to all unfaulted sections; this is the designed fuse-saving sequence for permanent faults

48. A 480V, three-phase, 400A panelboard with 400A bus. Load: 300A continuous + 50A noncontinuous = 350A. Per NEC 215.2(A)(1): OCPD = 125% × 300 + 50 = 425A → exceeds 400A bus. With 100%-rated 400A breaker: 350A ≤ 400A. The conductor at 75°C must handle 350A continuously. Per NEC Table 310.16: 500 kcmil = 380A (adequate with 8.6% margin). Is this installation compliant?

A. Yes — 350A ≤ 400A breaker and bus; 500 kcmil at 380A provides adequate ampacity (380 > 350) with 8.6% margin for the continuous load; the 100%-rated breaker eliminates the 125% adder, making the installation code-compliant

B. No — the conductor must provide 425A ampacity per the standard NEC 215.2 calculation

C. No — 500 kcmil is too small for 400A circuits

D. Yes — but 600 kcmil is recommended for better thermal margin

49. A three-phase, 480V system has a 3,000 kVA transformer (Z = 5.75%, X/R = 9) and 12 motors (combined FLA = 2,500A). Transformer fault = 36,130A. Motor contribution = 10,000A. Total symmetrical = 46,130A. Using X/R = 9 IEEE multiplier of 2.35, what is the peak asymmetrical current?

A. 65,200A (√2 × total)

B. 92,260A (2× total)

C. 46,130A (no asymmetry)

D. Peak = 2.35 × 46,130 = 108,406A — the 10,000A motor contribution (22% of total) significantly increases the peak from the transformer-only value of 84,906A; excluding motor contribution would undersize equipment momentary ratings by 22%, risking catastrophic bus failure during the first cycle of a fault

50. A 480V, three-phase, 200A feeder uses 250 kcmil THHN copper in steel conduit (R = 0.0541 Ω/1000 ft, X = 0.0442 Ω/1000 ft). The feeder is 650 feet long and serves a load at 0.85 lagging PF. What is the voltage drop percentage, and what action is recommended?

A. 1.5% — well within limits

B. V_drop = √3 × 200 × (0.0541×0.65×0.85 + 0.0442×0.65×0.527) = 346.4 × (0.02989 + 0.01514) = 346.4 × 0.04503 = 15.6V; 15.6/480 = 3.25%; exceeds the NEC 3% feeder recommendation; the engineer should upsize to 350 kcmil (R = 0.0367, X = 0.0407) which reduces the voltage drop to approximately 2.3%

C. 2.0% — within limits

D. 5.0% — grossly exceeds limits

51. Per NEC 110.14(C)(1), a 800A switchboard has terminals marked "90°C." The continuous load is 640A. Per NEC 215.2(A)(1): minimum ampacity = 125% × 640 = 800A. At 90°C: two parallel 500 kcmil = 2 × 430 = 860A (adequate). At 75°C: two parallel 500 kcmil = 2 × 380 = 760A (inadequate). Since the terminals are listed for 90°C, can the 90°C column be used?

A. Yes — terminals listed and marked for 90°C permit using the 90°C ampacity column per NEC 110.14(C)(1)(b); two parallel 500 kcmil at 90°C = 860A ≥ 800A required; each parallel set must be identical in material, size, length, and termination per NEC 310.10(G)

B. No — the 75°C column always governs for equipment over 100A

C. No — parallel conductors cannot use the 90°C column regardless of terminal rating

D. Yes — but three parallel sets are required for adequate margin

52. A 200 MVA synchronous generator has H = 4.5 MJ/MVA and delivers 160 MW when a three-phase fault occurs. Output drops to zero. Critical clearing angle = 115°. Relay = 0.015s, breaker = 0.035s, total = 0.050s. Using $\Delta\delta = (180f \times P\_a \times t^2)/(H \times S)$, what is the angle advance?

A. $\Delta\delta = (180 \times 60 \times 160 \times 0.050^2)/(4.5 \times 200) = (180 \times 60 \times 160 \times 0.0025)/900 = 4{,}320/900 = 4.8°$ — stability maintained with 110.2° margin; the ultrafast 0.050-second total clearing (achievable with modern optical relays and SF_6 breakers) produces minimal rotor advance

B. $\Delta\delta = 25°$ — marginal stability

C. $\Delta\delta = 115°$ — at critical clearing

D. $\Delta\delta = 50°$ — stability uncertain

53. A three-phase, 13.8 kV grounded-wye capacitor bank rated 10,800 kvar has four series groups of eight parallel units per phase (32 per phase, 96 total). Three units in the same series group of Phase C fail and their fuses blow. Five units remain. Each remaining unit sees 8/5 = 1.60× normal voltage (60% overvoltage). The neutral unbalance relay detects the condition and trips the bank. If the relay had failed to trip, what would happen next?

A. Nothing — the remaining units would operate normally at 160% voltage

B. The 60% overvoltage causes the remaining units to fail in rapid cascade

C. The bank would self-correct through automatic rebalancing

D. The 60% overvoltage far exceeds the IEEE C37.99 maximum 110% continuous rating; the remaining five units' insulation would rapidly degrade and fail, each failure further increasing voltage stress on surviving units; the cascade accelerates exponentially — within seconds to minutes, all five remaining units in that series group fail, potentially causing tank ruptures, dielectric fluid release, and fire; this scenario demonstrates why neutral unbalance protection with redundant relay systems is critical for large capacitor banks

54. A three-phase, 460V, 8-pole wound-rotor motor rated 1,200 HP has full-load speed 873 RPM. With external resistance: 330% starting torque at 340% FLA. A squirrel-cage Design D motor: 280% starting torque at 650% FLA. The application requires 320% breakaway torque. Only the wound-rotor can start the load. Calculate both motors' torque-per-ampere ratios.

A. Wound-rotor: 0.50; Design D: 0.43 — minor improvement

B. Wound-rotor: 0.97 (330/340); Design D: 0.43 (280/650); improvement factor = 2.26× — the wound-rotor achieves more than double the torque per ampere; additionally, only the wound-rotor meets the 320% requirement (330% > 320%), while the Design D cannot (280% < 320%), making the wound-rotor the ONLY viable option

C. Both achieve equal ratios

D. Design D has the superior ratio

55. Per NEC 310.15(C)(1), a raceway contains eight three-phase circuits (24 phase conductors) serving nonlinear loads. Five of the eight circuits have neutrals carrying significant triplen harmonics (5 neutral conductors counted). Three circuits have neutrals not carrying harmonics (excluded). Six EGCs are also present. What is the total count and adjustment factor?

A. 29 (24 phase + 5 neutrals); adjustment factor for 21-30 conductors = 0.35 per NEC Table 310.15(C)(1) — this extreme derating makes a single raceway completely impractical; the conductors would need to be approximately 3× larger than without the derating; splitting into at least four parallel raceways (approximately 7 conductors each) restores the 0.70 adjustment factor

B. 24 (phase only); factor = 0.35

C. 35 (all conductors); factor = 0.30

D. 29; factor = 0.40

56. A 480V, three-phase, 1,200A LVPCB main breaker has a 0.30-second STD. ZSI is installed with twelve feeder breakers. An optical arc relay and arc-resistant switchgear are also installed. The optical relay detects an arc in approximately 1.5 ms. The trip signal reaches the breaker trip coil in approximately 0.5 ms after detection. The breaker mechanism requires approximately 30 ms to open and interrupt. What is the total clearing time, and what calculated energy results (from original 55 cal/cm^2)?

A. Total = 1.5 + 0.5 + 30 = 32 ms = 0.032s; E = 55 × (0.032/0.30) = 5.87 cal/cm^2; but the arc-resistant switchgear redirects this energy away from the worker

B. Total = 0.30s; optical relay has no effect on clearing time

C. Total = 0.001s; optical relay instantaneously clears the fault

D. Total = 0.032s; E = 5.87 cal/cm^2; this represents an 89% reduction from the unmitigated 55 cal/cm^2 — combined with the arc-resistant enclosure redirecting energy, the worker's effective exposure is near zero; the permanent-magnet trip mechanism ensures the breaker opens even if the arc event destroys the control power supply

57. A protection engineer sets a 51 overcurrent relay (IEEE very inverse) on a 13.8 kV feeder. CT = 600:5 (120:1). Maximum load = 500A. Minimum fault = 1,800A. Pickup = 5A (primary = 600A). TD = 2.5. At the maximum fault of 12,000A: secondary = 100A; M = 100/5 = 20. Using $t = TD \times (19.61/(M^2-1) + 0.491)$, what is the operating time?

A. t = 1.0s — good operating speed for a feeder relay

B. t = 2.5 × (19.61/399 + 0.491) = 2.5 × (0.0491 + 0.491) = 2.5 × 0.5401 = 1.35s; this is the clearing time at the maximum fault current; at the minimum fault of 1,800A (M = 2.5): t = 2.5 × (19.61/5.25 + 0.491) = 2.5 × (3.735 + 0.491) = 2.5 × 4.226 = 10.57s — unacceptably slow at minimum fault; the pickup should be reduced to 4A (primary = 480A, just above max load) to increase M at minimum fault to 3.125

C. t = 5.0s — too slow

D. t = 0.25s — extremely fast

58. A 345 kV, 400-mile line has $Z_1 = 32 + j300\ \Omega$ total and $Z_0 = 96 + j900\ \Omega$ total. Source: Z_1_src = j20 Ω, Z_0_src = j30 Ω. For a bolted SLG fault at the remote end, calculate I_SLG and the ratio $|Z_0$_total$|/|Z_1$_total$|$.

A. I_SLG = 500A; ratio = 2.5

B. I_SLG = 200A; ratio = 4.0

C. Z_1_total = 32+j320; $|Z_1|$ = 321.6; Z_0_total = 96+j930; $|Z_0|$ = 934.9; ratio = 2.91; Sum = 160+j1,570; |Sum| = 1,578; V_f = 199,186V; I_SLG = 3 × 199,186/1,578 = 379A — the 400-mile line's extreme impedance limits SLG fault current to only 379A; the ratio of 2.91 indicates significant voltage elevation on unfaulted phases during SLG faults

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

59. Per NEC 700.10(B)(1), emergency wiring must be independent from normal wiring. A high-rise hospital has a central electrical shaft containing both emergency and normal raceways. The emergency conduits are in a fire-rated enclosure within the shaft (2-hour rated barrier between emergency and normal raceways). Is this installation compliant?

A. Yes — the 2-hour fire-rated barrier within the shaft provides the required separation between emergency and normal wiring systems; NEC 700.10(B)(1) requires independence of the wiring systems, and a fire-rated barrier within a shared shaft achieves this by preventing a fire in the normal wiring from affecting the emergency circuits during the 2-hour rated period

B. No — emergency and normal cannot share the same shaft

C. Yes — but only if the shaft is 4-hour rated

D. No — only separate shafts satisfy NEC 700.10(B)(1)

60. A three-phase, 480V, 225A panelboard has: Motor 1 = 96A (largest), Motor 2 = 52A, Motor 3 = 34A. Continuous lighting = 80A. Noncontinuous receptacles = 20A. Panelboard bus = 225A. Per NEC 430.24 and 215.2(A)(1): OCPD = 125% × 96 + 52 + 34 + 125% × 80 + 20 = 120 + 86 + 100 + 20 = 326A → next standard = 350A → exceeds 225A bus. With a 100%-rated 225A breaker: load = 96 + 52 + 34 + 80 + 20 = 282A. But 282A > 225A. What is the resolution?

A. The 100%-rated breaker does not help because 282A exceeds the 225A bus and breaker rating

B. Install a 300A panelboard with 300A bus

C. Reduce the lighting load to bring total below 225A

D. The panelboard must be upgraded to at least a 300A bus to accommodate the 282A total load; even with a 100%-rated breaker (which eliminates the 125% adder), the total load of 282A exceeds the 225A bus rating — the bus is the physical constraint that cannot be overcome by breaker selection alone

61. A balanced three-phase, 4,160V source feeds a 14,000 kW load at 0.68 lagging PF. Q = 14,000 × 1.078 = 15,092 kvar. The utility penalizes $5.00/kvar/month for excess above 0.95 PF. Q_allowed = 14,000 × 0.329 = 4,606 kvar. Excess = 10,486 kvar. Penalty = $52,430/month. What capacitor bank size eliminates the penalty?

A. 14,000 kvar (corrects to unity — oversized)

B. 10,486 kvar bank; monthly savings = $52,430; annual = $629,160; at approximately $20-30/kvar installed cost for a 13.8 kV capacitor bank, the total installation cost is approximately $210,000-315,000 — payback in 4-6 months; this is one of the highest-ROI investments available in any industrial facility

C. 5,000 kvar (partial correction only)

D. 15,092 kvar (eliminates all reactive power)

62. A 480V, three-phase MCC has 20 motors with combined FLA of 4,000A. Motor contribution = 16,000A. Transformer provides 45,000A. Total symmetrical = 61,000A. System X/R = 13. Using IEEE multiplier of 2.32, what is the peak asymmetrical current?

A. Peak = 2.32 × 61,000 = 141,520A — the enormous motor contribution (26% of total) drives the peak to extreme levels; excluding motor contribution would underrate equipment by 26%

B. 86,300A (√2 × total)

C. 122,000A (2× total)

D. 61,000A (no asymmetry)

63. A three-phase, 13.8 kV underground cable system is 50 miles long with charging current of 6.0A per mile per phase. A zero-sequence CT with 12A relay pickup and 0.5-second delay is installed. During normal energization, the cable charges at 300A per phase (900A total three-phase). A ground fault of 15A zero-sequence current develops. Does the relay operate correctly?

A. No — the relay sees 315A and trips immediately on overcurrent

B. Yes — but the relay sees 915A from combined charging and fault

C. Yes — the zero-sequence CT sees only the 15A fault current (balanced 300A/phase charging cancels to zero residual); since 15A > 12A pickup, the relay trips after 0.5 seconds; the massive 900A total charging current has absolutely zero effect on the zero-sequence CT measurement — this is the fundamental advantage of window-type zero-sequence CTs for ground-fault detection on long cable systems

D. No — 15A fault is too close to the 12A pickup for reliable detection

64. Per NEC 430.24, a feeder serves: Motor A = 515A (450 HP), Motor B = 414A (350 HP), Motor C = 302A (250 HP), Motor D = 242A (200 HP), Motor E = 180A (150 HP). Continuous lighting = 150A. Noncontinuous HVAC = 80A. What is the minimum feeder conductor ampacity?

A. 2,000A

B. 1,600A

C. 1,200A

D. 125% × 515 + 414 + 302 + 242 + 180 + 125% × 150 + 80 = 643.75 + 1,138 + 187.5 + 80 = 2,049.25A — this extremely high feeder ampacity requires multiple parallel conductor sets per phase, each with its own EGC per NEC 310.10(G)

65. A distance relay on a 230 kV line has Zone 1 at 85%, Zone 2 at 120% (0.35s). Z_line = 5 + j60 Ω. A fault occurs at 87% with 3 Ω fault resistance. Z_meas = (0.87×5 + 3) + j(0.87×60) = 7.35 + j52.2 Ω. |Z_meas| = 52.7 Ω. Zone 1 reach = 0.85 × 60.2 = 51.2 Ω. The fault is 1.5 Ω ABOVE Zone 1 reach. What protection operates?

A. Zone 1 — the mho circle may still contain this impedance at the line angle

B. Zone 2 trips after 0.35 seconds — the fault at 87% with 3 Ω resistance places the impedance slightly outside Zone 1 (52.7 > 51.2 Ω); the pilot scheme (if active) enables high-speed clearing through overreaching Zone 2 detection; without pilot, Zone 2 provides backup at 0.35 seconds

C. Zone 3 at 1.0 second

D. No zone detects the fault

66. A three-phase, 4,160V system has an NGR rated 400A, 10 seconds. A ground fault through 30 Ω develops. R_NGR = 6.005 Ω. I_fault = 2,402/36.005 = 66.7A. The relay pickup is 20A. At what fault resistance does the relay no longer detect the fault?

A. 50 Ω

B. 80 Ω

C. 100 Ω

D. R_max = V_LN/I_pickup − R_NGR = 2,402/20 − 6.005 = 120.1 − 6.005 = 114.1 Ω; any fault resistance above 114 Ω produces current below 20A and goes undetected; at the current fault (30 Ω, 66.7A), the relay has (66.7−20)/20 = 233% margin; this large margin provides good sensitivity for this moderate-resistance fault

67. Per NEC 480.9(A), all battery installations require ventilation considerations. A grid-scale battery energy storage system (BESS) uses lithium iron phosphate (LFP) cells in a containerized enclosure. The

system includes a battery management system (BMS) with cell-level monitoring. What ventilation design must address both normal operation and thermal runaway scenarios?

A. Standard lead-acid room ventilation is adequate for all lithium-ion chemistries

B. No ventilation is needed — the container is sealed and the BMS prevents all failure modes

C. Normal operation requires only standard HVAC for thermal management (LFP produces no hydrogen); however, the ventilation design must also address thermal runaway: (1) emergency exhaust fans sized to evacuate toxic off-gases (HF, CO, CO_2, electrolyte vapors) during a cell failure, (2) deflagration venting panels if gas accumulation could reach explosive limits, (3) fire-rated exhaust ductwork directed away from personnel and air intakes, (4) gas detection (HF sensor, combustible gas sensor) triggering automatic emergency exhaust activation

D. Only fire suppression is needed — ventilation is irrelevant for lithium batteries

68. A three-phase, 480V, 225A panelboard has an available fault current of 25,000A. An IEEE 1584 study shows 9.2 cal/cm² at 24 inches with a 0.15-second clearing time. An optical arc relay (0.010 seconds) and arc-resistant panel are proposed. What is the calculated incident energy and the worker's effective exposure?

A. E = 9.2 × (0.010/0.15) = 0.613 cal/cm² — below the 1.2 cal/cm² threshold; combined with the arc-resistant enclosure redirecting energy, the worker's effective exposure is near zero; this represents the gold standard of layered arc flash protection: sub-threshold electrical clearing combined with physical energy redirection

B. E = 4.6 cal/cm²; PPE Category 1 required

C. E = 9.2 cal/cm² (unchanged)

D. E = 0.613 cal/cm²; but the worker still needs Category 1 PPE because the optical relay may fail

69. A three-phase, 460V, 4-pole synchronous motor rated 3,000 HP drives a paper machine at 1,800 RPM. Pull-out = 230% FLT. H = 2.5 MJ/MVA. During a grid event, voltage sags to 74% for 0.7 seconds. Pull-out = 0.74 × 230% = 170.2% FLT. Load = 90% FLT. Margin = 80.2% FLT. Using H = 2.5 and the swing equation concept, what is the stability assessment?

A. Stable with excellent margin — the 0.7-second sag at 74% with H = 2.5 produces moderate rotor angle advance

B. Cannot be determined without detailed swing analysis

C. Unstable — 74% voltage always causes loss of synchronism

D. The 80.2% FLT steady-state margin appears adequate, but the swing equation must be evaluated: with H = 2.5 (moderate inertia for a large motor), the 0.7-second sag produces significant rotor angle advance; P_accel ≈ P_load − P_elec_reduced; the higher H (compared to 1.8 for smaller motors) slows the rotor acceleration, providing better stability performance; preliminary assessment suggests stability is maintained with moderate margin (angle advance approximately 20-35°), but a detailed transient stability simulation should confirm

70. A 230 kV, 300-mile line has Z_1_total = 24 + j225 Ω, Z_0_total = 72 + j675 Ω. V_f = 132.8 kV. I_SLG = 3 × 132,800/|Z_sum|. Z_sum = (24+j225) + (24+j225) + (72+j675) = 120 + j1,125. |Z_sum| = √(14,400 + 1,265,625) = 1,131.7 Ω. I_SLG = 398,400/1,131.7 = 352A. At this low current level, what is the primary protection concern?

A. 352A is adequate for all standard protection schemes

B. 352A on a 230 kV line is extremely low; the primary concerns are: (1) ground overcurrent relays must use very low pickup settings (potentially below normal load unbalance), creating false-trip risk; (2) distance relays measure impedance at the limits of their accuracy at low current; (3) pilot protection with communication-assisted tripping is essential for high-speed clearing because zone-distance backup may not reliably detect end-of-line faults; (4) line differential protection (87L) provides the most secure primary protection for this scenario

C. No protection concern — 352A is a standard fault current level

D. 352A is too low for any protection to detect

71. Per NEC 250.122(B), a 800A circuit has phase conductors of two parallel 500 kcmil (1,000,000 CM total), increased to two parallel 750 kcmil (1,500,000 CM total) for voltage drop. The minimum EGC from Table 250.122 for 800A OCPD = 1/0 AWG (105,600 CM). What is the proportionally increased EGC?

A. 1/0 AWG (no increase)

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

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

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

72. A balanced three-phase, 4,160V source feeds a 16,000 kW load at 0.70 lagging PF. The engineer installs a 14,000 kvar capacitor bank AND a 4,000 HP synchronous motor at 0.80 leading PF (η = 94%). What is the new bus PF?

A. Original Q = 16,326 kvar; cap = −14,000; sync motor: P_in = 3,174 kW; Q_sync = 2,381 kvar; net Q = 16,326 − 14,000 − 2,381 = −55 kvar (slightly leading!); P_total = 19,174 kW; PF = 19,174/19,174 ≈ unity — the combined correction slightly overcorrects, producing essentially unity PF; the engineer should slightly reduce the capacitor bank to avoid leading PF that could cause generator voltage regulation issues

B. PF = 0.95 lagging

C. PF = 0.90 lagging

D. PF = 0.85 lagging

73. A 100 MVA, 345/138 kV autotransformer has series impedance 10.5% on its own base. Three identical units in parallel. A 60 MVA generator (X"_d = 0.22 pu), a 40 MVA synchronous condenser (X"_d = 0.16 pu), a 25 MVA synchronous motor (X"_d = 0.20 pu), and a 15 MVA distributed solar inverter array (effective X"_d = 1.0 pu for fault contribution) are on the 138 kV bus. On a 100 MVA base, what is the total fault current?

A. I = (28.57 + 3.003 + 2.222 + 1.136 + 0.667) × 418.4 = 35.60 × 418.4 = 14,895A

B. 20,000A

C. 10,000A

D. Z_T_par = 0.105/3 = 0.035; Z_gen = 0.367; Z_SC = 0.40; Z_SM = 0.80; Z_solar = 6.667; I = (1/0.035 + 1/0.367 + 1/0.40 + 1/0.80 + 1/6.667) × 418.4 = (28.57 + 2.725 + 2.50 + 1.25 + 0.15) × 418.4

= 35.195 × 418.4 = 14,726A — the solar inverter's high effective impedance contributes minimally (0.4% of total), while the three parallel transformers dominate at 81%

74. A three-phase, 460V, 4-pole induction motor rated 250 HP operates at 1,770 RPM. A VFD reduces speed to 1,100 RPM for a centrifugal pump application. $P\_pump = 186.5 \times (1{,}100/1{,}770)^3 = 186.5 \times 0.240 = 44.8$ kW. VFD efficiency = 97%, motor efficiency at light load = 89%. What is the total supply power, and what is the annual energy savings versus full speed for 6,000 hours of reduced-speed operation at $0.080/kWh?

A. $P\_supply = 44.8/(0.89 \times 0.97) = 51.9$ kW; savings = $(186.5 - 51.9) \times 6{,}000 \times \$0.080 = \$64{,}608$/year

B. P_supply = 44.8 kW; savings = $67,920/year (motor losses not included)

C. P_supply = 100 kW; savings = $41,520/year

D. P_supply = 30 kW; savings = $75,000/year

75. Per NEC 430.32(A)(1), a motor with SF = 1.15 has maximum overload = 125% × FLA. A motor has FLA = 400A, SF = 1.20. The overload is set at 500A (125%). The motor drives a reciprocating compressor with cyclic loading that periodically reaches 115% FLA (460A) for 5 seconds every minute. Does the overload relay trip during the cyclic overload?

A. Yes — 460A exceeds the motor's continuous rating of 400A

B. No — the overload relay trips on the basis of equivalent thermal heating (I^2t), not instantaneous current; the cyclic overload of 460A for 5 seconds followed by 55 seconds of normal operation produces an equivalent heating effect well below the 500A continuous trip point; the relay's thermal model integrates the I^2t over time and does not accumulate enough thermal energy during the brief 5-second peaks to reach the trip threshold

C. Yes — 460A exceeds the 500A setting after accounting for the relay's safety margin

D. No — but only if the compressor cycle is less than 3 seconds

76. A 480V, three-phase system has a 3,500 kVA transformer (Z = 5.75%, X/R = 9) and a 2,000 kVA transformer (Z = 6.50%, X/R = 7) in parallel. I_T1 = 42,200A; I_T2 = 22,515A; total = 64,715A.

Twelve motors (FLA = 2,000A) add 8,000A first-cycle. Grand total = 72,715A. Weighted X/R ≈ 8.3. IEEE multiplier = 2.32. What is the peak asymmetrical current?

A. Peak = 2.32 × 72,715 = 168,699A — the combined transformer and motor fault current at this peak level produces forces on bus structures proportional to $(168,699)^2 = 28.5 \times 10^9$ A^2, demanding extraordinary mechanical bracing design

B. 102,850A (√2 × total)

C. 145,430A (2× total)

D. 72,715A (no asymmetry)

77. A three-phase, 4,160V, 12-pole synchronous motor rated 4,500 HP drives a ball mill at 600 RPM. Pull-out = 260% FLT. H = 1.5 MJ/MVA. During a catastrophic grid event, voltage drops to 60% for 2.0 seconds. Pull-out = 0.60 × 260% = 156% FLT. Mill = 100% FLT. Margin = 56% FLT. At H = 1.5 and t = 2.0 seconds, what happens?

A. Stable — 56% margin is adequate for any duration

B. Marginally stable — detailed analysis required

C. The motor trips on undervoltage relay before stability is a concern

D. Certain instability — at H = 1.5 (low inertia), the rotor accelerates rapidly during the 2.0-second sag; $\Delta\delta \propto t^2$, so 2.0 seconds produces 400× the angle advance of 0.1 seconds; even with 56% FLT margin, the accumulated angular momentum at this low H pushes the rotor far past the critical clearing angle within the first 0.5-1.0 seconds; the motor will lose synchronism well before the 2.0-second sag ends, likely within the first second

78. Per NEC 110.24(A), service equipment must be marked with available fault current. A facility originally had two 2,000 kVA transformers in parallel (Z = 5.75% each), producing 62,748A. One transformer is replaced with a 3,000 kVA unit (Z = 4.5%). The new paralleled combination no longer has identical units. What is the new total fault current?

A. 62,748A (unchanged — same number of transformers)

B. I_new_T1 = 2,406/0.0575 = 41,843A (original 2,000 kVA); I_new_T2 = 3,608/0.045 = 80,178A (new 3,000 kVA); Total = 122,021A — a 94% increase from the original 62,748A; this dramatically higher fault current requires comprehensive reverification of all downstream equipment SCCR ratings, updated NEC 110.24 marking, new arc flash study, and verification of all series-rated combinations

C. 80,178A (new transformer only)

D. 50,000A (the larger transformer reduces total fault current)

79. A 1,000 kVA, 480V/208Y/120V transformer has Z = 5.5% and X/R = 5.5. The symmetrical RMS fault current at 208V = 10,500A. Using the IEEE multiplier of 2.19 for X/R = 5.5, what is the peak asymmetrical first-cycle current?

A. 14,850A (√2 × symmetrical)

B. 21,000A (2× symmetrical)

C. Peak = 2.19 × 10,500 = 22,995A — this determines the momentary withstand for all 208V equipment; the peak-to-symmetrical ratio of 2.19 at X/R = 5.5 produces moderate asymmetry typical of medium-sized dry-type distribution transformers

D. 10,500A (no asymmetry)

80. A 400 kW, three-phase, 480V resistance heater operates as a continuous load, running 22 hours/day, 7 days/week, 52 weeks/year. Electricity costs $0.062/kWh. Per NEC 210.20(A), minimum OCPD = 125% of continuous load. What is the load current, minimum OCPD, annual energy consumption, and annual cost?

A. I = 481.1A; OCPD = 125% × 481.1 = 601.4A → next standard = 700A per NEC 240.6(A); E = 400 × 22 × 7 × 52 = 3,203,200 kWh; cost = $198,598/year — this nearly $200,000 annual energy cost for a single heater demonstrates the enormous financial impact of industrial resistance heating

B. I = 400A; OCPD = 500A; E = 3,203,200 kWh; cost = $198,598

C. I = 481.1A; OCPD = 600A; E = 2,000,000 kWh; cost = $124,000

D. I = 481.1A; OCPD = 500A; E = 3,203,200 kWh; cost = $198,598

Practice Exam 20: Answer Key and Explanations

1. B — The six-pulse VFDs inject 7th harmonic at approximately 20% of fundamental, dominating the resonance risk at h_r = 8.01. However, the 18-pulse drives' residual 7th (2% due to supply unbalance) is amplified by the near-resonance condition — even small currents near h_r experience significant voltage magnification. The AFE drives contribute negligibly. Detuning is driven by the six-pulse contribution, but the 18-pulse residual adds measurably to total harmonic injection.

2. D — Panel A (200 ft, 500 kcmil) has the lowest cable impedance → highest fault current. Panel B (350 ft, 350 kcmil) has moderate impedance. Panel C (500 ft, 4/0 AWG) has the highest impedance → lowest fault current. Each panel's arc flash energy varies with fault current per IEEE 1584, and each may require different PPE category labels.

3. C — NEC 430.52 establishes MAXIMUM overcurrent protection sizes, not minimums. Any OCPD at or below the maximum that permits the motor to start without nuisance tripping is compliant. A 300A time-delay fuse provides significantly tighter short-circuit protection than the 450A maximum, with lower let-through energy during faults, while the fuse's inherent time-delay characteristic accommodates motor starting inrush.

4. A — False differential = 75 − 30 = 45A (60% CT saturation). A dual-slope relay uses low slope (e.g., 20%) at low restraint for internal fault sensitivity and high slope (e.g., 60%) at high restraint to accommodate severe CT saturation during external through-faults. This adaptive characteristic provides dependability for internal faults while maintaining security against the extreme CT saturation caused by X/R = 28 DC offset.

5. A — X_eff = (1 − 0.45) × X_line = 0.55 × X_line. P_max = V_SV_R/X_eff = P_max_old/0.55 = 1.82 × P_max_old — approximately 82% increase. Distributing the 45% compensation at three points reduces peak voltage across each bank during faults (reducing subsynchronous resonance risk) and provides a more uniform voltage profile than single-point midpoint compensation.

6. B — Ratio = 1,000,000/700,000 = 1.429. EGC = 83,690 × 1.429 = 119,553 CM. From wire tables: 1/0 AWG = 105,600 CM (below — insufficient). 2/0 AWG = 133,100 CM (above — adequate). The minimum EGC is 2/0 AWG per the proportional increase calculation of NEC 250.122(B).

7. A — Sync motor: P_in = 1,984 kW; Q_sync = 1,488 kvar. Total correction = 7,000 + 1,488 = 8,488 kvar. Net Q = 9,352 − 8,488 = 864 kvar. P_total = 9,984 kW. PF = 9,984/10,021 = 0.996 ≈ 0.99. The

combined correction eliminates 91% of the original reactive demand while adding 2,500 HP of useful mechanical output.

8. C — Phase RMS = $\sqrt{(400^2 + 128^2)}$ = 420A. With 4 current-carrying conductors (0.80 factor): phase needs 420/0.80 = 525A base ampacity. Neutral needs 384/0.80 = 480A. The phase requirement of 525A governs. This is 31% larger than the 400A fundamental would suggest — demonstrating the dramatic impact of harmonics combined with derating on conductor sizing.

9. D — Reactor-grounded: I_SLG = 3/1.031 = 2.91 pu. Solidly grounded: I_SLG = 3/0.51 = 5.88 pu. The reactor reduces SLG to 49.5% of solidly grounded while maintaining the purely reactive (90° lag) character. Critically, the reactor-grounded SLG (2.91 pu) is now BELOW I_3Φ (5.0 pu), which simplifies equipment ratings and protection coordination compared to the solidly grounded case where SLG exceeds three-phase.

10. B — Each event: $(218.3/400)^2 \times (1.0/10) = 0.298 \times 0.10 = 2.98\%$. Three events = 8.93%. The 5-minute and 10-minute gaps between faults allow significant partial cooling of the NGR (thermal time constant typically 5-15 minutes), reducing actual thermal stress below the simple I^2t sum. The NGR retains approximately 91% of its capacity.

11. A — NEC 110.34(F) requires warning signs on metal-enclosed equipment over 600V. The sign must read "DANGER — HIGH VOLTAGE — KEEP OUT." The minimum letter height per the NEC is 0.5 inches (12.7 mm) to ensure visibility and readability from a safe distance.

12. C — k_max = 56.3%. Neither 90% nor 20% is near optimal. At 90%: P_Cu = 24,300W; E_out = 45,360 kWh; E_loss = 540.8 kWh. At 20%: P_Cu = 1,200W; E_out = 3,920 kWh; E_loss = 85.6 kWh. Total η = 49,280/(49,280+626.4) = 98.74%. Including stray losses yields approximately 97.2%. The heavy-load shift dominates both output and losses.

13. D — M = 150/5 = 30. t = 3.0 × (19.61/(900−1) + 0.491) = 3.0 × (0.0218 + 0.491) = 3.0 × 0.5128 = 1.538s. CTI = 1.538 − 0.005 = 1.533s. While coordination is maintained, the relay is unnecessarily slow at M = 30. Reducing TD to 1.5 would halve the operating time to approximately 0.77 seconds while maintaining CTI above 0.20 seconds.

14. B — |Z_meas| = 59.2 Ω with Zone 1 reach = 61.4 Ω → 3.6% margin. Combined CT error (±3%) and PT error (±3%) = worst-case 6% measurement error: 59.2 × 1.06 = 62.8 Ω > 61.4 Ω. The relay could see

the fault as outside Zone 1, reverting to Zone 2 (0.35s delay). This is precisely why Zone 1 is set at 80-85% — to provide margin for measurement instrument errors.

15. A — $P = 298 \times 0.72^3 = 298 \times 0.3732 = 111.2$ kW. Savings = $(298 - 111.2) \times 5{,}200 \times \$0.085 = 186.8 \times 5{,}200 \times 0.085 = \$82{,}534$/year. A 28% speed reduction produces a 62.7% power reduction through the cubic relationship — demonstrating the extraordinary savings potential of VFDs on centrifugal loads.

16. C — $H_2 = 1{,}200 \times 0.007 = 8.4$ ft^3/hr. Max $H_2 = 0.01 \times 15{,}000 = 150$ ft^3. ACH = 8.4/150 = 0.056. For mission-critical data centers, the ventilation must include: N+1 redundant fans, hydrogen detection with automatic fan start, UPS-powered ventilation to maintain airflow during utility outages, and BMS alarming. A ventilation failure during extended battery charging is a potentially catastrophic scenario.

17. C — The sudden load rejection causes transition from above-SIL to below-SIL. The line's shunt capacitance now generates excess reactive power, causing rapid voltage rise. The SVC responds within 1-2 cycles (fastest device) by absorbing maximum reactive power. Shunt reactors are switched on for sustained absorption. The SVC's fast response prevents transient overvoltage while slower mechanical switching provides continued correction.

18. A — During plugging: the supply voltage (−480V) opposes E_a (+460.8V). I_plug = (480 + 460.8)/0.12 = 940.8/0.12 = 7,840A — catastrophically high without current limiting. R_limit = (480 + 460.8)/320 − 0.12 = 2.94 − 0.12 = 2.82 Ω to limit to 200% rated (320A). The limiting resistor is essential for safe plugging operation.

19. D — Every transformer and generator is a separately derived system: 3 service transformers + 3 generators + 8 PDU transformers + 4 lab isolation transformers + 2 UPS isolation transformers = 20 total. Each requires its own bonding jumper at its source per NEC 250.30(A)(1), establishing an independent ground reference and fault return path.

20. B — E = 48 × (0.022/0.30) = 3.52 cal/cm^2. The Type 2B arc-resistant switchgear redirects all arc energy away from the front. The permanent-magnet trip mechanism ensures the breaker opens even if the arc event destroys control power. The worker's effective exposure at the front is near zero through this layered defense.

21. A — All equipment on the faulted phase must be rated for the SLG fault level of 5.08 pu, which exceeds the three-phase value of 4.35 pu by 17%. While symmetrical interrupting ratings are based on

three-phase faults, the single-phase duties (bus bars, CTs, cables on the faulted phase) must withstand the higher SLG current. Ground-fault relay coordination must account for this elevated current level.

22. C — Per NEC 430.24: 125% × 414 = 517.5A. Other motors = 302 + 242 + 180 = 724A. Per NEC 215.2(A)(1): 125% × 220 = 275A. Noncontinuous = 65A. Total = 517.5 + 724 + 275 + 65 = 1,581.5A. The 125% applies independently to the largest motor and the continuous non-motor load.

23. D — On 50 MVA base: I = (20.0+14.29+11.11+8.33+2.50+1.67+1.0) × 6,940 = 58.90 × 6,940 = 408,766A. Seven parallel sources produce this extraordinary fault current. All equipment must have extremely high SCCR ratings, and current-limiting devices are essential throughout the distribution system.

24. B — The series combination must be re-evaluated whenever modifications affect available fault current per NEC 110.24(B). If utility upgrades, transformer changes, or parallel source additions increase the available fault current, the fuse let-through at the new level must be verified below panelboard SCCR. Fuse replacements must use identical type and rating per the listing.

25. A — The maximum system voltage of 1,163.8V at −25°C exceeds the 1,000V DC equipment rating. This is a NEC 690.7 voltage violation separate from rapid shutdown compliance. The system must reduce string length to 18 modules (952.2V) or use 1,500V-rated equipment. The rapid shutdown optimizers function correctly but cannot fix the over-voltage design error.

26. D — I_T1 = 65,600A; I_T2 = 52,296A; Total = 117,896A. Peak = 2.33 × 117,896 = 274,698A. This quarter-million-ampere-plus peak creates extraordinary electromagnetic forces proportional to I^2_peak on the paralleled 480V bus. Mechanical bracing design is the dominant engineering challenge.

27. B — The near-end relay detects the fault in Zone 2 (95% > 85%) and receives a permissive signal from the remote end (which tripped on Zone 1). The POTT logic enables instantaneous tripping at the near end — the Zone 2 time delay is overridden by the permissive trip. Both ends achieve high-speed clearing simultaneously.

28. A — At 120% rated (low restraint level), the 20% low slope applies. Threshold = 20% × 5.0 = 1.0A. False differential of 1.5A > 1.0A → FALSE TRIP. Even 30% CT saturation at modest fault levels defeats the low slope. The relay's breakpoint should be set below this restraint level so the 60% high slope provides security during through-faults.

29. C — Maximum = 125% × 4,811 = 6,013.75A. Since this doesn't match a standard size, NEC 450.3(B) permits the next higher standard. The engineer must identify the next available standard size above 6,013.75A from the manufacturer's product line. The exact size depends on available fuse or breaker ratings at this current level.

30. D — The swing equation with P_a = 1.119 MW, H = 2.0, S = 4.4 MVA: $\Delta\delta$ = (180 × 60 × 1.119)/(2.0 × 4.4) = 12,085/8.8 = 1,373°. This enormous value indicates the motor WILL lose synchronism — the simplified formula confirms that 1.0 second at 70% voltage with H = 2.0 for a SAG mill motor produces catastrophic instability. The motor must be tripped on undervoltage.

31. B — I_T1 = 3,608/0.055 = 65,600A. I_T2 = 3,007/0.0575 = 52,296A. I_T3 = 2,406/0.06 = 40,100A. I_T4 = 1,804/0.0625 = 28,864A. Total = 186,860A ≈ 184,717A with rounding. Four parallel transformers produce this staggering fault current. At X/R ≈ 8, the peak asymmetrical approaches 430 kA, demanding extraordinary bus bracing.

32. A — Four violations: V_5 (10.1%), V_7 (6.8%), V_{11} (4.2%) exceed 3.0%, and THD (13.5%) exceeds 5.0%. V_{13} = 2.8% is within limits. Interim mitigation without VFD shutdown: install tuned passive harmonic filters (5th, 7th, 11th) on the 13.8 kV bus — these filters sink harmonic currents without requiring VFD modifications. Alternatively, connect an active harmonic filter to the bus.

33. A — Corrected = 0.6 × 1.3 = 0.78 Ω. Meets MIL-STD-188-124B (0.78 < 10 Ω) with enormous margin (factor of 12.8×). However, 0.78 Ω marginally exceeds the IEEE 80 substation target of 0.5 Ω if applicable. The appropriate standard depends on the facility classification — military communication sites typically apply MIL-STD, not IEEE 80.

34. C — 70 kvar = 82% of 85 kvar no-load magnetizing — below the absolute self-excitation limit but above the typical 67% manufacturer recommendation. 90 kvar > 85 kvar — UNSAFE, exceeding no-load magnetizing and risking self-excitation. P_in = 456 kW; Q_orig = 221 kvar; with 70 kvar: Q_new = 151 kvar; PF_new = 0.95. The engineer should confirm with the manufacturer regarding the 82% level.

35. D — Full: 250 × 2,000 = 500,000. 85%: 250 × 0.614 × 2,500 = 383,813. 65%: 250 × 0.275 × 2,800 = 192,220. 40%: 250 × 0.064 × 1,460 = 23,360. VFD total = 1,099,393 kWh. Full-speed = 2,190,000 kWh. Savings = 1,090,607 kWh (49.8%). The cubic relationship produces nearly 50% energy reduction across the four operating modes.

36. B — R = 0.0608 × 550/1000 = 0.03344 Ω. X = 0.0478 × 550/1000 = 0.02629 Ω. V_drop = √3 × 200 × (0.03344 × 0.83 + 0.02629 × 0.558) = 346.4 × (0.02776 + 0.01467) = 346.4 × 0.04243 = 14.7V. V_drop% = 14.7/480 = 3.06%. Exceeds the NEC 3% recommendation — upsize to 250 kcmil or 350 kcmil.

37. A — Z_T_par = 0.0333. Z_gen = 0.44. Z_SC = 0.16 × 100/35 = 0.457. Z_SM = 1.25. I_pu = 30.0 + 2.273 + 2.188 + 0.80 = 35.26. I = 35.26 × 836.7 = 29,502A. The three parallel transformers provide 85% of total, with rotating machines contributing 15%.

38. C — Total symmetrical = 111,265 + 11,200 = 122,465A. Peak = 2.34 × 122,465 = 286,568A. Over a quarter million amperes peak. The electromagnetic forces proportional to I^2_peak at 287 kA demand extraordinary mechanical bracing — approximately 1,000× the forces of a typical 42 kA single-transformer system.

39. D — R_g ≈ 200/(4×50) + 200/1000 = 1.0 + 0.2 = 1.20 Ω. Exceeds the 1.0 Ω target by 20%. The engineer must either expand grid area (reducing the first term — resistance ∝ 1/√A), add more buried conductor length (reducing the second term), or apply ground enhancement material to reduce effective soil resistivity.

40. A — Cable: R = 0.05362, X = 0.03724 Ω. Z_cable_pu = 0.0653/0.0922 = 0.708 pu. Total Z = 0.766 pu. I = 3,007/0.766 = 3,926A — only 9.2% of switchboard value. The 700-foot 3/0 cable dramatically reduces fault current and arc flash energy, but the engineer must verify that protective devices can still clear faults at this reduced current level.

41. C — Z_1_total = 0.2083 pu. Z_0_total = 0.0833 pu. I_3Φ = 4.80 pu. I_SLG = 3/(0.2083+0.2083+0.0833) = 3/0.50 = 6.0 pu. Exceedance = (6.0−4.80)/4.80 = 25%. The delta blocking source Z_0 creates a dramatically lower zero-sequence impedance, producing SLG current 25% above three-phase. This affects CT sizing, bus ratings, and relay coordination.

42. B — 45 kvar < 60 kvar (safe, 75% of no-load magnetizing). 70 kvar > 60 kvar (unsafe — 117% of no-load magnetizing). P_in = 272 kW; Q_orig = 140 kvar; with 45 kvar: Q_new = 95 kvar; PF_new ≈ 0.95. The 70 kvar exceeds the self-excitation limit and could sustain the motor's magnetic field after disconnection, producing dangerous overvoltage.

43. D — At 91.7A restraint (well above 3× rated breakpoint of 15A), the 60% high slope applies. Threshold = 60% × 91.7 = 55.0A. False differential of 59.6A > 55.0A → FALSE TRIP. Even the 60%

high slope is insufficient for 65% CT saturation at X/R = 30. The CT must be upgraded or the relay must use additional security features such as cross-blocking or waveshape analysis.

44. A — $I_{phase} = \sqrt{(450^2+180^2+90^2+45^2)} = \sqrt{245{,}025} = 495.0$A. Neutral: triplens only = 3×180 = 540A (5th and 7th cancel balanced). Ratio = 540/495 = 1.091. THD = $\sqrt{(180^2+90^2+45^2)}/450 = 206.3/450 = 45.8\%$. The neutral exceeds the phase by 9.1%, requiring oversized neutral and mandatory counting as current-carrying.

45. C — Splitting devices: Panel B → 4.2 mA (0.8 mA margin); Panel C → 3.7 mA (1.3 mA margin). This maximizes headroom across all three panels while avoiding the cost of a fourth panel. Panel A stays at 4.3 mA (0.7 mA margin). Cross-panel connections within the same operating suite are acceptable practice.

46. B — $\sin\delta = 900 \times 58/(362 \times 336) = 52{,}200/121{,}632 = 0.4292$. $\delta = 25.4°$. VR = (362−336)/336 = 7.74%. Stability fraction = $\sin(25.4°) = 0.429 = 42.9\%$. The line operates at 43% of its stability limit — adequate but requiring monitoring during contingencies that could reduce V_R or increase load.

47. D — The delayed curve (0.12s) is slower than the fuse total clearing (0.04s). The fuse blows at 0.04 seconds, isolating the faulted underground lateral. The recloser sees no fault current and holds closed, restoring service to unfaulted sections. This is the designed fuse-saving sequence: fast trip saves the fuse for temporary faults; delayed trip lets the fuse blow for permanent faults.

48. A — With 100%-rated breaker: 350A ≤ 400A breaker and bus. Conductor: 500 kcmil at 75°C = 380A ≥ 350A with 8.6% margin. The 100%-rated system eliminates the 125% continuous adder. The conductor carries the actual 350A load continuously within its 380A thermal rating.

49. D — Total symmetrical = 36,130 + 10,000 = 46,130A. Peak = 2.35 × 46,130 = 108,406A. The motor contribution of 10,000A (22% of total) significantly increases the peak. Excluding motors would undersize equipment momentary ratings by 22%, risking catastrophic mechanical failure during the first fault cycle.

50. B — $R = 0.0541 \times 650/1000 = 0.03517\ \Omega$. $X = 0.0442 \times 650/1000 = 0.02873\ \Omega$. $V_{drop} = 346.4 \times (0.03517\times0.85 + 0.02873\times0.527) = 346.4 \times (0.02989+0.01514) = 346.4 \times 0.04503 = 15.6$V. $V_{drop}\% = 3.25\%$. Exceeds 3% NEC recommendation. Upsize to 350 kcmil to reduce to approximately 2.3%.

51. A — Terminals listed and marked for 90°C permit using the 90°C ampacity column per NEC 110.14(C)(1)(b). Two parallel 500 kcmil at 90°C = 2 × 430 = 860A ≥ 800A required. At 75°C (760A), this would be inadequate. The 90°C rating saves the cost and space of larger conductors.

52. A — $\Delta\delta = (180 \times 60 \times 160 \times 0.0025)/900 = 4{,}320/900 = 4.8°$. The rotor advances less than 5° during the 0.050-second fault — far below the 115° critical clearing angle. The ultrafast clearing (achievable with modern optical relays and SF_6 breakers) provides outstanding transient stability with 110° of margin.

53. D — 8/5 = 1.60× normal voltage (60% overvoltage) far exceeds the IEEE C37.99 maximum 110% continuous rating. Without neutral unbalance relay protection, the remaining five units fail in rapid cascade — each failure increases voltage on survivors, accelerating the cascade exponentially. Within seconds to minutes, catastrophic bank failure occurs. Redundant neutral unbalance protection is essential.

54. B — Wound-rotor: 330% > 320% → starts successfully. T/I = 330/340 = 0.97. Design D: 280% < 320% → cannot start. T/I = 280/650 = 0.43. Improvement = 0.97/0.43 = 2.26×. Only the wound-rotor meets the 320% requirement while achieving more than double the torque efficiency per ampere.

55. A — Twenty-four phase + five harmonic-carrying neutrals = 29 current-carrying conductors (EGCs and non-harmonic neutrals excluded). Per NEC Table 310.15(C)(1) for 21-30 conductors: factor = 0.35. This extreme 65% derating makes a single raceway completely impractical — splitting into at least four parallel raceways is essential.

56. D — Total clearing = 1.5 ms (detection) + 0.5 ms (signal) + 30 ms (mechanism) = 32 ms = 0.032s. $E = 55 \times (0.032/0.30) = 5.87$ cal/cm² — an 89% reduction. The arc-resistant enclosure redirects this energy away from the worker. The permanent-magnet trip ensures breaker opening even if control power is destroyed.

57. B — At maximum fault (M = 20): $t = 2.5 \times (19.61/399 + 0.491) = 2.5 \times 0.540 = 1.35$s. At minimum fault (M = 2.5): $t = 2.5 \times (19.61/5.25 + 0.491) = 2.5 \times 4.226 = 10.57$s — unacceptably slow. Reducing pickup from 5A to 4A increases M at minimum fault to 3.125, significantly improving the operating time. This demonstrates the importance of optimizing pickup-to-load ratio.

58. C — Z_1_total = 32+j320; $|Z_1|$ = 321.6. Z_0_total = 96+j930; $|Z_0|$ = 934.9. Ratio = 2.91. Sum = 160+j1,570; |Sum| = 1,578. I_SLG = 3 × 199,186/1,578 = 379A. The 400-mile line limits SLG current to only 379A, and the 2.91 Z_0/Z_1 ratio indicates significant unfaulted-phase voltage elevation.

59. A — NEC 700.10(B)(1) requires independence of wiring systems. A 2-hour fire-rated barrier between emergency and normal raceways within a shared shaft provides the required separation. The fire rating ensures that a fire affecting normal wiring cannot reach the emergency circuits for at least 2 hours — adequate for life-safety evacuation timelines.

60. D — Total load = 96 + 52 + 34 + 80 + 20 = 282A. Even with a 100%-rated 225A breaker, 282A exceeds the 225A bus rating. The bus is the physical constraint — it cannot carry 282A continuously regardless of breaker type. The panelboard must be upgraded to at least 300A bus to accommodate the total load.

61. B — Excess = 10,486 kvar. Penalty = 10,486 × \$5.00 = \$52,430/month (\$629,160/year). A 10,486 kvar capacitor bank at approximately \$20-30/kvar installed = \$210,000-315,000. Payback in 4-6 months — one of the highest-ROI investments available in industrial power systems.

62. A — Total symmetrical = 45,000 + 16,000 = 61,000A. Peak = 2.32 × 61,000 = 141,520A. The motor contribution of 16,000A (26%) significantly impacts the peak. Excluding motors would underrate equipment momentary ratings by 26%, risking catastrophic bus failure.

63. C — The zero-sequence CT measures only residual (unbalanced) current. Balanced 300A/phase charging cancels to zero. The 15A fault produces 15A residual. Since 15A > 12A pickup, the relay trips after 0.5 seconds. The 900A total charging has zero effect on the zero-sequence CT — this is the fundamental advantage of window-type CTs for ground-fault detection.

64. D — Per NEC 430.24: 125% × 515 = 643.75A. Other motors = 414+302+242+180 = 1,138A. Motor subtotal = 1,781.75A. Per NEC 215.2: 125% × 150 = 187.5A. Noncontinuous = 80A. Total = 1,781.75 + 187.5 + 80 = 2,049.25A. Multiple parallel conductor sets per phase with individual EGCs are required.

65. B — |Z_meas| = 52.7 Ω exceeds Zone 1 reach of 51.2 Ω. The fault plus fault resistance places the impedance outside Zone 1. Zone 2 at 120% covers the fault. With pilot active, high-speed clearing occurs via POTT. Without pilot, Zone 2 provides backup at 0.35 seconds.

66. D — R_max = V_LN/I_pickup − R_NGR = 2,402/20 − 6.005 = 114.1 Ω. Any fault resistance above 114 Ω produces current below 20A pickup. At the current 30 Ω fault: I = 66.7A, giving 233% margin above pickup. This is the fundamental sensitivity limitation of LRG systems for high-impedance ground faults.

67. C — Normal LFP operation requires only HVAC thermal management (no hydrogen). The critical design is for thermal runaway: emergency exhaust sized for toxic off-gases (HF, CO, electrolyte vapors), deflagration venting, fire-rated ductwork away from personnel, and gas detection triggering automatic emergency exhaust. Standard lead-acid or NiCd ventilation guidelines do not apply.

68. A — E = 9.2 × (0.010/0.15) = 0.613 cal/cm² — below the 1.2 cal/cm² threshold. Combined with arc-resistant enclosure redirecting energy, the worker's effective exposure is near zero. This represents the gold standard: sub-threshold electrical clearing combined with physical energy redirection.

69. D — The 80.2% FLT steady-state margin appears adequate, but the swing equation evaluation is critical. At H = 2.5 (moderate inertia), the 0.7-second sag at 74% produces approximately 20-35° of angle advance. The higher H (compared to smaller motors) slows acceleration, providing better stability performance. Preliminary assessment suggests stability is maintained, but transient stability simulation should confirm.

70. B — I_SLG = 352A is extremely low for a 230 kV system. Ground overcurrent relays need very sensitive settings (risking misoperation). Distance relays have reduced accuracy at low current. Pilot protection with communication-assisted tripping is essential. Line differential (87L) provides the most secure primary protection for end-of-line faults at this low current level.

71. C — Ratio = 1,500,000/1,000,000 = 1.50. EGC = 105,600 × 1.50 = 158,400 CM. From wire tables: 2/0 AWG = 133,100 (below). 3/0 AWG = 167,800 (above — adequate). The minimum EGC is 3/0 AWG per the proportional increase calculation.

72. A — Original Q = 16,000 × 1.020 = 16,326 kvar. Cap = −14,000. Sync motor: P_in = 3,174 kW; Q_sync = 2,381 kvar. Net Q = 16,326 − 14,000 − 2,381 = −55 kvar (slightly leading). PF ≈ unity. The combined correction slightly overcorrects — the engineer should reduce the capacitor bank to avoid leading PF that could cause generator voltage regulation issues.

73. D — Z_T_par = 0.035. Z_gen = 0.367. Z_SC = 0.40. Z_SM = 0.80. Z_solar = 6.667. I_pu = 28.57 + 2.725 + 2.50 + 1.25 + 0.15 = 35.195. I = 35.195 × 418.4 = 14,726A. The solar inverter's high impedance contributes only 0.4% of total, while three parallel transformers dominate at 81%.

74. B — P_pump = 44.8 kW. P_supply = 44.8/(0.89 × 0.97) = 51.9 kW. Savings = (186.5 − 51.9) × 6,000 × $0.080 = 134.6 × 6,000 × 0.08 = $64,608/year. The cascade of reduced motor efficiency (89% vs 95% at full load) and VFD losses adds 7.1 kW but is trivial compared to the 135 kW saved.

75. C — The overload relay's thermal model integrates I^2t over time. Cyclic loading of 460A for 5 seconds per minute produces equivalent heating = $(460^2\times5 + 400^2\times55)/60$ = (1,058,000 + 8,800,000)/60 = 164,300 A^2s/s equivalent ≈ 405A equivalent continuous. Since 405A < 500A trip setting, the relay does NOT trip. The brief peaks never accumulate enough thermal energy.

76. A — Total symmetrical = 64,715 + 8,000 = 72,715A. Peak = 2.32 × 72,715 = 168,699A. The electromagnetic forces proportional to $(168{,}699)^2$ demand extraordinary mechanical bracing. Motor contribution of 8,000A (11%) adds measurably to the peak.

77. D — At H = 1.5 (very low inertia) with t = 2.0 seconds at 60% voltage: $\Delta\delta \propto t^2$ means 2.0 seconds produces 400× the advance of 0.1 seconds. The motor will lose synchronism well before the 2.0-second sag ends — likely within the first 0.5-1.0 seconds. The combination of low H, deep voltage sag, and extremely long duration makes instability virtually certain.

78. B — I_T1 = 2,406/0.0575 = 41,843A (original 2,000 kVA, Z = 5.75%). I_T2 = 3,608/0.045 = 80,178A (new 3,000 kVA, Z = 4.5%). Total = 122,021A — a 94% increase from 62,748A. The larger kVA AND lower Z% combine to dramatically increase fault current, requiring comprehensive downstream equipment verification.

79. C — Peak = 2.19 × 10,500 = 22,995A. The X/R = 5.5 produces moderate asymmetry at approximately 2.19× symmetrical RMS. This determines the momentary withstand rating for all 208V equipment downstream of the transformer.

80. A — I = 400,000/(√3 × 480 × 1.0) = 481.1A. Min OCPD = 125% × 481.1 = 601.4A. Per NEC 240.6(A), the next standard above 601.4A is 700A (standard sizes include 600, 700). E = 400 × 22 × 7 × 52 = 3,203,200 kWh. Cost = 3,203,200 × $0.062 = $198,598/year. This nearly $200,000 annual cost demonstrates the enormous financial impact of industrial resistance heating.