THE ACHIEVABLE VOLTAGE MEASUREMENT UNCERTAINTY OF THE BUSHING TAP METHOD DURING THE INDUCED VOLTAGE TEST OF POWER TRANSFORMERS

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Abstract: The induced voltage test with increased frequency is one of the most critical factory routine tests of a power transformer. Therefore the test voltage shall be measured accurate and in compliance with IEC 60060-2 Ed. 3.0 [1]. The use of a dedicated capacitive divider for the voltage measurement can be avoided to save additional reactive power consumption as well as test area space. The dangerous capacitive voltage rise during the induced voltage test with increased frequency can be minimised. The bushing tap method is using the transformer's condensor bushing tap in combination with a low voltage arm integrated in the pd quadripole used during the simultaneous partial discharge measurement. The measuring procedure including the necessary prior calibration of the bushing tap measuring circuit is described and the general achievable voltage measuring uncertainty is derived. Oil impregnated paper condensor bushings (OIP) as well as resin impregnated paper condensor bushings (RIP) are considered. The uncertainty calculation is deliberately kept general and not related to a specific bushing type and voltage class. Assuming an adiabatic energy absorption the dissipation energy approach [2] is used to generate the model function needed to derive the uncertainty budget in compliance with IEC 60060-2 Ed. 3.0 [1].

1 INTRODUCTION

Distribution and power transformers have to be dielectrically tested during the induced voltage test with increased test voltage values at increased test frequency to avoid a transformer core saturation. For distribution transformer the test and measuring procedure is quite simple. The double value of the nominal voltage will be applied and measured 3 phase on the low voltage side. With respect to a considerably high design safety margin an accurate voltage measurement on the high voltage side according to IEC 60060-2 Ed. 3.0 [1] is not required. Due to the capacitive voltage increase especially at increased test frequencies the induced high voltage is generally higher than the calculated value of the high voltage using the measured values of the excitation voltage on the low voltage side multiplied with the transformer ratio.

For power transformers with higher voltage/power ratings and much higher financial risk for both vendor and customer the induced voltage test and measuring procedure is by far more sophisticated and critical. Power transformers are generally in a single phase test configuration when exposed to the induced voltage test. Simultaneously to the induced voltage withstand test a sensitive partial discharge measurement is performed for having a criteria for the dielectric quality of the transformer under test. Depending on the specific single phase test configuration the induced voltage on the high voltage side for one or two phases and the insulated star point if not grounded should be measured. Some utilities also apply 3 phase induced test voltages to power transformer after transportation to proof its unchanged dielectric conditions. In all these cases the induced high voltage shall be measured directly with a measuring accuracy according to IEC 60060-2 Ed. 3.0 [1]. Due to series resonance phenomena the induced voltage test of power transformers is the more critical to execute the higher the test frequency in combination with the short circuit impedances and test capacitances of the test setup including test object is. Furthermore the required test power should be optimised to keep the power front end size (power source, compensation, step up transformer) reasonable. Therefore significant additional capacitive load by means of a high voltage measuring system with a dedicated capacitive voltage divider (1..2 nF) should be avoided. The use of a voltage measuring system based on a compressed gas capacitor (30 .. 100 pF) is a low capacitive and technically sound but more expensive solution especially for higher test voltages. Using the condensor bushing mounted on the transformer as capacitive divider could be an economical solution (bushing tap method).

IEC 60060-2 Ed. 3.0 [1] states for an approved alternating voltage measuring system that the peak/$\sqrt{2}$ value shall be measured with an expanded uncertainty $U_M \leq 3\%$. For having a general measuring uncertainty statement independent of the bushing size the specific dissipation loss approach [1] was chosen and applied for oil impregnated paper bushings (OIP) as well as for resin impregnated paper bushings (RIP).

2 BUSHING TAP METHOD

2.1 Principal condensor bushing design

A condensor bushing consists of concentric aluminum (Al) foil layers between the centre conductor and the grounded mounting flange with oil or resin impregnated paper as dielectric insulation in between. The high voltage capacitance C_1 is formed by the dielectric insulation between the centre conductor and the C_1 Al foil. The C_2 capacitance is formed by the bushing tap insulation between the C_1 Al foil and a grounded C_2 Al foil or the grounded mounting flange itself. The C_1 Al foil is internally connected to the inner stud of the voltage tap. C_1 and C_2 work as a voltage divider. During normal bushing operation the C_2 capacitance is either shortened by the metallic cap of the bushing tap or the voltage drop across C_2 is used for the operation of relays.

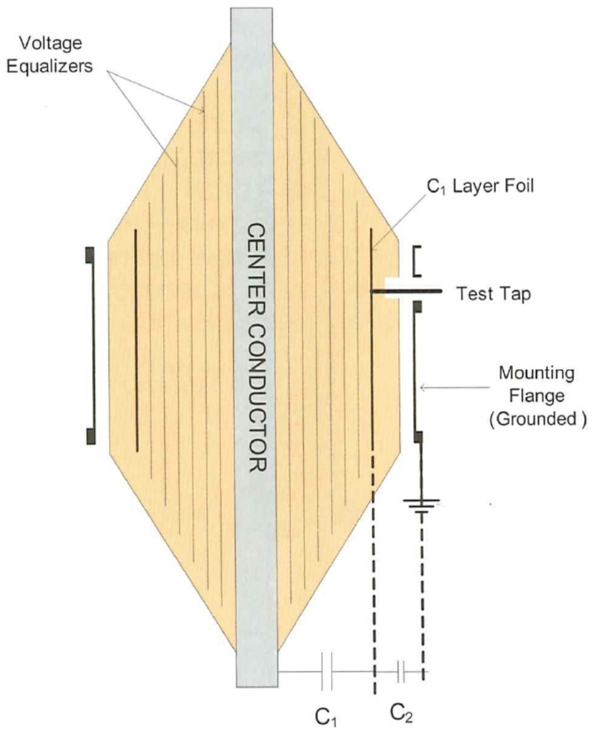

Fig. 1: Principle condensor bushing design [3].

2.2 High voltage measuring system by using the bushing tap

The C_1 capacitance can be used as high voltage capacitance (high voltage arm). Together with a secondary unit (low voltage arm) a capacitive divider can be built up. As display unit a digital multi-meter or a digital partial discharge detector might be used. Using a secondary unit in combination with a digital partial discharge detector is a very economical solution since the partial discharge activity of a power transformer during the induced voltage test has to be recorded anyway.

Fig. 2 shows the equivalent circuit diagram of a condensor bushing capacitance C_1 in combination with the secondary unit (low voltage arm) AQS 9110 [4] and the partial discharge detector DDX 9121 [5]. C_{LV} and R_1, R_2 are a low voltage capacitor respectively low voltage resistors within the secondary unit/coupling quadripole AQS 9110.

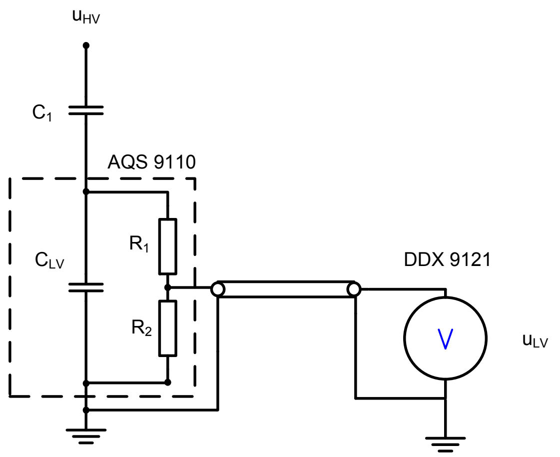

Fig. 2: Equivalent circuit diagram of a voltage measuring system using the bushing tap method.

2.3 Calibration

Since there are manufacturing tolerances of any bushing capacitance C_1 a calibration of the voltage measuring system is required. Details of the calibration procedure are described in the relevant standard [2]. As voltage reference system a damped capacitive voltage divider type CS [6] measuring system with a dedicated AC secondary unit might be used. Small damped capacitive dividers (< 400 kV_{peak}, LI) are normally used for impulse measurements on the LV winding of a transformer. They normally have approx. 25% of its LI peak rating as AC rms rating. Another possibility for the calibration is using a standard capacitor in combination with a C, tan δ measuring bridge for broader test frequency ranges (15 .. 1000 Hz) [7].

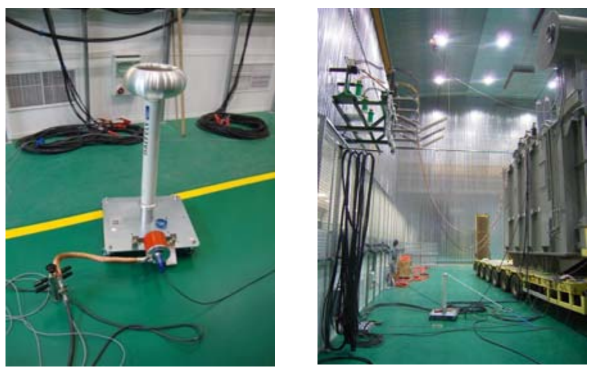

Fig. 3: Damped capacitive divider CS 400-1000 without external damping resistor, 400 kV_{peak} LI, 100 kV_{rms} AC, 1 nF (left), DUT (right).

3 THE DISSIPATION ENERGY INFLUENCE

Since a voltage calibration is in any case required prior to the measurement and the measuring time is relatively short for the induced voltage test the consideration of the long term stability, the ambient temperature effect and the proximity effect with respect to the voltage measuring uncertainty is not needed. The voltage linearity might be checked by comparing the measured excitation voltage of the transformer under test with the measured HV output voltage. The induced voltage test is a test under no load conditions and a resistive heating of the bushing's centre conductor due to the output current will not occur. Therefore only the capacitance changes (ΔC_1, ΔC_{LV}) and resistance changes (ΔR_1, ΔR_2) caused by the temperature rise ΔT due to the dissipation energy respectively resistive losses and their contribution to the measuring uncertainty are considered.

3.1 The dissipation energy equation

Assuming an adiabatic energy absorption during the induced voltage test the bushing's respectively the secondary unit capacitors dissipation energy are completely stored in their heat capacity as described by equation (1):

$$2 \cdot \pi \cdot f \cdot C \cdot U^2 \cdot \tan\delta \cdot t = \rho \cdot V \cdot c \cdot \Delta T \quad (1)$$

f: test frequency of induced voltage test
C: capacitance C_1 respectively C_{LV}
U: induced test voltage
tan δ: dissipation factor
t: test duration
ρ: density of dielectric material
V: volume of dielectric material
c: specific heat capacity of dielectric material
ΔT: temperature rise during the test

Dividing equation (1) by the infinitesimal dielectric volume ΔV and using the formulas (2),(3) and (4) for infinitesimal fractions generates the dissipation energy density equation (5):

$$\Delta C = \frac{\Delta Q}{\Delta U} = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot E \cdot \Delta A}{E \cdot \Delta x} = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot \Delta A}{\Delta x} \quad (2)$$

$$\Delta U = E \cdot \Delta x \quad (3)$$

$$\Delta V = \Delta A \cdot \Delta x \quad (4)$$

$$2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r \cdot E^2 \cdot \tan\delta \cdot t = \rho \cdot c \cdot \Delta T \quad (5)$$

Q: charge within bushing dielectric
ε_0: permittivity ($8.8541878176... \cdot 10^{-12}$ F/m)
ε_r: relative permittivity of dielectric material
E: average rms electrical field strength during the induced voltage test
Δx, ΔA: infinitesimal section x respectively area A
ρ: density of dielectric material

The dissipation energy density equation (5) is used to calculate the temperature rise ΔT of a bushing dielectric independent from any bushing geometry. The dissipation energy equation (1) is used to determine the temperature rise ΔT of the capacitors within the secondary unit. With the temperature rise ΔT the capacitance changes ΔC_1 and ΔC_{LV} are calculated.

3.2 Material properties

Material properties for OIP bushings, RIP bushings and secondary unit capacitors with PET dielectric:

	OIP	RIP	PET
ε_r	3.5	4	3.2
tan δ	0.003	0.005	0.01
ρ [kg/m³]	1000	1200	1390
c [J/(kg·K]	1300	1200	1300
α [1/K]	$2.5 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	$4.62 \cdot 10^{-4}$

Table 1: Material properties OIP, RIP and PET [8].

PET: polyester film
α: temperature coefficient

The resistors used in the secondary unit (Fig. 2) are metal film power resistors with a temperature coefficient α of $2.5 \cdot 10^{-4}$ K^{-1} and a hot spot temperature rise of 75 K/W.

3.3 Model function and sensitivity coefficients

The model function f [8] for the high voltage u_{HV} to be measured by the bushing tap method is derived from Fig. 2.

$$u_{HV} = f(C_1, C_{LV}, R_1, R_2, u_{LV}) = \left(1 + \frac{C_{LV}}{C_1}\right) \cdot \left(1 + \frac{R_1}{R_2}\right) \cdot u_{LV} \quad (6)$$

The combined standard uncertainty u(y) and the expanded uncertainty with a 95.45% confidence level (k= 2) are defined as [1], [9]:

$$u(y) = \sqrt{\sum_{i=1}^{N} \left[c_i \cdot u(x_i)\right]} \quad (7)$$

$$U = k \cdot u(y) \quad (8)$$

The sensitivity coefficients c_{C1}, c_{CLV}, c_{R1}, c_{R2}, c_{uLV} [1], [8] needed for the uncertainty budget are derived as partial derivatives from the model function (6).

$$c_{C_1} = \left.\frac{\partial u_{HV}}{\partial C_1}\right|_{C_1,C_{LV},R_1,R_2,u_{LV}} = (-1)\cdot\left(\frac{R_1+R_2}{R_2}\right)\cdot\frac{C_{LV}}{(C_1)^2}\cdot u_{LV} \quad (9)$$

$$c_{C_{LV}} = \left.\frac{\partial u_{HV}}{\partial C_{LV}}\right|_{C_1,C_{LV},R_1,R_2,u_{LV}} = \left(\frac{R_1+R_2}{R_2}\right)\cdot\frac{1}{C_1}\cdot u_{LV} \quad (10)$$

$$c_{R_1} = \left.\frac{\partial u_{HV}}{\partial R_1}\right|_{C_1,C_{LV},R_1,R_2,u_{LV}} = \left(1+\frac{C_{LV}}{C_1}\right)\cdot\frac{1}{R_2}\cdot u_{LV} \quad (11)$$

$$c_{R_2} = \left.\frac{\partial u_{HV}}{\partial R_2}\right|_{C_1,C_{LV},R_1,R_2,u_{LV}} = (-1)\cdot\left(\frac{1+C_{LV}}{C_1}\right)\cdot\frac{R_1}{(R_2)^2}\cdot u_{LV} \quad (12)$$

$$c_{u_{LV}} = \left.\frac{\partial u_{HV}}{\partial u_{LV}}\right|_{C_1,C_{LV},R_1,R_2,u_{LV}} = \left(1+\frac{C_{LV}}{C_1}\right)\cdot\left(\frac{R_1+R_2}{R_2}\right) \quad (13)$$

The total measuring uncertainty for the HV measurement with the bushing tap method using an AQS 9110 [4] and a DDX 9121 [5] depends on the variations of C_1, C_{LV}, R_1 and R_2 due to the temperature change ΔT caused by the dissipation energy (C_1, C_{LV}) and the resistive losses (R_1, R_2) as well as the measuring error of the voltage measuring card (u_{LV}) within the DDX 9121 [5].

4 UNCERTAINTY BUDGET

To investigate the measuring uncertainty of the bushing tap method three OIP bushings and three RIP bushings with 460 kV, 275 kV and 140 kV test voltage will be analysed. The secondary unit AQS 9110 is designed for three selectable voltage ranges. In case the test voltage is induced the corresponding low voltage shall be 60 V. The considered voltage measuring range is from 10% to 100%. The volume of the used polyester film capacitors is 3.45 cm^3. The resistive divider ratio is always 10 with R_1= 270 kΩ and R_2= 30 kΩ at 20°C. The voltage across the bushing equals not necessarily the induced test voltage on a transformer [10] and is therefore assumed as $2 \cdot U_0$.

4.1 Temperature and capacitance variations

	OIP			RIP		
U_{test} [kV]	460	275	140	460	275	140
C_1 [pF]	450	500	480	450	500	480
C_{LV} [µF]	3.53	2.27	1.199	3.53	2.27	1.199
$E_{av,2\cdot U0}$ [kV_{rms}/cm]	70	70	70	70	70	70
f [Hz]	150	150	150	150	150	150
t_{test} [s]	3600	3600	3600	3600	3600	3600
$\Delta T_{max,2\cdot U0}$ [K]	11.9	11.9	11.9	20.4	20.44	20.44
$\Delta T_{min,0.2\cdot U0}$ [K]	0.12	0.12	0.12	0.2	0.2	0.2

	OIP			RIP		
ΔC_{1max} [pF]	**1.34**	**1.49**	**1.43**	**6.44**	**7.16**	**6.87**
ΔC_{1min} [pF]	**0.013**	**0.015**	**0.014**	**0.064**	**0.072**	**0.069**
$\Delta T_{CLVmax,60V}$ [K]	69.3	44.51	23.51	69.3	44.51	23.51
$\Delta T_{CLVmin,6V}$ [K]	0.69	0.45	0.24	0.69	0.45	0.24
ΔC_{LVmax} [nF]	**113**	**46.64**	**13**	**113**	**46.64**	**13**
ΔC_{LVmin} [nF]	**1.13**	**0.47**	**0.13**	**1.13**	**0.47**	**0.13**

Table 2: Temperature and capacitance variations due to the dissipation energy.

4.2 Temperature and resistance variations

	R_1	R_2
$\Delta T_{Ri,\ max}$ [K]	0.81	0.09
$\Delta T_{Ri,\ min}$ [K]	0.0081	0.0009
$\Delta R_{i,\ max}$ [Ω]	**54.675**	**0.675**
$\Delta R_{i,\ min}$ [Ω]	**0.547**	**0.00675**

Table 3: Temperature and resistance variations due to the resistive losses, i= 1, 2.

4.3 Maximum error of the voltage measuring card

The maximum error of the voltage measuring card inside the DDX 9121 [5] is 1% of reading. Therefore the lower and the upper limit of the voltage measurement error Δu_{LV} is -0.06 V respectively 0.06 V.

4.4 Calculation of the different uncertainty budgets [1], [9]

Since only the upper and the lower limits for the value of the quantity variations (ΔC_1, ΔC_{LV}, ΔR_1, ΔR_2, Δu_{LV}) can be estimated a rectangular probability distribution between the minimum and maximum limits has to be assumed [1], [9].

The square of the standard uncertainty is then calculated as follows:

$$u^2(T) = \frac{1}{12}\cdot(a_+ - a_-) \quad (14)$$

T: temperature
a_+: upper limit of quantity variation/error
a_-: lower limit of quantity variation/error

quantity X_i	estimate x_i	uncertainty $u(x_i)$	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$
C_1	450 pF	0.382·pF	$-1.04681 \cdot 10^{15}$ V/F	-231.4 V
C_{LV}	3.533 µF	0.0323 µF	$1.33 \cdot 10^{11}$ V/F	4304.80 V
R_1	270 kΩ	15.625 kΩ	1.57042 V/Ω	24.54 V
R_2	30 kΩ	0.1929 Ω	14.1338 V/Ω	2.73 V
u_{LV}	60 V	0.0346 V	78521.11	2720.05 V
Y= u_{HV}	y= 460 kV			u(y)= 5107.93 V
Expanded uncertainty U= k·u(y) (95.45 % confidence level, k= 2)				**U= 2.22%**

Table 4: Uncertainty budget OIP bushing 460 kV

quantity X_i	estimate x_i	uncertainty $u(x_i)$	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$
C_1	450 pF	1.8405·pF	$-1.04681 \cdot 10^{15}$ V/F	-1926.99 V
C_{LV}	3.533 µF	0.0323 µF	$1.33 \cdot 10^{11}$ V/F	4304.80 V
R_1	270 kΩ	15.625 kΩ	1.57042 V/Ω	24.54 V
R_2	30 kΩ	0.1929 Ω	14.1338 V/Ω	2.73 V
u_{LV}	60 V	0.0346 V	78521.11	2720.05 V
Y= u_{HV}	y= 460 kV			u(y)= 5444.53 V
Expanded uncertainty U= k·u(y) (95.45 % confidence level, k= 2)				**U= 2.37%**

Table 5: Uncertainty budget RIP bushing 460 kV

quantity X_i	estimate x_i	uncertainty $u(x_i)$	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$
C_1	500 pF	0.4247·pF	$-5.448 \cdot 10^{14}$ V/F	-231.40 V
C_{LV}	2.27 µF	0.0133 µF	$1.25 \cdot 10^{11}$ V/F	1599.42 V
R_1	270 kΩ	15.625 kΩ	0.9082 V/Ω	14.19 V
R_2	30 kΩ	0.1929 Ω	8.1738 V/Ω	1.58 V
u_{LV}	60 V	0.0346 V	45410	1573.05 V
Y= u_{HV}	y= 275 kV			u(y)= 2255.30 V
Expanded uncertainty U= k·u(y) (95.45 % confidence level, k= 2)				**U= 1.64%**

Table 6: Uncertainty budget OIP bushing 275 kV

quantity X_i	estimate x_i	uncertainty $u(x_i)$	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$
C_1	500 pF	2.04503·pF	$-5.448 \cdot 10^{14}$ V/F	-1114.13 V
C_{LV}	2.27 µF	0.0133 µF	$1.2 \cdot 10^{11}$ V/F	1599.42 V
R_1	270 kΩ	15.625 kΩ	0.9082 V/Ω	14.19 V
R_2	30 kΩ	0.1929 Ω	8.1738 V/Ω	1.58 V
u_{LV}	60 V	0.0346 V	45410	1573.05 V
Y= u_{HV}	y= 275 kV			u(y)= 2504.82 V
Expanded uncertainty U= k·u(y) (95.45 % confidence level, k= 2)				**U= 1.82%**

Table 7: Uncertainty budget RIP bushing 275 kV

quantity X_i	estimate x_i	uncertainty $u(x_i)$	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$
C_1	480 pF	0.40775·pF	$-3.1224 \cdot 10^{14}$ V/F	-127.31 V
C_{LV}	1.199 µF	0.00372 µF	$1.2 \cdot 10^{11}$ V/F	464.81 V
R_1	270 kΩ	15.625 kΩ	0.4998 V/Ω	7.81 V
R_2	30 kΩ	0.1929 Ω	4.49805 V/Ω	0.87 V
u_{LV}	60 V	0.0346 V	24989.167	865.65 V
Y= u_{HV}	y= 140 kV			u(y)= 990.79 V
Expanded uncertainty U= k·u(y) (95.45 % confidence level, k= 2)				**U= 1.42%**

Table 8: Uncertainty budget OIP bushing 140 kV

quantity X_i	estimate x_i	uncertainty $u(x_i)$	sensitivity coefficient c_i	uncertainty contribution $u_i(y)$
C_1	480 pF	1.96323·pF	$-3.1224 \cdot 10^{14}$ V/F	-613.00 V
C_{LV}	1.199 µF	0.00372 µF	$1.25 \cdot 10^{11}$ V/F	464.81 V
R_1	270 kΩ	15.625 kΩ	0.4998 V/Ω	7.81 V
R_2	30 kΩ	0.1929 Ω	4.49805 V/Ω	0.87 V
u_{LV}	60 V	0.0346 V	24989.167	865.65 V
Y= u_{HV}	y= 140 kV			u(y)= 1158.11 V
Expanded uncertainty U= k·u(y) (95.45 % confidence level, k= 2)				**U= 1.65%**

Table 9: Uncertainty budget RIP bushing 140 kV

5 CONCLUSION

The main contributions to the high voltage measuring uncertainty budget of the bushing tap method come from the capacitance change ΔC_1 of the bushing capacitance due to the absorbed dissipation energy followed by the capacitance change ΔC_{LV} of the low voltage arm capacitance. An OIP bushing shows a slightly lower voltage measuring uncertainty compared to a RIP bushing due to a factor 2.8 lower temperature coefficient α (Table 1).

An expanded voltage measurement uncertainty of less than 3% can be achieved if the following conditions are fulfilled:

- each bushing capacitance C_1 together with the low voltage arm (C_{LV}, R_1, R_2) has to be calibrated first by a reference measuring system. The prior calibration also eliminates the need to consider any impact of the ambient temperature, the long term stability and proximity effect to the measuring uncertainty.
- The expanded uncertainty of the calibration procedure which also includes the combined standard uncertainty of the scale factor of the reference measuring system shall be low enough to keep the expanded voltage measuring uncertainty U_M of the bushing tap method below the 3% [1]. The before discussed uncertainty budgets did not include

the expanded uncertainty U_{cal} of the calibration which has to be added as follows to achieve the expanded uncertainty of voltage measurement U_M:

$$U_M = \sqrt{(U_{cal})^2 + (U)^2} \quad (15)$$

It is recommended to use a voltage measuring system as reference with an expanded measuring uncertainty $U_{M,ref} \leq 1\%$ to keep the contribution of the voltage calibration uncertainty $U_{cal} \leq 1.5\%$ [2] and therefore $U_M \leq 3\%$.

- A suitable secondary unit (low voltage arm) with appropriate voltage measuring ranges and a suitable voltage measuring instrument shall be used.

As shown an expanded voltage measuring uncertainty of less than 3% as required by IEC 60060-2 Ed. 3.0 [1] can be achieved with the bushing tap method during the induced voltage test of power transformers but it has to be ensured that the above conditions are met.

After discussing the details of the voltage measurement via the bushing tap method it is obvious that using an independent voltage measuring system consisting of a compressed gas capacitor with a low capacitance (≤ 100 pF) and a suitable measuring device is the more time efficient and the more reliable voltage measuring method.

A compressed gas capacitor might be available for the precise C, tan δ measurement. The two devices could be used at least for the voltage calibration or even for the complete voltage measurement in case the voltage rating is sufficient. In case the following conditions are fulfilled today's state of the art high precision C, L & tan δ measuring bridges [7] with enhanced voltage measuring features are able to comply with the requirements of a voltage measuring device:

- broad measuring frequency range (e.g. 15 .. 1000 Hz) to cover the increased test frequency during the induced voltage test as well as the harmonic content of a possibly distorted test voltage
- U_{rms} and $U_{peak/\sqrt{2}}$ voltage measurement feature
- Voltage distortion measurement feature (e.g. THD, $(U_{peak}/(\sqrt{2} \cdot U_{rms})-1) \cdot 100\%$)
- enhanced spark over withstand capability due to the increased spark over probability during the induced voltage test
- initial calibration of the measuring chain (compressed gas capacitor, measuring cable, high precision C, L & tan δ measuring bridge) according to IEC 60060-2 Ed. 3.0 [1]

6 ACKNOWLEDGMENTS

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