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Transformer Bushings: Current Technology Trends , Developments & it's relevance in Monitoring of Bushings in Service

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SUMMARY

Transformer Bushings are expected to be highly reliable components of Transformers. In the event of Failure of Transformer Bushings, usually the result is downtime of several weeks of a power transformer accompanied by financial losses & urgency to restore the system at the earliest. Majority of the Bushings in service (for past many years) are Bushings with OIP (Oil Impregnated Paper) Insulation System. In India, major usage of RIP (Resin Impregnated Paper) Insulated Bushings commenced in 2011-12 & recently in 2018 RIS (Resin Impregnated Synthetics) Insulated Bushings have been also introduced in Indian Grid. OIP Bushings are well established up to 800kV & RIP Bushings are now in use up to 420kV and RIS Bushings are reported to be available up to 245kV. This paper reviews the Current Technology Trends.

In view of Various Insulation Technologies in use , it is essential to understand technical aspects of Insulation Degradation Mechanism and their effects on Service Behaviour of Bushings. This paper describes these aspects in detail. Tan Delta has been considered as a vital health monitoring parameter for OIP Bushings & different utilities have adopted stringent limits for Tan Delta (when compared with IEC Limits of 0.007). Data based evaluation & trend analysis of increase in Tan Delta gives a preliminary clue about Bushing Health, however this needs to be supplemented by DGA Analysis of Oil Sample. This paper describes it in detail.

For dry RIP & RIS Bushings, however Capacitance and Partial Discharges Monitoring reveals the information about health of these Bushings. Tan Delta reveals status of pre-commissioning health. This paper describes in detail, associated technical aspects to help identify more relevant/reliable and safe practices for condition monitoring and interpretation of tests in case of dry RIP/RIS bushing fleet. Described in detail are the difference in Tan Delta behaviour between OIP Bushings & RIP Bushings. The experimentation results of Temperature Dependence of Tan Delta of OIP & RIP are shared in this paper. Various site conditions which influence the Tan Delta measurements & the precautions to be taken to prevent wrong conclusions are described .

KEYWORDS

Transformer, Transformer Bushings, Condenser bushings, OIP, RIP, RIS, Tan Delta, Bushing condition monitoring

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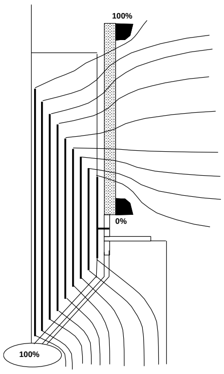
INSULATION SYSTEMS IN USE FOR BUSHINGS

OIP (Oil Impregnated Paper): It's use is reported since 1950 & OIP Bushing manufacturing Technology is now well established for past 70 years up to 800kV rating. Majority of Bushings in service still have OIP as insulation. **RIP** (Resin Impregnated Paper): Truly a Solid Insulation System. The Popular RIP Bushings in the market are free of Insulating Oil. Although RIP has been developed for other applications such as Insulated Busbars, the bulk usage of RIP for Bushings is reported from around 1970. Now the RIP Bushings are available up to 420kV mainly for Air to Oil Type Application & few RIP Bushings are also reported to be available even at 800kV Level and for Oil to Oil & Oil to SF6 Application. In India, the bulk use of RIP Bushings for Air to Oil Type Application Commenced in @ 2011. **RIS** (Resin Impregnated Synthetics): This is a truly Paperless Bushing (free of cellulose) and is also truly a Solid Insulation System like RIP Bushings & it has been a fairly recent development and it's reported to be undergoing field trials since 2012. First trial of RIS Bushings in India is reported to have started in 2018-19. These Bushings are readily available up to 170kV Rating, trial usage RIS Bushings is also reported up to 245kV class. **RBP** The earlier type of RBP (Resin Bonded Paper) is not discussed, as the Technology is now obsolete and the manufacturing of RBP Bushings has already stopped & hence is not discussed in the Paper. Now let us look at some of the Current Technology Trends in Bushings using OIP, RIP & RIS Technologies;

OIP Bushings: The OIP Technology is a mature technology from the Product & Process Viewpoint. However, in view of service experience, where some of the explosive failures of the OIP Bushings have caused severe damage to Transformer and surroundings, the main focus in OIP Technology has been to enhance in-service reliability of OIP Bushings. Some of the Product Features like "Shatterproof Resin Moulded Oil End Insulator" have been used by most of the Bushing Manufacturers around the world. In order to avoid shattering of Air End Insulator, Bushings with Polymeric Insulators have been designed, type tested and also are reported to be in use. However, such Bushings with Composite Insulators as Air End Insulator, are yet to become popular. Besides these product features, the focus has been to ensure and enhance reliability of Condenser Core and Drying of Paper Insulation to minimise remaining Moisture Content. So also, the focus of the manufacturers has been to ensure good quality oil (Dried and Degassed) is filled in the bushing. In order to correctly assess the Bushings' quality, IEC Standard has undergone significant changes, such as Routine Impulse Testing of Bushings above 72.5kV in IEC60137:2017, Routine AC HV Testing at higher voltage (i.e. 10% higher than Transformer Insulation Level). Also, some customers have made the Tan Delta limits stringent (e.g. 0.4% instead of 0.7%). The major focus has been to evolve Tests to identify defective bushing & remove it from service before it causes explosive failure & damage to Transformer. Some such offline tests have been Low Frequency Tan Delta, DGA of Oil. There are few installations in the world and in India, where On-Line Monitoring of Bushing health also has been implemented. These will be discussed later in the paper.

RIP / RIS Bushings: RIP Bushing usage for Transformer Application is now nearing 50 years & the Product and Manufacturing Process has been mastered by few reputed manufacturers. The main technology trend is towards developing and establishing manufacturing capabilities for higher kV Class (>420kV) RIP Bushings for Air to Oil Type Application. Around 1970, when the RIP Bushings were manufactured there were several types of constructions i.e. Porcelain Housing + Oil Filling or Porcelain Housing + Foam etc. However nowadays the RIP Bushings available are all with Silicon Housings, unless end user specifically calls for use of Porcelain. There are two types of constructions in use at present. The first type uses Hollow Composite Insulator & Gap between RIP Condenser Core and ID of Insulator is filled with Dry Insulating Foam & in second type the Silicon Insulator is directly moulded on RIP Core. The challenge is in Direct Moulding of Silicon Sheds on Higher kV Class RIP Condenser Cores. Also, manufacturers are working on enhancing yield of first-time pass from the viewpoint of PD Performance. Another aspect on which some developmental activities are taking place is on how to reduce the moisture absorption during handling , transport & storage, although usage of Oil Filled / Dry Gas Filled tank on Oil end is more popular nowadays. For in-service condition monitoring, for RIP Bushings the main focus is on developing a low-cost on-line health monitoring device based on Capacitance Variation Method. For RIS Bushings the main efforts are in developing and productionising Air to Oil Type Bushings higher than 170kV Class. Also, close monitoring of RIS Bushings installed about 6-7 years back, is being done in order to find out whether any unknown problems need attention. This will decide the further evolvement of RIS Bushings.

Condenser Grading Concepts



In order to understand the basics of Health / Condition monitoring, it is essential to look at the condenser grading concepts. The sketch shows, a Typical Electrical Field (Equipotential Lines) Configuration of Oil to Air Type Bushing (OIP/RIP/RIS). As can be seen the Condenser Grading is required to control & uniformly distribute electrical field along the Air End Insulator and Oil End Insulator. The main function of Condenser Grading is also to control Radial Voltage Stress inside the Condenser Core, so that the Insulation System can be optimally and compactly designed. The condenser grading is achieved by placing Wider Aluminium Foils of different lengths at different diameter locations. Typically, in 145kV OIP Bushing around 30 Nos. of Grading Foils are used and whereas in 145kV RIP / RIS Bushings around 15 Nos. of Grading Foils are used. The lesser number of Grading Foils in RIP/RIS Bushings is due to fact that Resin Impregnation requires more space between paper / synthetic films (arranged between aluminium foils). The outermost Grading foil is connected to Test Tap & then externally connected to earth.

Capacitance & Tan Delta of Bushings

In OIP Bushings, Insulating Kraft Paper Layers are tightly wound on the Central Pipe / Central Rod and at predetermined Diameters , Condenser Grading Aluminium Foils are inserted at predetermined Locations. The Tight and Compact winding is achieved by winding the condenser core on a machine, this is necessary to minimise the oil film thickness and thus attempt to reduce adverse effects of Oil Ageing. Insulating Kraft Paper thickness used is in the range 0.075mm to 0.125mm & the grammage used typically in the range of 60GSM to 80GSM. The grade & quality of Insulating Paper used decides the dielectric constant & hence the Capacitance Value and thus the Capacitance values for same kV Class can vary between various different designs / manufacturers. Since the Condenser Cores are tightly wound, it takes few weeks for drying of the paper insulation (i.e. Removal of Moisture) under heat (@100 Deg. Cent.) & finer vacuums (finer than 0.05mBar). After the drying is completed, the Condenser is impregnated by use of well dried and degassed Mineral Insulating Oil. The dried & degassed oil at room temperature has a Tan Delta of ~ 0.001 and the total tan delta of OIP Condenser Core is mainly decided by the grade of paper used and the winding technique used. The paper to oil ratio (typically around 100:10 , based on the compactness of paper winding) is a critical parameter to decide Capacitance & Tan Delta. Typical Tan Delta values of OIP Bushings is in the range of 0.003 to 0.004.

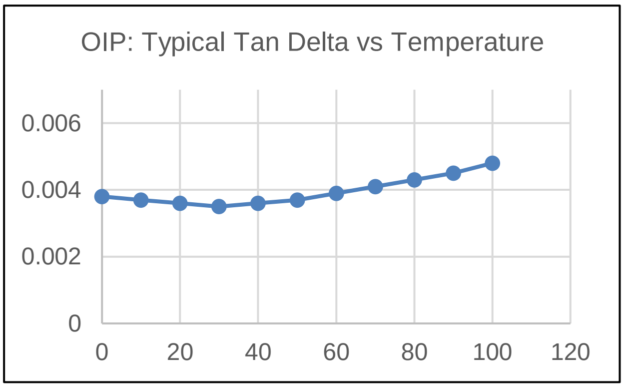
In RIP Bushings, Insulating Crepe Paper Layers are wound on Central Pipe / Central Rod and at predetermined Diameters , Condenser Grading Aluminium Foils are inserted at predetermined Locations. The optimum winding tightness is ensured to achieve impregnation by Resin Mix & also to ensure the Condenser Grading Aluminium Foils stay in position during handling and during the process of Drying and Impregnation. The typical paper to resin ratio is around 60:40. Since the crepe paper winding is not as tight as Condenser Cores for OIP, the drying (i.e. Moisture Removal) process is shorter and lesser in time than ~ 50% of Condenser Cores for OIP. The resin component itself has a relatively higher tan delta when compared with Oil. In view of higher resin content in RIP the Typical Tan Delta Values is in the range of 0.004 to 0.005 at room temperature. The only difference between RIP & RIS Bushings is, Crepe Paper is used in RIP whereas Synthetic Film is used in RIS. Thus, in case of RIS an elaborate drying of Paper similar to OIP/RIP is not required as Synthetic Film is used in RIS.

IEC-60137-2017, specifies a Limit for Tan Delta of 0.007 (Maximum) for OIP , RIP and RIS Bushings at temperatures of 10 & 40 Deg. Cent.

Tan Delta vs Temperature

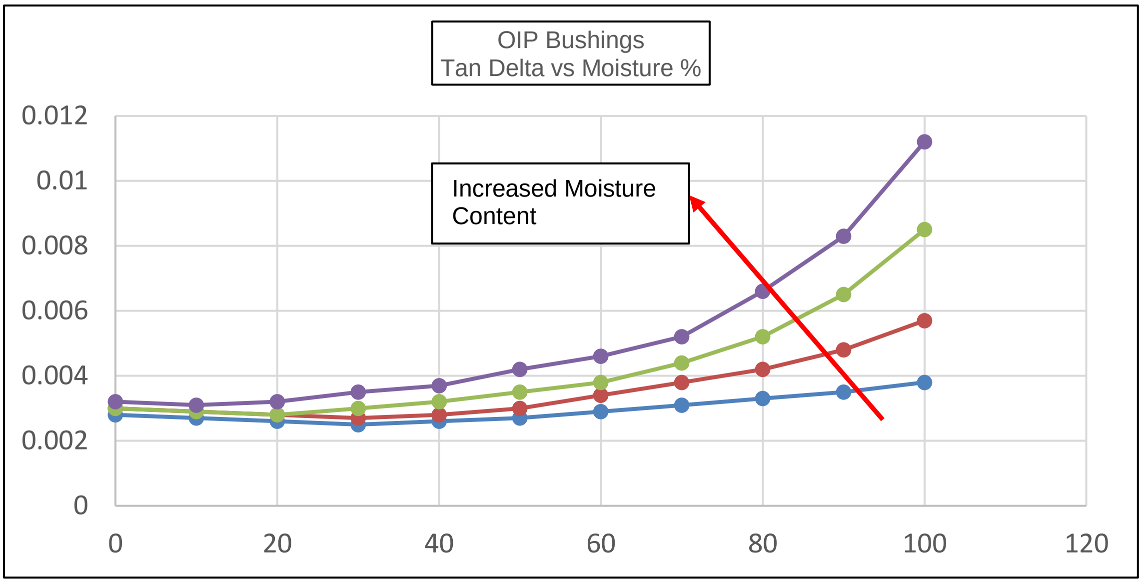
The Air to Oil Type Bushings are mounted on the Transformer Tank & Oil End Part is immersed in Hot Oil Inside the transformer and thus based on the Transformer Load conditions, oil side of bushings in service are continuously exposed to surrounding temperatures of 60 Deg. Cent. to 90 Deg. Cent. Whereas the factory tests are carried out on Bushings at Ambient Temperatures.

Thus, it is important to understand and appreciate the variation of Tan Delta with reference to Temperature of OIP , RIP and RIS Bushings & assess its performance at test bed and also during service. Based on the extensive experiments carried out on prototypes of OIP & RIP Bushings, we are sharing our findings on Tan Delta vs Temperature.



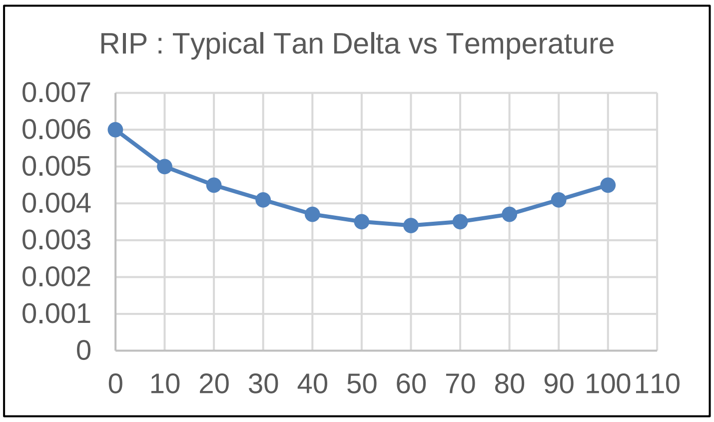
Typical Tan Delta vs Temperature Characteristics of OIP Bushings is shown in the Graph. As can be seen there is a variation in Tan Delta when the temperature is increasing. Lowest value is observed in between 20 Deg. Cent. and 50 Deg. Cent.

For OIP Bushings, the varying Moisture Content in Paper Insulation (Balance after the Drying Cycle), the Tan Delta is observed to be higher at Temperatures in excess of 60 Deg. Cent. This is illustrated in the representative graph given below;

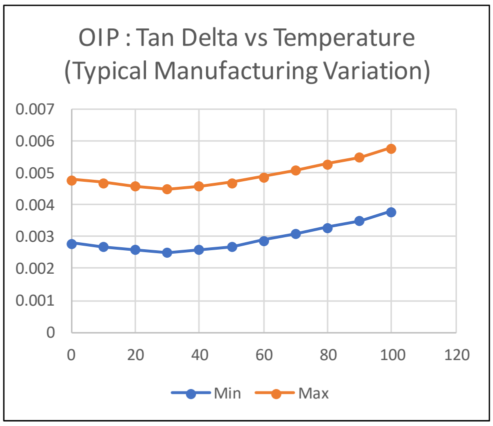


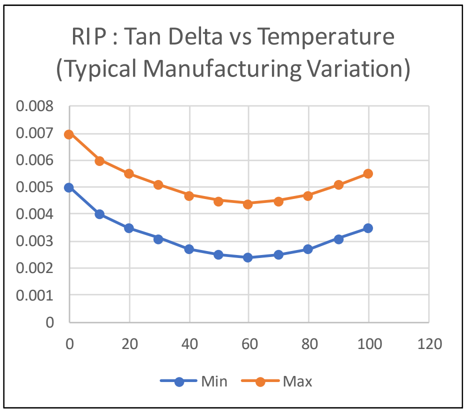
As can be seen, the higher the Moisture Content, the Tan Delta can reach very high Tan Delta values at Temperatures 60 to 90 Deg. Cent. and can result into thermal runaway and cause OIP Insulation & ultimately Bushing Failure.

In case of RIP Bushings, in view of the Inherent Resin Material Characteristics, higher Tan Delta variation (when compared with OIP) is observed w.r.t. Temperature, as shown below;



As can be seen from the graph, the RIP Bushing has lowest Tan Delta value at Temperature of @ 60 Deg. Cent. The Tan Delta keeps increasing as Temperature goes below 60 Deg. Cent. A similar Tan Delta behaviour is reported in RIS Bushings also with slightly lower values than in RIP Bushings. Based on statistical analysis of data on variations in manufacturing processes of OIP & RIP Bushings, below mentioned Minimum & Maximum limits have been arrived at;





From the above description, it is essential that the users seek the data of Tan Delta vs Temperature from the Bushing Manufacturer and use it as a guidance during health assessment based on site measurements. Also, it can be concluded that for OIP Bushings, a Stringent limit on Tan Delta such as 0.004 can be adopted, however for RIP / RIS Bushings being Solid & has practically non ageing insulation, Tan Delta limit does not need to be stringent and limit of 0.007 can be adopted for RIP & RIS. So also, the variation in Tan Delta with Temperature has to be given consideration while evaluating measurements carried out at Bushing Factory, Transformer Factory & Site Measurements.

Capacitance vs Temperature : Capacitance has a linear variation with temperature & is mainly decided by variation of Composite Dielectric Constant variation with Temperature. The typical variations of Capacitance of OIP, RIP & RIS are 0.025% per Deg. Cent. for OIP ; 0.08% per Deg. Cent. for RIP & 0.03% per Deg. Cent for RIS. If we consider, a Bushing has a Capacitance Value of 350pF at 20 Deg. Cent., and if we estimate Capacitance at 50 Deg. Cent. based on above Temperature Coefficients; in case of OIP Bushings the Capacitance will be 352.6pF , for RIP Bushings it will be 358.4pF, for RIS Bushings it will be 353.2pF. Another consideration is, if we have 50 nos. of Condenser Foils for 245kV Bushing (this means we have 50 capacitors in series) & in case there is a puncture of one foil (i.e. short of one capacitor), the change in capacitance expected is approx. 350pF x 1/50 = 7pF. Thus, during site measurements, we need to take into account Temperature of Insulation at the time of Capacitance measurement & change in capacitance caused by puncture of one foil segment and then decide health and status of Bushing. An easy method to decide whether puncture or temperature effect caused the variation is to compare similar bushings in similar conditions, typically the 3 phases on a same transformer: same increase on 3 phases is most probably due to temperature or environment; variation on one phase is probably due to a puncture.

Insulation Degradation in Service: As it has been reported in several technical papers and confirmed by our experience, for OIP Bushings the Insulation Degradation is mainly caused by decrease in Insulation Resistivity caused by Moisture Ingress (caused by leakages thru sealing) & Contamination external to Condenser Core (due to degradation of Oil). This causes increased resistive loss and thus increase in Tan Delta value. This results in increased dielectric heating thus further increase in Tan Delta & eventually breakdown due to thermal runaway. PD (Partial Discharge) activities start in small segments but with periodic larger size discharges & these keep on increasing with time. As the discharges increase, puncture holes of smaller size containing conducting path are created & these result in increase of Capacitance Value. Thus, in OIP Bushings, all three parameters viz. “Capacitance” , “Tan Delta” & “DGA” are important to be monitored. Whereas in case of RIP/ RIS Bushings, the Insulation degradation takes place due to PD activity taking place over a smaller area in RIP / RIS Condenser Core. As PD Activities increase, tree like structure gets converted into small hole and as the discharges further increase, the hole size increases; ultimately resulting in creating a shorting / conducting path between two or more condenser foils. Thus, there is an increase in Capacitance. The Condenser Core does not have oil and hence does not interact with Oil like OIP Bushings and thus no adverse effect on Tan Delta in case of RIP/ RIS Bushings. In case of RIP / RIS Bushings, during service Tan Delta remains steady and show insignificant changes. Thus, for RIP/RIS , Capacitance monitoring is an effective method.

Health Monitoring in Service In order to prevent Explosive failures of Bushings (causing severe damage to Transformers and surroundings), health monitoring of Bushings has gained significant importance. As reported in CIGRE Report 755 published in Feb-2019, about 83% of users follow the Off-Line Diagnostic methods. About 96% of these users still follow Capacitance & Tan Delta measurement. The off-line diagnostic measurement periodicity followed is between 2 & 4 years. Few of critical aspects of measuring Capacitance & Tan Delta at Factory (Bushing & Transformer) vs Site Measurements are listed below;

- Factory measurements are more accurate due to measurements in interference free environment in shielded laboratory & use of loss free standard capacitor.
- Site measurements are mainly dependent on characteristics of standard capacitor in the portable bridge & the measurement method used.
- Adverse Effects of Surface Contaminations on Tan Delta measured at site. This effect is more pronounced for bushings of lower kV Classes (36kV to 72kV) and having been exposed to environmental condition for longer time.
- Effect of Temperature at the time of measurement at site. External ambient temperature may be lower , however the time gap between shutdown and measurement will decide the actual temperature of condenser body & hence will affect results measured. CIGRE Report 755 elaborates the method of assessing Actual Bushing Temperature.

Tan Delta Limits for New Bushings & for Bushings at pre-commissioning and in Service

New Bushings: IEC 60137 limits of Tan Delta for OIP, RIP & RIS Bushings of 0.007 (Maximum) between Temperatures of 10 & 40 Deg. Cent. is adopted by most of the utilities in the world. This is due to the fact that Tan Delta does not reflect healthiness of RIP & RIS Bushings. **Pre-Commissioning**: In RIP Bushings, Condenser Core itself forms the Oil End Portion (similar in RIS Bushings). In view of Moisture Absorption by RIP Condenser Core (i.e. by exposure of Oil End Part to ambient), there is an adverse effect on increase of Tan Delta at pre-commissioning stage. Hence RIP Bushings are usually supplied fitted with Oil / Gas Filled Metallic Containers fitted at Mounting Flange Level, to prevent the moisture absorption due to long exposures to ambient. In case of OIP Bushings, there is a possibility of De-Impregnation (drying of OIP condenser core) if not stored as per manufacturer's recommendation. Hence, some users follow the practice of vertical storage of OIP Bushings to prevent the de-impregnation. To account for the difference between factory and site measurements, it is recommended to allow variation of +/-0.001 between Factory and Pre-commissioning results at site and comparable temperatures. This is aimed at taking into account effects mentioned in above paragraphs. **In Service**: Tan Delta as a monitoring parameter is most important for OIP Bushings and it is not important monitoring parameter for RIP/RIS Bushings, as Tan Delta remains steady during service. There can be two methods of monitoring Tan Delta in service, first is the absolute limiting value and second is the rate of increase of Tan Delta. Based on study of Technical Literatures and our experience, limit of absolute Tan Delta as 0.008 (and / or Double of Pre-Commissioning Value) is recommended for OIP Bushings. Rate of increase of Tan Delta <0.0002 per year can be treated as healthy & however sudden increase of Tan Delta within two readings from normal increase of 0.0002 to 0.001 should be treated as a sign of concern & as a "Warning" signal. **Tan Delta measurements at Different Frequencies (15Hz to 400Hz at 2kV or 4kV):** On account of difficulties in correct assessment of Tan Delta in service based on 50Hz measurement for OIP Bushings, through research by experts around the world have evolved Tan Delta measurements at different frequencies. The Low Frequency Tan Delta measurements give a definitive indication of Moisture Presence for OIP Bushings. About 13% of the users are reported to have followed these measurements as a tool to confirm degradation of OIP Insulation. In recent CIGRE-Session 2018, POWERGRID-India presented case studies on these measurements. It is established that lower frequency measurements, show moisture content distinctively and thus more of a confirmation test. CIGRE document gives guidelines on new and aged bushings.

DGA of Oil Sample from OIP Bushings: In order to supplement evaluation based on Tan Delta, DGA is more of a conclusive measurement. Broad Guidelines are available in IEC-61464 and limits on DGA are given in these standards. Oil Sampling from Bushings needs extreme precautions to be exercised as recommended by manufacturers, to prevent moisture and Gas ingress during sampling. Limiting quantity of Oil Sampled (less than 25mL) is best suited for multiple analysis during entire service without refilling of oil. Trend of Increase in gases is the best method to follow rather than limits on gases. Refer limits given in IEC 60599.

Online Capacitance Monitoring: This is practiced by few users around the world. The main principle is to assess variation in Capacitance of a set of three bushings. There are some case studies where users have reported success. The most efficient method to conclude if changes are due to environment, to grid variations or to bushing failure is to couple a HV-voltage divider with the bushing to be monitored and compare both values on real-time. However, these are only used at kV Classes > 245kV, in view of prohibitive costs of such devices.

SUMMARY:

A larger population of OIP Bushings is in Service, & Monitoring of the Healthiness of OIP Bushings is important to prevent Explosive Failures. Methods adopted are Limiting Values of Tan Delta in Service or Detecting Rate of Change of Tan Delta. Capacitance Change to provide clue on Puncture of Foil Segments. DGA is a must for 245kV & 420kV Bushings , Oil Volume Sampling to be limited to 25mL. PD Evaluation in a Laboratory can be treated as a confirmation Test. RIP Bushings are popular since 2011 in India, due to distinct advantages. Fool-proof Storage, to prevent Moisture Absorption & degradation of Tan Delta before commissioning. Limiting Values of Tan Delta for RIP / RIS can be higher than OIP. Recommended to follow IEC Limits of 0.7% (Take into account Temperature vs Tan Delta behaviour). Lower Tan Delta Limit at ambient temperature does not necessarily mean better quality product for RIP / RIS Bushings (provides no information regarding tan Delta at operating temperature). Tan Delta not expected to reveal health of RIP/RIS in service, Hence Capacitance Change to be adopted as a health monitoring tool. For RIS Bushings, more Service Experience needs to be gained to define the health monitoring strategy, however till such time Capacitance Based Monitoring like RIP Bushings can be followed.

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