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Case Study

Transformer Bushings

Understanding the phenomena of **‘negative tan delta’** and its simulation through experiments

Preamble

Negative tan delta is sometimes measured and encountered on transformer bushings either while bushings are manufactured, or transformers are manufactured or during measurements in service. Hence, it is necessary to understand how ‘negative’ tan delta is measured: is it due to its measuring technique or due to an abnormality in the bushing? After referring to and studying specialised technical literature, we present easy-to-understand basics of the phenomenon in this paper.

Also, the simulation of negative tan delta phenomenon was carried out through experiments on three oil impregnated paper (OIP) bushings of 36 kV, 800 A, 0BCT. While experimenting, a narrow band dielectric frequency response (DFR), ie, tan delta measurements between 15 Hz and 400 Hz have been used for providing additional information during experimentation. This is detailed in the paper.

Key words: Contamination, dielectric frequency response, dielectric relaxation, phase shift

Introduction

Transformer bushings are vital and essential components of power transformers. Dielectric or thermal breakdowns can cause catastrophic failures of transformer bushings and can lead to fire and catastrophic failure of transformers, resulting in huge collateral damage to neighbouring substation equipment and significant revenue loss. A study shows that bushings account for 17% of all power transformer failures and are the third most common cause of breakdowns. OIP bushings are the most prevalent cause of transformer fires, causing nearly 50% of all serious ones. During service, OIP bushings experience some typical issues such as moisture ingress. Some other issues may also be found when routine electrical tests are carried out while manufacturing bushings. The measurement of tan delta qualitatively indicates such abnormality in insulation of OIP bushings.

Regular offline monitoring of transformer bushings is essential and crucial for detecting an abnormality in the bushing and for taking preventive actions that avoid catastrophic failures. Capacitance and tan delta measurements at 50 Hz is the most common method of offline monitoring. Offline tan delta monitoring detects early signs of insulation degradation in transformer bushings. An increase in tan delta values can indicate insulation deterioration, which if left undetected, can lead to equipment failure or breakdown. The capacitance and tan delta tests at site are generally carried out at 10 kV and are compared with factory test results of bushings.

DFR is used to measure an insulating material's capacitance and dielectric losses over a given frequency range and is fast becoming popular because of its diagnostic advantages. During routine measurements or offline monitoring, negative tan delta is sometimes measured, and it becomes difficult to understand the dielectric health of the bushing.

Detailed in the paper are the theoretical understanding of negative tan delta. It aims at helping the user identify probable root causes and taking necessary actions. By carrying out studies through simulation experiments on 36 kV bushings and by using DFR measurements, negative tan delta is further explained.

Tan Delta Basics & Tan Delta Measurements

An insulation or dielectric material is expected to behave as a perfect capacitor during normal operating conditions, although it is practically impossible. The insulating material has dielectric losses due to polarisation and ionisation. In a perfect capacitor, there is a 90° phase shift between the charging (capacitive) current and voltage. Contaminants such as moisture and dirt, combined with aging, can create a conductive channel for an electric leakage current in the insulation. Resultantly, a resistive current will flow through the insulation from the line to the Earth. In such a case, the phase shift between the current and voltage will be less than 90°. The phase shift is an indicative measure of the level of insulation contamination. The insulation's health is determined by the ratio of resistive current and capacitive current, known as dissipation loss factor or tan delta. The total current is the vector summation of capacitive current and resistive current. Figure 1 shows the representation of tan delta.

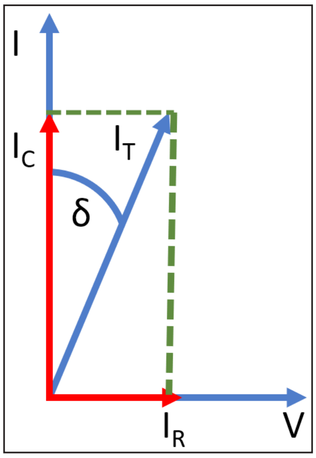

Figure 1: Tan delta = I_R / I_C

Where tan delta is the dissipation factor, δ is also known as loss angle, I_R is the resistive component of the total current (I_T), and I_C is the capacitive component of the total current (I_T). An increased value of I_R indicates higher contamination in insulation. Tan delta depends on temperature. IEC 60137 specifies the limits of tan delta for OIP and RIP/RIS bushings between 10°C and 40°C as ≤ 0.7% (ie, 0.007).

Tan delta measurements: Transformer bushings with condenser graded insulation of 36 kV and above rating are provided with a test tap (at the mounting flange level) and the capacitance and tan delta of the main insulation are measured between HV terminal and test tap terminal and is referred to as C1. At site, during pre-commissioning and during service, these C1-capacitance and tan delta measurements are carried out at voltages between 2 kV and 10 kV. Measurements done at 10 kV are then compared with those measured on the bushings during factory testing.

Negative Tan Delta

As seen in Figure 1, Angle δ will be less than 90° and tan delta will always have a positive sign for insulation with dielectric loss. If tan delta is to be negative, the angle δ will need to be higher than 90°; this means that watts are generated by insulation. This proves that negative tan delta values are not real and are related to product measurement issues.

Higher surface leakage currents or creep currents inside an insulation system or more commonly on the surface of insulation system causes changes in potential distribution, resulting in decreased or negative tan delta values. Such negative tan delta phenomenon is particularly observed on products such as bushings that have low capacitance values (few hundreds pF).

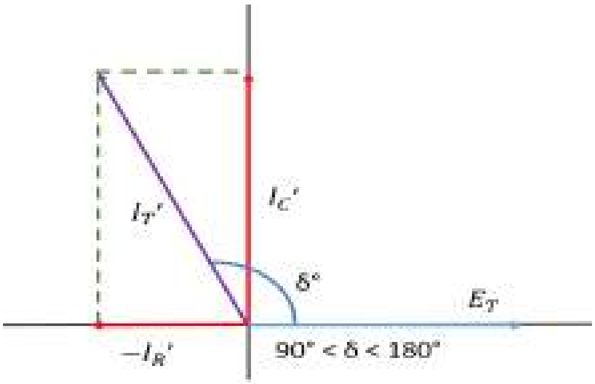

Figure 2: Negative tan delta

Mathematical & Vectorial Explanation of Negative Tan Delta

The creep current (surface leakage current) is mainly responsible for negative tan delta measured, as seen in above paragraphs.

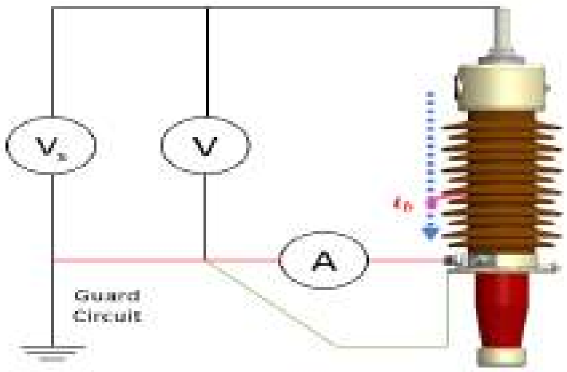

Figure 3: Creep current or surface leakage current

As seen in Figure 3, the surface leakage current I_B originates somewhere within the insulation and passes through a low resistance path to the ground; thus, the current measured by 'A' does not include this creep current.

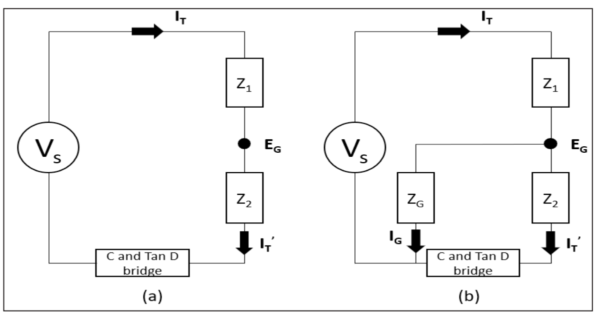

Figure 4: Electrical circuit

On the left side of Figure 4 is seen a circuit that does not have surface leakage current, whereas the circuit on the right side shows creep or surface leakage current from E_G point to ground, bypassing the capacitance and tan delta bridge here.

Z_1 and Z_2 together is the capacitance 'C1' of the bushing and Z_G is the low resistance path to the ground. E_G is the voltage at the point from where the creep current I_G is flowing to the ground. The total current I_T is the vectorial sum of $I_{T'}$ and I_G.

When there is no creep current (refer Figure 4a),

$$E_G = \frac{V_S Z_2}{Z_1 + Z_2} \text{ and } I_T = \frac{V_S}{Z_1 + Z_2} \quad (1) \text{ also, } I_T' = \frac{E_G}{Z_2} = \frac{\frac{V_S Z_2}{Z_1 + Z_2}}{Z_2} = \frac{V_S}{Z_1 + Z_2} = I_T$$

In case of Creep Current (Refer Fig.4b),

$$I_T = I_T' + I_G \text{ and } Z_{eq} = \frac{Z_2 Z_G}{Z_2 + Z_G}$$

$$E_G = \frac{V_S Z_{eq}}{Z_{eq} + Z_1} = \frac{V_S Z_2}{Z_2 + Z_1 + \frac{Z_1 Z_2}{Z_G}}$$

$$I_T' = \frac{E_G}{Z_2} = \frac{V_S}{Z_2 + Z_1 + \frac{Z_1 Z_2}{Z_G}} \neq I_T \quad (\because I_T = \frac{V_S}{Z_1 + Z_2})$$

The capacitive reactance and relations between currents and voltages are presented in terms of phasors in Figures 5a and 5b, respectively. The measured angle θ extends to 2θ, indicating the phase angle shift:

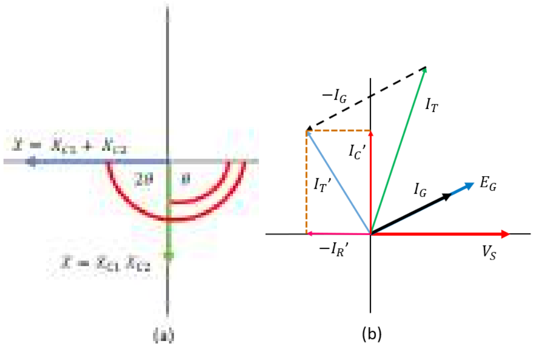

Figure 5: Phasor representation

As seen in Figure 5, the voltage measured by the bridge is V_S and the current measured by the bridge is $I_{T'}$; the angle between V_S and $I_{T'}$ is >90°, thus measuring negative tan delta.

$Z_2 = -jX_{C2}$, however, $Z_G = R_G$

$$\therefore\ E_G = \frac{V_s Z_2}{Z_2 + Z_1 + \frac{Z_1 Z_2}{Z_G}} = \frac{-j\, V_s X_{C2}}{(-jX_{C2}) + (-j\, X_{C1}) - \frac{X_{C1} X_{C2}}{R_G}}$$

Further, current I_T',

$$I_T' = \frac{E_G}{Z_2} = \frac{\frac{-jV_s X_{C2}}{(-jX_{C2}) + (-jX_{C1}) - \frac{X_{C1}X_{C2}}{R_G}}}{-jX_{C2}} = \frac{-V_s}{(jX_{C2}) + (jX_{C1}) + \frac{X_{C1}X_{C2}}{R_G}}$$

Moreover, to simulate theoretically at 50 Hz, the phase shift of leakage current, ie, tan delta, even if there existed an angle of 1° between V_S and E_G, did not make substantial change in tan delta performance. We assumed main capacitance C1 divided into portions

– C11 and C12. The maximum effect of the leakage path will be when C11 = C12. Lowering C11, which is somewhat higher than C1, means that the leakage current to ground will occur closer to the outermost foil. A higher C11 indicates that the junction between C11 and C12 is closer to the HV end, and the leakage current to ground will occur from that end to the Earth; the possibility of a higher leakage current in such a case is unlikely due to the increased distance. Leakage current to ground from the centre of the condenser core was estimated. Tan delta is typical (0.005) when the R_G is high but goes on decreasing to 0.004 when R_G goes to 10 GΩ and is near zero tan delta when R_G goes to 2 GΩ. The overall picture can be realised from the vector diagram as illustrated in Figure 6.

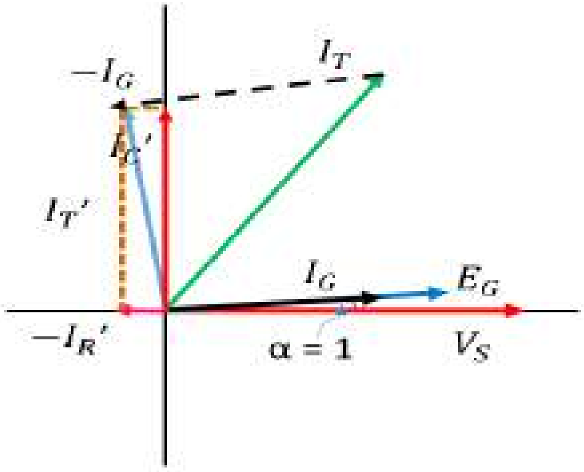

Figure 6: Vector representation based on theoretical estimation

DFR Basics

DFR is a diagnostic tool used for evaluating the quality of electrical insulation systems in high-voltage equipment such as transformers and bushings. DFR testing consists of applying a sinusoidal voltage at different frequencies (below 50 Hz and above 50 Hz) to the insulation and examining the resulting dielectric response. The insulation's response to the variable frequency signal is then measured and studied. Different frequencies induce polarisation and relaxation processes inside the insulating material to behave differently. These reactions can be analysed over a range of frequencies for providing significant information about the insulation's quality. DFR tests typically include capacitance and dissipation factor (tan delta). These measurements are sensitive indications of insulation status, eg, tan delta measured at lower frequency is indicative of moisture presence in the insulation. While carrying out experimental simulation of negative tan delta, we measured DFR during experimentation.

Experiments to Simulate Negative Tan Delta

Experiments were carried out on three numbers of 36 kV 800 A 0 CT bushings and a total of 15 intermediate frequency DFR readings were recorded between 15 Hz and 400 Hz; 5 kV was applied during tests. During measurements, the temperature and humidity were 31°C and 32% RH, respectively.

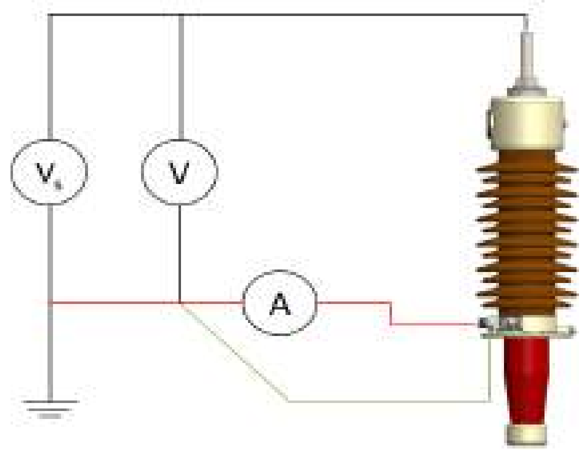

Figure 7: Measuring circuit

Measurements of capacitance and tan delta were carried out using UST test mode as in Figure 7. A current flowing to a grounded terminal is sent directly to the AC source return and removed from the measurement.

Experiment 1: Saltwater Spraying

Contaminated water was prepared by mixing salt in deionised water (EMPLURA®, Merck) to achieve water conductivity of approximately 10 μS (± 10%). Conditions were tested in two stages: with salt water first sprayed on the upper portion of the porcelain insulator and then on the lower portion. Refer to Figures 8a and 8b.

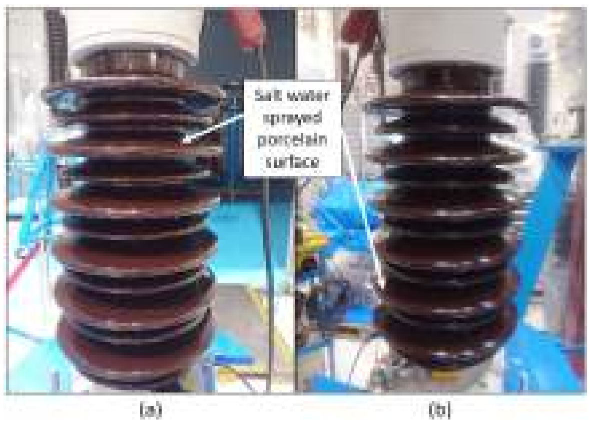

Figure 8: Saltwater spraying

Experiment 2: Aluminium Foil Wrapping

10 μm thick aluminum foil was wrapped over the upper and lower halves of the porcelain insulator. The test setup is displayed in Figures 9a and 9b.

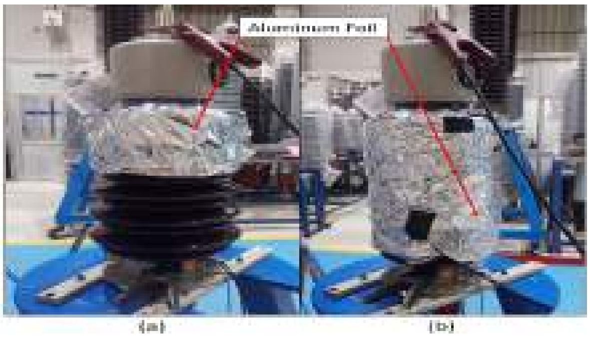

Figure 9: Aluminum foil wrapping

Test Results

Tan delta vs frequency are plotted individually for all three bushings. Tan delta curves include: normal condition (norm), saltwater upper side (SWUP), salt water lower side (SWLP), aluminium foil wrapping upper side (ALUP), aluminium foil wrapping entire side (ALES).

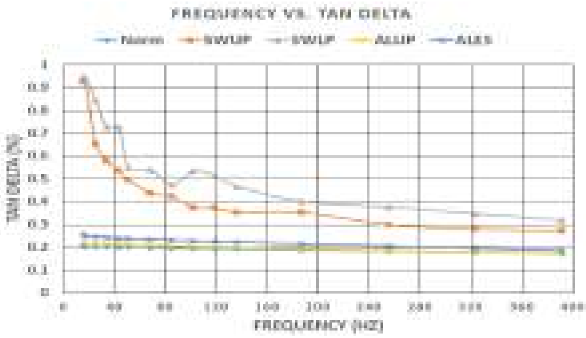

Figure 10: Bushing-1 tan delta results

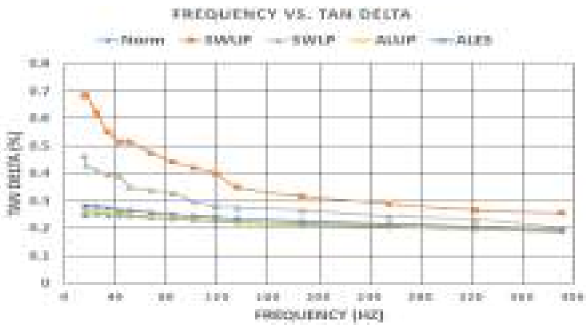

Figure 11: Bushing-2 tan delta results

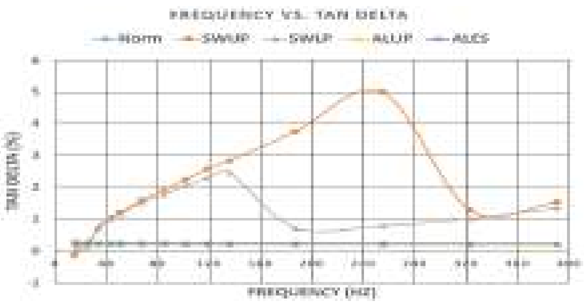

Figure 12: Bushing-3 tan delta results

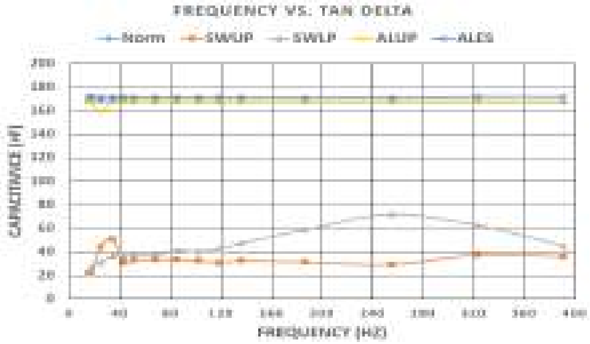

Figure 13: Bushing-3 capacitance results

Summary of Test Results

- Bushing-1 and bushing-2 show similar patterns of results, ie, at lower frequencies, the saltwater spraying abnormally increased tan delta at 15 Hz.
- Bushing-3 showed negative tan delta values at 15 Hz and 17 Hz in saltwater spraying condition. This was accompanied by reduced capacitance values, thus confirming significantly low resistance path by saltwater spraying.

Most Probable Root Causes of Negative Tan Delta

Some most common causes of negative tan delta (which cause creep current or surface leakage current):

- Moisture layer: Insulation surface internal or external to the product contains moisture layer or moisture film.
- Foreign particle contamination: Dirt and other pollutants or contaminants on the insulation surface internal or external to the product causes creep current.
- Carbonisation: As insulation materials age or are exposed to high temperatures, they may carbonise. Carbon deposits along the surface of insulation internal or external to the product causes creep current.
- Chemical contamination: Deposits over internal insulation surface causes creep current.

How to Eliminate Effects of External Factors?

As seen in most probable root causes, factors that can cause creep currents and ultimately negative tan delta include both, factors internal to the product and also those external to it. This makes it essential to eliminate probable external causes, as explained below:

- Thorough cleaning of external insulation surfaces of air-end and oil-end insulator. Since the oil-end insulator is shorter in height as compared to the air-end insulator, more concentration must be given on cleanliness of external surface of oil-end insulator.
- This thorough cleaning aims at removing moisture or foreign particle contamination or chemical contamination.

Usually, negative tan delta values are experienced on products of kV classes lower than 72 kV, in view of shorter distance between HV and the Earth. However, in the event of defect internal to the product, even the higher kV class products have been reported to be with negative tan delta.

Summary & Conclusions

- Explained in detail are various aspects of negative tan delta, including explanation of what is negative tan delta, mathematical and vectorial explanation of negative tan delta.
- The mathematical simulation indicates that when parallel path resistance (R_G) goes to below 2 Gohms, tan delta value goes down from 0.005 to 0 tan delta (and ultimately negative tan delta).
- Experimental simulation has been carried out using saltwater and aluminum foil wrapping on three 36 kV bushings. The saltwater contamination shows that in one bushing, tan delta values became negative at 15 Hz and 17 Hz.
- Most probable root causes of negative tan delta have been listed with precautions to be taken for eliminating external effects.

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Authors

Pramod Rao, an electrical engineer with over 45 years of industry experience is Sr. Technical Advisor, Yash Highvoltage Ltd

Gautam Nikam, an electrical engineer with over 15 years of experience is Head-Technology, Yash Highvoltage Ltd

Dr. Mihir Velani, a PhD in electrical engineering with over 13 years of experience, is Assistant Manager -Research & Development cell, Yash Highvoltage.