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Insulation Assessment of Oil Impregnated Paper Condenser Bushings using Dielectric Frequency Response Technique

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Abstract

Objectives: Investigation of insulation to judge the health of the condenser bushing with different techniques has been the area of interest for the researchers in recent past. Power transformers and their bushings are manufactured with oil impregnated paper insulation but their insulation integrity is comprised due to absorbed, residual or liberated moisture/ water which leads to further deterioration and catastrophic failure. **Methods:** Conventional measurement technique taken at rated power frequency only gives relative indication of specific dielectric properties and health of the condenser bushings. This article introduces a new approach for insulation assessment of the condenser bushings where OIP insulation as a key component has been investigated in a wide frequency response spectrum and to confirm the validity of this approach, measurements were taken on several condenser bushings of same type and age. **Findings:** The advance technique is a non-destructive method which evaluates the water concentration of the test object. The resulting curve is highly determined by the behavior of solid insulation and it is also sensitive to oil conductivity and insulation geometry of the bushing. Furthermore, the interpretation scheme related to dielectric response is explained. **Applications:** The signatures achieved helps in reliable data analysis and can be used in qualitative comparisons of bushings which compliments the available quality assurance techniques in the factory. This approach can also be used for frequent monitoring and effective moisture management at site.

Keywords: Condenser Bushing, Dielectric Spectroscopy, Insulation Assessment, Oil and Paper Insulation

1. Introduction

Reliability is out most important with today's scenario in the energy market. We can see such examples of Reliability in the life of power transformer which is almost more than 50 years. This also implies to high voltage condenser bushings which are critical components of all major electrical networks around the world[1]. A failure in HV condenser bushing can be catastrophic in nature which may result in damage of equipment in its vicinity and also result in revenue loss. Internal insulation failure is the ma

in reason for majority of failures of condenser bushings. Hence different utilities have adopted various methods and tests to monitor the reliability of this power equipment.

Solid insulation paper impregnated with transformer oil work as the chief insulation component in the condenser bushing. Hence ageing of pure (cellulose) paper becomes important aspect in judging the life of high voltage bushing. The dielectric strength of OIP insulation is comprised by factors such as temperature, present moisture and acids in the transformer oil. The residual or absorbed moisture in the new product will cause hydro-

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lysis in the chemical reaction with cellulose paper which results in more water as a by-product. With this phenomenon keeping in mind, we can say that water serves as an accelerator in aging process of the solid insulation of the HV bushing and can be critical for further deterioration and catastrophic failure.

Measurement of capacitance and dissipation factor at rated frequency is relatively easy to conduct and inferences can be made of overall condition of the insulation. However in recent developments, dielectric response methods using Polarization-Depolarization Current (PDC) and Frequency Dielectric Spectroscopy (FDS) has been established to evaluate the status of the insulation viz. moisture and aging state of the Oil and Paper Insulation (OIP)[2,3]. Using frequency domain Spectroscopy, the insulation can be investigated over and wide range in frequencies and the signatures can be recorded and investigated. To speed up the tests, PDC method is generally used at very low frequencies[4].

In our work, numerous HV condenser bushings were investigated after the manufacturing process had been completed and their insulation behaviour is studied in the entire range of frequencies and compared with conventional test results, which are generally adopted during high voltage laboratory testing. The use of dielectric response techniques (PDC & FDS) over wide frequency range is a useful technique for alert and to take actions against the start of degradation of the insulation due to moisture and prevent potential failure of the equipment. The article further briefs about bushings and its different insulation diagnostics methods firstly. Then it focuses on dielectric response measurements achieved at wide frequency band with its detailed reliable analysis and interpretation scheme.

2. High Voltage Oil Impregnated Paper Condenser Bushing

A bushing is defined as equipment which serves to insulate a conductor that is carrying high-voltage current through a grounded enclosure[5]. The current flowing through high voltage conductor is at some distance above and it should be isolated from the walls of power transformer which are grounded. Thus we can relate this with an example of a bridge where the potential is the length of the bridge and longer the bridge more supports it must have so that it must not make any contact with the ground[1]. The current path will serve as number of lanes on the bridge. So suddenly the chances of accidents increases if we reduce the no. of lanes and increase the traffic flow in these narrow lanes causing multiple pile-up of cars.

Transients in the power system and overstressing on center conductor may damage the internal puncture strength of the bushings while overvoltage would lead the bushing to external flashover. From the above example, we can say that the insulation system of bushing should protect the product from over voltage and the high voltage conductor should be able to carry the overcurrent caused in the system. So, the condenser bushing should have a voltage gradient from the center of conductor to ground. Several layers of insulation paper and aluminum foils are made filled with transformer oil as an insulating fluid. These layers will form several capacitors which will grade down the voltage. Figure 1, C_1 forms the main insulation and few layers at the end form as C_2 insulation. The Tap Electrode is at the junction point between C1 and C2. The tap electrode is referred to "Test Tap". Tan delta and capacitance value measurements at rated frequency are carried out in high voltage labs on these layers of insulation

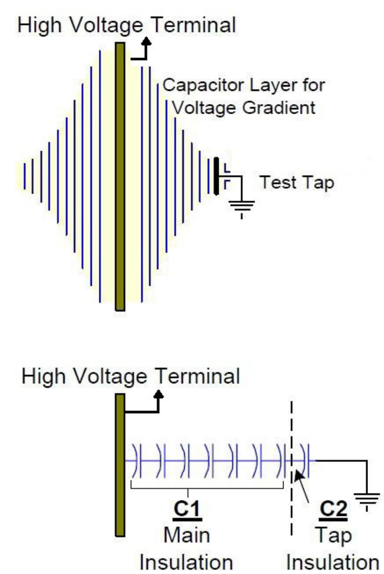

Figure 1. Schematic diagram of High Voltage Condenser Bushing .

Figure 2 shows us the actual pictorial inside the condenser core of the bushing. The electrical stress control can be achieved by distributing the voltage gradient radially and axially along the length of condenser core[6]. So floating equalizer screens made of aluminum foils are inserted cylindrically along the center conductor at equal distances in the power equipment. They are placed in such a way that it achieves an ideal balance between the external flashover and internal puncture of graded capacitive layers.

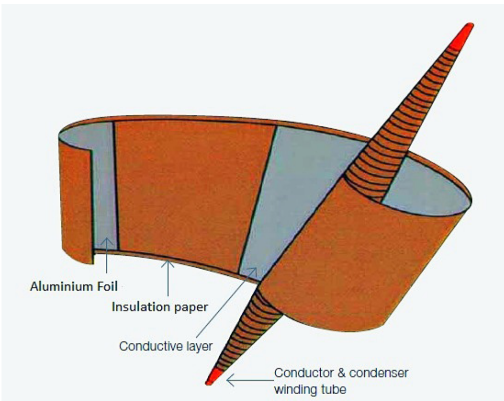

Figure 2. Inside Pictorial of the Condenser Core in bushing.

3. Insulation Diagnostic methods: Condenser Bushings and Power Transformers

Primary inspiration for the development of dielectric response methods were the lack of methods for quick on-site moisture assessment in the power transformer and its bushings[7]. Insulation behavior serves as a key indicator in determining ageing and performance of power equipment. So in this regard, new approaches like measurement of Polarization and Depolarization Currents (PDC) and Frequency Domain Spectroscopy (FDS) show deficiencies in the insulation system and determine the water concentration in the asset. Hence, following methods have been discussed which are developed in recent years to investigate the dielectric response to evaluate moisture in paper or pressboard from dielectric properties.

3.1 Recovery Voltage Method (RVM)

The test setup for this method is similar to traditional dissipation factor measurement at rated frequency[8]. Measurements are taken after applying the DC voltage for long periods which are then short circuited for a while and immediately open circuited. By this repeated charging and subsequent relaxation for definite time, charge restricted by polarization turn into free charges and polarization spectrum is created. Evaluation of water concentration in the product is done through the time constant in this polarization spectrum. According to CIGRÉ, the relationship based between dominant time constants in the spectrum and the water concentration is incorrect.

3.2 PDC Measurement Technique

When a totally discharged insulation is exposed to a fixed DC voltage, a resultant current will be produced from activation of the polarization species with different time constants and due to conductivity of the insulation[9]. This resultant current is known as charging or polarization current. When all polarized species are oriented themselves in the direction of the field, the current achieves a steady state condition which is primarily due to DC conduction[10]. If the voltage is now switched off, the polarized species tend to relax resulting in depolarization current. A typical test arrangement for PDC measurement is shown in the Figure 3.

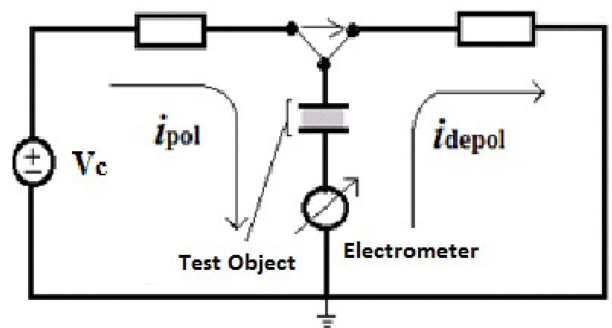

Figure 3. PDC Measurement technique.

3.3 Frequency Domain Spectroscopy (FDS)

Frequency domain measurements are derived from old known dissipation factor measurements, yet with a frequency range particularly enhanced for low frequencies. The derived measurement method is called frequency domain spectroscopy[11]. Figure 4shows the typical S-shaped curve of the dissipation factor over wide frequency range and scientifically agreed interpretation scheme for the condenser bushings. As we can see that the frequency band near 50 Hz is dominated majorly by paper insulation but measurement cables and connection techniques will also influence this region[12]. A steep slope is followed after this wherein dissolved conductive aging by-products and acids increase the oil conductivity and influence this area. The hump in the signature is basically due to the insulation geometry and interfacial polarization process. Finally the dielectric properties of insulation paper of bushing appear again near 5 Mhz which reflects water concentration and manufacturing process of the power equipment.

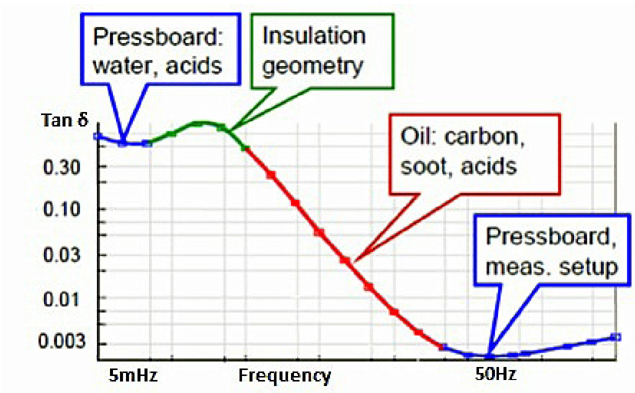

Figure 4. Scientifically agreed dissipation factor signature curve of OIP condenser bushing.

4. Dielectric Response Measurements on EHV Condenser Bushings

FDS &PDC method were used on numerous condenser bushings of same type and age. The main motive in our research work was to measure and analyse the effect of dielectric responses over wide frequency response spectrum. For oil paper insulation, the dielectric response consists of following three components:

1. The response of cellulose insulation.
2. The response of transformer oil.
3. The interfacial polarization effect.

Apart from these parameters the other parameters viz. oil conductivity, insulation geometry, moisture content, temperature of bushing and conductive ageing by-products influence the resulting curve[13]. Typically the dielectric response of pure paper (cellulose material) is an S shape curve. Figure 4 influenced by geometry and permittivity of the insulation. Dissipation factor slope shows minimum at high frequency and maximum at lower frequency.Figure5shows the response signature of 15 condenser bushings which were ready to dispatch to sites after all conventional high voltage test including partial discharge test.

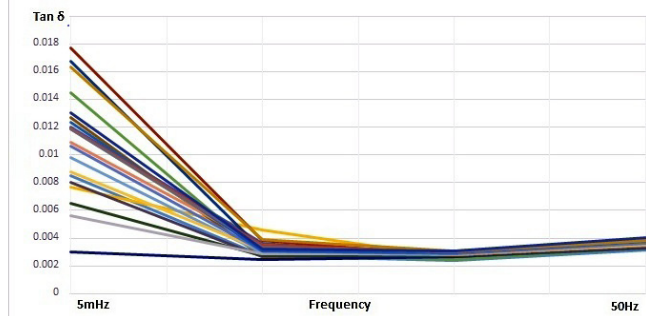

Figure 5. Signatures of new and healthy bushings of same kV class.

Typical characteristics were obtained for oil impregnated paper insulated condenser bushing which were influenced by insulation geometry, temperature, moisture content. For the frequency band near 50 Hz, curve is flat for which polarization dominate the response[14]. At lower frequencies near 5mHz, the losses are much higher resulting in a steep increasing dissipation factor which is due to the fact that transformer oil shows conductive behavior without polarization process. Hence the dielectric properties of cellulose insulation and oil is superimposed with interfacial polarization where charge carriers such as ions accumulate at the interfaces. Clouds with dipole-like behavior are formed at these interfaces[15]. This kind of polarization is only effective in lower frequencies. So it is interesting to observe that as the product is new, healthy and completelaging has not taken place and the shift is purely due to geometry, oil insulation paper nature and insulation dryness.

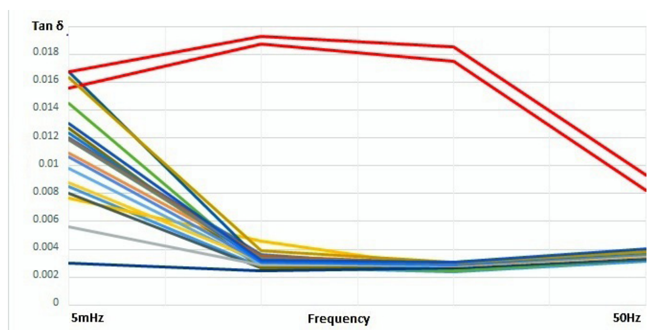

Figure 6. Signatures of bushings including distortions.

From the cluster of these signature curves it can be inferred that, for this typical construction and insulation dryness, this signature could be taken as the characteristic signature of this type of EHV condenser bushing. It is also interesting to observe the dispersion in the lower frequency range, even for typically healthy condenser bushings, whose 50 Hz dissipation factor is well below the acceptable norms in the conventional wisdom for fresh OIP insulation is shown in Figure 6.

Any significant deviation from this characteristics curve could mean a known or a developing defect. Compared to other signatures, there is a complete deviation in two signatures, wherein increase in dissipation factor in high and as well as low frequency range is seen. While an increase in the dissipation factor at 50 Hz is evident, correlation with reductions in dissipation factor at dual multiple frequency bands needs further study. However, we can easily confirm through frequency sweep test that a defect has evolved. This is very handy alternative tool at site to isolate a product at very early stage, where frequent oil sampling is difficult and not recommended for obvious reasons[16].

5. Interpretation Scheme

For an effective quality assurance of condenser bushings, a reliable interpretation scheme is needed so that funded decisions can be taken after reviewing the health of the product. Figure 7 shows an example of an interpretation scheme using the discussed measurement techniques. Besides the dielectric response, other measured values could also be used. However, this scheme is restricted to dielectric measurements, moisture content and oil conductivity within the bushing.

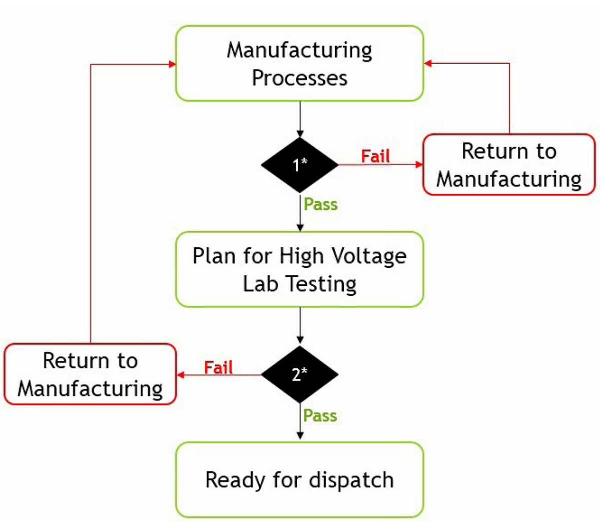

Figure 7. Quality assurance flowchart based on results of dielectric response of bushing.

Following values might be used for analysis of dielectric response:

Step 1: PDC and FDS measurements:
- Dissipation factor in wide frequency range
- Water content (e.g. W.C < 2.2%)
- Oil conductivity (e.g. β_{oil} < 10 pS/m)

Step 2: Conventional High voltage lab testing:
- DF at 50 Hz (e.g. $DF_{50\ Hz}$<0.01)
- Capacitance value (e.g.C_{50HZ}< 500 pF)

The interpretation scheme consists of two qualitative assurance steps. The first step can be done with PDC and FDS measurements at lower frequencies during the standing time of the bushing which is after the completion of manufacturing processes. If the bushing fails, it probably has a defect during manufacturing process or moisture ingress is progressive. Due to dielectric spectroscopy at wide frequency range, we understand the probable cause of failure and so the product can be returned to the particular manufacturing process. If the first step is passed by the condenser bushings then it can be planned for conventional testing in high voltage laboratories.If the condenser bushing passes the second test then it is ready for dispatch from the factory. For the condenser bushing which fail the second step, a replacement plan should be formulated for such type of bushings.

6. Conclusion

The frequency domain spectroscopy is useful tool both at factory and also at site as a non-destructive test with very simple test setup. A mere comparison with healthy signature pattern can reveal an evolving defect in the test object. It is imperative to mention the response spectrum is very sensitive to geometry of test object, composite dielectric constant of insulation, temperature of bulk insulation under investigation. Hence interpretation of test results need to be done with care.

While number of tests could be conducted on healthy condenser bushings from production line, the investigations required known defects to be introduced in healthy complete condenser bushing (as the signature curve is geometry dependent), which is very costly and time consuming exercise. Hence all types of defects could not be investigated.

More theoretical research work will be needed to correlate a particular type pattern, the type of defect and relevance to a particular frequency range. Since the ageing and moisture content significantly influence the signature pattern in the very low frequency range, the relevance of this technique, in a permanently sealed non-breathing product like condenser bushing is an interesting aspect of investigation.

From the author's opinion, three direct benefits are obvious. In the production line, this test can be pre-test before the final high voltage test to isolate a non-conforming product which can be beneficial keeping in mind the utilization of high voltage laboratory. As part of condition monitoring at site, this test could be used as preliminary test before a confirmatory DGA could be planned on a suspected product. If used as a routine condition monitoring tool, due to its simplicity in test setup, any evolving defect could be captured before it can lead to measure failure in future.

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