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Proposition for Power Line Carrier-based Transmission Line Vegetation Contact Detection

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Abstract: *A substation based transmission line status monitoring for vegetation contact and intermittent fault detection system is proposed utilizing existing, deactivated, or new power line carrier (PLC) systems. The PLC based line monitoring system can provide the most effective tool for continuously, real-time, watching the line for detecting and locating the random, unpredictable foreign-object or vegetation contacts, the harbingers of disastrous electrical failures and wildfires. The proposed transmission line status monitoring system would provide an alert for effective utility vegetation control and preventive maintenance, and thus reduce the root cause of outages and decrease power line caused wildfires. Previous studies on experimental verification are represented to convince practical soundness of the PLC-base method with errors in message stream as a promising discriminator between normal and intermittent fault conditions. In addition, practical approaches for utility industry are proposed. Experiments in actual transmission lines or testing facilities would further assess the validity of the PLC-based transmission line status monitoring for animal and vegetation contact detection.*

Keywords: *Power line communication, carrier signal, intermittent fault detection, vegetation control, wildfire, PLC.*

I. Introduction

MAJORITY of electric service interruptions and arcing fires occur when trees grow or fall into overhead lines, or when a line makes a contact with other object due to line equipment failure or high wind.

As the cause of the well-known, most disastrous wildfire in California, Camp Fire in 2018, California Department of Forestry and Fire Protection ("CAL FIRE") determined that the Camp Fire was caused by electrical transmission lines [1]. It also determined that the second ignition source was vegetation contact to electrical distribution lines. According to a CAL FIRE statistic, about 2% of vegetation fires are caused by power lines [2]. The fire investigation reports identified several brush fires as power line related fires ignited by power line contact with tree, power line contact with cable, power line detached from insulator contact with adjacent power line, and broken and downed but energized power line [3 - 7]. In one power line related fire, a 33kV power line, detached from its supporting insulator, swayed under the influence of string wind and made contact with the adjacent conductor on the same cross arm, which caused arcing that ignited the fire. Another fire was reported to be caused by a downed conductor's ground arcing igniting dry grass. Other power line caused wildfires shared the similar characteristics of arcing as the root-cause initiated by downed but still energized lines or power line touching other wires, under wind condition or long undetected and uncared situation of slow degradation.

In Texas, more than 4,000 power line related wildfires occurred in the period of three and a half years in early 2010 causing millions of dollars of damage [8].

Electrical failure as the origin of bushfires was also reported in another continent. The Kilmore East fire, one of the most damaging 15 bushfires in February 2009 in Victoria, Australia, was reported to be caused by live conductor contact with a supporting pole, and subsequent arching which ignited vegetation near the pole [9].

If these line conditions were early detected in their initial stages, the lines could be de-energized and the fires would be prevented. However, intermittent faults in transmission line are often completely missed by conventional monitoring and detection devices. Monitoring devices installed at substation may not be able to detect such short and small disruption from a faraway location in the circuit. Due to the random and non-reproducible nature of the incidents, such intermittent faults are the most frustrating, elusive, and expensive faults to detect and locate in transmission lines.

This paper discusses proposition of deployment of power line carrier (PLC)-based detection system as a status monitoring tool of transmission lines to help utilities with vegetation control, and prevention of wild fires caused by power line arcs. This approach, once completed and its feasibility and reliability assessed, would hold a promise of being readily applicable to the transmission lines for vegetation contact detection. Even though the traditional PLC system loses its position as a pilot for relaying and tele-protection and is being replaced by fiber optic communication, it can now find a new life playing a critical role of detecting intermittent events in the line. The application of a simple PLC system could become a valuable tool for reducing the root cause of outages or fires.

The paper is organized as follows. In the next section, using published research results, we summarize the low-frequency PLC technology and its devised method for detection of intermittent faults in terms of communication errors. Also described are the experiments performed using a prototype system and the preliminary result from the experiments. Section III describes the suggested implementation options of the PLC based transmission line monitoring system of utility industry. We conclude the paper in section IV.

II. MONITORING USE OF POWER LINE CARRIER SYSTEM

This section intends to summarize what PLC based detection system is and how it is built and validated, using the publications of the author and others. The original idea of using PLC in intermittent fault detection came from the fact that, since a random and unpredictable intermittent event would be detected, if detectible, only when the event is active, the ideal solution method would place something continuously on the wire system that could be causally influenced by the event on the wire. The approach populates the wire system with carrier signal as "something" so that the wire is under observation all the time, and disruptions and thus errors made in the carrier signal caused by the event on the wire indicate such a disruptive event. One such convenient entity is a low-frequency PLC system which had long been used for communication purpose in the utility [10].

A carrier wave or carrier signal is waveform of a specific frequency in a communication channel that is modulated with an input signal to be transmitted for information exchange. Power line carrier communication is a method of transmitting data through electrical lines alongside electrical current. This traditional application of using narrowband power line carrier can be found in some applications in the development of smart motor that combines both the power and control lines into a single wire [11]. Related to fault detection, Taylor and Faulkner proposed direct-sequence spread-spectrum modulation on power line carrier, and outlined optimal signal processing techniques and frequency domain correlation techniques for the on-line test in high voltage line [12]. Lately, slightly different use of spread spectrum was reported from the research result on detecting avionic wire problems [13].

In terms of signal communication, the received carrier signal against expected signal reveals the status of the wire as carrier signal channel characteristics. Since it is believed that an intermittent fault along the line would disrupt the carrier signal, enough would be even a simple carrier signal modulation scheme like frequency shift keying (FSK) which varies the frequency of the carrier signal according to the value of each bit in the digital data stream transmission [13].

In practice, with the FSK scheme, transmitted over electrical interconnect system, carrier signal would not be disrupted if the medium is clean, healthy, and quiescent, and therefore there would not be errors in the received data. However, when the medium is under intermittent excursions, the carrier signal would be disrupted, which in turn results in error in the data stream. The erroneous information or missed information against the correct information between a transmitter and a receiver would indicate that the carrier signal communication channel, the segment of the electrical wire between the transmitter and the receiver is faulty [10]. Also, an open circuit can be easily recognizable by the no received data stream for a period.

A. Prototype PLC Transceivers and Experiment Set-Up

Kim and Johnson detailed development of a prototype PLC transceiver system in [10]. They utilized an off-the-shelf modem chip of FSK with a microcontroller along with accessory components for coupling. Their FSK chip was STMicroelectronics' ST7537HS1 modem which had a half-duplex, asynchronous 2400bps, using a carrier frequency of 132.45 kHz. In addition, an external line driver and a transformer were used to interface the PLC system with power line. They set up a transmitting station (TX) at one end of a wire segment that transmitted message and a receiving station (RX) at the other end that received the message and compared it with the TX transmitted message as depicted in Figure 1.

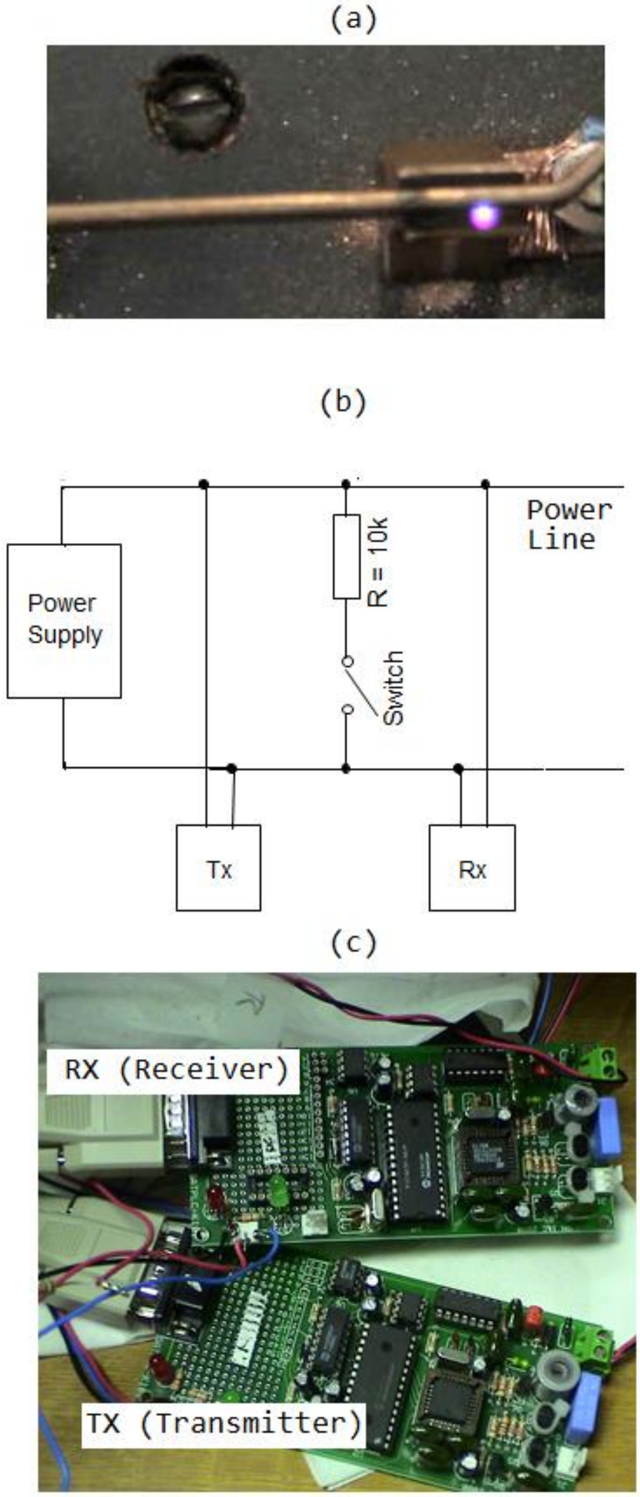

Fig.1. PLC transceiver prototypes and experiment setup with a knife switch to simulate intermittent wire contact with foreign object. (a) vertical arcing from the knife switch, (b) experiment setup configuration diagram, and (c) PLC transceivers.

The wire, solid in gauge 22, was supplied 60Hz 110V system via a wall outlet. The circuit was set up to simulate a spark/arc situation between two wires through high resistive (10kohm) contacts. In the set-up, the PLC signal through a coupling circuit passed into the circuit, resulting in the co-existence in the circuit of 110V 60Hz power signal and 10mV 130 kHz PLC signal. The connection points were made by twisting the wires tightly together and soldering them. This was done in order to ensure secure connections and reduce the possibility of any unwanted electrical noise in their own setup.

The arc/spark generator for staging intermittent fault conditions was done by rubbing the contact blades of a knife switch or touching a copper strip sporadically on a revolving drum with a hanging wire.

The impulse spikes generated by the rubbing action of switch and measured in the oscilloscope is depicted in Figure 2 with the background of sinusoidal PLC signal of around 130 kHz. With the time scale shown in the figure, we could see that the frequency of the rubbing switch impulse spikes was in the range of 300 kHz - 30MHz. In real transmission and tree-contact arc, the frequency would be further lowered by the inductance of the line. Anyway, the frequency range of the impulse spike overlaps with the frequency range of the burst noise in vegetation contact tests with power line. The frequency range of voltage signals in the tests was reported to be 50 - 400 kHz [14 - 15] while that of voltage and current in vegetation fault signature in another test was reported with the range of 10 kHz - 1 MHz [16].

Therefore, in terms of the frequency contents, the experiment with rubbing a knife switch can be considered simple, good replication mechanism of power line's vegetation contact and ignition.

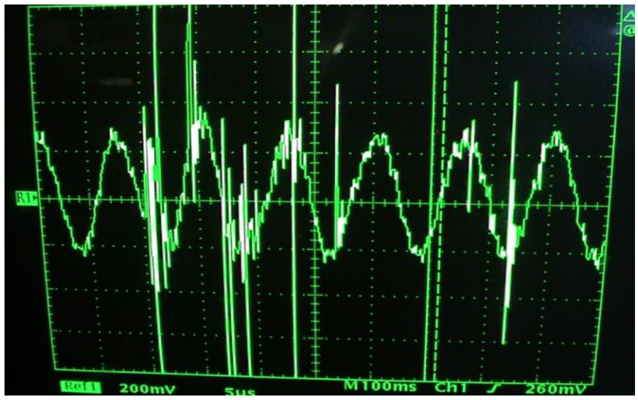

Fig. 2. The impulse spikes generated by knife switch rubbing disrupting the sinusoidal PLC signal transmitted in the wire.

B. PLC Signal in Normal and Intermittent Fault Conditions

The PLC signal and message analysis under staged intermittent faults was extensively done and reported in [17]. Along the line in the circuit, the TX transmitted modulated signal of a digital message (or text or a number) and the RX received the signal and demodulated it and decoded to retrieve the digital message. When the receiving station received the message, it compared the received data with what was expected and calculated the number of bytes and bits that were incorrect.

Each message consisted of 18 data bytes and 6 house-keeping bytes, the latter of which included identification bytes of a transmitter and a receiver. Fig. 3 shows streams of digital data (upper trace) and their corresponding carrier signals of FSK modulation (lower trace).

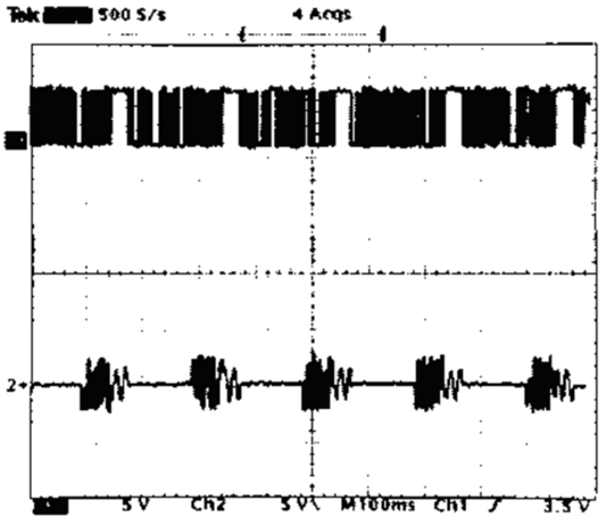

Fig.3. Digital bit stream generated by TX (upper trace) and its FSK modulated carrier signal over the wire (lower trace) [17].

At the RX side, the modulated signal was FSK demodulated accordingly, and the data stream was reconstructed. If the received data stream matched with the data stream from a transmitter, it could be said that the communication medium, the wire, was quiescent and healthy. In such quiescent non-fault circuit, it was expected to have the identical digital data streams of both transmitter (upper trace) and receiver (lower trace) as depicted in Fig.4. The time shift between two data streams, determined by the bit rate of the carrier signal modem, is clearly seen in the figure.

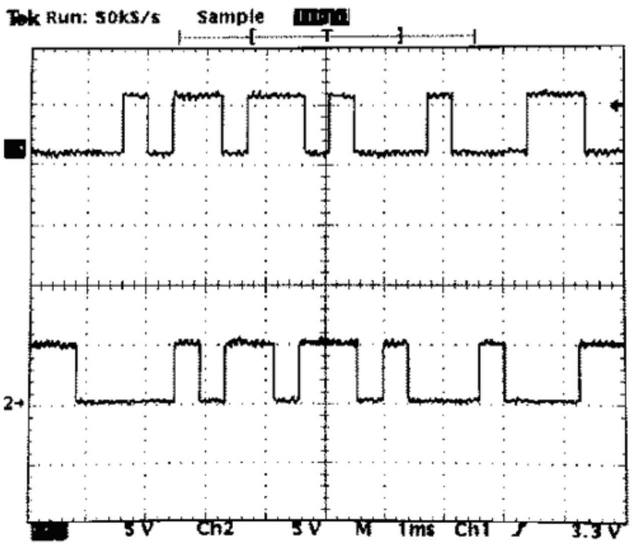

Fig.4. The same digital bit stream of TX (upper trace) and RX (lower trace) sides under normal condition [17].

When the PLC channel of wire system was disrupted by intermittent faults, the signal over the wire would also be interrupted. In Fig. 5, the upper trace is data streams generated in the TX, and the lower trace shows the modulated carrier signals over the wire which was disrupted by a staged intermitted fault condition. The carrier signals are much different from those in Fig. 3 of normal condition.

Then, the received data stream would be also different from the transmitted data stream. Fig. 6 shows the erred received data caused by the disrupted carrier signal in the receiver side (lower trace) against the data stream sent from a transmitter (upper trace). The received data in lower trace is starkly different from the transmitted bit stream of the upper trace.

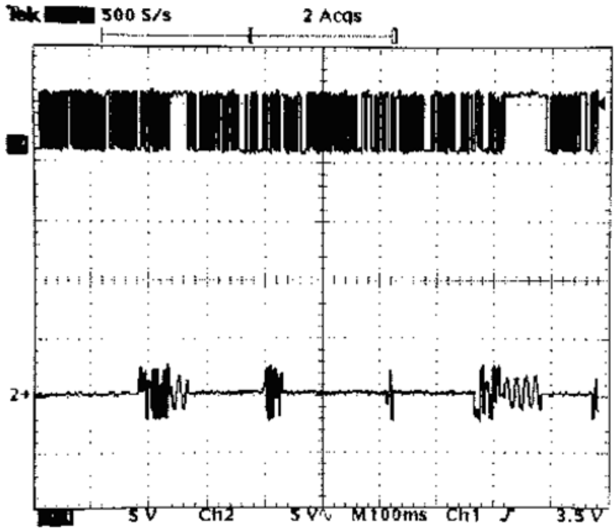

Fig.5. The generated bit stream (upper trace) from the TX and the disrupted carrier signal over the wire (lower trace) caused by rubbing spike noises [17].

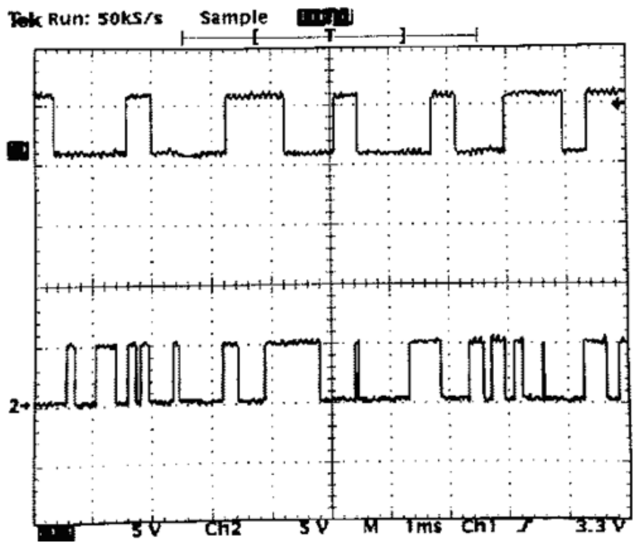

Fig.6. The difference between the transmitted digital bit stream (upper trace) and the received (lower trace) under a fault condition [17].

As illustrated, using the PLC scheme, by analyzing the erred received data stream against expected data, random abnormalities in electrical system can be detected.

C. Feasibility Test

A feasibility test of PLC system is reported in [10] done under normal and fault conditions. We summarize the reported test here. Considering the frequency behavior of the switch spikes, and some inherent noise present in the power line, the index they devised was a message error rate, called "single byte error rate (SBER)," which compares the number of messages which had a single byte error out 18 data bytes with the total number of messages received. To establish the baseline for the intermittent fault detection, the authors tested their prototype PLC transceiver boards under a normal condition. One test run consisted of 1000 message transmissions and tens of runs were conducted and an average error rate was obtained. The baseline SBER was thus established as 1.63 %.

For SBER under intermittent faults, they staged two types of electric arcing conditions: intermittent faults were staged between two lines (vertical arcing) and in the splice of one line (horizontal arcing). With a similar number of runs conducted, they found that SBER with vertical arcing was 9.18 % and that with horizontal arcing 13.52 %. Therefore SBER based error comparison seemed a good indicator for intermittent fault detection in power line.

III. Proposition of Transmission Line Monitoring with Substation PLCs

The previous chapter established the main idea of PLC message error based intermittent fault detection in power line and, based on the test and validation, this chapter proposes practical implementation solutions.

Therefore, this section focuses on how a carrier based monitoring system can be implemented for rural transmission lines and provide benefit to utility industry of earlier determination of, but not limited to, tree contact, foreign object contact, line contact, and downed but still energized condition of the line.

First of all, the PLC system with message error comparison can be immediately applicable to any transmission lines either utilizing the existing PLC systems in the substations which were/are being used for tele-protection of the line or those decommissioned, or installing a new PLC system dedicated for a line monitoring purpose for vegetation contact detection. Nowadays, PLC systems are gradually decommissioned and replaced by dedicated fiber-optic communication systems, and they are being disconnected from computer relaying systems. These idling PLC systems are the best candidates to be utilized in realizing the line monitoring system. The only additional equipment at each PLC system is a computer which transmits/receives message stream with the PLC system and analyzes the error rates and reports detection of intermittent faults and vegetation contact in the transmission line.

Utilization of the existing PLC systems needs a careful study on the types and makers of the systems and on the transmission lines of great interest of a utility district. The following description shows an example of such study conducted in a utility company on the existing PLC systems and candidate transmission lines to be monitored. The proposed approach and method developed for the example may be applied to other utility companies which in particular have decommissioned PLC systems. After that, we will explore options for adopting PLC-based detection method.

A. Study on the existing Substation PLC systems

Understanding the present carrier system in the transmission lines (TLs) is an important first step in developing an effective strategy for its line monitoring use. The investigation should start from a high wildfire risk district and find candidate TLs and the substations they are connected to. The next step is to study the PLC system, on- or off-line, in the substations.

There is a good chance that the PLC system is of General Electric's 61A series carrier system which was popularly installed before for high-speed transfer-trip relaying. A GE 61A system had been configured as either a transmitter or receiver, but a transmitter and multiple receivers could be stacked together at a substation for operation on a TL when the TL connects to more than 2 substations. The receiver comprised of several modules, each having front and back panel terminals for additional measurement uses, including filter, oscillation, and signal noise and carrier level monitoring.

Other popular PLC systems were Westinghouse's TC series or RFL Electronics'sRFL9780 digital carrier system.RFL9780 is equipped with a single unit transceiver for transmission and reception of carrier signals. In both 61A and RFL9780 carrier systems, access to the information of the carrier system such as transmission failure and signal noise level and of carrier signal of transmission and reception was possible by tapping to the communication port of the modules via appropriate communication or data sampling equipment, without disrupting the intended tele-protection scheme. Of course, the exiting line traps ("wave trap") in the substations can be utilized to confine the carrier signal in the transmission line of interest.

B. Options for Line-Monitoring Carrier System Deployment

Considering the present PLC system status, we propose four different options to adopt, ranging from utilizing the existing PLC systems to installing a new and dedicated system for TL status monitoring, under different time and financial constraints or urgency in demand. Either one option can be taken or, alternatively, or a combination of a few options can be taken progressively, one at a time. A summary of the options is discussed below.

Option 1 (Utilization of Carrier Noise Information from Existing PLC System): For GE61A system, the carrier signal noise information can be obtained by tapping into the SIG NOISE/CARR LVL MONITOR module. There are three parameters of noise information, namely, spike output, noise output, and level output of RF carrier signal received at the receiver system, that can be obtained via a modest speed sampling device and a computer. The noise information would be valuable for line status monitoring since the disruption in the line, caused by tree or foreign object contact or loose connection in wire and other latent failures, would affect the carrier signal and thus the carrier noise contents. However, the rudimentary information of level and the level change only may not be sensitive enough for effective line monitoring. On the other hand, for RFL9780 system, the SOE (Sequence of Events) can be obtained via RS232 communication with a computer for carrier transmission failure events. Also, the carrier signal level can be obtained through the EXT terminal of the TX/RX LINE I/O module via a modest speed sampling device and the computer. Again, the rudimentary information of carrier level and level change alone may not be sensitive enough for effective line monitoring. The advantage of this option though is that it is a cheap and simple option which can be immediately applicable.

Option 2 (Utilization of Carrier Signal and Noise Information from Existing PLC System): For GE61A system, further information on the carrier signal can be obtained, in addition to the carrier signal noise information, through the terminals of OSC MIXER for both RF and IF components. The RF component requires very fast sampling device for acquiring and analyzing the carrier signal. However, IF component, which may be used for line status monitoring, can be acquired with a modest speed sampling device. For RFL9780 system, on the other hand, the carrier signal can be obtained from the RX terminal of TX/RX LINE I/O module via a fast speed sampling device and PC. If a signal mixer is applied, the demand of the high speed sampling can be relaxed. The advantage of this option is simple and that RF and IF signals are available for analysis, which, however, requires high sampling rate which may be achieved by a power quality monitor installed at the substation.

Option 3 (Utilization of the Deactivated PLC System):Chances are that there are many idling PLC systems in utility substations, replaced by modernized communication systems. There may be an idling GE61A transmitter, which once was used to send carrier signal to substations but disconnected now, that can be utilized as a complete transmitter and receiver system, combined with the inactive receiver at the other substation connecting a transmission line. The complete system, with tele-protection function suppressed, could provide an ideal transmission line status monitoring system with all the level and RF and IF information of the carrier signal. In addition, it would provide with unlimited access to the signal points in the internal boards of the system. Most importantly, the data to be sent through the carrier can be selected and programmed for better monitoring of transmission line between two substations.

Option 4 (Utilization of New PLC System): This option purchases new PLC systems of any model or product and installs for any TL at two connecting substations, each equipped with a tuner circuit and a wave trap, and optionally, an IRIG (Inter Range Instrumentation Group) standard time generator and synchronizer for future advancement in locating the intermittent faults. The biggest advantage of this option is in its freedom of TL choice; the biggest hurdle however is the required cost of the carrier system and additional components and of the installation of the components.

C. Realization of the Options

The proposed transmission line monitoring system as configured in Figure 7is composed of a set of PLC system, line coupler, and a computer at each of the two substations connecting the transmission line. Line traps (wave traps) as installed confine the PLC carrier signal only in the transmission line between two. This monitoring system is expected to enhance utility's capability in detecting otherwise unnoticeable intermittent events of tree or foreign object contact and latent defects and in preventing by early corrective action such as vegetation management from developing into permanent faults that may cause destruction, explosion, or fire.

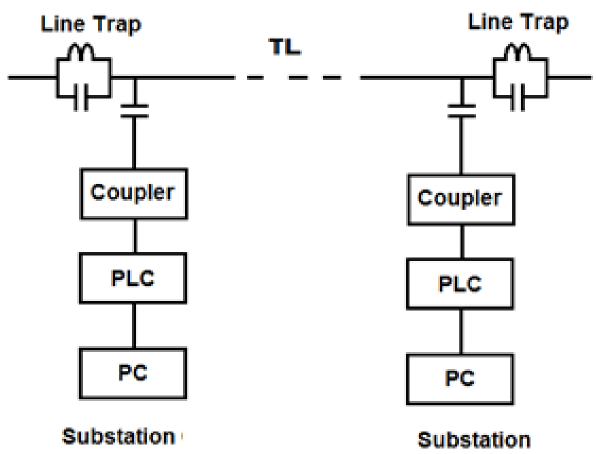

Fig. 7. A proposed PLC configuration for transmission line monitoring for vegetation or foreign object contact.

This PLC approach, with several installation options proposed, holds a promise of being readily applicable to any actual transmission lines or, if available, testing facilities for further validation. Even though the traditional carrier system loses its position as a pilot for relaying and tele-protection and is being replaced by fiber optic communication, it may now find a new life in playing a critical role of detecting intermittent events in transmission lines and reducing the root cause of wildfires. A demonstration project would help assess the validity of the suggested PLC line monitoring method.

IV. Conclusions

The majority of electric arcing fires occur when trees grow or fall into overhead lines and when a line make a contact with other object due to line equipment failure or high wind. Early detection of intermittent faults in the overhead power line caused by vegetation or foreign object contact is critical to utility industry for reducing service disruption and wildfires. The proposed transmission line status monitoring based on low-frequency PLC system would provide an alert for effective utility vegetation management and preventive equipment maintenance and thus decrease arcing-induced wildfires. The PLC based line monitoring system can provide the most effective tool for continuously, real-time, watching the line for detecting and locating the random, unpredictable intermittent contact, the harbingers of disastrous arcing fire. Additional expected benefit of the proposed PLC based line monitoring system can be found in its decision-making aid role on de-energizing object contacting or downed transmission lines. A further benefit is expected in solving the nagging problem of insulator latent defects which are not visible but still producing self-clearing outages. A demonstration project of practical experiments in actual transmission lines or testing facilities would further assess the validity of the proposed line monitoring method of PLC system.

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