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REVIEW ARTICLE

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Achievable Accuracy in Industrial Measurement of Dissipation Factor of Power Capacitors

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Abstract: Modern dielectrics used in power capacitors can exhibit a dissipation factor lower than 0.005 %, which approaches the limits of presently available measurement techniques. This article reviews techniques, apparatus, and available calibration services for dissipation factor with regard to lowest achievable uncertainties. It is shown that further metrological advances are necessary to lower uncertainty in the measurement to levels at least five times less than presently achievable, in order to ensure traceable and quality-assured measurement of modern dielectrics with such low dissipation factors.

1. Background

The dielectric loss angle of insulating materials is defined for sinusoidal voltages as the angle δ by which the phase difference between applied voltage and the capacitive current through the capacitor deviates from π/2. The dissipation factor is defined as the tangent of the loss angle δ, and is a basic quality parameter for insulating materials [1]. For small values of dissipation factor, it becomes close to the ratio between active power and reactive power. A low dissipation factor is desired both to reduce energy loss, and to reduce heating of the capacitive object, which can have a deleterious effect on its reliability and life expectancy.

Power capacitors are used in power grids for power factor corrections and filtering purposes. The cost accrued from losses over the life-time of a capacitor is one of the more important evaluation factors in procurement and correct measurement of dissipation factor is therefore highly important. Power capacitors are used at all voltages levels in the power grid, with single elements employed in low voltage systems and with banks of series and parallel connected elements at high voltages.

Power capacitors were traditionally manufactured with metal foils insulated with oil-impregnated paper. These had a typical dissipation factor on the order of 0.3 %, obtained for well-dried paper. Development of materials has however led to ever better capacitors where dissipation factors of 0.02 % are guaranteed by manufacturers; see, for example, [2, 3]. Even lower values ranging from 0.01–0.005 % have been measured by the author on commercial high-voltage capacitors (obliquely mentioned in [4]). Measurement to verify the dissipation factor should have an uncertainty appreciably lower than the value to be measured. Since a safety margin between measured value and the uncertainty of 3–10 times is often cited, an uncertainty of less than 0.001 % is indicated as desirable. As will be shown in this article, even National Metrology Institutes (NMIs) have difficulties to provide this as their best measurement capability at high voltage and power frequency. In an aside, it can be noted that NMIs neither supply nor measure the high reactive power needed for these objects.

In a nearby technology niche, extruded power cables utilizing high-quality cross-linked polyethylene insulation will in undamaged condition have very low dissipation factor. Example [5] cites results where 0.004 % dissipation factor has been measured, indicating that other industrial areas also face the problem of measuring very low dissipation factor at high voltage.

The achievable accuracy will be limited by several factors, including resolution and stability of the measuring apparatus and, even more important, the possibility to calibrate the reference standards and the measuring instruments by comparison to higher-echelon reference standards such as those maintained by NMIs. These factors will be explored in detail.

The combined effect of these influences should be evaluated by methods given in the Guide to the Expression of Uncertainty in Measurement (GUM) [6].

Instrumentation and equipment to connect to the high-voltage, high-current circuit for the measurement of power capacitors is described and discussed with regard to available techniques and their pros and cons. An overview of available traceable calibrations worldwide is made, based on the database of best Calibration and Measurement Capability (CMC) maintained by the Bureau of Weights and Measures (BIPM). Finally, a detailed discussion is made

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of possible contributions to uncertainty ending with a worked-out uncertainty budget, showing the state-of-art in this field.

2. Measuring Equipment

2.1 Overview

Measurement of high-voltage capacitor dissipation factor is performed by comparison with a reference capacitor with low and known dissipation factor. Gas-insulated capacitors are generally used as references for this purpose, since they exhibit excellent voltage stability and extremely low dissipation factor. The comparison is usually done by a bridge method to ensure sufficient resolution and accuracy, although digital methods are maturing into similar performance.

2.2 Schering Bridge

This bridge [7], Figure 1, has been in use for close to a century and is a classical bridge technique with the unknown capacitor Z1 and the reference Z2 in the high voltage branches. The low voltage branches comprise resistors R_3 and R_4 to balance the ratio of capacitances Z1 and Z2. Capacitor C_4 is used to balance the dissipation factor. Calibration of the bridge ratio can be done by determination of the resistance values of the low voltage arms. It is, however, important that the resistors are of very low inductance to maintain a zero-error for dissipation factor.

The balance for dissipation factor can be calibrated by measurement of the capacitors comprising C_4. For accurate measurement a screen at guard potential for the bridge diagonal is essential. The accuracy of the Schering bridge is not explicitly given in the manuals, so that even though resolution can be well below 0.0001 % for the measurement of dissipation factor, uncertainty may be larger [8, 9] and is not easily quantified.

2.3 Transformer Ratio Arm Bridges

These bridges [10] were developed in the 1960s and permit accurate comparison of very disparate capacitor values, a ratio of 1000:1 (and for some bridges 10000:1) is possible. A simplified schematic is shown in Figure 2, where the ratio windings of a current comparator are connected to the reference capacitor C_N and the unknown C_X. The capacitance ratio is obtained from the settings of the ratio windings and the dissipation factor is obtained from the setting of an error compensating network, which has been omitted in favor of clarity.

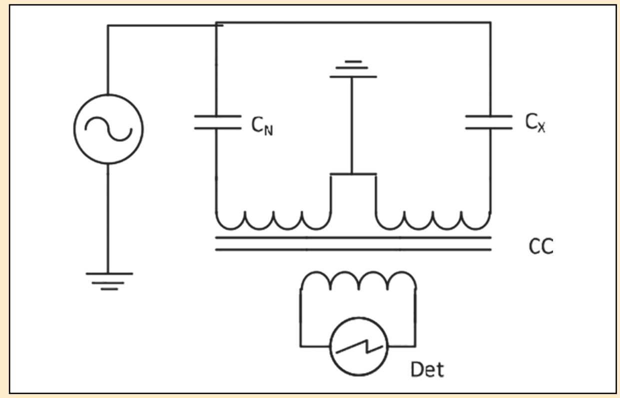

Figure 2. Simplified schematic of a current comparator capacitance bridge.

Since the bridge is based on winding ratios, an excellent stability over time can be expected. Stated accuracy for both capacitance and dissipation factor of these bridges usually ranges from 0.01–0.001 %, with resolution down to 0.0001 % [11–14]. Calibration can be performed by injecting currents with known ratios into the bridge arms, e.g., using digital to analog converters [15] or networks with precisely calibrated capacitors [16–18].

2.4 Digital Methods

Recently, sampling techniques have reached maturity and offer a possible alternative to classical bridges [19–21]. In a sampling system, current shunts are used to convert the capacitive currents into a voltage that can be recorded by the sampling instruments as shown in Figure 3. A voltage divider is usually needed to bring the voltage level down to what is acceptable input for the sampler.

Both shunt, voltage divider and sampler are crucial components and must have excellent phase behavior. The raw digital data must be analyzed to determine the dissipation factor, usually by means of Fourier Transform methods, which establish the phase displacement at the fundamental frequency. The stated uncertainty of sampling techniques ranges down to about 0.002 %, although systems under development

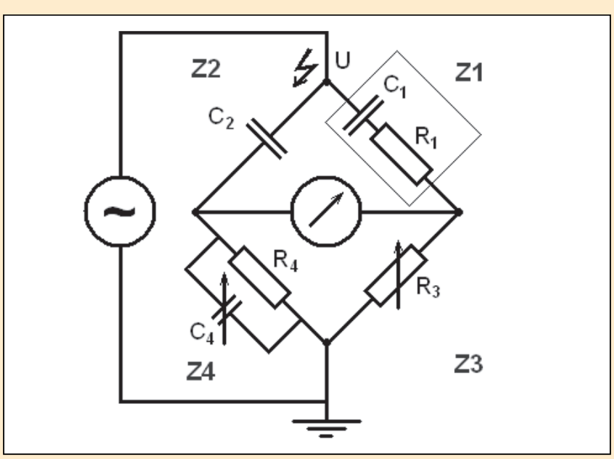

Figure 1. Schering bridge (courtesy Philippe Mertens, Wikimedia).

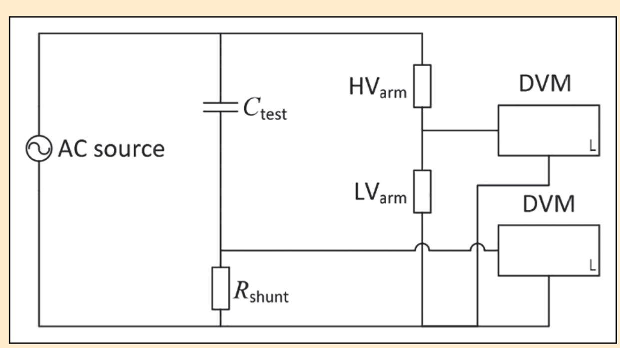

Figure 3. Principle of a sampling capacitance measuring system.

now approach 0.0001 % for the sampler [20]. Voltage divider and shunt do however present problems that are not yet well known, possibly limiting the performance of the measuring system to higher uncertainty than transformer ratio arm bridges.

A variation of the sampling techniques is to determine the losses by integration of instantaneous active and reactive power over an integer number of cycles and dividing active by reactive power [4] to obtain an estimate of the dissipation factor.

2.5 Extension of Current Range

The current through capacitors with large reactive power rating is in general larger than the input capability of existing measuring instruments. Precision current transformers have to be used to adapt to the levels acceptable in the instrument. Several technologies are available, ranging from metering-type current transformers to current comparators, with or without electronic aid [10]. The stated accuracy can be as low as 0.001 % for ratio and 10 μrad for the phase displacement, corresponding to a dissipation factor of 0.001 %. These devices are calibrated as current transformers, albeit with stringent requirements on precise reference equipment.

3. Calibration and Traceability

3.1 Uncertainty of Measurement

Measurement uncertainty is a "*non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand"* VIM term 2.26 [22]. It takes into account unavoidable dispersion in the measurement process and components arising from systematic effects such as corrections, quantity values of reference standards, etc.

The uncertainty is usually expressed as an expanded uncertainty with an estimated coverage probability of 95 %. The combined uncertainty from all pertinent contributions needs to be assessed systematically. Methods for this purpose are given in the GUM [6].

3.2 Metrological Traceability

Acceptance of a measurement result needs to have assurance that it can be possible to compare with results obtained by others. Ultimately, it must be possible to link to definitions of the basic units in the SI system.

The definitions in the SI system are transferred into measurable reference standards in a process called realization, which is long and difficult process, rarely performed. Quantum mechanical phenomena are instead employed to achieve very stable and reproducible representations of basic electrical units. As an example, the Josephson effect is used to link the second, Planck's constant, and the charge of the electron, to the unit for electromotive force (voltage) [23] and doing this is one of the tasks performed by National Metrology Institutes (NMIs). To ensure international equivalence and acceptance of the established traceability, comparisons are made between NMIs.

The best Calibration and Measurement Capabilities (CMCs) of NMIs worldwide are identified by the International Bureau of Weights and Measures – BIPM [24]. The listings are subjected to intense quality control, including:

- participation by the institute in reviewed and approved scientific comparisons;
- operation by the institute of an appropriate and approved quality management system; and
- international peer-review (regional and inter-regional) of claimed calibration and measurement capabilities.

A realized unit is brought to bear on industrial applications through a chain of calibrations, starting from the realized value and ending in the industrial process. This chain constitutes Metrological Traceability, which is defined formally as:

> 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 [22] (VIM term 2.41).

It should be noted that each step in a calibration chain introduces further uncertainty, it is indeed often noted that uncertainty becomes three to ten times larger with each step.

In the case of measurement of dissipation factor of power capacitors, the traceability chain starts from realizations of dissipation factor performed at low voltage and 1 kHz, and continues on to lower frequency and higher voltage by means of calibrations and scientific analyses. For this reason, attention should be paid both to capabilities of NMI's at low voltage and 1 kHz, as well as to high voltage and power frequency.

3.3 Realization of Capacitor Dissipation Factor

A small number of NMIs perform realization of dissipation factor on a regular basis as detailed in Table 1 [25, 26].

The values cited constitute the lowest uncertainties for dissipation factor that can be obtained traceably in the world and are taken from the CMC tables at BIPM [24].

3.4 Capacitor Dissipation Factor at Power Frequency and High Voltage

The reference capacitor used in high-voltage measurements is in virtually all cases a compressed gas capacitor [27]. This device is almost ideal and has a low inherent dissipation factor that can be reliably calibrated at low voltage against a precise low voltage capacitor. The achievable accuracy is usually limited due to unavoidable effects of stray effects present in the high-voltage environment. Furthermore, the validity of this calibration has to be verified with respect to both the different frequency (power frequency instead of 1 kHz as normally used in the realization) and to the much higher voltage needed for industrial applications (kV instead of V). These considerations lead to appreciably higher uncertainties.

NIM, China, have reported realization of dissipation factor at power frequency up to 2 kV with very good results as seen in Table 2. At present, no other efforts to realize dissipation factor at high voltage and power frequency are known.

With the notable exception of China at voltages up to 2 kV, the lowest uncertainty available worldwide is 0.001 %. However, above 2 kV also China has 0.001 % as the best uncertainty.

3.5 Capacitance Bridge

Only one country has listed an entry for capacitance bridge dissipation factor at power frequency (see Table 3).

Institute	Frequency	Capacitance range	Expanded absolute uncertainty %
NIM, China	1 kHz	100, 1000 pF	0.0001
PTB, Germany	1 kHz	10, 100, 1000 pF	0.00057
VNIIM, Russia	1 kHz	1 to 100 pF	0.00005
SP, Sweden	1 kHz	100, 1000 pF	0.0003
	0.5–1 kHz	10 pF	0.0002

Table 1. Best CMCs for capacitor dissipation factor at low voltage.

Country	Frequency	Dissipation factor range	Expanded absolute uncertainty %
Inmetro, Brazil	50, 60 Hz	0.000001–0.1	0.002

Table 3. Best CMCs for capacitance bridge calibration for dissipation factor.

4. A "Best" Uncertainty Budget

4.1 General

An uncertainty budget is a listing of all relevant contributions to uncertainty and usually a discussion on how they are estimated. The sensitivity of the result for a certain contribution is investigated from the mathematical relation between them. The type of statistical distribution underlying the estimate of each contribution influences how the standard uncertainty of the contribution is estimated. For example, a contribution arising from a normal distribution will have the standard uncertainty defined directly from the standard deviation, whereas one where the values are sure to be within a symmetrical limit, called a rectangular distribution, will have a standard uncertainty equal to the half-width of the interval divided by $\sqrt{3}$.

The standard uncertainty contributions are added quadratically to obtain the combined standard uncertainty (or, in other words, the variances are added). It is customary to collect the information in tabular form for easy reference.

It is common to express uncertainty as a relative number (e.g., in %). In the case of uncertainty of dissipation factor, this can be slightly misleading, and in this context absolute uncertainty is therefore used.

Further guidance for expression of uncertainty in measurement is given in the GUM [6]. Briefly, the GUM requires that all known errors be corrected for and that all uncertainty sources be accounted for and estimated. The central limit theorem is fulfilled if there are at least three contributions to uncertainty that are of the same order of magnitude, in which case a normal distribution can be assumed. The combined standard uncertainty (for statistical contributions the standard deviation) is multiplied with a coverage factor to obtain the expanded uncertainty, which for a coverage factor of 2 approximately corresponds to a 95 % coverage probability.

Institute	Frequency	Voltage kV	Expanded absolute uncertainty %
NMIA, Australia	60 Hz	to 550	0.001
INMETRO, Brazil	50, 60 Hz	1–200	0.0022
NRC, Canada	50, 60 Hz	to 100	0.001
Canada	60 Hz	100–500	0.001
NIM, China	40–60 Hz	2–10	0.001
	40–60 Hz	1–2	0.0001
CMI, Czech	45–60 Hz	to 200	0.003
MIKES, Finland	45–60 Hz	to 200	0.001
LNE, France	40–60 Hz	Not stated	0.002
NIM, China	50 Hz, 1 kHz	Not stated	0.001
INRIM, Italy	50 Hz	1–50	0.001
VSL, Netherlands	45–65 Hz	1–100	0.001
NIM, China	50 Hz	1–350	0.005
NIM, China	50 Hz	0.75–300	0.001
UME, Turkey	not stated	1–400	0.0023

Table 2. Best CMCs for capacitor dissipation factor at high voltage.

4.2 Representative Example

In order to investigate the achievable accuracy, a representative measurement setup has to be defined in order to identify possible contributions to measurement uncertainty. In this case we consider measurement of a power capacitor using a transformer ratio arm bridge with a compressed gas capacitor as reference and using a two-stage current transformer for the current from the test object.

The choices have been made to take into account the performance of state-of-art equipment. It has been assumed that calibrations have all been made with the best available reference equipment at NMI level worldwide. In this way the estimate on achievable uncertainty will be state-of-art. The digital bridge [20] is a possible candidate to replace the ratio arm bridge, but does require shunts for very small currents, and will be prone to phase displacement errors due to capacitive loading, and it is not immediately clear if this is a better choice.

4.3 Test Conditions

The losses of a power capacitor will in general be dependent on the applied voltage so testing at nominal voltage is therefore essential.

The capacitor will generate reactive power, which can be substantial, meaning that a high-power supply is needed. Depending on whether low-voltage or high-voltage capacitors are tested, either high voltage or high current (or both) will be required. The high-power circuit can influence the measurement circuit through induction and influence. Other environmental influences such as temperature and humidity are not treated in this context as they are not expected to contribute to uncertainty of dissipation factor measurement.

4.4 Induction Effects

The current flowing through the capacitor will generate a magnetic field around the power supply circuit. Use of coaxial cables for signals, and proper routing of them, can reduce this effect to a negligible level. It is, however, known that measuring bridges based on magnetic circuits can be sensitive to such effects, and may need to be located outside the immediate neighborhood of the power supply circuit. This contribution can usually be neglected.

4.5 Electric Field Influence

The electric field from the high voltage circuit can have a direct effect on the measurement if, e.g., coaxial cables with single shields are used in an area exposed to the high voltage field. The importance of properly shielded cables is stressed in most treatises on high-voltage measuring techniques, see, for example, Section 6.3.3 in [28] for examples of good practice. The effect on dissipation factor measurement should, however, be negligible if cables with double shielding are used.

4.6 Voltage Drop on Connecting Lead

The reactive current drawn by the capacitor may cause a voltage drop on the connecting leads between power supply and capacitor. It is therefore often necessary to separate current and potential connections between the capacitor and the measuring instrumentation in order to avoid the resistive voltage drop on current-carrying conductors from being included in the measurement of losses of the capacitor, especially when large capacitors are measured, as this effect can be large. The technique to separate these circuit is referred to as “four-terminal measurement” [10]. In short, the earth reference for the bridge should be carefully chosen so that no undue voltage drop can occur and that the high voltage connection of the reference capacitor is taken directly from the high voltage terminal of the test object. In this way, erroneous results due to voltage drop on the leads supplying the test object can be avoided. This topic is further discussed in [11] and in section 4.10.

4.7 Influence of Frequency Variations

The dissipation factor of a capacitor is for moderate frequency variation, in the first approximation, frequency independent. In fact:

> For discrete electrical circuit components, a capacitor is typically made of a dielectric placed between conductors. The lumped element model of a capacitor includes a lossless ideal capacitor in series with a resistor termed the equivalent series resistance (ESR), as shown in [Figure 4]. The ESR represents losses in the capacitor. In a low-loss capacitor the ESR is very small (the conduction is low leading to a high resistivity), and in a lossy capacitor the ESR can be large. Note that the ESR is not simply the resistance that would be measured across a capacitor by an ohmmeter. The ESR is a derived quantity representing the loss due to both the dielectric’s conduction electrons and the bound dipole relaxation phenomena mentioned above. In a dielectric, one of the conduction electrons or the dipole relaxation typically dominates loss in a particular dielectric and manufacturing method. [29]

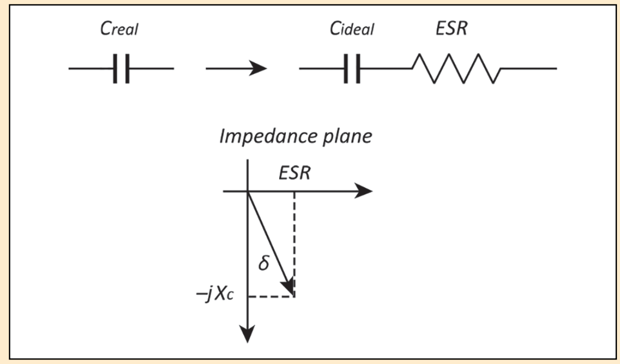

Figure 4. Relation between equivalent series resistance ESR and capacitance.

The circuits in bridge-type instruments usually use a combination of a capacitor and a resistor to balance the dissipation factor of the test object. The combination of resistor and capacitor is, however, not frequency independent, and any deviations in test voltage frequency will therefore show up as a deviation in recorded dissipation factor.

The effect of frequency fluctuations on the bridge-type measuring instrument is therefore linear and can be conservatively estimated to give a standard uncertainty contribution of 0.2 % of dissipation factor reading for normal grid frequency deviations of less than 0.1 Hz. The grid frequency deviation has here been estimated from data for the European Continental Grid where variations in frequency less than 0.01 Hz are not controlled and a deviation of 0.15 Hz is considered to be acceptable in normal grid operation [30]. The contribution to standard uncertainty due to frequency variations is taken as $0.002 \cdot x$, where x is the recorded dissipation factor.

Measurements using sampling instruments and Fourier Transforms may be sensitive to frequency variations occurring during the acquisition of data for one transform. This effect is a form of spectral leakage and will predominantly show up as an increased experimental standard deviation and is therefore not considered a separate contribution.

4.8 Influence of Voltage Distortions

Voltage distortion in the test voltage for the capacitor could be a source of error. However, as most instruments operate in narrow frequency band, this is not a large concern. Furthermore, in the case where the power source is inductively compensated to reduce the current drawn from the electricity grid, this problem is sharply reduced because the compensation forms a resonant circuit with the power capacitor, reducing distortions significantly. It is not expected that voltage distortion will lead to a significant contribution to uncertainty.

4.9 Reference Capacitor

The calibration of the dissipation factor for the high-voltage reference capacitor can be obtained at best with an expanded uncertainty of 10^{-5} (see Section 3.4). Assuming that a compressed gas capacitor is used as the high voltage reference, it can be assumed that the stability of dissipation factor over time is substantially better than the calibration uncertainty and negligible in comparison to the calibration. The contribution to standard uncertainty due to calibration of reference capacitor is taken as 5×10^{-6}.

4.10 Measuring Instrument

There is at present only one announced capability in the CMC-tables for calibration of instruments for high voltage capacitance and dissipation factor, that being INMETRO in Brazil (see Section 3.5). The expanded uncertainty is stated as 0.002 %.

Some other NMI's are however known to offer services for transformer ratio arm bridges, e.g., NRC in Canada and RISE in Sweden. These use a capacitor set to obtain known current ratios in the branches of the bridge. The best uncertainty is typically 0.001 % for the dissipation factor, but as they have not announced their capabilities at BIPM, they will not be further considered.

In transformer ratio arm bridges there is often a built-in circuit to compensate for effects of lead impedance [11], which in principle should remove all effects of voltage drop on the connection between capacitor and instrument. In practice, a contribution to uncertainty should be estimated from measurement of dissipation factor with and without an intentional extra lead resistance. No generally-valid estimate can be given, but in an example from one of the bridges used by the author, an intentional error of 0.4 % could be reduced to 0.0015 %. For the sake of argument and a less extreme case, an error of 0.1 % should be possible to reduce to 0.0004 %, which for a rectangular distribution corresponds to a standard uncertainty of 0.00017 %.

There is an insidious contribution from the capacitance to earth of the coaxial cable, where the voltage drop across the resistance of the transformer winding in the bridge will lead to a small capacitive current being drawn through the capacitance to earth of the coaxial cable. This works out as an error in dissipation factor, dependent only on the earth capacitance and the winding resistance. Schemes to correct for this can be injecting a current directly into the winding [11], to compensate numerically or to drive the cable screen to the same potential as the center conductor. Uncompensated, this can typically lead to errors in the range 0.0001–0.002 %. When compensated, the contribution is negligible.

The best specifications of dissipation factor measurement with commercial transformer ratio arm bridges is 0.001 % plus 1 % of reading [14], 0.0015 % plus 0.5 % of reading [13] and 0.002 % plus 1 % of reading [31].

In summary, the most important limitation is the uncertainty of the best available traceable calibration and the contributions to standard uncertainty are taken as 0.001 % for the calibration of the measuring instrument at zero dissipation factor and 0.00017 % for the lead impedance compensation.

The uncertainty of dissipation factor reading due to linearity of the measuring instrument is taken as $\frac{0.005}{\sqrt{3}} \cdot x \approx 0.0029 \cdot x$, where x is the recorded dissipation factor.

4.11 Current Transformer

Since the test current needed for testing of power capacitors easily exceeds the current capability of measuring instruments, a suitable device is needed to transform the current magnitude. The accuracy requirement makes it imperative that the transformer has extremely small phase displacement, in fact, the only viable alternative is to use so-called zero-flux transformers. There are several manufacturers of such devices in the world, and they generally specify the phase displacement uncertainty to 15 µrad [32, 33].

Calibration of current transformers has a best CMC of 2 µrad for currents up to 100 A, 5 µrad for currents up to 1,000 A and 15 µrad above (PTB in Germany) [24].

Stability of a zero-flux current transformer is normally excellent within the bounds of its specification, and it should be reasonable to compensate for calibrated errors, using the uncertainty of its calibration as uncertainty estimate.

The contribution to standard uncertainty from calibration of current transformer is taken as 2.5×10^{-6}.

Contribution	Value	Std uncert	Sensitivity coefficient	Uncertainty contribution
Recorded dissipation factor	x	St.dev(x)	1	St.dev(x)
Ref. cap. Calibration	0	5	1	5
Instr. Calibration	0	10	1	10
Lead impedance compensation	0	1.7	1	1.7
CT calibration	0	2.5	1	2.5
Frequency	0	0.002*x	1	0.002*x
Instr. Linearity	0	0.0029*x	1	0.0029*x
Combined standard uncertainty, excluding first and two last contributions				11.6
Combined expanded uncertainty for a coverage factor of k = 2				23

Table 4. Absolute uncertainty contributions for dissipation factor in 10^{-6}.

4.12 Statistical Dispersion

In an actual measurement situation, a certain variability of measurement is expected. It has been observed by the author that this variability is usually of minor importance, especially with classical bridges, compared to other sources of error. In adherence to good practice, the standard deviation of this contribution should, however, always be considered.

4.13 Overall

The best uncertainty for a best possible measurement of dissipation factor can be estimated from the above discussions, with the diverse contributions listed in tabular form. For the contributions considered, a simple model function consisting of products has been assumed (see Table 4). This leads to sensitivity factors that are equal to unity.

For objects with very low dissipation factor and for a best practice measurement, an ultimate traceable uncertainty that can reasonably be claimed is thus 23×10^{-6}. To this should, in each individual case, be added contribution from the statistical dispersion of results, the effects of frequency deviations on the measuring instrument and the uncertainty of dissipation factor reading due to linearity of the measuring instrument. Therefore, for small values of dissipation factor a lowest expanded uncertainty is defined as

$$2 \cdot \sqrt{(11.6 \times 10^{-6}) + stDev(x)^2 + (0.002 \cdot x)^2 + (0.0029 \cdot x)^2},$$

where x is the recorded dissipation factor.

5. Outlook and Discussion

The best possible traceable uncertainty is ultimately limited by available calibration services to an estimated best uncertainty of 0.0023 %, which is barely lower than the lowest dissipation factors that can be encountered. Site-specific contributions should be estimated in each individual case and may increase the uncertainty even further. It is, however, a heavy task for an industrial facility to obtain calibrations with the required accuracy, and to assess all the pertinent contributions to uncertainty. It can be concluded that industry will need further advances in measurement and calibration performance to meet future demands on dissipation factor measurement on power capacitors.

National metrology institutes need to provide ameliorated metrological infrastructure in the field of dissipation factor at power frequency. Two main tasks are of importance, to provide realization of dissipation factor at high voltage and power frequency, and enhanced calibration services for high-voltage capacitance bridges.

Funding

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