21, rue d'Artois, F-75008 PARIS
https : //www.cigre.org

CIGRE US National Committee
2023 Grid of the Future Symposium

Discovering and Diagnosing Protection Anomalies on Distribution Systems

J. WISCHKAEMPER*, C. BENNER, B.D. RUSSELL, K. MANIVANNAN
Texas A&M University
USA

SUMMARY

Overcurrent protection is a vital component of power delivery. Transmission lines use a variety of sophisticated protection schemes, but most distribution circuits rely on layers of time-overcurrent protection to respond to fault conditions. Practices vary widely between distribution circuit owners, but a common protection arrangement in North America would involve a reclosing circuit breaker at the substation combined with one or more midpoint reclosers (three-phase or single-phase) to sectionalize the circuit, branches protected by relatively large fuses (e.g., 40-100 amps), and individual loads protected by smaller fuses (e.g., 6-20 amps). Whatever the specific arrangement, the overarching philosophy of distribution overcurrent protection is straightforward: clear the fault as quickly as possible while affecting the smallest possible number of customers; in many cases, attempt to restore power automatically via auto-reclosing; and provide backup protection in case a particular device fails to operate.

Although failures of overcurrent protection systems do occur from time to time, protection systems generally are quite robust. They are so robust, in fact, that protection engineers often simply assume they work, and as a result are often unaware of abnormal protection operations until a catastrophic event brings them to their attention. In addition, historically, the paucity of relevant data has limited the ability for practitioners to know the actual performance of their protection systems, particularly those involving purely electromechanical or hydraulic protection.

Researchers at Texas A&M University have engaged in a multi-decade project monitoring distribution circuits, currently in five countries, obtaining and archiving high-fidelity waveform recordings from normal and abnormal events across 2,500 circuit-years of exposure during routine operations. Included among these events are multiple misoperations of distribution protection, several of them surprising.

KEYWORDS
Overcurrent protection, distribution protection, protection failures, waveform analytics

jeffw@tamu.edu

Introduction

Faults are an unfortunate reality on power systems, posing a danger to both people and property. Since the earliest power systems, designers have employed protection devices to disconnect short circuit conditions to prevent them from damaging the system or causing injury. On distribution systems, this generally entails a mix of fuses and automatic reclosing devices, distributed along the circuit and in substations. Protection practices vary from company to company, but a common arrangement might involve a relay and circuit breaker at the substation, several line reclosers along the length of the circuit (sometimes more than a dozen, depending on the length and complexity of the circuit), and many fuses to protect major branches, tap lines, and individual loads. Recent advances in protection on distribution systems have introduced new possibilities (e.g., FLISR, situational enablement of alternate fast-trip settings, etc.), but at a conceptual level these developments are incremental improvements on the concepts that have long underpinned the protection system: operate quickly if there is a fault, do not operate if there is not a fault, and isolate the fault to the smallest section of line possible so as to affect the fewest number of customers and to narrow search areas for faults.

Although system protection has proven to be generally very reliable, it does fail from time to time. Because the protection system is generally designed with redundant layers, a backup device may operate to clear a fault when a downstream device does not [1]. As this paper will show, however, there are surprising ways in which the protection system can fail on distribution systems, often unbeknownst to the circuit owner.

Data Source: Distribution Fault Anticipation

Researchers at Texas A&M University have been engaged in a decades-long project to monitor active distribution circuits with the goal of finding and fixing failing apparatus before they cause catastrophic failures and outages. Over the course of the project, researchers have instrumented hundreds of circuits with high-fidelity waveform recording devices designed to trigger recordings far more sensitively than a typical relay or power quality monitor. By recording sensitively, researchers have been able to see early-stage precursors for many classes of events, enabling circuit owners to locate and repair incipient failures. A natural additional benefit of the Distribution Fault Anticipation (DFA) project is the creation one of the largest known databases of normal and abnormal power system transients, currently consisting of over 13 million waveform records over 2,500 circuit years of exposure.

In the course of the project, DFA has documented multiple misoperations or unintended operations of power system protection. This paper will detail several case studies.

Case Study 1: Excessive recloser operations

Automatic reclosing systems are designed to deenergize a faulted circuit or segment, wait a specified amount of time, then reapply power (reclose). Many power system faults are temporary, so removing and then restoring power greatly improves the reliability of the power system. Some studies indicate that as many as 90% of power system faults are cleared with three reclosing attempts [2-9]. (Authors note: the most recent studies of this type are at least decades-old and rely on data that may no longer be valid. The authors' DFA dataset contains over 50,000 overcurrent fault sequences, which the authors plan to mine to assess the continuing validity of certain older fault studies.) Figure 1 shows current waveforms produced by a fault cleared by a line recloser with a common "four trips to lockout" setting, using a 2A2B (two fast trips followed by two delayed trips) scheme. This practice gained popularity due to the large number of hydraulic reclosers in service in the middle part of the 20th century.

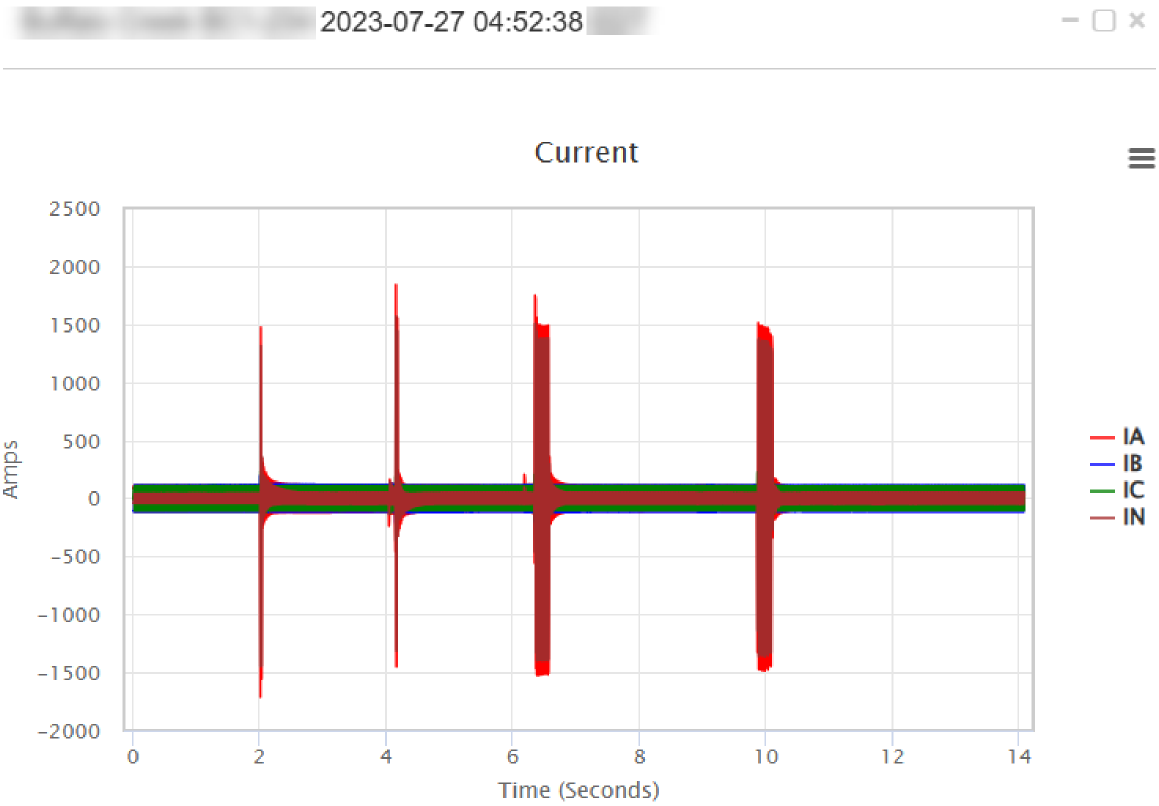

Figure 1. Four trips to lockout (2A2B)

Hydraulic reclosers have reasonably good reliability, but they are subject to failures in their mechanical apparatus. Further, they generally have no monitoring or communications, and a circuit owner often has no effective way to assess their performance, except by reading their operations counters periodically or by performing physical testing and inspection. DFA instrumentation has recorded multiple cases in which line reclosers that were configured to lock out after three or four trips instead have operated more times, for example, six times. DFA also has documented a dozen extreme cases, at six distinct distribution companies, in which line reclosers have auto-reclosed dozens or even hundreds of times over periods of minutes to tens of minutes. The authors have adopted the shorthand term “recloser pumping” to refer to this phenomenon.

Table 1 summarizes the twelve documented cases of extreme recloser pumping. In most of these cases, the circuit owner was unaware that pumping had occurred. Two of the involved reclosers experienced pumping on more than one occasion, leading one to speculate that a recloser that has behaved this way in the past has increased risk of doing so again. Cases 9 and 10 involved a certain recloser that experienced pumping 740 times in case 9 and then, six months later, 320 times in case 10. Cases 11 and 12 similarly involve 1100 operations of a certain recloser and then, three months later, 73 more operations of the same recloser. In summary, the twelve documented cases involved ten distinct reclosers at six distinct distribution companies.

Figure 2 shows DFA-recorded current for a one-minute period of case 10 of Table 1. During that one-minute period, the recloser tripped and auto-reclosed thirteen times. In totality, the recloser tripped and auto-reclosed approximately 320 times over a period of 22 minutes.

Table 1. Twelve documented cases of recloser "pumping"

Case #	# Auto-reclose operations without lockout	Period spanned by those pumping operations
1	800 operations	24 minutes
2	680 operations	26 minutes
3	107 operations	3 minutes
4	88 operations	2 minutes
5	140 operations	12 minutes
6	120 operations	2 minutes
7	120 operations	6 minutes
8	300 operations	14 minutes
9	740 operations	26 minutes
10	320 operations	22 minutes
11	1100 operations	33 minutes
12	73 operations	3 minutes
Cases 9 and 10, which occurred six months apart, probably involved a single recloser.		
Similarly, cases lines 11 and 12, which occurred three months apart, probably involved a single recloser.		
The twelve cases of pumping involved ten distinct reclosers at six distinct distribution companies.		

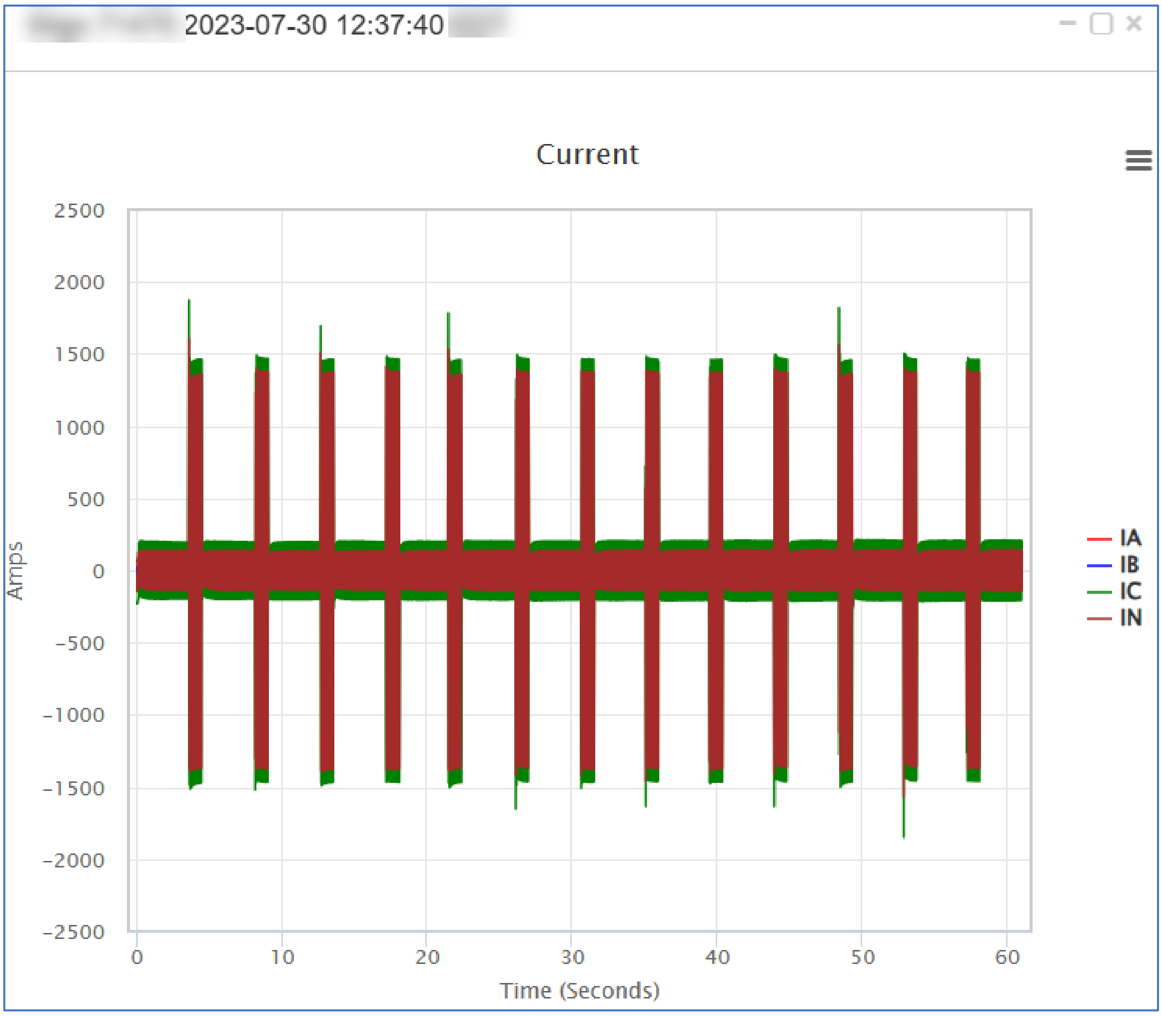

Figure 2. Substation-recorded line current during one-minute period of recloser pumping (part of case 10 of Table 1)

Consequences of such events are manifold, including the following.

1. Failure of a line recloser to clear a fault in a timely manner prolongs safety hazards.
2. Each fault pulse represents potential for igniting a fire, and the prolonged series of fault currents increases that risk.
3. Each trip and auto-reclose causes a momentary interruption to all customers beyond the recloser and a voltage sag to all customers on the entire circuit and even on other circuits served by the same substation bus.
4. The series of fault pulses may create cumulative damage to conductors and perhaps other apparatus directly involved in the fault event, increasing the possibility of burndown or other catastrophic event.
5. The substation transformer and all line components upstream of the fault are subjected to electromagnetic and thermal stresses associated with repetitive passage of fault current, potentially creating damage and/or reducing their expected lifespan.
6. The pumping line recloser itself experiences cumulative stress of interrupting, in a few minutes, more faults that many line reclosers experience in decades of normal service, causing accelerated oil contamination, contact pitting, and potentially other mechanical degradation.

The precise mechanism behind this phenomenon is not known, but it is believed to be associated with the failure of the lock-out mechanism on a hydraulic recloser. Key takeaways are that this phenomenon is not a one-off situation and that modern data systems can help uncover previously hidden phenomena.

Case Study 2: Fast tripping after a fault has self-cleared
In an effort to reduce ignition risk, some circuit owners have begun to employ fast, sensitive trip (FST) settings on substation breakers and line reclosers in high fire risk areas. They generally enable FST settings only during hot, dry, windy periods that present elevated ignition risk. FST settings trip with no intentional delay and inhibit reclosing. Some circuit owners have credited FST settings with reducing wildfire ignition, but FST settings also cause undesired reduction in service continuity. System protection design inherently involves balancing protection reliability (i.e., tripping when there is a fault) and protection security (i.e., not tripping when there is not a fault, or tripping for a fault where a downstream device should have operated first). Enabling FST settings during periods of elevated ignition risk tips the balance toward protection reliability at the expense of protection security and service continuity. This trade-off is a conscious decision made in an attempt to reduce ignition risk.

For circuits with FST settings enabled, the circuit owner’s procedures may require a patrol of the entire deenergized section prior to restoring service, a process that may take hours and that may be complicated by factors such as weather and daylight hours. A worst-case scenario occurs when a patrol results in “no cause found.” Such a patrol generally takes an extended period and leaves the circuit owner with the choice of trying to reenergize the line without knowing what caused the trip or repeating the patrol in hopes of finding the cause.

Narrating the remainder of this case study requires this two-paragraph aside to describe the electrical phenomenon that often accompanies the incipient-failure period of a medium-voltage cable fitting. During this incipient-failure period, a cable termination may produce current pulses of substantial magnitude (e.g., hundreds or thousands of amperes) but short duration, often less than one-half cycle. The pulses self-clear, without operation of a fuse, recloser, or any other protection device. A failure of a single fitting may cause multiple such incipient pulses, over periods of hours to months, with quiescent periods of minutes to days between consecutive pulses [10-11].

Figure 3 illustrates a typical current pulse from an incipient cable-fitting failure. The recording comes from CTs at the substation head of the affected circuit and contains 200 amps (peak) of normal load current, plus a pulse that adds an additional 400 amps (peak) for a fraction of a cycle, prior to self-clearing. This was one of dozens of similar pulses, over a period of months, associated with the incipient failure of a single cable fitting.

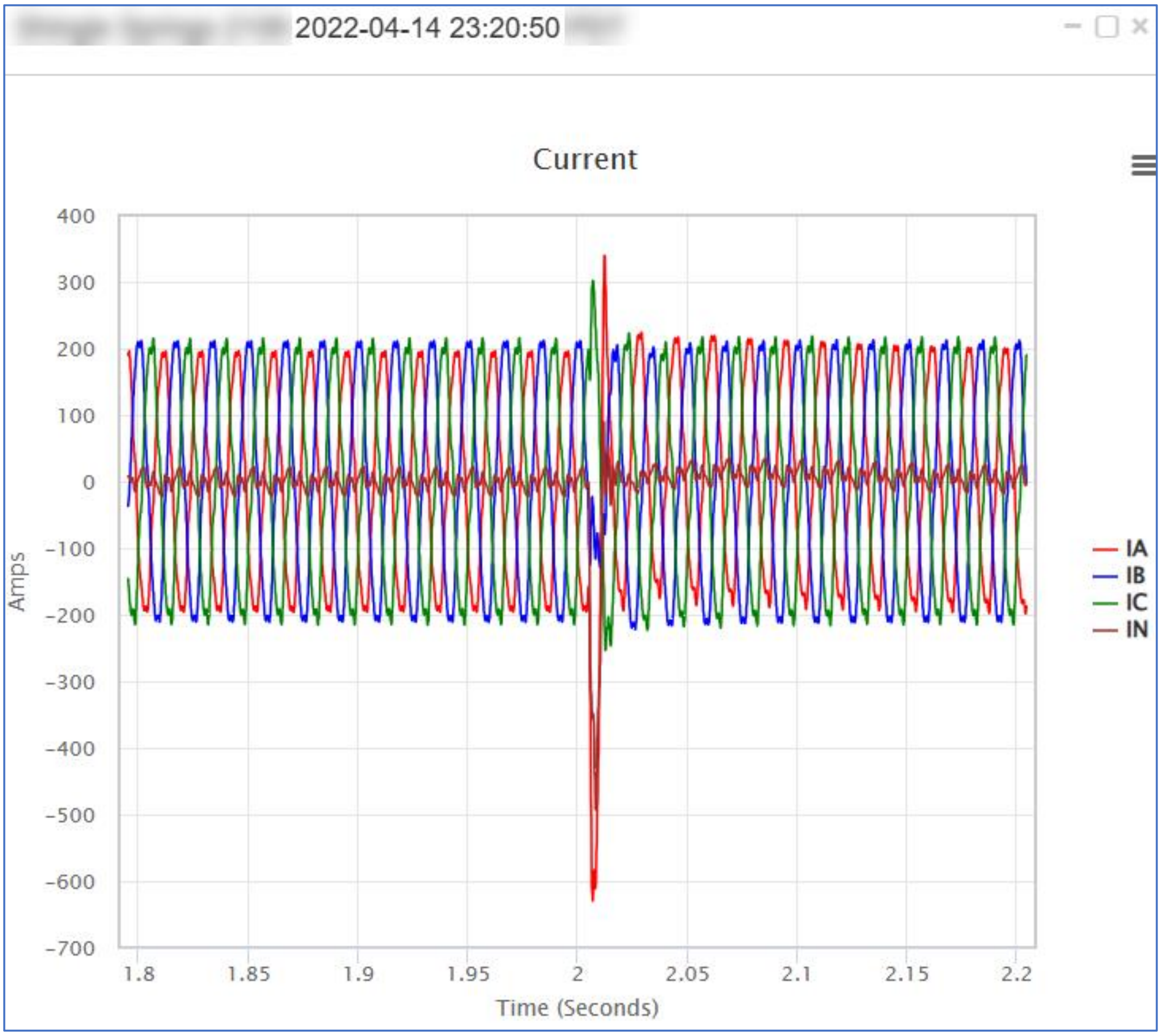

Figure 3. Self-clearing, sub-cycle current pulse caused by incipient failure of an MV cable fitting

The case study at hand involves the intersection of FST settings and incipient failure of a cable fitting. Pulses from such an incipient failure can initiate the process of tripping of an FST-enabled line recloser, but then self-clear before the line recloser mechanically has time to open. For example, Figure 4 shows a current pulse, followed by a significant drop in three-phase load current when a line recloser tripped 1900 customers. Figure 5 zooms in on that same event and shows that the current pulse had self-cleared two cycles before the line recloser tripped. Tripping of the line recloser effectively was an undesirable, nuisance operation in response to a condition that already had self-cleared. The self-clearing pulse directly interrupted no customers, but the associated trip of the FST-enabled line recloser interrupted 1900 customers. The result was an outage of extended duration, because the required patrol had nothing to find. Figure 6 shows a timeline of 79 pulses, over a period of

6.5 months, arising from the single incipient failure of a cable fitting. Three of those occurred with FST settings enabled and tripped 1900 customers.

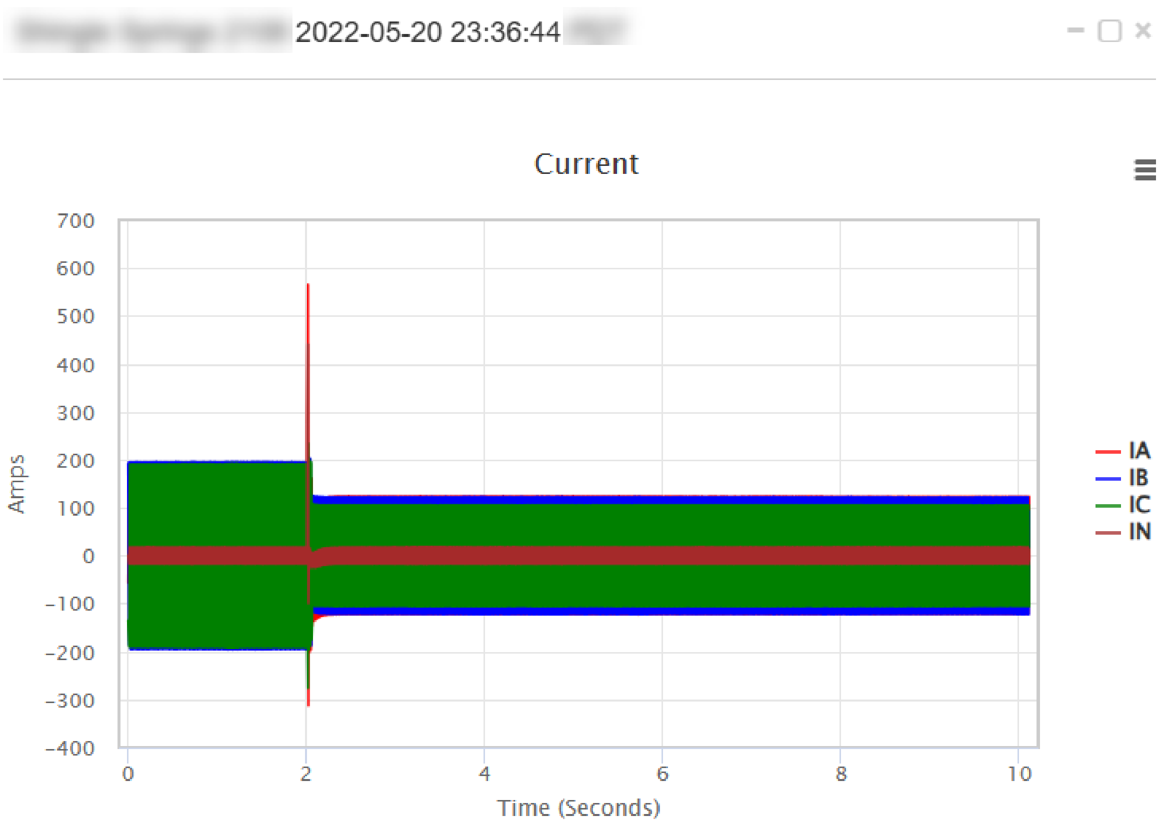

Figure 4. Short-duration fault and trip of FST-enabled line recloser

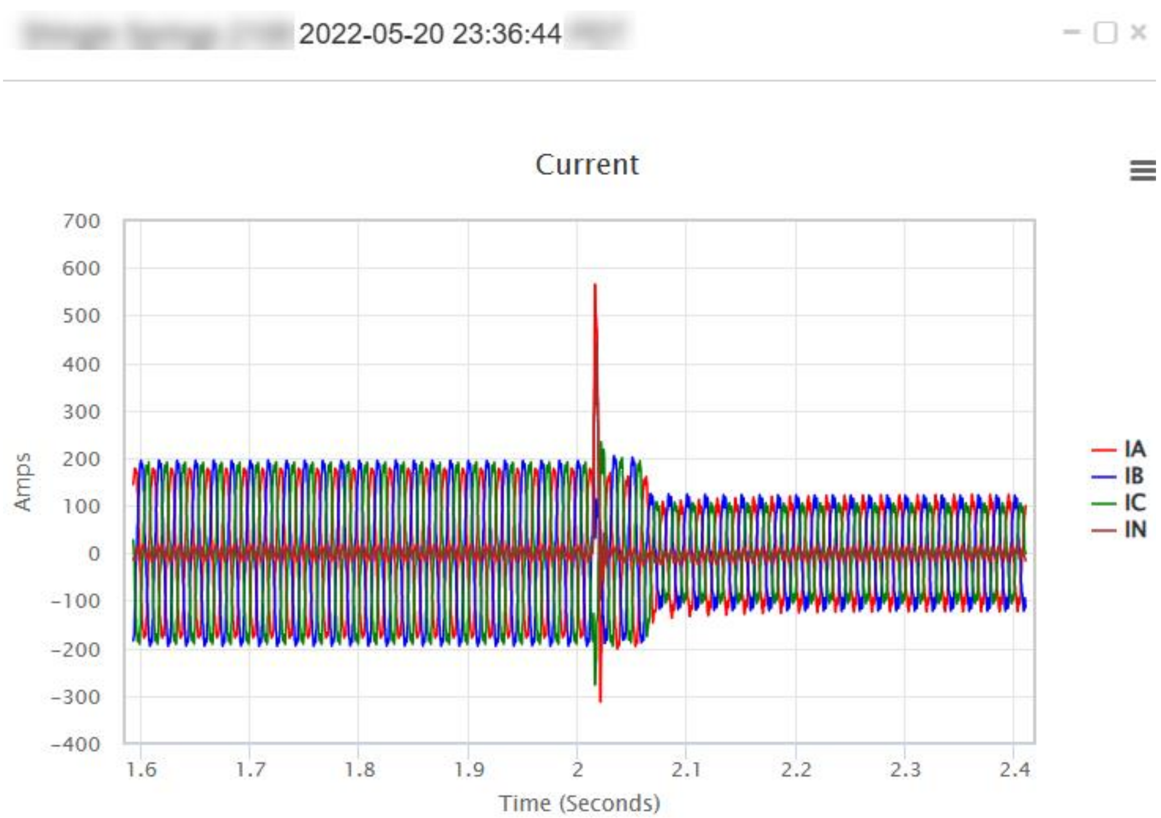

Figure 5. Event of Figure 4, zoomed to show that the FST-enabled line recloser tripped two cycles <u>after</u> the pulse self-cleared

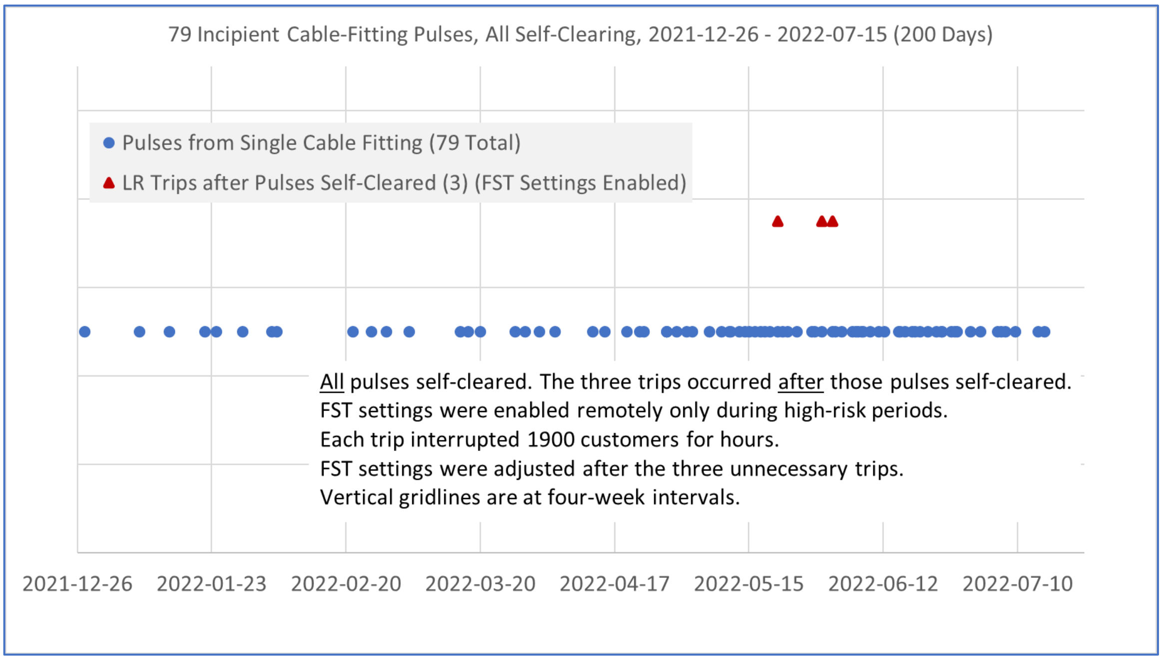

Figure 6. Timeline of 79 current pulses, all self-clearing, including three that tripped FST-enabled line recloser

The aforementioned undesirable operations associated with FST-enabled protection were illustrated with examples of self-clearing pulses arising from incipient failure of a cable fitting. DFA installations also have documented multiple cases where a fuse operates to clear a fault quickly, but then an FST-enabled line recloser trips a cycle or so later. The fuse-blowing case differs from the incipient-pulse case only in that the incipient pulse requires no protection operation to clear. Both cases result in nuisance interruption of larger-than-necessary numbers of customers and can result in larger, longer-duration patrols.

Case Study 3: False tripping of energized downed-conductor (high-impedance fault) detection technology

Detecting an energized conductor on the ground, which often presents as a high-impedance fault, is a challenging problem. Multiple developments have occurred in the decades since two of the authors of this paper developed the first commercialized downed-conductor detection algorithms, and detailing all of them would be a meaningful paper on its own. That said, efforts to detect downed conductors, even on multi- or uni-grounded systems, always has involved significant trade-offs between protection reliability and protection security. A key design goal of a protection system always has been to operate when there is a fault, but engineers traditionally considered it almost equally important to not operate when there was not a fault present. Protection against a high-impedance fault is substantially more difficult than protection against a conventional bolted fault, because a high-impedance fault may have current magnitude similar to or in some cases significantly less than that of normal system loads, making it difficult to detect high-impedance faults reliably without suffering false trips from normal load variations, including routine transients. This is particularly true on four-wire, multi-grounded systems where loads are connected phase-to-neutral, and it is difficult or impossible to use sensitive ground fault protection. Anecdotally, in the 1990's, when developing early commercial downed-conductor detection algorithms, industry advised the authors that even a small number of false trips, across an entire distribution system, would cause a circuit owner to disable the technology, even if it performed well for actual downed lines. In other words, clear industry bias was toward protection security, even at the expense of some degree of protection reliability. Further to the mindset of the day, industry guidance at the time also was to not trip a high-impedance fault, even its presence were known with

100% confidence, without first waiting a substantial amount of time, on the order of tens of seconds, to allow every chance for a small fuse or other downstream protection to operate to create a small outage and small patrol zone.

Industry priorities and guidance have evolved substantially in the ensuing three decades. In the extreme, some circuit owners today are willing to deenergize circuits proactively in areas of high ignition risk, even with no fault present. They also are more willing to tolerate false trips for technologies which have the potential to detect some number of energized downed conductors. It is important to note, however that "more willing to tolerate false trips" does not mean "infinitely willing to tolerate false trips." There always is, and indeed must be, a balance between protection reliability and protection security against false tripping. The lowest risk of powerline-caused ignition comes from a power system one never energizes and that delivers no power, but such a system is not terribly useful.

This case study discusses episodes in which DFA installations have documented multiple likely false operations of an extra-sensitive ground protection (ESGP) scheme, generally one to two seconds after normal clearing of a line fault. As of this writing, the precise mechanism that leads to the likely false ESGP trips remains under investigation. The ESGP implementation is not of Texas A&M's design, but the Texas A&M team is involved in the investigation of the likely false trips, because of their deep background knowledge of the behavior of high-impedance faults, including downed conductors, and because of their expertise in the interpretation of data recordings from the DFA system.

Figure 7 shows the current recording associated with one such episode. A line-to-line fault occurs at t=2s and quickly causes a line recloser to trip and interrupt 1.98 MW of load. With FST settings enabled, that is deemed proper operation. But then 1.2 seconds later, at t=3.2s in the figure, a second line recloser trips, farther upstream, interrupting another 0.98 MW. This second trip is being investigated as a likely false ESGP trip. Of note, the only fault was the initial line-to-line fault, with no ground fault at any time during the sequence of events, which is a perplexing situation, because ESGP protection is intended only to respond to ground faults.

As an aside, the DFA platform records longer-duration records than conventional relays and recloser controllers, typically at least ten seconds in duration, and these longer records can provide significant value in root-cause analyses, particularly where operations of multiple devices are involved. The circuit owner associated with this case study has ready access to records showing which line reclosers operated, but readily accessible timestamps on those records have time accuracy on the order of one minute. Having GPS-grade timestamping from all devices is the most obvious solution for time-aligning records from multiple devices, but that is not a reality for many circuit owners and will not be broadly available for many circuit owners for quite some time to come, particularly for devices not located in a substation. The DFA recording is this circuit owner's only reasonably accessible source for knowing the precise timing between the two line reclosers that operated, 1.2 seconds apart in this particular case. All DFA records are sent to a central master server automatically and accessible to personnel within a few minutes of the underlying event.

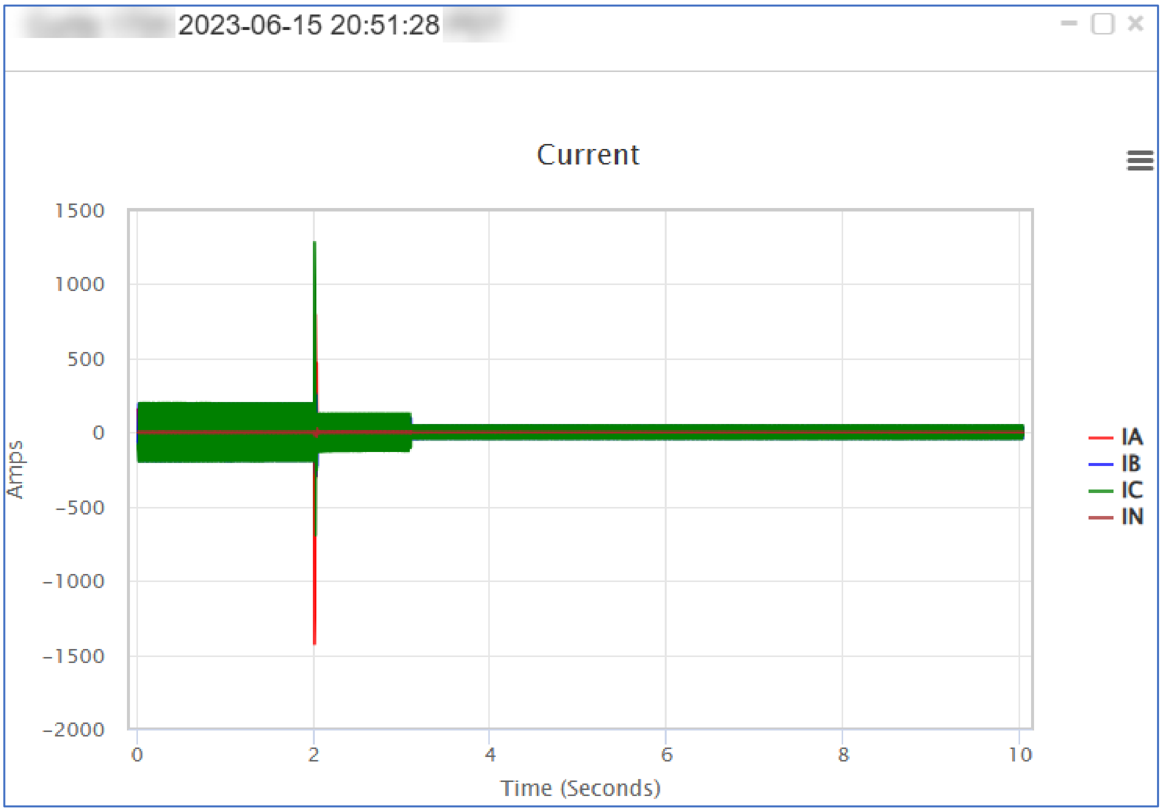

Figure 7. Sub-cycle fault that caused two line reclosers to trip, the second one 1.2 seconds after the fault

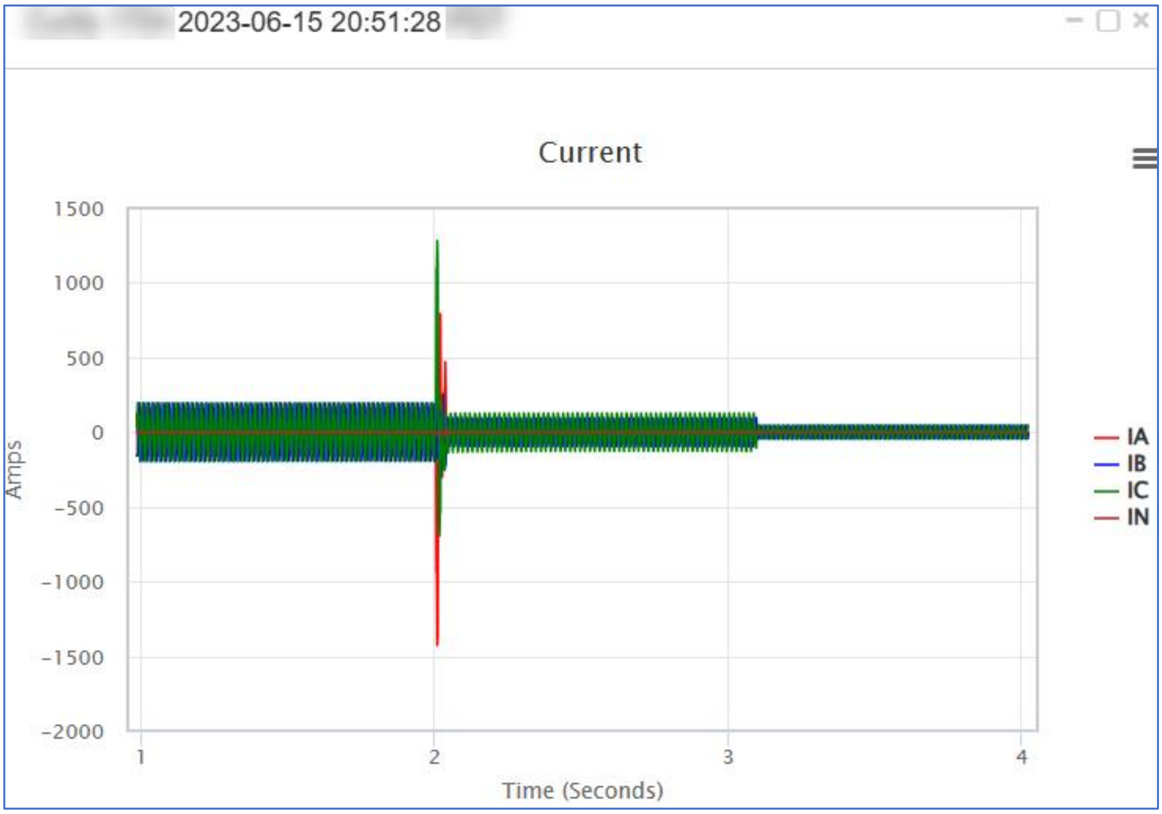

Figure 8. Event of Figure 7, zoomed to show the trips at t=2s and t=3.2s.

CONCLUSIONS

System protection provides a critical role in any power-delivery system. Design of these systems has multiple requirements, some of which are in tension with one another and require art and judgement to balance. One of the most obvious is the natural trade-off between tripping circuits when necessary but otherwise leaving the lights on. Striking the proper balance requires understanding the priorities of a particular situation. For example, in recent years, reducing ignition risk is a bigger driver than just a few decades ago, and circuit owners are devising new protection philosophies in response, with a tendency to be more accepting of unnecessary nuisance trips than in the past. Some of the ramifications of new techniques and settings are, if not fully desirable, at least expected, but others are not.

As new technologies and schemes are developed, the increase in complexity also increases the likelihood of unintended interactions between both new types of protection with other schemes, and new types of protection with traditional time-overcurrent protection. Based on traditionally available data sources (e.g., SCADA), circuit owners may identify *when* unintended operations occur, but may be unable to fully diagnose *why* they occurred. In other cases, circuit owners may have no knowledge that unintended operations are happening at all.

The advent of better data enables a more complete understanding of the expected and unexpected ramifications of changing protection goals and practices. Better data also allows discovery and action related to maloperations of conventional protection systems in general, one specific such case being reclosers that trip more times than desired, in some cases many, many more times than desired or previously recognized.

BIBLIOGRAPHY

[1] Investigation Report on ConEdison’s July 2019 Outages in Manhattan and Brooklyn, New York Department of Public Service, November 2020

[2] E. W. Robinson and S. J. Spurgeon, "Automatic Reclosing of High-Voltage Circuits," American Institute of Electrical Engineers, Transactions of the, vol. 48, pp. 981-987, 1929.

[3] A. E. Anderson, "Automatic Reclosing of Oil Circuit Breakers," American Institute of Electrical Engineers, Transactions of the, vol. 53, pp. 48-53, 1934.

[4] Johnston, L., Tweed, N. B., Ward, D. J., and Burke, J. J., “An Analysis of Vepco’s 34.5 kV Distribution Feeder Faults as Related to Through Fault Failures of Substation Transformers,” IEEE Transactions on Power Apparatus and Systems, vol. PAS- 97, no. 5, pp. 1876–84, 1978

[5] "Distribution Line Protection Practices Industry Survey Analysis," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-102, pp. 3279-3287, 1983.

[6] Ackermann, R. H. and Baker, P., “Performance of Distribution Lines in Severe Lightning Areas,” International Conference on Lightning and Power Systems, London, U.K., June 1984.

[7] "Distribution line protection practices-industry survey results," Power Delivery, IEEE Transactions on, vol. 3, pp. 514-524, 1988.

[8] W. M. Strang, R. M. Westfall, A. N. Darlington, P. R. Drum, D. Fulton, E. Guro, J. D. Huddleston, III, T. L. Kaschalk, J. R. Latham, W. J. Marsh, M. J. McDonald, R. J. Moran, R.

D. Pettigrew, R. P. Taylor, and J. T. Tengdin, "Distribution line protection practices industry survey results," Power Delivery, IEEE Transactions on, vol. 10, pp. 176-186, 1995.

[9] T. A. Short, Electric Power Distribution Handbook. Boca Raton, FL, USA.: CRC Press, 2004

[10] N. T. Stringer and L. A. Kojovic, "Prevention of underground cable splice failures," in IEEE Transactions on Industry Applications, vol. 37, no. 1, pp. 230-239, Jan.-Feb. 2001, doi: 10.1109/28.903154.

[11] Wischkaemper, J. A., Benner, C. L., Russell, B. D., Manivannan, K., "Online Automated System for Incipient Fault and Failure Detection of Distribution Apparatus Using Waveform Disturbances." CIRED 2023 International Conference & Exhibition on Electricity Distribution. Rome, Italy. June 2023