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INFLUENCE OF ELECTRIC SUBSTATION DISTURBANCES ON DIELECTRIC DISSIPATION FACTOR VARIATION AT 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 original equipment for on-line monitoring of bushings. The paper presents a study of the temperature field, using the finite element method. For carrying out this study, the 3D modelling of the above mentioned bushing was performed. The analysis study is done taking into account the extreme thermal stresses, focusing at the level of the first cooling wing section of the ceramic insulator. This fact enables to justify the tanδ variation in time, depending on the transformer loading and the environmental conditions.

KEY WORDS

Isolated 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 any time with no previous warning.

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.

Based on the authors' experience in the field of monitoring of electric networks parameters and power transformers thermal condition [1], a digital equipment for the monitoring of bushings insulation, with an original conception, was finalized .

2. Contributions to the condition-based maintenance of the bushings by their monitoring

2.1 The importance of on-line monitoring of bushings

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.

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

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 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.

2.2 Off-line diagnosis of bushings

As we have shown in Chapter 2.1, off-line measurements of tan δ and C cannot be reliable methods for the diagnosis of bushing insulation.

Consequently, the only solution for off-line diagnosis of insulation is by dielectric measurements in time domain, namely by analysis of polarization and depolarization currents (PDC), by extending the PDC method which has been successfully applied on high power transformers and which offers information related to oil moisture, ageing and quality on the main insulation condition. [7]

I.e. a polarisation current $i_p(t)$ measured at a voltage step U during a charging time t_c and a depolarisation current $i_d(t)$ measured at the subsequent grounding are fitted with a number of exponentially decreasing currents $i_j(t)$ wich are realted to a number of parallel R_jC_j series elements with $\tau_j=R_jC_j$:

$$i_p(t) = \sum_j i_j(t) + i_\infty = U \cdot \sum_j (\frac{1}{R_j} e^{-t/\tau_j}) + \frac{U}{R_\infty} \quad \text{for } t < t_C$$

$$i_d(t) = -U \cdot \sum_j \frac{1}{R_j}(1 - e^{-t_C/\tau_j}) \cdot e^{-(t-t_C)/\tau_j} \quad \text{for } t > t_C \qquad (2)$$

Eq. (3) gives a better approximation:

$$i_p(t) + i_d(t + t_C) = \sum_j (\frac{U}{R_j} e^{-(t+t_C)/\tau_j}) + \frac{U}{R_\infty} \cdot \qquad (3)$$

Polarization currents at different temperature for OIP bushings with 1.8% water in insulation are presented in Figure 1, and polarization currents for different moisture contents in the insulation of an OIP (oil impregnated paper) bushing at room temperature are presented in Figure 2.

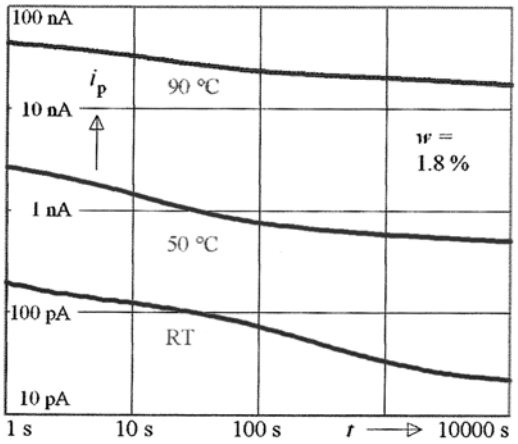


Figure 1 – Polarisation currents at different temperatures through OIP samples with 1.8% water

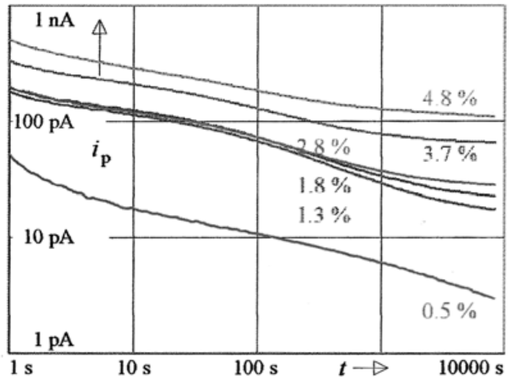


Figure 2 – Polarisation currents for different water contents through OIP samples at room temperature RT and 0.1 kV/mm, oil

The method offers very important and rather accurate indications on the bushing insulation, as compared to the other methods of off-line diagnosis, but it has the drawback of requiring de-energizing the transformer, which is very difficult to do.

2.3 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].

$$P(\theta) = \frac{1}{2}\varepsilon_0 \varepsilon_r(\theta) \cdot E^2 \cdot \omega \tan\delta(\theta) \qquad (4)$$

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.

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:

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

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

$$\begin{aligned} I_r &= 2 \cdot \pi \cdot f \cdot U \cdot C = 2 \cdot \pi \cdot f \cdot E \cdot d \cdot \frac{S}{d} \cdot \varepsilon_0 \cdot \varepsilon_r = \\ &= 2 \cdot \pi \cdot f \cdot \varepsilon_o \cdot \varepsilon_r \cdot S \cdot E \end{aligned} \tag{8}$$

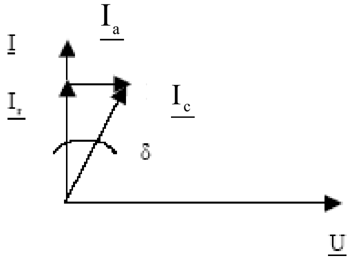


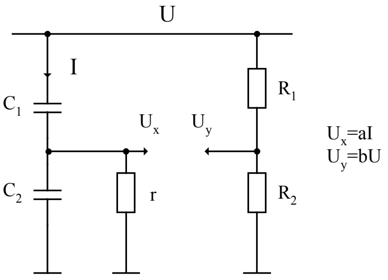
Figure 3 – The phasor diagram

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 4 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 $\varphi[U_x, U_y] \sim k\,tg\delta$

Figure 4 – The measuring diagram

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.

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)

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

$$M_1 = \frac{2}{T} \int_0^T f(t) \cos(\omega t) dt \tag{12}$$

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: $\delta_1 = \varphi_1 - \varphi_1^{'}$ (15)

The loss dielectric factor is:

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

For non-sinusoidal state we have:

$$i = C \frac{du}{dt} = \sum_1^{\infty} \sqrt{2} k C \omega U_k \tag{17}$$

From here: $I_k = k C \omega U_k$ (18)

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

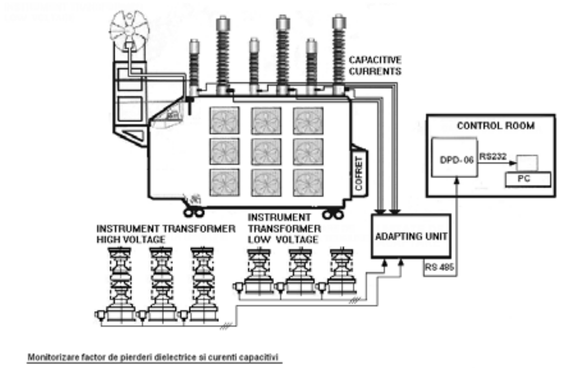


Figure 5 – Monitoring equipment mounted in the Station

3. Modelling of the thermal field for capacitor-type bushing

Following the variation of the dielectric losses during a week, the diagram from Figure 6 can be got.

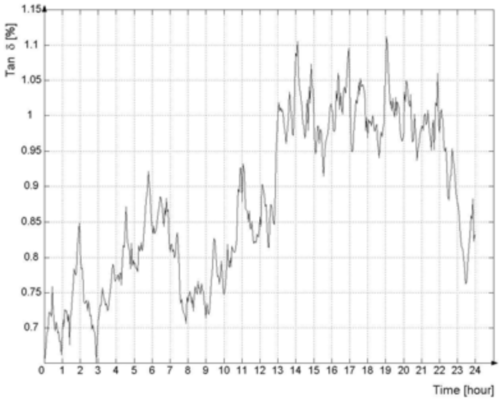


Figure 6 - Variation of the dielectric losses during a week

Thus, it is found that in certain days, at the time when the load peak appears, a significant increase of the dielectric loss value appears, which could be even 50%.

One could ask if there is certain theoretical explanation for this significant increase of the value measured on site.

That is why, together with the specialists from the University of Craiova, Faculty of Mechanics, one tried to find the theoretical explanation of this jump, analysing, by the finite element method, the temperature field under non-stationary condition, for the 123 kV, 1600 A capacitor-type bushing, during an autumn day.

The determination of the average temperature for each element of the bushing is aimed at, knowing the temperature variation of the environment where the bushing is operating, the variation of the terminal heating as a result of network load variation, too. The 123 kV, 1600 A isolated outdoor bushing is shown in Figure 7.

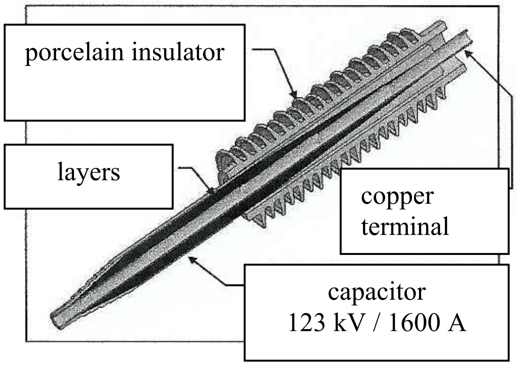


Figure 7 - The 123 kV, 1600 A isolated outdoor bushing

The thermal study is done for the duration of an autumn day (for the time interval t = 0...24 h). The temperature variation depending on time, for the environment where the bushing is operating, is given in figure 8.

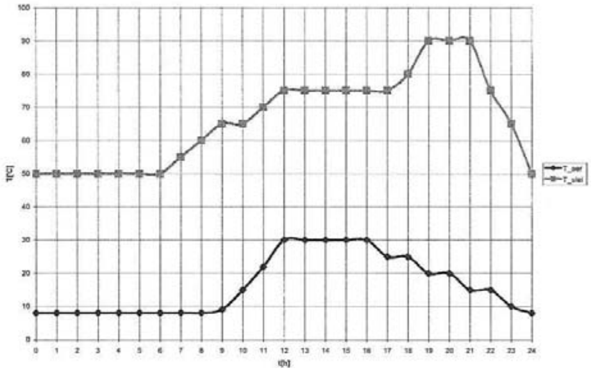


Figure 8 - Graphical representations of the temperature variation depending on time

Thermally, the most stressed section of the isolated bushing is the section corresponding to the first shed which is adjacent to the flange for fixing the bushing on the transformer tank (Figure 9)

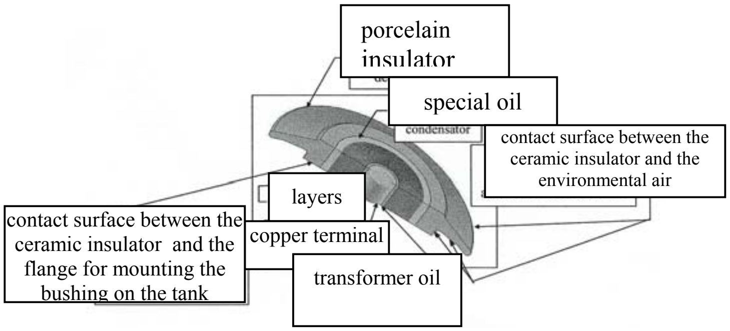


Figure 9 - Fixing the bushing on the transformer tank

It is interesting to follow also the average temperature variation for each element of the bushing, along the 24 hours of operation, under the influence of the variation of the environment thermal load and power consumers connection to the network. This variation is shown in Figure 10.

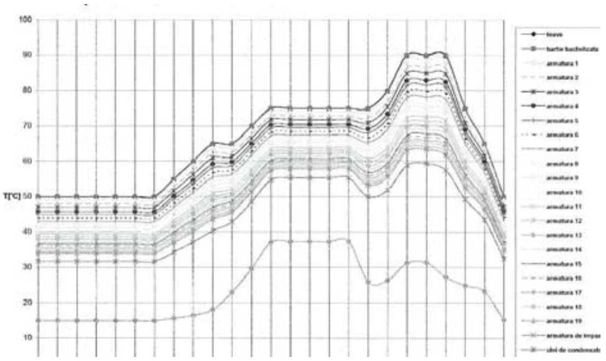


Figure 10 - Temperature variation on the elements of the 123 kV, 1600 A bushing

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 [5]:

$$\tan\delta_m(t) = \tan\delta(t) + \Delta\tan\delta_w(t) + \Delta\tan\delta_r(t) \qquad (19)$$

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:

$$\tan\delta_{pa} = \tan\delta_{p-1} + \frac{\tan\delta_{pm} - \tan\delta_{p-1}}{k} \qquad (20)$$

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

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.

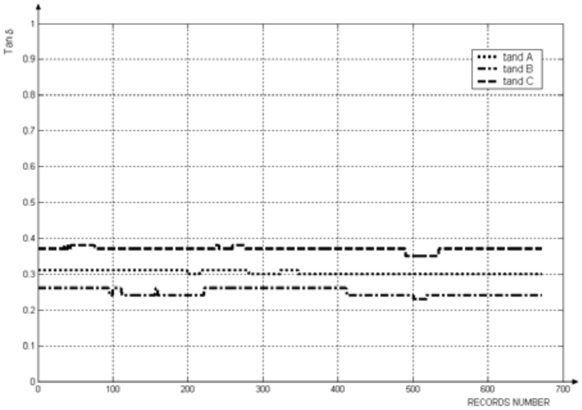


Figure 11.a – The time variation of tanδ at the bushings on the outputs of 400 kV

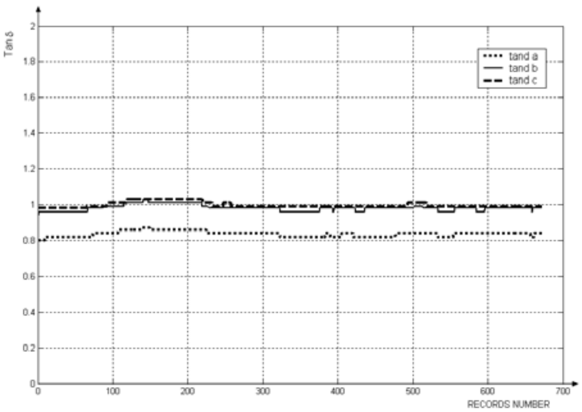


Figure 11.b – The time variations of tanδ at the bushings on the outputs of 220 kV

4. Dependence of dielectric loss variation on the load factors and environmental conditions

By analysing the got results, it is noticed the identical behaviour of the dielectric layers, namely a significant increase of the average temperature, due to the increase of the environmental temperature, especially in the hours of load peak (17 – 22), even when the environmental temperature decreases significantly. The dielectric losses per unit volume within the bushings are [9], [10]:

$$\overline{p}_{\theta} = \frac{\varepsilon_r \cdot f \cdot \tan\partial}{1{,}8 \cdot 10^{-4}} \qquad (21)$$

But the material parameter depends also on the temperature, according to the relation:

$$\overline{p}_{\theta} = \overline{p}_{\theta_0} \cdot \exp\left[a\left(\theta - \theta_0\right)\right] \qquad (22)$$

where „a" is a constant depending on the dielectric nature

Since the term $\frac{\varepsilon_r \cdot f}{1{,}8 \cdot 10^{-4}}$ does not depend on temperature, it results: $\tan\partial = \tan\partial_0 \exp\left[a\left(\theta - \theta_0\right)\right]$ (23)

For the bushings with resin-lacquered paper insulation , as a results of the laboratory experiments, the variation of tanδ as a function of temperature is as shown in Figure 12

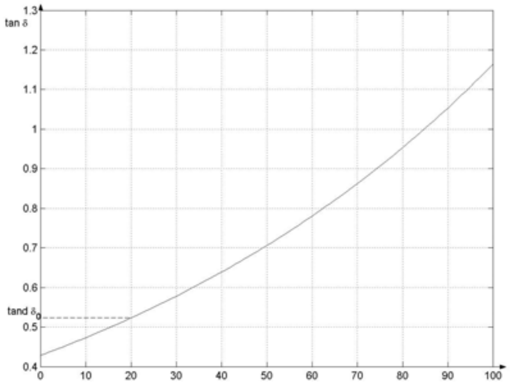


Figure 12 - The variation of tanδ as a function of temperature

From here, the explanation of the very high variation of the dielectric losses in the course of one day and, especially, the dependence on the network load variation can be very clearly obtained.

The application of this information is very useful because it confirms the accuracy of the measurements performed with the monitoring equipment designed and manufactured by ICMET Craiova, placing confidence in this equipment utilization for protecting the capacitor-type bushings, the high power transformer, key-factors in the good operation of power systems, implicitly.

5. 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.

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

As a result of the experiments, the equipment has been provided with soft filtration enabling to remove the influence of load variation and environmental factors on the variation of dielectric losses, making possible a rigorous monitoring and just-in time alarm in case of a fault occurrence.

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