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MONITORING OF DIELECTRIC LOSSES AND OWN CAPACITY FOR BUSHINGS

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ABSTRACT

At present, the tendency to implement the condition-based maintenance (CBM), which allows the optimization of the expenses for equipment monitoring, is more and more evident; also, the transformer substations with remote monitoring are increasingly used. This paper reviews all the advantages of the on-line monitoring and presents an equipment for on-line monitoring of bushings, which is the own contribution of the group of specialist who are the authors of this paper.

KEY WORDS

Bushing; capacitor; insulator; transformer.

1. INTRODUCTION

Power transmission and distribution systems from the economically developed countries are already aged being, in many cases, more than 30 years old. All the fixed assets of the power systems have a standardized life time of maximum 30 years.

From now on, any equipment is in danger to fail at all times with no previous warning.

The electricity is an integral part of the modern life and therefore a failure causing power shortage in the cities leads to the hindering of their activities, major damages of some equipment and even losses of human lives.

Because the rate of equipment failure is higher and higher it becomes necessary either to replace the old equipment, being at the limit of the life time, or to find methods and tools for extending the lifetime.

The replacement of this equipment is a very laborious operation, extremely expensive and absolutely unnecessary when it is possible to find efficient and safe methods for prolonging the life time.

Under these conditions the on-line monitoring is one of the most useful methods for prolonging the life time up to the failure time limit and for replacing the assets or recovering them in the last moment.

Because the bushing is a key element in the operation of electrical power equipment, its safe operation is a special issue because its degradation leads, in many cases, to the explosions followed by fires with very grave consequences for the stations and the substations.

If up to the present the time-based maintenance (TBM), with periodical revisions, was used, in the last years one tries to find solutions to pass to the condition-based maintenance (CBM) which allows the minimization of the costs, the prolongation of equipment life time and the decrease of the risks of failure in exploitation with grave consequences.

Base on the authors' experience in the field of monitoring of electric networks parameters and power transformers thermal condition [2], a digital equipment for the monitoring of bushings insulation, with an original conception, was finalized .

2. CONTRIBUTIONS TO THE CONDITION-BASED MAINTENACE OF THE BUSHINGS BY THEIR MONITORING

2.1. The importance of on-line monitoring of bushings

Further on there are presented the strategical elements which determine the adoption of on-line monitoring strategy for bushings:

- ageing of the transformers from the power system;
- improved use of the assets;
- lack of a data base (for many assets the on-line monitoring of the trend was not performed, and the profile of the equipment and other information are lost for ever);
- JIT (Just in Time) maintenance;
- too slow current sampling;
- very difficult replacement;
- limitation of direct costs;
- limitation of failure indirect costs;
- limitation of interruption costs;
- help for health and safety;
- reliable and important instrument for
- the networks;
- problems generated in the organization (sometimes it is named "the factor causing troubles to the manager of the unit." Difficult to quantify, but very real).

The damage of bushings is one of the main causes leading to the improper operation of the transformers or even to the explosions. The statistics confirmed that 30% of the transformer damages are due to capacitor-type bushings. The European statistics show that 80% of the damaged bushings are between 12 and 20 years old and therefore the monitoring is necessary even before the middle of their life time [1].

The high electric field gradients in the bushing insulation and the high working temperature contribute to the acceleration of insulation ageing.

The lack of bushings monitoring can lead to important damages with very grave consequences. The explosion of the bushing can damage the transformer tank, can generate an extended fire by transformer oil ignition, and fire in the bundle of cables in the electric switch box or in the control room through the secondary wiring.

A damage of the bushing leads to financial losses (between 1 and 3 million of dollars) to the insurers, both for physical damages and for the disturbances of the affairs in the companies they are serving.. These losses can reach, in exceptional situations, tens million of dollars.

The explosion can generate material damages and human life losses because of the porcelain pieces spread at long distance and with a very high speed.

The traditional diagnosis systems of the bushing insulation are based on periodical measurements of insulation loss factor, once within 2-3 years. In such case, it is necessary to put the transformers out of service and to measure tanδ at an applied voltage of 10 kV.

The practice proved that this system is not very efficient. The disadvantages of this traditional method for monitoring the bushing insulation are the following:

- The testing frequency arbitrarily chosen is not usually correlated with the failure rate development. The practice proved that the period between the measurements must not exceed 100 days to detect 95% from the defective bushings, and this is practically unacceptable;
- The measurements for tanδ performed at an applied voltage of 10 kV are not relevant for the actual condition of the bushing insulation. The measurements at rated voltage, performed on the bushings where partial discharges appear, showed values of 5-8 times higher than those measured at 10 kV. The oil deterioration at high temperatures generates chemical modifications and sediment accumulations leading to the failures of the bushings. The detection of this type of fault at the voltage of 10 kV can be very difficult, even by tanδ measurement at the rated voltage.
- The traditional testing methods require a lot of work and the putting out of service for a long time.

By these reasons it is preferable to use on-line monitoring methods for the bushings. These ones can be episodical and continuous measurements.

On-line episodical monitorings are recommended for the bushings being in the first ten years of life and mounted on transformers which are not installed in strategic zones. For the other types of bushings the on-line continuous monitoring is recommended.

By rigorous monitoring, exact interpretations of the diagnosis and realistic implementation of the operation / maintenance strategies the following will be achieved:

- Identification of economical loading conditions of assets and evaluation of maximum operation efficiency;
- Minimization of premature failure risks;
- Evaluation of remanent life time and early planning of the asset replacement.
- Prolongation of the time life by implementation of correct operation and cost effective maintenance strategies;
- Improvements of the system performance, assuring high reliability and availability of the equipment.
- Minimization of the operation costs on long- term;
- Costs saving by the elimination of unplanned maintenance;
- Minimization of the interruption periods;
- Planning of the relocation / putting out of service;
- Early purchase of the spare parts to obtain competitive productivities;
- Increase of the overall reliability of the system;
- Correct risk management;
- Search of hidden data to predict the future behaviour ("data mining”).

2.2. Digital equipment for on-line monitoring of bushings

For on-line monitoring of bushings it is ideal to monitor the time variation of dielectric losses and of bushings own capacity.

In a quasi-homogeneous dielectric, in homogeneous electric field, the losses in dielectric depend on the electric field strength and temperature. The losses increase proportionally to the square of the electric field strength but they strongly depend also on the temperature θ in dielectric [6], [8].

$$P(\theta) = \frac{1}{2}\varepsilon_0 \varepsilon_r(\theta) \cdot E^2 \cdot \omega \tan\delta(\theta) \qquad (1)$$

$$P(\theta) = k \cdot \varepsilon_r(\theta) \cdot E^2 \tan\delta(\theta) \qquad (2)$$

$$P(\theta) = k \cdot \varepsilon_r(\theta) \cdot \tan\delta(\theta) \qquad (3)$$

At high electric fields, the losses have even more accentuated increase related to the electric field strength.

The heat produced by Joule losses from the central conductor of the bushing generate also a temperature rise in the insulating material, which overlaps on that one due to the dielectric losses.

At medium voltage bushings, the Joule losses are much higher than the dielectric ones while at high voltage bushings the dielectric losses have a great importance for the resulted heating.

This paper does not insist on the study of the dependence of dielectric losses on the temperature because this subject was developed another time [4].

Because of dielectric losses, the alternating current which passes through a bushing is not purely reactive I_r, but it has an active component I_a named leakage current. The δ angle between the reactive current and the total current is named dielectric dissipation angle, and its tangent is named dielectric dissipation factor:

$$\tan\delta = \frac{I_a}{I_r} \tag{4}$$

Let us consider an elementary capacitor with the aria of the armature S, the thickness d, at the voltage U and the frequency f, which has the losses P:

$$P = p_\theta \cdot v \cdot E^2 \tag{5}$$

where: p_θ are the specific volume losses (v = the volume of dielectric) at the temperature θ and, at the stress with the electric field having the strength E:

$$I_a = \frac{P}{U} = \frac{p_\theta \cdot v \cdot E^2}{E \cdot d} = \frac{p_\theta \cdot S \cdot d \cdot E^2}{E \cdot d} = p_\theta \cdot S \cdot E \tag{6}$$

$$\begin{aligned} I_r &= 2 \cdot \pi \cdot f \cdot U \cdot C = 2 \cdot \pi \cdot f \cdot E \cdot d \cdot \frac{S}{d} \cdot \varepsilon_0 \cdot \varepsilon_r = \\ &= 2 \cdot \pi \cdot f \cdot \varepsilon_o \cdot \varepsilon_r \cdot S \cdot E \end{aligned} \tag{7}$$

$$\tan\delta = \frac{I_a}{I_r} = \frac{p_\theta}{2 \cdot \pi \cdot f \cdot \varepsilon_0 \cdot \varepsilon_r} \tag{8}$$

The phasor diagram is presented in the figure 1:

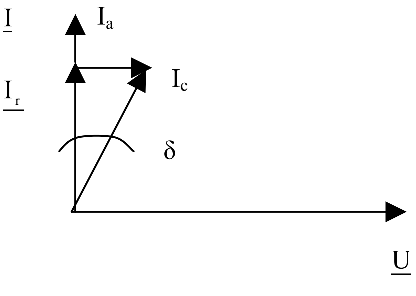


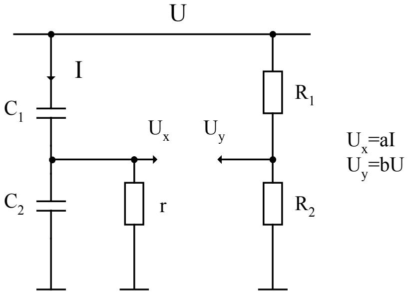
Figure 1

The dielectric losses of a bushing are:

$$\begin{aligned} P &= U \cdot I_a = U \cdot I_c \cdot \sin\delta = U \cdot I_r \cdot \tan\delta = \\ &= 2 \cdot \pi \cdot f \cdot U^2 \cdot C \cdot \tan\delta \end{aligned} \tag{9}$$

In order to monitor the dielectric loss factor and the own capacity of the bushings, at ICMET Craiova a group of specialists finalized an equipment for on-line monitoring of the bushings.

The used measuring diagram presented in the Figure 2 is the classical one.



C_1, C_2 - bushing or CT under test
R_1, R_2 - high voltage resistive divider (capacitive divider or voltage transformer)
r - additional shunt resistor
$r << X_{C2}$
After calibration $\varphi[U_X, U_y] \sim k\ \mathrm{tg}\delta$

Figure 2 – The measuring diagram

The equipment is composed by an unit for signals conditioning and adaptation (UCAS), which takes over the current information from the test taps of the transformer bushings through the adapters Ac(A), Ac(B), Ac(C), Ac(a), Ac(b), Ac(c) and the reference voltage information corresponding to each bushing, from the secondary measuring winding of measuring voltage transformers through the adapters A_U(A), A_U(B), A_U(C), A_U(a), A_U(b), A_U(c) and applies them at the inputs of two microcontrollers which perform the sampling, the storage and the transmission of the signals through the adapting blocks (BA1), (BA2), (MUX) towards the microcontroller of the central processing unit (UC). These ones perform the calculation of the dielectric loss factor, using a Fourier series algorithm for the decomposition of the non-sinusoidal periodic current and voltage signals, measurement of phase displacement between the fundamentals of the voltage and current signals, the calculation and the display of tan δ and currents measured at the terminals on the alphanumeric display (LCD), the creation of a data base in the external memory of the central unit, the generation of light signals and energizing of relay contacts when exceeding the thresholds rated for alarm, the communication with a compatible computer IBM-PC for the data visualization, the setting of parameters, alarms and the archive downloading.

The proposed solution has the following advantages:

- it solves the problem of monitoring the evolution of loss dielectric factor, tan δ, current at the terminals of the bushings afferent to the power transformers;
- it allows the identification of the bushing with high dielectric losses by activating the corresponding alarm;
- it carries out the rejection of the disturbances generated by climatic and electric factors, by the implementation of a numerical recursive filter;
- it allows the calculation of the bushing own capacity and its monitoring.

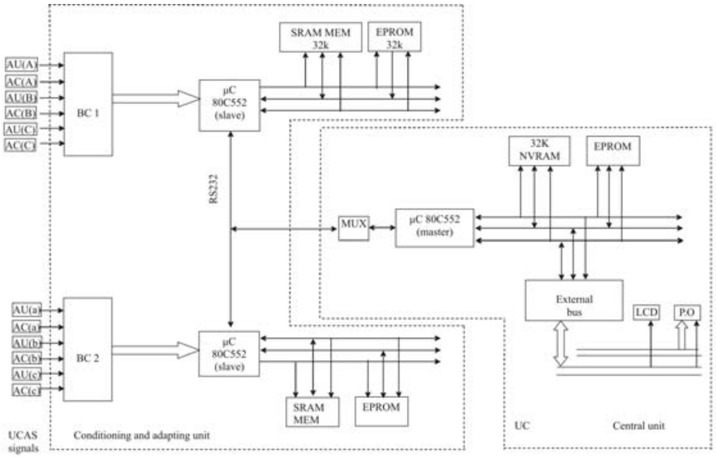


Figure 3 – The block diagram of on-line monitoring equipment for tan δ

The voltage adapters $A_U(A)$, $A_U(B)$, $A_U(C)$, $A_U(a)$, $A_U(b)$, $A_U(c)$ are step-down transformers especially calculated without phase angle error in the measuring range , supplied in the primary with the voltage from the secondary of voltage measuring transformer, 100/√3 V a.c., and these transformers offer in the secondary the voltage of 1 V eff. The adapter is built on toroidal core with uniformly distributed windings and it is foreseen with protecting screens for the windings.

These ones assure:

- the practical elimination of the phase displacements between the primary and the secondary;
- the elimination of the earth loops;
- the elimination of the disturbing signals.

To eliminate the phase difference on the secondary one mounts a resistive load in order to carry out a constant consumption and to eliminate the time variation of the phase differences.

The current adapters perform the conversion of the bushing leakage current in voltage signal in phase with that one. Their construction is compact and they replace the short-circuiting switch existing at the measuring terminal of the bushing achieving the same protection degree.

The conversion is done by non-inductive resistive elements and very low capacities. Over-voltage protective elements are foreseen.

The signals from the specified adapters are applied to some blocks for signal conditioning BC1, BC2. These ones perform the adaptation and the amplification of the signals at the voltage of 2,5 V_{vv}, single pole voltage, compatible with TTL.

The signals coming from conditioning blocks are applied on the analogical input ports of the two microcontrollers.

The adapting blocks perform the adaptation of the signals from RS 232 TTL to RS 232 standard and RS 485 for remote transmission of signals.

The master microcontroller is integrated into a central unit including a keyboard, non-volatile external memory, a digital display LCD and alarm elements.

These elements are connected to the address bus BA, the data bus BD and the control bus BC and they operate according to the processing and analysis program implemented in the external memory EPROM.

For each monitored bushing the method presumes the acquisition of two signals: one signal taken over from the test tap of the bushing and the second signal, representing the reference voltage, taken over from the instrument transformer corresponding to the monitored bushing [3].

The taken over signals have non-sinusoidal periodical character and they have the following form:

$$f(t) = A_0 + \sum_{k=1}^{\infty}\left[M_k \cdot \cos(k\omega t) + N_k \cdot \sin(k\omega t)\right] \tag{10}$$

The implemented program performs the calculation of tan δ by the extraction of fundamentals from the sampled signals by a Fourier analysis algorithm.

The calculation algorithm presumes:

- determination of the coefficients M_k and N_k for the fundamentals of the two signals (k=1)

$$M_1 = \frac{2}{T}\int_0^T f(t)\cos(\omega t)dt \tag{11}$$

$$N_1 = \frac{2}{T}\int_0^T f(t)\sin(\omega t)dt \tag{12}$$

The coefficients M_1 and N_1 are determined for each acquired quantity:

- determination of initial phases of the fundamentals

$$\varphi_1 = \arctan\frac{M_1}{N_1} \tag{13}$$

$$\varphi_1^{'} = \arctan\frac{M_1^{'}}{N_1^{'}} \tag{14}$$

where,

φ_1 = the initial phase of the fundamental of the signal taken over from the measuring terminal of the bushing;

$\varphi_1^{'}$ = the initial phase of the fundamental of reference signal taken over from the measuring terminals of the voltage transformer corresponding to the measured bushing.

Noting:

$$\delta_1 = \varphi_1 - \varphi_1^{'} \tag{15}$$

one calculates the loss dielectric factor by the relation:

$$\tan\delta = \tan\left(90^0 - \delta_1\right) \tag{16}$$

For non-sinusoidal state we have:

$$n = \frac{1}{C}\int idt \tag{17}$$

$$i = C\frac{du}{dt} = \sum_1^\infty \sqrt{2}kC\omega U_k \tag{18}$$

From here:

$$I_k = kC\omega U_k \tag{19}$$

Thus, by calculation, the own capacity of the bushing is obtained.

The Figure 4 shows the mounting mode in the station of the bushings monitoring equipment for the power transformers.

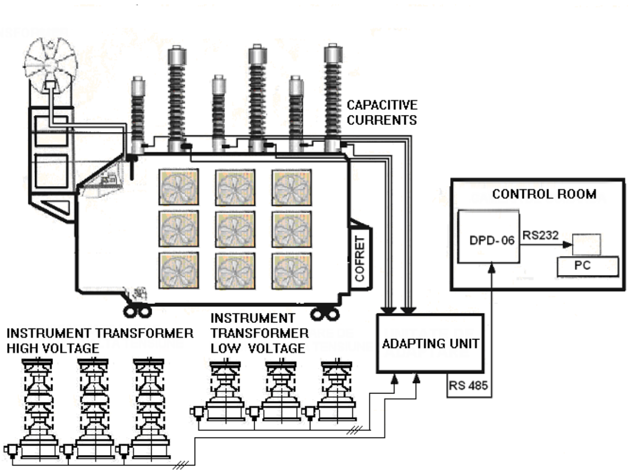


Figure 4 – Monitoring equipment mounted in the station

During the experimentations improvements were made in order to reduce the influence of tan δ variation with the load, with the environment factors and with the electromagnetic disturbances, filtering the disturbing influences.

It is necessary to get the variation tendency from the monitored data, using an adequate filter for eliminating the influences of the disturbing factors and for allowing to pass only the slowly variable component of the losses in the main insulation.

Without any influence, the variation of the dielectric loss factor series would be very slow.

Because of the influence of everyday and seasonal variations of the environment temperature and humidity the variation of the dielectric loss factor is cyclic. Besides, for the influence of the random effect of signal and electromagnetic disturbances transmission to a substation, there are many singular points in the data.

Therefore the series of the on-line monitored dielectric loss factor ($\tan\delta_m$) can be decomposed in the following way [7]:

$$\tan\delta_m(t) = \tan\delta(t) + \Delta\tan\delta_w(t) + \Delta\tan\delta_r(t) \tag{20}$$

where:

- $\tan\delta(t)$ is the main component which reflects the actual condition of the insulation which can be considered as the component with slow variation;
- $\Delta\tan\delta_w(t)$ is the component which reflects the everyday and seasonal influences on the environment and of other factors with slow variation (e.g. the load variation) and can be considered as the low frequency component;
- $\Delta\tan\delta_r(t)$ is the component which reflects the influences of the random factors including unusual climatic conditions, electromagnetic disturbances, etc. (its frequency band is wide and in the greatest part it is in the high frequency section).

If the tendency for $\tan\delta(t)$ can be deducted from the initial data, the efficiency of the fault diagnosis can be much improved.

If an adequate software recurrent filter is applied each component can be got directly from the loss coefficient series.

The dielectric loss factor, tanδ, is filtered according to the relation:

$$\tan\delta_{pa} = \tan\delta_{p-1} + \frac{\tan\delta_{pm} - \tan\delta_{p-1}}{k} \tag{21}$$

where: $\tan\delta_{pa}$ = the present displayed value
$\tan\delta_{p-1}$ = the previous value (measured and displayed)
$\tan\delta_{pm}$ = the present measured value
k = the filtration coefficient (k = 20000 – 25000)

The interval between the readings is of the order of minutes. It is possible to attenuate random influences with a relatively short duration (minutes, hours and possibly days).

As a result tanδ(t) is obtained when both the high frequency component and the low frequency one are eliminated. The filtration method is useful because it reduces the complexity of the diagnosis since the data can be directly processed, without the need of extended samples.

The Figures 5.a and 5.b show, as example, the time variations of tanδ in a high-voltage substation at a transformer of 250 MVA, 400/200 kV.

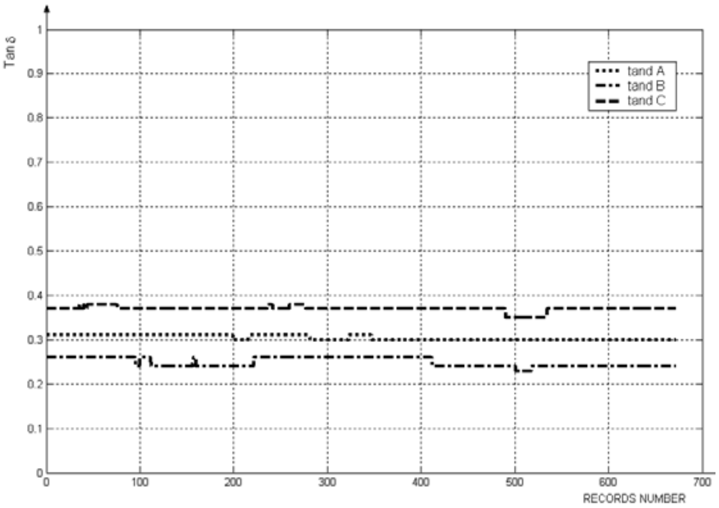


Figure 5.a – The time variation of tanδ at the bushings on the outputs of 400 kV

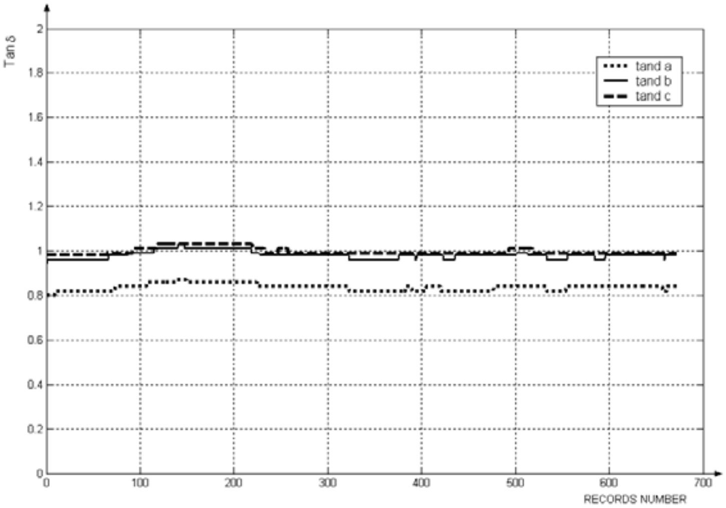


Figure 5.b – The time variations of tanδ at the bushings on the outputs of 220 kV

As it can be noticed, the bushings on 400 kV outputs have the values of tanδ of about 0.3, as oilpaper bushings, while the bushings on 220 kV outputs have the values of tanδ of about 0.9, as resin varnished paper bushings. The bushing on *a* phase has a value lower than the two others since it has only 3 years of service in comparison with the two others that have more than two years of operation.

3. CONCLUSION

This work presents the advantages of on-line monitoring and especially of on-line continuous monitoring of the bushings on the power transformers.

On-line monitoring methods for the own capacity of the bushings are known. These ones present the disadvantage that information concerning the variation of the losses in dielectric and implicitly the ageing of the insulation is unknown.

Other equipment monitors the vector addition of the capacitive currents through the insulation of the bushings and it detects their residual current; thus, it is sent information concerning the degradation of a bushing without detecting which one it is.

The method is used especially in the United States where there are utilized bushings with paper armatures having applied a semi-conducting varnish on them, which migrates in time in oil. Following this disequilibrium all the 3 capacitor-type bushings are replaced.

The method presented in this paper allows the early detection of the faulty bushing and its replacement before the appearance of a failure danger.

At present 11 pcs. of this type of monitoring equipment are mounted and they are continuously monitored being susceptible of permanent improvements.

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