TRACEABLE MEASUREMENT OF DIELECTRIC DISSIPATION FACTOR AT VERY LOW FREQUENCY

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Abstract: Very Low Frequency (VLF) tests are often used for after-laying tests of power cables since the reactive power demand is much lower at VLF than at 50 Hz. In order to augment the usefulness of the test, it is often complemented by a measurement of dielectric dissipation factor (tan δ), where the acceptance of the tested object is based on this measurement. A traceability chain for dissipation factor at high voltage and very low frequency has as yet not been recognized by the International Bureau of Weights and Measures (BIPM), which results in difficulties to prove the quality of the measurement. The measurement is complicated by the limited range of the current in the test object that can be resolved by available high voltage test equipment, thus limiting the possible choices of reference systems. A novel reference measuring system that can fulfil these needs has been developed at SP Technical Research Institute of Sweden in the capacity as National Measurement Institute. The traceability of the system to National Standards of Measurement is ensured by careful scientific work and analyses. This measuring system has the ability to measure dissipation factor at 0.1 Hz in the voltage range from 0.5 kV up to 50 kV with an uncertainty better than 0.004 %.

1 INTRODUCTION

High-voltage on-site testing of extruded insulation cable systems is an important aspect of quality assurance after laying of the cable. The DC voltage test method common for oil-paper cables cannot be used, as it comes with an unacceptable risk of damaging the insulation. Except for short cables, 50 Hz test equipment becomes exceedingly heavy and presents problems in the logistics for on-site testing.

Research has shown that testing at Very Low Frequency (VLF) does not come with the risk of damaging sound cable insulation, combined with an ability to reliably detect defects [1-2]. Equipment capable of generating VLF test voltages has been developed by several manufacturers, and more often than not, provide the possibility to measure the dielectric dissipation factor of the insulation. Quality assurance concerns for testing imply that this measurement must be possible to calibrate traceably.

Consequently, there is a need for reference measuring systems for dielectric dissipation factor suitable for VLF and with properly proven traceability. The typical range of capacitance is from several tens of nF up to several µF with test voltages usually less than 100 kV. A reference system for dissipation factor measurement has been developed by SP, and the results of this research are presented here.

In this new field, scant research has been done; indeed, no publications on the subject of traceable measurement of dissipation under VLF voltage have been found. Furthermore, according to the key comparison database maintained by the International Bureau of Weights and Measures (BIPM), there is no publicly announced calibration service available for dissipation factor measurement below 45 Hz.

2 DIELECTRIC DISSIPATION FACTOR

The dielectric dissipation factor of a capacitor, under sinusoidal conditions, is defined as "*the tangent of the loss angle*", which is "*angle by which the phase difference between applied voltage and resulting current deviates from $\pi/2$ rad, when the dielectric of the capacitor consists exclusively of the dielectric material*" [3]. It is obvious from the definition that for small dissipation factors, the loss angle will have the same numerical value when expressed in rad.

The dissipation factor may also be expressed by the active power divided by the apparent power under sinusoidal conditions, for small loss angles.

The dissipation factor is in general dependent on both voltage and frequency. It should be noted that the common equivalent circuit consisting of a pure capacitor and a resistor, is by no means a physical description of the relation between loss and frequency. A quick deliberation proves this statement; the equivalent circuit can either be a series or a parallel circuit. The dissipation factor increases with frequency in the series circuit and decreases with the parallel circuit. Therefore neither can be a true model, except at one single frequency (see also note 1 to term 2.5 in [3]). For practical insulators it is often found that the dissipation factor can be almost constant over several decades of frequency range.

Several techniques are available for measurement of dissipation factor. Traditionally, Schering bridges and transformer ratio arm bridges have been used. In the present context of very low frequency, these are not very practical, and have largely been superseded by methods based on sampling techniques, where evaluation is done in software.

3 REFERENCE MEASURING SYSTEM FOR DISSIPATION FACTOR AT VLF

3.1 Description of the SP setup

The current through the capacitive test object is captured using a precision shunt from SP's Digital Sampling WattMeter (DSWM) series [4-5]. The applied voltage is captured with a voltage divider.

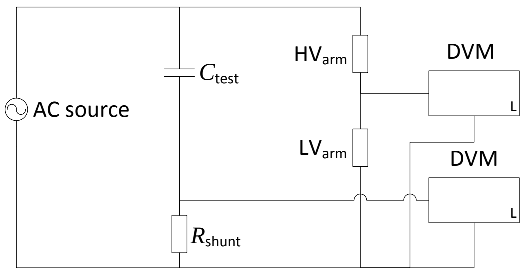

Figure 1: Test circuit with test object, current shunt and voltage divider

The signals from the current shunt and the voltage divider were measured with two 8½ digit digital volt-meters (DVMs), Hewlett Packard/Agilent 3458A, in digitizing mode with synchronized sampling. The dissipation factor is determined from the digitized records of the voltage and current signals.

3.2 Shunt

Two precision shunts with well established characteristics were available. They are designed for a nominal current of 10 mA and 0.16 mA respectively (corresponding to 80 and 5000 Ω). In the present application for measurement of the dielectric dissipation factor, the crucial parameter is the phase error at the test frequency. Two different parasitic effects have to be taken into account;

- the interaction between shunt (source) resistance and the capacitance to earth in the instrument and the leads to the instrument,
- the loading of the test object C_{test} by the shunt.

Both effects lead to errors in the evaluated dissipation factor – i.e. a phase error is introduced.

Figure 2: Current shunt 200 mA similar to the 10 mA shunt used.

The first effect is estimated from the typical input capacitance C_{in} of the DVM of 250 pF in parallel with 2 m coaxial cable having 100 pF/m. Since $\tan(\delta) = \omega \cdot R_{shunt} \cdot C_{in}$ it can be shown that the error of the measured tan(δ) for the 80 Ω shunt is 0.023 * 10^{-6} at 0.1 Hz and for the 5000 Ω shunt it is 1.4 * 10^{-6}. These are both negligible.

The influence of the second effect can be estimated for a typical case where C_{test} = 0.4 μF. The measured tan δ will increase by 20 * 10^{-6} when using the 80 Ω shunt and by 1256 * 10^{-6} using the 5000 Ω shunt. It can be concluded that the 80 Ω shunt can safely be corrected for, but the 5000 Ω shunt should be used sparingly because the uncertainty of the correction is not negligible. The value of C_{test} is within the range of capacitance that can be expected in an application on-site.

The observant reader will have noticed that the second error could be avoided if the high voltage measurement were taken only over C_{test}. However, since a resistive high voltage divider was chosen, this option would have been even worse because the resistive current through the divider is measured by the shunt in that case.

3.3 High voltage divider

A first attempt was to use a capacitive divider based on a compressed gas capacitor and a precision low voltage arm consisting of NP0 ceramic capacitors. This divider is the same divider as used for traceable measurement of VLF high voltage at SP [6]. This divider did not work well due to unexpected effects of minute charging currents (on the order of pA) into the low voltage arm of the capacitive divider, causing a large scatter in results. A precision 50 kV resistive DC divider (Vishay) was investigated instead and found to give stable and accurate readings.

SP maintains several DC reference voltage dividers with ratings from 50 to 200 kV. These have been proven for high precision DC applications in an international intercomparison [7], where an uncertainty of better than 0.003 % could be proven. The 50 kV divider was investigated for application at 0.1 Hz. At this frequency a non-negligible phase displacement due to interaction between the unavoidable stray capacitances and the high resistance of the divider is probable and necessitates an investigation.

Figure 3: Vishay DC reference voltage dividers for 50 and 100 kV

DSWM (Digital Sampling WattMeter) voltage dividers are available at SP for up to 1000 V input and are characterized to within 10 ppm for the ratio and less than 1 µrad phase displacement at 0.1 Hz. The 1000 V divider was used to characterize the 50 kV Vishay divider. The difference in phase displacement due to voltage in the range from 1 kV to 50 kV is estimated to be entirely negligible. The DC ratio change of the divider has been estimated by other methods to less than 0.001 %.

Measurements show an error of approximately 2400 µrad at 0.1 Hz for the Vishay divider. However, adding capacitance in parallel to the low voltage arm makes it possible to adjust the response to better than 2 µrad at 0.1 Hz. Checks proved that the same adjustment is valid at 0.2 Hz, attesting to the validity of the adjustment.

3.4 Need to filter

Inspection of gathered data shows a noise that is particularly prominent in the current signal, due to the differentiating action of the capacitive test object C_{test}. A simple circuit to filter the applied VLF voltage, see Figure 4, results in a substantial decrease in the magnitude of noise in the current signal and also much reduced the scatter in results. Figure 5 shows the amelioration in signal quality. The components used are rated for high voltage and can be used at voltages up to 25 kV.

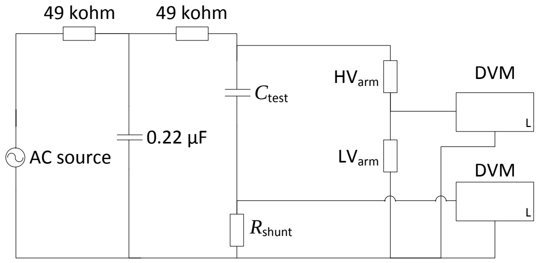

Figure 4: Measurement circuit including noise filter

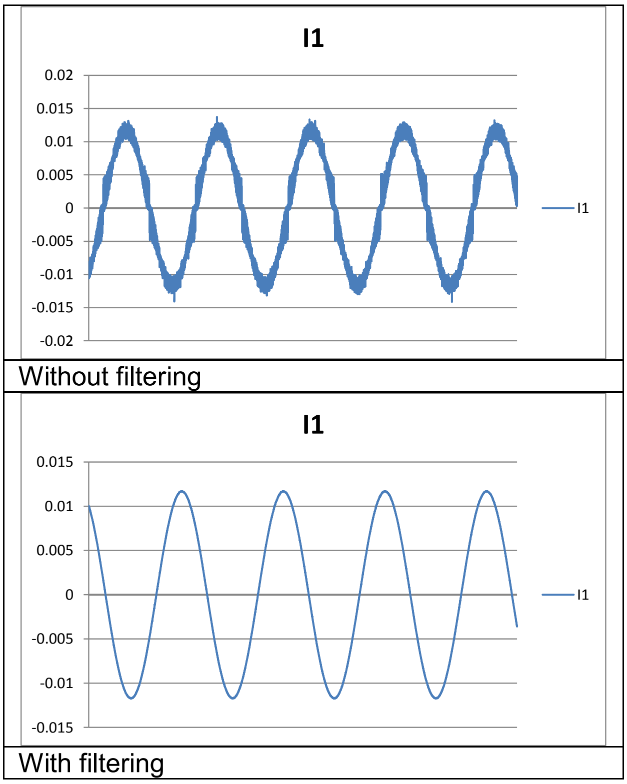

Figure 5: Amelioration of noise on the current circuit achieved with filtering at 400 V across 0.4 µF. Test frequency 0.1 Hz.

3.5 Analysis methods

3.5.1 General The dissipation factor can be determined by several different methods, with different advantages. Common to all the methods investigated, is that the analogue signals are recorded with sampling techniques before evaluation.

The results of measurements are exemplified below with results obtained for a commercial oil-paper-plastic capacitor intended for phase-correction in power grids, rated to 25 kV and with a capacitance of 0.4 µF.

3.5.2 Sampling The voltage and current signals are sampled with the maximum available number of samples in high resolution mode of the HP3458A, i.e. 32788 samples, taken over slightly more than 5 cycles. The DVMs are externally synchronized to ensure minimal phase error between the channels. The phase error has been measured and is less than 1 µrad at VLF frequencies. The amplitude accuracy is on the order of 0.001 % and is therefore far better than needed for this application.

3.5.3 Fundamental fit method The phases of current and voltage signals are obtained by fitting a pure sine wave of the fundamental frequency to the measured points. The difference in phase, from $\pi/2$ radian, between the two fitted curves is the phase displacement of the capacitor. The measured values are low and the numerical value is therefore closely equal to the dissipation factor.

This method is pleasing in its simplicity, where a perfect sine is fitted to the original signal, but experience proves that the scatter between two measurements is not negligible, see Figure 6.

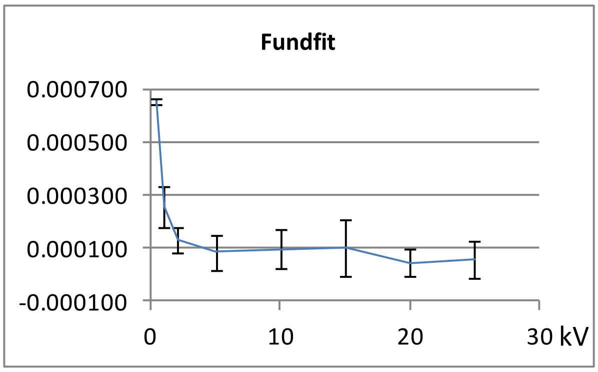

Figure 6. Result of evaluation of capacitor dissipation factor using fundamental fit method. The error bars represent the standard deviations for 5 repeated measurements.

3.5.4 Multi-tone fit method The fundamental fit method is expanded on by extending the fit to include higher order harmonic tones as well. The standard deviation of repeated measurements is however still quite large and including more tones do not necessarily decrease the spread. In reality, no ensured amelioration can be established compared to the fundamental fit. The mean values are however in agreement with each other.

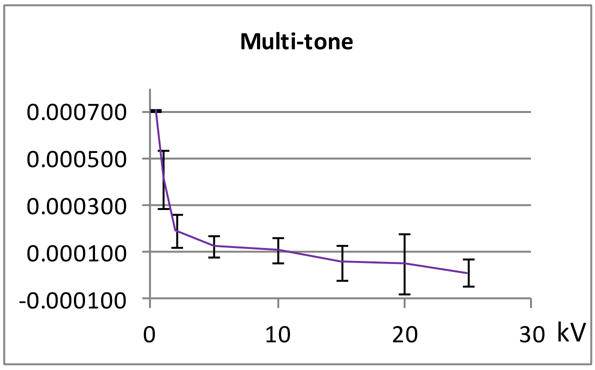

Figure 7. Result of evaluation of capacitor dissipation factor using a multi-tone fit method. The error bars represent the standard deviations for 5 repeated measurements.

3.5.5 Fourier Transform The sampling rate could not be set to synchronize with the test voltage and therefore a Digital Fourier Transform (DFT) is used together with a Hanning window to reduce the influence of evaluating a record that is not an integer number of cycles.

The standard deviation of the evaluated waveforms is however large, and the method is not satisfactory. The simplistic approach chosen means that better application of the Fourier transform is possible and should be investigated.

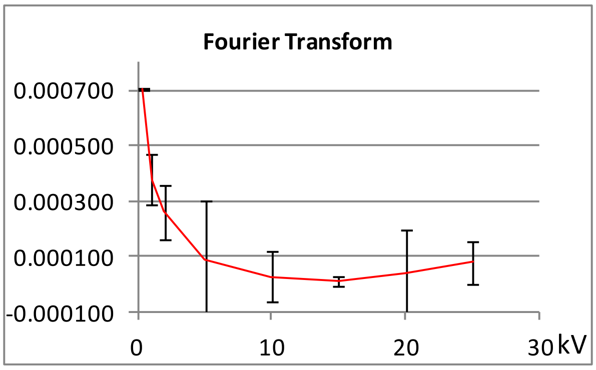

Figure 8. Result of evaluation of capacitor dissipation factor using Fourier Transform to find the phase displacement. The error bars represent the standard deviations for 5 repeated measurements.

3.5.6 Evaluation of power The active and the apparent power are calculated over four complete cycles. Since the sampling is not phase-locked to the voltage source, a perfect match cannot be assured, therefore the end points are interpolated between the actual samples. The dissipation factor is calculated as the active power divided by the apparent power, with the latter being the product of U_{rms} and I_{rms}.

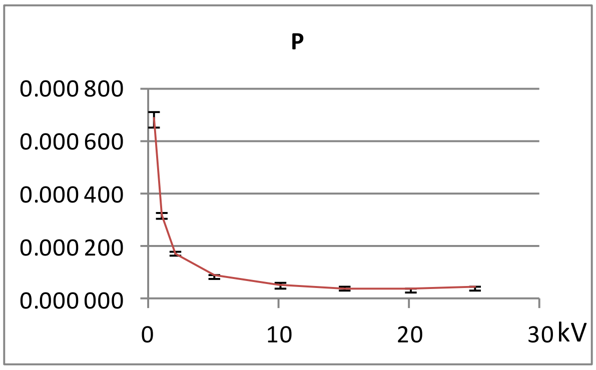

Figure 9. Result of evaluation of capacitor dissipation factor by calculation of total loss. The error bars represent the standard deviations for 5 repeated measurements.

The advantage of this method is its robustness as proven by the very low standard deviation. The disadvantage is however that it gives the total loss, i.e. if there are loss components at other frequencies, these will be added to the losses at fundamental frequency. This can cause errors, especially if the dissipation factor varies appreciably with frequency.

3.5.7 Summary Several different methods have been investigated for application on determination of dissipation factor/phase displacement at VLF. The standard deviations range from more than 100 µrad down to 10 µrad. Considering that the value to determine is in the range 50 to 700 µrad, only the most robust method should be used, i.e calculation of active power divided by the apparent power.

3.6 Uncertainty

All measurements have an uncertainty and the task of metrology is the estimate the magnitude of uncertainty that can be reasonably attributed to the measurand. The methods and the process are given in the Guide to the Expression of Uncertainty (GUM) [8]. Quite often, contributions to uncertainty can be assumed to be uncorrelated. If there are at least three uncertainty contributions of comparable value, an assumption of normal distribution of the combined uncertainty is usually justified.

The GUM recognizes that the experimental standard deviation in the measurement process in many practical cases is only a small contribution to the total uncertainty. The methodology given separates uncertainty contributions into Type A as those obtained by statistical means (e.g. experimental standard deviation) and into Type B for all other types of estimates. Both types are in the further analysis handled by the same methods taken from statistics.

It is customary to set up an uncertainty budget that discusses the possible contributions and specifically gives the estimates for all Type B uncertainties. Finally the uncertainty estimate is taken as twice the combined standard deviation, which in effect gives a conventional coverage probability of 95 % for the result.

3.7 Traceability

It is important to ensure compatibility between measurements carried out in different locations and by different organisations. The tool for this is called Traceability, which is the "*property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty*" (term 2.41 in the International Vocabulary of Metrology [9]).

3.8 Uncertainty budget

3.8.1 Amplitude error Amplitude errors are dismissed since the dissipation factor is a relative quantity.

3.8.2 Statistical contribution The standard deviation of the mean of a set of measurements needs to be considered as a Type A contribution.

3.8.3 Phase error between the two DVM's The deviation of phase between two DVM's HP/Agilent 3458 is less than 10 µrad at 50 Hz. Since this effect is due to timing errors, it can be concluded that this Type B contribution to uncertainty is less than 0.0001 % at 0.1 Hz.

3.8.4 Phase error of shunt The output of the shunt is loaded by the capacitance of the connecting lead and the input of the DVM. This capacitance is less than 500 pF in the setup used and thus $\tan(\delta) = \omega \cdot R_{shunt} \cdot C_{in}$ is calculated to less than 2 µrad at 0.1 Hz for the 5 kΩ shunt used in certain checks. For the 80 Ω shunt used in most measurements, this Type B contribution to uncertainty is negligible.

3.8.5 Phase error of DSWM voltage divider The voltage divider was used to adjust and calibrate the Vishay DC divider. The phase error of the DSWM 1 kV divider is less than 10 µrad at 50 Hz. At 0.1 Hz this error is less than 0.1 µrad and this Type B contribution to uncertainty is negligible.

3.8.6 Phase error adjustment of Vishay divider The Vishay DC divider was adjusted with a capacitor in parallel with the low voltage arm, using the DSWM 1000 V divider as reference. The adjustment could be made to better than 1 µrad and is stable within 5 µrad. This Type B contribution is regarded as having a rectangular distribution with a standard uncertainty of 0.0003 %.

3.8.7 Phase error stability of Vishay divider Repeated checks of the adjustment of the Vishay DC divider showed that the change was not more than 10 µrad in the time period of the measurements. This Type B contribution is regarded as having a rectangular distribution with a standard uncertainty of 0.0006 %.

3.8.8 Shunt loading of the test object The reference voltage is measured across the combination of shunt and tested capacitor C_{test}, see Figure 1. The apparent dissipation factor error due to the presence of the shunt is $\tan(\delta) = \omega \cdot R_{shunt} \cdot C_{test}$. For the 80 Ω shunt and a test object of 0.4 µF, this correction is 20 µrad. This correction has a Type B contribution that is estimated as a rectangular distribution with a standard uncertainty of 0.0003 %.

3.8.9 Consistency of analysis methods The analysis using active power for dissipation factor estimation has a standard deviation of less than 10 ppm for 5 repeated measurements. The fitting methods exhibit standard deviations that are in the range 0.001 to 0.01 %, but the agreement for the mean value of dissipation factor is within the standard deviation, and thus supports the results of active power measurement. This Type B contribution to standard uncertainty is conservatively estimated to 0.0015 %.

3.8.10 Effects of distortion Distortion in the applied test voltage can lead to errors especially for the method based on measurement of active power, if the dissipation factor is dependent on frequency. In the present case the distortion of the test voltage is low and it is furthermore verified that the loss factor is essentially the same at both 50 Hz and 0.1 Hz, and therefore this contribution is regarded as negligible

3.8.11 Scale error This quantity has not been expressly studied, but it is estimated to be better than 5 % of reading of dissipation factor, resulting in a standard uncertainty Type B contribution of 3 % with rectangular distribution.

3.8.12 Combined uncertainty of measurement of dissipation factor at 0.1 Hz

Table 1: Uncertainty Budget

Contrib. (clause reference)	Value	Std uncert	Sensitivity coefficient	Uncertainty contribution
3.8.2	x	St.dev	1	St.dev
3.8.3	0	0		0
3.8.4	0	0		0
3.8.5	0	0		0
3.8.6	0	0.000 003	1	0.000 003
3.8.7	0	0.000 006	1	0.000 006
3.8.8	-0.000 020	0.000 003	1	0.000 003
3.8.9	0	0.000 015	1	0.000 015
3.8.10	0	0		0
3.8.11		0.03*x	1	0.03*x
Combined standard uncertainty, excluding first and last contribution				0.000 017
Combined expanded uncertainty for a coverage factor of k=2				0.000 034

Excluding the uncertainty of reading and scale error, the expanded combined uncertainty of the measurement of dissipation factor of a capacitor with very low losses is 0.000 034 p.u.

4 CONCLUSIONS

A unique measuring system for determination of dissipation factor of capacitors at Very Low Frequency has been developed by SP Technical Research Institute of Sweden. The best performance of the measuring system is 0.000 034 p.u. up to 50 kV and at 0.1 Hz. The traceability to national and international standards of measurement has been proven by measurements and scientific analyses.

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