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WIRELESS SENSOR NETWORK BASED PD MONITORING OF UNDERGROUND CABLE SYSTEMS

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ABSTRACT

Maintenance of underline cable systems requires periodic measurement of many physical variables at numerous locations. This task can potentially be accomplished with wireless sensor networks. This paper describes the PD-sensing algorithms(Discrete Wavelet Transform) for the inspection of electrical power cables. The diagnostic sensor array includes thermal, visual, dielectric, and acoustic sensors for the measurement of cable status. Laboratory tests demonstrate the ability of integrated sensors to measure parameters of interest with the resolution required by the application. Field tests in the underground cable system demonstrate the ability of the designed platform to sense along the cable, and communicate with the host computer.

KEYWORDS

Underground Cable, PD, Wavelet, Wireless Sensor Network.

INTRODUCTION

Ensuring reliable and uninterrupted operation of transmission and distribution networks poses a key challenge in the area of monitoring and maintenance of power engineering systems. Indeed, monitoring the condition of high-voltage (HV) systems and cable networks is becoming increasingly important as customers demand cheaper electricity with greater security of supply. In turn, this translates to increased loading of HV cable circuits, whilst reducing overall maintenance and repair costs. Moreover, with unscheduled shutdown of equipment, additional costs are often incurred, which are subsequently found to be significantly above the cost of necessary repairs. A satisfactory online method of anticipating failure of key components is therefore required, so as to attain an economic lifetime extension of high-voltage equipment.

The development of wireless sensor networks(WSN) for monitoring and maintenance of underline cables is becoming more important among power utilities. The progress in this area is driven by the advancements in such enabling fields as ubiquitous computing, AI technologies, wireless communication, sensing, and power scavenging. The deployment of wireless sensor network systems can bring such advantages over traditional monitoring and maintenance methods as lower cost, higher measurement accuracy, and greater reliability of system operation. Due to the deregulation and the resulting increasing competition among utilities, the economic efficiency of daily operations is becoming increasingly important in power industry. One of the most costly tasks in the power industry is maintenance of power system infrastructure, namely, generating plants, transmission lines, substations, and distribution networks. A large portion of electric power distribution is accomplished through cable networks. A typical power utility maintains millions of miles of installed cables. Many urban cable installations, targeted in this project, are installed in tunnels, conduits, or pipes, which makes them accessible for WSN. Existing cable maintenance practices fall into one of the two categories: unplanned maintenance or planned maintenance. Unplanned maintenance is a response to a failure that may have caused a power outage. Planned maintenance is a scheduled inspection or replacement of power cables. Although planned maintenance ultimately delivers a more reliable continuous service, it is not an economical option for utilities. High reliability of an installed network requires conservative estimations of the remaining cable lifetime. Premature replacement of cables leads to economic losses, which could be avoided if the replacement decision were based on the specific site data rather than on generic estimates. Condition based maintenance is often viewed as a possible solution in the industry. Case studies showed that up to 2/3 of the cable systems scheduled for replacement could be kept in service with predictive diagnostics. A key component of condition based maintenance for cable systems is obtaining accurate information about the condition of each cable. Existing techniques for monitoring the aging of distribution networks require manual inspection of individual cables by maintenance staff or by outside consultants. The instrumentation used for such tasks varies from simple handheld devices to vans equipped with highly sensitive measurement devices. In all cases, the cable inspection is a costly process. A broad spectrum of sensing principles is used for the inspection tasks. Some of these sensing methods, especially acoustic detection, are greatly enhanced by the ability to take measurements along the cable, as opposed to relying on measuring parameters at the ends of the cables. The goal of this project is to develop an WSN platform that can inspect underground power distribution cables, thus providing utilities with accurate information regularly and at a lower cost.

OPERATIONAL ENVIRONMENT

The underground cable environment is not as geometrically simple as a pipe and requires a much more adaptable design for WSN. Fig. 1 shows an example of the cables and their surroundings in a 154kV underground installation at S district, Seoul, Korea.

Figure 1: A typical installation of the underground 154 kV power cables at S district ,Seoul, Korea

Discrete Wavelet Transform

Wavelet based analysis of signals is an interesting, and relatively recent, new tool. Similar to Fourier series analysis, where sinusoids are chosen as the basis function, wavelet analysis is also based on a decomposition of a signal using an orthonormal (typically, although not necessarily) family of basis functions. Unlike a sine wave, a wavelet has its energy concentrated in time. Sinusoids are useful in analyzing periodic and time invariant phenomena, while wavelets are well suited for the analysis of transient, time-varying signals.

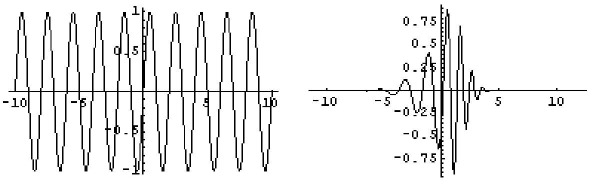

Figure 2: Sine Wave vs Wavelet.

A wavelet expansion is similar in form to the well known Fourier series expansion, but is defined by a two parameter family of functions

$$f(t) = \sum_k \sum_j a_{j,k} \psi_{j,k}(t) \qquad [1]$$

where *j* and *k* are integers and the functions $\psi_{,k}(t)$ are the wavelet expansion functions. As indicated earlier, they usually form an orthogonal basis. The two parameter expansion coefficients $a_{j,k}$ are called the discrete wavelet transform (DWT) coefficients of f(t) and Equation 1 is known as the synthesis formula (i.e., inverse transformation). The coefficients are given by

$$a_{j,k} = \int f(t) \psi_{j,k}(t)\, dt \qquad [2]$$

The wavelet basis functions are a two parameter family of functions that are related to a function $\psi(t)$ called the generating or mother wavelet by

$$\psi_{j,k}(t) = 2^{j/2}\, \psi(2^j t - k) \qquad [3]$$

where *k* is the translation and *j* the dilation or compression parameter. Therefore, wavelet basis functions are obtained from a single wavelet by translation and scaling. There is, however, no single and universal mother wavelet function. The mother wavelet must simply satisfy a small set of conditions and is typically selected based on the signal processing problem domain. Almost all useful wavelet systems satisfy the multi resolution condition. This means that given an approximation of a signal f(t) using translations of a mother wavelet up to some chosen scale, we can achieve a better approximation by using expansion signals with half the width and half as wide translation steps. This is conceptually similar to improving frequency resolution by doubling the number of harmonics (i.e., halving the fundamental harmonic) in a Fourier series expansion. It is important to note that the wavelet functions never actually enter into the calculation of the discrete wavelet transform. The computation of the transform may be formulated as a filtering operation with two related FIR filters.

The 1D discrete wavelet transform is calculated using Mallat's algorithm. The transform coefficients, c_k and d_k at different scales, are calculated using the following convolution-like expressions:

$$c_k^{j-1} = \sum_n h_{n-2k} c_n^j \qquad [4]$$
$$d_k^{j-1} = \sum_n g_{n-2k} c_n^j$$

where *j* denotes the resolution and *k* is the index for the samples. The operation defined in Equation 4 is a linear digital filtering operation using filters *h* and *g*, followed by down-sampling. The coefficients c_k^j and d_k^j are known respectively as the level *j* scaling and wavelet coefficients. The top-level coefficients c^J represent the original signal. For a signal of length *N*, where *N* is a power of two, we get J=Log [2, N]. In such a case, the iteration may be repeated *J* times with the last stage being of length one, one scaling coefficient, and one wavelet coefficient. Note that the iteration is performed over the scaling coefficients only. Here is an illustration for N=8.

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$$\begin{pmatrix} c_0^3 \\ c_1^3 \\ c_2^3 \\ c_3^3 \\ c_4^3 \\ c_5^3 \\ c_6^3 \\ c_7^3 \end{pmatrix} \longrightarrow \begin{pmatrix} \begin{pmatrix} c_0^2 \\ c_1^2 \\ c_2^2 \\ c_3^2 \end{pmatrix} \\ \begin{pmatrix} d_0^2 \\ d_1^2 \\ d_2^2 \\ d_3^2 \end{pmatrix} \end{pmatrix} \longrightarrow \begin{pmatrix} \begin{pmatrix} c_0^1 \\ c_1^1 \end{pmatrix} \\ \begin{pmatrix} d_0^1 \\ d_1^1 \end{pmatrix} \\ \begin{pmatrix} d_0^2 \\ d_1^2 \\ d_2^2 \\ d_3^2 \end{pmatrix} \end{pmatrix} \longrightarrow \begin{pmatrix} (c_0^0) \\ (d_0^0) \\ \begin{pmatrix} d_0^1 \\ d_1^1 \end{pmatrix} \\ \begin{pmatrix} d_0^2 \\ d_1^2 \\ d_2^2 \\ d_3^2 \end{pmatrix} \end{pmatrix} \qquad [5]$$

Filters *h* and *g* are FIR quadrature-mirror filters known as the scaling and wavelet filters, respectively. The scaling filter is a lowpass filter, while the wavelet filter is highpass. For an even-length scaling filter, the two are related by the following formula:

$$g_n = (-1)^n h_{N-1-n}, \qquad n = 0, 1, \ldots, N-1 \qquad [6]$$

We used two well known families of scaling/wavelet filters, and decomposed signals from underground cable line as shown in Figure 3.

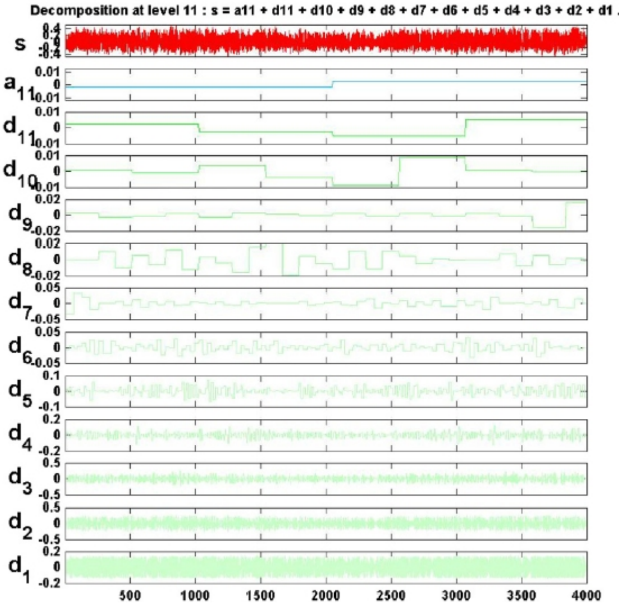

Figure 3: An example of wavelet decomposition of the signal from underground cable line.

Infrared Sensors for Hot Spots

Excessive heat build-up contributes significantly to the premature breakdown of the insulation in distribution cable networks. The consequences of premature cable failure include costly replacement and unexpected loss of power service. Factors that cause overheating include current overloading, physical damage, insulation aging, partial discharges, changes in ambient temperature, and proximity to other cables and water/steam pipes . Overheating rarely affects the entire length of the cable. Typically, so-called “hot spots” form at the points of excessive mechanical stress, water seepage, or crossings with other cables. The industrial solutions for detection of hot spots include installing fiber optic sensors along the cable length, manual inspection, or avoiding the problem and waiting until the cable fails (which is acceptable in some situations). The method presented here has never been tried with power cables and still has to prove its usefulness in an industrial setting. Infrared sensors do not need physical contact with the cable. In a few years, as technology develops, infrared sensors are likely to be replaced with infrared cameras in this application. Temperature data is acquired continuously and used for used by the control board for detection of possible incipient faults. Fig. 4 shows an artificially created hot spot measured by the infrared sensor in the laboratory conditions. As experiments continue, much more sophisticated pattern recognition algorithms will be used for pre-processing of sensor data.

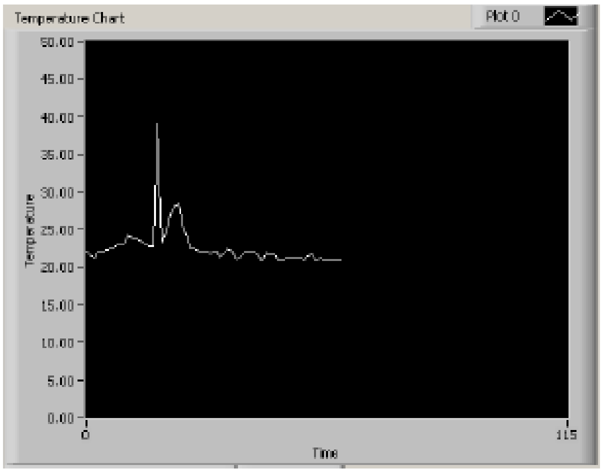

Figure 4: A screen snapshot of the temperature measurement time sequence in the user interface.

Sensors for Partial Discharges

Partial discharges (PDs) occur when a failure in the cable’s insulation causes a rapid energy release, usually resulting in a detectable acoustic vibration. In many cases, PDs are a precursor to total cable failure, and therefore are an important tool for estimating the remaining service life of a power cable.

Attenuation of the acoustic wave makes it impractical for conventional “static” distributed sensor methods to use this monitoring technique. There are significant advantages for using acoustic sensing. For instance, an acoustic emission sensor is not affected by electrical interference.

Acoustic sensing has been very successful for switchgear and transformers. However, the accurate recognition of the acoustic emissions from a partial discharge in the overall vibration pattern of the cable is a challenging task.

Attenuation pattern and the signal time-frequency characteristics are both important factors in identifying a PD. These characteristics are both dependent on the internal geometry of the cable, interfaces between the materials, absorption by the material (higher frequency components

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are removed), and the frequency dependent propagation. One of the most significant challenges when implementing the acoustic emission sensor is processing large amounts of data, which requires considerable computational resources. This is problematic due to size constraints and the harsh operating environment found in underground networks. However, the ability to transmit the raw data back to the host computer via wireless connection is not always guaranteed. Therefore, the processing of the acoustic emissions data will take place on board and the results can then be relayed back to the host computer when a connection is available.

Dielectometry Sensors for Aging Status

Measurement of dielectric properties of the outer layer of cable insulation can provide valuable insights into its status. The most obvious application is the measurement of presence of water in the bulk of the cable insulation. Water trees and electrical trees are the most common causes of partial discharges. These trees typically develop from a small initial crack, void, or delaminated area. It takes several weeks to several years before the incipient fault causes cable failure. The dielectric spectroscopy sensor is installed on WSN to make continuous measurement of the cable surface and detect abnormalities, which are not necessarily at the surface of the insulation layer. The periodic measurement, admittedly, does not guarantee detection of all processes. Partial discharges may be intermittent in time, as environment conditions change. For example, a cable with a small crack may remain dry and be in working condition in the dry hot summer. As weather changes, water may act as a conductor after this crack becomes wet, allowing for electrical discharges. In this case the acoustic sensor would not detect the water tree unless the WSN was in the right place and the right time. The fringing field dielectrometry sensor may still detect the voids in the insulation, even if they are not filled with water, although the signal change would be weaker in this case. In other words, the fringing electric field dielectrometry sensor tests the actual condition of insulating material rather than the resulting partial discharge activity . Measurement of dielectric properties can also determine the aging status of the insulation material. The changes of various physical and chemical properties of materials are reflected in the change of dielectric properties. However, this type of measurement requires highly sensitive instrumentation. It will be a very challenging task to use the existing sensor technology in order to obtain information about dielectric property changes in field conditions. The shape of the dielectrometry sensor head can vary depending on the task. Usually, the sensor head looks like an array of coplanar electrodes, possibly following the curvature of the cable.

CONCLUSIONS

A WSN based PD monitoring system for detection of incipient faults in electric power cables has been developed and tested in laboratory and in field conditions. The analysis of detectable physical phenomena led to a selection of necessary sensing principles. Four types of sensors for measurement of physical properties of the distributed infrastructure were integrated into the WSN platform and tested in laboratory conditions. The WSN based inspection method provides a viable solution to the task of monitoring and maintaining underground cable systems.

FUTURE WORK

The next immediate step of this research project is to test performance of the sensors and the platform itself in a wide variety of field conditions. Ultimately, the WSN will have to work in many different environments with many different cable configurations. Therefore, the miniaturization and the improvement of electro mechanical performance of WSN are important areas of further research. The use of energy scavenger, in the framework of WSN, is also an important direction of future work.

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GLOSSARY

WSN: Wireless Sensor Networks
PD: Partial Discharge