Sensors for measurement of moisture diffusion in power cables with oil-impregnated paper

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Abstract. Some old power cables use oil-impregnated paper as the insulation material, which is enclosed by a layer of lead sheath. As cracks can form on the sheath of aged cables, the oil-impregnated paper can be exposed to the environmental conditions, and ambient moisture can diffuse into the paper through the cracks, causing a reduced breakdown voltage. To understand this diffusion phenomenon, multi-wavelength dielectrometry sensors have been used to measure permittivity and conductivity, aiming to obtain information on the moisture content. Different electrode-grouping strategies have been suggested to obtain more detailed information. Effectively, an electrode-grouping approach forms a type of electrical capacitance tomography sensor. This paper presents different sensor designs together with a capacitance measuring circuit. Some analytical results are also presented.

1. Introduction

In the power industry, some old power cables with oil-impregnated paper as the insulation material are still in use. It is important to determine the condition of the oil-impregnated paper because it can influence the reliability of electricity supply. Moisture is one of the most important parameters to be considered because cracks can form on the sheath of aged cables and the invasion and diffusion of moisture into oil-impregnated paper through cracks can cause a reduced breakdown voltage and could cause a disaster.

In Sweden, dielectric spectroscopy was applied for non-destructive measurement of humidity in oil-impregnated paper in power cables [1], [2]. They used a balancing circuit to measure the loss tangent of capacitance between the core conductors and the lead sheath, in a frequency range from 1 kHz to 1 MHz. From the minimum loss tangent, the average moisture content in a whole cable can be estimated. They also developed a mathematical model to estimate the diffusion coefficient as a

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function of moisture content and temperature. One of the limitations of this approach is that it can provide detailed information neither on local moisture content nor on the moisture diffusion process.

The aim of this work is to investigate different designs of segmented capacitance sensors, including multi-wavelength dielectrometry sensor, multi-channel sensor and tomography sensor, for the measurement of the moisture content and the moisture diffusion process.

2. Multi-wavelength dielectrometry sensor

2.1 Sensor structure

At MIT, multi-wavelength dielectrometry sensors, which are also called multi-wavelength inter-digital sensors, have been developed for years [3], [4], [5]. Fig.1 shows a typical multi-wavelength dielectrometry sensor with three wavelengths, 1, 2.5 and 5 mm. Effectively, it is a comb-structure capacitive sensor, which makes use of fringe effect to measure capacitance. Different sensing depths can be achieved by changing the electrode width and electrode spacing. The sensor shown in Fig.1 is printed on a substrate for mechanical support, and the opposing face is held to a fixed potential to eliminate the external interference affecting the sensor response.

This sensor shown in Fig.1 can provide 3 different sensing depths and can be conformed to a planar or cylindrical geometry, depending on the requirement. For power cables the cylindrical setup is needed. The orientation of the electrodes is periodic in the angular direction (\( \varphi \) periodic), or along the cylinders axis (\( z \) periodic) as shown in the left and right pictures respectively in Fig.2.

A limitation of this type of sensor is that the measurement strategy is fixed. Always half of the electrodes are grouped together for excitation and the other half for detection. As a result, the sensing depth is determined by predetermined periodicity of the electrodes and cannot be changed without replacing the sensor.

2.2 Analysis of multi-wavelength dielectrometry sensor

The sensor shown in Fig.1 can be modeled analytically with excellent results [5] if a few approximations are permitted, e.g. the electrode periodicity is assumed to extend to infinity, and the electrodes are infinitely long and infinitely thin. For low frequency excitations, the Laplace equation is applied and a separable form may be found. Three geometries have been considered: (1) planar, (2) cylindrical with periodicity in \( \varphi \) and (3) cylindrical with periodicity in \( z \). The solutions are exponentials for the planar case, \( r^n \) for the \( \varphi \) periodic case, and Bessel functions for the \( z \) periodic case. The Fourier theory and the collocation method have been used to determine the field solutions along with expressions for the admittance between the excitation and detection groups of electrodes.
To measure capacitance, the excitation electrode of a sensor is connected directly to a sinusoidal source and the backplane is connected to ground. The detection electrode is connected to a current-to-voltage converter with feedback capacitance, $C_f$. The test material is modeled as a frequency-dependent capacitance $C(\omega)$ in parallel with a frequency-dependent conductance $G(\omega)$. The transfer function of the sensor is

$$\frac{V_{\text{detection}}}{V_{\text{excitation}}} = \frac{j\omega C(\omega) + G(\omega)}{j\omega C_f}$$

(1)

Experimental results and simulation suggest that the thickness of electrodes relative to the spacing between electrodes is primarily accountable for differences between the theoretical results and measurements. In one sensor design the electrodes are made of a copper cladding on a Teflon substrate. The electrodes extend $17 \, \mu m$ above the surface of the Teflon, which is $7\%$ of the $250 \, \mu m$ gap between adjacent electrodes on a typical $1 \, \text{mm}$ wavelength sensor. This results in a measurable parasitic capacitance. For a $5 \, \text{mm}$ wavelength, the thickness of electrodes is only $1.4\%$ of the gap width and the theoretical assumption has minimal impact. For large wavelengths the thickness can reasonably be ignored and experimental results are typically in good agreement with theory. A derivation taking into account the thickness of electrodes has been made for the case of a planar geometry [6].

The moisture content and temperature of the cable insulation affects its permittivity and conductivity. It is necessary to investigate this relationship experimentally.

2.3 Measurement of moisture dynamics

The sensor shown in Fig.1 has been used to measure permittivity and conductivity of power cables with oil-impregnated paper as the insulation material. The sensor was attached to a $12 \, \text{cm}$ in length sample of a cylindrical power cable with its outer sheath removed. The electrodes aligned with the axis of the cylinder forming a $\phi$ periodic sensor geometry.

A clamping mechanism insures intimate contact between the surface of oil-impregnated paper and the sensor. The clamp also serves to limit the moisture entrance primarily to the ends of the cable rather than the cylindrical surface. The cable and the sensor were placed inside a sealed chamber with the temperature regulated to $83^\circ C$. The chamber was evacuated to remove humidity from the cable. Moist air was injected to the chamber, raising the relative humidity to $50\%$ at day zero. Dielectrometry measurements were continuously taken at 10, 100, 1,000, and 10,000 Hz for six days, after which moisture was removed using a vacuum pump.

The ambient moisture diffuses into the cable, causing the permittivity and conductivity to increase. Fig.3 shows the measured results on the $2.5 \, \text{mm}$ wavelength channel. At day zero, the response is approximately frequency-independent, with a gain of $-65 \, \text{dB}$, and a phase angle of $180^\circ$. As the experiment proceeds, the amplitude and phase of measurements at $10 \, \text{Hz}$ shows the most dramatic changes, due to an increased conductivity and $G(\omega)$. The increase in permittivity represented by $C(\omega)$ is apparent in high frequency measurements. Note that spikes in the data correspond to brief drops in temperature, due to failure of the controller hardware. The data clearly shows the long term effect of these temperature irregularities is negligible.
3 Multi-channel sensor

3.1 Sensor structure
The sensor shown in Fig.1 has two primary limitations: (1) the wavelengths are fixed, and (2) the spatial resolution is limited to the direction perpendicular to the electrode surface. To overcome these limitations due to the fixed measurement strategy, multi-channel sensors have been considered. With this type of sensor, the minimum sensor periodicity is limited to the physical periodicity of electrodes and effective periodicities can be achieved in discrete quantities by pairing consecutive electrodes for excitation or detection. For example, in the traditional configuration, electrodes are used for $EDED$, where $E$ stands for excitation and $D$ detection. With the new configuration, however, the effective wavelength can be doubled by an arrangement of $EEDDEDD$. Furthermore, if each detection electrode is independently measured a profile can be generated in the direction of electrode periodicity.

Various electrode configurations and the resulting sensing depth have been analyzed theoretically. To demonstrate the ability of creating a complex profile along the direction of periodicity, a multi-channel sensor with fixed periodicity has been developed (see Fig.4). It features 6 independent 5 mm detection channels with 2 electrodes each (grey). This sensor can be used in a $z$ periodic configuration to observe moisture diffusion in the $z$ direction.

3.2 Initial experimental results
To demonstrate the concept a dry wooden rod of approximately 9 cm in length was wrapped up by the multi-channel fixed periodicity sensor shown in Fig.4. Moisture was allowed to enter through only one end of the rod and all other surfaces are sealed. Fig.5 shows the gain of each channel relative to the gain at time zero. The excitation frequency is...
400 Hz. Moisture entered from position 0 cm, and moved to the right. The data points are drawn at the nominal position of the electrodes. The diffusion process is clearly visible. The amplitude increases as the moisture diffuses into the rod. The resolution is 1 cm except for the gap in the center. This indicates substantial improvement over the previous sensor. With the appropriate hardware, the resolution could be increased to 2.5 mm for the same electrode periodicity. This technology will be applied to the cables of interest.

Figure 5: Amplitude measurements of 6 channels at 400 Hz

4 Tomography sensor
At the University of Manchester, electrical capacitance tomography (ECT) sensors have been investigated for generating cross-sectional images. The sensors discussed above are actually special cases of ECT sensor. Fig.6 shows a typical ECT sensor with 16 measurement electrodes surrounding a power cable. In this design, all electrodes can be used either for excitation or detection. When one electrode is energized, the induced currents are measured from all other electrodes. With a 16-electrode sensor, there are \(16 \times (16-1)/2 = 120\) independent measurements, from which a cross-sectional image can be reconstructed [6], representing permittivity and possibly conductivity distributions. Further work will be done with this type of sensor.

In Fig.6, if each electrode is energized in turn but measurements are only taken from adjacent electrodes, then all capacitance measurements from adjacent electrode pairs can be averaged to present a single capacitance measurement, which is the same as the measurement from a single-wavelength dielectrometry sensor. Multi-wavelengths can also be achieved using an ECT sensor by electrode combination and selective spacing between a combined excitation electrode and combined detection electrodes. For example, when electrodes 1 and 2 in Fig.6 are energized, a measurement can be taken from electrodes 5 and 6 and a second measurement from electrodes 13 and 14. Effectively, the wavelength is doubled of the single electrode measurement strategy.

Figure 6: ECT sensor with 16 measurement electrodes

5 Capacitance measuring circuits
Fig.7 shows a design of capacitance measuring circuit. In this design, two CMOS switches are used to connect the non-inverting input of an op-amp either to an AC excitation source or to ground. A third
CMOS switch is used to enable direct feedback from the output to the inverting input of the op-amp. In Fig. 7 (a), when the non-inverting input is connected to an excitation source and the third switch is closed, connecting the output directly to the inverting input of the op-amp, the potential on the electrode is the same as the excitation source and hence the electrode is used for excitation. In Fig. 7 (b), when the non-inverting input of the op-amp is connected to ground and the third switch is open, the op-amp is configured as an inverting amplifier and used to convert an AC current, which is induced from an excitation electrode, into an AC voltage. In this case, the electrode is used for detection. Note that the switch across the feedback capacitance is always needed as a means of discharging the capacitor prior to measurements.

![Diagram of excitation and detection](image)

**Figure 7**: Design of first stage of capacitance measuring circuit

Alternatively, a charge/discharge capacitance measuring circuit, which is commonly used in ECT, may be employed. This circuit is stray-immune, fast response and low cost. However, it requires frequent calibration because of charge injection of CMOS switches used. More details of this circuit can be found from literature [8].

### 6 Conclusions and discussion

The invasion of moisture into old power cables with oil-impregnated paper is a common problem. In this paper, a sensing technique based on capacitance measurement has been presented, which can be used to monitor moisture diffusion in such power cables. Laboratory measurements using these sensors provide an understanding of moisture diffusion in the cables and its effects on the electrical properties of the insulation. The work presented in this paper may benefit the power industry by replacing old cables prior to imminent failure.

Currently, 3D imaging is an active research topic [9], [10]. As indicated in Fig. 2, a multi-channel sensor can take a form of multi-strips or multi-rings. If these two forms are combined together, it becomes a 3D sensor. While the relationships between moisture content, temperature, permittivity and conductivity can be analyzed theoretically, it is useful to carry out simulation using a finite element software package, e.g. from Ansoft or COMSOL, to verify the analytical results. Computational fluid dynamics (CFD) simulation packages, e.g. Fluent, are commonly used to investigate mass and heat transfer in process engineering. At the University of Manchester, significant simulation work using Fluent has been done to investigate fluidized bed drying processes, which is, in principle, the inverse of a moisture diffusion process [11]. A future work is to investigate the moisture diffusion process by software simulation using Fluent.
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