RF Transmission-line Methods for In-service Probing of Concentric Neutral Wires in Underground Power Distribution Cables

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Abstract—Failure of concentric neutral (CN) wires in an underground power distribution cable can drastically reduce its useful life. New on-line approaches are needed to assess the deterioration of the CNs and to prevent unscheduled service disruptions. In this paper, we present new methods for probing the integrity of CN wires in underground power distribution cables using RF-waves. The primary advantage of our techniques compared to traditional CN diagnostics is the ease of applying our methods to energized underground power distribution cables. This paper briefly describes two methods for transmitting RF-waves through underground cables: a surface RF-wave, also called the Goubau Wave (GW), guided by all the CNs within the cable, and an RF-wave coupled to a two-wire transmission line composed of adjacent CNs. We focus on the use of GW to probe for CN degradation, due to good coupling of the wave to the underground cable. We show experimental results demonstrating the change in the signature of the transmitted GW signal through a section of degraded (broken) CNs.

Keywords: underground cable diagnostics, RF probing methods, Goubau waves, concentric neutrals

I. INTRODUCTION

Concentric neutral (CN) degradation is a significant failure mechanism for underground distribution cables. It causes loss of protective shielding as well as lack of properly grounded current return path. Existing cable diagnostic techniques, such as TDR require the cable to be disconnected from the grid, causing service disruptions during the testing operation.

In this paper, we present novel methods for testing the integrity of the CNs in an underground power distribution cable without de-energizing it in order to perform the measurement. Our methods use RF signals coupled to in-service cables via capacitive couplings at cable endpoints (in underground distribution vaults.) We describe two methods for transmitting RF-waves through these cables: a surface RF-wave, also called the Goubau Wave (GW), guided by all the CNs within the cable, and an RF-wave coupled to a two-wire transmission line composed of adjacent CNs.

In the first method, the GW is launched along the cable using a conical launching device (funnel) and a non-invasive capacitive coupling to the CNs. The GW is then guided along the cable, and any discontinuities, breaks, or corrosion in the CNs will reflect and attenuate the signal transmitted to a neighboring vault.

In the second method, a pair of adjacent CNs is treated as a 2-wire transmission line with distributed R,C,L and G parameters over the length of the cable with a typical characteristic impedance \( Z_0 \). A short voltage pulse applied through a non invasive capacitive coupling to the CNs, can be used to excite the two-wire transmission line. Any cable impairment such as open breaks, short circuits, localized corrosion or other defects will result in reflections of the transmitted signal.

II. TYPICAL UNDERGROUND DISTRIBUTION CABLE

The structure of a typical underground distribution cable is shown on Fig. 1. The cable consists of a central conductor, made out of aluminum or copper (1), and covered with an inner layer of a semiconductive polymer called semicon (2). The semicon layer is encased in an insulated material (3) (such as PE). The insulator is covered with an outer layer of semicon (4). A set of spiraling CNs (5) are places on top of the outer semicon layer. Newer cables contain an outer jacket extruded over the CNs (6).

Figure 1. A typical underground power distribution cable.
III. RF-TRANSMISSION LINES

A. Surface-guided RF Waves (Goubau)

The initial idea of coupling an RF-wave to a conductor with dielectric coating was originally proposed by George Goubau [1]. The wave is guided by the conductor, and its energy is confined in the space around the wire. The dielectric coating restricts the extent of the field. The coupling of the RF signal from a feed coaxial cable (TEM-mode) to the surface-guided mode (TM-mode) is performed using conical launching devices (funnels), such as shown in Fig. 2a (from [2]). The idea is to couple the Goubau Wave (GW) to the concentric neutrals of an underground distribution cable in vault A, perform time-domain reflectometry (TDR) on the returned signal, and perhaps also detect the transmitted signal to vault B (as outlined in Fig. 2b).

![Figure 2](image)

Figure 2. a: (from [2]) Conical launching device used in a commercial application to couple surface-guided RF waves to overhead power distribution lines. b: Outline of our concept for using the GW for probing underground distribution cables. The probing wave is launched from vault A, attenuation of the transmitted wave is measured in vault B, and TDR is performed on the reflected signal at vault B.

B. Two-wire Transmission Lines

A two-wire transmission line carries at one instant a forward load current in one conductor and a return current in the opposite direction. The two lines have distributed series impedance consisting of resistance $R$ and inductance $L$ per unit length and distributed parallel admittance consisting of conductance $G$ and capacitance $C$ per unit length. The transmission line has a characteristic impedance $Z$, angular frequency $\omega$, and velocity of propagation $v$ dependent on the above four parameters. Typically $R$ and $G$ are very small as compared to the impedances $j\omega L$ and $1/j\omega C$. For the two-wire transmission line with wires of diameter $a$ separated by distance $d$, the expressions for $L$ and $C$ are given by equations (1-3) [3]:

\[
\frac{\varepsilon}{C} = \frac{L}{\mu} = \cosh^{-1}\left(\frac{a}{d}\right) \quad (1)
\]

\[
Z = \sqrt{\frac{\mu}{\varepsilon}} \quad (2)
\]

\[
v = \frac{1}{\sqrt{\mu\varepsilon}} \quad (3)
\]

The CNs are in galvanic contact with the semicon layer beneath them. The typical conductivity of semicon is about 1 Siemens/meter and the capacitance is about 300 pF/meter, resulting in a typical time-constant $\tau = 300$ ps (assuming an intact cable with CNs making good contact with the semicon over its length). If the semicon layer separates from one of the CNs over a significant length, which is to be determined experimentally, the resistance between the two increases along with the time-constant $\tau$. This enables detecting a reflected pulse using two-time Time Domain Reflectometry (TDR) and approximating the location of the CN-semicon separation.

IV. EXPERIMENTAL SETUP (GOUBAU)

We now describe the experiments conducted on coupling the GW to an underground power distribution cable. All experiments have been conducted using a 90 feet section of a 1” 10 CN jacketed TRXLPE cable (ICC Brand-MTT, #2 Solid Al, 175 Mils TRXLPE 15KV, Insulating PF Jacket). The launching and receiving funnels were made out of 5 mils thick soft copper foil, with an outer diameter of 11.5 inches, and an inner diameter of 2 inches. The funnels were attached to 11.5 inch long coaxial sleeves, which were meant to encourage the transition from TEM to TM mode. The RF-signal was generated using an Agilent E8251A programmable signal generator, and modulated with a pulse from an Agilent 33220A arbitrary function generator. A 4-channel 2GHz digital oscilloscope (Agilent Infinium DSO80204B) was used to register both the transmitted and received signals. The power of the received signal was also recorded using the Agilent 8562EC spectrum analyzer. The cable was elevated on ten 29 inch tall plastic traffic cones, to avoid the interaction of the wave with the reinforced concrete floor underneath. The cable looped around the room; the transmitting and receiving funnels are separated by approximately 6 feet.

V. EXPERIMENTAL RESULTS (GOUBAU)

A. Galvanic Coupling to the CNs

Initial experiments were conducted to determine our ability to couple the GW to the CNs of a power distribution cable. In this setup, the central conductor of a signal-carrying coaxial cable was galvanically connected to all the CNs (via a hole in the sleeves), while its shield was galvanically connected to the sleeve. Fig. 3 shows the receive power versus frequency for an applied 14 dBm signal, indicating an optimal coupling frequency of around 300 MHz. A screen capture from the DSO80204B oscilloscope showing the time domain analysis of the superimposed transmitted (yellow) and received (green) 300 MHz 14 dBm signal modulated with a 90 ns square pulse is shown on Fig. 4, indicating a clear delay as the pulse follows the entire length of the cable.

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Figure 3. The receive power (measured at the receiving funnel) versus frequency plot for an applied 14 dBm signal (at the transmitting funnel).

Figure 4. Screen capture from the DSO80204B oscilloscope showing the time domain analysis of the superimposed transmitted (yellow) and received (green) 300 MHz 14 dBm signal modulated with a 90 ns square pulse. A \( \approx 100 \) ns delay can be seen, indicating that the pulse follows the entire length of the cable.

B. Capacitive Coupling to the CNs

In order for us to use the GW to perform on-line diagnosis of energized power distribution cables, it is desired to couple the signal without making galvanic contact with the CNs. To achieve this, we installed a capacitive coupling to the CNs at both the receiving and transmitting funnels. The signal-carrying central conductor from the coaxial cable was connected with a 4.5 inch wide copper sleeve wrapped around the cable jacket. Both capacitive couplings were located within the sleeves of the funnels. The insertion loss associated with the capacitive coupling was measured to approximately 1-2 dB, and 300 MHz was determined to be the optimal frequency for the capacitive coupled GW.

However, time domain analysis shows that part of the signal is now transmitted through free-space radiation, increasing the effective insertion loss of the coupling. Fig. 4 shows a screen capture from the DSO80204B oscilloscope of the time domain analysis of the superimposed transmitted (yellow) and received (green) 300 MHz 14 dBm signal modulated with the 80 ns square pulse and transmitted through the capacitive couplings at the transmit and receive funnels. A \( \approx 100 \) ns delayed pulse (1) is clearly visible, however part of the signal is transmitted through radiation, as it is indicated by a radiated pulse (2). The radiated signal is very susceptible to noise in the environment around both funnels, and exhibits a great deal of variability.

Figure 5. Screen capture from the DSO80204B oscilloscope showing the time domain analysis of the superimposed transmitted (yellow) and received (green) 300 MHz 14 dBm signal modulated with a 80 ns square pulse, transmitted through the capacitively coupled cable. A \( \approx 100 \) ns delayed transmitted pulse (1) is clearly visible, however part of the signal is now transmitted through radiation, as it is indicated by the radiated pulse (2).

C. Effects of CN Degradation

We have investigated the effects the degradation of the CNs has on the capacitive coupled GW. Figs. 6 and 7 show the transmitted (1) and radiated (2) pulses before and after a 5 inch gap was cut in all the CNs, respectively. The cut was made approximately 20 feet from the receiving funnel. One can clearly see an increase in the radiated pulse (2), and a decrease in the transmitted pulse (1). This indicated that some of the power is now radiated away at the CN break.

Next, we investigated the effects of the length of the gap on the signature of the transmitted pulse. Although still clearly present using a modulated pulse at 80 ns, the change is best visible when we increase the length of the modulated pulse to 100 ns. Fig. 8 and 9 shows the transmitted signal through a 5 inch and a 60 inch gap cut through all the CNs, respectively. Again, clearly visible is the decrease in size of the transmitted pulse (1), and the increase in size of the radiated pulse (2).
Figure 6. The transmitted (1) and radiated (2) pulses (80 ns modulation) prior to the cut in the CNs.

Figure 7. The transmitted (1) and radiated (2) pulses (80 ns modulation) after a 5 inch cut was made in all the CNs.

Figure 8. The transmitted (1) and radiated (2) pulses (100 ns modulation) after a 5 inch cut was made in all the CNs.

Figure 9. The transmitted (1) and radiated (2) pulses (100 ns modulation) after the cut was enlarged to 60 inches.
VI. CONCLUSIONS

We are investigating the use of RF transmission lines as a method for probing the integrity of concentric neutrals in energized underground power distribution cables. We have looked at two approaches: the first approach couples a surface-guided RF wave (Goubau wave) to the concentric neutrals, while the second approach uses a two-wire transmission line between the adjacent concentric neutrals. Both approaches are applicable to probing the CN integrity without disconnecting and de-energizing the cable from the grid.

For this paper, we have concentrated on the application of the Goubau wave (GW), and have experimentally shown that a significant change occurs in the signature of the transmitted GW signal if the signal encounters a break in the CNs. Our data indicates that a gap in the concentric neutrals causes an increase in the amount of energy that is radiated away from the cable, thus changing the signature of the transmitted and received pulses in the time domain analysis. We are currently working on understanding the mechanism of the observed changes to the transmitted signal. We believe that such understanding will allow us to generalize the observed pattern to a set of markers that can then be employed to look for degraded spots in legacy underground power distribution cables.

We are also currently in the process of analyzing the information content of the reflected signal. Among other, we are interesting in examining the effect of changes to the characteristic impedance between the CNs and the semicon, such as induced by a layer of corroded material, on the reflected (as well as transmitted) signal.

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