Journal of Energy

VOLUME 73 Number 1 | 2024

journal homepage: http://journalofenergy.com/

Measurement Uncertainty in On-line Bushing Monitoring

Wiesław Gil, Wiktor Masłowski

Summary **— The high voltage bushing on-line monitoring has been performed for many years to prevent unexpected rapid power network failures. Network unbalance correction, based on separate voltage phase measurement or phasor technique, effectively improves the measurements of bushing dielectric dissipation factor tg*δ* and capacitance factor C_1. The newly implemented monitoring units reveal that the uncertainty of station voltage measuring transformers manifest the greatest influence on the overall uncertainty budget, regardless of the measurement method.**

Keywords **— Online bushing monitoring, power network unbalance, measuring uncertainty of isolation coefficients.**

I. High Voltage Bushing Monitoring

The properties of bushings are susceptible to gradual degradation caused by material aging accelerated by temperature changes, weather conditions, and disturbances occurring during power grid operation. These processes can lead to sudden failure of the bushing, resulting in, at least, a transformer shutdown. [1].

For many years a systematic assessment of the condition of the bushing has been carried out, based not only on the results of periodic tests and measurements, but also on online monitoring. This assessment involves the continuous values analysis and trends evaluation related to bushing dielectric loss coefficient tgδ and its capacitance C_1. These parameters are determined based on leakage current or voltage measured at the bushing's measure taps. Measuring systems, based on probes located in bushings' measuring sockets and monitoring modules, are installed to collect data and determine the insulation indicators mentioned above. Remote or local servers process and collect data over a long period of time, presenting the results through charts, tables, warnings and alarms.

In the oldest solutions from the last century, the leakage currents of bushings operating in three-phase autotransformers and transformer systems were summarized and the total leakage current was measured. [2]. After the year 2000, methods known as the relative methods were developed for online measurements of insulation indicators. These methods do not directly determine the insulation indexes, but specify changes relative to their initial values. A relative voltage method is one of such methods. Additionally, there are direct methods known, were the values of leakage currents or the parameters of the relevant voltage vectors are directly evaluated by phasors measurements.

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II. Relative Voltage Method

The relative voltage method [3] is based on the model shown in Fig. 1 and 2. The C_1 represents the so-called main bushing capacitance, which reflects the resultant capacitance of the cylindrical capacitors forming its core. The capacitance C_2 represents the capacitance between the measuring tap and the ground potential. A reference capacitor C_W is connected to the bushing's measuring tap by the use of special probe. Thus, a divider of phase voltage U is created to measure the V voltage.

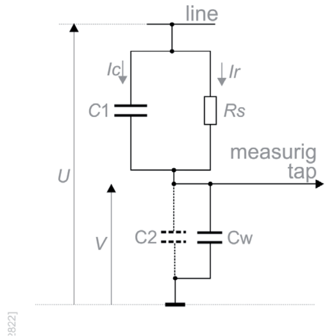

Fig. 1. Equivalent of the bushing with the capacitor Cw connected to the measuring tap

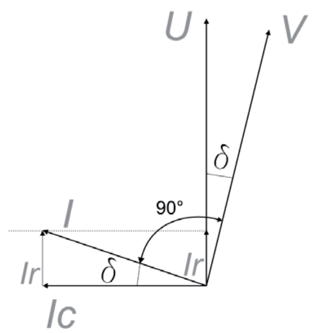

Fig. 2. Vector V displacement by δ angle

The C_W capacitance is selected to obtain V voltage of approximately 50V at the measuring tap. The capacitance C_2 can be neglected as it is several hundred times smaller than C_w. The resistance R_s represents the bushing's loss. The current I of the capacitor C_W is the sum of currents I_c and I_r. The tgδ value of the δ angle between

Wiesław Gil, Wiktor Masłowski, Measurement Uncertainty in On-line Bushing Monitoring, Journal of Energy, vol. 73 Number 1 (2024), 14–17
https://doi.org/10.37798/2024731509

the U and V voltage vectors, indicates the value of the bushing's dielectric dissipation factor. The described method is relative because it does not directly determine the insulation coefficient, but instead assesses their relative changes in relation to the initial values of C_{1p} and tgδ_p, which are obtained during off-line measurements or adopted according to the manufacturer's data.

During calibration, the C_W value is determined according to equation (1), for the actual phase voltage U_p and the measurements voltage V_p.

$$C_w = C_{1p}\left(\frac{U_p}{V_p} - 1\right) \tag{1}$$

Then, bushing capacity C_1 values are calculated according to the equation (2) in relation to the voltage changes on C_w.

$$C_1 = \frac{C_w}{\frac{U_p}{V_p} - 1} \tag{2}$$

If the tgδ_p value is known from off-line measurements, the current values and changes in the dielectric loss factor tgδ are determined relative to the initial tgδ_p value. If a change of dielectric properties, causing the change of the vector angle, occurs only in one phase A as shown in Fig. 2, then the value of tgδ_{AD} can be determined basing on the eq. (3).

$$\tan\delta_{AD} = [\tan(\delta_{AD} - \delta_{Ap}) + \mathrm{arctg}\delta_{Ap}] \tag{3}$$

Where:

δ_{AD} – actual angle displacement of phase A bushing voltage

δ_{Ap} – initial angle displacement of phase A bushing voltage vector, based eg. on last bushing service measurements

In earlier applied solutions [3], the initial values of δ_{Ap}, δ_{Bp}, δ_{Cp} angles were determined for each phase basing on off-line tgδ_{Ap}, tgδ_{Bp} ,tgδ_{Cp} measurements, and the positions of the phase voltage vectors V_A, V_B, V_C were corrected, as depicted in Fig. 3. One of the voltages $V_{(A,B,C)}$ was chosen as the reference voltage, and the angular displacements of the other two vectors were measured in relation to it. Similar relationships were applied to the other phases. However, due to the unbalance of the power network, the position of the V_D vector fluctuates, as shown in Fig. 4.

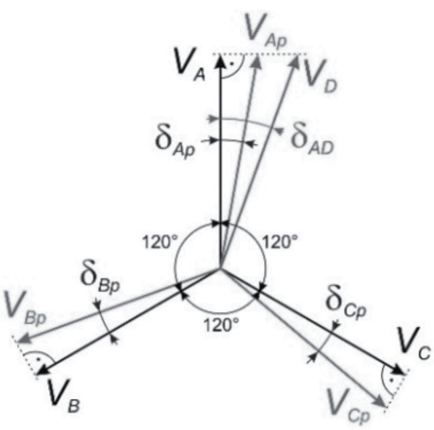

Fig. 3. Change in the positions of vectors VA, VB, VC, and the new position of vector VA due to increased dielectric losses

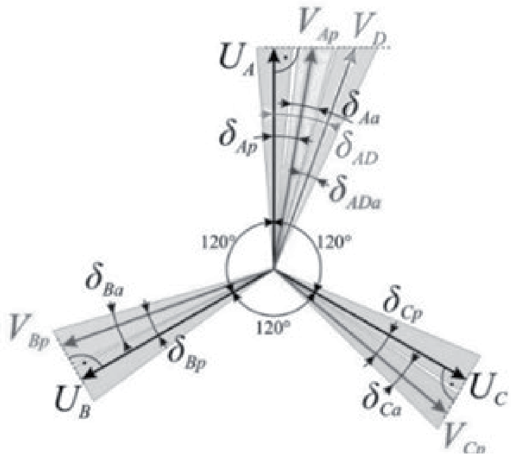

Fig. 4. Fluctuation in the positions of vectors VA, VB, VC, due to power network unbalance

Voltage unbalance is extremely important in "the depth "of the power network. For example, a momentary change of the δ angle between 10 and 30 minutes can result in a change in tgδ ranging from 0.3% to 0.8%. Such a change should be identified as exceeding the permissible tgδ value for OIP bushings. Even greater voltage unbalances than the above may occur in the power grid. As a result, the insulation coefficient measurements using the discussed method becomes very imprecise. This dysfunction was limited by the use of object learning algorithms, various filtration methods, and averaging results, even within 24 hours.

III. Monitoring with Power Network Unbalance Correction

In dozens of bushing monitoring systems operating in Poland, a power network unbalance correction has been introduced [4]. In the monitoring system, denoted as MM in Fig. 5, an independent converter was dedicated to measuring the voltage modules and phase angles at the substation voltage transformers. Having knowledge of modules and phase angles of voltage vectors measured at voltage transformers allows to determine the relative values of the corrected tgδ and C_1 coefficients for each bushing. Fig. 6 illustrates the MM-F modification introduced in 2021 to the MM systems. This modification involves the direct measurement of voltage vectors from voltage transformers in a single device, including measurements of voltage vectors from bushing measuring probes. All voltages are sampled synchronously. In the modified method, the phasors of the voltages measured at the measuring taps are determined every second in relation to the voltages from the station voltage transformers.

The capacitances C_1 of individual bushings in the modified system (MM-F) are determined in analogously to the unbalance correction method (MM). However, the vector modules and their angles are synchronously determined for the bushings and transformers HV and the LV line voltages. The modification removes additional errors in the angle and amplitude measurements caused by the lack of synchronization of sampling between the calculation module and the additional converter.

https://doi.org/10.37798/2024731509

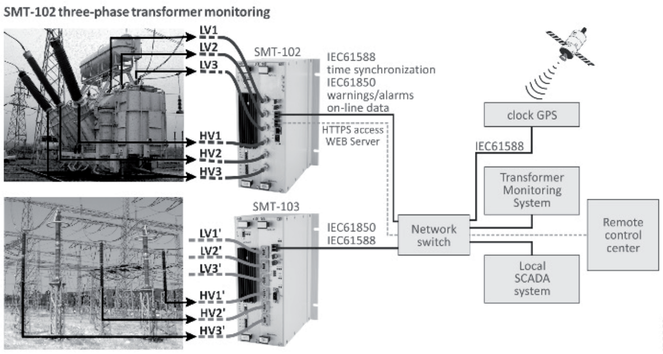

Fig. 5. Bushing monitoring measurements based on power network unbalance correction (MM)

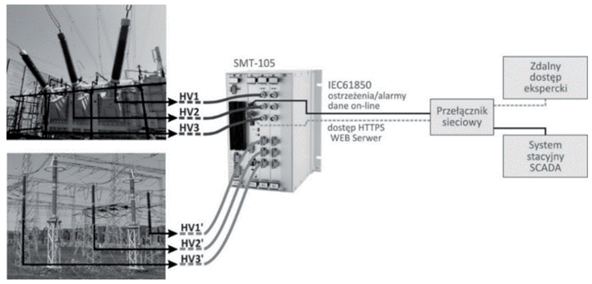

Fig. 6. Modified measuring device (MM-F)

IV. Factors Influencing Measurement Uncertainity

The determined values of C_1, tgδ and their changes over specific periods of time are compared to the criteria values established to inform about any occurring irregularities. It is important to identify the factors that influence the uncertainty of the conducted measurements, because it affects the reliability of the indicators, consequently, the usefulness of the installed bushing monitoring.

The measuring module properties are determined by the resolution and linearity of the measurement inputs, the temperature drift of the used components and the system's resistance to electromagnetic interferences. These factors influence the measurements on the basis of which the insulation coefficients are calculated. During laboratory tests of MM and MM-F units, the standard uncertainty of voltage measurement $u(U)$=0.01[V], and the measurement of the angle $u(°)$=0.002' was demonstrated.

The quality of the components in the measuring probe not only affects measurement stability, but also the reliability of the monitored transformer [5]. Failure of the measuring probe installed in the bushing measuring socket may lead to arcing, corrosion or other damage to the measuring tap, and in critical cases, it can lead to damage of the bushing. High quality polypropylene capacitors were applied in the probes to create the C_w capacitance. The average temperature drift of the probe was assessed to be 0.43nF/°C. It corresponds to a capacitance change C_1 of about 2pF/10°C. The change in the measured angle due to the temperature influence, converted to the value of tgδ, introduces the maximum standard uncertainty u(tgδ)=0.004 [%].

The uncertainty budget should include ***the bushing ratio uncertainty***. This uncertainty arises from the ratio variability between the phase voltage and the voltage measured at the test tap. The relevant characteristics were made in the transformer test room and the standard uncertainty of the voltage measured at the measuring terminal $u(V)$ was estimated in the range from 0.04 to 0.12 [%]. Lower uncertainties $u(V)$ were obtained after calibrating the system to compensate the permanent errors. When calibration was not carried out, then significantly higher uncertainties were observed.

The uncertainties of the station voltage transformers should be taken into account because the measurements obtained from these devices are used to evaluate and correct the phase unbalance. Therefore, based on the test protocols of class 0.2 station transformers, the uncertainties of angle and phase voltage measurements were determined for both calibrated and uncalibrated systems. These results are presented in Tab. 1. Based on the angle measurements uncertainty $u(°)$, the maximum uncertainty equivalent contributed to the tgδ calculations was determined to be 0.01% for a calibrated system and 0.1% for an uncalibrated system, respectively. The uncertainty of the line voltage measurements was taken into account when calculating the combined uncertainty of the capacitance measurement $ud(C_1)$, using the total differential method.

Table I.

Uncertainity of Station Transformers

calibrated		uncalibrated	
u(°) [']	u(V) [%]	u(°) [']	u(V) [%]
0,15	0.01	3,4	0.1

V. Measurement Uncertainity of tg(δ)

For both presented systems, tgδ measurements were conducted on a laboratory stand, and the expected uncertainties in station conditions were estimated. The obtained results were then compared to the actual results at the power station. The measurements and the estimation uncertainty budget are presented in Tab. 2. When determining the extended uncertainty U(tgδ) in the laboratory, the standard deviations u(tgδ) resulting from the scattering of measurements and the equivalent uncertainty of the angle measurement u_Δ(tgδ) resulting from two independent measurements of the angle difference in two devices in the MM system and a single angle measurement in one device in the MM-F system were taken into account. The temperature of the probe was not specified in the budget because the measurements were conducted at a constant temperature. It was assumed that permanent errors were compensated for during the calibration of the laboratory system.

In the estimation for the station conditions, the standard measurement system uncertainty *u(tgδ)* was assumed based on measurements conducted in laboratory conditions. The equivalent u_Δ(tgδ) uncertainty resulting from the angle measurements on the station voltage transformers was taken into account - twice for the MM and once for the MM-F systems. The equivalent $u(T)$ resulting from the temperature influence on changes in the tgδ coefficient was also considered.

The complex standard uncertainty u_c(tgδ) in laboratory conditions is more than 100% higher in the MM system compared to the MM-F system, in which simultaneous sampling of voltages from measuring terminals and voltage transformers has been implemented. The estimation for station conditions shows an uncertainty of approximately 50% greater in the MM system than in the MM-F system. In the calibrated MM system, the complex standard uncertainties u_c(tgδ) estimated for station conditions are about 50% higher than in the MM-F system. The obtained results confirm the better measurement properties of the MM-F system. The lack of calibration increases multiple times the uncertainty in both the MM and MM-F systems.

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Tab. 2 also presents the uncertainty of $tg\delta$ measurements for the MM and MM-F systems, based on actual measurements conducted over a 15-day period performed at several power stations. In the MM system, the extended uncertainty $U(\mathrm{tg}\delta)$ ranges from 0.02 to 0.08. In the MM-F system, the maximum uncertainty is twice lower than in the MM system, which confirms its superior measurement properties. The actual maximum uncertainties are several times lower than the estimation for uncalibrated systems, in which constant errors have not been compensated. The minimum actual values of $U(\mathrm{tg}\delta)$ are analogous to the estimates for compensated systems.

Table II.

Uncertainity Budget Of Tg(Δ)[%] Measurements

uncertainity tgδ [%]		laboratory		assessment for station condition				actual stations measurements	
				calibrated		not calibrated			
description	symbol	MM	MM-F	MM	MM-F	MM	MM-F	MM	MM-F
device dispersion	$u(\mathrm{tg}\delta)$	0,003	0,002	0,007	0,003	0,007	0,003	-	-
phase angle 1	$u_\Delta(\mathrm{tg}\delta)$	0,004	0,002	0,005	0,005	0,099	0,099	-	-
phase angle 2	$u_\Delta(\mathrm{tg}\delta)$	0,004	-	0,005	-	0,099	-	-	-
probe temperature	u(T)	-	-	0,004	0,004	0,004	0,004	-	-
complex	$u_c(\mathrm{tg}\delta)$	**0,007**	**0,003**	**0,01**	**0,007**	**0,14**	**0,1**	**-**	**-**
extended (95%)	$U(\mathrm{tg}\delta)$	**0,02**	**0,01**	**0,02**	**0,02**	**0,3**	**0,2**	**0,02-0,08**	**0,02-0,04**

VI. Measurement Uncertainity of Ci

Similar to the tgδ measurements, C_1 measurements were performed in a laboratory. The expected uncertainties in station conditions were estimated and compared to the results obtained for real data. The measurements uncertainty budget and estimation are presented in Table 3. In the laboratory conditions, the $U(C_1)$ determination takes into account the standard deviation $u(C_1)$ resulting from measurements scattering, and the equivalent uncertainty $u(\Delta C_{1max})$ resulting from the calibration uncertainty of the measuring system. The uncertainty $u_d(C_1)$ resulting from the influence of the uncertainty of simulated line voltage measurements on the simulated voltages at the measuring terminal was considered. The probe temperature was not taken into account, as the measurements were conducted at a constant temperature. It was assumed that permanent errors were compensated during calibration.

Table III.

Uncertainity Budget OF Ci [pF] Measurements

uncertainity C_1(pF)		laboratory		assessment for station condition				actual stations measurements	
				calibrated		not callibrated			
description	symbol	MM	MM-F	MM	MM-F	MM	MM-F	MM	MM-F
device dispersion	$u(C_1)$	0,01	0,01	0,17	0,15	0,17	0,15	-	-
calibration	$u(\Delta C_{1max})$	0,04	0,03	-	-	-	-		
U/V relativ influence	$u_d(C_1)$	0,16	0,14	0,61	0,56	1,73	1,59	-	-
Probe temperature	u(T)	-	-	-	-	-	-	-	-
complex	$u_c(C_1)$	**0,17**	**0,15**	**0,63**	**0,58**	**1,74**	**1,6**	**-**	
extended (95%)	$U(C_1)$	**0,4**	**0,3**	**2**	**2**	**4**	**4**	**1,1-3,1**	**1,1-1,4**

In the estimation for station conditions, the standard uncertainty of the measurement system $u(C_1)$ was assumed based on laboratory measurements. The uncertainty $u_d(C_1)$ resulting from the influence of the uncertainty of measuring the actual phase voltage on the measuring tap voltage of the voltage transformers was also taken into account. The uncertainty resulting from the temperature $u(T)$ influence has not been taken into account. It was assumed that compensation is possible due to the observed linear nature of this influence, which causes an increase in the measured value of C_1 by approximately 2pF/10 °C increase in temperature.

Taking into account the monitoring module uncertainty under laboratory conditions, it was estimated that the extended uncertainty $U(C_1)$ of the capacitance measurement for a range of 400 to 500 pF in substation conditions will not exceed 2pF. If the measurement system is not calibrated, the voltage measurement uncertainty should be assumed as $u(U)$=0.1% of the measured value. For the uncertainty $u(V)$, which is 0.12% according to the tests, the expanded uncertainty of the capacitance measurement $U(C_1)$ reaches 4 pF. In the MM-F version, the maximum expanded uncertainties $U(C_1)$ determined based on the real measurements are more than twice as low in comparison to the MM system. This is due to the simultaneous sampling of the voltage at the measuring terminal and the phase voltage, which results in greater immunity to momentary voltage changes caused by short-term disturbances.

VII. Conclusions

In online monitoring systems for high-voltage bushing insulation indicators, the correction of the influence of power network unbalance determines the usefulness of the obtained results in assessing the condition of the bushings. Calibration is necessary to compensate for constant errors introduced by individual system components. The uncertainties of voltage transformer parameters and the influence of temperature should be taken into account in the uncertainty budget.

In the calibrated measurement system, under real conditions at the power station, it is possible to obtain the measurement uncertainty of the dielectric loss factor tgδ of no more than 0.02% in absolute conventional percentage units, which is the traditional unit for expressing this factor. In a calibrated measuring system with reference voltage measurement on voltage transformers, the uncertainty of C_1 capacitance measurements can be kept within a maximum of 2pF. However, the lack of calibration significantly increases the tgδ measurements uncertainty, resulting in values of even 10 or 15 times bigger to the value of 0.2% or 0.3%. The uncertainty of C_1 measurement increases then to +/-4pF.

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