DIELECTRIC LOSS MEASUREMENT OF POWER CABLES USING HAMON APPROXIMATION

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ABSTRACT

For many years dielectric loss measurement has been a well known technique for condition assessment of all types of MV cable insulation like XLPE, EPR and PILC. Different measurement methods have been established in frequency domain, frequency domain spectroscopy (FDS), Time Domain and even combined ones. This paper presents measurements of the dielectric loss spectrum of artificial models as well as MV PILC and EPR cables by using the Hamon Transformation. The results are compared to classical tanδ measurements, using a sinusoidal VLF source. The portable prototype is composed of a sensor unit and a cosine rectangular-alike VLF voltage source, to determine the loss spectrum at different voltage levels. Hereby the Hamon Transformation takes advantage of giving a loss spectrum in the range of 0.02Hz – 1Hz using an excitation voltage with a frequency of 0.1Hz. More information about the test object can be gathered in the same measurement duration applied by a classical system. A loss spectrum distributes higher support for interpretation and evaluation of an aging condition of the test object in comparison to a single tanδ value determined at 0.1Hz.The measurement duration is reduced multiple times compared to classical measurement systems. This fact makes it highly interesting for field application.

INTRODUCTION

Publications about the phenomena of water treeing in XLPE and humidity in paper-mass cables are manifold. Different measurement techniques, like frequency domain spectroscopy (FDS), relaxation current analysis (IRC), return voltage measurement (RVM) and time domain spectroscopy (TDS) have already been established and are well known for doing diagnosis on power cables. Nevertheless the investigations towards new and more applicable measurement systems never stops. This paper considers the application of the so called Hamon approximation, which transforms the dielectric loss factor spectrum out of the measurement of polarisation or depolarisation current, on power cables. The transformation may be associated with dielectric loss measurement / spectroscopy of power transformers, general oil dielectrics or even in MV power cables. [3, 4, 6 ,7, 9]

The measurement system takes advantage by the Hamon approximation determining the loss factor spectrum within one VLF cycle, either at 0.1Hz or at 0.01Hz. More information can be gathered regarding the spectral distribution of the tanδ, while conventional FDS methods obtain the loss factor at the applied test frequency of the VLF source. So, significant measurement time could be saved.

Furthermore for XLPE cables it was shown at [8] that spectroscopy could also give more information about the type of defect. In particular for paper-oil objects the effect of humidity could be clearly seen by typical distribution of the tanδ in frequency.

THEORETICAL BACKGROUND

The Hamon approximation was invented by B. V. Hamon in the year 1951 and uses the charging current to calculate a frequency spectrum. In [2] the verification of the approximation was done by using an AC bridge.

The key issue is to measure the polarisation and depolarisation current, because these currents are determined by different known effects like, electronic polarisation, ionic polarisation, orientational polarisation, interfacial polarisation and tapping / hopping of charge carriers. [1, 10]

In the case of water treeing in PE insulation or humidity in paper-oil systems the orientational polarisation caused by water ingress contributes a large part to the measured polarisation current. This allows the application of diagnostics tools for monitoring water ingress of energy cables.

The Hamon approximation (2) uses in its limitations (0.3 < n < 1.2) a piecewise application of the "Curie von Schweindler" model. In terms of equations the decay function (1) could be expressed like:

$$\Phi(t) = \beta \cdot C_0 \cdot t^{-n} = A \cdot t^{-n} \quad (1)$$

Since the measured polarisation current fits the given bounds the approximation is applicable. Furthermore it could be concluded, that the smoother the distribution of the current is the closer the approximation (2) will be. [5, 2]

The Hamon approximation can be expressed as:

$$\tan\delta(0.1/t) \approx \frac{i_{pol}(0.1/t)}{\omega \cdot C_0 \cdot U} \qquad (2)$$

The polarisation current is chosen for measurement, because of the following reasons:

- measurement of the current including the cable conductance, because it is mainly affected by water ingress.
- continuos VLF voltage sources do not allow measurement of depolarisation current.
- measurements done by [4] showed good correlation of polarisation current and VLF

The polarisation measured can be expressed as the sum of current of the conductance, the geometric capacitance and the absorption current. If the Debey model is considered, which represents an equivalent circuit for modelling any linear dielectric, like depicted in Fig. 1, the absorption current is determined by the R_iC_i – elements (i = 1…n).

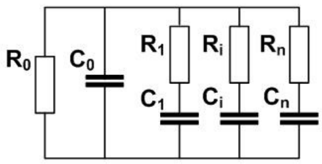


Figure 1. Debey model for linear dielectric

$$\tan\delta(\omega)=\frac{\frac{1}{\omega R_0}+\sum_{i=1}^{n}\left(\frac{\omega R_i C_i^2}{1+(\omega R_i C_i)^2}\right)}{C_0+\sum_{i=1}^{n}\left(\frac{C_i}{1+(\omega R_i C_i)^2}\right)} \quad (3)$$

Applying the equivalent circuit of Fig.1 the corresponding dielectric loss factor tanδ of any combination for (i = 1..n) can be determined by (3).
The section "Assessment of artificial cable model" of this paper shows the verification of the measuring results by Hamon approximation of artificial models following the Debey equivalent circuit to the theoretically calculated loss factor by (3).

THE MEASUREMENT EQUIPMENT

The measurement equipment is composed of a VLF rectangular alike source, which is able to power up test objects to 20kVrms. The source provides the option either to apply the set voltage with a frequency of 0.1Hz or 0.01Hz. The sense of the modus will be clarified by explaining the limits of the system. In addition to the source a measurement sensor, which captures accurately voltage, current and the test object capacitance is used. The measurement take place at high potential, which forces to set up the sensor in a proper way on a isolated tripod. The sensor will be plugged with a short connection cable to the test object and another HV-cable to the source. Since the measurement is done at high potential the galvanic isolation is provided by a radio link to the reception box, which is controlled by the application software. Fig. 2 shows the set up of the sensor connected to a XLPE test object.

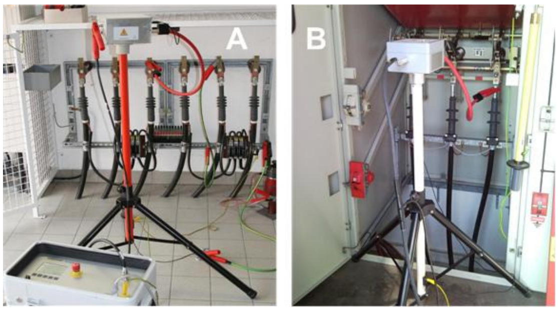
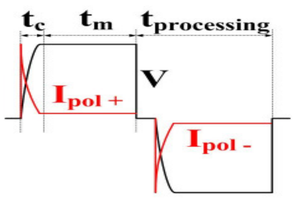


Figure 2. Hamon system (A) – FDS system (B)

Limits of the Hamon transformation using the measurement equipment

Fig.3 displays the principle distribution of the voltage powered by the source and the corresponding polarisation current in one period.
By the usage of a common VLF source an ideal voltage step could not be expected, due to the limited current. The voltage needs about t_c = 0.3s to reach the set voltage level, during this time the measured current is mainly determined by the VLF source, not by the object parameters. Therefore the Hamon approximation is not applicable in this time. As a consequence the upper bound (4) of the tanδ spectrum could be calculated. The lower bound is given by the frequency applied by the VLF source. The VLF source has two modes to apply: 0.1Hz (t_m = 5s) and 0.01Hz (t_m = 50s). Taking into account the two modes the lower bound of the tanδ spectrum can be calculated by (5) and (6).



$$f = 0.1/t = 0.1/0.3s = 0.33Hz \quad (4)$$

$$f_{VLF\,0.1Hz} = 0.1/5s = 0.02Hz \quad (5)$$

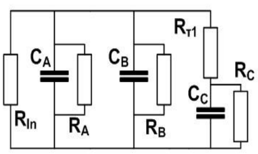
$$f_{VLF\,0.01Hz} = 0.1/50s = 0.002Hz \quad (6)$$

Figure 3. VLF voltge and current principle

The sensor is configured to measure the positive voltage cycle only. The negative cycle is used to do the processing like, transfer captured measurement data to the control software.
The accuracy depends directly the accuracy of the voltage, current and capacitance measurement, since out of those parameters the tanδ is calculated see (2). So far a total measurement accuracy of the tanδ about ± 1·10-3 is expected.

ASSESSMENT OF ARTIFICIAL CABLE MODEL

In order to prove and to understand the Hamon approximation it is demonstrated by applying an artificial model. The model was built by following the Debey model for linear dielectrics. Its tanδ value was calculated to be in the range of a common healthy PILC cable. The modelling of the cable capacitance is done by different capacitances and resistances, see Fig. 4. Since all capacities got a finite dielectric loss, like depicted in Fig. 4 C_A, C_B and C_C, the tanδ of each capacitance must be determined first.



$$R_0 = R_{In} // R_A // R_B //(R_{\tau 1} + R_C)$$
$$R_0 = 1.622G\Omega$$
$$C_0 = C_A + C_B = 208nF$$
$$R_1 = R_{\tau 1} = 17G\Omega$$
$$C_1 = C_C = 51nF$$

Figure 4. artificial model of a cable

The measurement was performed by applying the FDS system of SebaKMT. The calculation of the resistance representing the dielectric loss can be done straight forward using (3) for R_0 and C_0. To transfer these information to the common Debey model the parameters can be expressed as follows: Using (3) the tanδ of the model can be theoretically calculated and gives the basic distribution of the tanδ in frequency. Fig.5 shows the comparison of the different methods Hamon and FDS to the theoretical calculated spectrum. The green curve shows the Hamon Approximation of this model. Since the polarisation current in low frequencies is mainly expressed by the current flowing towards the conductance R_0, its value is given in the range of μA. Applying the voltage with a non ideal source the voltage control gives very tiny variation in current, which has direct influence on the tanδ values. Moreover the Hamon curve was fit with a 4^{th} degree polynomial distribution, to give proper values at the frequencies measured by FDS. Table I shows the results.

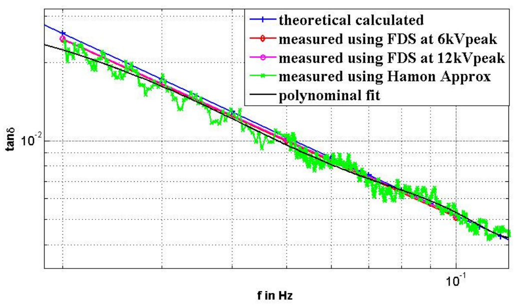


Figure 5. Comparsion different methods at artificial model

The measuring results are absolutely comparable in the given accuracy range and laboratory conditions.

TABLE I. LOSS FACTOR VALUES OF MEASUREMENT AT MODEL

U in kVpeak	6			12		
f in Hz	0.02	0.05	0.1	0.02	0.05	0.1
tanδ theo	25.8	10.3	5.17	25.8	10.3	5.17
tanδ FDS in 10-3	24.5	9.97	5.09	24.6	10.1	5.19
tanδ Hamon in 10-3	23.0	9.98	5.09	24.1	10.4	5.23

FIELD MEASUREMENTS

To prove the suitability of the Hamon approximation in the field application, a healthy PILC was measured. It is demonstrated, that the approximation shows comparable results, for doing integral evaluation of insulation degradation in power cables. Furthermore the capability of the Hamon method was shown in [7], which is discussed as second object. The non linear enhancement of the tanδ with rising voltage stress has to take place independently of the chosen method, i. e. Hamon or FDS. The fact that the theoretical tanδ calculation and the measurement done by the FDS method showed very good correlation, the measurements with FDS serves as tanδ reference for comparison. The measurements were performed at identical ambient conditions, so influences, like cable temperature and ground noise could be neglected.

Object 1: Healthy PILC cable

The first object was given by a mainly 20kV PILC cable (NAEKBA) with the length of 548m. The connections to air insulated substations were done by XLPE (NA2XS2Y) about 8m length. So two transitions, 3 oil filled joints and slip-on terminations represent the implemented accessories. The measurement procedure started with the FDS method at different frequencies and different voltage levels at all 3 phases, it was continued with the Hamon method. Fig. 6, and Table II show the results.

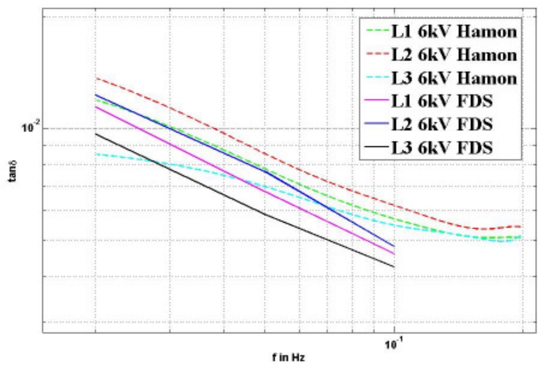


Figure 6. Spectroscopy at 6kVrms of PILC

TABLE II. LOSS FACTOR VALUES – PILC

Frequency in Hz		0.02	0.05	0.1
tanδ FDS in 10-3	L1	11.4	6.75	4.6
	L2	12.3	7.94	4.8
	L3	9.66	5.85	4.24
tanδ Hamon in 10-3	L1	11.8	7.4	5.2
	L2	13.6	8.33	6.08
	L3	9.5	6.75	5.04

The PLIC cable is in healthy condition, the tanδ value does not rise significantly with voltage stress. A difference in the measured values is observed between FDS and Hamon, which is mainly due to noise ripple in current measurement. After the ripple was optimised by the usage of filters the results change in direction of the FDS values. This was done manually in one example. This will be one of the main topics for future work.

Object 2: new EPR cable

The second example is given by a new EPR cable, which was measured presented in [7]. The fact that, it was used a different measurement apparatus for proving the applicability of the Hamon approximation shows the good suitability as an alternative for condition diagnosis.
In Fig. 7 the measurement results are presented. It was measured the depolarisation current as well, which makes the influence of the insulation resistance R_0 (Figure 1) quite obvious.

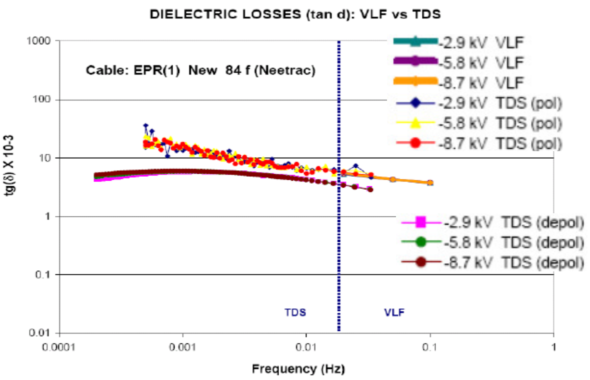


Figure 7. correlation of tanδ measurements between FDS and Hamon, at a new EPR cable – published by [7] (page 12)

The second example demonstrates the correctness of using the polarisation current for tanδ correlation to FDS method.

CONCLUSIONS

Besides good matching at artificial models the suitability of the Hamon method in field application was shown. Healthy PILC as well as new EPR cable were evaluated and showed good correlation to FDS in the range of accuracy. Therefore the same evaluation guidelines for tanδ values suggested in IEEE 400 [11] are applicable. The immense saving in measurement time makes the method highly interesting for dielectric spectroscopy. Considering e. g. a measurement using FDS, of five tanδ values at three voltage steps, without calibration of the system at one cable phase can be saved several minutes in measuring time. The combination of tanδ measurement and cosine alike or even cosine VLF sources furthermore allow to benefit form the advantage in terms of charging capabilities of the cosine VLF sources versus the sinusoidal ones.

FUTURE WORK

The current development allows additional improvements of the design, to gain more efficiency. The following topics will be improved:

- Noise suppression of current and voltage measurement by usage of digital filters.
- Improvement of the VLF source by implementing energy feedback, in order to enhance the charging time significantly. This allows an extension of the tanδ spectrum exceeding 1Hz margin and additionally makes the charging of larger object capacitance, i. e. longer cables, possible.
- Continuing in investigating the suitability of the Hamon approximation in field applications.

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