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Sympathetic Events Resulting from Capacitor Transients

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SUMMARY

It is convenient to think of the various levels of the electricity transmission and distribution system as islands unto themselves: the transmission system is the transmission system; substations are substations; a distribution circuit is a distribution circuit. The truth is that all levels are connected, and an event at any level causes electrical perturbations that can propagate to other levels. Such perturbations, of sufficient magnitude and having other specific characteristics, can cause faults and failures elsewhere on the interconnected system.

Based on more than two decades of applied research, researchers at Texas A&M Engineering developed a sensitive monitoring system that currently is installed on several hundred distribution circuits in the United States and several other countries. Using data from these field installations, not staged or simulated events, they have collaborated with utility companies to document multiple cases in which faults or other events have caused sympathetic responses elsewhere on the same circuit, on other circuits, and even on a circuit served by a different distribution substation. This paper focuses on a subset of sympathetic events, specifically events induced by capacitor transients. The cases that are presented document failures in which normal or abnormal transients from a given capacitor cause failures of lightning arresters and other capacitors elsewhere, some multiple miles distant from the capacitor that is the source of the initial transient.

A key takeaway is that diagnosing the true root cause of a given failure may be challenging, particularly if the root-cause event is distant from the failure of immediate focus. Accurate diagnosis of the root cause of such events often is possible if electrical data of sufficient fidelity is available, but that data generally cannot be had from conventional systems, including SCADA, relays, digital fault recorders (DFRs), or power quality meter (PQMs).

KEYWORDS
Sympathetic failures, capacitor transients, capacitor arcing, capacitor failures, arrester failures

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Background and Data Source

The Power System Automation Laboratory in Texas A&M's Department of Electrical and Computer Engineering has performed multiple decades of applied research in the use of high-fidelity current and voltage measurements to detect events occurring on distribution circuits. The research team currently has near-real-time access to data coming from monitors on distribution circuits in multiple states in the United States and several countries abroad. Monitoring system characteristics that provide suitable data and facilitate analysis include the following.

1. Conventional CTs and PTs at the substation. Each monitoring device takes input from conventional current and potential transformers, because of their pervasiveness in substations. Most utilities "daisy chain" the monitors into CTs and PTs already in place for protection or metering. Because monitoring occurs at the substation, measured currents contain the circuit's load current in addition to current from the event of interest. Software embedded in the monitoring device estimates steady-state load current and attempts to isolate it from event current of interest.
2. Per-circuit monitoring. Per-circuit monitoring facilitates location of the source of events better than bus-level monitoring. A single distribution circuit may have tens of miles of exposure, and monitoring a four-circuit bus would result in four times the number of miles in the potential search area. If monitoring were done at the bus level, operations and records from single-circuit relays and other overcurrent devices guide searches for high-current events, but they would not guide searches for low-current events, which are inherently more challenging to locate even when the circuit is known.
3. 19 effective number of bits (ENOB) of resolution at 256 samples/cycle. Wide range and resolution are necessary to faithfully record high-current faults (e.g., 10,000 amps primary) and with the same circuitry discern the presence and waveform shape of events that cause only a few amps of primary current.
4. Sensitive triggering, especially for current signals. Early stages of some incipient failures have minimal effect on line currents and almost no effect on voltages. Early detection of this category of incipient failure therefore requires triggering thresholds substantially smaller than those typically used for conventional devices, such as protective relays and power-quality meters, that can record waveforms. For example, if a circuit that has 300 amps of normal load current has a hotline clamp that is developing series arcing (i.e., an intermittently arcing "hot spot" in the contact surfaces of a current-carrying device), that incipient failure may cause only a few amps of variation in line current and less than one percent variation in the voltage available for measurement at the substation.
5. Long record lengths (and mass storage implications). Reliably detecting the electrical signatures of certain incipient failures and differentiating those signatures from normal line current variations requires recordings that are multiple seconds in length, sometimes multiple tens of seconds. Each monitoring device has a configurable recording length, typically configured for two seconds before the triggering event and eight seconds after the triggering event. Events that retrigger one or more times after a recording has begun extend the recording duration and can result in recordings with durations up to 60 seconds, with the possibility of immediately re-triggering a new recording if the event persists. The monitoring device performs all recording at the full 256 samples/cycle rate. Some low-current incipient failures cause "flare ups" that result in numerous recordings over a period of hours to days. Active periods may cause dozens to hundreds of recordings, and each recording may have a duration ranging from ten to sixty seconds, at 256 samples/cycle, so the per-circuit monitoring device is designed to accommodate multiple tens of gigabytes of on-device storage. Mass archival storage occurs on the master station, discussed below.
6. Automated retrieval of and ready access to data. When a monitoring device has recorded a data file (i.e., waveform file), it analyses the file with sophisticated signal processing and pattern-recognition software that recognizes multiple types of line events, normal and abnormal. It then automatically sends the file and algorithm-generated reports to a central master station via encrypted network connection. The master station is a computer server

loaded with software designed to automate retrieval of data from a fleet of hundreds of per-circuit monitoring devices and provide long-term archiving. The master station also has a web-based user interface that provides encrypted, password-protected data access for utility partners and the research team to enable efficient viewing and other analysis of the data.

In the preceding discussion, the term "monitoring device" means the substation-based hardware device that monitors a single circuit, and the term "monitoring system" means the entirety of the fleet of hundreds of per-circuit monitoring devices and the central master station that provides long-term archiving, user interface, and other functions.

Capacitor Transients – Routine and Abnormal

This section reviews fundamental information on transients arising from routine switching of capacitor banks and provides an overview of the phenomenon of capacitor arcing (i.e., arcing in the path of capacitor current).

When a capacitor bank switches on, it causes voltage and current transients, a phenomenon arising from fundamental physics and well-known to the industry. Switching a capacitor on instantaneously connects the previously isolated capacitor to line voltage, causing a rapid change in capacitor voltage. Capacitor current is proportional to the rate of change of its voltage (dv/dt), and the magnitude of the voltage and currents transients is a function of the closing angle, the bank size (i.e., kvar rating), and other system parameters. Routine switching on of distribution capacitors produces transients that typically have frequencies of several hundred to a few thousand Hertz and that decay with time, generally a fraction of a cycle, the frequency of oscillation and the decay rate being functions of system impedances. When a capacitor bank switches off, it does not produce this type of transient, but the capacitor retains voltage (charge) that diminishes or "bleeds off" gradually over time through a discharge resistor internal to the capacitor bank. Because a capacitor's current and voltage are in quadrature, and because the current tends to extinguish at a natural current zero crossing, the retained voltage tends to be at the sinusoidal peak, either positive or negative. If a capacitor switches on soon (e.g., within seconds to a minute or so) after switching off, then, depending on the angle of opening and the angle of closing, the retained voltage can result in transients having larger magnitude than those from normal switching, theoretically approaching twice that magnitude.

An imperfection in any part of the capacitor-current path can cause a special type of arcing. Texas A&M's applied research program has documented multiple cases of this "capacitor arcing," with underlying causes arising from failing contacts in capacitor switching apparatus (e.g., oil switches, vacuum switches, fused cutouts) or from a poor connection internal or external to the capacitor itself. Study of electrical waveform data associated with multiple cases of capacitor arcing shows the following.

1. An elementary model for capacitor arcing is rapid and repetitive opening and closing of a "switch" in the capacitor-current path. From an electrical perspective, this is akin to closing a capacitor that only recently was opened and has substantial retained voltage.
2. Capacitor arcing occurs on a half-cycle basis but is a stochastic process, affecting some half cycles but not others.
3. Transients arising from capacitor arcing have frequencies like those of normal capacitor switching but can have greater magnitudes. The increased magnitude occurs when the modelled "switch" opens during a half cycle of one voltage polarity and closes shortly thereafter during a half cycle of the opposite polarity.
4. Arcing inside a vacuum switch associated with a capacitor bank can differ from other scenarios of capacitor arcing. This special case occurs when a vacuum switch on a capacitor bank has lost partial vacuum and is in the open position, whereas other forms of capacitor arcing occur when the switch is in the closed position but there is an imperfection in the current path.

5. Capacitor-related transients, arising both from normal switching and from capacitor arcing, propagate across the entire circuit and to the substation bus, which means they also propagate to other circuits. As outlined in one of the case studies, capacitor transients initiating on the transmission system also can propagate to the distribution system.

Case Studies

Texas A&M Engineering's applied research program has documented multiple cases of capacitor arcing. This section reviews several of those cases, plus one case arising from normal capacitor switching. All data comes from the previously described monitoring devices installed on several hundred distribution circuits during routine operations, nothing staged or simulated. As a reminder, all measurements are from conventional bus PTs and from conventional CTs on individual circuits, installed in substations, so the measured currents contain load current in addition to the capacitor-related current of specific interest.

Case Study 1: Fault and Blown Fuse Caused by Upstream Capacitor Arcing

A line crew responding to an outage on the subject circuit found an MOV (metal oxide varistor) lightning arrester that had experienced catastrophic failure and a blown fuse upstream of the failed arrester. They replaced the arrester and then the fuse, restoring service to all affected customers. They found no immediately apparent cause for the arrester failure.

Data from the monitoring device at the head of the circuit was examined the next day and revealed the root cause of the failure: arcing in a capacitor bank upstream of the blown fuse. The one-line diagram of Figure 1 shows the relative positions of the arcing capacitor, the blown fuse, and the failed arrester. The sequence, as determined from analysis of the data from the monitoring system, follows, with the numbers in the descriptive text below corresponding to the numbers in the one-line diagram.

1. The capacitor began arcing, which generated near-continuous voltage and current transients of significant magnitude.
2. All circuit apparatus, including the subject arrester, experienced the transients. Those transients caused the arrester's catastrophic failure, which in turn caused a single-line-to-ground fault.
3. The fault caused the subject line fuse to operate to clear the fault from the circuit.
4. Data from the monitor indicate that the capacitor arcing continued for some seconds and then caused the fuse on the capacitor bank to open, which disconnected the capacitor from the circuit and ceased the capacitor arcing.
5. After locating and replacing the failed arrester, the line crew replaced the blown line fuse to restore service.

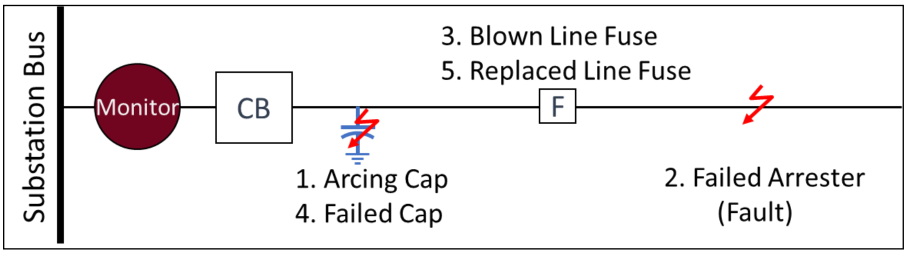

Figure 1. One-line diagram for Case Study 1

Figure 2 shows approximately two cycles of voltage and current waveforms that the circuit's monitoring device recorded a fraction of a second before the arrester failed. Each half cycle has a significant transient. The "normal" portion of each half cycle represents circuit load.

Each current transient has magnitude of hundreds of amps but is time-limited to a millisecond or so. The voltage transients also are substantial and are experienced by all apparatus on the subject circuit and on other circuits served by the same substation bus. It is reasonable to assume that, on the subject circuit, the magnitude of the voltage transients is greater at a distant point on the circuit than at the relatively stiff substation bus.

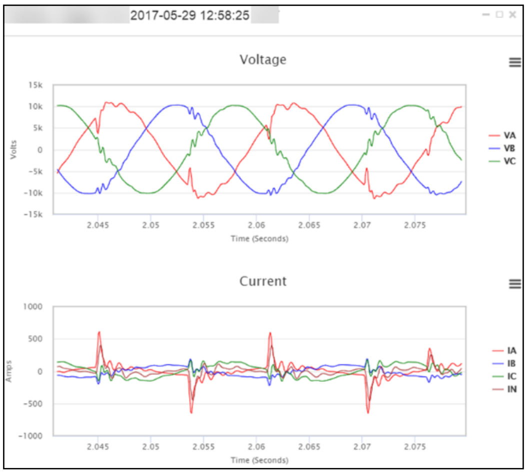

Figure 2. Two cycles of substation-measured bus voltages and line currents caused by capacitor arcing, a fraction of a second before the arrester failure

Figure 3 shows per-phase reactive power flows for the event. The timestamps of Figure 3 are consistent with those of Figure 2, but Figure 3 shows a longer period that encompasses the initial capacitor arcing, the resulting arrester failure and overcurrent fault that blew the line fuse, the continuing capacitor arcing, and the simultaneous cessation of capacitor arcing and loss of phase-A kvars, when the capacitor fuse opened.

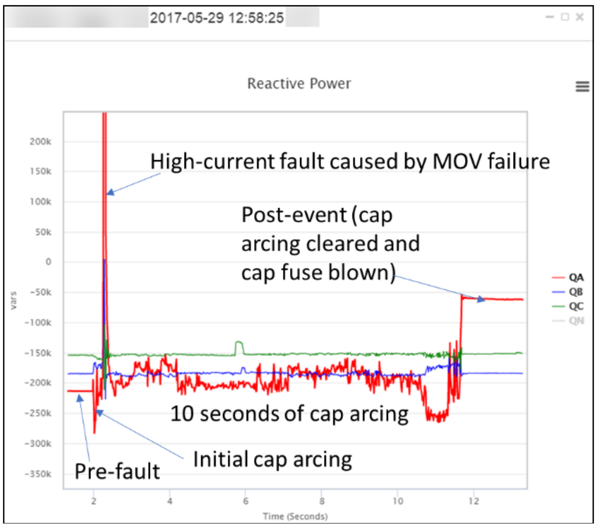

Figure 3. Per-phase reactive power flow during ten seconds of capacitor arcing

Case Study 2: Arrester Failure Caused by Capacitor Arcing on Another Circuit

Figure 4 provides a one-line diagram for this second case study. As with the previous case study, capacitor arcing caused catastrophic failure of an MOV arrester, which in turn caused a single-line-to-ground fault and operation of conventional overcurrent protection. The major difference in this case was the “reach” of the capacitor transients, which originated on one circuit, labelled Circuit 30 in the figure, and caused failure of an arrester on a different circuit, labelled Circuit 50. These two circuits and others were served by the same substation bus.

Exact distances were not determined, but the circuits are long rural circuits, so the distance between the arcing capacitor and the failed arrester was easily many miles to several tens of miles. The sequence of events was as follows, with numbers in the descriptive text again corresponding to the numbers annotated on the figure.

1. Capacitor arcing began on Circuit 30, causing near-continuous voltage and current transients of significant magnitude.
2. The transients propagated across Circuit 30, to the substation bus, and from there to other circuits, subjecting all circuit apparatus to the transients. Those transients precipitated catastrophic failure of an arrester on Circuit 50, the failure in turn causing a single-line-to-ground fault.
3. The fault caused an oil circuit recloser on Circuit 50 to trip and auto-reclose. The fault did not resume upon reclosing.

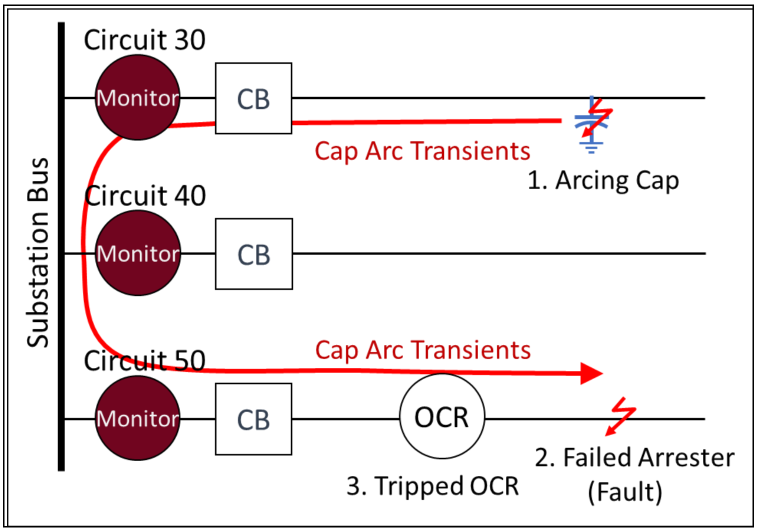

Figure 4. One-line diagram for Case Study 2

Case Study 3: Arrester Failure Induced by Transmission Capacitor Switched at Remote Substation

As with the previous two cases, this third case study involves catastrophic failure of an arrester induced by a capacitor-generated transient. This third case had two chief differences: 1) the capacitor transient resulted from routine capacitor switching, not capacitor arcing; and 2) the capacitor was a transmission capacitor, not a distribution capacitor. With reference to labels in the one-line of Figure 5, the failed arrester was on a 12 kV distribution circuit served by substation 2. The transmission capacitor was at substation 1. The two substations are connected by a 138 kV transmission line. The sequence of events was as follows.

1. A capacitor bank at substation 1 switched on, which generated current and voltage transients on the 138 kV transmission line. The transients propagated across the transmission line to other substations, including substation 2.
2. The transient propagated through the power transformer at substation 2 and onto connected distribution circuits, inducing failure of the lightning arrester on the subject distribution circuit.
3. The catastrophic arrester failure caused a single-line-to-ground fault, which caused a line fuse to open.

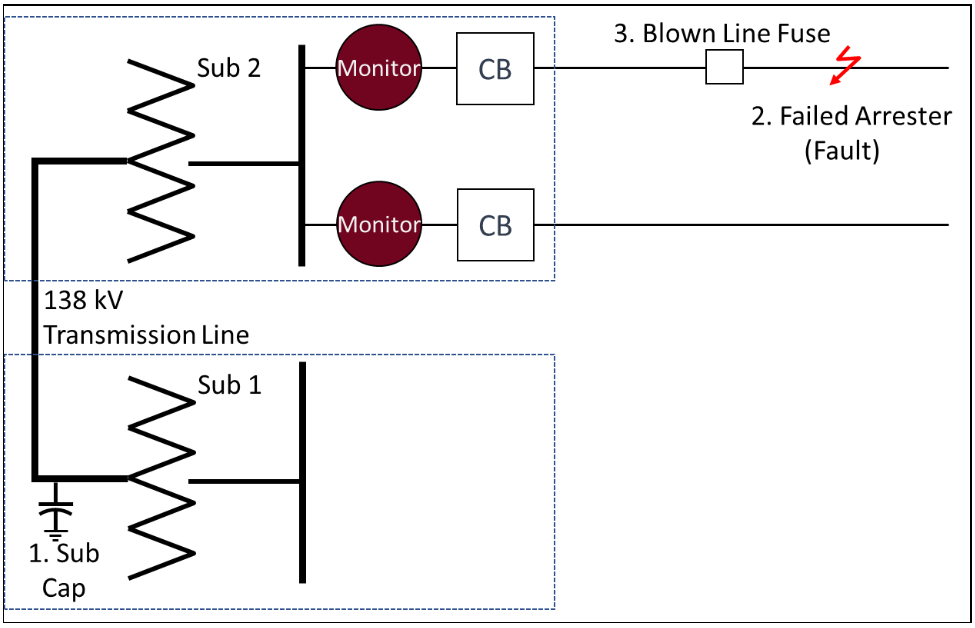

Figure 5. One-line diagram for Case Study 3

Case Study 4: Blown Fuses in Three Capacitor Banks Because of Arcing in One Bank

Figure 6 provides a one-line diagram for this case study, in which arcing developed between the contacts of a switch on one phase of a capacitor bank on Circuit 1. Over a period of four days, the switch continued arcing internally whenever it was in the closed position. At the end of that period, the switch failed fully, in an open position, bringing the event to an end. During the four-day period, the arcing capacitor on Circuit 1 caused a blown fuse in another capacitor on Circuit 1 and a blown fuse in a capacitor on Circuit 2, all on the same phase. This case did not cause an arrester failure or operation of a line fuse or recloser. The sequence of events was as follows, where the numbers in the sequence reference those in the figure.

1. Capacitor arcing began in an oil switch on one phase of a capacitor bank of Circuit 1 and generated near-continuous voltage and current transients of significant magnitude.
2. The transients propagated up and down Circuit 1, to the substation bus, and from there to other circuits, subjecting all circuit apparatus to the transients. Those transients caused fuses to blow in another capacitor bank on Circuit 1 (2a) and a capacitor bank on Circuit 2 (2b).
3. Continued arcing in the initial bank's switch eventually caused the switch to burn open, thereby ending the event.

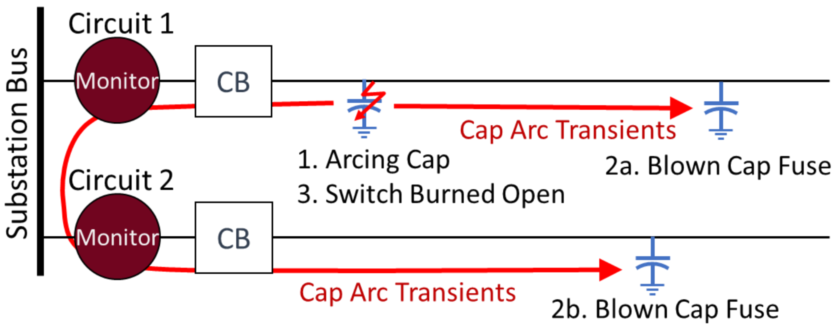

Figure 6. One-line diagram for Case Study 4

The mechanism by which one arcing capacitor can cause sympathetic activity (in this case, blown fuses) of other capacitors may not be immediately obvious but is explained by the fundamental physics of capacitors. As discussed in this paper's introductory discussion of capacitor transients, a capacitor's current is proportional to its rate of change of voltage (dv/dt). This principle applies to all electrically interconnected capacitors, not just the one initiating the transients. Voltage transients emanating from one switched or arcing capacitor are experienced by all other capacitors on the circuit and, by extension, by capacitors on other circuits on the bus, so the currents of those other capacitors are affected. Thought of another way, those other capacitors supply at least part of the current being drawn by the capacitor that initiates the transients. In the subject case, the fuses of the multiple capacitors opened because of the cumulative effect resulting from the extended period of transients, which were generally similar to those of Figure 2.

Remarks on Other Forms of Sympathetic Events

To maintain reasonable length, this paper has focused on sympathetic events arising from capacitor-generated transients, both from routine capacitor switching and from abnormal capacitor arcing. There are other forms of sympathetic events, including without limitation:

1. Fault-induced conductor slap (FICS) – The flow of current induces a magnetic field, which in turn can cause mechanical forces. When fault current flows to a fault in one conductor and returns on a parallel conductor (e.g., another phase conductor), it results in magnetic forces that push the two conductors away from each other. When the fault is interrupted, typically because a mid-point protection device operates, the sudden removal of the forces enables the displaced conductors to pendulum back toward each other. Under the right conditions, this results in the two conductors contacting one another upstream of the now-open mid-point protection device, which causes a second fault, closer to the substation, sometimes miles distant from the initial fault. The second fault is sympathetic to the first. Using conventional data and approaches, FICS is difficult to diagnose, but proper diagnosis is important, because a span that experiences FICS once tends to experience it repeatedly in the future. Correcting the underlying condition usually is straightforward, such as re-tensioning the offending span or adding a spacer or a pole, but that occurs only if FICS is diagnosed properly. Field installations have documented multiple cases of FICS, including multiple cases in which FICS has occurred repeatedly in a given span, sometimes separated by months or years.
2. Series arcing induced by passage of fault current – When a circuit experiences a fault, all apparatus between the serving substation and the fault point conduct the fault current. That passage of fault current can stress all current-carrying devices and can precipitate series arcing in the contact surfaces of such a device. Series arcing occurs when the contact surfaces of a current-carrying device, such as a switch or hotline clamp, develop an imperfection that leads to contact-to-contact arcing, which manifests as a "hot spot." Field installations of the monitoring system described in this paper have provided data that demonstrates that a device can experience series arcing intermittently for minutes to weeks. During period of active series arcing, current and voltage to downstream load are "modulated," which causes electrical variations that are not measurable by conventional systems but that are measurable and distinctly recognizable as series arcing by a sensitive monitoring system. In a case where passage of fault current precipitates the series arcing in a current-carrying device, the series arcing is sympathetic to the initial fault, though the initial fault likely has no relationship to the current-carrying device, other than being served through it.

Conclusions

It is convenient to think of the various levels of the electric transmission and distribution system as being independent of one another, but in some cases an event on one portion of the system causes sympathetic response on another portion, sometimes miles distant. A sensitive monitoring system on several hundred distribution circuits has enabled Texas A&M Engineering's research team, working collaboratively with multiple utilities, to document multiple such cases and determine true root causes of events. These installations have documented several varieties of such sympathetic events. This paper has detailed multiple types of failures that were sympathetic to normal capacitor switching and abnormal capacitor arcing and has briefly mentioned some other forms of sympathetic events.