Sympathetic Events Resulting from Capacitor Transients

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Everything's Connected

- How we think: Transmission, substations, and distribution systems are islands that do not affect each other.
  - We know this isn't true, but we subconsciously think and act as if it is.
- Reality: Everything is connected to everything (it's a matter of degree).
- Root-cause analyses often focus on the point of failure, but the real cause can be miles away.
- There are multiple categories of sympathetic events. This presentation will focus on capacitor-induced sympathetic failures.

Source Data for Examples

Data for examples in this presentation…

- Use Texas A&M Engineering’s database (1400 circuit-years).
- Are real-world events.
- Occurred during routine utility circuit operations.
- Are not staged or based on simulated data.

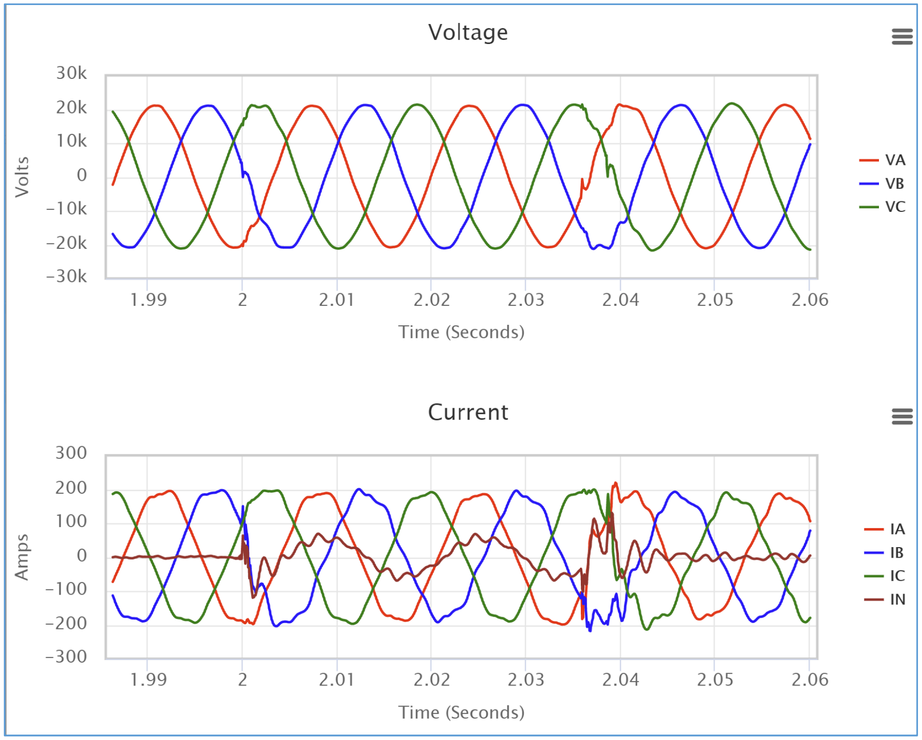
Characteristics of Data Used for Examples

- Purpose-designed monitor system
- Per-circuit monitoring at distribution substation
- Conventional circuit CTs and bus PTs
- 19 ENOB (effective number of bits) at 256 samples/cycle
  - Bits and sample rates are necessary but not the only considerations!!!
- Sensitive triggering
  - Necessary for detecting low-magnitude anomalies
  - Many detections rely on currents, not just significant voltage sags/surges
  - Results in multiple recordings per circuit per day
- Long records: 10s of seconds instead of 10s of cycles (necessary for some events)
- Accessibility: Monitoring system automatically makes records available at a central location within a few minutes of event.

Routine Capacitor Transients – Physics

- Capacitors don't like instantaneous voltage changes! (***I = C dV/dt = high***)
- On a distribution circuit, energizing a capacitor (switching it on) causes high-frequency voltage and current transients of significant magnitude.
  - Usually a few hundred Hertz; usually damped in a fraction of a cycle
  - Switching a capacitor off does not suddenly change capacitor voltage and therefore does not cause similar transients.
- The transients propagate across the circuit, to the bus, and beyond.

Routine Capacitor Transients – Field Measurement

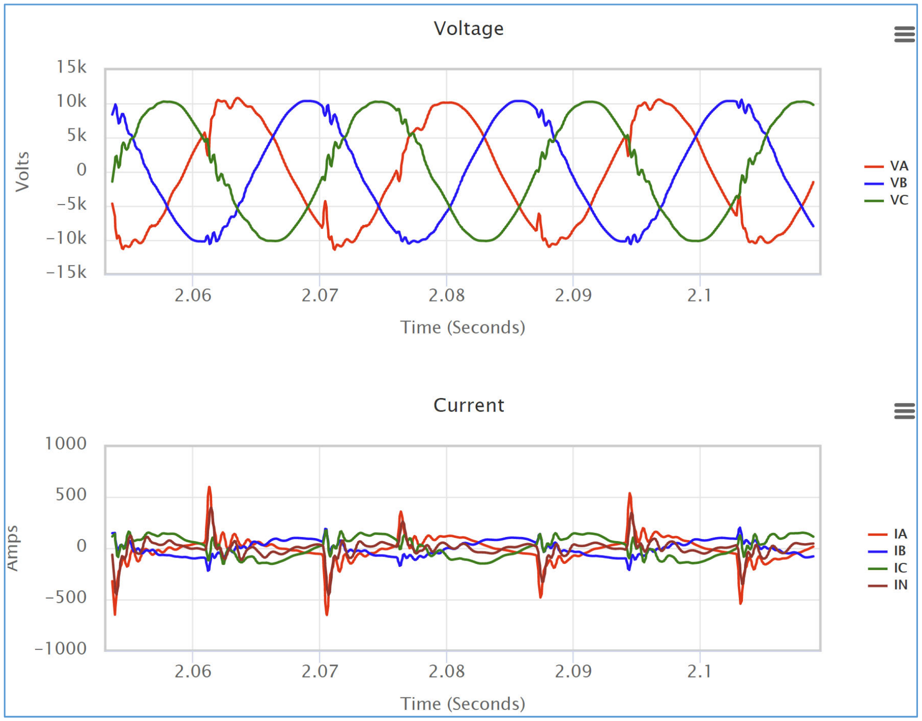


- Measurement during capacitor switching
- Circuit CTs and bus PTs at substation
- Transients are evident in currents and voltages.
- In this example, the phase-B capacitor switched two cycles before the other two phases. This is common on distribution.
- Also common on distribution is the steady-state harmonic content (distortion), particularly in the currents.

Capacitor Arcing Transients – Physics

- Opening a capacitor switch leaves trapped charge (voltage).
  - Current stops at current zero, trapping (retaining) peak voltage (+/-).
- One half-cycle later, the voltage across the open contacts is 2X peak.
  - Closing the switch again (or arcing across) at that instant results in 2X dV/dt.
- A poor connection in the path of capacitor current results in capacitor arcing, which roughly approximates opening and closing a switch every half cycle.
  - The poor connection can be in the switch contacts or in any bad connection internal or external to the capacitor 'can.'
- Capacitor arcing therefore manifests a series of repeated, high-frequency transients of significant magnitude.

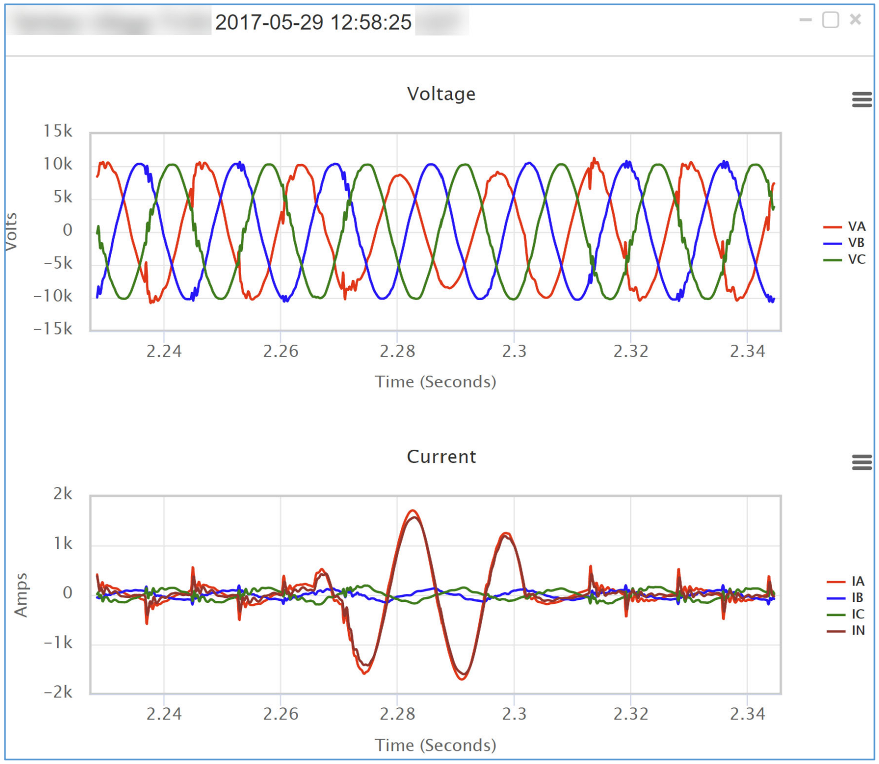
Capacitor Arcing Transients – Field Measurement



- Measurement during capacitor arcing
- Circuit CTs and bus PTs at substation
- Transients are evident in most half-cycles.
- Transient currents have significant magnitude (500 amps) but are too time-limited (a millisecond or so) to blow a capacitor fuse quickly, if at all.
  - Capacitor arcing can persist a long time (documented cases up to several days).
- Transients are measured at bus, so these voltages are experienced by other circuits.

Example 1

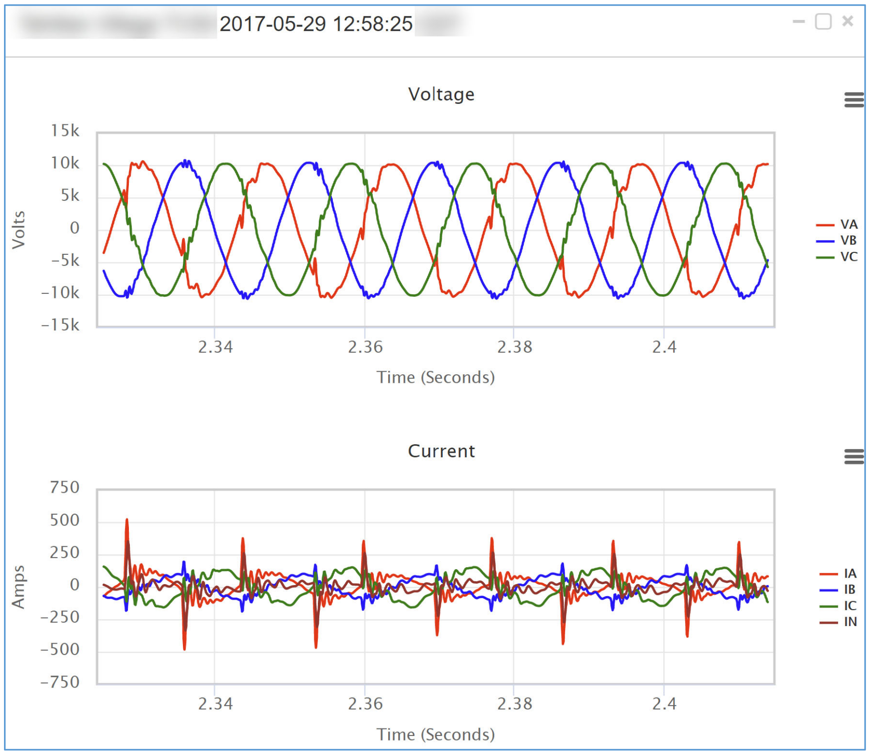
Fault Caused by Arcing Upstream Capacitor



- A fault caused a fuse to blow, and a patrol identified a failed MOV surge arrester downstream of the fuse.
- The fault recording shows a 2-cycle fault on the order of 1kA.
- But the high-bandwidth recording shows repeated transients, before <u>and after</u> the fault blew the fuse.
- How can the transients persist after the fault blew the fuse???

Example 1

Fault Caused by Arcing Upstream Capacitor



- Transients before the high-current fault have substantial magnitude but are too time-limited to operate most protection.
- Transients after the high-current fault are substantially the same as before the fault.
- Repeat: How can the transients persist after the fault blew the fuse???

Example 1

Fault Caused by Arcing Upstream Capacitor

- The 19-second recording has 256 samples/cycle, but this RMS graph provides optimal big-picture understanding of the event.
- The high-current fault lasted only two cycles, but the full event lasted ten seconds (2s < t < 12s in the graph).
- There is a low-current increase right before the high-current fault, and low-current activity after the fault.
- What could cause this?

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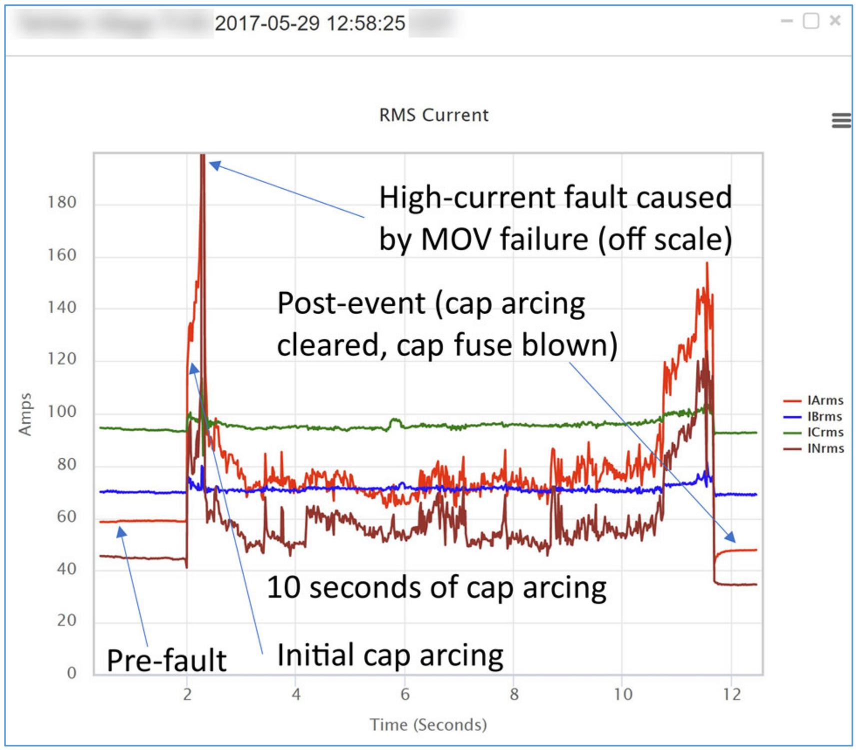
Fault Caused by Arcing Upstream Capacitor



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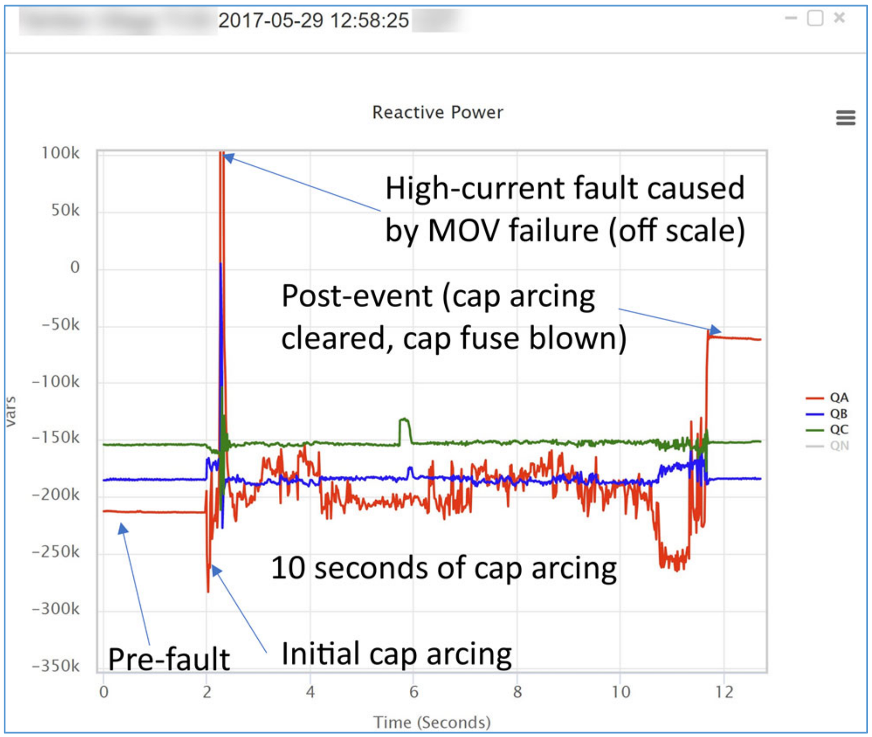

- Reactive power (kvars) provides key understanding.
  - Post-event QA: -62 kvar
  - Pre-event QA: -214 kvar
  - Net increase: 152 kvar
- That net change suggests loss of phase-A of a 450-kvar capacitor bank.
- And the high-frequency transients 2s < t < 12s are consistent with capacitor arcing.
- It is known that capacitor arcing can precipitate MOV failures.

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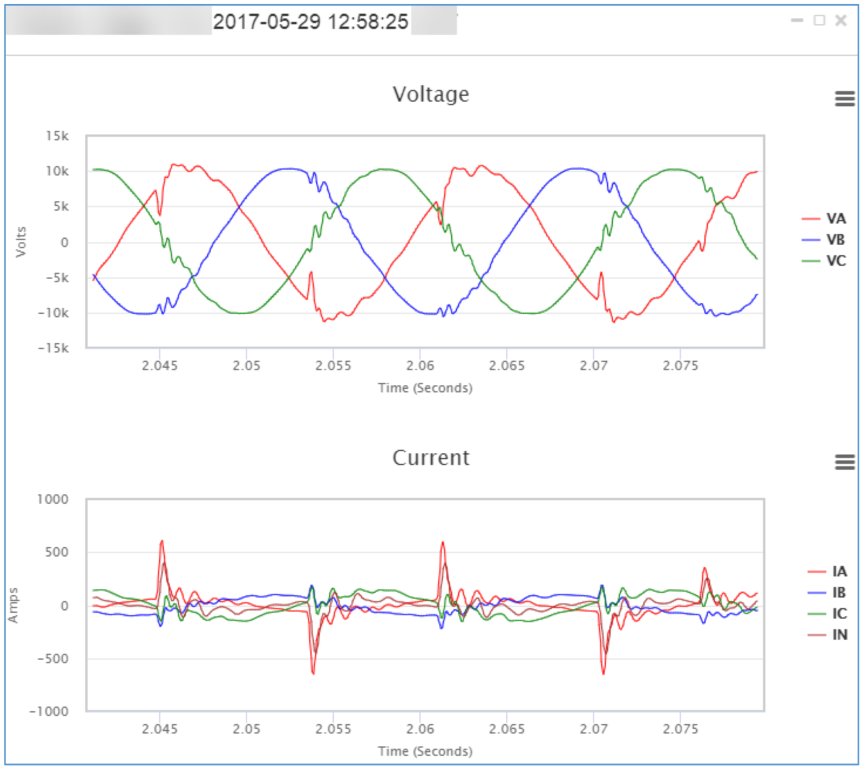
Fault Caused by Arcing Upstream Capacitor

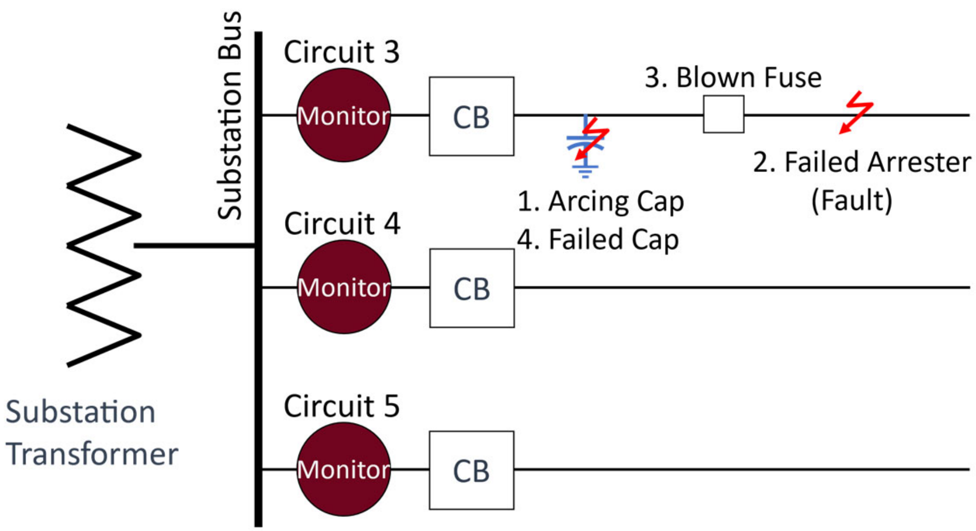


Fact Summary

- Capacitor arcing causes long periods of high-frequency transients.
- Transients from capacitor arcing propagate across entire circuits and to other circuits and are can precipitate MOV arrester failures, even miles away.
- This event has 1) a blown phase-A MOV arrester and 2) phase-A capacitor arcing.

Example 1

Fault Caused by Arcing Upstream Capacitor

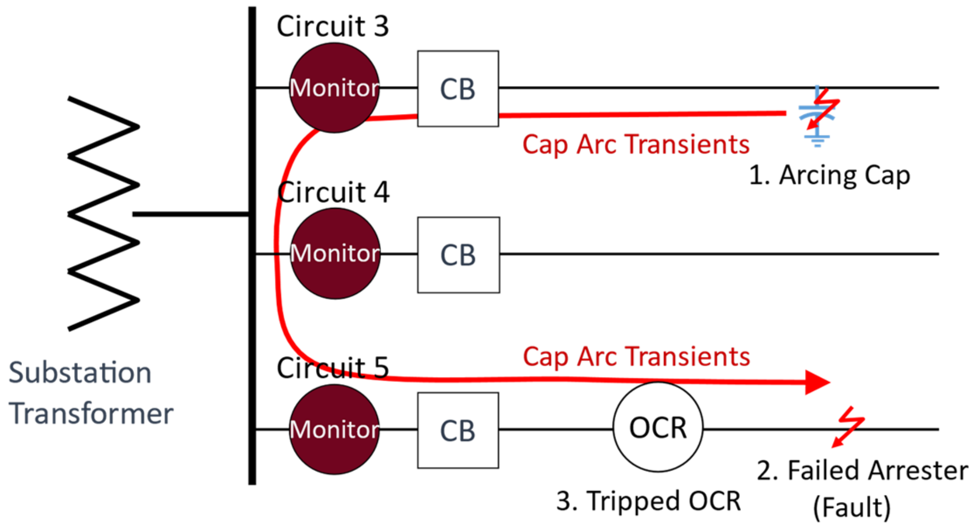


Inferred Sequence of Events

1. Capacitor arcing was the first thing to happen. It caused transients.
2. Those transients caused an MOV arrester to fail.
3. The arrester failure caused the fault that blew the fuse.
4. The capacitor arcing continued for 10 seconds and then failed the capacitor (blew its fuse).

Example 2

Fault Caused by Arcing Capacitor on Another Circuit

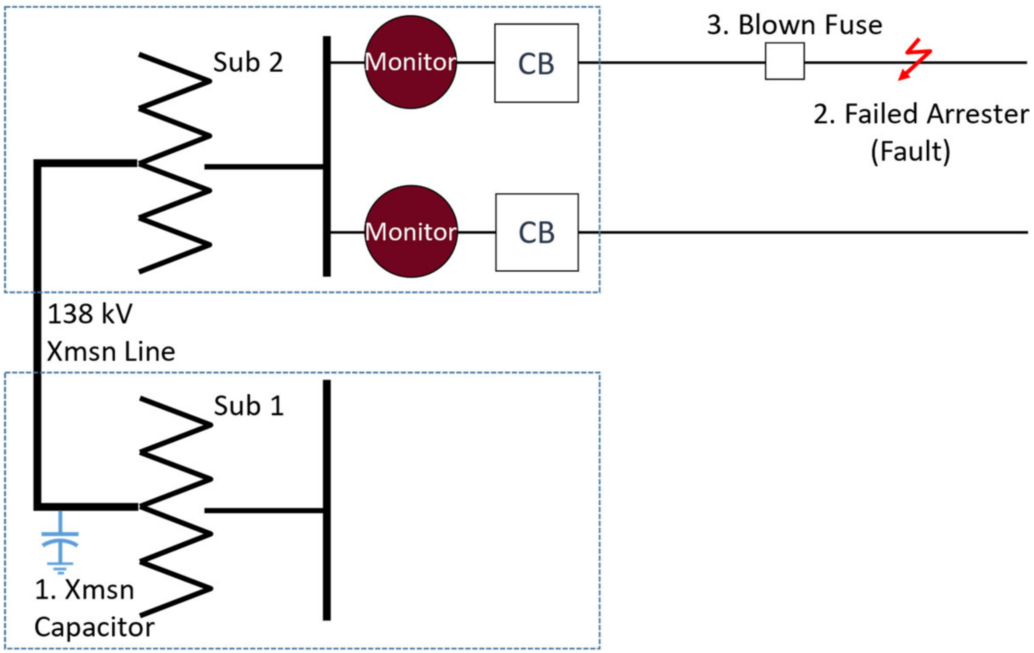


<u>A Similar Case</u>

1. Capacitor arcing on Circuit 3 caused transients on all circuits on the bus. The capacitor arcing (again) was the first thing to happen.
2. Those transients caused the arrester failure on Circuit 5.
3. The arrester failure caused the fault that tripped the OCR.

Example 2

Fault Caused by Arcing Capacitor at Another Substation



<u>Another (Third) Similar Case</u>

1. A transmission capacitor at Sub 1 switched on (normally).
2. Switching transients coupled through 138 kV to Sub 2, through its transformer, and onto the 12 kV distribution circuits.
3. Those transients caused an arrester failure that caused a fault and blew a fuse.

Faults Caused by Distant Capacitor Arcing

Conclusions

- In these three cases, capacitor-related transients caused far-away MOV failures, which in turn caused faults and protection operations.
- Understanding the root cause required recordings having 1) extended duration (10+ seconds) and 2) high fidelity (bits and sample rate).
- Without adequate data, an incorrect conclusion (i.e., that the root cause of the fault was simply a failed MOV) would likely occur.

Broader Thoughts and Conclusions

- A conundrum:
  - A short recording is adequate for understanding well-behaved faults, but well-behaved faults seldom need extensive analysis.
  - Complex events are the ones usually requiring analysis and investigation, and short records are inadequate for long-duration events.
- Some faults have root causes far from where you find the “broken thing.”
  - Faults induced miles from the source of capacitor arcing.
  - Fault-induced conductor slap, which creates a second fault miles from the initial fault and results in apparent (but not truly) protection miscoordination.
- Long recordings are invaluable for understanding the big picture.
- High fidelity (not just sample rate and bits!) is necessary for understanding complex behavior and transients.

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