Feeder Interruptions Caused by Recurring Faults on Distribution Feeders: Faults You Don't Know About

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***Abstract*—Weather, equipment failure, and contact by foreign objects cause faults, trips, interruptions, and outages. Most faults are either permanent, requiring repairs before service can be restored, or truly temporary, causing no lasting impairment to the system.**

Monitoring programs at Texas A&M University have instrumented dozens of feeders at North American utility companies for multiple years. Sensitive monitoring and recording systems have documented multiple instances in which failing apparatus, vegetation intrusion, and other factors have caused multiple faults and momentary interruptions, over significant periods of time, without causing sustained outages. A recurrent fault can easily escape notice when a pole-mount recloser is the interrupting device, because there often is no telemetry (e.g., SCADA) to report that anything happened. Even recurrent faults that trip a substation breaker can escape notice when time intervals between operations are sufficiently long for operator memories to fade. Fault current and arcing from recurrent faults can further damage already weak apparatus, eventually causing a permanent outage, at which time there may be more consequential damage to apparatus, including burned-down lines.

This paper documents multiple examples of recurrent faults and interruptions, including their causes and consequences. It also documents other events that cause poor power quality and/or reliability after a significant period in which a degraded condition produces electrical "warning signs." These "warning signs" have always been present on feeders but they could not be used to prevent or mitigate problems because the symptoms previously were unknown or inadequately understood.

***Index Terms*—Power system reliability, Power system faults, Incipient faults, Apparatus failure, Condition-based maintenance**

I. Introduction

FAULTS are a fact of life on power systems. Multiple factors cause failures and faults at all levels of the power delivery system, including distribution feeders. Protection schemes utilize relays, fuses, and automatic circuit reclosers to clear faults in an attempt to minimize system damage while maintaining reliable service to customers. Faults generally fall into two categories. The first involves permanent faults, which typically occur when line or system apparatus incur permanent damage or otherwise fail. Permanent faults cause service outages and require repairs before service can be restored. The second category involves temporary faults. These occur when a transient condition initiates a fault, but the fault can be cleared by temporarily removing the power source (e.g., so that plasma produced by a power arc can dissipate). Protection schemes utilizing automatic reclosing facilitate removal of faults by tripping, but then make one or more automatic attempts to restore power. This may subject feeder apparatus to multiple high-current events and momentary interruptions for a single permanent fault, but it also enhances service continuity by reducing the likelihood of a transient condition causing permanent outage. It is common for weather (e.g., lightning) to cause temporary faults, although other factors can produce temporary faults as well.

Permanent faults cause outages and generally cause customers to notify the utility company. For permanent faults that trip the substation breaker, SCADA systems may provide an initial alert. Utility companies often have less information and give less attention to temporary faults, because automatic reclosing devices prevent permanent outages by tripping and reclosing the circuit (or part of a circuit) one or more times, and thereby allow the transient condition to correct itself.

Long-term monitoring by Texas A&M University has documented multiple fault and failure conditions that do not strictly fall into either of the aforementioned categories. Incipient failures have been documented to cause temporary faults that heal themselves for significant periods of time but then recurring [1,2,3]. For example a damaged insulator or bushing may experience a high-current flashover if sufficient moisture is present on its surface because of rain or high humidity. This will cause overcurrent protection to trip, but automatic reclosing may reenergize the failing component after a short period of time. Localized heat generated by the fault current flashing across the surface of the bushing may dry it sufficiently to temporarily restore its insulating capability and prevent continued fault current. To the protection system, this appears to be a temporary fault that is cleared by a momentary interruption. However, it leaves a failing component or other condition in place on the system, which generally results in future recurrences and eventually to sustained outages.

Conventional wisdom holds that recurrent faults and momentary interruptions result in customer complaints in short order. Cases documented in this paper show that in reality it is common to have multiple episodes of recurrent faults without the utility receiving a single customer complaint. When utilities receive customer complaints for "blinking lights," they may assume that the lights have only blinked a time or two. Clearly this often may be the case, but it also may be true that in some cases there have been many more "blinks" before the first customer places a call.

This work was supported in part by the Electric Power Research Institute and by Texas A&M University.

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II. Data Collection Project and Methodology

With sponsorship by the Electric Power Research Institute (EPRI) and the cooperation of multiple EPRI-member utility companies, Texas A&M began a project in the late 1990's to document incipient faults and failures on distribution feeders. The goal of that project is to use sensitive monitoring to "anticipate" failures and thereby enhance reliability, enabling utilities to correct substandard conditions before they escalate and causes outages or other negative consequences. This effort has become known as distribution fault anticipation (DFA).

Participating utility companies have installed prototype DFA equipment in their substations. These devices detect and record faults and more-subtle anomalies with high fidelity and broad bandwidth. Each system continuously monitors from two to eight feeders and records current and voltage waveforms with high resolution when anomalies occur.

A Master Station at each utility company automatically retrieves captured data from that company's DFA equipment via Internet, as depicted in Fig. 1. A "Master Master" Station at Texas A&M headquarters automatically retrieves the same data from all utilities' DFA monitors. In this way utility engineers and Texas A&M researchers both have ready access to the same data.

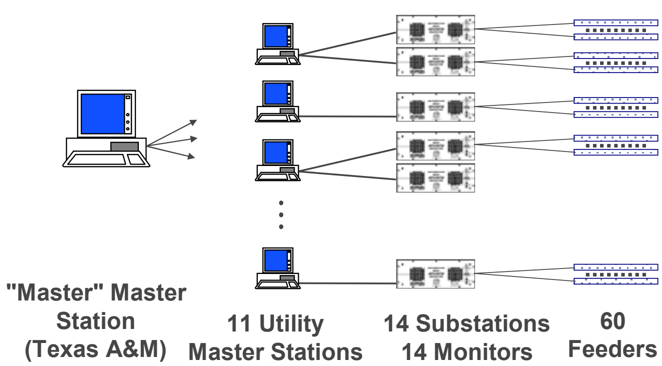

Fig. 1. Distributed data collection system

III. Recurrent Fault Case Studies

The DFA project has documented numerous failures and incipient failures. There has been a notable number of recurrent faults from insulation failure, vegetation, animal contact, and other causes. It has been instructive (and counter to conventional wisdom) to observe how often recurrent faults and accompanying momentary interruptions occur without customer complaints resulting or the utility company having any indication the problem is happening.

It is important to note that all current and voltage measurements for this project are obtained from conventional substation-based current and potential transformers (CTs and PTs). Therefore the measurements included load current in addition to fault current.

A. Tree Limb Burns Down Line Over 24-Hour Period

A fault was recorded on a DFA-monitored feeder at 7:58 AM on November 2, 2004. A three-phase pole-mount recloser tripped in response. When it reclosed after two seconds, fault current resumed almost immediately. The recloser responded by tripping and reclosing again. Fault current did not resume after the second reclose, so the recloser remained closed and no outage occurred. Fig. 2 shows substation-based RMS current recorded during this sequence of faults, trips, and recloses. Interestingly a similar fault had been recorded an hour earlier, at 6:57 AM. It caused one trip and reclose of the same three-phase, pole-mount recloser. No sustained outage resulted from either episode and the utility received no customer calls. Weather conditions were fair at the time of both episodes.

Shortly after midnight on November 3, 2004, another fault occurred, this one causing one trip and reclose of the same pole-mount recloser. Fault characteristics were very similar to the two that had occurred 16 hours earlier. The fault recurred ten times between midnight and 6:19 AM. Each episode resulted in a single operation of the three-phase recloser. Still there was no sustained outage and no customer calls were received. Fig. 3 illustrates the final episode, at which time the line burned down and caused a 62-minute outage for 140 customers (8 680 customer-minutes).

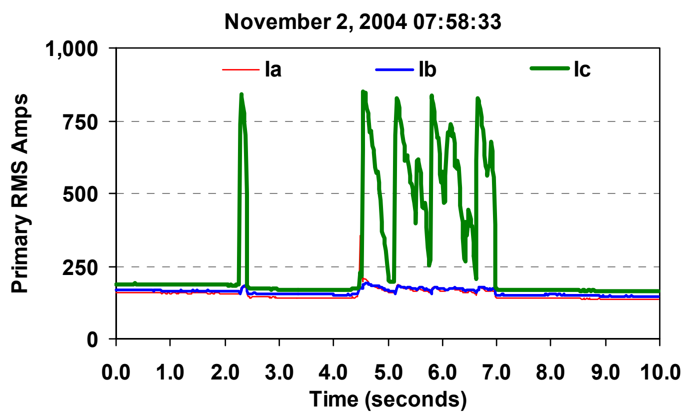

Fig. 2. Fault causing two trips and recloses but no outage

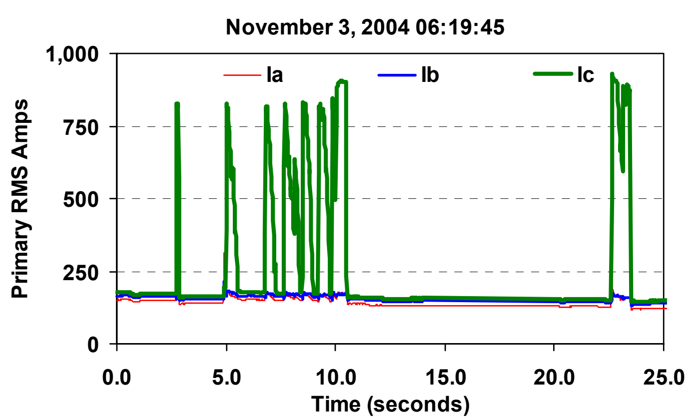

Fig. 3. Fault current leading to burn down of line

The sequence of events was investigated and documented. The affected area receives service from a single-phase line which has its phase conductor near the top of the pole and its neutral several feet lower on the side of the pole. The cause was determined to have been a forked tree limb that fell and hung on the phase conductor. Its weight caused the phase conductor to sag closer to the neutral conductor than normal. The limb made permanent contact with the phase conductor and intermittent contact with the neutral. This caused intermittent short circuits and eventually burned the line down.

Several things are noteworthy about this case:

- The fault occurred 13 distinct times over a 24-hour period.
- The number of trips was more than adequate to cause protection to lock out, but the timing of the individual episodes prevented it. Intervals between individual trips were generally a few minutes to a few tens of minutes.
- 140 customers experienced a momentary interruption each of these 13 times, but zero customer calls resulted prior to the final, sustained outage. This is partially explained by the fact that most of the interruptions occurred during late-night hours, but it is interesting that not even one customer called during this period.
- Because the trips involved a pole-mount recloser instead of the substation breaker, the utility had no indication of a problem (except from the DFA, which was operating as a research tool, not integrated with utility operations).

B. Latent Animal-Caused Bushing Damage – Part I

This is another case involving recurrent, high-magnitude faults that caused a pole-mount recloser to operate without locking out. As before no customer calls resulted, despite the fact that these momentary interruptions occurred under fair-weather conditions during daytime hours.

The first episode of the subject fault occurred on the morning of December 11, 2005. A single-phase fault produced roughly 3 000 amps of fault current, as shown in Fig. 4. A single-phase, pole-mount recloser (i.e., not the substation breaker) tripped to clear the fault. When it reclosed two seconds later, the fault did not resume, so no outage resulted.

The utility had no indication that the fault had happened and no customers complained. Even if the utility had known this single event had occurred, they likely would have assumed it had a temporary cause (e.g., a small animal causing a short circuit but being thrown clear as a result). In fact it was later determined that the cause of the initial fault was a squirrel crossing the primary bushing on a pole-mount service transformer, but that initial contact caused latent bushing damage.

Another fault episode occurred on the same phase of the same feeder on December 13, 2005. The same single-phase, pole-mount recloser operated once and maintained service without sustained outage. The utility received no customer complaints, despite the fact that there had been two daytime, fair-weather interruptions in a period of two days.

The following day (December 14) the utility reviewed data recorded by the DFA and took note of two similar, fair-weather faults just two days apart. This utility had previously experience with recurrent faults and recognized that there was a possible problem.

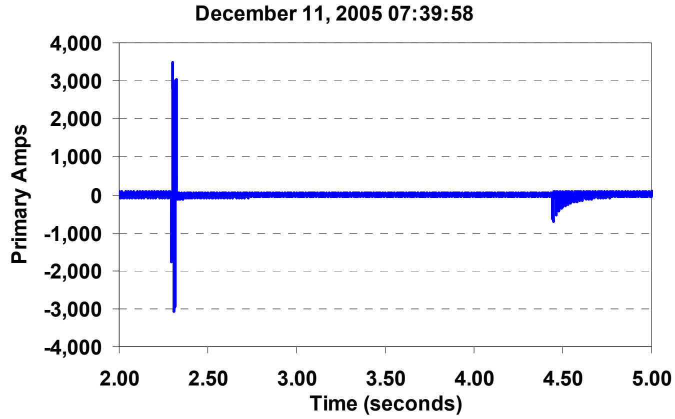

Fig. 4. Animal-induced fault cleared by recloser

The utility used fault magnitude and other characteristics to determine the portion of the feeder likely to be causing the faults. As a result, the problem was identified by a two-man crew in less than one hour. They found a dead squirrel at the base of a pole. They then inspected the bushing on the transformer at the top of that pole and found that it had flash damage. They surmised that the squirrel caused the initial fault and fell clear as a result. They further surmised that the flash of that initial fault caused latent damage to the transformer bushing. That latent damage caused the second fault episode.

Of interest from a research perspective, there was a third episode, this one on December 18, 2005. When the utility identified the damage on December 14, they put its repair on a list but did not immediately make the repair. The third episode prioritized the repair and the transformer was replaced before any further episodes occurred.

To summarize:

- Failure of a single apparatus caused three fair-weather faults over a one-week period.
- Each fault tripped and reclosed a single-phase, pole-mount recloser one time.
- No outage resulted.
- No customer calls resulted, despite conventional wisdom that would suggest that three fair-weather momentary interruptions in eight days would cause multiple complaints.
- Because the substation breaker was not involved, and because no customers called, the utility had no indication that a problem existed (other than from DFA-recorded data).
- The third episode was a clear indication that faults would continue.
- Eventually this relatively benign event would have occurred enough times to generate customer complaints (at which time the utility would begin a search based on limited-value information from customers) or it would have caused additional damage and a permanent fault.

C. Latent Animal-Induced Bushing Damage – Part II

A single-phase fault caused a three-phase pole-mount recloser to trip and reclose on June 3, 2006. It did so again a week later, and again a week after that, and again a week after that, …, ultimately causing six faults, the last of which caused a permanent outage seven weeks after the initial fault. The recloser was very close to the substation, so it interrupted 907 customers every time the fault occurred and it caused a 35-minute outage to this number of customers when it locked out (31 745 customer-minutes). However the substation breaker was not involved, so SCADA did not report anything to the utility. In total, the DFA at the substation recorded the following:

- 6/3/2006 08:02:46 – First fault episode
- 6/10/2006 07:27:38 – Second fault episode
- 6/17/2006 10:16:34 – Third fault episode (Fig. 5)
- 6/24/2006 08:29:46 – Fourth fault episode
- *6/28/2006 07:32:45 – Unrelated single-phase fault*
- 7/4/2006 06:07:12 – Fifth fault episode
- 7/24/2006 07:29:25 – Sixth fault episode (Fig. 6)

In the aftermath of the final fault and outage, the utility determined the cause to be very similar to the previously cited case. It was determined that an animal crossed a primary bushing and caused the first episode on June 3. The animal likely was thrown clear during that first episode, but the fault created latent damage to the bushing, which in turn caused the subsequent faults and the eventual outage.

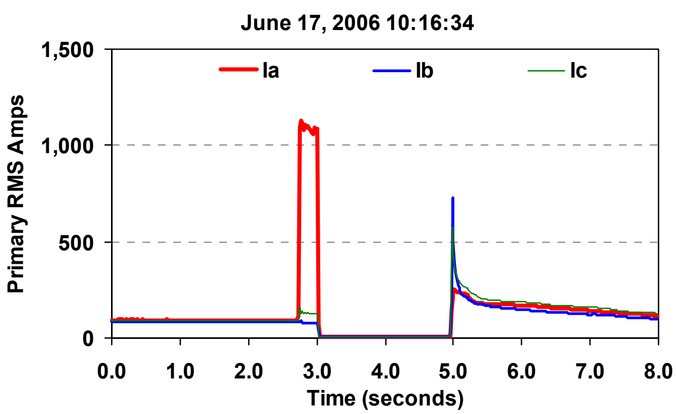

Fig. 5. Third episode of recurrent fault

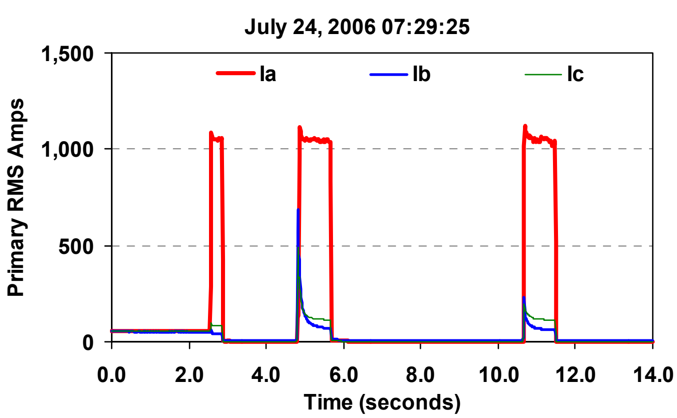

Fig. 6. Final fault, which caused 907-customer outage

This case is even more counter to conventional wisdom than those previous. Over a seven-week period, 907 customers experienced five momentary interruptions, all during daytime hours, and <u>not a single complaint resulted</u>!

This case raises an obvious question: If there were multiple faults over a period of seven weeks, why did no one take note and take action to avoid the permanent outage? Data from the DFA was available and the utility in question had previous experience with recurrent faults, so why did no one see this one coming?

The answer lies in the timing of the individual episodes. Prior experience had led the utility to develop a routine of examining the most recent one-week period to look for multiple, similar faults. In this case, however, the first four faults coincidentally happened at seven-day intervals. They also all happened to be on Saturdays. As a result when the utility engineer checked his records on Mondays, there never was more than one fault episodes in the examined interval. Each episode was viewed "in a vacuum," appearing to be an isolated event. No pattern worthy of special attention was evident.

To summarize:

- Six faults occurred over a period of weeks. The first five were cleared successfully with one trip and reclose.
- Each fault momentarily interrupted 907 customers.
- The utility received no customer complaints.
- The utility had no indication of a problem (other than from DFA recordings).
- A relatively minor problem (damaged bushing) gave five "warnings" before escalating into a 907-customer outage.
- It becomes increasingly clear that customer calls are not a reliable mechanism to learn of recurrent faults.

D. Failure of Line Switch

This case study does not relate to recurrent faults per se. However it is another good example of failing apparatus that gave warning weeks before it causes a fault that put nearly 300 customers in the dark for multiple hours.

Fig. 7 depicts a fault on the evening of November 14, 2007. The fault was on the feeder's main three-phase trunk and drew significant current. It began as a two-phase fault, tripped and reclosed the substation breaker, resumed two seconds later as a two-phase fault, evolved to a three-phase fault, and tripped the substation breaker again. When the breaker reclosed a second time some thirty seconds later, the fault did not resume. Service was maintained for all customers.

There was nothing particularly unusual or noteworthy about the fault or protection operation sequence. What was unusual, however, was the behavior of the phase-A current after the fault was cleared. Fig. 8 illustrates the RMS current a few seconds after the final, successful reclose of the substation breaker. The phase-A current is more erratic than the other two phase currents and it is more erratic than would be accounted for by the normal load fluctuations that occur following a fault/trip sequence. This unusual behavior occurred for a minute or so and then subsided.

Later the same evening a very similar fault sequence occurred. The fault again involved several thousand amperes of fault current on multiple phases, including phase A. It also

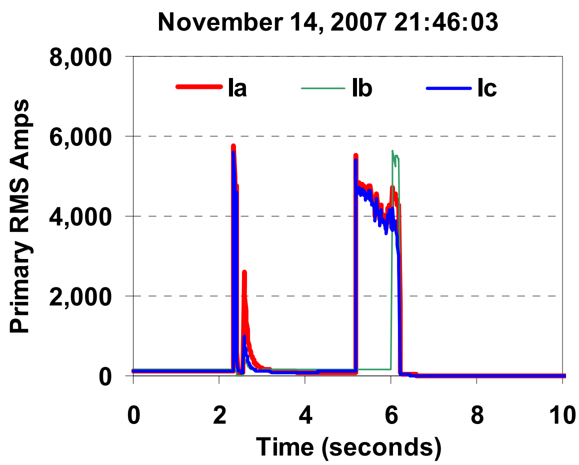

Fig. 7. Temporary fault that triggered incipient activity

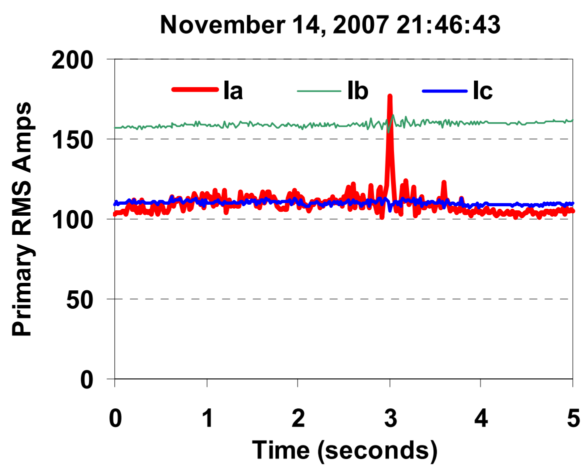

Fig. 8. Troublesome electrical signals after temporary fault

involved multiple operations of the substation breaker, but again there was no sustained outage. The substation breaker reclosed successfully, but the phase-A current again was erratic. This time the activity was more erratic and lasted longer before subsiding.

The next event of interest occurred one month later. On the evening of December 15, 2007, the subject feeder experienced another fault close enough to the substation to require operation of the substation breaker. Multiple phases were involved and the fault drew several thousand amperes. The substation breaker tripped and reclosed two times to successfully clear the fault. Following this sequence of events, there was even more erratic behavior in the phase-A current and it persisted longer than in previous occurrences.

Another sequence of faults and trips occurred later that evening. The phase-A current again exhibited erratic behavior after the substation breaker tripped and reclosed twice to clear the fault. The magnitudes of the transients were significantly larger than in previous instances and they did not subside. Shortly thereafter there was a 9 000-amp, phase-A fault, which caused the substation breaker to trip to lockout. The result was an outage to 297 customers that lasted nearly 2-1/2 hours (43 846 customer-minutes).

In the aftermath of the outage, the utility determined that there had been a failure of the main line switch on phase A just outside the substation. It was electrically "close in" and carried all of the feeder's customers.

Further investigation determined that a lineman had difficulty opening the subject switch back in September 2007, three months before the ultimate outage, while making repairs necessitated by an unrelated fault on the feeder. The switch had been visually inspected shortly thereafter and had been put on a work list for replacement, but the replacement had not been accomplished.

It is surmised that the elderly switch had experienced sufficient wear and tear over time that its contacts became worn and pitted. During normal load current conditions, the switch carried 100-200 amperes and it likely could have continued to do so for some time to come. The faults on November 14 and December 15 drew thousands of amperes, which produced mechanical and thermal trauma that further aggravated the switch's already substandard condition. It is believed that this caused localized heating at the "weak spot" in the switch contacts. This in turn produced a high-impedance condition in the switch, thereby producing series arcing and the observed erratic currents. The arcing further degraded the switch contacts. During early episodes the switch maintained sufficient integrity for the problem to subside in the minutes following the high-current events. Over time, however, the cumulative damage progressed until the degraded contacts could no longer recover. Arcing in the contacts eventually burned the contacts open and caused a phase-to-ground flashover from the switch to supporting hardware. This flashover was the final, 9 000-amp fault that locked out the feeder.

In summary:

- A main line switch failed over a substantial period of time.
- The switch had been put on a repair list several months earlier, as a result of a line crew having trouble opening it.
- Multiple overcurrent faults over a period of a month aggravated the condition and accelerated final failure.
- The switch produced electrical evidence of its impending failure following each high-current fault, but the information was not available to operations personnel, so they could not use it to prioritize switch replacement.
- Final failure resulted in an extended outage for several hundred customers.

E. Improper Capacitor Controller Operation

This is another example that is not about recurrent faults, but it gives an additional indication of things that occur on distribution feeders, on a regular basis, without utility companies generally knowing about them. Like many utilities, the utility involved in this case has an annual program to inspect and maintain its feeder capacitor banks. On August 9, 2004, routine annual maintenance was performed on a capacitor bank on a feeder monitored by a DFA. The process included replacement of the bank's controller. The crew finished the maintenance in late morning and left the scene, believing the bank was operating correctly. They did not plan to return until the next year's annual maintenance.

Shortly after noon the bank switched OFF, but then it switched back ON a few minutes later. It cycled OFF and ON more 22 times the remainder of the day. The utility noted the abnormal level of capacitor switching activity on its DFA Master Station the next morning. As a result a crew was sent to troubleshoot the problem. They adjusted a controller setting and thereby eliminated the improper switching behavior.

Other project participants have documented capacitor controllers switching excessively. One particular utility took a unique approach to the DFA project: They let the feeder operate as if the DFA monitor were not in place. As a result that utility documented how failures and other problems take their normal course. In the following narrative, this utility will be referred to as the "passive" utility, and the one that corrected its problem will be referred to as the "active" utility.

Over a two-month period, the "passive" utility documented operations numbering between a few per day and well over 100 per day. The most active day produced 186 operations in a 24-hour period. In total this capacitor cycled several thousand times in a two-month period. Excessive mechanical wear and tear ultimately was sufficient to compromise the integrity of one of the bank's switches. Degraded switch contacts then arced internally and caused severe transients on a feeder-wide basis for a period of several days.

Not surprisingly the severity and repetition of transients was sufficient to cause capacitor "cans" in the subject bank to fail. Somewhat more surprisingly, these transients also caused sympathetic failure of cans in another bank on the same feeder and even in a bank on another feeder served by the same substation bus. Severe transients occurred for much of the time over a period of several days, creating a significant power quality concern, especially for sensitive loads.

In summary:

- Preventative maintenance can fail to rectify problems.
- Preventative maintenance can even cause problems. The "active" utility's capacitor bank operating correctly before it was maintained.
- The "passive" utility's capacitor switched several thousand times in two months. The "active" utility used its awareness of the problem to solve it less than 24 hours later, thereby limiting the undesirable operations to a minimal value of 22 cycles and avoiding additional negative consequences. The capacitor was not otherwise scheduled to receive any additional attention until a full year later. If the bank continued switching 22 times per day, it would accumulate 22 x 365 = 8 030 operations in that period of time. It seems most likely that the capacitor cans, switches, or something else would fail before the year was up and potentially result in other negative consequences.

IV. Conclusions

Distribution feeders are subject to a wide variety of phenomena and damage scenarios that cause faults, interruptions, and outages. Protection practices have evolved from many decades of experience. They attempt to achieve balance between the goals of system protection, safe operations, and reliable service – goals which sometimes are at odds with one another. Automatic reclosing practices enhance reliability by clearing temporary faults from the system, without prolonged customer outages or the need for utility personnel to search for sustained fault conditions when none actually exist.

Modern electronics, instrumentation, and fault recording technologies provide information previously unavailable regarding fault behavior and the system's response to those faults. Long-term monitoring at Texas A&M University has recorded numerous faults and other abnormal or undesirable conditions on 60 feeders across North America over a period of multiple years. This project has resulted in the documentation of numerous examples of recurrent faults, in which line apparatus begins to fail and cause momentary flashovers and faults, without causing permanent faults and sustained outages. These faults may be cleared temporarily by momentarily tripping a feeder or portion of a feeder and then automatically reclosing after a brief period. The latent condition then can produce additional faults and possibly apparatus damage, eventually resulting in customer complaints and/or sustained outages.

Conventional wisdom holds that customers have a low threshold of pain when it comes to "blinking lights," and that they complain to the utility quickly after one or two momentary interruptions, particularly if those interruptions occur during fair-weather conditions. Results of Texas A&M's monitoring project show that this sometimes may not be the case. There have been multiple instances in which vegetation, cracked insulators/bushings, etc. have caused multiple momentary interruptions over periods of hours to days to weeks. In many cases no customer complaints result and the utility has no knowledge that a problem is developing.

Texas A&M's monitoring program has also documented numerous other substandard or undesirable conditions that can occur on distribution systems without the utility's knowledge. Apparatus and control equipment may operate in substandard ways for long periods of time, with the utility becoming aware of a problem only after the condition escalates and causes further damage, interruptions, and outages. In the past the utility company only saw the final outage or catastrophic failure and was left to guess at events leading to that final result. Modern electronic monitoring and recording systems show that much more is happening on these systems than previously believed.

V. Acknowledgment

The authors gratefully acknowledge the support of the Electric Power Research Institute and EPRI's member utility companies. Their support provides the data upon which this investigation is based. Participating utilities also provide support by investigating and helping to document failures, faults, and other recorded anomalies.

VI. References

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VII. Biographies

Carl Benner (M'1988, SM'2004) received B.S. and M.S degrees in Electrical Engineering from Texas A&M University in 1986 and 1988. He serves as Research Engineer in the Department of Electrical and Computer Engineering at Texas A&M University. His work centers on the application of advanced technologies to the solution of challenging power system problems, with an emphasis on the application of computer-based monitoring and control.

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Dr. Russell is Past President of the Power Engineering Society and IEEE Division VII Director. He is a registered Professional Engineer in the State of Texas, Vice President of USNC CIGRE, and a member of the National Academy of Engineering.

Ashok Sundaram (M'1989) is a Project Manager in the Power Delivery and Utilization Department at the Electric Power Research Institute in Palo Alto, California. He joined EPRI in April 1993 and has been responsible for management of projects related to Power Electronics in Transmission and Distribution Systems, Power Quality, Distribution Systems Operation, Maintenance and Reliability.

Mr. Sundaram started his career as an entry level engineer responsible for the operation of a 450 MW coal fired power plant in India. He then moved to internationally known Switchgear and Electric Motor manufacturing company Crompton Greaves Ltd., as a Project Engineer.

Prior to joining EPRI, Mr. Sundaram was a Design Engineer with Behlman Electronics in Carpinteria, CA a manufacturer of solid state frequency converters primarily used in the aerospace/defense industry. He found better opportunities in San Diego, CA as a Senior Engineer with the Elgar Corporation, where he was involved in the design and development of power electronics based equipment to enhance power quality, such as uninterruptible power supplies, ultra precision line conditioners, AC to AC frequency converters and high isolation transformers.

Mr. Sundaram received a BSEE degree from the University of Madras, India, in 1978, an MSEE from Southern Illinois University in 1984. His areas of specialization are Power System Analysis, Electrical Machines, Control Systems, Power Electronics and Power Quality. He has been an invited speaker, lecturer, and session chairman at many power quality related conferences and seminars and has published several articles and papers in this field.