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Long Wire Antenna-like behavior of Un-Insulated Overhead Distribution Cables

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Abstract—Un-insulated overhead distribution cables are evaluated in terms of their propagation and radiation behavior when excited by a partial discharge pulse. Low attenuation levels at high frequency and a traveling wave radiation pattern are observed for a single Aluminum cable. The dominant radiated frequency components of surface discharge and dry-band arcing are experimentally evaluated, and a high level of activity is observed in the 400 – 600 MHz and 900 – 1000 MHz bands. High directivity values at specific angles are also recorded at 400 and 900 MHz for both single and three cable distribution systems. These findings show that a partial discharge signal will travel for a significant distance along a cable and leak radiation predominantly in a specific direction, thus assisting the design of RF based discharge detection and localization system.

Index Terms— Partial Discharge, long wire antenna, traveling wave radiation, RF sensors, aluminum cable

I. INTRODUCTION

Partial discharge (PD) is a key contributor to failures in high voltage (HV) electrical insulation systems. These failures often lead to catastrophic events such as pole top fires and bush fires, and cause damage to power infrastructure worth of millions of dollars. The electrical industry has implemented preventative measures to avoid damage due to electrical discharges by using new epoxy insulator materials which can handle the stress from the partial discharge, and by quality controlling insulator manufacturing. However, existing infrastructure using outdated technology still presents a problem for the electrical industry. Hence a real time PD detection mechanism which can detect and locate discharges in their early stages is essential in the prevention of catastrophic failure.

Partial discharge is a random activity with a very narrow pulse width. It has been shown that the magnitude of a PD pulse can be related to the charge inside a cavity fault and the voltage across the insulator [1]. Previous research shows that this PD pulse consists of a broad band range of frequencies,

even up to the GHz region [2-4]. The UHF components generated by PD activity is currently used to detect and locate faults in HV transformers and Gas Insulated Substations [5-7]. While UHF couplers have widely been used in these scenarios, Radio Frequency (RF) sensors have rarely been used in the detection and location of faulty HV distribution insulators. The detection of PD in the VHF range has been proposed [8]. However RF detection systems at higher frequencies could be advantageous, as interference from common communication bands can be easily avoided.

The Rogowski Coil is a commonly used sensor for various detection techniques. It has been widely used in detecting faults from XLPE cables [9-12], and it has also been used in PD localization systems [9]. However it is impractical and hazardous to use a Rogowski Coil to detect PD pulse from bare Aluminum cables since direct attachment of the sensors is required. The Rogowski coil is also incapable of detecting very high frequency components such as in the GHz region. Therefore it is important to look at the possibility of using RF sensors for PD detection and localization in bare cable distribution systems.

A representation of the proposed PD detection system using RF sensing is shown in Fig. 1. A PD pulse from a faulty insulator propagates along a bare Aluminum cable, radiating energy in a specific pattern at each frequency. With an understanding of the propagation and radiation behavior of these cables, sensing antennas can be used to receive and monitor radiation at given angles for a particular frequency. If a PD signature is detected by more than one of these monitoring stations, a localization algorithm can determine the exact position of the faulty insulator.

Critical performance criteria for HV cable sensing systems are: PD pulse propagation, attenuation of particular frequency components, and radiation from the cable into the far field. XLPE cables are covered conductors that are widely used in the HV industry, and have been extensively evaluated in terms of PD pulse propagation. It has been shown that the XLPE cable displays significant attenuation at high frequencies due to its insulation layer [13, 14], and also that its core has less contribution towards the attenuation than the insulation layer [14]. This paper investigates PD propagation along an un-insulated Aluminum cable (AS 1531 Conductors) [15], which are primarily used in 11 kV power distribution systems. The

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propagation is assessed in terms of the ability of the cable to be used as part of a detached RF detection and localization system for faulty HV insulators in distribution networks.

Fig. 1. The proposed RF sensing architecture

II. CST MICROWAVE STUDIO AND THE FINITE INTEGRAL TECHNIQUE (FIT)

The propagation and radiation from a single wire earth return (SWER) cable at 100 kHz has previously been investigated using theoretical model created in MATLAB [16]. ATP and EMTP simulations employing a quasi-static approximation using Carson and Polaczek theory has shown PD pulse propagation along an XLPE cable [12, 17, 18]. This theory assumes that the height of the cable is significantly small compared to the wavelength at the frequency used for simulation [19]. Fundamental antenna theory and Maxwell's equations can be used to reduce inaccuracies associated with high frequency simulations [19]. 3D simulations based on the Finite Element Method (FEM) and the Finite Integral Technique (FIT) (which apply Maxwell equations) can be used in these situations, since they enable the simulation of the real physical cable or system.

The Finite Integral Technique uses the integral form of Maxwell's equation rather than their discrete forms. This can be used for the numerical simulation of various electromagnetic problems ranging from static field calculations to high frequency scenarios in either time or frequency domain [20]. CST Microwave studio is a commercial software package that uses FIT in combination with the Perfect Boundary Approximation (PBA) to yield a high accuracy. Unlike FEM based software it is capable of simulating electrically large structures in the time domain, which is more computationally efficient than using the frequency domain [21]. However, significant computer resources are still required to accurately evaluate large (in terms of a wavelength) problems.

III. ANALYSIS OF PD PULSE PROPAGATION IN UN-INSULATED ALUMINUM CABLES

A. Simulation Setup

The typical PD can be approximated numerically by a Gaussian pulse [22]. A Gaussian pulse with centre frequency of 1.25GHz, bandwidth 2.5GHz and a 1 V amplitude has been used as the excitation source. The cable structure simulated in CST is shown in Fig. 2. A 5 m long un-shielded Aluminum overhead distribution cable resides 10 m above a ground plane made of dry soil. To minimise the effect of reflection, perfectly matched layer (PML) boundaries were employed at the edges of the simulation cell. Voltage monitors are located at every meter along the length of the cable, including one at the source. A discrete port has been used to excite the cable, connected via a 50 Ω resistor to minimize impedance mismatch.

Fig. 2. Overhead distribution cable structure for the pulse propagation simulation

B. Pulse propagation

Fig. 3 shows the signal recorded at each of the voltage monitors along the length of the 5 m cable. The voltage monitor at 0 m shows the input pulse after transition through the discrete port. This is assumed to be the reference level at the input to the cable. As the pulse traverses along the cable, the amplitude drops slightly, and the tail of the pulse is distorted slightly by the frequency dependant characteristics of the cable.

A Discrete Fourier Transformation (DFT) was performed in MATLAB to analyze the Power Spectral Density (PSD) of the

signal observed at each voltage monitor. This was used to calculate the attenuation versus frequency, the results of which are shown in Fig. 4. It has been shown that XLPE cables have considerable attenuation at high frequencies due to the surrounding dielectric layer [13, 14], a typical value being 2 dB/m at 1 GHz. The simulation results for bare Aluminum cables show a significantly lower level of attenuation. At 2.5 GHz, an attenuation of only 0.14 dB/m is recorded.

Fig. 3. Pulse propagation along an un-insulated cable from 0 m to 5 m

Fig. 4. Attenuation per meter vs frequency for un-insulated Aluminum cable

It can be deduced using antenna theory [23] that the radiation loss from the power line is very low, and is only a minor contributor to the total power loss [16, 24]. Hence we can assume that the power loss (attenuation) occurring in this Aluminum cable is mainly due to ohmic loss.

$$\delta = \frac{1}{\sqrt{\pi f \mu_0 \sigma}} \quad (1)$$

$$R_{loss} = \sqrt{\frac{\pi f \mu_0}{\sigma}} \frac{l}{2\pi(a - \delta/2)}$$

Equation (1) shows the loss resistance due to conductor loss. In (1) δ is the skin depth, 'a' is the cable radius, σ is the conductivity, 'l' is the length of the cable under test, 'f' is frequency in Hz and μ_0 is the permeability of free space. R_{loss} is plotted in Fig. 5 as a function of frequency. The loss resistance at 2.5 GHz only reaches approximately 0.15 Ω /m.

Therefore we can conclude that the power dissipation due

to ohmic loss is very low. Hence the attenuation values obtained from the simulations can be justified.

Fig. 5. Loss resistance vs frequency for Aluminum cables

IV. RF RADIATION FROM A SINGLE OVERHEAD POWER LINE DUE TO PARTIAL DISCHARGE

The wave propagation along a power line has been discussed previously [19, 25], along with UHF and VHF radiation from insulators [5 - 8]. However there has been minimal discussion on the electromagnetic radiation pattern created when a PD signal travels along a cable. It has been demonstrated that there is a significant level of radiated energy due to PD, which can be detected in the VHF and UHF regions. Earlier simulation works show that the radiation from an insulator generating PD displays an omni-directional radiation pattern [26, 27], and that the radiation energy from the PD activity is enough to excite the power cable.

A power cable excited by a PD pulse exhibits distinctive traveling wave radiation patterns at different frequencies. The plots in Fig. 6 display these patterns at various frequencies for the simulation setup given in Fig. 2. The radiation patterns in Fig. 6(b)-(f) display a travelling wave shape [23] since the cable's electrical length of 5 m is equal or longer than one wavelength at that particular frequency. Fig. 6(a) does not show the travelling wave radiation pattern since the cable's electrical length is 0.33 wavelengths at 20 MHz. This is an artefact of the limited simulation size, as a travelling wave radiation pattern would result if the simulated cable length was extended to 15m (or greater), which is a full wavelength at 20 MHz.

A long wire antenna is a straight wire or cable with the length of one or more wavelengths [23]. It is an elementary antenna which has been used in short wave transmissions for a very long time. Long wire antennas exhibit a travelling wave radiation pattern. Hence, uninsulated Single Wire Earth Return (SWER) distribution cables can be classified as long wire antennas when the cable length is in excess of a wavelength at a particular frequency.

Fig. 6. Radiation patterns in the x-z plane from a single un-insulated power cable at various frequencies
(a) 20 MHz (0.33 wavelengths) (b) 60 MHz (1 wavelength) (c) 100 MHz (1.67 Wavelengths) (d) 400 MHz (6.67 Wavelengths)
(e) 900 GHz (13.33 Wavelengths) (f) 1.1GHz (18.33 Wavelengths)

Directivity is a measure of how well an antenna emits or receives radiation in a particular spatial direction. The directivity of the un-insulated power cable in the direction of the main radiation lobe rises as frequency increases, as shown in Table I. Therefore higher frequency components of the propagating PD signal will show more significant radiation in a particular direction than lower frequency components. The angle between the cable direction and the maximum of the radiation pattern main lobe has reduces with incrementing frequency component. Hence, a judiciously placed RF can be used to efficiently detect radiated high frequency components universal to PD.

V. ELECTROMAGNETIC RADIATION FROM A TYPICAL ELECTRICAL DISCHARGE

Partial discharge can have various incarnations such as cavity discharge, surface discharge and dry-band arcing. Previous research has shown that cavity discharge is capable of generating high frequency components, particularly in 800 MHz - 1100 MHz region [2, 4]. However due to the quality control procedures used in insulator manufacture, the possibility of cavity discharge is significantly low. Surface discharge and dry-band arcing have been observed as common causes of insulator failure. Both result from insulation pollution and/or the presence of moisture. Hence it is

important to examine power cable behavior for real PD signal collected experimentally.

TABLE I
DIRECTIVITY AND MAIN LOBE DIRECTION AT VARIOUS FREQUENCIES

Frequency MHz	Electrical Length of the 5m long cable	Directivity (dBi)	Direction of the main lobe From Cable (Degrees)
20	0.33λ	-9.9	72
60	1λ	-2.6	47
100	1.67λ	0	37
400	6.67λ	6.1	19
900	15λ	9.1	12
1100	18.33λ	9.9	11

Fig. 7. Experimental setup to measure the radiated electromagnetic signal from PD

Fig. 7 presents the setup used to experimentally determine the common form of radiated signal from surface discharges and dry-band arcing. An 11.1 cm x 14 cm x 1.6cm dry Perspex sample was employed to investigate the surface discharge caused by 7 kV 50 Hz power supply. A wideband horn antenna located 1 m away was used to measure the electromagnetic radiation from the discharge. Distilled water was then sprayed on to the sample to induce dry band arcing using the same HV power supply. Time domain data was collected each minute by a Tektronix TDS5104 oscilloscope with a sampling rate of 5 GS/s. This was then converted via a Discrete Fourier Transformation (DFT) to the frequency domain over the range of 0 to 2.5 GHz.

Selected time and frequency domain responses of the two different discharges are shown in Fig. 8 and Fig. 9. Both

surface discharge and dry-band arcing show a high level of activity in 20 – 100 MHz frequency band. Elevated spectrum levels are also evident in the bands from 400 – 600 MHz and 900 – 1000 MHz. Therefore, as detectable levels of radiation in these frequency bands are common to both types of PD activity they are of considerable interest for RF sensing. Referring to Table I, antenna directivity in these bands is high for a signal traveling along a un-insulated power cable, hence assisting detection.

Fig. 8. Time and frequency domain representation of surface discharge

Fig. 9. Time and frequency domain representation of dry-band arcing

Common communication and broadcast bands such as keyless remote controls (433.05 MHz - 434.79 MHz), UHF television transmission (520 MHz – 820 MHz) and cellular mobile telephones (820 MHz – 915 MHz) may create disturbances for PD detection systems in the identified bands.

However, these potential interferers are narrow band services, hence the detection frequency of an RF PD sensor can be designed to avoid these bands. For the practical implementation of a PD detection system for distribution lines, an extensive study of the signal to noise ratio and advanced noise filtering techniques is essential.

VI. RADIATION FROM AN 11 KV THREE PHASE CABLE SYSTEM

Section IV primarily discussed the radiation activity of a single un-insulated power cable due to PD pulse propagation. Distribution networks are predominantly three phase systems, hence the investigation of signal propagation and coupling in a three cable architecture is important. Power distribution system cables are spaced apart from each other in order to minimize the interference from the electric fields of a propagating 50 Hz AC signal. The coupling between adjacent cables at higher frequencies resulting from propagating discharges is examined using the simulation setup shown in Fig. 10. Three 5 m long Aluminum cables are separated by a distance of 60 cm, which is a standard spacing for 11 kV overhead power distribution. The central cable has been excited by a Gaussian pulse, emulating a fault on the middle insulator. Voltage monitors connected to each cable are used to measure the signal in each cable.

The voltage signals detected at the end of each of the three cables are given in Fig. 11. The induced pulse measured on the left and right side are around 20 times smaller than the pulse measured from the middle cable, which had the directly connected input pulse. The pulse shape has changed considerably, indicating that the coupling is frequency dependant. For a PD detection system employing RF sensors, the affect these adjacent cables have on the radiation pattern of a propagating pulse is of primary concern.

The radiation patterns displayed in Fig. 12 compare the single and three cable systems at 400MHz and 900MHz in all three primary planes. As discussed in Section V, 400MHz and 900MHz are in the detectable radiation bands for surface discharges and dry-band arcing. The radiation patterns for the three phase cable system still displays the basic traveling wave shape. Distortion of the three cable pattern is seen in the y-z plane due to the presence of the adjacent cables. A slight variation in the directivity on the main radiation lobe is also evident.

Fig. 10. Simulation configuration of a three cable system with the middle cable excited.

(a) Pulse measured at the end of the middle cable (Cable with PD source)

(b) Pulse measured at the end of the left cable

(c) Pulse measured at the end of the right cable

Fig. 11. Pulse measured at the end of each of the three cables

A directivity comparison is provided in Table II. The directivity of the three cable system is about 1 dB higher than single cable system. This may be due to the induced pulse on the outer cables causing each cable act as an individual element of an array [23], resulting in increased directivity.

TABLE II
DIRECTIVITY COMPARISON FOR SINGLE AND THREE CABLE CONFIGURATIONS

Frequency (MHz)	Directivity (dBi)	
	Single cable system	Three cable system
400	6	7
900	9.1	10.37

VII. CONCLUSIONS

A discussion of the propagation and radiation behavior of PD on un-insulated overhead distribution lines has been presented in this paper. The bare Aluminum overhead cable shows very low attenuation levels, even at GHz frequencies. Hence high frequency components of a PD signal will travel for a significant distance along a cable, allowing for remote detection.

An analysis of the dominant frequency components of both surface discharge and dry-band arcing was experimentally deduced. It was shown that the frequency bands from 400 – 600 MHz and 900 – 1000 MHz show a detectable level of radiation for both types of discharge.

The radiation patterns for the high frequency components of PD propagating on single wire and three phase systems have also been investigated. Traveling wave radiation patterns analogous to a long wire antenna are observed. High directivity values are recorded at 400 and 900 MHz, which are in the high radiation bands for surface discharge and dry-band arcing. Knowledge of the changing directivity and direction of main lobe radiation with frequency can be used to efficiently configure the orientation of an RF sensor in a PD detection an localization system.

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(a) Radiation pattern for 400MHz

(b) Radiation pattern for 900MHz

--- Single cable system X-Z plane --- Three cables system X-Z plane Single cable system X-Y plane
 Three cables system X-Y plane Single cable system Y-Z plane Three cables system Y-Z plane

Fig. 12. Radiation patterns at 400MHz and 900MHz for single and three cable systems

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X. BIOGRAPHIES

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Khoi Loon Wong received the B.Eng (1st class) and Ph.D degrees in 1997 and 2001 respectively. He is currently an Associate Professor in the School of Electrical and Computer Engineering at RMIT University. His research interests include the development of novel detection method for condition monitoring in power distribution and transmission system, investigation of pole top fire phenomena and mitigation method, long term performance of polymeric insulators and finite element analysis on electrical insulation system. He carried out many consultation works for power transmission and distribution companies in Australia.