

Module 2.5 — Switchboards, Switchgear & Transformers (Troubleshooting)

Transformer symptoms and testing with real numbers, switchgear fault trees, pad-mounts, busway, power-quality surveys, and restoring power safely.

Why this module. Switchboards, switchgear, and transformers carry the most energy in the building, so an arc flash here can kill. Most diagnosis is done by measuring from outside the gear, then de-energizing to inspect and test. This module walks step by step through transformer symptoms (heat, noise, wrong voltage, trips), testing a transformer with real pass/fail numbers, switchgear faults (breakers that will not close or trip with no load), liquid-filled and pad-mount units, busway, a power-quality survey, and putting power back on safely after an outage.

Part A — Transformer Symptoms

DRY-TYPE TRANSFORMER — SYMPTOM → CHECK

OVERHEATING	→ Overload (clamp the secondary) · blocked ventilation · wrong taps · harmonics (non-linear loads)
EXCESSIVE HUMMING / NOISE	→ Loose core/coil clamping · loose mounting · overload · or just normal magnetostriction
WRONG SECONDARY VOLTAGE	→ Tap set wrong (re-check vs supply) · supply high/low · wrong connection
TRIPS / FAILS	→ Winding-to-ground breakdown (MEGGER it) · shorted turns · overload protection sized wrong

Overheating, noise, wrong voltage, or tripping. Each points to a short list of causes.

Symptom	Check, in order
Overheating	Clamp the secondary (overloaded?) → neutral current (harmonics) → ambient and blocked ventilation → wrong taps → connections
Excessive hum or noise	Shipping braces or core-clamp nuts on a new unit → loose panels or rigid conduit → worn isolation pads → overvoltage → normal hum for its size
Wrong secondary voltage	Measure all six secondary voltages → open primary fuse or pole → tap setting vs. measured supply → open neutral
Trips or fails	Inrush on energizing → winding-to-ground breakdown (megger) → shorted turns (TTR) → protection sized wrong

Energized measurements are energized work. Voltage readings, clamp readings, IR scans with covers off, and logger hookups are done by a qualified person inside the arc-flash boundary, in the PPE on the label, with a CAT III or CAT IV meter. Apprentices watch and record.

Step by step: an overheating transformer

1. **Read the nameplate:** kVA, primary and secondary voltage, temperature rise, and required clearances. Rated secondary current = $\text{kVA} \times 1000 \div (1.732 \times \text{secondary line-to-line volts})$.
2. **Clamp all three secondary phases and the neutral** under normal load with a true-RMS clamp meter.
3. **Compare to rated current.** Eaton: "Continuous overload capability is not intentionally designed into general purpose transformers."
4. **Check the neutral.** If the neutral carries as much current as the phases or more while the phases are balanced, harmonic currents from electronic loads are adding on the neutral. Log the harmonics (Part G); Module 1.5C Part F covers the fix.
5. **Measure the air at the intake.** Eaton's limits: 40°C maximum, and a 24-hour average of 30°C or less. Above that the transformer must be derated (NEMA ST-20).
6. **Check ventilation** (de-energized if you must get close). NEC 2026 450.11 (450.9 in 2023) requires ventilation that will "dispose of the transformer full-load heat losses without creating a temperature rise that is in excess of the transformer rating," openings "not blocked by walls or other obstructions," and the clearances marked on the unit. Horizontal tops must be "marked to prohibit storage." Boxes stacked on top are a violation and a heat trap.
7. **Clean it** (de-energized, Schneider): vacuum first. If you use air, keep it at 25 psi or less with a dew point of -50°F or lower. "Do not use liquids, solvents, or detergents." Clear dust out of the coil ducts.
8. **Check the connections:** IR-scan them energized, then measure contact resistance de-energized (Part B).

Worked example 1. A 75 kVA, 480 V delta to 208Y/120 V transformer. Rated secondary current = $75,000 \div (1.732 \times 208) = 208$ A. The clamp reads 231 A on one phase. $231 \div 208 = 111$ percent. The transformer is overloaded by 11 percent; move load to another source or replace it with a larger unit.

A hot top is not proof of trouble. On a dry-type with a 150°C rise rating, an enclosure 50°C above room air is normal (Eaton). Judge by current and by comparison with its own past readings.

Hum and noise

Situation	Likely cause (Schneider, Eaton)
Normal levels for comparison	45 kVA about 45 dB; 75 and 112.5 kVA about 50 dB
New install, loud	Shipping braces still in, core-clamp nuts not loosened per the manual, loose panels, rigid conduit bolted to the enclosure (use flexible conduit)
Getting louder over months	"Inspect the sound isolation pads for signs of physical deterioration."
Loud, primary reading high	Overvoltage. Limits: 5 percent over rated secondary at rated load, 110 percent at no load. Measure the primary.

Step by step: wrong secondary voltage (measure all six)

1. Measure the primary line-to-line voltages at the transformer disconnect: A-B, B-C, C-A.
2. Measure the six secondary voltages: line-to-line X1-X2, X2-X3, X3-X1, and line-to-neutral X1-X0, X2-X0, X3-X0.
3. Measure neutral-to-ground at the first secondary disconnect. It should be about 0 V.
4. Match the readings to the table.

Pattern of the six readings	Likely cause	Next step
All six low (or high) by the same percent	Supply is off nominal, or the tap is wrong	Compare the measured primary to the tap setting
One line-to-neutral near 120 V, two low and about equal, one line-to-line near 0	One primary phase is open (blown primary fuse or open breaker pole) on a delta primary	Check the primary fuses and poles before blaming the transformer
Line-to-neutral unequal, line-to-line normal	Open or high-resistance neutral, or missing system bonding jumper	Inspect X0, the bonding jumper, and the neutral lugs
One line-to-neutral at 0, the rest normal	Open secondary winding or lug	Contact resistance and winding tests (Part B)

Why an open primary looks that way. With one primary phase lost, one winding still gets full line voltage. The other two windings sit in series across that same voltage, so each gets about half, pointing the opposite way. An engineer on Eng-Tips summed it up: "Two phases will be at 1/2

volts, and the third at full volts." Running motors can regenerate the missing phase and partly hide it, so check the primary fuses directly. Learn the pattern; the exact voltages vary with load.

Tap math. Secondary volts $\approx$ primary volts $\times$ 208 $\div$ tap volts (for a 480 to 208Y/120 V unit).

Measured primary	Tap	Secondary
480 V	+2½% (492 V)	$480 \times 208 \div 492 = 202.9 \text{ V}$
480 V	-2½% (468 V)	$480 \times 208 \div 468 = 213.3 \text{ V}$
456 V	480 V (nominal)	$456 \times 208 \div 480 = 197.6 \text{ V}$
456 V	456 V tap	about 208 V

Change taps only with the transformer de-energized and locked out. UFC 3-560-01: "Never operate no-load (or manual) tap changers when the transformer is energized." Because voltage sags 2 to 3 percent from no load to full load (Module 1.5C), measure both loaded and unloaded before picking a tap.

Trips when you energize it

1. An instant trip the moment the primary breaker closes, with little secondary load, is usually **magnetizing inrush**, the large current a transformer draws for a few cycles while its core magnetizes (theory and the Table 450.5(B) sizing option in Module 1.5C).
2. Megger the windings first (Part B) so you know you are not closing into a real fault.
3. Read the breaker type: magnetic-only, or adjustable instantaneous. Check whether the primary breaker was sized at 125 percent with no allowance for inrush. Check whether the transformer is reverse-fed (fed from its low-voltage side), which raises inrush (Eaton).
4. Fix it by design (breaker type or setting chosen by the engineer). Never by closing again and again (Part H).

For a transformer that trips or fails in service, run the megger, TTR, and winding-resistance tests in Part B, and recheck its overcurrent protection against NEC 2026 450.5 (450.3 in 2023).

Hunting a secondary ground fault

Services of 1000 A or more at 480Y/277 V have ground-fault protection (GFPE). Under NEC 2026 230.95(C) (230.95(A) in 2023), the "maximum setting ... shall be 1200 amperes, and the maximum time delay shall be one second for ground-fault currents equal to or greater than 3000 amperes." Under 230.95(E) (230.95(C) in 2023) it is performance tested at first install by primary current injection, with a written record for the AHJ.

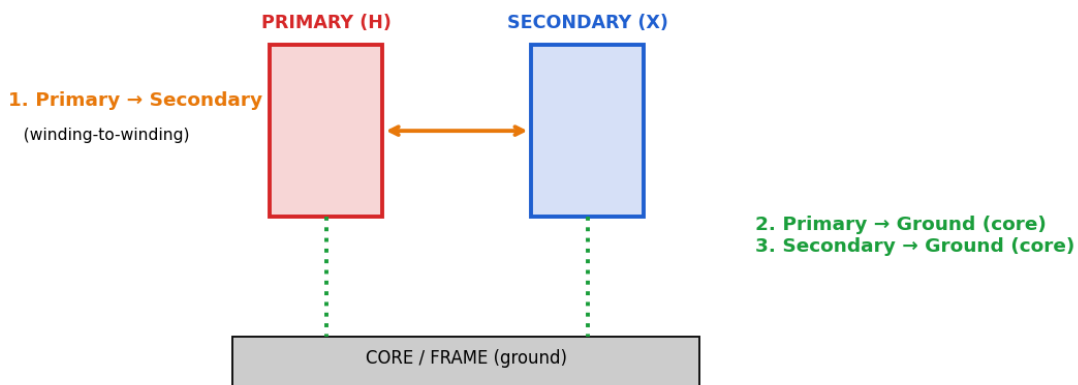
1. Read the trip unit's G flag and event log before resetting anything.
2. Lock out and verify dead. Open all feeders.
3. Isolate surge protective devices (SPDs), meters, control power transformers, and the ground-fault sensing wiring.

4. Megger each feeder phase to ground at 1,000 V DC. When one feeder reads low, split it at its next panel and test again until you find the section with the fault.
5. Also megger neutral to ground with the bonding jumper lifted. A neutral-to-ground bond downstream lets normal neutral current read as a ground fault (Module 2.4 Part F).

High-resistance grounded systems alarm instead of tripping on the first ground fault. Use the system's pulser: "The current pulses can be noted with a clamp-on ammeter ... The fault may be located at the point where the pulsing current drops off or stops" (Eaton). The pulse is about 4 A above the standing ground current. NEC 2026 250.36 allows impedance grounding at 480 to 1000 V only with qualified maintenance, ground detectors, and no line-to-neutral loads.

Part B — STEP-BY-STEP: Testing a Transformer

TRANSFORMER INSULATION TESTS (de-energized, with a Megger)



All three should read HIGH megohms. A LOW reading on any pair = insulation breakdown (moisture, contamination, or a failing winding).

Megger three insulation pairs: primary-to-secondary, primary-to-ground, secondary-to-ground.

1. **Record energized data first:** the six voltages, phase and neutral currents, and an IR scan.
2. **Create an electrically safe work condition** (Part D), with both primary and secondary disconnected. Let the coils cool: Eaton labels them a "Burn hazard."
3. **Look it over.** Dirt blocking airflow, loose lugs, tap boards, and "tracing or carbonization" on insulation (Schneider); "tracking (discharge), breaks, cracks, or burns" (Eaton).
4. **Contact resistance** with a low-resistance ohmmeter (DLRO) on bolted connections. Investigate any connection reading "more than 50%" above the lowest similar values (Schneider). Repair and torque the connections that failed this test or showed heat on the IR scan, to the label value with a calibrated torque wrench (NEC 110.14(D)).
5. **Insulation resistance (megger).** Lift the primary and secondary cables and the X0 bonding jumper. Jumper H1-H2-H3 together, and X1-X2-X3-X0 together. Test high-to-low, high-to-ground, and low-to-ground at 1,000 V DC for 1 minute each. Ground each winding at least 1 minute between tests to drain the charge.

6. **TTR (turns-ratio) test** on every tap and every phase. Phases should agree within 0.5 percent (Schneider). One bad phase after a fault means shorted turns.
7. **Winding resistance** (usually units over 500 kVA, done by a test company): within 5 percent of the adjacent coils and of the baseline, corrected for temperature.
8. **Ground bond**: measure from the system grounding point to the enclosure, core, frame, and clamps, and compare to the baseline.
9. Reconnect everything you lifted, install the covers, energize, and re-measure the six voltages.

Test	Acceptance	Source
Megger, dry-type 0-600 V at 1,000 V DC	500 megohms or more	ANSI/NETA ATS and MTS
Megger, liquid-filled 0-600 V	100 megohms or more	ANSI/NETA ATS and MTS
Megger, absolute floor	"at least 1 megohm. Lower readings may indicate the presence of moisture."	Schneider IB 43006-850-01
TTR	Within 0.5 percent between coils	Schneider
Winding resistance	Within 5 percent of adjacent coils and baseline	Schneider
Contact resistance	Investigate over 50 percent above similar connections	Schneider

Crew rule: under 1 megohm, do not energize. Between 1 and 500 megohms, compare to the commissioning readings and call it in. A wet transformer can be dried with heated air at 110°C or less (Eaton). Test annually in clean rooms, every 3 to 6 months in dirty ones, and "after any severe electrical short circuit, ground fault, or environmental event (e.g., flooding)" (Schneider).

Part C — Switchboard & Switchgear Inspection

Step by step: thermography

1. Scan under stable load and record the percent load for each image. Heating rises with the square of current, so a joint at half load makes a quarter of the heat it will make at full load.
2. Set the camera's emissivity and distance correctly; Schneider warns that setup errors "can cause significant errors."
3. Opening covers to scan is energized work. Where the gear has IR windows, scan through them instead.
4. Grade each finding with the table.

ΔT vs. similar part, similar load	ΔT vs. ambient	Action (ANSI/NETA MTS Table 100.18)
1–3°C	1–10°C	Possible deficiency; investigate
4–15°C	11–20°C	Probable deficiency; repair as time permits
—	21–40°C	Monitor until corrected
Over 15°C	Over 40°C	Major deficiency; repair immediately

Step by step: repairing a hot bus joint

1. Create an electrically safe work condition on the section (Part D).
2. Inspect the flagged joint for discoloration, pitting, and Belleville (cone) washers that are no longer flat.
3. Measure it with a DLRO. Investigate a joint more than 50 percent above similar joints (NETA ATS, Module 1.5B).
4. Replace pitted or de-plated parts. Do not sand or file plated bus. NEC 110.12(B) says busbars must not be "damaged or contaminated by foreign materials such as ... abrasives."
5. Torque to the label on the gear. Example values for Square D QED-2 Grade 5 hardware:
3/8-16 bolts 20 ft-lb, 1/2-13 bolts 50 ft-lb.
6. Megger the section, re-energize, and re-scan at stable load.

Repair the joints the scan flags; leave the rest alone. Do not re-torque every bus joint on a schedule. Torque is applied only to a joint you have taken apart or one that showed heat or high resistance, and only de-energized.

Insulators, barriers, and draw-out breakers

- **Insulators and barriers:** look for cracks and **carbon tracking** (black tree-shaped tracks, a flashover path forming). Clean per the manufacturer.
- **Draw-out breakers:** check the primary disconnect fingers, lubrication, and racking mechanism. Exercise the breaker (open and close) so it stays free.
- **Protective relays and trip units:** verify the settings against the coordination study and functional-test where possible.

Fault tree: the breaker will not close (check in this order)

1. **Closing springs charged?** Schneider: "Stored energy mechanism not charged. Charge the mechanism manually." On electrically operated GE breakers the motor needs at least 85 percent of rated control voltage.
2. **Trip indicator or bell-alarm lockout reset?** Schneider: "The reset button signalling a fault trip has not been reset." Find out why it tripped before you reset it.
3. **Interlocks:** padlock, key interlock, or a transfer interlock ("interlocked mechanically in a source changeover system").
4. **Racking position.** Schneider: "not completely connected." Between TEST and CONNECTED the breaker is held trip-free and cannot close.

5. **Undervoltage release powered?** Schneider's MN release needs more than 85 percent of rated voltage; GE's UVR allows closing only above 80 percent.
6. **Standing shunt-trip signal?** Schneider: "MX opening voltage release permanently supplied ... The order must be cancelled." Trace the emergency power off (EPO), fire alarm, and ground-fault relay contacts.
7. **Close-coil control power** (0.85 to 1.1 times rated) and the control power transformer fuses.
8. **Trip unit seated** properly (GE).
9. **Closes, then trips with a fault flag:** Schneider calls it "Closing on a short-circuit." Stop and megger the load side.

GE warns that repeated close attempts on a latched-tripped breaker "will damage the breaker mechanism."

Fault tree: the breaker trips with little or no load

Trip flag	Look for
G (ground fault)	Downstream neutral-to-ground bond, missing or miswired neutral sensor on a 4-wire system, a ground fault on an idle feeder (Part A)
I or S	A load-side fault, or settings below the inrush current. Compare to the coordination study.
No flag	A shunt trip (EPO, fire alarm, transfer switch logic) or undervoltage release dropout: "MN undervoltage release supply voltage too low."
Trips on inrush, 1200 A or larger	Energy-reducing maintenance switch left ON. Check its status light first (240.87(B)(3)).

NEC 2026 240.87 applies where the breaker "is rated or can be adjusted is 1200 amperes or higher." It bars "Temporary adjustment of the instantaneous trip setting to achieve arc energy reduction" and requires a performance test at first install. Replacement trip units must be listed for the breaker they go in (240.89).

Relay flags on medium-voltage gear (awareness)

Photograph every relay flag and download the event records before anyone resets them. Common device numbers: 27 undervoltage, 47 negative-sequence voltage, and 59N neutral overvoltage can detect single-phasing; 50/51 is overcurrent; 86 is a lockout relay that must be reset by hand and blocks closing until it is.

Blown medium-voltage fuses

- **Voltage transformer (VT) primary fuses** (UFC 3-560-01): modern draw-out VTs "automatically disconnect and ground the transformers." On older gear, de-energize and verify with "a suitably rated voltmeter (a handheld test meter with a high-voltage probe is not acceptable)." A dark lamp on the VT secondary "is not an adequate indication." Pull the secondary fuses before replacing the primary fuse.

- **Customer medium-voltage switch fuses:** find and megger the fault before you re-fuse.
- **Pad-mount fuses** (Bay-O-Net) are usually the utility's (Part E).

Tracking and partial discharge (awareness)

Partial discharge is small sparking inside insulation that grows into a failure. Signs: black tracks or white powder on insulators, an ozone smell, and a hiss or crackle. Test companies use a TEV probe on the enclosure plus an ultrasonic detector at gaps and cable boxes; EA Technology describes the sound as "a sizzling frying pan" and treats a reading more than 20 dB over background as needing further testing. It occurs in metal-clad gear "operating above 2500V." An apprentice's job: report it, keep the door shut, and never open a crackling cubicle.

Part D — Do It Safely

This gear can kill from across the room. De-energize and lock out. If you must work it live, follow the arc-flash label and rated PPE (Module 2.1). Use **remote racking** from outside the boundary. Never defeat an interlock.

The electrically safe work condition (NFPA 70E 2024, 120.6)

1. Identify all sources of supply from drawings and labels, including backfeed from generators and tie breakers.
 2. Interrupt the load current and open the disconnecting devices.
 3. Verify that the blades are open or draw-out breakers are "withdrawn to the 'test' or fully disconnected position."
 4. Release stored electrical energy (capacitors).
 5. Block or release stored mechanical energy, such as charged closing springs.
 6. Apply lockout/tagout devices.
 7. Test each phase "phase-to-phase and phase-to-ground" with a meter proven on a known source before and after.
 8. Apply grounds where induced or stored voltage is possible.
- OSHA 1910.333(a)(1): de-energize unless that is infeasible or creates a greater hazard.
 - Racking (UFC 3-560-01): "Utilize remote racking mechanisms when available," open the breaker first, "Discharge the stored-energy mechanism," and "Check that protective interlocks are functioning." Remote racking distances are in Module 1.5B.
 - UFC 3-560-01: "Consider all transformers energized and at full voltage unless they are disconnected from primary and secondary wires." A transformer can be backfed from its secondary.
 - **Labels:** NEC 110.16 requires an arc-flash label on switchboards, switchgear, panelboards, and MCCs likely to be serviced while energized (read the printed code for its exact contents). 110.24 requires non-dwelling service equipment to be "legibly marked in the field with the

available fault current," with the date, and recalculated after changes. A new utility transformer makes both labels out of date.

- NEC 110.17: servicing is done by qualified persons, per the manufacturer's instructions, with "identified replacement parts."

Part E — Liquid-Filled and Pad-Mount Transformers (Awareness)

A liquid-filled transformer has its core and coils in a tank of insulating oil. A pad-mount is a liquid-filled unit in a locked steel cabinet on a concrete pad, usually owned by the utility.

- **Fittings to recognize** (Eaton): pressure-relief device, fill plug, external no-load tap changer, drain valve and sampler, liquid-level gauge, Bay-O-Net fuses, and tank ground pads. Read the level against the marks on the gauge and record it.
- **Pressure and vacuum** (UFC 3-560-01): relieve pressure "slowly." Never open a relief valve in "precipitation or high humidity, except on failed transformers and when re-fusing." "Never draw an oil sample, open a pressure relief valve, or otherwise open a transformer when there is an internal vacuum on an energized transformer. Doing so can cause an explosion."
- Energized pad-mounts must be "locked or otherwise secured when unattended."
- **Dissolved gas analysis (DGA)**: a lab tests an oil sample for gases such as hydrogen, methane, ethylene, and acetylene. IEEE C57.104: "Formation of acetylene becomes appreciable only at temperatures nearing 1000 °C," so acetylene points to arcing inside the tank. Samples are drawn by trained testers with a gas-tight syringe. Apprentices never pull samples.
- **The utility boundary**. The NEC does not cover installations under the exclusive control of an electric utility (NEC 90.2, "Not Covered" list). Measure at your service disconnect, then call the utility. Never open the primary compartment of a utility pad-mount.

Part F — STEP-BY-STEP: Busway Hot Spots (Article 368)

Busway is factory-built bus bars in a metal housing, with bolted joints every section and plug-in units for taps.

- NEC 2026 368.30: supports "not exceeding 1.5 m (5 ft) unless otherwise designed and marked." 368.12(D): not in wet, damp, or outdoor locations unless identified. 368.60: connected to an equipment grounding conductor. 368.3 bans reconditioned busway of certain types.
 1. IR-scan every joint and plug-in unit at full load (Eaton Pow-R-Way III).
 2. For a hot joint: de-energize and lock out, pull the joint covers, and look for "gaps in the contact surface areas, cracks in the insulators, and contaminants or corrosion."
 3. Clean or replace the parts, then torque the joint to its label. Eaton Pow-R-Way III joints take 55 to 65 ft-lb, and the Belleville washers sit flat when torqued. Other brands differ.

4. Clean with a brush, vacuum, or rag. "Do not use a blower or compressed air" (Eaton Pow-R-Flex).
5. Megger the run (below). Replace any section that took on moisture.
6. Re-energize and re-scan.

Busway megger test (Eaton)

1. Disconnect the busway from transformers, switchboards, and meters first.
2. Test at 1,000 V. A 4-wire run takes 10 readings: three phase-to-phase, three phase-to-neutral, three phase-to-ground, and neutral-to-ground.
3. Minimum megohms = $100 \div \text{run length in feet}$.
4. To find a short, split the run at a middle joint and test each half. Another method injects about 25 percent of rated current and IR-scans for where the bus changes from warm to cold (EC&M).

Worked example 2. A 250 ft run must read at least $100 \div 250 = 0.4$ megohms. A 40 ft run must read at least $100 \div 40 = 2.5$ megohms.

Part G — STEP-BY-STEP: Power-Quality Survey

A power-quality logger records voltage, current, harmonics, and events over days so you can see what a single meter reading misses. The Fluke 1738 is an example: it measures three phases and neutral, is rated "1000 V CAT III/600 V CAT IV," uses flexible current probes for 10 to 1500 A, logs at intervals from 1 second to 30 minutes, records harmonics 2 to 50, THD, unbalance, dips, swells, interruptions, and inrush, and stores "10 logging sessions of 8 weeks with 1-minute intervals."

1. **State the question:** a hot transformer, nuisance trips, lights flickering at 7 a.m. Pick the point: the transformer secondary main or the panel main.
2. Get the energized-work permit and wear the label PPE. A qualified person connects the fused or magnetic voltage leads.
3. Set the logger for 3-phase wye, the nominal voltage, the current range, and the interval: 1 minute for a week-long load study, 1 second for an event hunt.
4. Clamp the flexible probes on the three phases and the neutral, arrows toward the load.
5. Run the logger's connection check, which flags reversed probes and wrong phase order.
6. Close up and log through a full operating cycle; a week covering weekdays and the weekend is common shop practice, not a code requirement.
7. Read the results: phase and neutral current against the nameplate, voltage THD against IEEE 519's 5 percent guideline, current THD, unbalance, and any dips or inrush at the times breakers tripped.
8. Write a short report with screenshots, compared to the transformer kVA and breaker settings.

Part H — STEP-BY-STEP: Restoring Power After an Outage or Trip

Do not reclose until you know it is safe. OSHA 1910.334(b)(2): after a circuit is de-energized by a protective device, "the circuit may not be manually reenergized until it has been determined that the equipment and circuit can be safely energized." Repeated manual reclosing is prohibited. UFC 3-560-01: if the trip is not a known overload, "do not reclose."

1. **Collect the evidence:** trip flags, relay targets, event logs, what was running, visible damage, and utility status.
2. **Create an electrically safe work condition** on the affected section.
3. **Megger the bus and feeders** with SPDs, meters, ground-fault sensing, and control power isolated. Eaton's SPD manual: meggering with the SPD installed "WILL CAUSE INTERNAL DAMAGE TO THE SPD. THE SPD WILL ALSO CAUSE THE TEST TO FAIL."
4. **Water or fire damage:** NEC 2026 408.3 says equipment "damaged by products of combustion, corrosive influences, or water ... shall be specifically evaluated by its manufacturer or a qualified testing laboratory prior to being returned to service." Schneider calls for full testing after a flood or severe fault.
5. **Repair** what you found, then reconnect everything you lifted for testing.
6. **Before re-energizing** (UFC 3-560-01 Appendix J): inspect and remove tools and nonessential items, warn workers, remove grounds, remove LOTO devices, confirm all clear, and "Check voltage and phasing before re-energizing."
7. **Turn everything downstream OFF.** Close the upstream main, then the feeders one at a time, then the branch circuits. EC&M: "Energize the breaker or switch feeding the busway first, followed by feeder devices and then branch circuit devices. Do not energize with loads applied."
8. **Stagger transformers and large motors** so their inrush currents do not add up and trip the main's instantaneous or ground-fault element.
9. **Verify:** re-measure the six voltages, check motor rotation, IR-scan at stable load, and write the event record.

Common Mistakes

Mistake	Why it matters
Reclosing into a fault	OSHA 1910.334(b)(2); damages the breaker mechanism and can cause an arc flash
Meggering with SPDs, meters, CPTs, or GF sensors connected	Damages the devices and fails the test
Condemning a transformer that is single-phased by an open primary fuse	Check primary fuses and all three primary voltages first
Meggering without lifting the load cables and X0 bond	You test the building wiring, not the coil
Moving taps with the transformer energized	Prohibited by the manufacturer and UFC 3-560-01
Resetting a GF trip or 86 lockout with no cause found	The fault is still there
Re-torquing every bus joint on a schedule	Torque only flagged or disassembled joints, de-energized
Maintenance switch left ON, or an unlisted trip unit	Nuisance trips (240.87(B)(3)); violates 240.89
Shop-air blowout of busway or transformer coils	Pushes dirt and moisture into the insulation
Opening a pad-mount relief valve in rain or under vacuum	Moisture entry or explosion (UFC 3-560-01)

NEC 2026 Checkpoints (2023 number in parentheses where it moved)

- **110.12(B)** damaged parts • **110.14(D)** torque • **110.16** arc-flash label • **110.17** servicing • **110.24** available fault current • **110.26** working space • **110.41** pre-energization tests and report.
- **230.95(C)** (230.95(A)) GFPE setting • **230.95(E)** (230.95(C)) GFPE performance testing • **250.36** impedance grounding.
- **240.87** arc energy reduction • **240.89** replacement trip units.
- **368.3, 368.12, 368.30, 368.60** busway.
- **408.3** reconditioned and damaged equipment • **408.6** short-circuit rating.
- **450.5** (450.3) transformer overcurrent protection • **450.10** guarding • **450.11** (450.9) ventilation • **450.16** disconnecting means.
- Also: NETA MTS test values; NFPA 70E 120.6; OSHA 1910.333 and 1910.334(b)(2).

Hands-On Field Exercise

- Measure all six secondary voltages and the primary on a dry-type transformer, then work out the tap and check it against the supply.
- Clamp a transformer's phases and neutral and calculate percent of rated current.

- Megger the three insulation pairs of a de-energized dry-type with cables and X0 lifted, and grade the results against the table.
- IR-scan a switchboard under load, record percent load, and grade each joint with the NETA table. Repair one flagged joint de-energized.
- Walk a "breaker will not close" call through the nine-step fault tree on a draw-out breaker.
- Calculate the busway megger minimum for the runs on a job.
- Set up a power-quality logger on a panel main and read back one day of data.
- Write the restore-power sequence for a building with a main, three feeders, and two transformers.

Sources used in this module (public documents)

- NFPA 70, National Electrical Code 2026 (free read-only access at [nfpa.org](https://www.nfpa.org)). NFPA 70E, 2024 edition, 120.6.
- Schneider Electric, IB 43006-850-01 Dry-Type Transformers Class 7400; MasterPact NT/NW Maintenance Guide: se.com
- Eaton PUB53311 Dry-Type Transformer Installation, Operation and Maintenance Manual; Consulting Application Guide (Tabs 17, 19, 36); Pow-R-Way III and Pow-R-Flex busway instructions; Pow-R-Line CS and SPD Series manuals: eaton.com
- ABB/GE Power Break II GEH-6270; ABB K-Line breaker IB 6.1.12.1-1E: library.e.abb.com
- UFC 3-560-01 Electrical Safety, O&M (Change 3, 2023): wbdg.org
- ANSI/NETA ATS and MTS (InterNational Electrical Testing Association, netaworld.org).
- OSHA 29 CFR 1910.333 and 1910.334: osha.gov
- IEEE C57.104-2019 (dissolved gas analysis) and IEEE 519 (harmonics): ieee.org
- Fluke 1736/1738 power logger data sheet: fluke.com
- EA Technology UltraTEV Plus+ user guide: eatechnology.com
- EC&M, Busway Installation and Troubleshooting Tips (2024): ecmweb.com
- J. Horak, A Practical Guide for Detecting Single-Phasing on a Three-Phase Power System (WPRC 2002): wprcarchives.org. Eng-Tips forum thread on blown primary fuses: eng-tips.com

Next: Module 2.6 — Troubleshooting Motors, Controls & MCCs.