MEASUREMENT OF TEMPERATURE IN XLPE INSULATION OF POWER CABLES USING ULTRASONIC DIAGNOSIS

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Abstract: In power cable manufacture the production of the insulation system is the most important and most critical part due to high quality standards. In the cross linking process of the insulation material the temperature is a very important aspect. To avoid critical temperatures inside the cable insulation after the cross linking process, the production speed has to be reduced to ensure an adequate cooling of the core. Within this paper a new method is presented to measure and monitor the temperature at interfaces inside polymeric insulation systems as such as in power cable insulations. Therefore the acoustical characteristics of cross linked polyethylene (XLPE) are investigated. Exemplary ultrasonic measurements on synthetic test samples show strong dependency on temperature changes. After evaluating the ultrasonic data a coefficient is found, which is correlated to an acoustic model. As a result of this procedure an accuracy of about +/- 3 °C of determined temperature can be reached.

1 INTRODUCTION

Modern power cables consist of cross linked polyethylene (XLPE) as a standard insulation material. The polyethylene is extruded on a metallic conductor and afterwards cross linked in the cross linking line (CV-line). Due to the high temperature in the CV-line the conductor is heated up. After cross linking process the cable core is cooled down to room temperature by a water bath to stop the chemical cross linking process and to enhance mechanical stability of the cable core, which is spooled up on a drum for the next production step. Due to the metal conductor's heat capacity, the time between cooling and spooling of the cable core is a critical aspect. The cable core will be re-heated by the conductor especially at inner parts of the insulation system which degrades the mechanical stability and is able to restart a cross linking process due to the high temperature. Restarting a cross linking process can lead to gas inclusions and delaminations in the insulation system of the cable. To avoid critical temperatures inside the cable insulation, the production speed has to be reduced to ensure an adequate cooling of the core. Hence, the inner temperature is an important process parameter to find optimal speed and ensure quality of production at the same time.

Today, conductor temperatures after extrusion process can only be simulated based on boundary conditions in the working production line. Variations of those conditions during the production process, for example in a case of a failure in the production line, are not detectable. So, there is a risk of poor cable quality. In this paper a method is developed to measure and monitor interface temperatures with ultrasonic diagnosis such as the interface between the insulation and the semiconducting layer of a power cable.

2 BASICS ON ULTRASONIC DIAGNOSIS

Acoustical waves with frequencies above 22 kHz are classified as ultrasonic waves (ultrasound). Those mechanical waves can propagate in materials due to the mechanical coupling of the molecules. Ultrasonic waves are generated by using a piezo ceramic which is triggered by a voltage impulse in the range of usual 100 to 400 Volts [1]. Figure 1 shows a typical ultrasonic impulse.

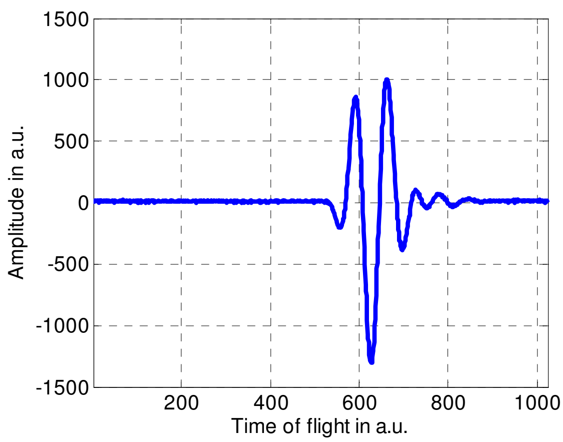

Figure 1: Typical ultrasonic impulse

2.1 Propagation of sound

Ultrasonic sound impulses, generated by a transducer, propagate in materials with a certain sound velocity *c* which is calculated by

$$c = \frac{2s}{t} \qquad \text{(F1)}$$

where *s* is the propagation distance inside the material and *t* the time of flight (TOF) needed by the impulse to propagate through the material [1]. Factor 2 results from the reflection and the way back to the transducer, where it is received. Thus, distance *d* is passed twice. In general, the sound velocity of polymeric materials shows a certain dependency on temperature. Hence, sound velocity *c* is a function of temperature ϑ [3, 4, 5].

Sound impulses propagating from the transducer through the sample are reflected at inner interfaces of two materials and propagate back to the transducer receiving the impulse. The reflection itself is caused by differences in the sound impedances *Z* of materials. The sound impedance is defined as product of density ρ and sound velocity *c* of the material:

$$Z(\vartheta) = c(\vartheta)\rho \qquad \text{(F2)}$$

For example, XLPE has a sound impedance of about $1.9 \cdot 10^6$ kg/(m^{2}s) at room temperature, and metal usually about $40 \cdot 10^6$ kg/(m^{2}s) – independent of temperature.

Similar to travelling waves on transmission lines for example the reflection of ultrasonic waves is described as follows

$$R(\vartheta) = \frac{Z_2(\vartheta) - Z_1(\vartheta)}{Z_2(\vartheta) + Z_1(\vartheta)} \qquad \text{(F3)}$$

where Z_i are the different sound impedances of the materials [1]. Due to the temperature dependency of sound velocity in polymeric materials the reflection coefficient of interfaces in polymers changes depending on temperature of the materials. However, especially for an interface between metal and polymer the independence of the metal's sound impedance will cause nearly constant reflection behaviour over temperature ($R \approx 0.91$).

2.2 Attenuation of sound

A typical ultrasonic impulse can be described as linear combination of several parameters such as reflection, transmission and attenuation in the propagation material.

$$p(t,\vartheta) = p_0(t,\vartheta) \cdot T_{in}(\vartheta) \cdot D(\vartheta) \cdot R(\vartheta) \cdot T_{out}(\vartheta) \qquad \text{(F4)}$$

$p_0(t, \vartheta)$ is the send sound impulse at a certain temperature ϑ, *T* the transmission factor of coupling the sound into the material and *R* the reflection coefficient of a reflecting interface. The term *D* describes the material specific attenuation of sound which also shows temperature dependency. It can be shown that the attenuation is from an exponential type [1]. Additionally, the attenuation of polymer materials shows frequency dependent behaviour [4, 5]. Hence the attenuation term is described as

$$D(\vartheta, f, d) = e^{(-2 \cdot \alpha(\vartheta, f) \cdot d)} \qquad \text{(F5)}$$

where *d* is the thickness of the material the ultrasonic impulse propagates through, and $\alpha(\vartheta, f)$ is the frequency specific and temperature dependent attenuation coefficient of sound inside the polymer. The factor 2 results from the doubled distance the impulse have to propagate, because the impulse is send into the material, reflected and travelling back to the ultrasonic transducer where it is received again.

2.3 Spectral analysis of ultrasonic signals

Due to the dependency of the attenuation on frequency, it is necessary to do the analysis of the ultrasonic signals in the signal spectrum. Therefore, the ultrasonic signals are transformed to frequency domain using FFT [2]. Based on the signal description (F4) the Fourier transform is

$$\begin{aligned} &P(f,\vartheta) = FFT(p(t,\vartheta)) = \\ &P_0(f,\vartheta) \cdot T_{in}(\vartheta) \cdot e^{(-2d\alpha(\vartheta,f))} \cdot R(\vartheta) \cdot T_{out}(\vartheta) \end{aligned} \qquad \text{(F6)}$$

Parts such as transmission *T* and reflection coefficient *R* are independent of time, so that they are transformed to constants independent of frequency. Figure 2 shows the frequency spectrum of the ultrasonic impulse from figure 1.

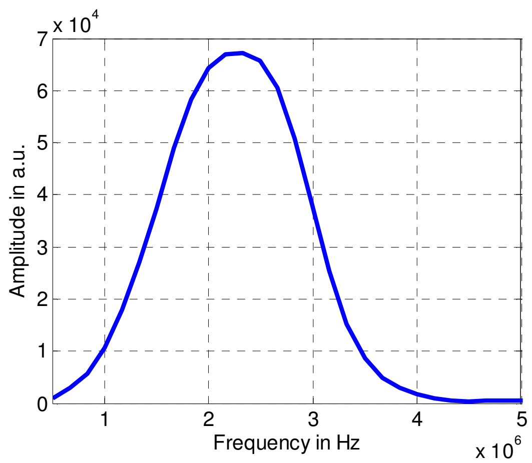

Figure 2: Frequency spectrum of a typical ultrasonic impulse

3 INVESTIGATIONS ON ACOUSTICAL PROPERTIES OF XLPE MATERIAL

For a proper modelling of ultrasound regarding formula (F4) several parameters have to be known. Hence, acoustical material parameters of cross linked polyethylene (XLPE) and their dependency on temperature are investigated in a first step.

The evaluation of the sound impedances of XLPE and carbonized XLPE calculated from sound velocity and density show linear decreasing behaviour over temperature (figure 3). Both are in the same range, thus a low reflection coefficient is expected.

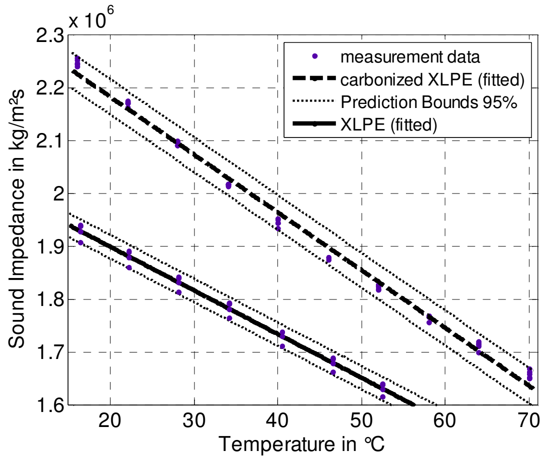

Figure 3: Sound impedances of XLPE and carbonized XLPE over temperature

Moreover, the different gradient of the impedances over temperature will lead to temperature dependency of the reflection coefficient. The resulting theoretical coefficient calculated using the linear fittings of the sound impedances given by formula (F3) is shown in figure 4.

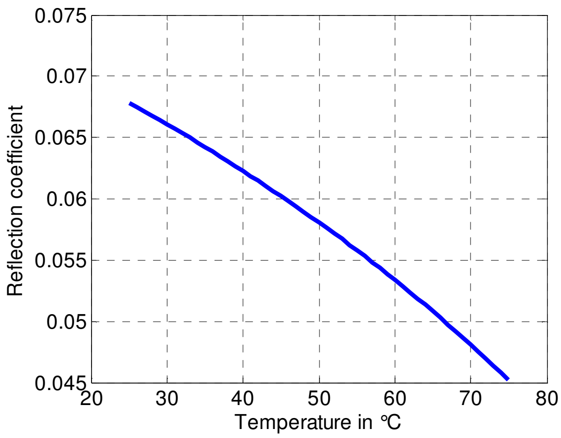

Figure 4: Calculated reflection coefficient of the interface between XLPE and carbonized XLPE dependent on interface temperature

The value of reflection ranges from 7 % to 4.5 % over a temperature range from 25 °C to 75 °C, which means that the amplitude of ultrasonic impulses reflected at the interface decreases on higher interface temperatures.

In a reverse conclusion the amplitude of an ultrasonic signal reflected at an inner interface of XLPE and carbonized XLPE and the theoretical reflection coefficient can be used to evaluate the interface temperature. Therefore, the reflection coefficient R in the formal description of ultrasonic signals (F4) has to be isolated by compensating the attenuation parts (D^2) and the initial sound impulse p_0. It can be shown that the linear combination of the transmission into and out of the material results in a negligible change over temperature (0.25 % over 50 °C), thus a further consideration is not necessary. Comparison between measured and theoretical calculated reflection coefficient makes it possible to determine the temperature at the interface. For example a measured reflection coefficient of 0.06 means an interface temperature of 45 °C.

As a last acoustical parameter in formula (F4) the attenuation has to be investigated. Measurements of the attenuation of sound in XLPE show a strong frequency dependency. High frequency parts of ultrasonic signals are addicted to higher attenuation than lower frequencies. Moreover, the attenuation effect becomes lower with increasing temperature of the XLPE. Figure 5 shows the attenuation coefficients of XLPE over frequency at different temperatures.

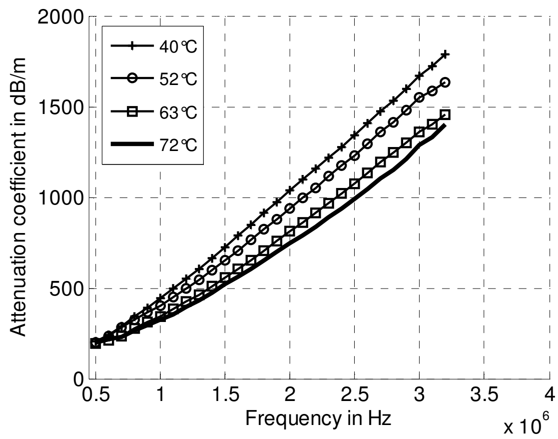

Figure 5: Attenuation of sound in XLPE

3.1 Compensation procedure of the acoustic attenuation of sound in XLPE

For isolation of the reflection coefficient in the formula (F4), it is necessary to compensate the attenuation of sound. With respect to the frequency specific attenuation, the evaluation of the reflection coefficient has to be done in the spectrum of the measured ultrasonic signal. Figure 6 demonstrates the procedure of evaluating the reflection coefficient.

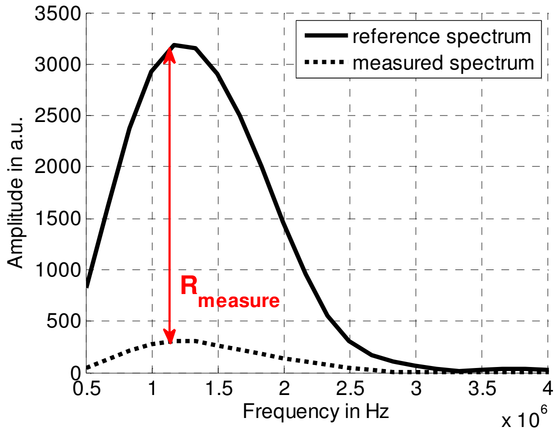

Figure 6: Comparison of signal spectrums to evaluate the reflection coefficient at a certain temperature

After FFT of the measured signal the amplitude's value at the middle frequency of the measured spectrum is set in relation to the amplitude of a reference spectrum. Those references are impulses, which are addicted to the same attenuation than the measured impulse, but reflected with $R = 1$. Due to the usage of the same transducer, it is ensured, that even p_0 (t, Θ) is the same for the measured and the reference impulse. Based on the general description of the ultrasound (F4) the relation leads to the reflection coefficient R of the interface. A correlation of the theoretical reflection coefficient (fig. 4) and the measured coefficient, leads to the temperature at the interface.

4 INVESTIGATIONS ON SYNTHETIC XLPE SAMPLES

For exemplary measurements a cubical XLPE sample with an interface to carbonized XLPE (fig. 7, left) is heated in a water bath in the temperature range from 40 °C to 68 °C. At certain temperature steps the ultrasonic signal reflected at the inner interface is recorded. The ultrasonic transducer is arranged orthogonal to the test sample's interfaces and sends 2 MHz impulses through the water into the samples, where the impulses are reflected at the inner interfaces. The temperature distribution inside the sample is homogeneous and stationary during the ultrasonic measurement.

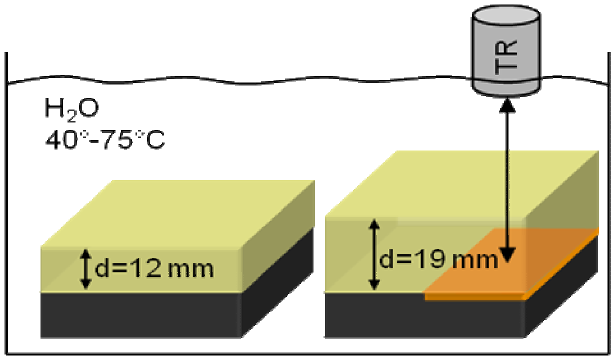

Figure 7: Test setup with synthetic samples, sample 1 with a carbon interface (left), sample 2 with metal reference (right)

Plotting the maximum ultrasonic amplitude over the sample's temperature shows a strong dependency on the material's temperature (fig. 8).

The exponential rise in amplitude can be explained by the decreasing attenuation in XLPE at higher temperatures, which has the main influence on the ultrasonic signal in comparison to the reduced reflection at high temperatures (cf. fig. 4).

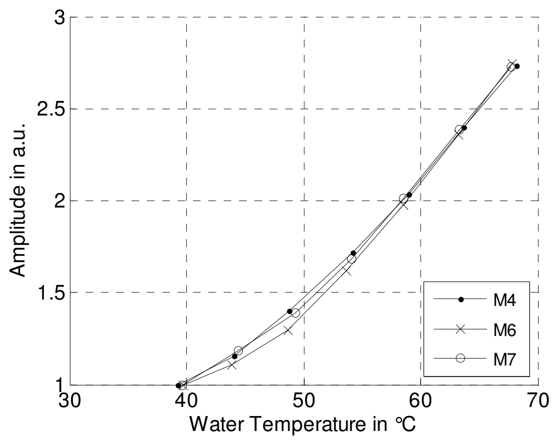

Figure 8: Maximum normalized ultrasonic amplitudes of the three ultrasonic measurements on sample type 1

Moreover, the three independent measurements show good reproducibility. If this plot is used as a calibration curve for the test setup, the interface temperature could be predicted with an accuracy of about +/- 3 °C.

5 COMPENSATION OF ATTENUATION BY REFERENCE SIGNAL

The second investigation deals with the compensation of the acoustical attenuation of XLPE. The setup is equal to the first measurements except the sample type. The second type (Smp2) is a cubical sample, which has two different inner interfaces: The first interface is also an interface to carbonized XLPE; the second interface is realized by a metal plate, which is placed in the same depth as the carbon interface (fig. 7, right). Hence, the propagation distance through XLPE to the metal and the carbon reflector are the same, so the metal reflection can be used as reference signal with $R = 1$. The sample is heated in a water bath in the range from 40 °C to 75 °C and in each temperature step the reflected impulse from the carbon interface and the metal plate is recorded and transformed via FFT for analysis. Figure 9 shows spectrums of both reflecting interfaces at exemplary temperatures of 48 °C and 75 °C.

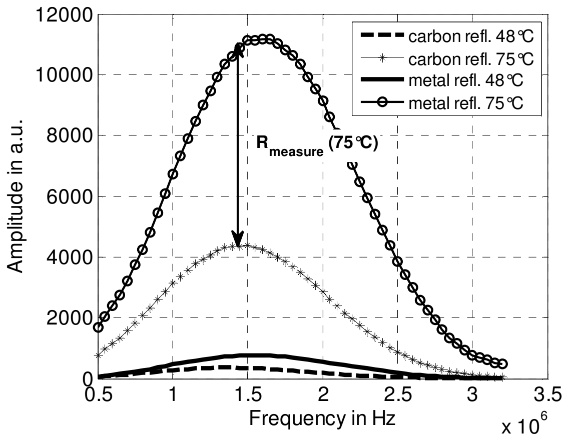

Figure 9: Exemplary frequency spectrums of the ultrasonic signals reflected at the metal interface and the carbon interface

Regarding the knowledge about the acoustical attenuation of XLPE, high temperatures lead to higher amplitudes, which can be verified in figure 9. Comparing the reflected signals at the same temperature, they show good similarity in frequency behaviour (fig. 9).

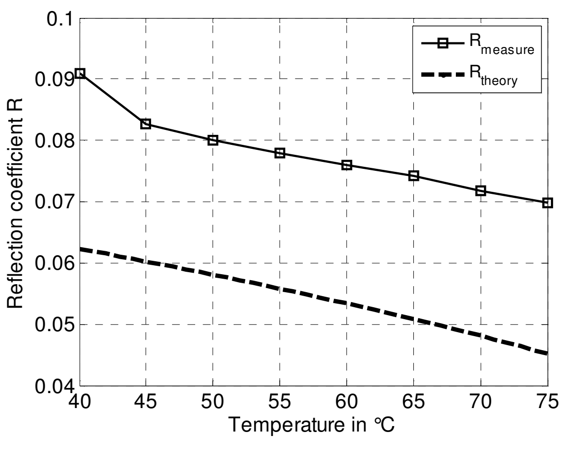

Figure 10: Reflection coefficient of the carbon interface over interface temperature, theoretical (dashed), measured (solid)

Based on the compensation procedure, described in chapter 3.1, the spectrums are evaluated at the centre frequency of the received impulse (f_{center} = 1.5 MHz) at each temperature step. The resulting reflection coefficient lies in the same dimension as the theoretical coefficient (fig. 10).

Furthermore, the dynamic of the measured reflection coefficient is consistent with the theory but shows a static offset of about 0.023, explainable by mechanical effects due to temperature changes. Polymers, such as XLPE, expand with rising temperature. So the inner interfaces (metal and carbon) can vary their orientation to the transducer. Such changes cause variations in amplitude and frequency of the received ultrasonic impulse due to scattering of sound. Hence, the reflection coefficient will differ from the theoretical coefficient calculated with respect to ideal and not changing reflector orientation.

6 SUMMARY

Within this publication investigations on the acoustic parameters of cross linked polyethylene (XLPE) are carried out. Special focus lies on the temperature dependency of the material characteristics and an evaluation procedure to measure the temperature at inner interfaces, especially at the interface between XLPE and carbonized XLPE as such as in a power cable. The exemplary measurements are done on synthetic test samples of XLPE which are tempered in a water bath. At several temperature steps ultrasonic measurements are executed. The ultrasonic measurement data are evaluated with a new analysis method to estimate the temperature at the interface between XLPE and carbonized XLPE.

As a result it is found that ultrasonic signals, reflected at the interface, are strongly dependent on temperature changes. Moreover, the measured ultrasonic amplitudes show good reproducibility, so that calibration curves (cf. fig 8) can be used for an estimation of the sample's temperature. The accuracy of the estimated temperature is in the range of +/- 3 °C. Using the compensation procedure, described in 3.1, it is possible to determine the interface temperature correlating the theoretical reflection coefficient with the ultrasonic measurement. It is found that there is an offset of about 0.023 between the coefficient, calculated from the measurement data, and the theoretical coefficient. This divergence can be explained by thermo mechanical effects inside the samples. Due to changing temperature the polymer expands and mechanical forces can cause variation of the reflector's orientation to the transducer, which should be 90 ° in an ideal case. If the offset can be eliminated the accuracy of the temperature determination will be about +/- 3 °C, similar to the calibration method.

7 REFERENCES

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