Tree Times the Charm: A Cultivated Approach to Targeted Tree Trimming

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***Abstract*—Vegetation encroachment of overhead distribution lines is a common problem for electric utilities. Experience has shown these encroachments can be detected one to two years in advance by overcurrent assertions and/or trips in protective relays. The assertions are transient, usually lasting only a few cycles at most, so the protective relays often do not trip. Since no trip occurred, no engineering analysis of the records is carried out, and the data indicating an incipient event is wasted. Even when trips do occur, utilities often do not perform event analysis of momentary interruptions (single trip and reclose), so the data is still wasted.**

This paper presents a novel method for sensing encroaching vegetation using this transient relay data by a detection and filtering algorithm developed inside protective relays. The algorithm can send an encroachment alarm to engineering and/or system operators to start the process of locating the problem area for targeted, on-demand trimming.

The encroachment alarm can be improved to precisely locate the encroachment location by using strategically placed fault indicators. The paper illustrates how using these indicators can refine the algorithm from three-phase detection down to the exact phase(s) involved and a small location bandwidth, ideal for targeting taps with known vegetation problems.

I. INTRODUCTION

Electric utilities with overhead distribution lines have long had difficulties with tree or other vegetation contacts. Utilities use a programmatic approach to trim trees on a defined cycle, but even with a scheduled trimming approach trees can grow back faster than the trimming cycle restarts. Through analysis of thousands of protective relay events, the authors came to realize that, in many cases, vegetation encroachments cause transient short circuits, which can be detected by protective relays. These events often clear faster than the overcurrent curve timeout so the relay does not trip, and without a trip there is no indication the relay has just recorded useful data, so no analysis is performed. Valuable information goes wasted.

This paper demonstrates a fresh approach for collating these events inside the protective relay via a custom-built detection algorithm. The output of this algorithm is an encroachment alarm that can be sent to notify the relevant teams, usually system operations and reliability engineers, that a precursor event to an impending vegetation-caused outage is occurring. Those teams can then quickly perform an event analysis and fault-location study to initiate a targeted vegetation clearing.

This concept is expanded by adding fault indicators to improve the automated response. Fault indicators are used to narrow the algorithm detection down to the specific phase or tap of the vegetation encroachment and can be used to further refine the fault indication down to specific zones.

The expanded approach using fault indicators is useful for targeting problem areas exposed to repeated vegetation contacts and/or high wildfire risk areas because a protective relay can have only a limited number of fault indicators connected to it. This approach can be used to monitor specific sections of three-phase lines, specific taps, or multiples zones on a tap.

II. TRANSIENT VS. MOMENTARY VS. SUSTAINED

The remainder of the paper references the terms transient, momentary, and sustained in relation to vegetation contacts. These terms follow the IEEE 1366-2022 definitions [1], and are briefly explained below:

A. Transient

Transient contact is often, but not exclusively, subcycle in nature and does not result in a relay trip. For purposes of this paper, transient contact is considered any vegetation contact that asserts the relay overcurrent element(s) but does not result in a relay trip. In other words, the fault current was large enough in magnitude to assert the overcurrent element but did not persist on the system long enough to cause the curve to timeout and trip.

B. Momentary

Momentary contacts are those that result in a relay trip, reclose, and hold. A device can trip any number of times before resetting its reclosing relay and each trip is considered a momentary if the reclosing relay never reaches lockout state. For example, a device with four trips to lockout trips three times, recloses three times, then holds. Each trip is considered a momentary since there was no lockout.

C. Sustained

A sustained interruption is one that results in any number of consecutive trips that drive the reclosing relay to lockout before it resets. Recalling the above example, were the device to trip four times, reclose three times, with the fourth trip resulting in a lockout, the event is considered a sustained outage. The vegetation detection algorithm accounts for these distinctions.

III. THE IMPORTANCE OF EARLY VEGETATION DETECTION ON ELECTRIC UTILITIES

PPL Electric Utilities (the utility) maintains approximately 50,000 miles of lines. Per IEEE C37.104-2002, 85 to 90 percent of all faults are transient faults [2]. The utility implemented a fuse saving scheme, using a ground fast setting to clear transient faults before the distribution line fuse would operate. The ground fast scheme was implemented for the majority of the utility's telemetered reclosers. With the implementation of the fuse saving scheme, the utility identified many momentary interruptions on distribution lines due to tree encroachment, conductor slap, and other transient fault scenarios. From reviewing the event records, the utility identified several precursor momentaries that did not initiate a trip. Using the fault magnitude, the engineers determined a fault location for the reliability engineers to patrol for the suspected transient fault locations. To reduce the number of fuse saving trips on the overhead distribution line, they trimmed the tree at the trouble location ahead of schedule. This would improve customer experience by reducing momentaries and preventing a potential permanent outage from occurring in the future.

The benefit of including fault indicators for detecting transient faults allows electric utilities to examine the line with great fidelity. With fault indicators strategically installed at single-phase taps, utilities can sectionalize the line into multiple zones, identify the location of the fault, and provide local indication for field personnel to patrol the line for the potential cause of trouble. From identifying transient fault locations in the past, the utility discovered that there could be multiple suspected locations of the transient fault. Including fault indicators allows electric utilities to reduce the number of suspected locations because the sensors divide up the circuit into multiple sections. This allows for a more precise location when doing a fault-locating analysis and reduces field personnel time spent patrolling multiple spans of lines.

IV. VEGETATION ENCROACHMENT SEQUENCE

The sequence of vegetation encroachment follows a cyclic pattern: one to two years before an encroachment that causes an interruption in service, the relay will detect transient overcurrent events that sometimes initiate a trip, but not to lockout. Later, those transient events become more common as the encroachment worsens; more trips may occur. After that, repeated momentary outages will occur in rapid succession, from a few weeks to a few months in advance of the final encroachment, which ultimately results in a trip to lockout and the resulting permanent interruption.

To demonstrate this, a sample of this sequence from an actual relay history used in the development of this paper is shown in Table I.

Table I shows that once the encroachment cycle starts, the relay sequence of events shows a clear pattern of overcurrent assertions and trips that become more frequent as the final outage approaches, after which the problem vegetation is found and cleared. Recognizing this pattern led the authors to develop the vegetation encroachment detection algorithm discussed in this paper, with the end goal of performing targeted, on-demand tree trimming that prevents the final, permanent interruption.

TABLE I
SEQUENCE FROM ACTUAL RELAY HISTORY

Event no.	**Date**	**Time**	**Phase**	**Mag. (A)**	**Event type**
Event Group 1					
1	2/3/2023	13:39:07	AB	5612	Pickup
2	2/3/2023	13:39:17	ABC	6057	Trip
3	2/3/2023	14:05:40	BC	1016	In-rush
4	2/3/2023	14:05:46	ER	64	High-Impedance
5	2/3/2023	16:34:47	AB	2714	Trip
6	2/3/2023	16:34:52	ABC	5984	Trip
Event Group 2					
7	9/7/2023	21:32:57	AB	4073	Pickup
8	9/7/2023	21:32:58	BC	5664	Pickup
9	9/7/2023	21:33:03	AB	4616	Pickup
10	9/7/2023	22:54:31	ABG	826	In-rush
Event Group 3					
11	6/10/2024	10:42:23	BCG	3590	Trip
12	6/24/2024	17:03:55	AB	4112	Trip
13	6/26/2024	Protective relay trips to lockout.			

We can accelerate the encroachment detection if the protective relay has high-impedance fault (HIF) detection available. HIF detection can be used to identify arcing conditions that, when correlated with the relay overcurrent assertions and trips from the sequence of events, become a reliable indicator of a worsening problem that is almost always correlated with vegetation [3] [4].

For the relay sequence of events shown in Table I, the corresponding high-impedance sequence is shown in Table II. Table II shows that all three high-impedance events are directly aligned with a date and timestamp that match the regular sequence of events. In this instance, the very first vegetation contact on 2/3/2023 also asserted an HIF event, showing that this tree encroachment arced as early as one-and-a-half years before the final lockout event. Using the algorithm from this paper, this event would have been immediately identified as a problem and, once the fault location had been determined, the encroaching vegetation would have been proactively trimmed.

TABLE II
CORRESPONDING HIGH-IMPEDANCE SEQUENCE

Event no.	**Date**	**Corresponding Event From Table I**	**Event type**
1	2/3/2023	4	High-impedance arc detection
2	9/7/2023	10	High-impedance arc detection
3	6/10/2024	11	High-impedance arc detection

The five examples analyzed in detail for this paper all followed a similar pattern to that found in Table I and Table II. From the authors' experience analyzing thousands of such events, most vegetation encroachments follow this same pattern. There will of course be variations, so we encourage readers to experiment and customize the details to their use case.

The Phase column in Table I is the header taken directly from the relay history. The column is automatically populated when a relay event trigger occurs by unknown internal decision logic. This is sometimes important when multiple phases are shown but the actual fault location is on a single phase. For example, in Table I, the initial fault location involves AB and ABC phases but was eventually found to be a tree encroaching on Phase B. This happens for variety of reasons, which include the fault arcing to other phases or conductor slaps on incorrectly sagged sections, but most often the cause is the simple assertion of the 51P element on the other phases during the fault, often resulting from three-phase loads drawing additional current when the fault phase voltage dips.

Regardless of the phases identified, it is important to find the commonalities to distinguish the single-phase event. It is possible, and the authors have done so many times, to use this same approach to find conductor slap locations, but that is not within scope of this paper. Also, it is assumed a true three-phase event will result in a trip to lockout most of the time, so the location does not need to be correlated.

V. EXPLANATION OF VEGETATION ENCROACHMENT CYCLE

For purposes of this paper, we will call the event sequence the vegetation detection cycle (VDC). A detailed explanation of the VDC is shown below. The events that correspond with Table I or Table II rows are shown as Event *n*. The time is shown as the initial event [T] plus the next period in months. For example, T+18.5 would be 1 year, 6 months, and 15 days after the start of the cycle.

1. [T] Start of trimming cycle (in which vegetation is trimmed on a periodic schedule)
2. [T+12.0] First event cycle
    a) Vegetation encroaches on the line ahead of the next tree trimming cycle.
    b) Protective relay sees a transient event (Event 1).
    c) Protective relay trips (Event 2).
    d) Vegetation burns away.
3. [T+18.0 to T+24.0] Second event cycle
    a) Vegetation regrows closer to line.
    b) Protective relay sees more transients (Events 7, 8, and 9).
    c) Some vegetation burns away. More momentary trips occur. High-impedance alarms may occur.
4. [T+24.0 to T+36.0] Third event cycle
    a) Vegetation grows into line.
    b) Momentary trips become more frequent, with shorter durations between trips (Events 11 and 12).
    c) Vegetation reaches final encroachment state and causes a permanent fault. Protective relay trips to lockout (Event 13).

VI. NON-VEGETATION DETECTION RELAY EVENTS

It must be understood that the protective relay will record more than just the events we are looking for. This knowledge is important for filtering out unwanted information in the algorithm event counter. Primarily, these relay events take three forms: in-rush, consecutive trips, and other relay events. The intent is to finesse the algorithm so that it only counts the relevant events.

A. In-Rush

Magnetizing in-rush occurs after every reclose event and is usually 3.0 times the pre-fault load but can be as high as 10 to 12 times. We must be careful not to assert the decision logic on in-rush because it does not indicate vegetation encroachment. The protective relay phase overcurrent will often assert on magnetizing in-rush after any trip and reclose due to the high transient current. We must also consider that the protective relay can assert overcurrent on in-rush from the trip and reclose of a downstream device, usually a series recloser that has tripped and reclosed.

Since in-rush conditions can be detected by second harmonic waves, we use the protective relay second harmonic filter to block events that cause the overcurrent to assert but are not short circuits.

B. Consecutive Trips

Consecutive trips happen when the protective relay sees multiple faults in a row before either locking out or transitioning back to the reset state. We want to count the first of these trip events, not the subsequent trips, because a single event that results in three trips to lockout would immediately force the event counter to the maximum. We assume the utility is aware of relays that have tripped to lockout.

We also do not want to count events where there are two or three consecutive trips but no lockout. The authors have made a judgement call based on the reviewed data that more than one trip before transitioning to the reset state should not be counted in the algorithm because the utility is likely to investigate a protective relay that has tripped two or three times, then held. If this is not the case, the algorithm counting functions can be adjusted to include consecutive trips by reducing the timer settings.

C. Other Event Data

Other events include those that we do not want to include in the counting algorithm that are not overcurrent assertions or trips. These can be manual open/close commands, other protection elements such as voltage or frequency, or other functions that trigger an event record, such as a push button activation, or remote bit received (perhaps to clear targets). This event data is not normally included in the relay logic in a manner that would interfere with the detection and counting algorithm, so would not trigger false counts. However, the authors wish to impart that we have not found this data useful in detecting vegetation encroachment, so the algorithm has been crafted in a manner to ensure it is filtered out. This is because some utilities will trigger events on this data, and in rare cases have alarm assertions any time an event record (ER) is triggered, so we do not wish to add yet another alarm to monitor unnecessarily.

As an example, one might ask, “why not count any TRIP event?” To which the answer is: because TRIP can assert for non-protection reasons, such as a local or SCADA manual open.

D. On Resetting Counters

When to reset the counters manually is an open question based on how each utility wishes to monitor their lines and taps. The authors recommend resetting all counters upstream from the fault location whenever the fault is found, be that by patrol and trimming or when a trip to lockout occurs, but readers should experiment with what works best for their approach.

VII. ALGORITHM LOGIC

The algorithm logic diagram is shown in Fig. 1. For ease of discussion, each block of code is highlighted and has its own descriptive header.

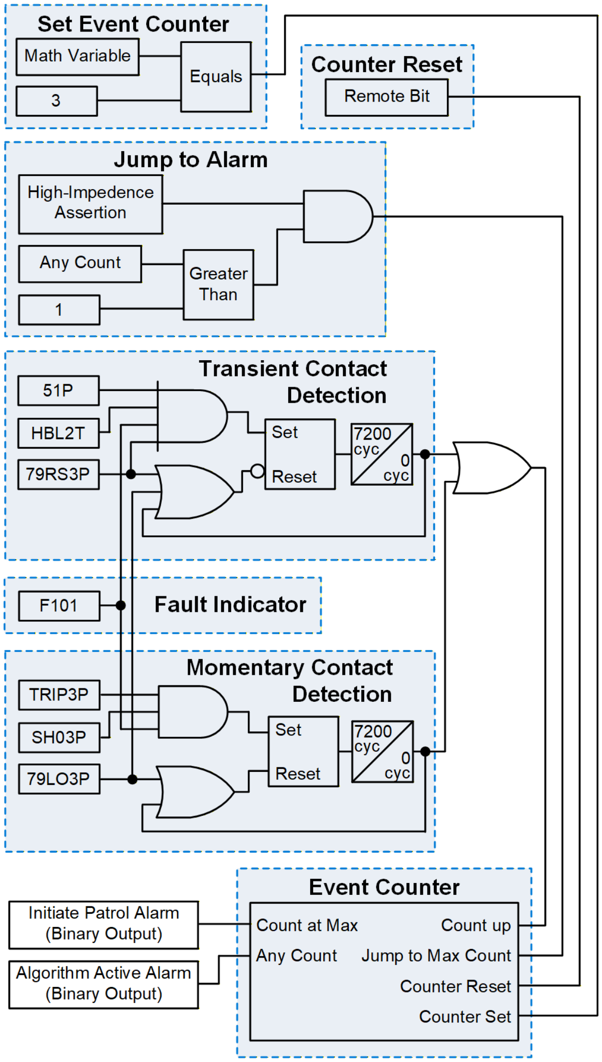


Fig. 1. Algorithm logic diagram.

1) Set Event Counter

We must define a maximum count for when we want the algorithm to assert the alarm. Based on our analysis, we set this count to three. Each count represents a precursor event—some electrical and relay activity that signifies a vegetation encroachment. The count is adjustable by changing the math variable.

2) Counter Reset

The counter can be reset manually by DNP3.0 remote bit. If the user utilizes a different communications protocol, the remote bit can easily be swapped for the equivalent command. For local reset, a push button could be included with the counter reset logic. We did not include a push button because we assume the utility will not wish to send a crew to clear the alarm locally.

3) Jump to Alarm

This block of code integrates the high-impedance logic into the algorithm. First, the algorithm must register any count of a precursor event. If an HIF alarm then subsequently occurs, we skip to the maximum count and assert the initiate patrol alarm.

The HIF algorithm looks at interharmonic content over time compared to a baseline average and will often not count in-rush events, which are rich in second harmonic. It is possible that the HIF algorithm will assert on in-rush, though rare, so the authors feel confident in including this logical filter to jump to the alarm. However, HIF algorithms have a way of misbehaving on different power systems, so we do encourage the reader to pilot this in a test mode before going live to ensure that HIF events are not falsely jumping the count.

4) Transient Contact Detection

This block of code constitutes the algorithm logic for detecting transient relay events, those defined as “the protective relay asserting an overcurrent element but not tripping.” These assertions are often the beginnings of the VDC and signal that vegetation has encroached on the primary wires, arced, caused a transient overcurrent assertion, then burned clear before the overcurrent element timeout.

These overcurrent assertions (51P) are the most sensitive detection and, as a result, often assert for non-protective conditions, mostly magnetizing in-rush current. We use the relay second harmonic blocking function (HBL2T) to supervise the overcurrent assertions to block assertions that are the result of in-rush current.

This section of the algorithm logic will only set the alarm latch while the reclosing relay is in the reset (79RS3P) state to avoid assertions that occur after a TRIP event. This assures that any count from this section of logic is based on only transient detections that were not part of a trip cycle. The TRIP detection logic is found in the Momentary Contact Detection block of code.

When the overcurrent element asserts and is not blocked by the second harmonic element, the alarm latch is set. FI01 is optional and can be removed from the logic if a fault indicator is not used. This latch feeds a timer, the combination of which acts as a filter for non-transient events. The intent is to ensure the algorithm rides through any assertions that subsequently cause one or more trip events or multiple transient contacts within the same timing window. We make the assumption that the utility is already aware of multiple events in a short duration. The timer can be adjusted if this is not the case.

The timer must be coordinated with the reclosing schedule and reclosing relay reset time of each utility. We recommend assuming two seconds for each protection trip plus the reclose intervals, for a total trip-to-lockout time of around forty-five seconds. We round this to sixty seconds to add safety margin. The assumed reclosing relay reset time is another sixty seconds, for a total timer ride through setting of one-hundred and twenty seconds.

The logic is self-resetting. The alarm latch will reset upon assertion of the timer, or when the reclosing relay transitions back to the lockout state, whichever happens first. This ensures the latch will not stay set and continually assert the timer. Additionally, the reclosing relay in the lockout state (79LO3P) will reset the latch. This avoids counting in the scenario where the overcurrent may be asserted but not tripping and the recloser is manually opened for any reason.

5) *Fault Indicator*

This block of code represents a binary input from a fault indicator. When the fault indicator senses a fault, it transmits a logical 1 to the relay. This binary input assertion acts like a location filter for the detection algorithms, only asserting their respective alarm latches if the fault indicator has also asserted, narrowing the alarm coverage to only those areas past the fault indicator. The binary input transmit time is usually subcycle, so it is not a concern for logic execution timing.

The fault indicator is not required for either detection algorithm to function, but does present an important filter for narrowing the fault location and thus the burden of locating the problem area. Without the fault indicator, the counting algorithm will assert for any downstream VDC detection on any phase. If multiple problem areas exist, this could lead to a quick count up to the maximum value for events that are concurrent but on different phases, indicating they are not at the same location.

In the scenario where the user does not utilize the fault indicators, we recommend increasing the count threshold to at least five, to avoid quick detections on multiple transients at different locations, as well as removing the FI01 relay word or setting it to 1 so it is always asserted.

Where the fault indicator is utilized, the location can be correlated to specific taps, and if a particular tap has multiple problem areas, can be used to further sectionalize the fault location on the tap. An example circuit layout for this configuration of fault indicators is shown in Fig. 2.

Using the circuit from Fig. 2, we apply a fault at the location shown in Fig. 3. Here, the recloser would detect the fault by overcurrent assertion, while Fault Indicator 1 would assert and narrow the location to that specific Phase A tap.

Next, we move the fault further down the tap, as shown in Fig. 4. The recloser would detect the fault by overcurrent assertion, Fault Indicator 1 would assert and narrow the location to that specific Phase A tap, and Fault Indicator 2 would assert, further narrowing the location to bottom half of that Phase A tap.

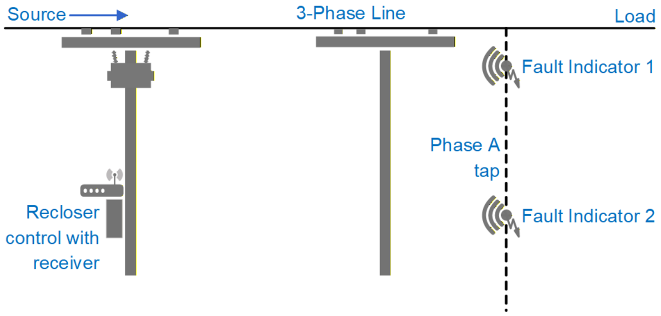


Fig. 2. Example arrangement with fault indicators.

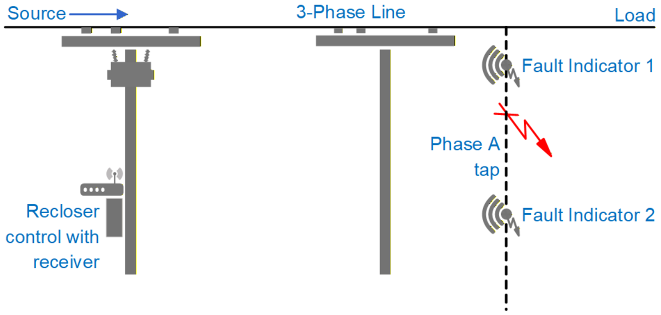


Fig. 3. Example of fault in first fault indicator zone.

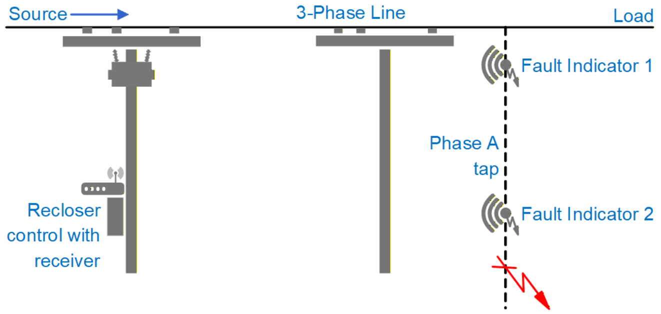


Fig. 4. Example of fault in second fault indicator zone.

In this way, multiple combinations of fault indicators can be used to monitor multiple taps and/or multiple locations on the same tap.

The most effective use case of the fault indicators is to modify the detection alarms to work on a per-phase basis, rather than three-phase (by using 51A/B/C elements rather than 51P), then select the problem taps for fault indicator installations. This ensures that the counting algorithm only asserts for detections in the chosen problem areas.

6) *Momentary Contact Detection*

This section constitutes the algorithm logic for detecting momentary relay events. The definition of momentary is defined in IEEE 1366-2022 as events lasting less than five minutes (i.e., not a permanent interruption). These events are often made up of one or two trips and recloses, after which the relay holds and transitions back to the reset state. They are often, but not always, caused by fuse saving fast trips.

This block of code works like the transient detection logic, but with subtle modifications. First, rather than looking at overcurrent assertions the relay looks at the TRIP relay word, which indicates the vegetation encroachment was severe enough to cause an overcurrent timeout and subsequent relay trip.

Second, it removes the second harmonic block because a properly set overcurrent element should not trip on magnetizing in-rush.

Third, rather than use the reclosing relay in the reset state (79RS3P), it looks at the reclosing relay at shot zero (SH03P). This is done for two reasons: one, because a TRIP event will cause the reclosing relay to immediately move into the cycling state (79CY) and out of the reset state (79RS3P), and two, because we only want to count the first trip, not subsequent trips, so we ensure the reclosing shot counter is at the first interval. This logic is built to prevent a single tripping cycle from immediately running the counter to maximum, the thought being the utility should already be looking at any events from a relay that trips multiple times and holds. The shot zero filter could be removed to count any trip if the user has a different use case in mind.

A manual or remote open will initiate a TRIP but will not activate the momentary detection logic because the reclosing relay will immediately transition to the lockout state (79LO), which will reset the alarm latch and dropout the timer. Like the transient detection logic, the alarm latch will also self-reset upon assertion of the timer.

7) *Event Counter*

The event counter is simply a relay counter with the normal inputs and outputs. We have labeled these I/O with the functionality, rather than their relay names, to facilitate better understanding of the algorithm. The idea is to count three precursor events, at which point the counter reaches its maximum setting and asserts an alarm. The timer output is mapped to a binary input or equivalent communications point and sent to engineering and/or system operations to initiate a review and targeted patrol and trimming.

The other counter output is the any count alarm, or what we are calling algorithm active, meaning the counter has registered a count but not reached the maximum output yet. This could be used to send an engineering-only alarm that indicates the algorithm is active and that some activity is occurring, or perhaps a display point for the system operators to show some activity has occurred but there is not yet enough information for them to take an action. Alternatively, it could be a reminder to reset the counter.

VIII. REVIEW OF EXAMPLES

Five examples were analyzed for this paper. A summary and interesting highlights from each example are presented, rather than an exhaustive exploration of each, since much of the information is repetitive. All examples were known tree contacts that resulted in a permanent interruption. The relay data was not retrieved until after the permanent interruption occurred.

A. *Example 1*

This example is interesting in that it followed the VDC pattern, with the exception that the fault current dropped slightly from the start of the VDC until the final lockout event. The relay history demonstrating this is shown in Table III.

TABLE III
VDC EXAMPLE WITH DECREASING FAULT CURRENT

Event no.	Date	Time	Phase	Mag. (A)	Event type
1	12/28/2023	00:34:01	AB	432	In-rush
2	12/28/2023	00:34:07	TRIP	0	SCADA
3	12/28/2023	06:31:55	AG	658	In-rush
4	12/28/2023	06:32:00	AG	2320	Trip
5	12/28/2023	12:10:03	BC	619	In-rush
6	12/28/2023	14:41:51	AG	2453	Trip
7	2/7/2024	01:51:45	AG	1575	Pickup
8	2/13/2024	06:50:11	ER	24	ER Trip
9	2/13/2024	08:13:34	TRIP	0	SCADA
10	2/29/2024	13:33:16	AB	445	In-rush
11	2/29/2024	13:33:21	AG	2226	Trip
12	5/22/2024	09:41:22	AG	2316	Pickup
13	5/22/2024	09:41:27	AG	2390	Pickup
14	5/22/2024	09:41:28	AG	2436	Pickup
15	5/22/2024	09:41:30	AG	2279	Trip
16	6/23/2024	02:30:57	ER	60	ER Trip
17	6/23/2024	03:38:27	TRIP	59	SCADA
18	10/8/2024	07:38:25	BC	514	In-rush
19	10/8/2024	07:38:30	AG	2195	Trip
20	11/10/2024	13:59:26	CA	586	In-rush
21	11/10/2024	13:59:31	AG	1848	Trip
22	11/12/2024	17:49.00	AB	551	In-rush
23	11/12/2024	17:44.50	AG	2123	Trip
24	11/24/2024	17:59.10	ER	562	ER Trip
25	11/24/2024	Protective relay trips to lockout.			

Table III, shows that the fault current ranged from 1,575 A (Event 7) to 2,453 A (Event 6), and every overcurrent assertion or trip involved Phase A. The mean fault current was 2,172 A, for a standard deviation of ±11 percent of the mean.

Knowing the range of fault currents allows us to choose a fault indicator setting that will capture all trip and overcurrent assertions by choosing a setting that is lower than the lowest end of the standard deviation. We recommend not using the event fault current, but instead the expected fault current from the area being monitored. The fault indicator should be about 20 percent less than the lowest expected fault current in this area. This ensures that all relevant events are captured, even those that may be outside the lowest range of the standard deviation.

For example, if the phase protection setting is 600 A, the lowest fault current in that protection zone must be at least

900 A, so the fault indicator setting would be about 720 A. This method would easily have captured every fault from Table III since the lowest fault current was 1,575 A, well above the suggested pickup of 720 A.

If the fault indicator pickup by the low end of the standard deviation range was chosen, two events would have been missed, Event 7 and Event 21. Despite the loss of these two captures, the initiate patrol alarm would still have been asserted correctly at Event 11, a full seven months before the final tree encroachment and two months (T+2) after the start of the VDC. The first count would occur at Event 4, the second count would occur at Event 6, and the third count would occur at Event 7 or 11, depending on the fault indicator setting. Both Event 7 and 11 are at T+2.

B. *Example 2*

This example experienced a wider range of fault currents over a similar period as Event 1, but with a greater standard deviation of ±26 percent. The event followed the VDC pattern, where fault current (mostly) increases over time. The highest magnitude fault current was experienced in the first few events of the cycle and the middle of the cycle, then lessened during later events.

An HIF event occurred early in the VDC, one hour after the first event, which resulted in a protection trip. This HIF event had no corresponding overcurrent assertion, as seen in the filtered record shown in Fig. 5. The unfiltered record for the same time stamp is shown in Fig. 6, where there is clear distortion in the current waveforms, which indicates arcing. The harmonic content of the phase and neutral currents is also shown in Fig. 6, which shows up to the 63rd harmonic. The most harmonic distortion is seen in the second, third, fourth, fifth, and ninth harmonics.

The HIF event that corresponds to the same time stamp as the events in Fig. 5 and Fig. 6 is shown in Fig. 7. Here we can see an initial spike in sum-of-difference current with corresponding counts of the arcing algorithms. The vegetation continued to arc for fifteen minutes more, as seen in the second arc detection algorithm asserting the T8n bits.

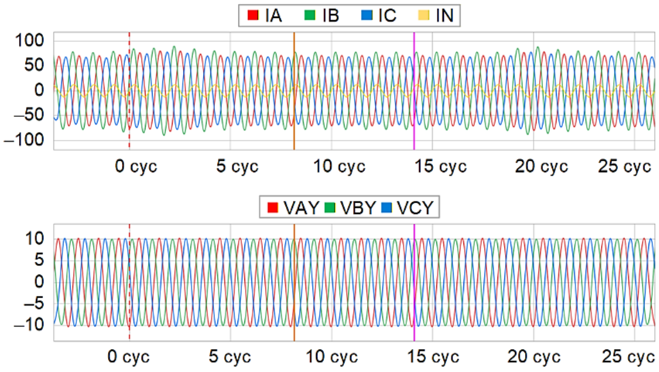
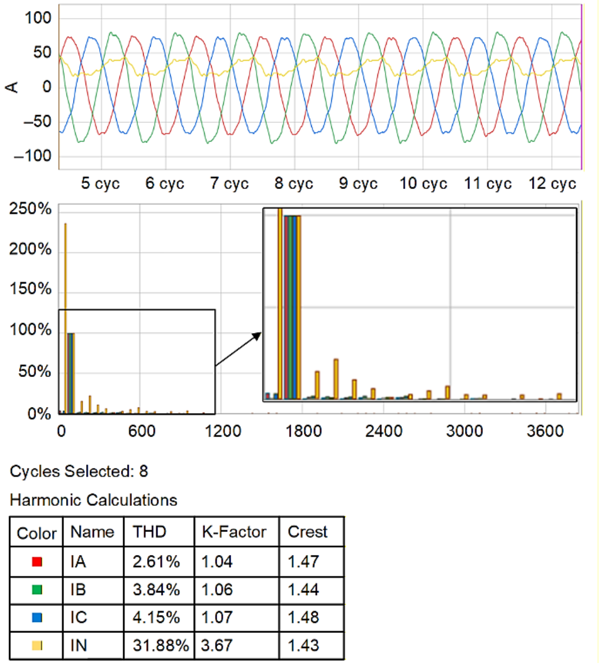


Fig. 5. Filtered fault magnitudes.



Cycles Selected: 8

Harmonic Calculations

Color	Name	THD	K-Factor	Crest
🟥	IA	2.61%	1.04	1.47
🟩	IB	3.84%	1.06	1.44
🟦	IC	4.15%	1.07	1.48
🟨	IN	31.88%	3.67	1.43

Fig. 6. Unfiltered fault magnitudes, including harmonic content.

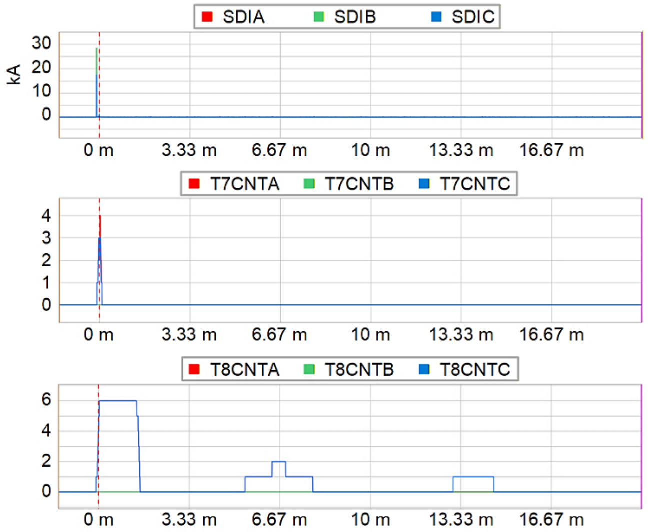


Fig. 7. Sum-of-difference current and arcing counts.

Normally, we would assume the vegetation burned clear after the arcing stopped, but perhaps there was a severe storm and wind event that blew the vegetation into the line, because the second trip occurred two hours later but did not assert a HIF event. Then nothing occurred for seven months (T+7). The final events occurred nine months after that (T+16) and were trips, eventually to lockout, completing the VDC cycle.

The algorithm would have reached the maximum count one hour after the first event when the HIF alarm asserted since this would satisfy the any count and HIF assertion logics, jumping the counter to the maximum value. Without HIF detection, the third count would happen at the (T+7) mark, a full nine months before the final outage at (T+16).

C. *Example 3*

This example continues the VDC pattern of fault current increasing over time. The unique features of this event are that the HIF algorithm did not operate until later in the cycle and was correlated with incorrect operations, and the VDC was much shorter, lasting only four months (T+4). The algorithm would have detected the event early in the VDC at Event 3 in Fig. 8, which is coincidentally the third grouping of events. The incorrect operations are unrelated to this paper so are not discussed here, but are mentioned to show that these would not have affected the algorithm outcome because they occurred late in the VDC cycle, after the counter had already asserted the initiate patrol alarm.

The range of fault currents for the VDC is shown in Fig. 8. The bottom of the graph is the first event, Event 13, while the top of the graph is the last event, Event 1. Events (13) through (5) all took place around the same time on the same day, resulting in three consecutive trips over a short time span and multiple overcurrent assertions. The protection device reclosed and held on each trip, but did not hold long enough to reset. The algorithm filters would sum all these events as a single count because the reclosing relay did not transition back to the reset state until the end of the tripping sequence.

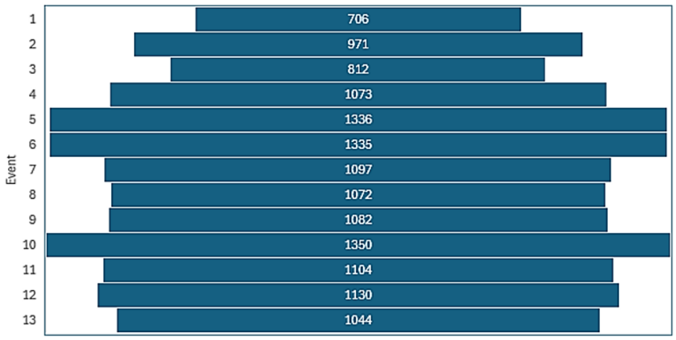


Fig. 8. Fault magnitude distribution based on ER assertion.

The next event, Event 4, was only a few days later and would have resulted in the second algorithm count. This was a single trip and reclose event.

The last few events were up to four months later (T+4); however, Event 3 would have resulted in the third algorithm count, activating the initiate patrol alarm. This event occurred less than one month after the start of the VDC (T+1) and three months before the final outage at (T+4).

D. *Example 4*

This example continues to follow the VDC pattern, matching the predicted outcome almost exactly. The unique aspect of this sequence is that all the events were identical—a single protection trip, reclose, and hold—and all occurred within a one-month window. The trips can be sorted into encroachment event groups that indicate a severe problem is repeatedly occurring in a short duration window, as shown in Table IV. We suspect this relay recorded more events prior to those shown, but these events were overwritten as the vegetation encroachment became severe and resulted in many momentary trips over a short time span.

TABLE IV
VDC EXAMPLE OF TIGHT FAULT MAGNITUDE RANGE

Event no.	Date	Time	Phase	Mag. (A)	Event type
Event Group 1					
1	8/9/2024	04:05:03	AG	3002	Trip
2	8/9/2024	04:13:50	AG	2947	Trip
3	8/9/2024	13:30:57	AG	2975	Trip
4	8/9/2024	23:57:50	AG	2975	Trip
5	8/9/2024	23:00:49	AG	3025	Trip
Event Group 2					
6	8/21/2024	09:47:03	AG	2999	Trip
Event Group 3					
7	8/26/2024	03:51:53	AG	2993	Trip
Event Group 4					
8	8/31/2024	11:18:08	AG	2989	Trip
9	8/31/2024	22:30:59	AG	3022	Trip
Event Group 5					
10	9/1/2024	00:23:56	ABG	3465	Trip
11	9/1/2024	00:23:54	AG	3504	Trip
12	9/1/2024	00:23:51	AG	3012	Trip
13	9/1/2024	00:23:49	ABG	3543	Trip
14	9/1/2024	Protective relay trips to lockout.			

Event Group 1 events all occurred on the same day. Event Groups 2 and 3 occurred a few weeks later. Event Groups 4 and 5 were a few days after that, and one day apart, and when the final trips and eventual outage occurred at T+1. This was a very small detection window, but it was still a success. The range of fault currents was a narrow ±7 percent.

The initiate patrol alarm would have asserted during Event Group 1, at Event 3, a few weeks before the final outage. The first count would occur at Event 1, where the relay trips, recloses, holds and resets. The second event, Event 2, was eight minutes later. With a reset time of sixty seconds, the relay transitioned back to the reset time after Event 1, allowing this count to occur only a few minutes later. The third event, Event 3, was seven hours after that, triggering the final count.

Despite the short event window, this sequence would still have asserted the alarm about twenty-five days before the final outage. Even if the relay did not record any prior events, this is still a successful indication of an impending problem that could be quickly addressed before the final interruption.

E. *Example 5*

The last example exhibited near identical characteristics to the other events. What makes this event unique is that the tree encroachment was across Phase B and Phase C, causing alternating single-line-to-ground (SLG) faults on those phases until the final outage, which was a line-to-line (LL) fault across Phases B and C (ground was not involved). The fault magnitudes were not consistent between the SLG faults, even though those faults were at the same location, just alternating which phase was faulted.

This example adds efficacy to using the individual phase counters, rather than the three-phase counter, to retrieve a more accurate picture of what is occurring. The phase counters would increment individually for the SLG faults, but together for the LL faults, creating a staggered increase that clearly shows an incipient event across those phases.

The records show that Phase B and Phase C did not record consistent fault data, indicating Phase C had more fault impedance for an unknown reason. Fig. 9 shows a clear SLG fault on Phase B of 2,104 A.

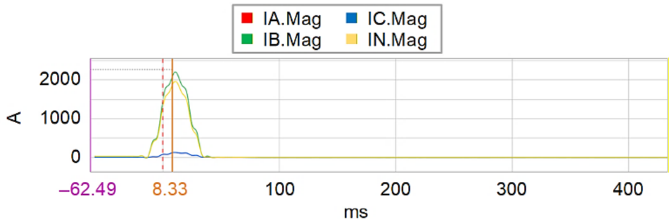


Fig. 9. RMS magnitude of fault current.

Contrast this with Fig. 10, which shows an SLG fault on Phase C of 1,415 A, approximately 25 percent less than the equivalent Phase B fault at the same location.

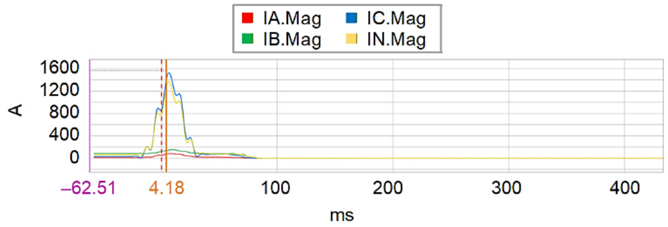


Fig. 10. RMS magnitude of fault current.

Lastly, the LL faults were of consistent current magnitudes and mostly occurred in the second half of the VDC, around the T+9 and T+10 marks. The final outage occurred at T+10. The LL fault magnitude of one of these events was 2,487 A, as shown in Fig. 11. Interestingly, the SLG was 0.866 pu of the LL fault, though this could just be coincidental.

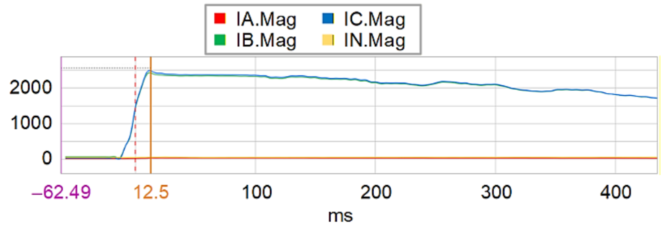


Fig. 11. RMS magnitude of fault current.

Since these events were staggered across phases during the VDC, the Phase B alarm would have asserted at T+3, and the Phase C alarm would have asserted at T+8. With the algorithm counter output set to three, the Phase B alarm would assert only three months into the VDC, a full seven months before the final outage event. Assuming the utility acted on only the Phase B alarm, the encroachment would have been found early on and the vegetation cleared long before the tree branch bridged Phases B and C.

IX. FUTURE APPLICATIONS

The methodology described for identifying vegetation encroachment via transient overcurrent activity has promising implications for many areas of fault detection, particularly in locating downed conductors and cable failures. Like vegetation-induced faults, downed conductors and failing cables exhibit brief, low-energy transient behavior that does not always result in a trip to lockout. These transients could hint at arcing, insulation breakdown, or intermittent contact with high-impedance surfaces, but without prolonged outages, these faults can go unnoticed. With slight changes in the logic and the integration of the fault sensors, the possibility to extend fault detection capabilities further increases. This will further increase the value of this idea as this will keep meters spinning, protect the public, and reduce the chances of vegetation-related arcing and fires.

X. ALGORITHM ADJUSTMENTS

Known gaps in the algorithm may result in false operations. The reader is advised that this algorithm, while highly effective, is not yet perfect and requires more time in development. We encourage readers to lab test their relay programming then pilot the algorithm in an engineering mode to ensure efficacy before going live to a wider audience.

A. Set Event Counter

We chose three counts based on the real events reviewed for this paper as well as the authors' personal experience. We are confident this count is the best place to start, but it is possible the count may need to be adjusted higher or lower based on local factors, such as reclosing attempts allowed, logic nuances, and vegetation types. Either way, the algorithm is not foolproof and will miss some events regardless of counts and may occasionally overcount for a contact that results in a sustained interruption, although the authors think this will be rare when using three or more counts.

B. Jump to Alarm

Not every relay has arcing detection and not every utility uses the arcing detection when available. If arcing detection is not used, this block of code can be eliminated. If arcing detection is used, readers should know it also not a perfect algorithm and will sometimes not detect arcs, and other times detect false events that are the result of unusual load signatures. This may result in a jump to alarm scenario that is not the result of early vegetation contact.

C. Transient Contact Detection

Transient contact requires the relay to assert an overcurrent element. Not all transient contacts will draw enough current to assert an overcurrent, so some contacts are missed. In rare cases the transient counter may assert under load, resulting in a false count. It is highly unlikely that load assertions would ever result in a full count to alarm.

D. Fault Indicator

Fault indicators are not required but are preferred for better locating. If fault indicators are not used, this block of code should be eliminated. Where fault indicators are used, there are several failure modes that could happen. These are: non-assertions (fault current less than the pickup), false assertions under load or in-rush, or assertions that have latency in the signal, resulting in a delayed message to the source relay, which in turn would prevent the counters from incrementing because the relay processing interval will have passed.

E. Momentary Contact Detection

Momentary detection requires a specific sequence of relay events to occur. Sometimes faults do not follow standard operating sequences. This can result in missed or false counts.

XI. CONCLUSION

This paper has demonstrated a novel method to use protective relay data that is readily available, but going unused, to build a counting algorithm that can send an alarm to utility recipients to take immediate action, in the form of targeted line patrol and fault-location analysis. Utilities with FLISR systems can fault locate directly from FLISR, while other utilities can use a manual process of reviewing event data and correlating with the system model to locate the problem.

The paper has demonstrated the effectiveness of this algorithm by playing it back through five examples that were confirmed tree contacts and resulted in a permanent outage to show that, in each case, the algorithm would have responded correctly and asserted an initiate patrol alarm in advance of the final interruption.

It has also demonstrated how this algorithm can be refined to target a specific location by utilizing fault indicators and single-phase alarms, rather than three-phase alarms, allowing a utility to monitor specific taps for vegetation encroachments.

XII. ACKNOWLEDGMENT

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XIII. REFERENCES

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[4] M. Kistler, F. Heleniak, C. Kennedy, and G. Maday, “Practical Experience With High-Impedance Fault Detection in Distribution Systems—Continued,” 49th Annual Western Protective Relay Conference, Spokane, WA, Oct. 2022.

XIV. BIOGRAPHIES

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