Characteristics of Line Tuner and Line Trap Failures in Carrier Relaying Channels

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***Abstract*— Continuous monitoring data from power line carrier (PLC) relaying channels has been used to identify line trap and line tuner failures in real-world installations. This paper compares PLC coupling circuit simulations to the data collected in real-world installations. Coupling circuits are opened or shorted at key points while observing changes in impedance magnitude, impedance phase angle, reflected power, voltage, and current at the line tuner input. The measurements are analyzed and compared with field data to determine which, if any, may provide a convenient means for discerning between certain failure modes. Finally, the paper demonstrates how utilities can apply the insights in practical field installations.**

Keywords—power line carrier; PLC; line tuner; line trap; phase angle; reflected power; impedance matching; continuous monitoring

I. Introduction

Power line carrier (PLC) systems provide a critical link between protective relays and associated control devices at opposing ends of a high-voltage transmission line. They are one type of "pilot protection" channel, used to transfer high-speed protection signals between substations. These signals are a key component of the speed, security and selectivity required for the high-speed line protection schemes that ensure the stability of the transmission grid.

Ensuring and maintaining the availability of these circuits is an important aspect of reliable grid operations. To that end, any communication alarms must be investigated and addressed with an urgency not found in less critical circuits. Key to the overall success of a utility in this regard is the availability of good data to direct engineers and technicians to the problem areas quickly.

A reliable metric for monitoring the quality of the channel is therefore desirable. For PLC circuits, "reflected power" measurements have been widely used since the early 2000's as a component in monitoring the quality of the PLC channel [1][2]. Recently, PLC-specific monitoring devices have become available which look at not only reflected power but also the complex impedance at the point of coupling. In fact, these two are closely related – the relationship of this impedance to the nominal system impedance ultimately determines the reflected power value [3].

Both measurements provide a good indication of the impedance matching quality of the PLC channel. Field investigation has suggested that complex impedance may provide information that is missing in reflected power measurements [3][4]. This paper follows up on the field tests using simulation and analyzes the results.

II. Background

A. Impedance Matching Overview

Before presenting an overview of carrier systems, a basic discussion of impedance matching is in order. The maximum power transfer theorem states that an electrical network consisting of a complex source and a complex load is "matched" when the load impedance Z_L is equal to the complex conjugate of the source impedance Z_S, or when:

$$R_S + jX_S = R_L - jX_L \tag{1}$$

where R and X are the real and reactive components of a complex impedance Z. In practical applications, the load and source impedances are rarely matched all by themselves. For most cases a matching network is required, as shown in Fig. 1.

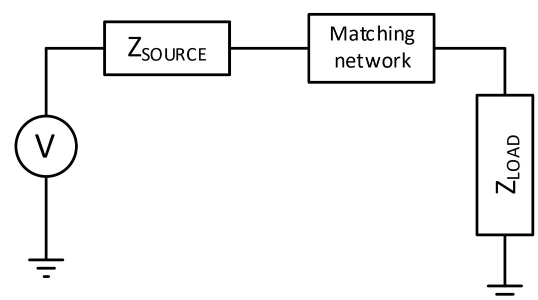

Fig. 1. Source and load impedance with matching network in-between

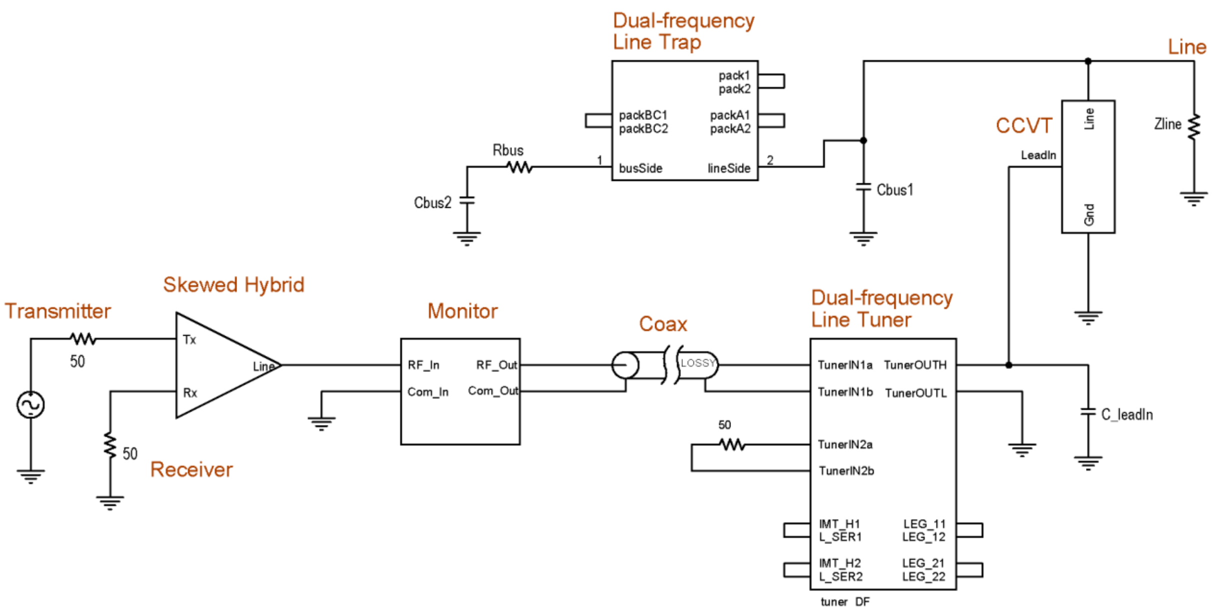

Fig. 2 Simplified PLC channel and overview of simulation test setup

The maximum power transfer theorem also states that when the load and source impedances are matched, the power transferred from the source to the load is *maximized*, and the power reflected from the load back to the source is *minimized*; these may be considered ideal operating conditions. In PLC relaying channels, matching is typically performed by the line tuner.

B. Power Line Carrier – Channel Overview

An example PLC circuit is shown in Fig. 2 (also a simplified view of the circuit used in simulations). The figure shows a single end of the PLC channel, i.e., at one substation. A full PLC channel encompasses the equipment at both ends of the transmission line as well as the line itself. The major components found at each station are typically:

- *Transmitter/receiver:* generates and/or receives the protection signals, monitors transmit and/or receive levels, signal-to-noise ratio, reflected power level
- *Hybrids:* combine signals while providing isolation between transmitters and receivers
- *Coaxial cable:* the connection from the control house equipment to the line tuner in the substation yard
- *Line tuner:* matches the impedance of the equipment in the control house with the CCVT and line impedance
- *CCVT:* provides the carrier signals with a low-voltage connection point to the high-voltage transmission line; resonates with line-tuner components to achieve impedance matching
- *Line trap:* minimizes the influence of the substation bus on the carrier system
- *Transmission line:* the 3-phase power line on which the carrier signals travel from one substation to another

C. Line Tuner

In terms of impedance matching, the line tuner can be considered as a sort of demarcation point. The tuner matches the equipment-side (to the left of the tuner in Fig. 2) with the line-side impedance (to the right of and above the tuner in Fig. 2). The CCVT is not a part of the line impedance itself, but it is in-series with the line impedance, so it is considered as part of the termination impedance when looking "out of" the line tuner towards the line.

The net impedance of the CCVT and power transmission line (including the trap and the bus) is typically capacitive and has a real component generally in the range of 200 – 600 ohms, shown in Fig. 3 as Z_{LOAD}. If $R - jX$ represents the net line-side impedance, the tuner must offer a range of $R + jX$ which can provide the matching network. When the impedances on either side of the tuner are matched, the input to the line tuner presents an impedance of 50 Ω and 0° [5].

Fig. 4 shows typical single-frequency and wideband line tuner configurations. The two components which are most responsible for matching are the series inductor (Ls1 Fig. 4) and the impedance matching transformer (IMT), whose input is Lpri1 in Fig. 4. The series inductor compensates for the capacitive reactance of Z_{LOAD}, bending the impedance vector back towards the real axis in Fig. 3. The IMT adjusts the real component to match it to the 50 Ω equipment impedance. Fig. 5 shows a dual-frequency tuner which can couple two carrier channels.

D. Line Trap

If the line tuner matches the impedances between its input and output, the line trap isolates the matched carrier system from changes and external influences. It also contains the carrier signals between the line terminals – minimizing the carrier energy that enters the substation bus, where it is not wanted, and attenuating spurious signals and other interference on the bus that may enter the transmission line and carrier system.

The line trap is essentially a large inductor with tuning components in parallel. The main inductor coil passes the 60 Hz line current while the combination of inductor coil and tuning components blocks the carrier signals, "trapping" them within the transmission line. The types of traps typically match the type of tuner for a given installation; examples of line traps are shown in Fig. 6 (single-frequency and wideband) and Fig. 7 (dual-frequency).

Whether they occur in or around the tuner, or in the line trap, equipment failures can alter the balance between impedances and matching; the system becomes mismatched, and the tuner input impedance reading changes. Types of tuner failures may be tuner connections or components going *open* or *short to ground.* In a line trap, a failure may be the *opening* of connections to its tuning packs, or opening of the tuning pack itself, allowing the bus to have more influence on the line-side impedance, changing the reading at the tuner input. In this sense the tuner input impedance carries a signature of the conditions which cause it.

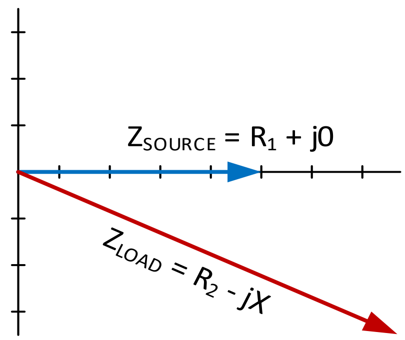

Fig. 3. Typical mismatch between the equipment-side (blue) and line-side (red) impedances (not to scale). The line tuner matches Z_{LOAD} to Z_{SOURCE}

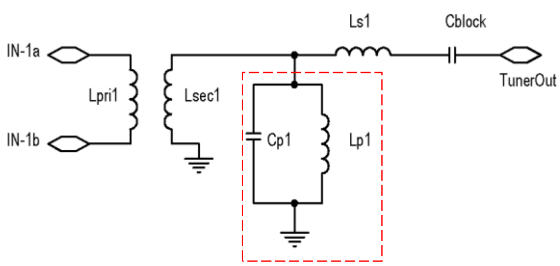

Fig. 4. Wide-band line tuner (for single-frequency tuner, Cp1 and Lp1 are not installed)

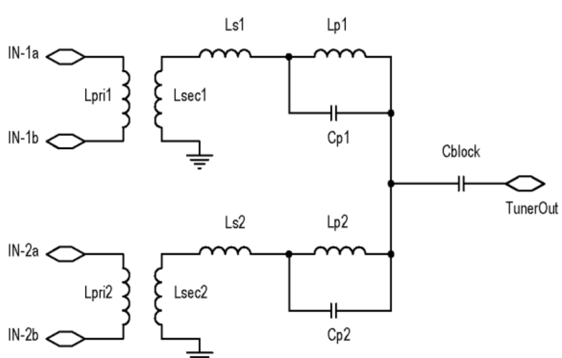

Fig. 5. Dual-frequency line tuner

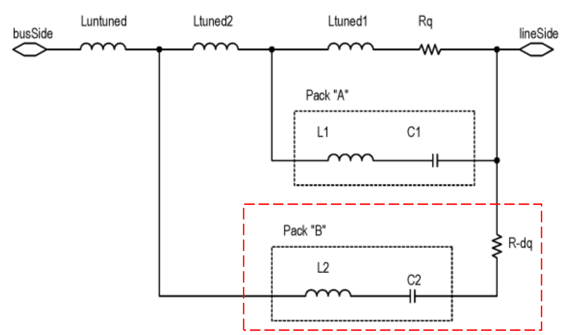

Fig. 6. Wide-band line trap (for single-frequency trap, R-dq and Pack "B" are not installed)

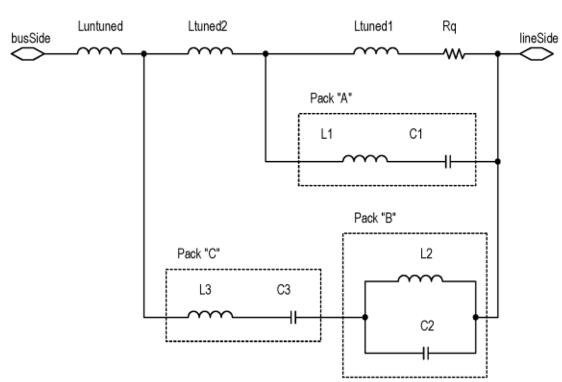

Fig. 7. Dual-frequency line trap

E. Monitoring the Impedance Matching

The input to the line tuner, therefore, is the primary location to monitor the quality of the impedance matching. To do this, manufacturers of transmitter devices have provided utilities with a "reflected power" measurement which is dependent on the termination impedance Z_{TERM}. The reflected power is related to the input impedance of the tuner by the following equations:

$$\rho = \frac{Z_{TERM} - Z_{SOURCE}}{Z_{TERM} + Z_{SOURCE}} \quad (2)$$

$$RP_{(\%)} = 100 * \rho^2 \quad (3)$$

where Z_{TERM} is the impedance looking into the tuner input and Z_{SOURCE} is 50 Ω, 0° [5]. The equations demonstrate the dependence of reflected power on Z_{TERM}. Fig. 8 demonstrates the relationship graphically.

III. Test & Simulation Setup

To investigate tuner and trap failures and their influence on the steady-state impedance measured at the tuner input, the systems were modeled and analyzed using PSPICE and MATLAB. Fig. 2 shows an overview of a simplified dual-frequency setup. Line tuner connections were either *opened* or *shorted to ground* at points of interest; similarly, line trap connections to tuning packs were opened at points of interest. To compare the results to practical field measurements, a simulated carrier monitor was placed between the skewed hybrid and the coaxial cable connection to the line tuner.

Tests were performed using single-frequency, wideband, and dual-frequency systems; models were created for all three cases. Further, the tests were run using different carrier frequencies to get a sense of the influence of frequency on the results. The frequencies used were 100 kHz, 150 kHz, and 200 kHz. In all cases the tuner and trap components were configured or "strapped" according to the manufacturer's recommendations [6-11]. Tables I and II show the tests run and the circuit locations of the simulated failures.

To benchmark the simulation circuit design, results were compared against the field measurements that kicked off the investigation. A reasonable "fit" was obtained with coaxial cable and several parasitic capacitances known to interact with carrier systems [5]. A comparison of results is displayed in Fig. 9, showing a fairly good correlation between measurements.

Field results were obtained with a wideband setup at 136 kHz; simulated results were obtained with a wideband setup at 150 kHz. The process demonstrates how field measurements of failure states can be used to characterize the reactive components of the local carrier network; the resulting simulated circuit is a powerful tool to analyze failure conditions that may occur in the future.

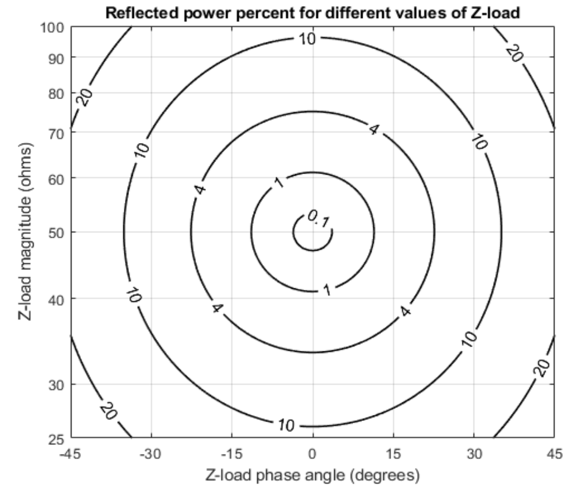

Fig. 8. Contour map of complex impedance Z_{LOAD} versus reflected power for Z_{SOURCE} = 50 ohms, 0 degrees

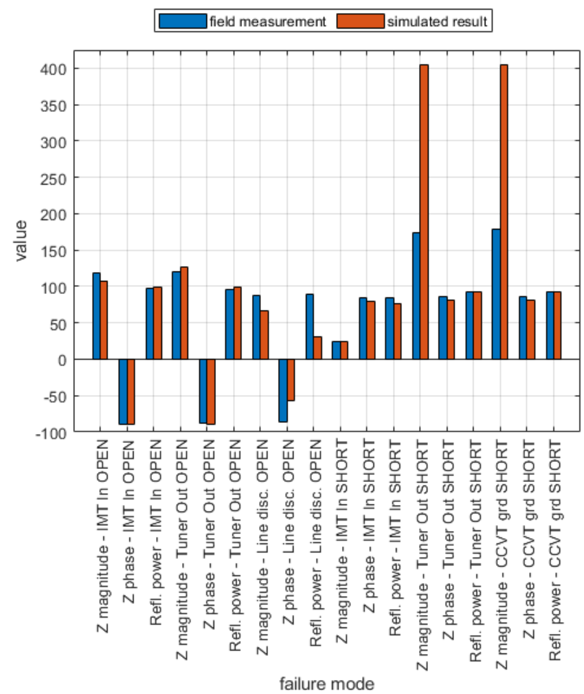

Fig. 9. Comparison of simulated versus field results, open/short connections in line tuner.

A. Locations chosen for testing

Points chosen for the line tuner testing are:

- *IMT in:* input to the impedance matching transformer
- *Ls out:* connection out of the series inductor, Ls1 or Ls2

- *Line:* the connection to the CCVT lead-in cable, from the output of the blocking capacitor *Cblock*; this is the location of the tuner ground switch
- *CCVT:* input of the lead-in cable to the CCVT / drain coil connection; in a real CCVT, this is the location of the CCVT ground switch

Points chosen for the line trap testing are:

- *All packs:* the connection from the main coil to all tuning packs
- *Pack A only:* only the connection to "Pack A" in Figs. 6 and 7
- *Pack B / Pack BC:* only the connection to "Pack B" or "Pack BC" in Figs. 6 and 7, respectively

B. Method of Measurement and Objectives

To make the measurements the simulations were run to steady-state, at which point a time-delayed switch was operated. The switches were configured to either *open* a series connection or *short to ground* a node at key points in the circuit. Voltage and current measurements were made at the monitor to determine the impedance magnitude and phase angle. Then using (2) and (3) the reflected power was calculated as:

$$RP\% = 100 * \left|\frac{(Z_{MAG}\cos\theta \ + jZ_{MAG}\sin\theta) - Z_{SOURCE}}{(Z_{MAG}\cos\theta \ + jZ_{MAG}\sin\theta) + Z_{SOURCE}}\right|^2 \quad (4)$$

where Z_{MAG} is the magnitude of the measured tuner input impedance, θ *(theta)* is the measured phase angle of the impedance, and Z_{SOURCE} is equal to 50 Ω at 0° ($\theta = 0$). Fig. 8 shows the reflected power for a range of Z_{LOAD} from 25 to 100 ohms and -45 to +45 degrees.

The primary objective of the testing was to observe changes to the tuner input impedance magnitude and phase angle under different failure conditions of the tuner and of the trap, and to see which measurements provide the best indication about the nature of the failure. A secondary objective was to observe the transmitter current into the tuner under different trap failure scenarios; some literature indicates that the transmitter current may be a very good indicator of trap failure; specifically, that the current out of the transmitter will increase when the trap fails [12].

IV. Test Results

A. Line Tuner Tests

Results of the line tuner simulations are shown in Fig. 10 (use Table I to see what failure condition is represented by the test numbers in Fig. 10). For each measurement in Fig. 10, three sets of data are shown: *open* failures, *short* failures, and normal values when the system is healthy. A measurement which is a good indicator of an open versus short circuit would clearly and consistently deviate from "normal" for all tests, and would deviate in opposite directions from "normal" for "open" versus "short" tests.

By these criteria, the impedance phase angle is the only measurement that presents itself as a reliable indicator of the type of tuner failure. The impedance magnitude, counterintuitively, can *increase* for a short circuit failure (when the short is on the line side of the tuner). Reflected power does show a significant deviation from "normal" but there is no way to reliably distinguish between a short and open failure – the values simply increase. Phase angle, meanwhile, moves distinctly towards +90° for short-circuit failures, and distinctly towards -90° for open-circuit failures.

For shorts and opens inside the tuner and on the equipment-side of the tuner (tests 1-18) the predominant circuit element contributing to the impedance value appears to be the coaxial cable. Several factors involving the coaxial cable, therefore, have an influence on the impedance measured for different failures: the length and type of coax, as well as inductive and/or capacitive coupling between the coax and other cables running alongside the coax from the control building out to the tuner.

For shorts on the line-side of the tuner, it is the tuner components themselves that are the dominant circuit elements presenting the impedance to the transmitter. If the line-side connection of the 60-Hz blocking capacitor is shorted (*Cblock* in Fig. 4 and Fig. 5), a path for the current still exists through the tuner; however, with the CCVT out of the circuit, there is no longer a tuned circuit at the center frequency, and the impedance seen by the transmitter is significantly affected.

For opens on the line-side of the tuner, the coax cable and the capacitance of the bus and lead-in cable appear as the dominant circuit elements causing the very negative phase angle.

An important insight in running the tests and comparing with field data and circuit analysis is that while the general features of these failures will be similar from site to site, the exact values measured in each failure state will vary with the characteristics of the site: length of coax, exact tuning of circuit elements in the tuner, lead-in capacitance, and bus capacitance, to name a few. The phase angle will have the same trend, but its exact value and the value of the impedance magnitude will vary from site to site.

A test or monitoring device, therefore, which can record the exact values of the impedance in the failure states can provide a quick reference if the failure occurs in an operational context. The line tuner short/open tests are straightforward to perform in the field at time of commissioning or maintenance; if the measurements are recorded then the operational alarm or failure state may be quickly compared to the reference states.

TABLE I. TEST NUMBER REFERENCE BY TYPE OF TEST – LINE TUNER

Fail-Open or Short	**Frequency and Line Tuner Type**								
	Single Freq.			***Wideband***			***Dual Freq.***		
	100 kHz	150 kHz	200 kHz	100 kHz	150 kHz	200 kHz	100 kHz	150 kHz	200 kHz
IMT in	1	2	3	13	14	15	25	26	27
Ls out	4	5	6	16	17	18	28	29	30
Line	7	8	9	19	20	21	31	32	33
Ccvt	10	11	12	22	23	24	34	35	36

TABLE II. TEST NUMBER REFERENCE BY TYPE OF TEST – LINE TRAP

Fail-Open	**Frequency and Line Trap Type**								
	Single Freq.			***Wideband***			***Dual Freq.***		
	100 kHz	150 kHz	200 kHz	100 kHz	150 kHz	200 kHz	100 kHz	150 kHz	200 kHz
All packs	1	2	3	4	5	6	13	14	15
Pack A only	-	-	-	7	8	9	16	17	18
Pack B/ BC	-	-	-	10	11	12	19	20	21

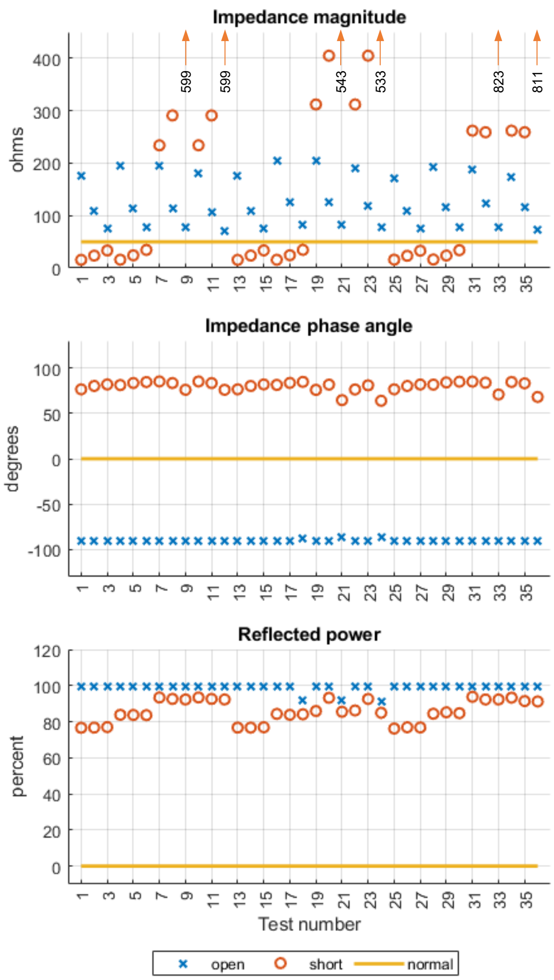

Fig. 10. Line tuner open/short simulations in different failure states. Impedance phase angle can clearly distinguish between *open* and *short* conditions.

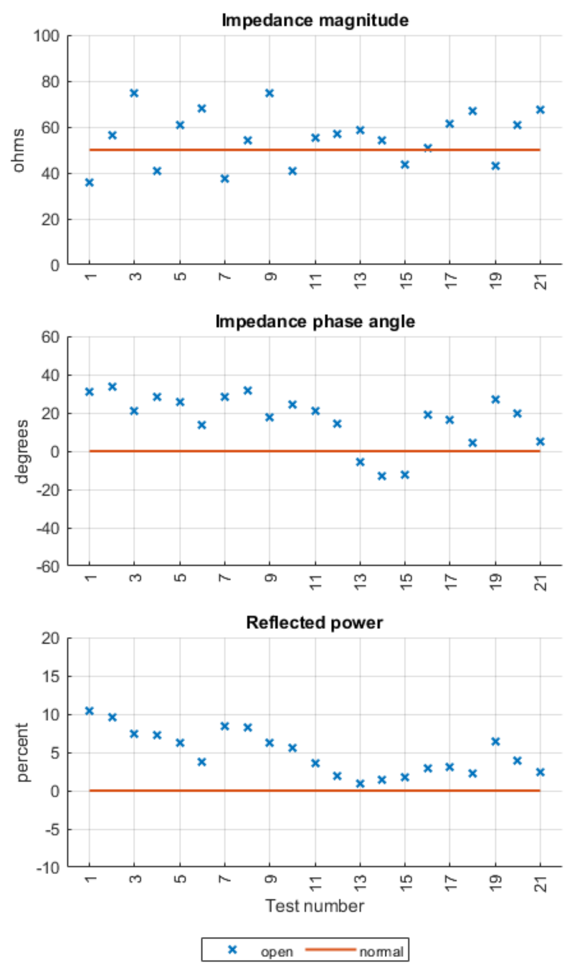

Fig. 11. Line trap "open" simulation results showing impedance magnitude, impedance phase angle, and reflected power in different test states.

B. Line Trap Tests

Results of the line trap tests and simulations are shown in Fig. 11 and Fig. 12 (use Table II to see which failure condition is represented by the test numbers in Fig. 11 and Fig. 12). This group of tests includes only an *open* test. Tests which would short out the full coil inductance of the trap do not have a practical application. However, follow-on tests might explore the results of shorting or opening individual components

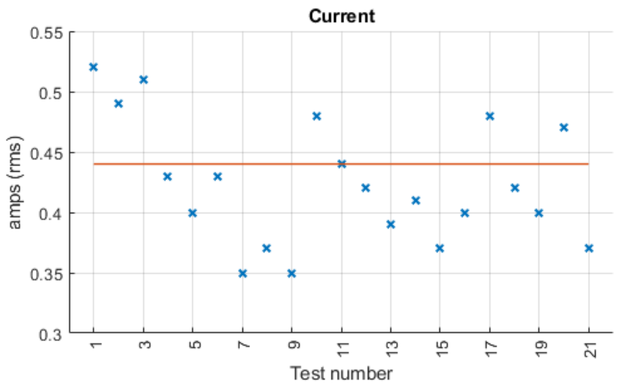

Fig. 12. Transmitter current into the tuner for line trap "open" simulations in different test states.

within a tuning pack, versus effectively disconnecting or ignoring the pack altogether.

Analyzing the line trap simulation results reveals several insights. First, the current out of the transmitter is *not* increased for all tuning pack failures (Fig. 12); in fact, most tests show a *decrease* in transmitter current. While the ratio of current into the bus versus the line is increased for line trap failures – since the trap's blocking impedance at the center frequency is reduced from its normal level – the failure of the trap also affects the line-side termination impedance; this, in turn, affects the input impedance seen at the line tuner input. The result is that the equipment-side is no longer matched to the line-side impedance; the total power transferred to the load, in this case, may be less. The current out of the transmitter is therefore not a reliable indicator of trap failure in all cases.

Second, the impedance magnitude and phase angle, and so the reflected power, show significantly smaller changes than in line tuner failures. This is expected, since the failure of the trap only changes the line-side impedance seen by the tuner; it does not leave the matching circuit "open" or "short". This behavior suggests that impedance changes at the tuner input are not sufficient to monitor the health of the line trap *on their own*. Other changes to line-side impedance are possible and may cause similar changes in the measured input impedance at the tuner, for example capacitor banks being switched in and out of the line [4][13].

Still, the results are in-line with measurements made on a single-frequency trap failure in the field (Fig. 13). Interesting in the field data is the fact that even closely-spaced frequencies – 56 kHz and 58 kHz – can see markedly different changes in the measured tuner input impedance. For example, the 56 kHz signal in Fig. 13 saw an increase in impedance magnitude at the tuner input, while the 58 kHz signal saw a decrease.

The simulations, field data, and observations above confirm that analysis of line trap failures must entail more data than just the tuner's input impedance magnitude/phase angle and resulting reflected power. A

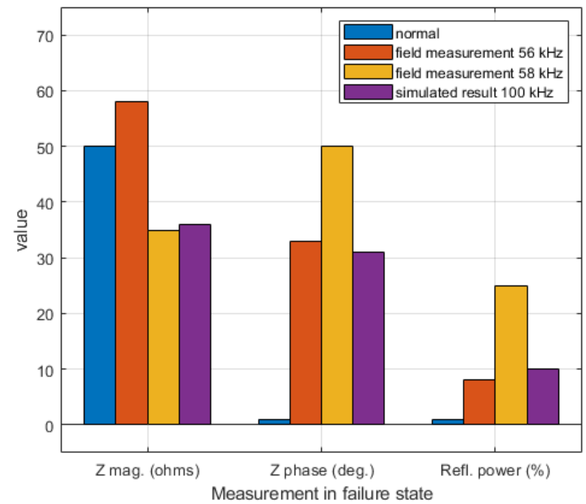

Fig. 13. Comparison of field data versus simulation for single-frequency trap failure (tuning pack open).

corresponding drop in local and remote receive levels as well as a corresponding increase in background transient activity help inform analysis of whether a line trap has failed. Further, having data available from both ends of the line, and even adjacent lines, will greatly improve the precision of the analysis [4][13].

All line tuner components, as well as the CCVT ground switch, are accessible from the ground by utility personnel. The trap, however, is typically mounted on a structure and requires either a lift to allow personnel access to the internal trap tuning packs, or equipment to lift the trap down to the ground and back up. Still, the value of simulating these trap failures at commissioning for reference down the road would be valuable, and to that end methods of performing these simulated tuning pack failures in the field should be explored in the future.

V. Conclusion

Continuous monitoring devices for carrier relaying channels have added to the data that is used for health-checks and fault-finding in PLC systems. The ability to measure and monitor complex impedance at the line tuner input, the point of matching in a PLC system, brings the monitoring one step deeper than reflected power did. For extreme cases of line tuner failures, the impedance *phase angle* has been shown to clearly distinguish between an *open* or *short* condition.

Line trap failures have less of an extreme effect on the tuner input impedance than failures in and around the tuner. Transmitter current was found to increase *or* decrease, depending on the failure, so it cannot be a reliable indicator of trap failure. The impedance and phase angle data are still an improvement over reflected power, providing more context about the change in circuit impedance.

If these open- and short-circuit simulated failures are part of a commissioning procedure, test and/or monitoring equipment can record the states for later reference. If an extreme failure occurs, like an open- or short-circuit somewhere in or around the matching network, the live measurements may be referenced against the states recorded at commissioning, reducing the time required for investigation, testing, and remediation.

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BIOGRAPHY

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