New Methods in Power Line Carrier Monitoring and Analysis

Real-World Examples and Implications for Protection System Reliability

Craig Palmer, Alan Jayson
PowerComm Solutions
Flemington, NJ USA
craig.palmer@powercommsolutions.com

Jeffrey E. Brown
Georgia Transmission Corporation
Tucker, GA USA

***Abstract*—Continuous monitoring devices for power line carrier protection channels provide robust data about the performance of PLC systems. This paper summarizes the significance of the monitoring device data and cites recent cases in its application and analysis. Field examples include remotely identifying failed PLC system components before a misoperation, various effects of capacitor banks, line trap monitoring, and more. A new method of event-based transient monitoring is also proposed. The potential for this type of data to improve PLC-based protection reliability is analyzed.**

Keywords—power line carrier; PLC; line-trap; transient; carrier hole; misoperation; checkback; spark gap; gas discharge tube; reliability; controlled switching; noise

I. Introduction

Power line carrier (PLC) technology has protected the US transmission grid for at least 94 years [1]. Yet to this day, utilities find that event records of these analog channels are not always robust enough to allow for full event analysis. The lack of good data has been a pain point when looking to reduce misoperations on the bulk electric system [2][3][4]. New methods of PLC monitoring and analysis are demonstrated here which reduce utility effort in maintenance and troubleshooting, give clarity on the causes of system events, and provide advanced warning of imminent component failure.

II. Background

Today's typical PLC systems monitor events on the channel using the most intelligent devices in the system – the transmitters/receivers [5]. When the system is healthy it appears that the devices are doing a good job – no alarms, all is well. But when alarms or events occur and no issue is found straight away, available records can appear as a jumble of timestamped event points, toggling high and low at mystical intervals that may or may not mean *something*. This binary trail leaves much to be desired when analyzing these complex analog systems.

To describe the challenges, a few quotes from recent papers on PLC issues are presented: "Power Line Carrier applications provide the most cost-effective installations but have limited self-monitoring and failure detection" [2]. As a result, "Equipment failures…may be hard to find" [6]. PLC-related misoperations "require significant time and effort in testing the PLC channel, as the requirement for investigations on NERC-reportable misoperations are quite stringent" [7]. "Often the result of the testing yields the undesirable result of 'no problem found'" [8].

Continuous monitoring data of PLC channels, sampled at 20 MHz wideband, with frequency-selective channels sampled at 20 kHz, makes things a lot easier. See Appendix A for a further description of how and where the data is captured.

III. New Methods

A. Frequency-Selective Carrier "Oscillography"

Like a transient recorder for the AC system, the subject device stores a "capture" of event-driven data (400 ms per event) about the *voltage on the coax* during normal operation and during transient events. The capture is taken in a 10 kHz bandwidth around the channel frequency. Figure 1 shows one of these records: three transients in the carrier band due to the controlled closing of a 115-kV shunt capacitor bank breaker.

Clearly visible, noise from the switching of all 3 phases found its way onto the coax in this single-phase-to-ground-coupled system. The normal signal is altered after the event due to the impedance change. The bursts are separated by 2.78 ms, or 60° at 60 Hz, a clear signature of controlled switching [9]. The third burst is the most disruptive and triggered the event in the device. It is likely that the third pole to switch was the pole on the carrier-coupled phase.

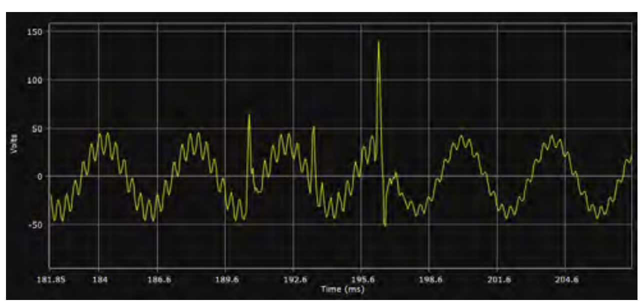

Fig. 1 – Sample Time-domain Voltage Capture Showing Cap Bank Switching

Also visible is a very brief loss of signal occurring in the third burst – in this case, an air gap firing due to the transient event. The result in the capture is strikingly similar to others that have been measured in the field at the same circuit location [10]. Carrier holes and loss of signal events much worse than this one will be examined later.

B. Spectrum Analysis

Dedicated software can perform a Fast Fourier Transform (FFT) on the time-domain data. The result is a spectrum plot with frequency and amplitude in the 10 kHz bandwidth of the channel. For example, a channel with a 100 kHz center frequency can find signals from about 95 kHz to 105 kHz.

There are many applications for this analysis, from overlaying one capture over another to compare the presence/absence of frequencies in the band as well as their amplitude, to observing the "noise floor" level, to analyzing very fast events and their effect on the signals. Figure 2 shows two transmit and three receive signals – levels, noise floor, and any stray or unknown signals are all immediately apparent.

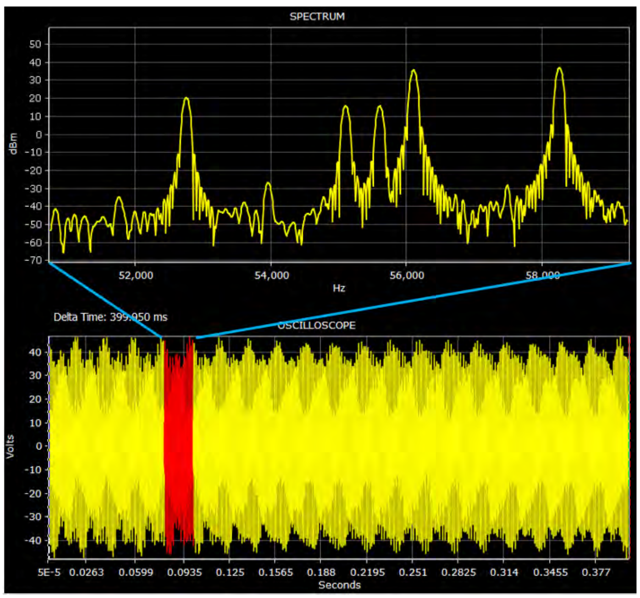

Fig. 2 – Sample spectrum analysis (FFT) showing five carrier signals

C. Impedance Monitoring

Good matching of source impedance (control house equipment: transmitters, receivers, hybrids, etc) to load impedance (generally the high-voltage transmission line) is one of the critical factors influencing the reliability of a given PLC channel. To meet NERC's channel monitoring requirements, a typical PLC transmitter today provides "reflected power" expressed in percent [11]. Continuous monitoring devices do calculate the reflected power, but primarily they monitor the *complex impedance* at the input to the line tuner.

What's the difference, and is one more accurate? The short answer is, reflected power is an effective go / no-go number, but gives little clue about the source or nature of the "no-go" state [12].

A close look at the math demonstrates the limitations of reflected power. The complex impedance, Z_{TERM}, and reflected power, $RP_{\%}$, are both related to the same complex number, the "reflection coefficient" or ρ ("rho"):

$$\rho = \frac{Z_{TERM} - Z_{SOURCE}}{Z_{TERM} + Z_{SOURCE}} \qquad (1)$$

where Z_{TERM} is the line-side impedance looking into the coax input of the tuner, and Z_{SOURCE} is the station-side impedance looking back into the control house. Both are complex impedances with magnitude and phase angle. For this paper, Z_{SOURCE} is assumed to be 50 Ω / 0° (by design in the US) [13].

Now consider reflected power percent. It is given by:

$$RP_{(\%)} = 100 * \rho^2 \qquad (2)$$

Although ρ appears in the equation, squaring it effectively reduces its complexity. Other impedance matching figures like VSWR or return loss in dB use the absolute value of ρ which has an effect like squaring. Basically, once the impedance matching is expressed in reflected power percent, the terminating impedance Z_{TERM} that caused it cannot be reliably known. See Appendix B for the reasoning behind this analysis.

Figure 3 illustrates the relationship between Z_{TERM} and reflected power for a Z_{SOURCE} equal to 50 Ω / 0° (the chart is generated using (1) and (2), above). It shows the reflected power calculated by an impedance meter (or PLC transmitter) connected to a line tuner input for different values of Z_{TERM}. Plotting the values in this way demonstrates that RP% values form a closed loop – so that for a 20% reflected power reading the actual Z_{TERM} magnitude could be 20 Ω, 130 Ω, 50 Ω, or anywhere in-between, with varying phase angle.

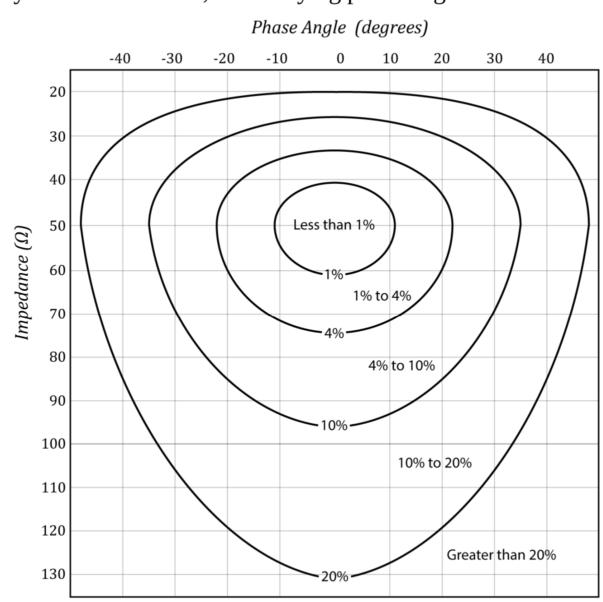

Fig. 3 – Reflected power by termination impedance, for a source impedance of 50 ohms / 0 degrees

D. *Trending*

One of the simplest new methods is the long-term trending of instantaneous analog PLC values. Levels, impedance magnitude, and impedance phase angle are recorded at regular intervals and the data may be plotted over time. Samples are typically taken at 1-hour intervals.

E. *RF Transient Detection*

In addition to frequency-selective measurements (10 kHz and narrow bands) the device also monitors the wideband voltage and current on the coax. By setting high-level threshold detectors the device can indicate the presence of a possible transient – voltage, current, or both. The levels are typically set at about 300 V-pk and 2 A-pk; at least 5 consecutive samples at 20 MHz must be seen (or 250 ns). To prevent chatter in the event log, the transient flag is held for 1 second after the condition is declared. These levels were selected based on hardware, prior research, and after review of continuous monitoring data from many real-world installations [10][14].

IV. Real-World Examples

The following examples are from real-world installations of PLC monitoring devices on eleven different transmission lines around the USA. Some examples are informative, showing signatures of carrier system events. Other examples show how the new methods helped utilities diagnose problems and take action to address them.

A. *Checkback failure*

Checkback issues can make for difficult troubleshooting if a problem is not found straight away. Show up on site and the tests run clean. The question lingers: is there an undiagnosed issue, waiting to cause more trouble? Figure 4 is a capture from such a case, observed at the initiating end in the middle of a failed test sequence. A healthy signal (in this case) should look like part of a clean sine wave, a smooth line. Instead, there is clear disturbance visible on the signal.

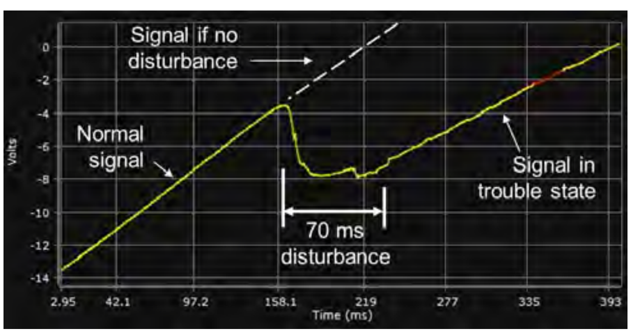

Fig. 4 – Slow degradation of transmit level during failed checkback sequence

Checkback tests passed again shortly after the issue occurred, and levels / signals were observed normal. Prior to reviewing the monitoring data, a different conclusion had been drawn about the source of the issue, so a quick review of the checkback sequence prevented unnecessary work. Monitoring continues and if the issue re-occurs, it will be caught. Note that not all checkback issues look like this one.

Using the continuous monitoring records, checkback test sequences can be evaluated to determine if the monitoring device saw a good sequence – in other words, is there a problem with the analog signal or not. In many cases a pass/fail result can be provided.

B. *Capacitor bank effect on impedance matching*

Table 1 – Effect of Untrapped Capacitor Bank on Impedance Phase Angle in a 115-kV System

	Cap Bank Out		**Cap Bank In**	
	Station A	**Station B**	**Station A**	**Station B**
Mag (Ω)	42.8	73.8	55.3	68.7
Phase (deg)	+4.8	-3.0	***-35.1***	***+54.8***
RP (%)	0.8	3.8	10.2	***29.2***
Transmit (dBm)	+38.9	+40.8	+40.4	+41.1
Receive (dBm)	+31.1	+31.9	***+7.8***	+25.4

On a 115 kV transmission line with un-trapped capacitor banks tapped off the line, the carrier system experienced receive level and reflected power alarms that were correlated with the capacitor banks being switched “in”. Un-trapped capacitor banks are known to cause trouble for carrier systems since they appear as a low impedance path to carrier-frequency energy [6]. At this site, monitoring devices were installed to prove the theory and gain insight.

The data is presented in Table 1, above. With the capacitor bank OUT, both terminals measured reflected power less than 4%, generally accepted as very good tuning. The cap bank IN state causes tuning issues. Notably, the effect of the insertion of the capacitor banks is more severe on impedance phase angle than magnitude. Further data on capacitor banks and their effect on PLC channels are presented later.

C. *Impedance phase angle and line tuner short/open*

In this example, a utility was getting intermittent loss of signal alarms from FSK receivers at both ends of a transmission line. The alarms were mostly fleeting and would clear by the time personnel were on-site. The device event record and trending log captured the first look at the trouble state, with an impedance magnitude of about 120 Ω at -85° (Figure 5).

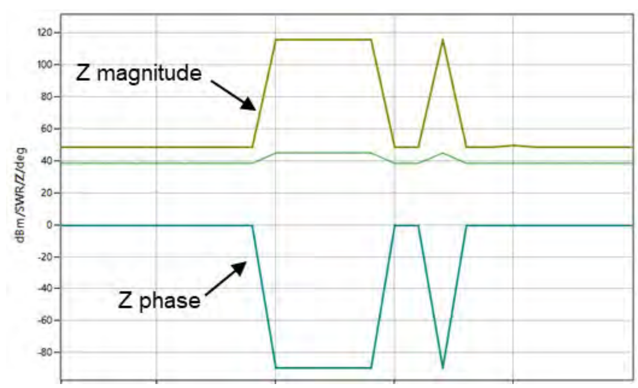

Fig. 5 – Trending data shows high impedance, very negative phase angle

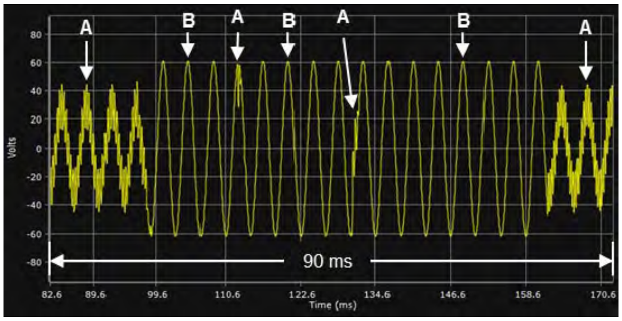

Fig. 6 – Time-domain captures show discrete changes of state, chatter
A = healthy, B = trouble

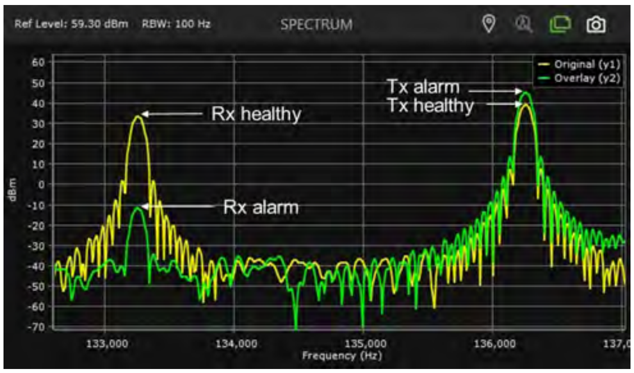

Fig. 7 – FFT Overlay of Healthy (Green) vs Trouble (Yellow) States
Rx (left) drops > 40 dB; Tx (right) jumps ~5 dB

Event captures showed signs of connection issues in the coupling circuit, like the Checkback example above. Here, however, the change occurs quickly, repeatedly, and tends to "chatter" at times (Figure 6). FFT with overlay analysis shows the trouble state caused more than 40 dB attenuation on the Rx signal, while the transmit level increased by 5 dB (Figure 7).

The utility took the initiative to do some testing and simulation to see if they could replicate the impedance magnitude and phase angle of the failed state. Given the increase in impedance in the trouble state, an OPEN condition was suspected somewhere in the coupling circuit. Various short and open conditions were simulated at different points in the coupling circuit. Two of the states showed a complex impedance like the trouble state (see Table 2). With the data informing the investigation, an OPEN connection was eventually found – on the back of the tuner protection unit.

TABLE 2 – IMPEDANCE TESTING SHOWS CORRELATION BETWEEN SHORT AND PHASE ANGLE

	Mag (Ω)	Phase (deg)	RP (%)
Baseline	49.8	0.0	0.0
Tuner input *shorted*	24.6	+84.3	85.2
Tuner ground sw. *shorted*	173.8	+86.5	93.4
CCVT ground sw. *shorted*	179	+85.9	92.9
Tuner input *open*	*117.9*	*-88.8*	96.9
Tuner prot. unit *open*	*120.3*	*-88.6*	96.5
Line disconnect *open*	88	-86.1	89.2

The testing and the data reveal that, for extreme conditions like a short or open in the coupling circuit, the impedance phase angle gives more reliable data about the nature of the trouble condition than impedance magnitude, and certainly more than reflected power. Counterintuitively, shorts at the tuner and CCVT grounds showed an *increase* in the impedance magnitude at the input of the line tuner, not a decrease.

D. Power System Events in PLC Channels

This section will examine the carrier-band signatures and the normal and abnormal effects of events on the power system. Analysis and identification of the effects of these transient events in carrier systems require context [15]. For that, transient detection, time-domain data and FFT analysis are taken together to build a picture of these very fast events.

Background

Many types of regular power system switching events generate transient energy. Faults, breaker switching (and re-striking, re-ignition, pre-striking), line switching, capacitor bank switching, reactor switching, lightning, arcing and more can generate these transient signals [16][17][18]. Years of wisdom gained from operating PLC channels in these harsh conditions has made the carrier channel extremely robust and reliable [5].

Lacking a widely-deployable monitoring device for carrier systems, researchers in the past have had to put forth much effort to probe the carrier channel effects of power system transients. While the tests all produced significant results and insights, some of them were limited to one installation and sometimes under no-load or lab conditions [8][19][20][21][22].

Considering the tight operating limits of transmission systems these days, it is difficult to imagine getting the clearance to re-run some of these tests – like BPA's 1955 classic on the Grand Coulee–Olympia line, where an arrow trailing a metallic wire was shot from a crossbow into target rings on the transmission line, thusly generating various faults and noise conditions for carrier tests [19]. But there may be no need for such tests anymore. Continuous monitoring capabilities demonstrate that detailed carrier analysis can be real-time and ongoing.

The data are bringing a new focus to insights from the past, while some assumptions are being understood in a new light.

Lightning

This section does not discuss direct lightning strikes to the transmission line or carrier equipment necessarily. Rather, it discusses the effects of lightning energy coupled by various means onto the power system and the coax [14][18]. Historical lightning data is freely available and extremely helpful for verifying storm activity [23]. *But is it important?* Beyond lightning's ability to cause faults, noise, and loss of signal, it turns out that it can have a lot to say about the health of line traps, as discussed in a later section.

Lightning is distinguished in time-domain captures by an especially fast transient, one or a few at random intervals, but not many [14][18]. Low-level white noise is also visible, its fair-weather level increased due to the storm activity [24][25]. On-Off / DCB systems with a low receive level are especially sensitive to lightning activity. Data from such sites during lightning storms will pick up small disturbances as the storm approaches, which then grow in amplitude and occur more frequently, then less frequently as the amplitude decreases and the storm passes. The correlation between the transient activity, captures, and historical weather data is remarkable.

Figures 8 and 9 are great examples of the possible severe effects of lightning on the carrier channel, with at least 4 significant loss of signal events visible among the two. These were captured during a storm that sat over the transmission line for at least 8 hours; the captures were recorded about 6 hours apart. Note that the transient bursts occur randomly with no evidence of a 60-Hz time base, and that the noise-floor increase is visible as a “buzz” riding on the carrier.

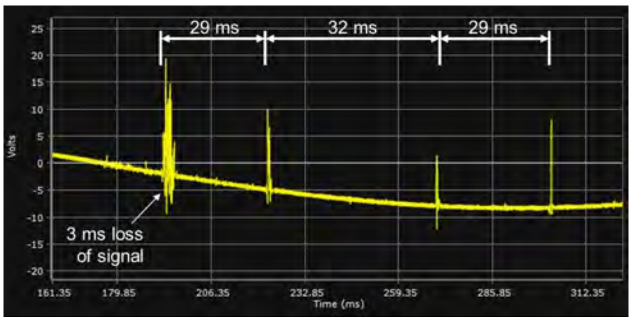

Fig. 8 – Transients due to multiple lightning strikes, showing up on the coax

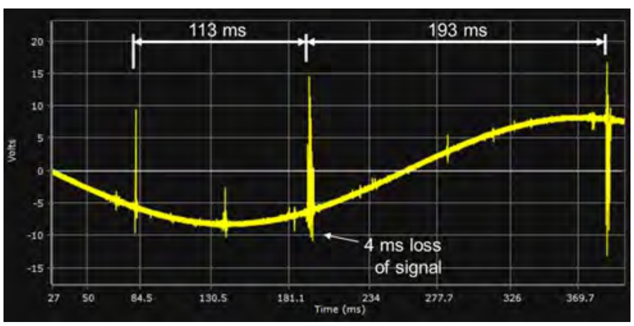

Fig. 9 – Lightning in the same FSK system, 6 hours later

Breaker Switching

A typical breaker operation in a healthy PLC channel looks like a single stroke of lightning – a single transient burst. Unlike lightning, the signal around the breaker operation is clean and without noise. The disturbance from a breaker operation, however, tends to last longer, on the order of one to several milliseconds. Note that disturbances as long as 9 ms have been tied to breaker operations in trouble systems.

Figures 10 and 11 below show two breaker operations from two different systems. Figure 10 is from an On-Off system, so the transient energy is the only energy on the coax (this makes On-Off channels good observation posts). Figure 11 shows the effect of a breaker operation on an FSK channel – note the signal clearly shorting from its clean carrier wave to a very noisy 0 V. In each of these installations, several component issues were discovered.

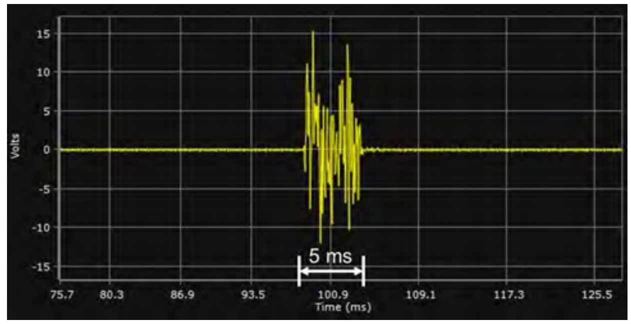

Fig. 10 – Effect of breaker operation in an on-off system

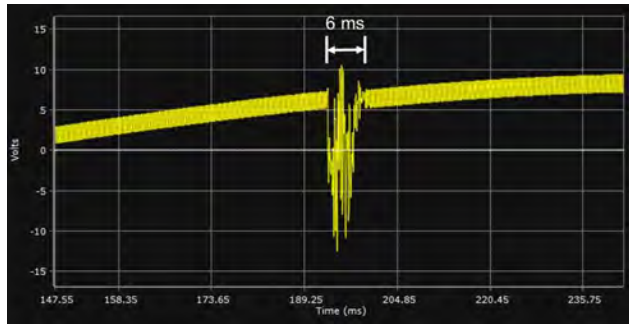

Fig. 11 – Effect of breaker operation in an FSK system

Disconnect Switching

If a breaker operation looks like a single lightning stroke, a disconnect switch operation looks like a steady stream of lightning. As with lightning and breaker switching, a typical PLC system encounters disconnect switching noise as a fact of life.

In continuous monitoring data, a disconnect operation is characterized by a cluster of chattery events in the log, with voltage and current transients typically detected at some point in the operation. Time-domain captures may show a fast onset of the disturbance, or the level may increase gradually with each subsequent peak before leveling out then clearing.

Periods of approximately 8.33 ms are almost always visible between the bursts, especially when averaged over 10 periods. The 8.33 ms signature represents a frequency of 120 Hz, due to the 60 Hz energy as it reaches its positive and negative peaks [22]. Note that a period of 8.33 ms indicates the noise is likely coming from the coupled phase only.

Figure 12 shows the effect on an On-Off carrier channel due to a line switch operation. Note how each burst is clearly distinguishable from the next and is damped quickly (less than 1 ms, see detail). The largest burst, in the middle of the capture, is the one that triggered the event. Observed in an On-Off carrier channel with no carrier energy present, Figure 14 looks remarkably like other field recordings of the high-frequency components of disconnect switching noise [26].

Alternatively, the FSK system in Figure 13 shows a somewhat steady 8.33 ms period but the bursts last several milliseconds. The regularity of the interval deteriorates as the bursts grow longer. Eventually they run into each other and create a loss-of-signal event measured at 17 ms. This is not a healthy response to a line switch operation. Note the trend of the bursts around 0 V, while the AC carrier signal moves above and below 0 V. This is clear evidence of a series of flashovers.

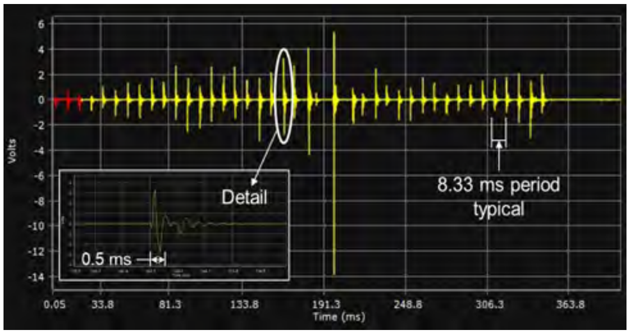

Fig. 12 – Noise from a line switch operation in an on-off system, showing characteristic 8.33 ms between bursts

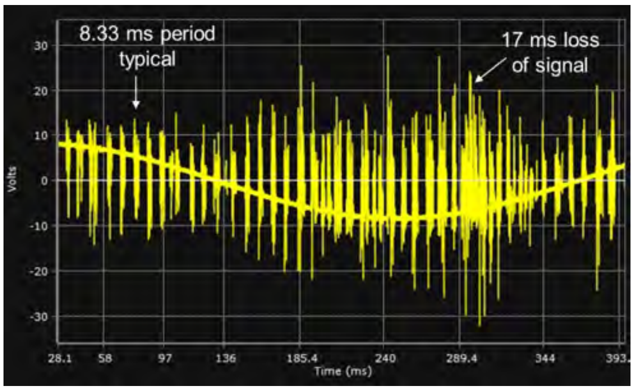

Fig. 13 – Line switching in an FSK system with too much noise, 8.33 ms period is clear at first but appears more random as arcing increases

Controlled (Synchronous) Switching and Cap Banks

Other cases illustrate noise in carrier systems that may be generated by controlled switching. These events are typically identified by three distinct bursts separated by 2.78 ms, or 60 degrees in a 60 Hz system. If the switch timing is precisely synchronous, very little transient noise is generated. [9]

Shunt capacitor bank switching is a common controlled switching operation in the transmission grid [9]. Field data from continuous monitoring devices have turned up hundreds of records showing a 3-phase, 2.78 ms controlled switching characteristic, sometimes showing of evidence of transient-induced loss of signal. These events are seen most frequently where there are line trap issues, dielectric breakdown issues, or in the presence of un-trapped components in the system, such as the un-trapped capacitor bank in Figure 1.

This is an interesting finding, because carrier engineering guidelines suggest that shunt capacitor bank switching does not pose a problem to the carrier channel. The reasoning holds that the dominant frequencies in these events are well below the carrier frequency band, and that the overvoltages caused by capacitor switching are sufficiently low enough to be "of no concern for the PLC equipment" [6].

Event records from continuous monitoring have sometimes seemed in conflict with this conclusion. While the analysis is logical, it might assume very good timing of switching, and ideal health of components such as spark gaps, gas tubes, line traps, arresters, coaxial cable, etc. It should also be noted that in 2004 access to monitoring devices like the one discussed here was limited.

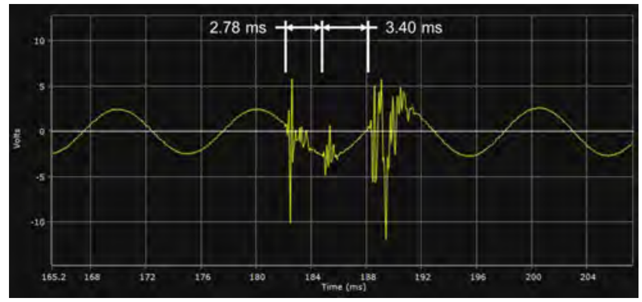

Fig. 14 – Suspected bad timing on 3rd pole of cap bank switching

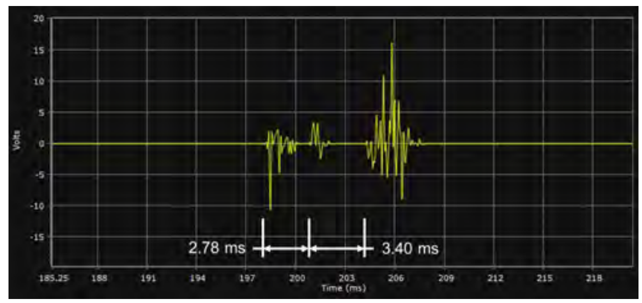

Fig 15 – The same cap switch transient event in an On-Off channel

Figures 14 and 15 shows the carrier-band effect of a suspected mis-timed controlled switching event. Because the monitoring device was configured for both FSK and On-Off channels, the effect of the transient in both systems can be observed. The first two transients in the captures are separated by 2.78 ms and tend to ride on the signal, suggesting good synchronous switching. The third transient occurs approximately 3.4 ms after the second, a timing error of approximately 0.62 ms or 13 degrees. This is apparently enough error to cause a transient-induced flashover and loss of signal, visible in the third transient burst in Figure 14.

The FSK and DCB channels shown in Figures 14 and 15 are roughly 80 kHz apart, with both falling between 100-200 kHz. This demonstrates the wideband nature of transients in switching events and the carrier events that they cause [14][17]. Counter-intuitively, the FSK channel in Figure 14 registered a Loss-of-Guard while the On-Off channel in Figure 15 recorded a Block Rx. This seeming contradiction demonstrates an important insight: the same types of events that may cause a loss of guard in an FSK receiver may cause a DCB receiver to "pick up" if no carrier is present; may cause a DCB receiver to "drop out" when carrier energy is present; may cause an FSK receiver to see Trip [21][25][27].

The event captured in Figure 16 was recorded by the monitoring device and it too implicates shunt capacitor banks. Significantly, it also caused a loss of guard in the transmitter/receiver (the receiver had an output wired to a monitoring device input to coordinate records and key captures). Interestingly, the monitoring device recorded a correct blocking operation about 800 ms before this event.

Investigation is ongoing, but current wisdom holds that this event was a capacitor bank being switched back into the system after reclosing. The way that the bursts are successively damped gives away a characteristic of capacitor bank switching, especially back-to-back switching [9][28][29]. Note that this was likely *not* a healthy switching operation.

Other abnormal breaker switching operations such as re-strike or pre-strike are likely problematic to the carrier channel, if experience is any guide. A probable re-ignition event – when the contacts across a breaker pole re-conduct within 90° of interruption – is pictured in Figure 17 [9][30]. The time between the first 3 bursts is 2.78 ms, with the smaller 4th burst occurring 3.84 ms later, or 83°.

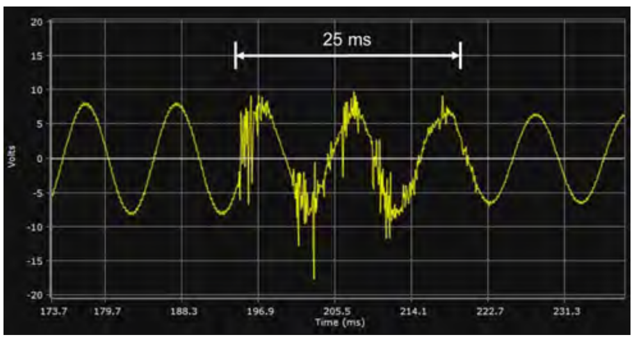

Fig. 16 – Transients from suspected cap bank switching cause loss of guard

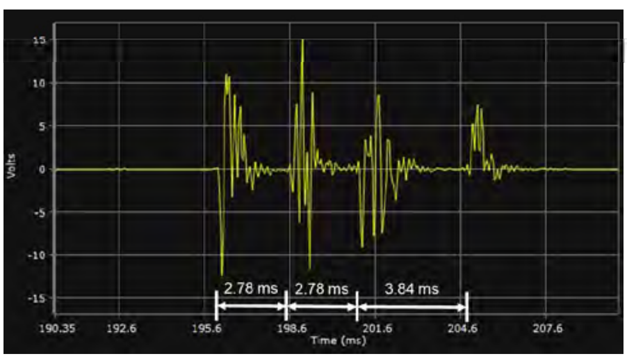

Fig 17 – Suspected re-strike in controlled switching operation

Three-phase noise on coax

Just as a series of noise bursts or noise with 8.33 ms period is the signature of 60 Hz noise from one phase, a period measured at 5.56 ms suggests the 120° phase separation of the 3-phase AC system. Events involving noise with a 3-phase signature are rare in carrier monitoring data, but they do occur. The events in Figures 18 and 19 were captured at one station but are almost identical to those at an entirely different station and system.

Where 3-phase noise is visible the in-band noise can be high, with 1 Vp-p at the upper range of background noise (Figure 19). In this state it may not interfere with the carrier receivers. Occasionally, the noise can increase and evolve into very sharp peaks with a seemingly random pattern, and here it can cause alarms – loss of guard in FSK, Block Rx in On-Off (Figure 18). These events tend to evolve slowly and represent a worsening of the initial condition. A close inspection of Figure 19, with the noise in a lower-intensity state, reveals some clues about the source of the noise.

In Figure 19, the period between bursts is measured at 5.56 ms, or a frequency of 180 Hz. Also, the bursts are relatively similar in amplitude, though each 3rd peak is relatively higher than its 2 neighbors. This suggests the 3rd peak represents noise on the carrier-coupled phase. These facts and the changing amplitude over time all suggest corona discharge as the source of the noise. The 5.56 ms period comes from the discharge occurring on the negative half-cycles of the 60 Hz phase voltages [15]. The presence of noise from all 3 phases indicates the efficiency with which carrier energy couples across the three phase conductors of a transmission line [25].

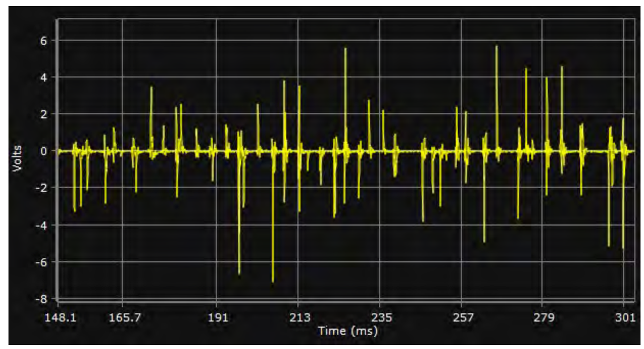

Fig. 18 – Seemingly random transient events look like a line switch operation, but 8.33 ms period between bursts is hard to find

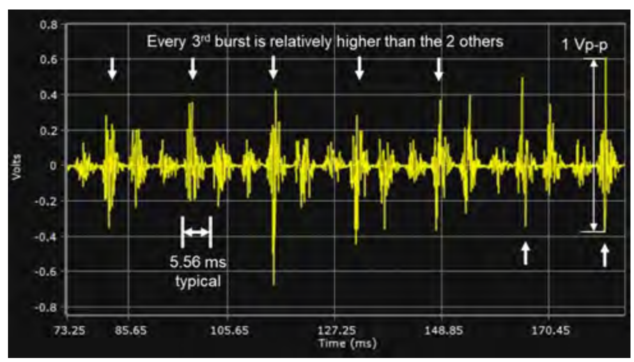

Fig. 19 –Regular 5.56 ms period (120°) between background noise bursts, similar amplitides indicate 3-phase noise source (corona discharge)

Carrier Holes

"Carrier holes have been a topic of discussion for eons and tend to be a mystery." A carrier hole event may be defined as simply "the lack of a signal where one should appear". The term also implies that the "lack of signal" is caused by *the flashover of overvoltage protective devices due to transient energy from the power system* [6]. Continuous monitoring data can capture these carrier holes as they happen, and detailed analysis of their characteristics can be performed.

In the data, a carrier hole event is recognized first by an event capture recorded in-time with a voltage transient, current transient, or both. This is the first clue. Time-domain analysis can provide context about the amplitude duration, and source of the event – was it lightning, a breaker operation, disconnect, cap bank switching, etc. FFT analysis will also reveal whether the event really was a carrier hole – did a “lack of signal” occur, and was there evidence of flashover?

While carrier holes are traditionally discussed in terms of On-Off systems, the term is equally valid for FSK systems. An example of a carrier hole event in an FSK system (this one lasted about 5 ms) is shown in Figures 20-22. In Figure 20, the healthy transmit and receive carrier signals are disrupted and *pulled* to a very noisy 0 V, like the disconnect operation in Figure 13. Also visible is the noise generated by the arcing in the protective device [31] – tell-tale signs of a carrier hole. Figure 21 shows the detail of the carrier hole itself.

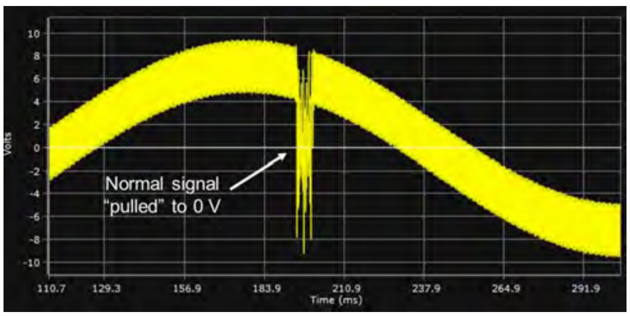

Fig. 20 – 5 ms loss of signal on transmit and receive

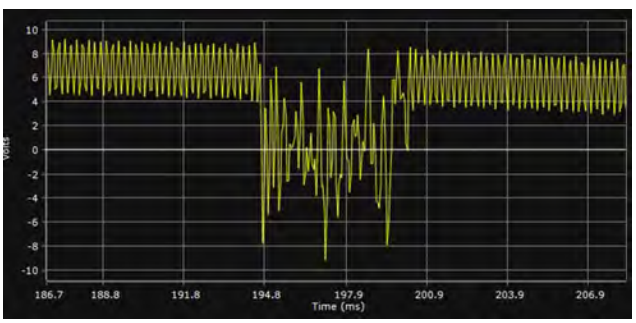

Fig. 21 – 5 ms loss of signal on transmit and receive (detail)

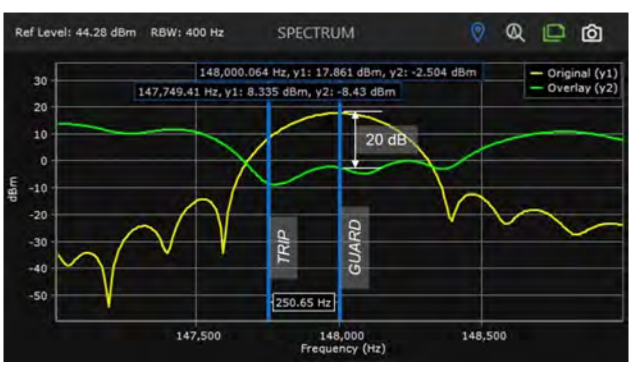

Fig. 22 –FFT overlay analysis of loss of signal (green) vs. normal (yellow)
Left vertical bar shows DTT Trip, right vertical bar shows Guard

Using FFT with overlay analysis, the 5 ms carrier hole was compared against 5 ms of healthy channel data. Shown in Figure 22, the detail in the comparison is striking. It shows that the receive signal is down 20 dB during this time, beyond the 15 dB margin used by most receivers. It also shows that no Trip energy was dominant during the event.

An IEEE report on carrier considerations states, “Power line carrier is a very robust communication medium. It is not normal for the signal to be interrupted during fault conditions. Observation and classification of carrier holes followed by an investigation will result in a more reliable protective relaying system” [6]. Others have echoed this sentiment [2][3][5][7].

The suggested methods for observation and classification of carrier hole events include visual inspection of gaps and tubes, BIL tests, as well as review of any block-extend timers going active in the relay logic during faults – effective but rather tedious, time-consuming, and without any context about the nature of the analog energy that might have caused the issue [5][6][7][22][25]. Not on the list: review of the time-domain characteristics of the event; what kind of transient energy (if any) was present at the time of the event; FFT analysis to check the frequency content of the event. When added to inspection and testing techniques, these new methods sharpen a utility’s ability to observe, classify, mitigate, and verify fixes for carrier hole events on their systems.

Directional Comparison Blocking (DCB) Operations

DCB with power line carrier is widely used for transmission line protection in the US [7]. Recent efforts to reduce protection misoperations have identified these schemes as still especially vulnerable to over-tripping due to loss of carrier signal (carrier holes) [2][3]. The ability to review the carrier portion of these protection scheme operations in granular detail is thus of great value.

While no mis-operations due to carrier holes have yet been observed, many successful blocking operations have been recorded and have provided good insights. They have also demonstrated the ease with which carrier holes are identified when they are recorded. Interestingly, noise due to *fault inception* is also regularly visible in these captures; in agreement with previous observation, it tends to dissipate very quickly and seems to pose little risk to the carrier channel [14][20][21]. Note that fault inception effects are separate from the effects of a sustained fault [14][20].

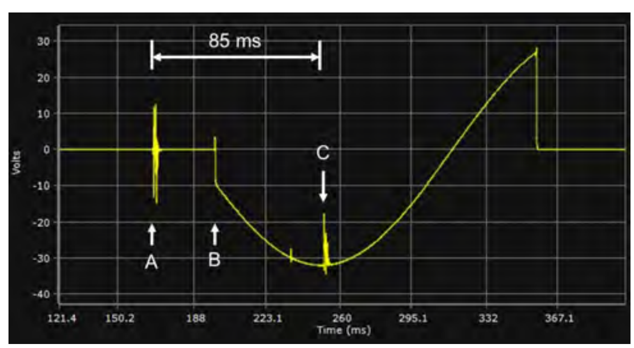

Fig 23 – Fault & block operation, showing carrier hole in the middle
(the carrier hole in this case did not cause an over-trip)

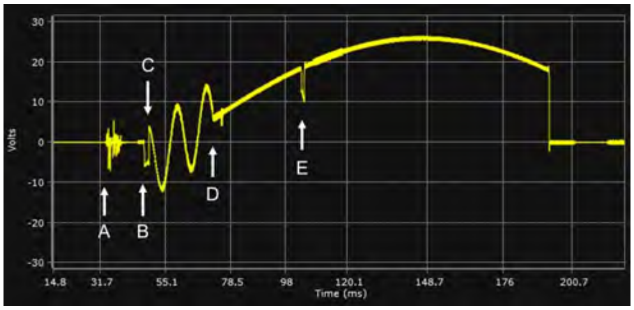

Fig 24 – Fault & block operation showing and START/STOP logic issue

Figure 23 shows the characteristics of a typical blocking operation. The onset of the fault sends out traveling waves that contain broad RF transient energy, which is visible here because it has made its way onto the coax (A). Soon after, a Block is sent out from the local transmitter (B). A significant disturbance is visible on the carrier about 85 ms after the onset of the fault – a carrier hole lasting approximately 1 ms (C). The block-hold logic of the receiver was able to ride through the disturbance because there was no over-trip.

Figure 24 shows a blocking operation in which both the local and remote Block signals can be seen in the FFT analysis. The fault inception occurs first (A). Then the local transmitter turns on (B), with the Block signal received from the remote end a few milliseconds later (C). After about 20 ms the remote carrier turns off due to a STOP input going active (D).

Midway through the local Block transmit signal in Figure 24, there is a 1 ms disturbance that looks a lot like a carrier hole (E). FFT analysis (not shown) revealed that this was the remote carrier turning back ON. Correlation with relay I/O data showed that this was an anomaly in the logic that occurred when START and STOP were de-asserted simultaneously.

Direct Transfer Trip (DTT) Misoperation

In one case, an unwanted DTT operation was reported at a 345 kV station. No monitoring device was installed at the site that misoperated, but there was one at the remote station. It captured what looked like a clear breaker switching event at the time of the DTT misoperation. Initially no breaker operations were noted nearby but the search was broadened and a breaker opening event was identified over 60 miles from the breaker that mis-operated.

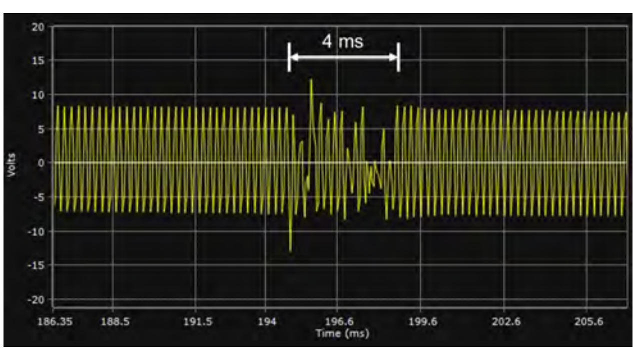

Fig. 25 – Small 4 ms transient noise (faraway breaker) causes DTT misop

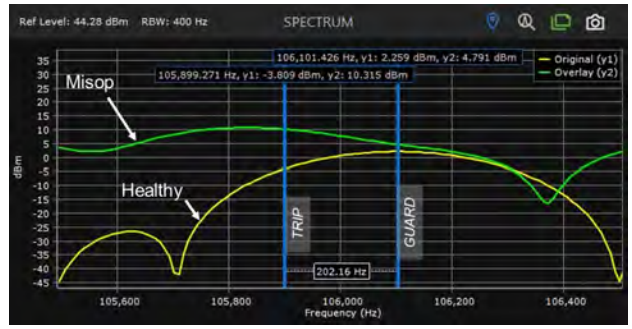

Fig. 26 – FFT overlay analyis of DTT mis-op (green) vs normal (yellow) Left vertical bar shows TRIP freq; Right vertical bar shows GUARD freq

Figure 25 shows the time-domain capture of the disturbance that caused the mis-operation. The disruption appears to last for 4 ms, but careful FFT analysis shows that trip energy was dominant for as long as 7 ms continuous. As carrier disturbances go, this one was not particularly remarkable in length or amplitude. In this case the receiver mis-operated because the transient noise had just the right TRIP profile, demonstrated in Figure 26. Compare this disturbance to the carrier hole event in Figure 22.

Interestingly, this was not one of the more severe transients in the record. The one that caused a misoperation was due to a faraway switching event with just the right energy profile. Misoperations in DTT systems tend to occur in these "sweet spots" given the various parameters of the receiver and logic that must be satisfied [21].

Line Trap Monitoring

In several installations, continuous monitoring data has been used to identify failing or failed tuning packs in line traps. Trending, time-domain, and FFT overlay analysis have been used to identify the trap issues. A typical analysis: trending data shows intermittent changes in impedance (mostly phase angle) in the range of 30 to 60 degrees in the trouble state (Figure 27); FFT overlay analysis shows receive signals significantly down, transmit signals relatively unchanged (Figure 28); even a small event can trigger a capture, though no time-domain disturbance is visible (Figure 29).

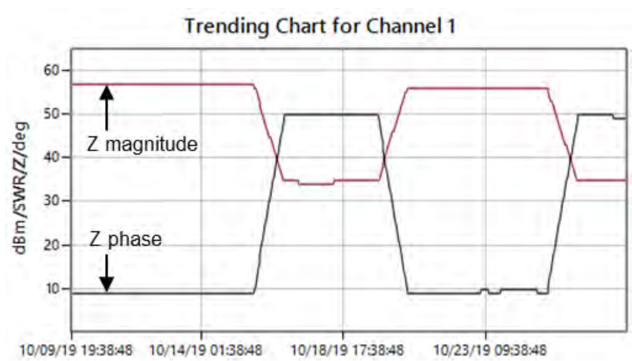

Fig. 27 – Trending shows intermittent impedance changes (magnitude and phase angle)

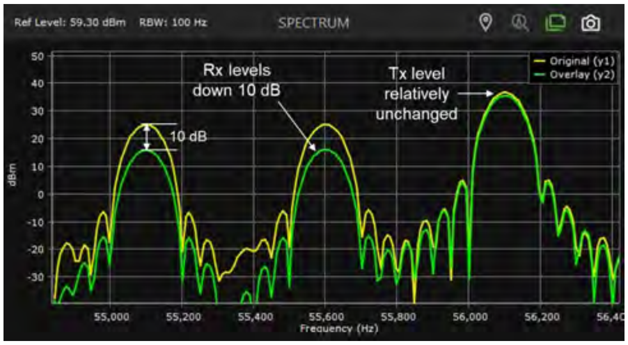

Fig. 28 – Part of overlay shows receive levels (left, middle) are approx. 10 dB lower during the trouble state, transmit level (right) is relatively unchanged

Fig. 29 – Overlay shows example of noise floor "blips" due to very small disturbances while the trap tuning pack was in its trouble state

Using continuous monitoring data in this manner, four line traps have been identified as having failed tuning packs (other sites are still waiting for tuning pack replacement before the ID can be confirmed). Where a device is installed at both ends of a line, the relative amplitudes of disturbances can be compared for context about where the source is. The methods get more reliable and accurate with each positive ID.

V. Risk-Based Monitoring – Trap, Gap, Transients

The fact that a carrier system lives on the power system can make some components especially difficult to access and test. Line traps and overvoltage protective devices, when they may need attention, require a hard-to-get outage before work can begin [25][32]. Failure or end-of-life of these same components may also increase the misoperation risk of a particular channel, so the ability to monitor and indicate imminent failure would be a good application of the continuous monitoring technology presented in this paper.

An approach to this end is being developed and is showing promising results. More field data must be gathered and analyzed but the basics appear relatively simple, measurable, and effective. The primary components considered in the monitoring approach are the line trap and any overvoltage protective devices (or other types of dielectric degradation, for instance on the coax). The tendency of these conditions to worsen the influence of transients on carrier systems is exploited.

Line Traps and Transients

Review of field data where failed line trap tuning packs were found demonstrated some interesting relationships between line trap tuning and transient events seen on the coax:

- Sites with failed line trap tuning packs were noted to have detected a relatively high number of events, especially transients
- The transient events were more likely to cause an event capture – to cause a disturbance in the tuned carrier band
- The captures show characteristics of switching and lightning, some with surprisingly low-amplitude disturbances

One key here is to remember that an important function of a line trap is to isolate the carrier system from transient energy generated by switching on the substation bus [5].

Transient events on the substation bus, by their nature, have a broad frequency spectrum [18]. Energy from these events regularly passes through the line trap and onto the transmission line. If the line trap is healthy, transient energy in the carrier band is significantly attenuated. So long as the out-of-band energy does not cause a dielectric breakdown somewhere, resulting in a carrier hole, the receivers are likely to be unaffected by these normal power system events.

The trap is a bidirectional device, so in the same way it blocks carrier energy from entering the local station bus, it blocks carrier-band transient energy from leaving the local station bus and getting onto the transmission line. Once carrier-band transient energy gets onto the line it has a tuned path straight to the PLC receivers at all terminals.

Air gaps / gas tubes and transients

Another significant pattern seen in continuous monitoring data relates to overvoltage protective devices (generally gas tubes and spark gaps though other types may still be found in-service) [22]. When these devices have been found compromised, the following characteristics are seen in the data:

- Transient events more frequently cause carrier-band disturbances and flashover
- When flashover occurs the carrier hole is "bigger" – the period of arc conduction tends to last longer than in a healthy device

Again, these are not remarkably new insights: "Every time there is a transient…the protective gap will likely flash over, which in turn builds up carbon, thereby decreasing the flash-over voltage of the gap. This carbon build-up may cause the gap to flash-over sooner than expected the next time and not seal-off in time, thereby creating a (severe) carrier hole" [5]. Gas tubes are de-rated in a similar manner as the electrodes sputter and coat the walls of tube [31][33].

When combined, these two risk factors – trap tuning pack failure, and the condition of protective gaps and component dielectric strength – may put the system at severe risk of misoperation. Here is the nightmare scenario, and probably the failure mode of more than one misoperation from the past:

- A tuning pack fails in a line trap, allowing more carrier-band transient energy from the substation bus onto the transmission line
- If the tuning pack failure results in reflected power alarms, perhaps the tuner is 're-tuned' into the bad trap to clear the alarm (not advisable) [32]
- The transient energy disturbs local and remote receivers
- The situation may be compounded (sooner or later) by a de-rated spark gap, gas tube, or other dielectric breakdown issue
- Frequent arcing accelerates the de-rating of the air gap or gas tube

If this is an FSK system, loss of guard or unblock events may be occurring. If it is an On-Off system, the Block Rx may chatter at seemingly random times. Checkback tests are unlikely to detect the issues. Given the difficulty in getting outages, the protective device in the tuner might be inspected but not tested, and the CCVT and trap will have to wait. Meanwhile the transient activity continues.

Eventually, a misoperation occurs.

Now assume similar conditions to the nightmare scenario above, but with a continuous monitoring device capable of detecting an increase in transient activity and measuring its relationship to alarms on the carrier channel:

- As transient activity starts to exceed the system's normal transient profile and alarms increase, an alert – "maintain-me-soon, transient risk high" – is sent out before the next maintenance cycle
- Event data and overall system statistics can be reviewed for insight into the issues, informing the decision to request an outage
- Review of data also informs the work to be done on-site when an outage is granted
- Whatever steps are taken can be immediately monitored to confirm the issue has been mitigated, or to inform next steps

If the line trap is implicated, trending data, captures and FFT analysis will reveal the issue, and the line trap is requested to come down for maintenance at the next outage. The urgency of the outage may be qualified by what is found in the data.

If the air gap or gas tube is implicated, captures and FFT analysis will show the deterioration as frequent, extended carrier holes occurring frequently. Other dielectric failures may show different characteristics than the air gaps and gas tubes.

Quantifying transient risk

The approach, as stated, is rather simple. Whenever a transient is detected it is recorded and counted, weighted according to its intensity. A voltage-only transient is assigned the lowest weight, a current-only transient is assigned a nominal weight, and a voltage- and current-transient event gets the highest weighting. If a channel event is recorded within a pre-defined window of time around the transient, it is counted as a transient-induced event. The event is similarly weighted based on intensity and counted in another index.

These numbers are summarized by day and tracked over time. Interestingly, review of continuous monitoring data from carrier installations reveals that these systems tend to have a transient profile that follows a 7-day schedule. Most transients tend to occur during the weekdays, when more regular switching is happening on the station bus and on nearby systems. With this fact in mind, a 7-day moving average is used to track transient activity and transient-induced alarms.

A sample analysis is shown in Figure 30. The continuous line represents the moving average index. This value should never go over 1 – if it does go over, the system enters the high-risk zone. The vertical bars in Figure 30 represent an answer to the question, how affected is the carrier band by normal power system transients? Each data point in the graph represents one day on the system.

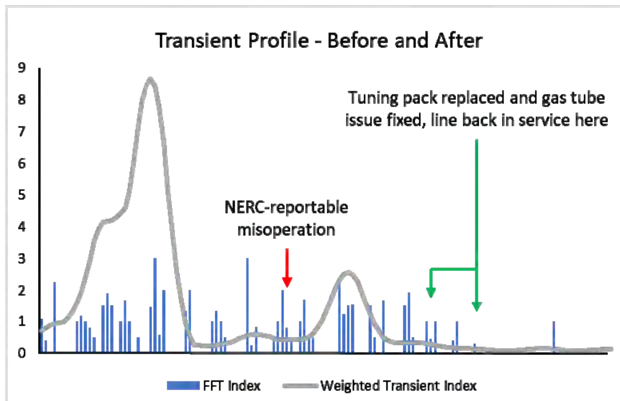

Fig. 30 – Transient Profile shows significantly improved transient resilience after on-site work (replace failed tuning pack and fix issue with gas tube)

The data in Figure 30 come from an installation in which a NERC-reportable misoperation occurred near the middle of the graph. Work was done on-site between the green arrows. During this time, a failed tuning pack was found in the line trap and a significant issue with a gas tube was found which would cause it to arc over at a lower voltage than specified by its design. After the tuning pack was replaced and the issue with the gas tube was corrected, the line was placed back in service. *Transient activity was still regularly detected but only one transient event caused a channel disturbance*, and that was a routine breaker operation.

Going forward, more field data will be evaluated in this manner and the technique will continue to be refined. Emphasis is placed on reporting a single figure of merit which is not prone to chatter – it must represent the long-term trend and not "blip" into the alarm region during a day or two of intense lightning or station switching. Like the other new methods and applications presented in this paper, this technique has potentially big implications for improvements in carrier system reliability and reduction in carrier-related outages and maintenance costs.

VI. Implications for Reliability

In 2013 the North American Electric Reliability Corporation (NERC) published the findings of a task force which analyzed transmission system protection misoperations in the US. Regional entities like SERC, MRO, and WECC (to name a few) provided historical system data to the task force. The goals: research data from past misoperations; find the top 3 causes of misoperations and develop sub-causes for each; and make suggestions for reducing future misoperations [2].

The findings relevant to PLC systems were significant: 17% of transmission system misoperations were caused by the communications channel (396 out of 2279). Further, 12% of misoperations were reported as having "unexplainable" cause (273 out of 2279) [2]. NERC's most-recent "State of Reliability" report from 2020 confirms that "communication failures" have consistently been a top 3 cause of misoperations since data collection started in 2011 [4].

Reading in-between the lines for clues about which communication technologies were involved, an estimate is made here from the 2013 NERC report's data: for the total number of transmission system misoperations caused by communications, 30% involved PLC systems. That's roughly 5% of all transmission system misoperations documented in the report. [2] Appendix C details how these numbers were determined.

Part of the reason for the high share of misoperations by PLC systems is undoubtedly their wide installed base. Another major reason that cannot be ignored is simply a lack of good data available to utility engineers and technicians. As the 2013 NERC report notes, "Improvements in data, while not directly reducing misoperations, help entities determine areas to improve by identifying misoperation causes and proper mitigation steps. Without this analysis, entities will not be able to fix root causes that, potentially, could prevent additional misoperations" [2].

Conclusions

Continuous monitoring for power line carrier represents a step forward in the analysis and operation of these historically reliable protection channels [5]. The ability to identify and analyze events in sharp detail is incredibly valuable. Further, the ability to prioritize maintenance and troubleshooting activities based on predictive analytics related to transients has the potential to dramatically improve the operation and performance of these channels. Taken together, the capabilities ultimately reduce the effort, uncertainty, and costs involved in carrier maintenance and event analysis.

As one relay engineer put it, "To only review…data after obvious misoperations is analogous to a doctor ignoring your reports of anxiety, tightness in chest, nausea, and shortness of breath and only treating you for a heart attack if you actually experience cardiac arrest." [30] With enhanced ability to monitor the vital signs of a carrier system and to hear its complaints, continuous monitoring helps mitigate severe events by identifying those sites most in need of attention so that they can be treated before suffering an acute crisis.

Acknowledgements

The authors would like to acknowledge Danny Worrell of Georgia Power for his contributions and insights.

References

[1] A. S. Fitzgerald, "A Carrier-Current Pilot System of Transmission Line Protection" Transactions AIEE, September 1927

[2] NERC Protection System Misoperations Task Force, "Misoperations Report," April 2013

[3] NERC, "Lessons Learned – Initiatives to Address and Reduce Misoperations 20181201," December 2018

[4] NERC, "2020 State of Reliability Report – An Assessment of 2019 Bulk Power System Performance," July 2020

[5] M. P. Sanders, "A Reliable Power-Line Carrier-based Relay System – Avoiding Mistakes that Cause PLC Systems to Misoperate or Fail to Operate," Texas A&M Protective Relay Conference, March 2012

[6] IEEE Power System Relay Committee, Working Group H9, "Special considerations in applying power line carrier for protective relaying," 2004

[7] Z. P. Campbell, Y. Xue, R. C. Dixon, "Power Line Carrier Directional Comparison Blocking Misoperation Event Analyses & Avaoidance Techniques," 67th Georgia Tech Protective Relay Conference, 2013

[8] T. Bell, "Mitigating Carrier Holes in Power Line Carrier," Georgia Tech Protective Relay Conference, 2018

[9] D. Goldsworthy, T. Roseburg, D. Tziouvaras, J. Pope, "Controlled Switching of HVAC Circuit Breakers: Application Examples and Benefits," 34th Western Protective Relay Conference, 2007

[10] G. A. Franklin, S. Hsu, "Power Line Carrier Interference Caused by DC Electric Arc Furnaces," 2003 IEEE Power Engineering Society General Meeting

[11] NERC PRC-005-6, 2016

[12] R. Ray, A. Jayson, R. Fella, J.E. Brown, N. Stone, R. Baldwin, "The Advantages of Continuous Monitoring of PLC Channels Applied to Protection Systems", Texas A&M Relay Conference, 2017

[13] IEEE C93.5 – Standard for Power Line Carrier Trnasmitter/Receiver Equipment used to Transfer Discrete Teleprotection Signals

[14] T. Udo, M. Kawai, "Fault Generated Impulse Noise Voltage in a Transmission Line," IEEE Transaction on Power Apparatus and Systems, Vol. PAS-86, No. 6, June 1967

[15] R. C. Cheek, J. D. Moynihan, "A Study of Carrier-Frequency Noise on Power Lines – Part I – Theoretical Considerations and Measuring Techniques," Transactions of the American Institute of Electrical Engineers, Vol. 70, Issue 2, 1951

[16] W. C. Kotheimer, "The Source and Nature of Transient Surges," IEEE Transactions on Industry Applications, Vol. IA-13, No. 6, November/December 1977

[17] W. C. Kotheimer, L.L. Mankoff, "Electromagnetic Interference and Solid-State Protective Relays," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-96, no. 4, July/August 1977

[18] A. Greenwood, "Electrical transients in power systems, 2nd ed.," Renselear Polytechnic Institute, Electric Power Engineering Department, 1991

[19] A. W. Adams, "Field Tests and Operating Experience with Carrier-Transfer Trip Relaying for Line Protection," Transactions of the American Institute of Electrical Engineers, Part III: Power Apparatus and Systems, Vol. 76, Issue 3, August 1957

[20] D. E. Jones, "Staged Fault Tests with Power-Line Carrier Transferred-Trip Relaying for Line Protection," Transactions of the American Institude of Electrical Engineers, Part III: Power Apparatus and Systems, Vol. 78, Issue 3, August 1959

[21] B. Bozoki, "Effects of Noise on Transfer-Trip Carrier Relaying," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-87, No.1, January 1968

[22] J. J. Meinardi, M. P. Sanders, “Investigation and Analysis into the Mis-Operation due to Carrier Holes,” AMETEK Power Instruments & Florida Power & Light, 2008

[23] https://www.lightningmaps.org/

[24] R. C. Cheek, J. D. Moynihan, “A Study of Carrier-Frequency Noise on Power Lines – Part IV – Conclusions of Field Measurements,” Transactions of the American Institute of Electrical Engineers, Vol. 74, Issue 3, 1955

[25] IEEE 643 – Guide for Power Line Carrier Applications, 2005

[26] E. O. Schweitzer III, V. Skendzic, A. Guzmán, M. V. Mynam, J. L. Eternod, Y. Gong, “Mystery Solved: Five Surprises Discovered With Megahertz Sampling and Traveling-Wave Data Analysis,” 45th Annual Western Protective Relay Conference, October 2018

[27] P. J. Tatro, K. A. Adamsom, M. A. Eitzmann, and M. Smead, “Power line carrier interference from HVDC converter terminals,” *IEEE Transactions on Power Delivery*, Vol. 8, No. 3, July 1993

[28] M. Beanland, T. Speas, J. Rostron, “Pre-insertion resistors in high-voltage capacitor bank switching,” Western Protective Relay Conference, 2004

[29] ABB, “Capacitor switching comparison: the supremacy of diode technology,” 2015

[30] R. W. Patterson, “The Importance of Power System Event Analysis,” 8th Annual Fault and Disturbance Analysis Conference, April 2005

[31] IEEE-487 Recommended practice for the protection of wire-line communication facilities serving electric supply locations,” 2007

[32] J. E. Brown, “Power line carriers: simplified – a field engineer’s perspective,” PLCExperts.net, 2018

[33] Bourns (T. Ardley), “First principles of a gas discharge tube primary protector,” 2008

Appendix A – Measurement Techniques

Figure A1 shows the ideal place in the PLC circuit for continuous monitoring devices. Installation at the tuner input is important because this is the most accurate point to measure impedance matching. Also, it is a convenient measurement location because all signals entering and leaving the station are available at this point in the circuit.

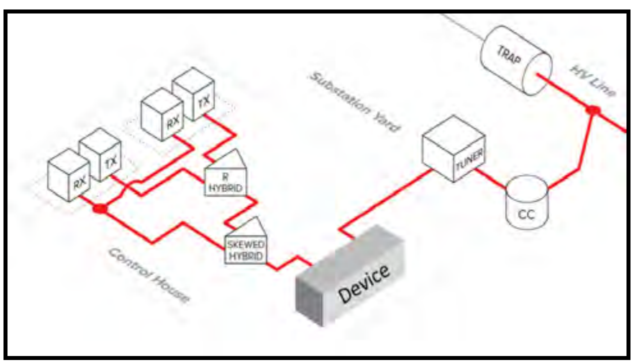

Fig. A1 – Monitoring device installation location

PLC signal data is processed and recorded at several different stages of the device: wide-band, 10-kHz intermediate frequency, and narrow-band (300, 600, 1200 Hz typical) – see Figure A2. Each stage provides different context about the signal and/or events.

Appendix B – Measurement Techniques

This appendix examines a method for calculating impedance from reflected power percent and analyzes the accuracy of this method.

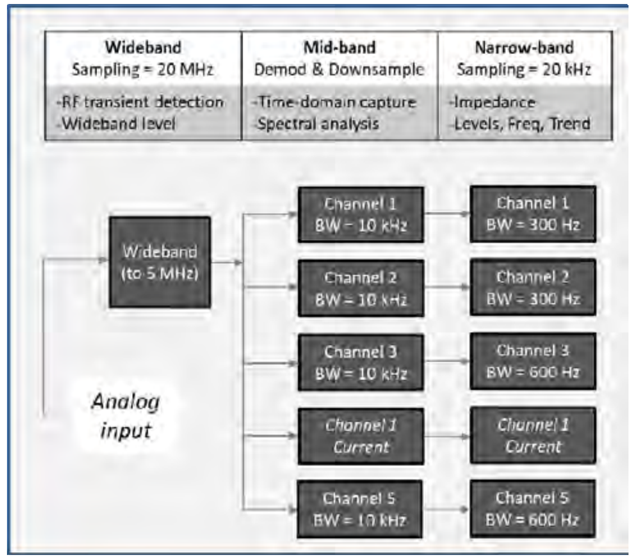

Fig. A2 – Monitoring device internal detail (example)

To obtain an equation that can calculate the termination impedance Z_{TERM} from reflected power, equations (1) and (2) are solved for Z_{TERM} in terms of reflected power percent:

$$Z_{TERM(RP)} = \frac{Z_{SOURCE}(1+\sqrt{RP})}{(1-\sqrt{RP})} \tag{B1}$$

Table B1 shows the resulting Z_{TERM} value calculated from reflected power. Note that each impedance magnitude result in the table has a phase angle of zero. Table B2 shows the percent error introduced when using this method to calculate the line tuner input termination impedance Z_{TERM}.

Appendix C – NERC Misoperation Data

Section VI makes a claim that data in a 2013 NERC report suggest 30% of all communications-related misops were caused or sub-caused in some way by a PLC system. The reasoning and numbers behind that estimate are described here.

There were a total of 396 misoperations attributed in one way or another to “communication failures”. Descriptions of each of the sub-cause groups contained further data about the cases in those groups. For two of the sub-groups, a minimum number of cases with PLC communications could be determined

At least 34 were from sub-cause “Modulator Problems”: “In 34 cases the radios were replaced without further investigation.” Radio is understood to mean a PLC transmitter/receiver. 34 out of 130 total in this group is a rate of 26%.

TABLE B1 – TERMINATION IMPEDANCE Z_{TERM} CALCULATED FROM REFLECTED POWER USING EQUATION (B3)

Zterm magnitude (ohms)	Zterm Phase Angle (deg)								
	-40	-30	-20	-10	0	10	20	30	40
25	146	124	110	103	100	103	110	124	146
30	128	108	94	86	83	86	94	108	128
35	118	97	83	75	71	75	83	97	118
40	111	91	76	66	63	66	76	91	111
45	108	88	73	61	56	61	73	88	108
50	107	87	71	60	50	60	71	87	107
55	108	87	72	61	55	61	72	87	108
60	110	89	75	64	60	64	75	89	110
65	113	92	78	69	65	69	78	92	113
70	117	96	82	73	70	73	82	96	117
75	121	100	86	78	75	78	86	100	121
80	125	105	91	83	80	83	91	105	125
85	130	109	96	88	85	88	96	109	130
90	135	114	100	93	90	93	100	114	135
95	141	119	105	98	95	98	105	119	141
100	146	124	110	103	100	103	110	124	146

TABLE B2 – PERCENT-ERROR INTRODUCED WHEN CALCUALTING Z_{TERM} FROM REFLECTED POWER PERCENT

Zterm magnitude (ohms)	Zterm Phase Angle (deg)								
	-40	-30	-20	-10	0	10	20	30	40
25	484%	397%	341%	310%	300%	310%	341%	397%	484%
30	328%	259%	213%	187%	178%	187%	213%	259%	328%
35	236%	178%	138%	113%	104%	113%	138%	178%	236%
40	178%	127%	91%	66%	56%	66%	91%	127%	178%
45	140%	95%	61%	36%	23%	36%	61%	95%	140%
50	114%	73%	43%	19%	0%	19%	43%	73%	114%
55	96%	59%	32%	11%	0%	11%	32%	59%	96%
60	83%	49%	25%	7%	0%	7%	25%	49%	83%
65	74%	42%	20%	6%	0%	6%	20%	42%	74%
70	67%	37%	17%	5%	0%	5%	17%	37%	67%
75	61%	33%	15%	4%	0%	4%	15%	33%	61%
80	57%	31%	14%	3%	0%	3%	14%	31%	57%
85	53%	28%	12%	3%	0%	3%	12%	28%	53%
90	50%	27%	12%	3%	0%	3%	12%	27%	50%
95	48%	25%	11%	3%	0%	3%	11%	25%	48%
100	46%	24%	10%	3%	0%	3%	10%	24%	46%

At least 35 were from sub-cause "Station Signal Path Failure": "Of 69 records in this sub-cause, the majority can be attributed to power line coupling applications." A majority means at least more than half of 69, giving 35. 35 out of 69 is a rate of 51%.

For the four remaining groups, an estimated PLC rate of 20% was used to get a number of misoperations. The estimated rate is considered conservative as it is less than both of those groups above where the minimum percentage could be determined. This estimate is also informed by field experience.

- 22 from sub-cause "Insufficient Information" (111 total * 20%)
- 12 from sub-cause "Communications Medium" (63 total * 20%)
- 5 from sub-cause "Incorrect Logic Settings Issued" (24 total * 20%)
- The remaining sub-cause "Human Error" had 12 total misops. While it did contain a PLC-related misop in the description, it mentioned that this misop has already been counted in another sub-cause category.

34 + 35 + 22 + 12 + 5 = 108 PLC-related events

108 PLC events ÷ 396 total events = ***27% caused by PLC (round up to 30%)***

108 PLC events ÷ 2279 total events (NERC Misop Report, Figure 2 – NERC-wide Misoperations by Cause Code) = ***4.74% (round up to 5%)***

Craig M. Palmer received his Bachelor of Applied Science in Electronics and Computer Engineering Technology at the New Jersey Institute of Technology, Newark, NJ in 2011. He has worked on power system communications and pilot protection channels since then, first with RFL Electronics and now with PowerComm Solutions. He is an active participant in the IEEE Power System Relaying and Control Committee (PSRC), a member of the IEEE Power System Communications and Cybersecurity Committee (PSCC), and current chair of the PLC subcommittee in the PSCC (2021).

Alan Jayson has spent the last 35 years designing various audio tone and PLC communication and instrumentation products for the electric utility system protection industry. He started his career in 1986 with INIVEN, where he helped design protection communication systems that are still in use today. In 2012 he joined PowerComm Solutions as lead design engineer. Prior to that, he worked for Signalcrafters for 14 years. He is also a patent holder.

Jeffrey E. Brown graduated in 1997 with a Bachelor of Science in Engineering from Georgia Tech University. After graduation, he worked for Georgia Power for 23 years and finished as Team Leader for Power Line Carrier covering the state of Georgia. He presently works for Georgia Transmission Corporation as Principal Engineer Transmission and Power Line Carrier Support. He is a member of the North American Transmission Forum (NATF) and a member of the Power Line Carrier subcommittee in the IEEE PSCC. He is the author of "Power Line Carriers: Simplified."