

THE ADVANTAGES OF CONTINUOUS MONITORING OF POWER LINE CARRIER (PLC) CHANNELS APPLIED TO PROTECTION SYSTEMS

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INTRODUCTION

The critical nature of the power transmission system today makes it imperative that utilities keep up with the demand of routine maintenance of the protection system, as well as, monitoring the health of the system. In this manner, the reliability of the system can be assured. This paper will describe methods by which the system can be monitored and how the data can be used to predict the need for maintenance before system failure occurs.

Today the protection system is made up of microprocessor relays, which can monitor their health and alarm if there are problems with the system. Many of these protection systems employ the use of Power-Line-Carrier (PLC) equipment to aid in the simultaneous detection of the fault at all line terminals to clear the fault. Many of these PLC systems do not can monitor all aspects of their health. Also, we have not had the ability of being able to have an independent device (such as what a Digital Fault Recorder (DFR) does for the power frequency equipment) that can monitor transient responses of the RF portion of the PLC system. If this type of equipment were available, any abnormal transient behavior of the terminal equipment as well as the communications path can be monitored and problems can be detected before they become an issue affecting the reliability of the protection system. In addition, when unexpected system events occur, data will be available for in depth analysis of the communication path that can be synchronized and compared to other devices on the system. This data can be used to assist in analyzing what is occurring on the RF path when a PLC issue (e.g. carrier holes) has occurred.

PRC-005-002 Power System Maintenance Standard [4] now requires utilities to perform maintenance on their Protection Systems at specific maximum intervals based on the level of monitoring that exists. Complying with this relatively new standard can potentially be very costly to a utility. A DFR type of continuous monitoring system for the PLC system could drastically reduce the cost of the periodic maintenance. Information such as reflected power, levels, margins, and even system noise at carrier frequency could be maintained. When a maintenance cycle approaches real time data from the monitoring system would be captured and compared to archived data to determine what maintenance, if any, is needed. This real-time monitoring will reduce system down time while minimizing human interaction with live systems that sometimes lead to unexpected operational incidents.

FUNCTIONS IMPORTANT TO A PLC MONITORING SYSTEM

Standing Wave Ratio (%RFLP)/ % Reflected Power %RFLP Monitoring

Monitoring %RFLP/% Reflected Power provides valuable information to a Power Line Carrier protection user. The %RFLP of a PLC system is affected by changes in Impedance terminating the transmitter. When changes occur on the Power Line Carrier system they are typically a combination of the resistive, capacitive and inductive components. Knowing the Impedance and Phase Angle of the %RFLP is critical to the diagnosis of these changes. Having a device that is

capable of measuring both the impedance and phase angle with the %RFLP measurement is important for troubleshooting the change. Any changes in these elements provides clues to what may have caused the change in the reflected power reading. For example, a Power Line Carrier Monitoring (PCM) device located per Figure 11 with a zero % reflected power reading should measure an impedance of 50 Ω with a zero-degree phase angle.

An increase in the impedance of the measurement means that there was an increase in the impedance of the entire PLC system. A negative phase tells the user that there has been a change that has caused the system to become more capacitive to that frequency or if the angle is positive the impedance has become inductive. Some examples of what these detailed measurements can indicate are line trap failures, line tuner problems, overall line impedance changes for variation reasons.

If only the magnitude or percent reflected power is known, there is no way to know what is mismatched or what may have changed on the overall PLC system.

Table 1 shows examples that all represent a 10% reflected power reading. Note that each have significantly different resistive, capacitive and inductive components. Having the impedance and angle measurements now provides a clearer path to what has changed in the overall system.

**Table 1 - Impedances Resulting
in a 10% Reflected Power**

Z	Φ Angle
80.75 Ω	+23.95°
63.59 Ω	-32.71°
39.37 Ω	+32.75 °
36.68 Ω	-30.94 °

PLC Receiver Type Measurements

Having a monitor device that replicates the characteristics of a Power Line Carrier receiver not only provides a second way to detect problems, but this independent device is not restrained by the extra protections and timers needed to meet the desired security and dependability. An independent receiver/monitoring device can be set more sensitive to capture actual raw measurements. This is critical information that the regular receiver may see, but does not react to, based on its scheme and/or individual protective settings. A more sensitive device can provide valuable early detection to potential future problems before they occur. Adding long term trending (hourly/daily measurements) for Level or Reflected power enhances the opportunity to avoid possible mis-operations in the future. Trending can also provide insight to short term events that negatively impact the Carrier system, like adverse weather conditions. Time Synchronization of the event recorder is also valuable when comparing event logs between various protective devices in the systems.

Spectrum Analysis Using Fast Fourier Transform (FFT)

Using FFT's:

With time domain viewing (Oscilloscope) it is not possible to see the individual signal you are interested in because it shows a composite of all the signals present, including noise. To view multiple signals at the same time, using frequency domain (FFT's) is the best way.

With a time-domain display one is viewing amplitude on the Y axis and time on the X axis). With a frequency domain display one is viewing amplitude on the Y axis and frequency on the X axis.

The signal is sampled “N” times (total samples), at a frequency high enough to produce all frequencies in each band, and stored in a buffer. An FFT is run on the stored samples and an amplitude/frequency plot is produced. An example of a time domain plot vs a frequency domain plot is shown in Figure 1 below.

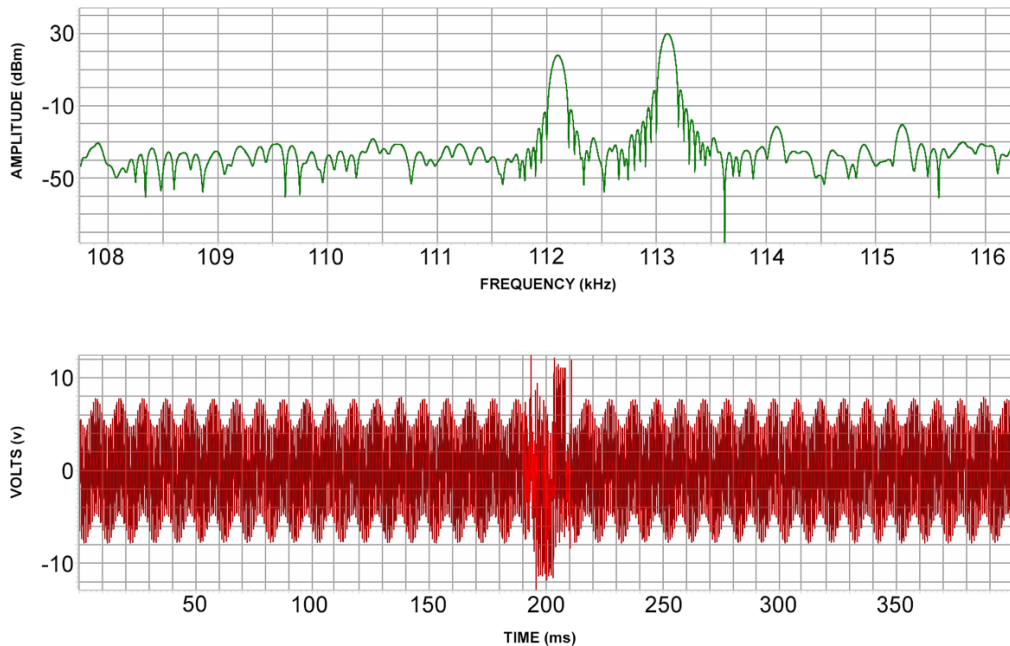


Figure 1 - Time domain vs frequency domain plots

Event Driven FFT's:

Event driven FFT'S provide an opportunity to see what has occurred on the RF path during a specific event. Examples of some of these events are loss of signal, received guard or trip, %RFLP out of range, etc. The captured spectral analysis provides more insight to what may have happened when one of these specific events is recorded. For example, some loss of guard events recorded by PLC receivers, can be caused by various events, not just by the loss of the actual signal (Guard). A transient noise event can cause the signal to noise ratio to decrease significantly which could cause the receiver to indicate a loss of guard even though the guard frequency is still present.

Figure 2 shows an FFT capture of a single FSK transmitter in its normal state. Figure 3 shows a capture of a transient noise event on the same line with the guard frequency still present. Note the Guard frequency is still present, although the signal-to-noise ratio is visibly worse. In some cases, this type of event can cause a receiver to clamp (not permit guard or trip), which can be recorded by the PLC Receiver or protective relay its tied as a loss of guard event. An FFT capture of this event helps the user identify that the transmitter and receiver seem to be operating as expected and thus saves significant time by eliminating the transmitter and receiver as the cause of the problem.

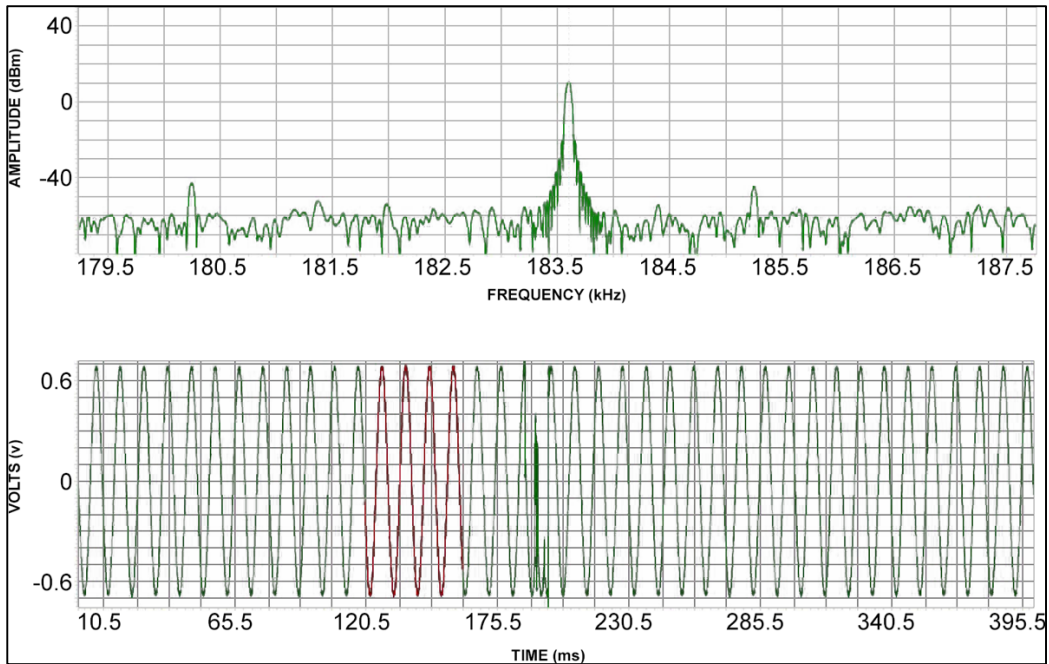


Figure 2 - Example of a Transmitter in its Normal State

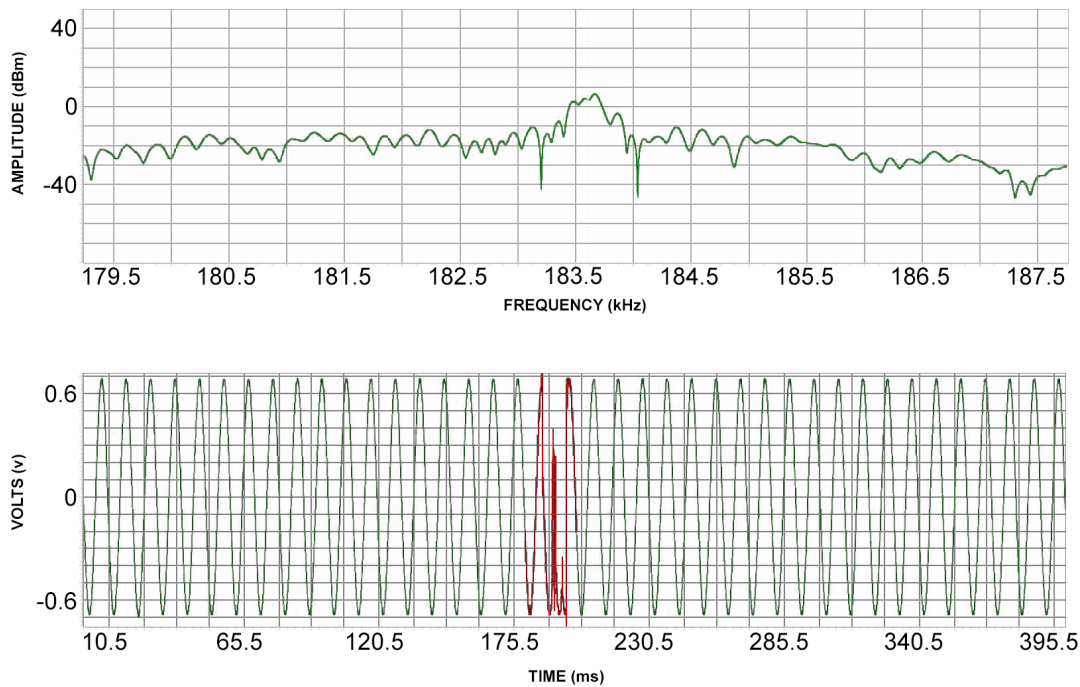


Figure 3 - Example of a Noise Event

Spectral Analysis Capture with Overlay

When commissioning a PCM device, the ability to capture a real time Spectral Analysis of the Channel can be an incredibly useful tool in analyzing changes or intrusions to the known frequencies on the line. A real-time capture permits the user the ability to identify all frequencies, levels and noise present at the time of commissioning and verify that they are known entities and acceptable levels. If this “commissioning” or acceptable state Spectral Analysis can be saved as a reference or baseline, the user now has an invaluable tool for future system analysis or

troubleshooting. When the user accesses the PCM device on a later date and captures a new Spectral Analysis of the same Channel and then imports the original capture as an overlay, they can see any changes that may have occurred. Figure 4 shows an initial Real Time Capture of a Channel with 3 frequencies present.

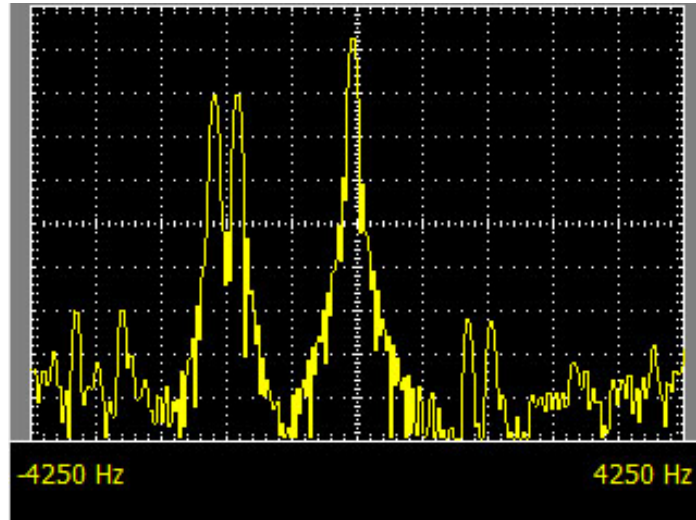


Figure 4 - Initial Real Time Capture

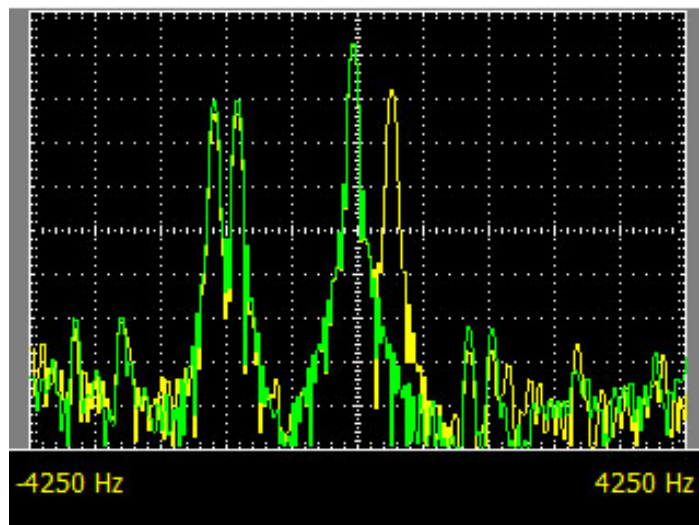


Figure 5 - Initial Capture Overlaid with a Later Capture

Figure 5 shows a present Spectral Analysis Capture with an original capture overlaid. The green capture represents the original capture and the yellow represents the present capture. Note that the new capture has a 4th frequency that did not exist at time of the original capture.

This overlay tool can be used to assist and identify many potential issues before they become actual problems or misoperations. For example, when any maintenance or new installs are performed only a few busses away from a site being monitored, often time frequencies can bleed through and show up at high enough levels to potentially interfere with an existing protection channel. Using the overlay process at any time can easily help identify potential problems quickly. There is also the possibility of detecting line trap failures simply because a new frequency has appeared in the present real time spectral analysis capture that once did not exist. Knowing that unexpected

frequency value permits a user the ability to identify where in their system that frequency may be coming from.

Long Term Monitoring – Maintenance Extension – Assist with NERC Compliance

A PCM installed permanently provides the utility a mechanism that can be used to more easily comply with PRC-005-002 maintenance cycles, but can also reduce costs. In addition, once installed, the PCM can be accessed at any time either remotely or locally to review measurements without the need for a PLC system outage. A permanently installed PCM device is like having multiple instruments in the system always. The PCM can be used to record “As Left Data” at commissioning or at any future time. This “As Left” data represents the present measurements of the PLC channels and when connected to a satellite clock can represent a maintenance test. This As Left reading can not only be used for maintenance testing, but also becomes a permanent electronic history of all maintenance measurements performed with time and date stamp.

APPLICATION OF A MONITOR TO THE PLC SYSTEM

How Location of the reflected Power Measurement Affects the Results

Before a discussion about the application of a monitor to a PLC system, it is important to know how the location where the %RFLP is measured will affect the reading. It is widely accepted that the best location to perform %RFLP measurements is at the RF input of the line tuner. When additional components like hybrids are inserted into the path between the %RFLP measurement and the tuner, the readings will not be the same. Common locations for %RFLP measurements can be seen in Figure 6 & Figure 7.

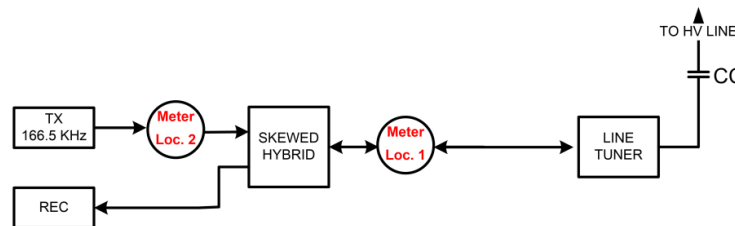


Figure 6 - %RFLP Variation Between Location 1 & 2

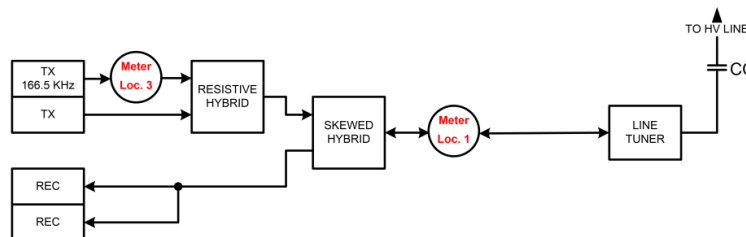
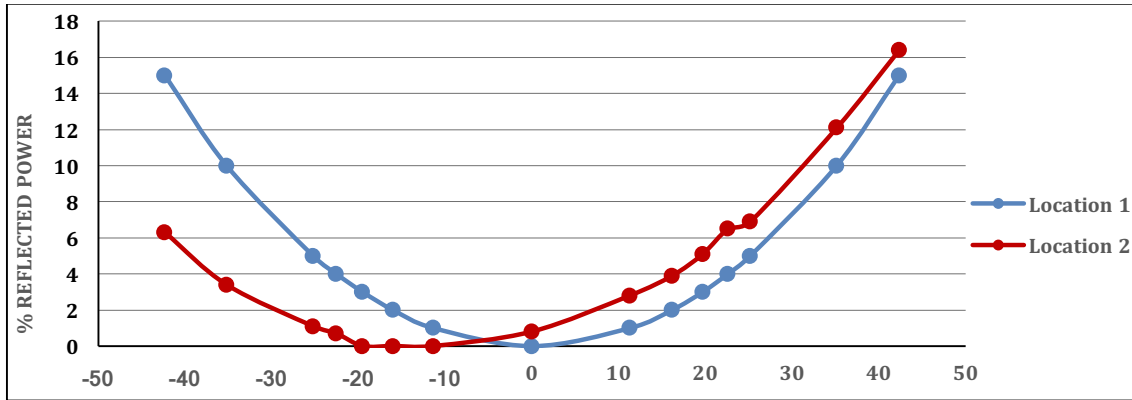


Figure 7 -- %RFLP Variation Between Location 1 & 3

Figure 8 shows %RFLP measurements made at both locations 1 & 2, with the Impedance constant at 50 Ω and a variable phase angle.



**Figure 8 - %RFLP Differences Between Locations 1 & 2:
Impedance Fixed at 50 Ω: Variable Angle**

Prior to the having the ability to measure the phase angle component of a %RFLP measurement, it was not possible to know how a capacitive or inductive change to the Carrier system would affect readings at different locations in the circuit. For the measurement scenarios shown in Figure 6 & Figure 7, two different measurement tests were performed for each figure shown. The first test kept the Phase Angle constant at Zero Degrees and varied the Impedance. The second test kept the Impedance constant at approximately 50 Ω and varied the Phase Angle. For Figure 6 (0° Phase Angle, Variable Z), the readings at Locations 1 & 2 are essentially the same, so no chart was necessary to show the differences. That is not the case when the phase angle changes. Per Figure 8, measurements at location 2 are noticeably affected when the Impedance stays constant at approximately 50 Ω, but the phase varies. Note that when the phase angle is negative, measurements at location 2 have difficulty detecting any change in the reflected power reading, although measurements at Location 1 still see the expected changes occurring on the path. In addition, this testing also identified that changing the frequency of the %RFLP measurement will also affect how different the reading will be between the two locations. Per these results, since differences in the readings are not linear, applying a correction factor to a device measuring at location 2 would not provide any confidence that the reading would correlate with readings at location 1.

This measurement difference becomes even more significant when a resistive hybrid is placed in the circuit along with a skewed hybrid (See Figure 7). In addition, when changes occur to either the impedance or phase angle, the %RFLP measurements are significantly affected between measurements made at locations 1 and 3. Figure 9 shows %RFLP measurements made at both locations 1 & 3, with the Impedance constant at 50 Ω and a variable phase angle.

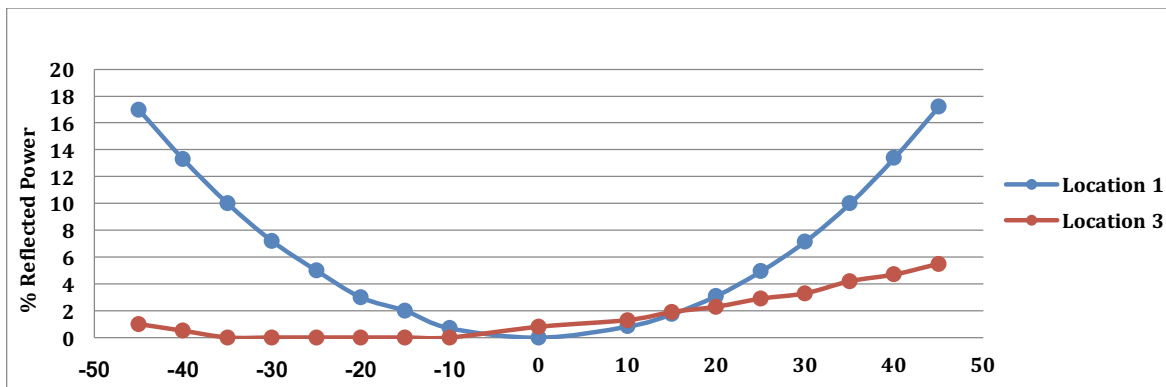


Figure 9 - %RFLP Differences Between Locations 1 & 3: Impedance Fixed at 50 Ω: Variable Angle

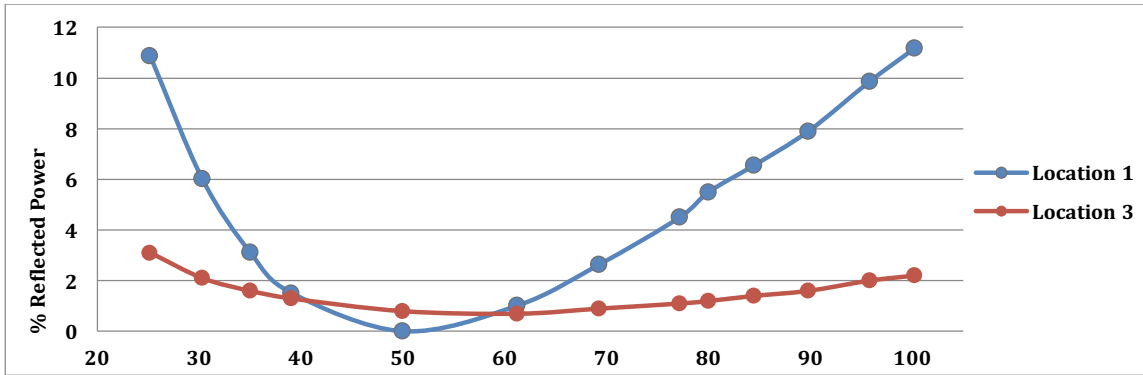


Figure 10 - %RFLP Differences Between Locations 1 & 3: 0 Degrees & Variable Impedance

Figure 10 shows %RFLP measurements made at both locations 1 & 3, with the phase angle constant at zero degrees and a variable impedance. Note the dramatic differences between measurements made at locations 1 & 3 when both a skewed and resistive hybrid are in the circuit. In addition, there is one very important measurement comparison that is not shown in Figure 10, but is critical to know. When there is no-load in the circuit of Figure 7 at the tuner, there is dramatic difference between the % Reflected power at locations 1 & 3. An example of a no-load condition on a PLC system could be a broken or disconnected coaxial cable in the path. As expected, the measurement readings taken at location 1 are 100% reflected power. Due to the inherent impedance characteristics of a typical resistive hybrid, the measurement at location 3 only reads 16.6 % reflected power, even though the cable is disconnected at the tuner.

This testing and resulting data clearly identifies that the optimal place to monitor %RFLP is at location 1 only. Measurements made at locations 2 or 3 cannot return the same results due to the affects that hybrids introduce in to the complex circuit which is a Power Line Carrier system.

Common Coupling Schemes

Since we are talking about a device that will do real time monitoring of both the steady-state conditions of the power-line-carrier system and capturing the transient conditions, we would expect to see the device applied somewhere in the power line carrier chain. If the device is a multi-channel monitor and based on the discussion in the previous section, then the best place for it to be located is in the coax just before it leaves the control house to go to the line tuner. Reference Figure 11.

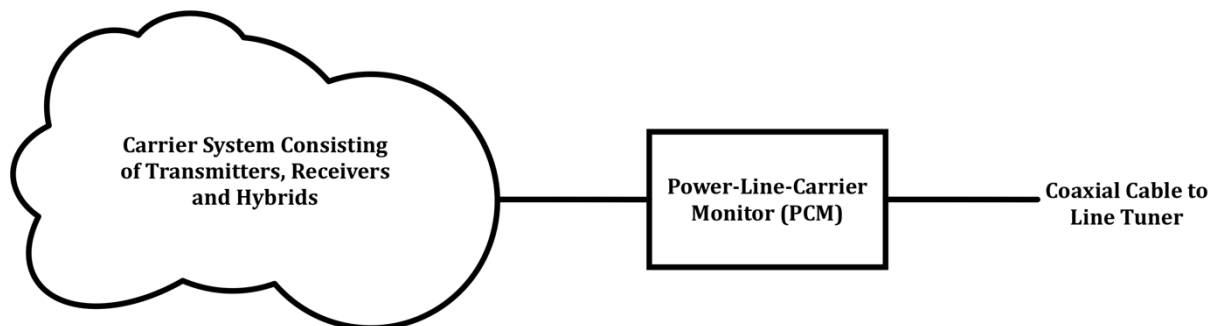


Figure 11 - General preferred location for a PCM

There are several reasons why this location is the best place for the PCM. First, like a Digital Fault or Transient recorder the monitor should be placed in a location where it sees the original signals entering & leaving the system. Second, if it is a multi-channel device it must be at a location so that

it can monitor all the desired frequencies in the system. Also, a third, one of the most useful quantities to be monitored is the reflected power from the line tuner. This quantity is most important to watch since it will tell the user the status and health of the line tuning system. Therefore, as shown in the previous discussion, the best place to observe reflected power is right before the coax cable leaves the control house. At this location, the reflected power hasn't been changed by any hybrids in the coupling chain and the correct phase angle of the impedance can be measured.

The above Figure 11 will suffice for all applications that involve a single coax leaving the control house to the switchyard. There is one exception to the single coax approach which will be discussed later.

However, what can be done with applications that involve multi-phase coupling. These applications can get a bit more involved. First, let's look at the most common phase-to-phase coupling scheme. This is show in Figure 12.

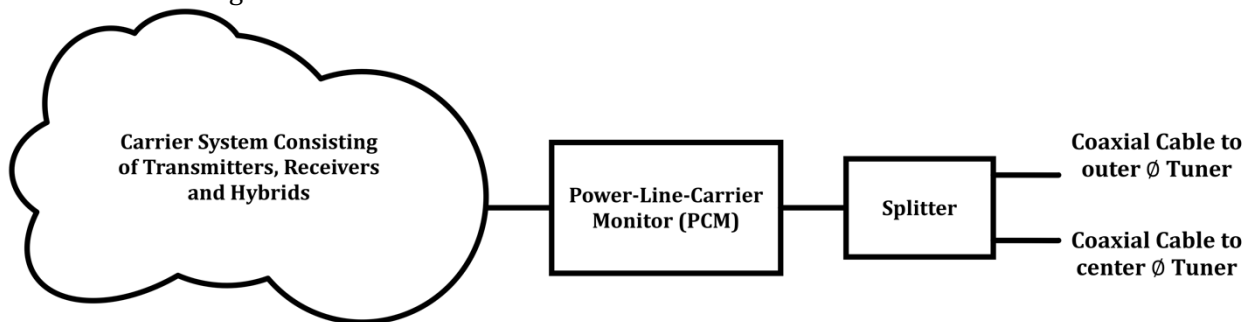


Figure 12 - PCM Location for Phase-to-Phase Coupling

At first glance, it appears that the rule of having the PCM in the coaxial cable right before the leaving the control house is violated. In this case, if the termination on the splitter outputs is the close to identical the effects on any characteristic of the signal being monitored is very minimal. This includes the reflected power. Let's digress and look at the splitter schematic in Figure 13.

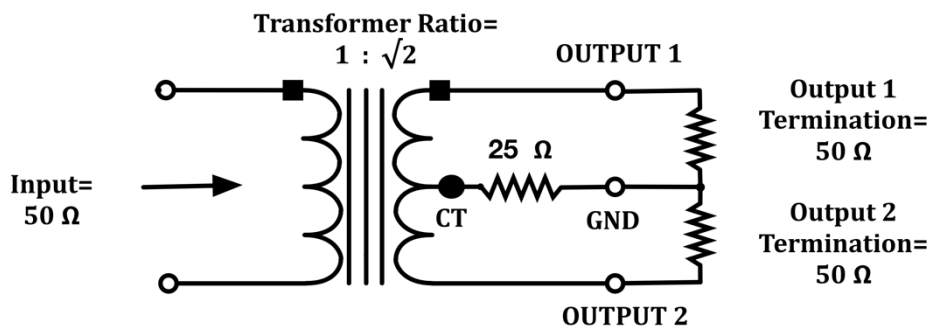


Figure 13 - General Circuit for a Splitter

With both outputs terminated the same then there is no current in the 25 Ω resistor and thus there is no losses and the input sees 50 Ω. The power at the output of the transformer is equal to the power into the transformer. Thus, each output sees one half of the input power and the current on each output (referenced to ground) is out of phase which is what one wants in phase-to-phase coupling.

As far as monitoring transmitters going out the power out seen by the PCM will equal the sum of the power on the combined phases. So, the transmitter monitoring will be correct. If the voltage is

received from the other end is equal and 180° out of phase, then there are no extra losses coming in and the voltage across the input side of the transformer is equal to the sum of the two phase voltages divided by the square root of 2 (turns ratio of the transformer). Even though this voltage is different than the sum of the two-phase voltages, the voltage the receiver will see (less the losses in any hybrids). This same argument also applies to the currents, and the angle between the currents and voltages received is not changed passing through the splitter.

If the splitter doesn't remain balanced, then losses will be incurred through it in both directions (transmit & receive). If the two phases don't terminate in the same impedance, then losses occur due to current in the 25 Ω resistor. This is ok from the monitoring of voltage and current magnitudes as well as angle if the terminations are resistive.

The only quantity that hasn't been discussed is the splitters effect on the monitored reflected power. Again, as above, there is no affect if the two phases terminate the signal in the same impedance. Let's look at an example. If I terminate each phase in 25 Ω and we measure the reflected power in each of the phases they both will read 46%. Since the termination is the same for each phase then there is no current the 25 Ω balancing resistor and it is not seen in the circuit. Thus, it appears that the transformer is connected to two 25 Ω resistors in series or 50 Ω. The 50 Ω translates across the transformer to 25 Ω on the primary. If we now measure the reflected power at the PCM location, it will read 46% (the same as on each phase).

What happens to the reflected power if the terminations are not the same? What might we consider to be the worst-case situation? Let's consider a single-line-to-ground fault near the coupling capacitor. The assumption to make here is that the fault will appear as a short circuit across one output of the splitter. See to Figure 14.

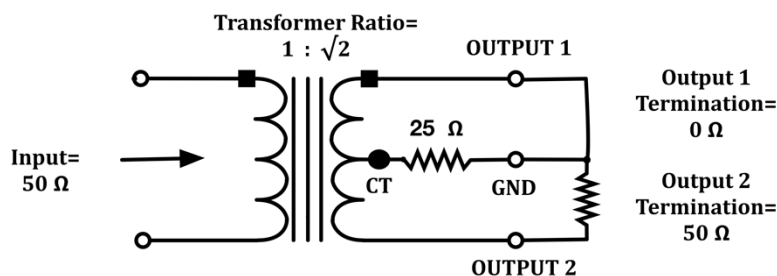


Figure 14 - Circuit for a Splitter with One Output Shorted

One half of the transformer is terminated with 25 Ω from output 1 to CT and the other half will be terminated in 75 Ω from output 2 to CT. There will also be an inter-action of currents from both outputs providing current in the 25 Ω resistor. Rather than attempt to simulate the results in a circuit analysis program it was decided to just measure it. The reflected power, if measured at output 1 is 100% and if measured on output 2 is 0%. The impedance at the input to the splitter is measured at 17 Ω at a 7.5° angle, which represents a reflected power of about 24%.

Now if on the other hand, the output 1 were an open circuit, then the measured impedance at the input to the splitter is 144 Ω at a 2.3° angle. Now the measured reflected power at the output of the PCM would read about 23%. In either of these cases the magnitude of the reflected power measured at the output of a PCM located as in Figure 12 is such that an alarm for reflected power in the PCM could be set at about 18% and alarm for either of these cases. The alarm is not sensitive enough to alarm for a mismatch of say 25 Ω on output 1 and 50 Ω on output 2. In this case the reflected power at the output of the PCM is only about 3% when the reflected power measured at output 1 will be about 11%.

The conclusion to take away from this conversation is that the application show in Figure 12 is acceptable for many carrier configurations. It can alarm for severe conditions on one of the outputs of the splitter transformer and it will correctly measure reflected power on the output of the phases on the line if both outputs are terminated in nearly the same impedance. However, if the user's requirements are critical and it is required to have an accurate representation of reflected power on both phases the circuit as shown in Figure 15 should be used.

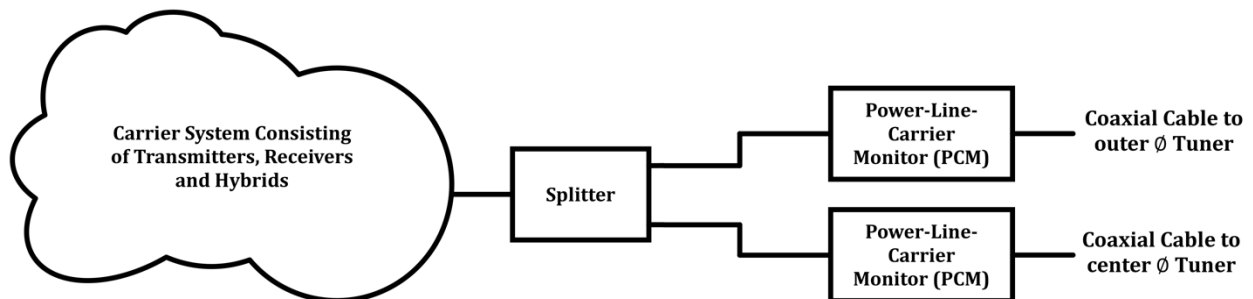


Figure 15 - PCM Configuration to Monitor Each Phase of a Phase-to-Phase System

A Mode 1 coupling scheme can get a bit more complicated to monitor since you are coupling to all three phases. Because of the added Splitter that is required to do Mode 1 coupling, I would suggest that the clearest information is obtained by using three PCMs and putting one in each phase prior to the line tuner. Figure 16 shows this configuration.

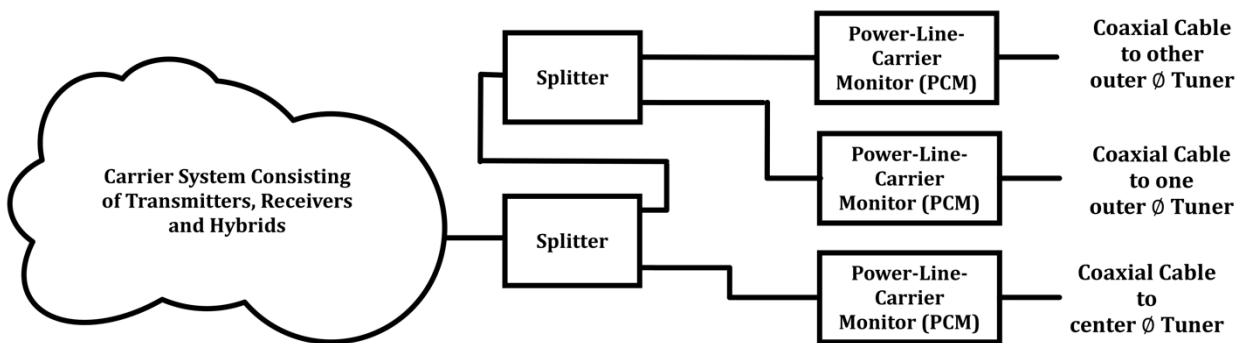


Figure 16 - PCM Configuration for Mode 1 Coupling

Application for Fully Redundant Coupling Schemes

When applying power-line carrier to EHV that are part of the bulk transmission systems, it is often considered that two redundant pilot protection systems be applied. There are many methods by which this can be accomplished. The issue to be considered here is the case where both pilot systems are on power-line carrier and coupled to the same line. Coupling schemes that are fully redundant (ie, no single component failure will but both systems out of service) may be required. This requirement makes for a much more complicated coupling system. Refer to Reference 3) for more information on this subject.

For this requirement, a single-line to ground coupling scheme will not be discussed since that system does not provide any redundancy at all. Phase-to-phase and mode 1 coupling will be discussed. Let's consider phase-to-phase coupling first. Figure 17 would be a design that would be considered a fully redundant coupling system. However, the same short comings apply here as

discussed in the non-redundant phase-to-phase coupling above with the PCM behind the balance transformer. In this case, the reflected power measurement will suffer since the monitor point is behind a combination of a splitter and a combiner (hybrid) the error becomes far greater than in Figure 12.

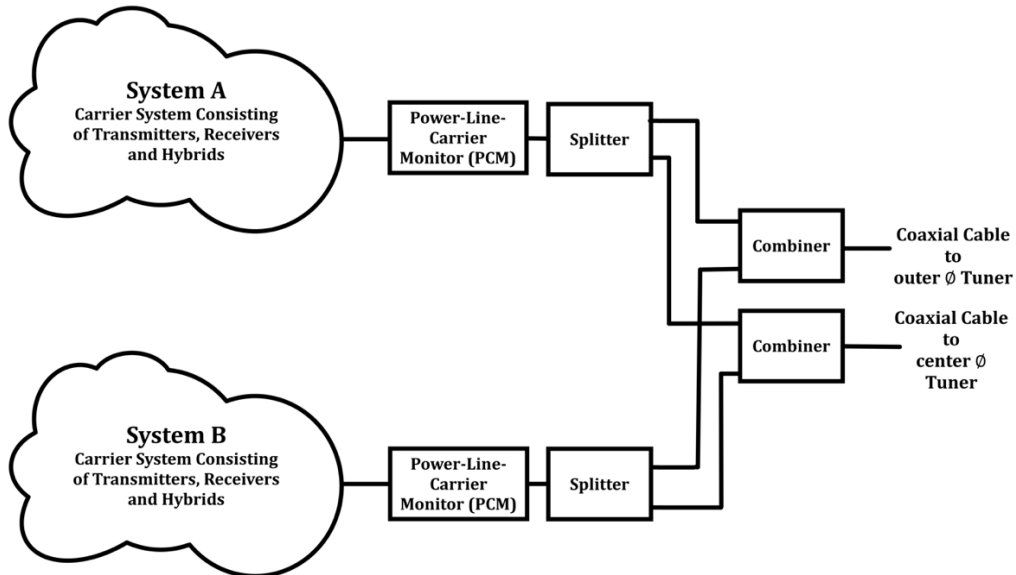


Figure 17 - Phase-to-Phase Fully Redundant Monitoring System

If for some reason **one is not going to measure reflected power**, Figure 17 would be the correct way to design the system. The reason this would be correct is that one PCM is monitoring system A and the other is monitoring system B. If on the other hand, one wants to monitor reflected power and obtain a correct reading you must change the position of the monitoring location to that shown in Figure 18.

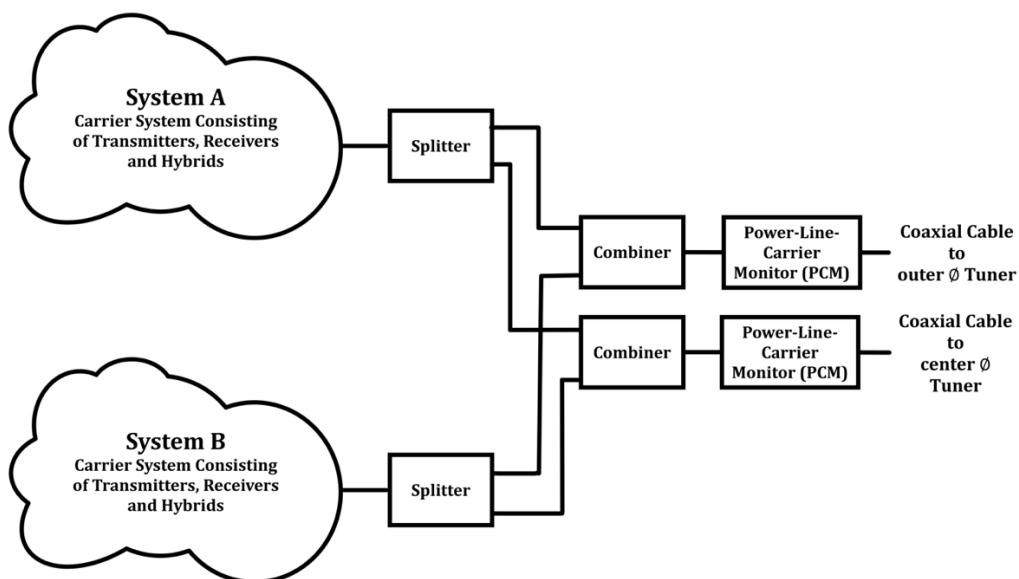


Figure 18 - Almost Fully Redundant Monitoring for Phase-to-Phase Coupling

Even though we can't call this scheme in Figure 18 fully redundant, it is as redundant as any system since the line tuner, coupling capacitor and line trap the PCMs are connected is no more redundant. A failure of anyone of those components will compromise both systems somewhat, but in most cases, will not cause a total failure of either protection system.

The input to output coax connector in the PCM will only have a current transformer in series with the center conductor and a voltage transformer across the coax center to shield. A failure of either of these units are the only components in the monitoring box that can compromise the system. These transformers, being very robust and passive components, add very little probably of failure to the overall probably of failure of the line tuner, coupling capacitor and line trap combination. So, the effect of having the PCM in the location shown in Figure 18 in terms of failure probably is very small.

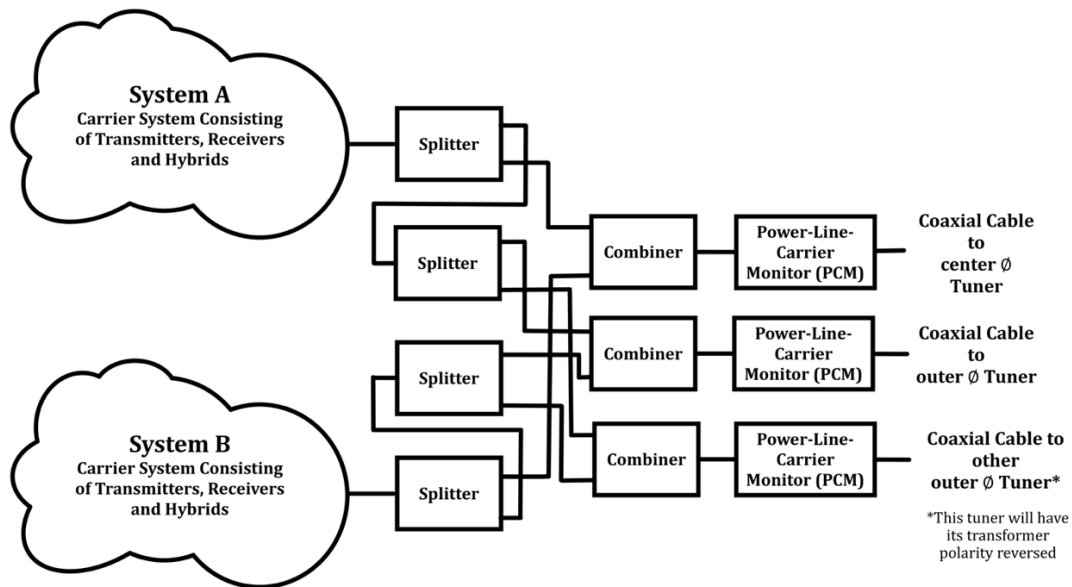


Figure 19 - Almost Fully Redundant Monitoring of Mode 1 Coupling

Figure 19 above shows how you would arrange the monitoring for a mode 1 coupling scheme. The same comments as stated above for the redundancy in Figure 18 also apply to the mode 1 coupling. Refer to Reference 3) for a detailed scheme showing transformer polarities and connections for the scheme on Figure 19

FIELD TESTING OF CONCEPTUAL DESIGN

PCM application Trial for Periodic Maintenance & meeting NERC requirements at Georgia Transmission Co.

In the past, periodic testing of pilot systems has been left up to the utilities. This has allowed the pilot systems to be in various stages of working order. Some utilities went overboard and were performing too much maintenance and others were neglecting their systems all together. In today's regulatory compliance led world this is no longer acceptable. While some minimum requirements have been set by the regulations, much of the up keep has still been left to the utilities (see Reference [4]). Only now, whatever your maintenance program, the government will audit the utilities to prove that your stated maintenance program is being implemented.

The maintenance process will typically involve testing of the relay and PLC system to validate the scheme is working correctly. This involves ensuring the correct settings are applied and the

inputs/outputs are functioning. Also, this means taking the schemes out of service, having people at both ends of the line, and taking various channel checks and reading levels. Once this information has been gathered and evaluated, the decision will be made whether to do further calibration on your traps and tuners. Maintenance on your traps require crews, man lifts and system outages. In all, the utility will have engineers/technicians and crews possibly tied up for days at a time depending on the size of the station that is due maintenance.

With a Power Line Carrier Monitoring System, periodic maintenance of your pilot schemes will become streamlined and more efficient.

Let's take for example a routine maintenance at a hypothetical Spring substation (see one line diagram in Figure 20) equipped with PCM's.

2017 Routine at Spring Substation

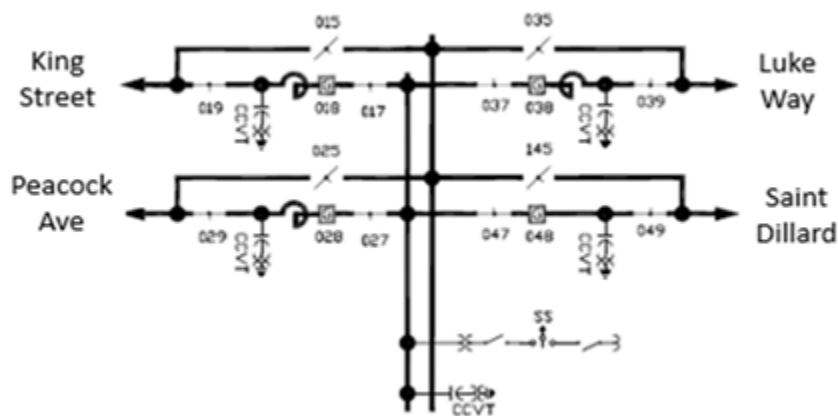


Figure 20 - One Line Diagram of Spring Substation

Three of the four transmission lines have Power Line Carrier.

Spring – King St 115kv Line has a DCB scheme.

Spring – Luke Way 115kv Line has a DCUB scheme.

Spring – Peacock Ave 115kv Line has a DCUB and TT Rx Scheme.

Spring – St Dillard 115kv Line is non-pilot and protected by Zone Protection.

All pilot schemes consist of the latest PLC equipment and microprocessor relays with remote access.

Each pilot scheme is equipped with a PCM.

For this discussion, the maintenance will be broken into two sections.

1. **The Control House** - This maintenance will consist of the checks on the relays and PLC equipment. This involves reading levels and setting margins to ensure the PLCs are in working order. Also, the inputs/outputs between the relay and PLCs are tested to be functioning correctly.
2. **The Field Equipment** - This maintenance will consist with the gathering of our channel quality checks, specifically, Reflected Power. It will also involve swapping signals with the remote terminal. This type of information will be used to determine if your tuner or trap needs attention.

The Control House

Spring – King St 115kv Line DCB Scheme

DCB Schemes using ON-OFF PLC equipment are required to have a periodic check back test. This test is done to verify the PLC set and the channel are in basic working order. A successful test verifies the PLC set is capable of keying/receiving a block signal which proves that the channel between the two stations is intact.

With a PCM, one can simply remote into the box and gather your first important piece of information. As can be seen from Figure 21 & Figure 22, the PLC set has successfully shifted from OFF to ON state for the transmitter and then a playback was received to verify the remote end.

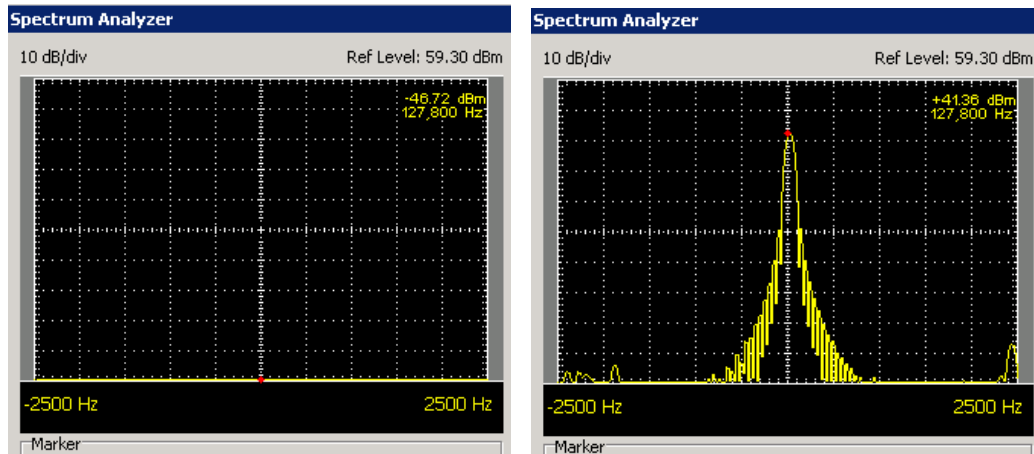


Figure 21 - Spectral Analysis of Transmitter in the OFF State & ON State

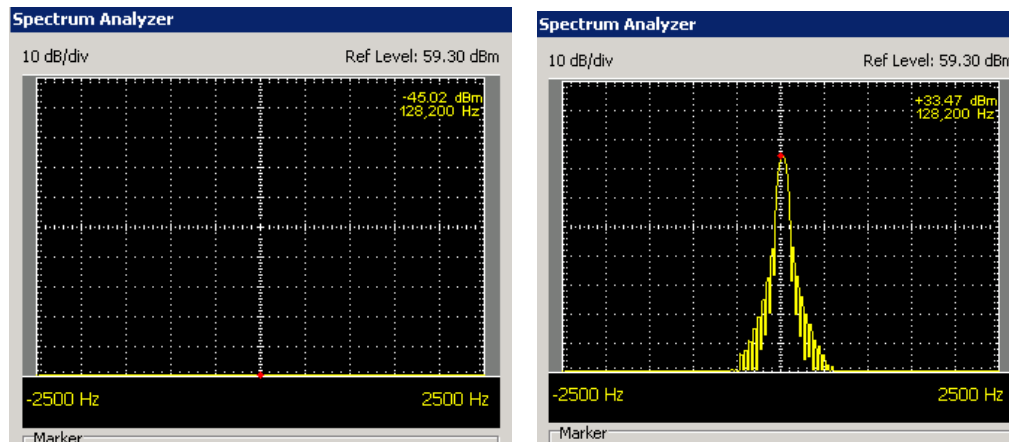


Figure 22 - The Corresponding Receive Signals

Spring – Peacock Ave 115kv Line DCUB Scheme

DCUB schemes have a normally “On” Guard Signal. With the PCM one can see the system shifting from Guard to Trip. Refer to Figure 23, Figure 24 & Figure 25.

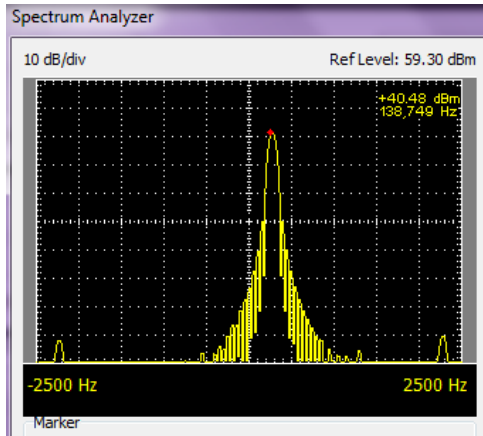


Figure 23 - DCUB in Guard

This spectral analysis was taken from a system event. The DCUB Transmitter is putting out a solid 10 watts at a 138.75 kHz guard frequency.

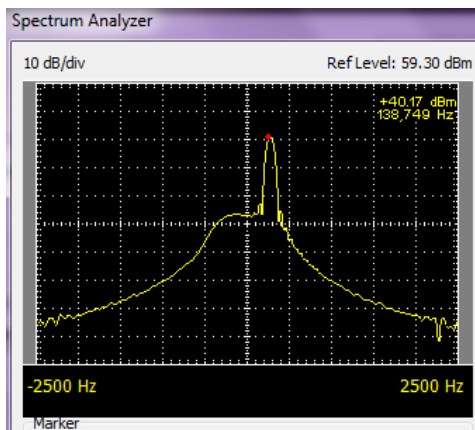


Figure 24 - Shifting to DCUB Trip

As a test is initiated, the radio is starting the shift from guard to trip. Information about the scheme can be gleaned from this event. For example, in the pilot relay, the actual relay output is exercised to the carrier set, where the actual input on the set is energized causing it to key. Essentially, the outputs and inputs associated with the correct functioning of the scheme is verified by the spectral analysis.

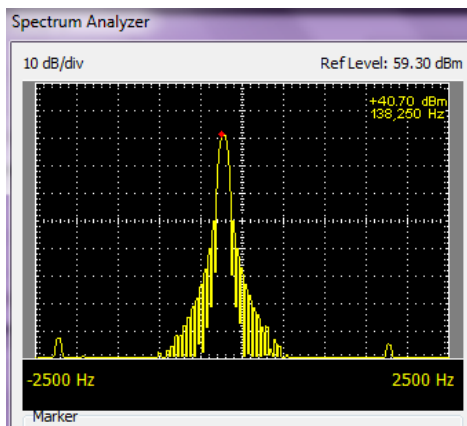


Figure 25 - DCUB in Trip

Here the radio completes its shift from guard to trip ensuring us that local end is functioning correctly. Depending on the type of event, there may be a companion receive event to go with this transmit event. Similar to the DCB scheme, an external check back system applied in the programmable logic of your pilot relay could be used to periodically check your input and outputs both locally and remotely.

Spring – Luke Way 115kv Line DCUB/TT Rx Scheme

DCUB Schemes have a normally on Guard Signal for transmit and receive. The Transfer Trip Receivers have good Guard Signals as well.

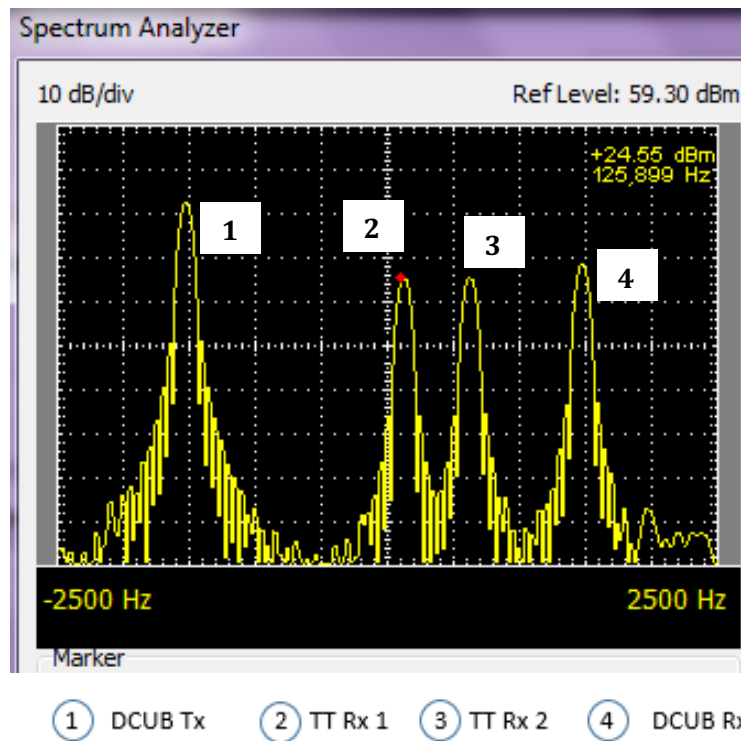


Figure 26 - Spectral Analysis Spring – Luke Way 115kv Line

This spectral analysis in Figure 26 captures the complete picture. It shows us the complete DCUB system and the two Transfer Trip receivers. These levels can be archived and used for future scheme evaluations.

Control House Conclusion

From actual events to check back tests, the schemes can be determined to have operated correctly. The inputs and outputs are validated. The spectral analyses show the carrier set is shifting and returning to normal. Levels are captured and archived. If data is gathered and maintained, some of your relay and radio maintenance can be avoided.

The Channel

Spring – King St 115kv Line DCB Scheme

Some of the basic readings and initial values were gathered from our Control House readings. To complete our checks of the pilot system involves taking reflected power readings. In the past, we submitted work requests to disable the schemes to insert our test equipment to take a reading. Now we simply remote in to the PCM and take actual in-service readings. A DCB scheme is normally off and it must be keyed to take a reflected

power reading. The PCM can key the radio by pulsing its output. It then can capture a reflective power reading.

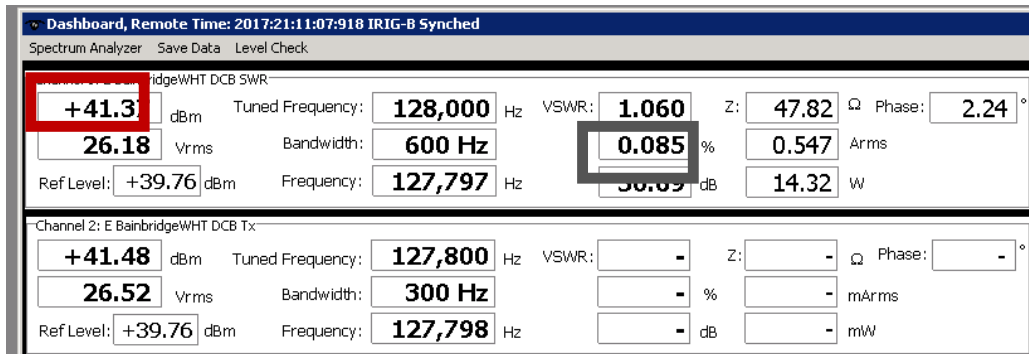


Figure 27 - In-service readings

Date & Time:		Notes:											
2016:06:08:17:29:12		PCM Cutin 6-8-16 Tx											
Channel	LEVEL			FREQUENCY			VSWR			IMPEDANCE			
	dBm	Vrms	Reference	Center	Freq	BW	Ratio	%	dB	Ohms	Arms	Watts	Phase
CH 1	+39.7	21.79	+39.76	128,000	127,797	600 Hz	1.049	0.057	32.41	47.66	0.457	09.96	0.17
CH 2	+39.76	21.79	+39.76	127,800	127,797	240 Hz	-	-	-	-	-	-	0.00

Date & Time:		Notes:											
2016:06:08:17:30:08		PCM Cutin 6-8-16 Rx											
Channel	LEVEL			FREQUENCY			VSWR			IMPEDANCE			
	dBm	Vrms	Reference	Center	Freq	BW	Ratio	%	dB	Ohms	Arms	Watts	Phase
CH 1	+32.85	9.817	+39.76	128,000	128,197	600 Hz	1.512	403.4	13.80	41.75	0.235	02.30	-159.26
CH 2	-35.88	0.003	+39.76	127,800	127,824	240 Hz	-	-	-	-	-	-	0.00
CH 3	+32.85	9.825	+32.83	128,200	128,197	240 Hz	-	-	-	-	-	-	-

Figure 28 - "As Left" Readings from Past Testing

As you can see from the above readings, the PCM can take an in-service reading that can be compared to a past "As Left" reading. If, for example, the reflected power changes by only a percent or two, it can be concluded that nothing significant has changed on your line, in your tuner, or with your line trap. If your initial equipment calibrations are documented correctly and the PCM is utilized, your maintenance for the above can be considered mute and unnecessary.

Periodic Maintenance Conclusion

Taking readings from a PCM takes a moment compared to the typical process of an engineer with a test set. One such maintenance interval for a single pilot scheme can save your company thousands of dollars.

So, in conclusion, a Power Line Carrier Maintenance device, if properly installed and maintained, can significantly reduce maintenance costs and scheme down times. Operations on your system will be easily identifiable and investigated. Proper "As Left" data can be used on any equipment trouble to help document and trend equipment issues. Proper trending with your spectral analysis could help utilities identify PLC issues that are the cause for system incorrect operations. The uses of a PCM will be only limited by your imagination.

PCM Application trial at Southern California Edison for Trouble Shooting PLC

Overview:

Southern California Edison's (SCE) Technical Support and Strategy (TS&S) group has performed a cost benefit analysis of permanently installing PCM's as a means of reducing the costs normally associated with the maintenance, operation and troubleshooting of our Power Line Carrier (PLC) schemes. SCE has determined that the costs related with maintaining and troubleshooting their PLC schemes have been increasing, largely due to the attrition rate of qualified technicians who have the necessary background and experience required to work on PLC systems. They've also determined that when their high-speed PLC protection systems are out of service, especially for extended periods of time, there are increased risks of clearing faults with the back-up protection systems.

SCE recently applied a PCM to one of its PLC systems, to explore ways to begin to reduce the costs of maintaining its PLC systems, and to provide continuous monitoring of the health of its PLC systems. They were intrigued by the ability of a PCM to provide a passive, non-evasive, method of capturing the carrier signal's spectral data. Further, they wanted to evaluate if applying a PCM would allow them to consider their PLC systems to fully-monitored, as a means of extending the maintenance intervals for their PLC systems.

Evaluation of a PCM:

SCE's Technical Support and Strategy group first evaluated the setup and operation of a PCM in their laboratory, located in Pomona, CA. While they could demonstrate some of the basic functionality of a PCM in their laboratory, it soon became apparent that their laboratory environment did not contain all the necessary, real world components of a true PLC system (line tuners, line traps, transformer hybrids, skewed hybrids, etc.). They soon determined that it was time to take the next step, and apply a PCM on one of their PLC systems. They also felt that even more ideal would be to apply a PCM to one of their PLC systems that had a history of reliability issues.

As luck, would have it, SCE's Substation Test group had been having issues in troubleshooting a power line carrier direct transfer trip (PLC-DTT) protection system applied to its Antelope – Whirlwind 500 kV transmission line. Refer to Figure 29 for the PLC connections. The PLC-DTT system had been producing spurious Trip Received signals from one of its two transmitter-receiver sets. These spurious Trip Received signals were being received at just one of the line terminals, specifically at Antelope. Unfortunately, there have been cases when this PLC-DTT system has incorrectly operated, tripping open the Antelope – Whirlwind 500 kV line at both ends, when spurious Trip Received signals were received at Antelope from both of this PLC-DTT' receiver.

Interestingly, in each case when the spurious Trip Received signals had been received at Antelope, there were no indications of the corresponding Trip Sent signal being sent from the opposite Whirlwind line terminal. This spurious Trip Received signal issue had been going on for well over two (2) years, and during that time, many different Test crews had spent time on site, troubleshooting this issue. This spurious Trip Received signal at Antelope has resulted in this PLC-DTT being removed from service for over two years, now. Fortunately, in accordance with SCE's standards, there's a second direct transfer trip system applied to this same 500 kV transmission line, which utilizes digital

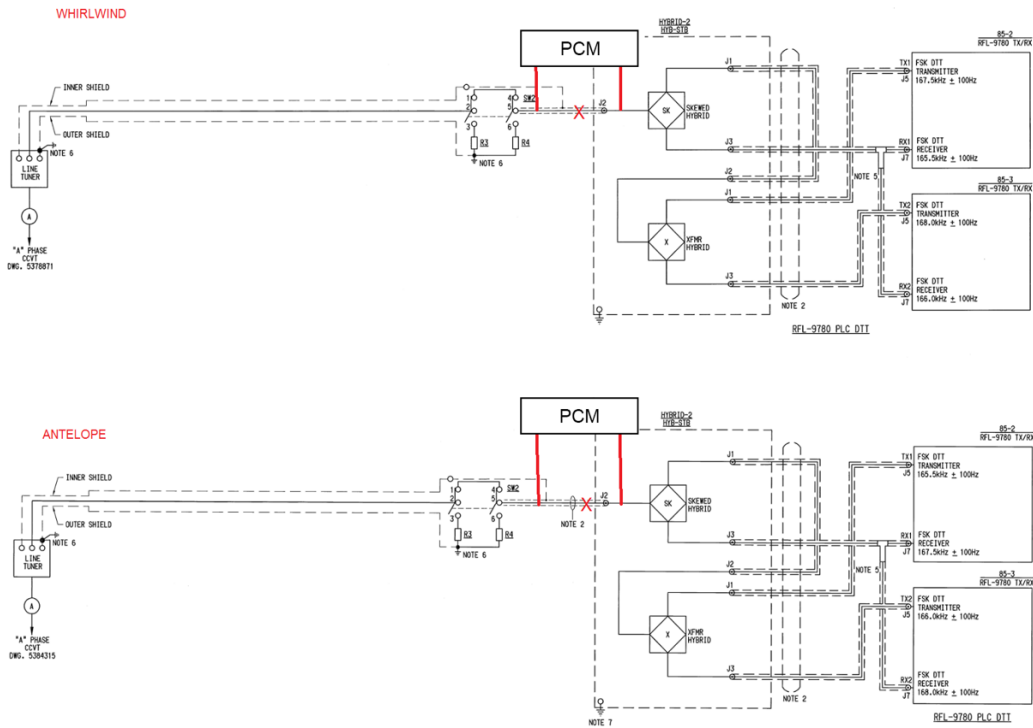


Figure 29 - SCE's Antelope-Whirlwind 500 kV PLC-DTT System Connections

microwave communications, commonly referred to as MW-DTT at SCE. Thus, even though this 500 kV line's PLC-DTT system has been out-of-service for more than two years, this same line's MW-DTT system has remained in-service, providing the direct transfer trip capabilities for this line.

As a last-ditch effort, SCE sent the transmitter/receiver units from this Antelope – Whirlwind 500 kV's PLC-DTT system back to the vendor, with the hopes that they could find some type of issue with their transmitter/receiver units. Unfortunately, they found no issues with these transmitter/receiver units, and they returned these units back to SCE. This Antelope-Whirlwind 500 kV PLC-DTT system has been out-of-service for over two years

Considering the above, SCE's TS&S group felt that this Antelope – Whirlwind 500 kV PLC-DTT system would be an ideal candidate to evaluate a PCM. The unreliability of this PLC-DTT system has cost SCE many man-hours of troubleshooting, operations switching cost, and the loss of one of the protection schemes on an in-service 500 kV transmission line. It was felt that applying a PCM to this PLC-DTT system would provide benefits because of the real-time data capture, and might even help SCE's Test crews to resolve the unreliability issues with this PLC-DTT system.

Pilot Application of a PCM:

In early 2016, SCE's TS&S group began their pilot evaluation of a PCM, as they worked together with field Test crews to install a PCM at each end of the Antelope – Whirlwind 500 kV line's PLC-DTT system. Figure 29 shows that at both Antelope and Whirlwind, a PCM was installed in series with the tri-axial cable connected between the hybrid combiner unit and the line tuner.

Looking back at the event records from this PLC-DTT system, it soon became apparent that there was no particular time of day that the Trip Received signals were being received at Antelope. In order to provide an accurate time stamp of the data to be recorded by these PCM's, a GPS receiver's IRIG-B time synchronization was connected to each PCM.

It was hoped that the PCMs would provide the ability to observe some of characteristics of the power line carrier signal, such as transmitted power, received power, and reflected power. Once these PCMs were installed and powered up, it was noted that these they the capability to monitor these three (3) characteristics of a power line carrier signal, along with many other characteristics (refer to Figure 27).

Capturing these power line characteristics over time allows detailed analysis to be performed, which may help to determine the cause of erroneous trips which occur due to spurious noise, intermittent loss of signal, etc. Further, the ability to store these power line characteristics, as they occur over a 24-hour time period throughout the year, can be very helpful in the effort to maintain the reliability of these power line carrier systems.

Data Collection and Analysis:

SCE's TS&S group has been taking advantage of the storage capabilities of these PCMs, in order, to capture event records stored within these two (2) PCM's.

"ID","Date","Time","FFT","Channel","Description"
"20","04/15/2016","16:46:27:267","0","0","RF Voltage in Range"
"19","04/15/2016","16:46:26:519","0","0","RF Voltage Overload"
"18","04/15/2016","16:44:58:887","0","0","Configuration Access"
"17","04/15/2016","16:44:58:615","0","0","Account Login admin"
"16","04/15/2016","16:00:31:457","0","5","85-3 FSK DTT RX Low Freq: GUARD"
"15","04/15/2016","16:00:30:783","1","5","85-3 FSK DTT RX Hi Freq: TRIP"
"14","04/15/2016","15:51:33:048","1","3","85-2 FSK DTT RX Hi Freq: GUARD"
"13","04/15/2016","15:51:32:349","0","3","85-2 FSK DTT RX Low Freq: TRIP"
"12","04/15/2016","15:32:19:109","0","1","85-2 FSK DTT TX Reflected OK"
"11","04/15/2016","15:32:18:900","0","5","85-3 FSK DTT RX Low Freq: GUARD"
"10","04/15/2016","15:32:18:900","1","3","85-2 FSK DTT RX Hi Freq: GUARD"
"9","04/15/2016","15:27:46:509","1","1","85-2 FSK DTT TX Reflected O/R"
"8","04/15/2016","15:27:46:309","1","5","85-3 FSK DTT RX Signal O/R: Low"
"7","04/15/2016","15:27:46:309","1","3","85-2 FSK DTT RX Signal O/R: Low"
"6","04/15/2016","13:09:46:452","0","0","Timed Account Logoff: admin"
"5","04/15/2016","12:41:59:102","0","0","IRIG-B Synch"
"4","04/15/2016","12:40:31:709","0","0","Configuration Change"
"3","04/15/2016","12:40:30:239","1","3","85-2 FSK DTT RX Hi Freq: GUARD"
"2","04/15/2016","12:40:30:237","1","2","85-3 FSK DTT TX Low Freq: GUARD"
"1","04/15/2016","12:38:56:021","0","0","IRIG-B Unsynch"
"0","04/15/2016","12:36:59:567","0","0","Audit Log Cleared"

Figure 30 - Example Event Records of a from SCE's Antelope Substation

The event records typically captured by a PCM (Figure 30) have allowed the end-user to observe time-tagged operational characteristics of their respective PLC system, in this case, for SCE's Antelope – Whirlwind 500 kV line's PLC-DTT system. For the Antelope – Whirlwind 500 kV line's PLC-DTT system being monitored by two (2) PCM's, the results have been very typical for thirty-six hundred (3,600) individual event records to be recorded over a forty (40) day period.

In addition to the ability of a PCM to capture and store these type of event records, a PCM also has the capability to capture and store Fast Fourier Transform (FFT) displays of the power -line-carrier signal being monitored. Figure 23, Figure 24 & Figure 25 show some examples of these types of FFT displays, and this set of three (3) displays shows the shift of one of the transmitters within SCE's PLT-DTT system from guard to its respective trip frequency.

Preliminary analysis of both the event and FFT data captured by the two (2) PCM's installed on SCE's Antelope – Whirlwind 500 kV line's PLC-TT system has shown a very distinct possibility of flashovers occurring across the drain coil's spark gaps applied on this PLC-DTT's system. The data captured by these PCM's show an intermittent loss of guard signal occurring at the Antelope line terminal. The addition of the GPS receiver's IRIG-B signal to these two (2) PCM's has proven to be extremely valuable, since these events have been shown to be very frequent and unrelated to weather. Further detailed analysis of the event records and FFT displays from these PCM's have shown that the likely source of these events is a result of power line noise, which is a result of the switching of power-factor correction capacitor banks applied to the solar and wind power generation installations, which are installed very close to the right-of-way of SCE's Antelope – Whirlwind 500 kV transmission line.

SCE is presently working together with the vendor of the transmitter/receiver equipment applied to its Antelope – Whirlwind 500 kV line's PLC-DTT system, to explore ways to modify some of the operating characteristics of their transmitter/receiver units, to make this PLC-DTT system more resilient to the above sources of power line noise. The decision to install a PCM at both ends of their Antelope – Whirlwind 500 kV line's PLC-DTT system has provided SCE's TS&S group with the technical data they needed to determine the cause behind the reliability issues they had been having with this PLC-DTT system.

CONCLUSIONS

A PCM type device provides the user a new tool to monitor, maintain and troubleshoot a power-line-carrier system used for system protection. The combination of extending maintenance cycles and monitoring the system for unexpected changes typically recovers the cost of the device in a relatively short time and helps the user better comply with NERC standard PRC-005-002 [4]. The event logs/alarms, trending and event driven spectral analysis provide long term monitoring of the system for years and a means for avoiding and/or evaluating misoperations that may occur in the future. This independent monitoring device provides the user added confidence that valuable information will be available (without the need for line outages) when needed to provide direction to a possible solution and cause of the problem.

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- 3) IEEE PSRC Working Group Report, "Redundancy in Coupling Power Line Carrier Channels to the Power Line", WG 15, 2011
- 4) NERC Standard, PRC-00502, "Protection System Maintenance"

AUTHOR BIOGRAPHY'S

Robert Baldwin

Robert received a B.S.E.E. from California State University, Long Beach in 1982, and an M.S.E.E. from California State University, Los Angeles in 2007. He's spent over 32 years at Southern California Edison (SCE), holding positions of Substation Electrician, Test Technician, Shop Engineer, Protection Engineer, Operations Trainer, Test School Supervisor, and most recently, Senior Technical Specialist in their Relay / Test group. During his tenure at SCE, his primary focus has been with the application, setting and testing of protective relays, power line carrier systems, and digital fault recorders. Robert is a past Chair of the Georgia Tech Transient Recorder User's Council.

Jeffrey Brown

Graduated 1997 with a Bachelor of Science in Engineering from Georgia Tech University. After graduation, he worked for Georgia Power for 25 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 the author of Power Line Carriers: Simplified.

Ray Fella

Ray received his Bachelor of Science in Electrical Engineering in 1987 from Rutgers University in New Brunswick, NJ. He has spent his 30-year career supporting the Electric Utility System Protection Communications industry. In 2001, he joined PowerComm Solutions, LLC as Business Development Director where he received his first patent. Prior to PowerComm Solutions, he worked for Signalcrafters and started his career with INIVEN. He is a 28 year member of IEEE, a member of the Power and Engineering Society, as well as number of working groups.

Alan Jayson

Alan has spent the last 31 years designing various audio tone and power line carrier communication and instrumentation products for the Electric Utility system protection industry. He started his career in 1986 with INIVEN, where helped design protection communication systems that are still in use today. In 2012 he joined PowerComm Solutions as lead design engineer and prior to that worked for Signalcrafters for 14 years. He is also a patent holder.

Roger Ray

Roger received a BS in Electrical Engineering at the Pennsylvania State University in 1964 and an MS degree at the New Jersey Institute of Technology in 1976.

He is a member of the IEEE and a member of the Power & Energy Society and the Communications Technology Society. He is past Chairman of (what was then) the IEEE Power System Communications Committee and is presently Chairman of the Power Line Carrier Subcommittee of the PSCC. He is also a member of the Power System Relaying & Control Committee. In the year 2000, he was also elected as a Fellow in the IEEE.

He is an author of two chapters in the Westinghouse Applied Protective Relaying Book. He authored several papers in his major fields of pilot relay systems and power system communications. These papers have been presented at major relay conferences around the country as well as conferences outside the US. He, along with co-author Shan Sun, received the IEEE Power Engineering Society Prize Paper Award for 1983 and he holds five patents in the US on subjects covering phase comparison relaying, power line carrier, and fiber optics.

Neil Stone

Neil received his BSEE - ITT Technical Institute, San Diego 1998 and PMP Certification - University Of Irvine Ca, 2010. He is also an IEEE Member.

Neil's work experience includes the following: Sony Corp, applications engineer, RF CDMA deployment with Qualcomm (3 years), Pentadyne Power, applications engineer, commercial flywheel UPS systems (4 years), ABB - Power One, field engineer, commission commercial UPS systems (4 years), Southern California Edison - Nuclear Test (3 years), Nuclear Startup Engineer (2 years), Nuclear Maintenance General Foreman (3 years), Southern California Edison - Technical Specialist / Scientist for Transmission & Distribution, Startup Engineer (3 years) and is currently working with Southern California Edison as Technical Manager for Transmission & Distribution, Relay Test and Technical Support (2 years).