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THE CALIBRATION OF PARTIAL DISCHARGE (PD)
MEASURING CIRCUITS

ACCURACY AND ESTIMATION OF ERRORS

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ABSTRACT

With increasing electrical stresses and further "tightening" of the construction of high voltage apparatus nondestructive tests like the partial discharge measurement are an important help for producer and user.

Limits for pd-values are based mainly on experience during the last 30 years with radio influence voltage (RIV) measurements in μV and widebandmeasurements of the apparent charge in pC. Even when following standards, possible errors with RIV measurements are higher than with wideband measurements of apparent charge. Errors can be kept in both cases within ± 3 dB, and should even for an earlier stage of pd measurements be smaller than + 10dB.

Exact knowledge of the data of comparable measurements is essential, therefore calibration and calibration standards are necessary.

RESUME

Avec l'augmentation des contraintes électriques ainsi que la rationalisation des constructions des appareils utilisés en H.T., les essais non destructifs comme les mesures de décharges partielles sont d'un important secours pour l'utilisateur comme pour le fabricant.

Les limites de décharges partielles sont surtout basées, après 30 années d'expérience, sur les mesures de perturbations radioélectriques et sur les mesures en bande large en pC. Les erreurs possibles peuvent être plus importantes avec les mesures de perturbations radioélectriques - même en appliquant les spécifications données - qu'avec les erreurs en pC. Les erreurs peuvent être comprises dans les deux cas dans une tolérance de ± 3 dB et devraient néanmoins être plus petites que + 10dB pour des mesures antérieures.

Les connaissances exactes des données comparables sont essentielles, donc l'étalonnage et l'étalon sont nécessaires.

ZUSAMMENFASSUNG

Mit zunehmenden elektrischen Beanspruchungen und kompakteren Konstruktionen der Hochspannungsapparate ist eine zerstörungsfreie Prüfung wie die Teilentladungsmessung eine wichtige Hilfe für Hersteller und Benützer.

Die zulässigen Grenzwerte für Teilentladungswerte gehen hauptsächlich auf Erfahrungen der vergangenen 30 Jahre mit Störspannungsmessungen in μV und Breifbandmessungen in pC zurück. Fehler können bei der μV -Messung höher sein - selbst bei Anwendung vorhandener Vorschriften - als bei der pC-Messung. Fehler können in beiden Fällen innerhalb ± 3 dB gehalten werden, sie sollten aber selbst für weiter zurückliegende Messungen kleiner als + 10 dB sein.

Genauere Kenntnis aller Daten von zu vergleichenden Messungen ist wesentlich, deshalb sind Eichung und Eichnormale unbedingt nötig.

1. INTRODUCTION

For a long time, the safest means for checking the **elctrical** Insulation of high voltage equipment before putting it into service was to apply severe test methods using test voltages which were high compared with the operating voltages, and of long duration. Weak points in the insulation cause in most cases a complete breakdown. Sometimes however the quality of the insulation is reduced by the test, so that breakdown occurs perhaps after only several years of operation. In spite of the low electrical stresses and the large safety margins in those days, this already presented difficulties for the designer, but nowadays the problem is much more severe. The need to economise in electrical equipment and systems and to reduce costs for reasons of competition compels the producer to increase electrical stresses and tighten construction to the point, where the safety factor is small but still adequate to guarantee satisfactory operation. This raises not only the problem which tests should be applied, but furthermore by what methods damage caused by a test can be revealed. Such a nondestructive check of the insulation is the partial discharge (**pd**) measurement, when applied before and after a test voltage.

The amounts of partial discharges, the changes of these amounts during tests that can be tolerated for safe operation, and the values which shall be established as pd-limits at operating voltage must be based on the experience in partial discharge behaviour of high voltage equipment during the last thirty years. This experience includes uncertainties in the measuring methods and of the measurement accuracies. In order to receive comparable results of pd-measurements for the various makes of high voltage equipment, it is necessary to standardize measuring circuits, measuring quantities, measuring instruments, and calibrating methods. In the past thirty years all these parameters have been changed or improved respectively and were settled finally 1968 in the IEC recommendations Publication No. 270 "Partial discharge measurements" (1). Up to that time the radio influence voltage (RIV) in μV had been prescribed by most national standards as the measuring quantity. But IEC No. 270 recommends beside some other measuring quantities the "apparent charge" in picocoulombs, and does not accept RIV anymore - except as a mere indication. In order to make full use of all μV -measurements up to now, μV -values must therefore be transferred to picocoulombs. This is done by either applying a factor of e.g. 1,0 (see 4.) generally or by performing parallel

measurements in μV and in **pC** for every type of test sample, thus determining its individual conversion factor. Considering the variety of existing measuring circuits and calibrating methods, and the accuracy of **RIV-measurements**, the latter method appears to be more reliable. But as the method of parallel measurements in μV and in **pC** is applicable only as an exception, the accuracy of different pd-measuring methods is discussed in the following paragraphs.

Generally it must be kept in mind, that the actual discharge quantity neutralised in a void or gap can be measured only in very special cases; in fact partial discharges in a test object result for the test object as a whole in a voltage drop and change of charge (=the apparent charge) causing transients in the measuring circuit, which are detected by the measuring Instruments. The measured quantity is much smaller than the actual discharge quantity in most cases and may be different for different terminals of the test sample. This latter property is used for locating partial discharges in high voltage equipment (2), but is not discussed here.

2. THE RADIO INFLUENCE VOLTAGE (RIV) MEASUREMENT (μV)

2.1. RIV-METERS

When partial discharge measurements were started on a wide scale in the 1940's, only sensitive radio noise meters were generally available. As there was practically no alternative, they were used in USA for partial discharge measurements also, according to the early **NEMA** standard (3), which was revised in 1964 (4).

Two principal types of RIV-meters were developed, namely the American and the CISPR radio noise meter (5). They indicate a "weighted" voltage, which means, that the reading of the meter for an impulse (remaining unchanged in **size** and shape) increases with its repetition rate. But the relative increase of the meter reading is different according to the two standards: this means e.g. for an increase of the number of discharges per half cycle of a 50 Hz sine wave from one to 10, that the reading of an US RIV-meter increases **c.30%**, that of a CISPR RIV-meter **c.70%**. The CISPR reading dependence on the repetition rate is adapted to the sensitivity of the human ear. This dependence on repetition rate might be in some cases the **same** one as for a damage done to electrical insulation, but rather unlikely in general.

The accuracy of the RIV-meters varies between $\pm 1,5 \text{ dB}$ (c. $\pm 18\%$) and $+ 3 \text{ dB}$

(+ 35 %), the difference between readings at the lower or at the upper portion of the scale may be up to 2 dB, when changing from one range to another. Comparison measurements with various instruments showed in general rather good agreement, when PC-pulses or sine waves were applied (6,7).

The dependance of RIV-meters on the pulse repetition rate can be instead of max. + 6 dB (according to CISPR) 8 to 12 dB (6) for some instruments (related to 1 pulse per half cycle). With many different instruments in use (and out of use again) in the past thirty years, the maximum difference between Instrument readings for the same input, just caused by the errors of these instruments, thus could be c.12 dB (+ 3 makes 6, and additional dependance on repetition rate 12-6 = 6), corresponding to a factor of 4 between the extrem readings - the maximum error being c.9 dB (factor of c.3 for too high values).

2.2. CALIBRATION OF THE MEASURING CIRCUIT BY VOLTAGE COMPARISON

The NEMA standard 1940 (3) prescribes a selfcontained calibrating signal-source for the calibration of the measuring instrument, but not necessarily a calibration of the measuring circuit as a whole. The transferfunction between high frequency voltage input at the high voltage apparatus under test and the reading of the instrument is checked only with the compensated circuit, but not with the ordinary circuit: two curves show the error due to stray capacitances of the test object. This procedure seemed to be justified by the high capacitance of the coupling capacitor with not less than 2500 pF. In the compensated circuit however a radio frequency source is applied across the test object and so the ratio determined by which the readings are to be multiplied. The 1964 NEMA standard substituted the 2500 pF of the coupling capacitor by 1000 pF, the 600 ohm of the measuring Impedance by 150 ohm and changed the time constant of the detector (charging/discharging time) from 10/600ms to 1/600ms. (CISPR RIV-meter: 1/160ms). As Harrold and Dakin point out, It was hoped when introducing the new standard, that these changes would compensate each other roughly, and that therefore existing corona test limits would not have to be changed: which is about valid for apparatus with a capacitance between 100 and 500 pF, as the values remained similar, but not for transformers with capacitances between 300 and 5000 pF, where the values approximately doubled at low pulse repetition rate, coming to better agreement with Increasing pulse repetition rate (7).

At the application of NEMA standards, but with CISPR Instruments and error of up to e.g. 6 dB (factor of c.2) compared with

the results of a NEMA-instrument could arise, and so simulate a better circuit RIV-factor: the NEMA instrument for itself has a high impedance, so that the current distribution in the measuring circuit is not affected, if the instrument is connected either to the coaxial cable leading to its measuring impedance Zm or to the object under test, whereas a CISPR-instrument with its low impedance shifts the current distribution when being connected once to the measuring point at high voltage and then to the object under test with the radio frequency generator. Therefore during the calibration of a NEMA circuit with a CISPR instrument: two Instruments should be used simultaneously, or an equivalent impedance inserted alternately.

It is often supposed, that the amount of the measuring impedance influences directly the μV -measurement. This is true for the reading of the instrument. But with calibration according to NEMA with voltage comparison this reading is corrected by the circuit RIV-factor, which is the ratio of the reading of the instrument to the voltage input at the test sample. Therefore the calculated "true" value is independent of the amount of measuring impedance.

as the reading of RIV-meters is dependant on the repetition rate of partial discharges, the frequency of the test voltage is of influence too. With higher frequency the number of discharge/s is directly increased, assuming the same number of discharges/cycle.

The following table gives the approximate factors for some samples- of pulses per half period referring to 50 Hz as 1,0:

Hz	Pulses per 1 half period	2	4	8
50	1,0	1,0	1,0	1,0
100	1,25	1,2	1,11	1,1
150	1,38	1,26	1,17	1,14

As the table shows, the higher the pulse repetition rate per half cycle, the lower is the influence of the frequency of the test voltage.

2.3. CALIBRATION OF THE MEASURING CIRCUIT BY COMPARISON OF CURRENTS

Instead of calibration by voltage comparison at the test sample and at the measuring impedance according to NEMA (see 2.2.), the German VDE Standards (8) use a radio frequency current of constant amount as partial discharge calibrator. This current is produced either by a series connection of a sine wave generator with c.50 pF or by a pulse calibrator and is applied to the measuring circuit in parallel to the test sample. It is measured once directly by inserting a

measuring impedance in series to the current source and *once* by inserting the same measuring impedance in series to the coupling capacitor (or to the test sample instead). The circuit RIV factor may vary with the kind of radio frequency generator (-if it gives the same results grounded or not grounded-), the length of the coaxial cable (if used at all), the way of connecting this coaxial cable to the series capacitor, to the measuring impedance and finally to the test object itself: a spread of 6 dB (factor of 2 between minimum and maximum) seems to be not unusual, although c.10 dB can be found too. But e.g. 8 or 16 μV as result of the partial discharge test means for an instrument transformer the essential difference of being accepted or of being rejected respectively. Compared with a radio frequency generator the pulse **calibrator** seems to be less problematical in application (see 2.4.).

In contrast to the calibration of the measuring circuit by voltage comparison (see 2.2.), the amount of measuring impedance influences the result directly, although not exactly proportionally. As long as the whole current of the radio frequency generator (or pulse generator) passes the measuring impedance (direct series connection), the Instrument reading corresponds directly to the change of the measuring impedance. But if the measuring impedance is in series to the coupling capacitor (or test sample instead), the whole current distribution of the measuring circuit is shifted by a change of the measuring impedance and therefore the current through the measuring impedance itself too. The deviation will be relatively small though, and the circuit RIV-factor **will** change only little. But the instrument reading increases with increasing measuring impedance, so that the calculated "true" value increases too. Therefore RIV-measurement with calibration by current comparison **is** dependant on the amount of measuring impedance.

The circuit RIV factor itself is frequency dependant, but in a different way as the circuit RIV factor found by calibration by voltage comparison, as once the **current** is kept constant and once the voltage respectively in these two methods. This means, that only a specific amount of measuring impedance at a **specific** radio frequency gives the same **pd**-results as received by measurements with calibration by voltage comparison and 150 ohm.

2.4. CALIBRATION OF THE MEASURING CIRCUIT BY A PULSE CALIBRATOR.

The pulse calibrator (9, 10) recommended by CIGRE facilitates the calibrating **procedure** also for RIV measuring

circuits, as its application is very simple. It leads to the same results as the correct application of a radio frequency sine wave generator, but leaves less chances for errors. For this reason the partial discharge standard for instrument transformers (11) of the Swiss **Electrotechnical Association** recommends **Only** the pulse calibrator for RIV-measurements as well as for PC-measurements. To facilitate comparisons of RIV-measurements **furtheron** only one measuring impedance for RIV-measurements, namely 150 ohm is permitted (see 2.3. last section). Besides, the direct comparison of μV with **pc**-values is established.

2.5. SURVEY OF POSSIBLE ERRORS AND DEVIATIONS FOR PD-MEASUREMENTS WHEN USING RIV-MEASURING CIRCUITS.

see :

Accuracy of modern RIV-instruments	\pm 2dB	(2.1.)
former ones	+ 3dB	
Influence of repetition rate on former instruments up to	+ 6dB	(2.1.)
NEMA 1964 standards against 1940 up to	+ 6dB	(2.2.)
NEMA standards with CISPR instruments up to	\sim + 6dB	(2.2.)
Testfrequency of 150 Hz instead of 50 Hz	+ 3dB	(2.2.)
VDE standards with sine wave generator by unlucky choice of connections	c. \pm 3dB	(2.3.)
VDE 60 ohm against NEMA 150 ohm	- 8dB	(2.3.)

Certainly these errors were partly compensated by not calibrating at all (in former times), or by choosing **measuring** frequencies with low response to **pd's**, or by a more or less lucky choice of radio frequency generator arrangement (e.g. standing waves).

So the spread of pd-measurements **during** the last thirty years when applying standards in good trust should be less than approximately **+ 10dB** of the true values. Certainly this range is much smaller in all those cases, in which **pd**-measurements were performed continuously through the years with long series of high voltage apparatus by means of one stable method or by several methods, the relations of which to each other were known.

3. THE MEASUREMENT OF APPARENT CHARGE (pc)

3.1. PARTIAL DISCHARGE DETECTORS.

As already mentioned (see 1.), only in special cases it is possible to **mea-**

sure the actual charges being discharged and **neutralized** in a partial discharge. In fact only the resultant changes of voltage or charge on the test object **as a whole** can be determined. RIV-instruments measure the voltage drop caused by a pd just within a narrow frequency band transforming it by a weighting circuit according to the sensitivity of the human ear. Broad band partial discharge detectors measure the maximum peak values of apparent charges within one half cycle of the industrial frequency. This gives results more independent of the frequency behaviour of test object and measuring circuit. Such instruments are available on the market for the measurement of the apparent **charge** according to IEC 270 and have an accuracy of c. + **1dB**. As the reading of most instruments can be adjusted to the **pc-input** value at the test object during calibration, a separate calculation of the transfer factor is not necessary in most cases.

3.2. CALIBRATION OF THE MEASURING CIRCUIT BY A PULSE CALIBRATOR.

The shape of discharge pulses **is** far from a pure **sinewave** of any frequency, although discharges may cause travelling waves similar to sinewaves. Therefore CIGRE recommends pulse generators (see 2.4.) for calibration of **pd-measuring** circuits. The application of these calibrators is less problematical for everyday measurements in a test plant, than radio frequency generators. Despite that straycapacitances cannot be disregarded and the connections should therefore be **as short as possible**. At the beginning of "apparent charge" measurements only measuring instruments with built in calibrators were used. These calibrators inserted the pulses just at the input of the coaxial cable (coming from the testobject) into the measuring instrument. The **transferfactor** was calculated. However checking these calculated amounts suggested then **a** direct calibration by inserting the calibrating pulses across the terminals of the test sample. Therefore it is essential for the comparison of **pd-testresults** to be aware of the method of calibration. If only the internal calibrator is applied - possibly even without "calculating" a transfer **behaviour** -, an error of **+ 10dB** (factor of 3) is not unusual, which means that the recorded **values** are only 1/3 of those found after direct calibration. The pulse calibrators themselves available on **the market** should be accurate within **+ 1dB**.

Generally it must **always be ascertained**, if the test circuit is discharge free, so **that measured discharges** do not come from other elements **of the circuit**. This must

be checked especially in cases, where the test object has a high capacitance compared with the other elements, **because discharges** from a **low capacitance** are recorded much more sensitively than those from the testobject (6). After the calibration across the test sample, the transfer behaviour of pd's coming from small capacitances in the circuit should be checked.

The accuracy of instruments and pulse calibrators is **± 1dB** each; if the pulse calibrator is applied at its **- 1dB** to the instrument at its **+ 1dB** point, but the latter changes during measurement to its **- 1dB** point, then the whole error is **- 3dB**. The accuracy of a correctly calibrated circuit then is **± 3dB**.

3.3. SURVEY OF POSSIBLE ERRORS FOR DISCHARGE MEASUREMENTS WHEN MEASURING THE APPARENT CHARGE WITH WIDEBAND INSTRUMENTS.

see :

Accuracy of wideband partial discharge detectors	± 1dB	(3.1.)
Accuracy of pulse calibrator	± 1dB	(3.2.)
Resultant accuracy	± 3dB	(3.2.)

Measurements from the past without calibration across the test object and just calculated transfer function may have an error of e.g. **+ 10dB**.

4. RELATIONSHIP BETWEEN μV and **pc**.

For the conversion of **μV** to **pc** it is necessary to know: the type of high voltage apparatus under test, the measuring instrument, the measuring circuit and the applied standard, the frequency of the test voltage, the radio frequency for the **RIV-measurement** and the method of calibration (radio frequency generator or pulse calibrator, voltage- or current comparison). The amount of measuring impedance is especially important, if the current comparison method was used (see 2.3.).

IEC 270 (1) recommends a conversion factor for **pc/ μV** of 1 (using a measuring impedance of 150 ohm), which was adopted also by the Swiss standards for instrument transformers (11). (7) gives for transformers a margin dependent of the pd-location and the capacitive network of the transformer from about **0,2** to **60**, with an average from **0,25** to **5**, and for other high voltage apparatus like switchgear, lightning arresters, bushings c. 1 (measuring impedance **150 ohm**), (12) gives **2,6 pc/ μV** for 100 pulses/s and a measuring impedance of **60 ohm**. For the actual reading in **μV** (without correction by the circuit RIV **fac-**

tor and including a measuring impedance of 60 ohm) (6) gives a margin between 5 and 100 for the **relation pC/ μ V**. (All instruments narrowband either **ASA** or CISPR standard.)

Results from a measuring circuit with a 60 ohm impedance and calibrated by the current comparison method (see 2.3.) must be calculated for a 150 ohm impedance by multiplying with a factor of max. **2,5** (- If the calibration was done by voltage comparison (see 2.2.) the amounts remain unchanged (see 2.2.)).

5. CONCLUSIONS.

Limits for permissible pd-values at operating voltages of high voltage apparatus are agreed upon partly on theoretical reasons but mainly on experimental data. As these data were collected during the last thirty years, it is essential to know exactly the type of measuring **instrument** and its electrical characteristics, the amount of measuring impedance, the method of calibration (radio frequency or pulse generator, voltage or current comparison, connections), the industrial frequency of the test voltage, the measurement radio frequency, the characteristics of the coupling capacitor, the data of the measuring circuit and the applied standards or recommendations. With this knowledge it should be possible to estimate the probable error of the measured values: if they stay within the limits of approx. **+ 3dB** given by the used instruments, or if wider tolerances have to be assumed. More and more limits for pd-values during tests are being specified officially by technical committees for high voltage equipment. As these limits are essential for acceptance or rejection of apparatus, it is necessary to check measuring instruments and calibrators from time to time. Therefore it is desirable, that the national bureaux of standards (**or** equivalent offices) establish calibration stations for such instruments and calibrators.

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