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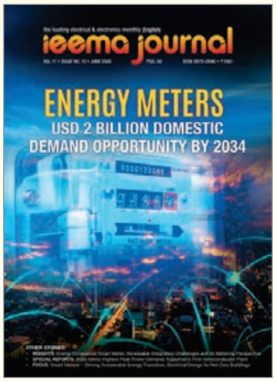

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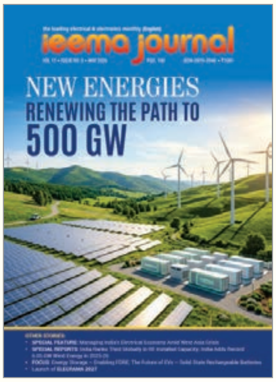

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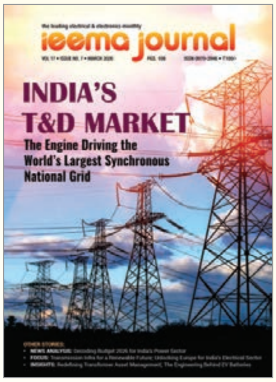

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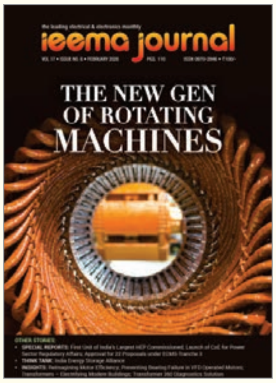

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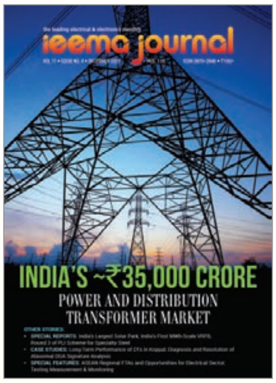

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Contents

COVER STORY

India's Power & Distribution Transformers: Transforming to an Energy Efficient Future 12

With the global transition towards clean energy, expansion of power infrastructure, grid modernisation, increasing electricity demand and ageing transmission systems, there is a swelling need for new transformers world over. The coming decade represents a landmark opportunity for the Indian power and distribution transformer industry. Investments in advanced materials, smart monitoring technologies, indigenous manufacturing capabilities, and world-class quality systems will enable India's transformer manufacturers to meet the evolving needs of utilities worldwide.

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FOCUS

Efficient & Futuristic Transformer Plants 44

This paper by **Shridhar Gokhale** and **Rajeev Shevgaonkar of North Star Electricals** along with **Dr. Mrunal Deshpande, Professor & Head of Marathwada Mitra Mandals College of Engineering,** and **Ramchandra Vinayak Markale, independent management consultant,** focuses on aspects of a transformer manufacturing facility. It presents key elements of plant engineering, broad technical requirements of various types of equipment, and concepts and logics for selecting a particular type over other options.

Mandating Standardised Occupational Safety Provisions on Power Transformers 61

Girish Ramesh Nimbalwar, Jayesh Magrde, and **Vivek Pawar** of **CG Power,** highlight critical safety risks encountered while working on transformers and identify practical, feasible provisions that can effectively mitigate them. They further emphasise the need for uniform safety guidelines across the industry, proposing that these provisions be progressively standardised within transformer specifications.


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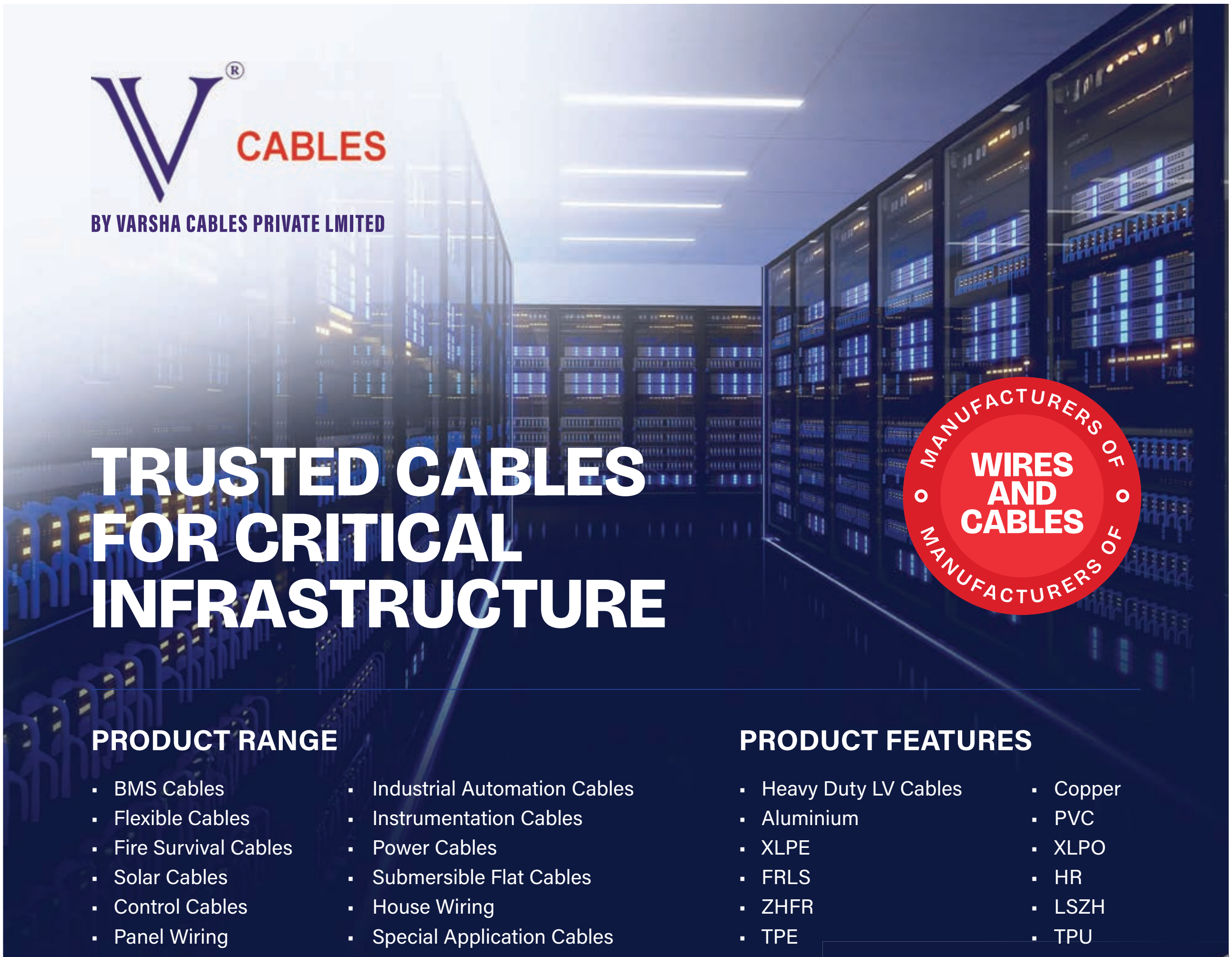

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CONTENTS

INSIGHTS

Large Power Transformers: A Strategic Approach to Overcome Retrofitting & Refurbishing Challenges 30

This paper by **Nilesh Meshram** and **Komelabbas I Lakhani** of **Siemens Energy India Limited** explores retrofitting and refurbishment as practical alternatives to full replacement. It reviews current literature and presents a detailed case study of a 65-year-old transformer to highlight real-world challenges and proposes actionable strategies including standardised transformer designs, shared spare part reserves, and stronger collaboration between utilities and government agencies.

Negative Tan Delta of a Power Transformer – Phenomenon, Causes, and Diagnostic Considerations 57

This paper by **Ghanshyam Lalwani, AGM (TRE-Power Transformer), BHEL Jhansi,** examines the phenomenon of negative tan delta in power transformers, its physical meaning, measurement principles, possible causes, and diagnostic significance. Practical case observations and recommendations for interpreting such results are presented, with the objective of preventing misdiagnosis of healthy equipment and ensuring effective insulation monitoring.

Condition Assessment Techniques of OIP & RIP Transformer Bushings 68

Gautam Nikam and **Pramod Rao** of **Yash Highvoltage** review and describe various health monitoring and condition assessment techniques adopted by various users and recommend sequence of tests and evaluation methods.

IEEMA EVENTS

ELROMA 2026 75

The 11th edition of ELROMA 2026 – the international conference on electrical rotating machines, drives, and applications – focused on 'Powering Sustainable Industry with Energy Efficient Rotating Machines'.

IEEMA ACTIVITIES

Winning the Decade: IEEMA's Strategic Meet 81

Workshop on 'AI & Generative AI for Electrical Manufacturing Excellence' 82

Training Programme on '5S – The First Step to Building a World-Class Organisation' 84

POLICY UPDATES 86

- India and Oman energise new trade gateway through Comprehensive Economic Partnership Agreement.
- Consultative Committee meeting held for Ministry of Power.
- MNRE launches scheme guidelines for accelerating small hydro power development.
- Guidelines for quantifying GHG emissions from offsite water drawl and treatment.
- 75 lakh households targeted for rooftop solar installations by December 2026.
- 14th meeting of India-Philippines Joint Working Group on Trade and Investment held in Manila.
- General implementation timelines for ISTS projects.
- Commerce Secretary urges enhanced trade, investment and business engagement at India-Tajikistan Joint Commission meeting.

NEWS

NATIONAL 88

- POWERGRID receives LoI for WR-ER inter-regional network expansion project.
- NHPC partners with Arunachal Pradesh Government for 3,097 MW Etalin hydropower project.
- SECI, Mahagenco REL partner to develop RE projects.
- Centre approves Rs1.27 billion for EV charging infra in Delhi.
- POWERGRID approves SCADA upgrade and JPY 80 billion loan facility.
- Arunachal Pradesh signs agreement with Greenko Demwe for 1,750 MW hydroelectric project.

INTERNATIONAL 89

- India, UK launch critical minerals global supply chain observatory.
- Meta and CleanMax partner for over 900 MW of RE capacity in India.
- Singapore, ADB renew MoU to support ASEAN power grid projects.

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Prevention of Sudden Explosive Failures: Condition Assessment Techniques of OIP & RIP Transformer Bushings

In this paper, **Gautam Nikam and Pramod Rao** of **Yash Highvoltage** review and describe various health monitoring and condition assessment techniques adopted by various users and recommend sequence of tests and evaluation methods.

Transformer bushings are most important and critical components of transformers, and hence, are expected to be highly reliable products. In the event of transformer bushings failure, it usually results in explosive and catastrophic failure of transformers. The effect is downtime of several months of a transformer or reactor accompanied by financial losses, as against the urgency to restore the system at the earliest.

Most bushings in service (for past many years) are bushings with oil impregnated paper (OIP) insulation system. India has commenced largely using resin impregnated paper (RIP) bushings, with a few installations of resin impregnated synthetics

(RIS) bushings in Indian grids. OIP bushings are well established up to 800 kV, RIP bushings are now in use up to 420 kV, and RIS bushings are reported to be available up to 245 kV.

In view of various insulation technologies in use, it is essential to understand technical aspects of insulation degradation mechanism and their effects on the service behaviour of bushings. It mainly aims to take preventive actions to avoid bushing failure, and thus, prevent transformer or reactor failure.

This paper reviews the various health monitoring and condition assessment techniques adopted by various users. It also recommends the sequence of tests and evaluation methods based on experiences of the authors. Since the tests and measurements are carried out at site, the paper describes the precautions to be taken to prevent wrong interpretation and wrong conclusions. The paper focuses on the condition monitoring techniques for OIP and RIP bushings.

1. Insulation Systems Used in Bushings

Synthetic resin bonded paper (SRBP): The first use of condenser type SRBP bushings was reported in 1913. RBP bushings are no longer manufactured and have been replaced at many sites because of major failures due to partial discharges. Thus, it can be referred to as obsolete technology. However, there could be some SRBP bushings in service on old transformers.

OIP: Its use has been reported for the past ~100 years. Its manufacturing technology has now well established for the past 70 years with up to 800 kV rating. Most bushings (more than 50 percent) are still in service.

RIP: Contains solid insulation system as they are free of insulating oil. The bulk usage of RIP bushings is reported from about 1970. In India, the bulk use of RIP bushings commenced in about 2011.

RIS: This is a truly paperless bushing and is a latest development. It is reported to have been in satisfactory service for about 12 years. In India, the initial installation of RIS bushings is reported to have undergone a successful service period of about seven years.

2. Dielectric Construction of OIP RIP Bushings

OIP bushings: Insulating Kraft paper layers are tightly wound on the central pipe / central rod and at designed diameters, condenser grading aluminium foils are inserted at pre-decided locations. The tight and compact winding is achieved by winding the condenser core on a machine. Insulating Kraft paper thickness used is in the range 0.075 mm to 0.125 mm and the grammage used typically in the range of 60 GSM to 80 GSM. The grade and quality of insulating paper used decides the dielectric constant and hence the capacitance value. Removal of moisture from condenser core is carried out in autoclaves at a temperature ~100 °C and finer vacuums (finer than 0.05 mbar). After the drying is completed, the condenser core is impregnated by use of well dried and degassed mineral insulating oil. Usually, uninhibited mineral oil is used.

RIP bushings: Insulating crepe paper layers are wound on central pipe / central rod, and at designed diameters, condenser grading aluminium foils are inserted at pre-decided locations. The optimum winding tightness is ensured to facilitate impregnation by resin mix and also to ensure the condenser grading foils stay in position during handling and during the process of drying and impregnation, specially coated aluminium foils are used.

3. Bushing Failure Modes and Mechanisms

OIP bushing failure

There are three failure mechanisms identified with OIP bushings: Insulation failure; thermal failure; and mechanical failure.

Mechanical failure results in breakage of porcelain insulators and can be caused by seismic events or rigid connection on air end terminal causing unusual force being exerted due to sudden temperature changes. Thermal failures are usually caused by heat generation due to poor contact between air end terminal of bushings and the terminal connector. Thermal failure can also be caused by gas bubble generation due to sudden change of temperature. These gas bubbles will result in partial discharge (PD) and ultimately failure of bushings.

Insulation failure in OIP bushings is because of moisture ingress or degradation of OIP insulation or poor earthing of test tap of bushing or insulation oil ageing or flashover across air end insulator or flashover around oil end electrode of the bushing. Almost all failure modes of insulation are detected by Capacitance and Tan Delta measurements and some of the failure modes are detected by evaluation of oil sample from bushings.

RIP bushing failure

In RIP bushings also, thermal failure and mechanical failure mechanisms exist. The probability of mechanical failure causing severe damage or bushing failure is remote as in RIP bushings, as composite or polymer insulators are used in RIP bushings. The mode of insulation failure starts with PD over a small surface inside the condenser core; it ultimately results in creating conducting path and it bridges two or more capacitor segments. Other capacitor segments are stressed more and there could be PD generation in other capacitor segments, creating conducting path and bridging two or more capacitor segments. Bridging capacitor segments will result in increase in capacitance, and hence, such incidents can be detected by measurement of Capacitance and Tan Delta.

Detectability of different bushing failure defects by measurements on bushings is summarised in the table given below.

Defect	Capacitance	Tan Delta	PD
Insulation ageing	–	Yes	Yes
Moisture ingress	–	Yes	--
Contamination on surface	–	Yes	Yes
Shorting of capacitor segments	Yes	Yes	Yes
Test tap earthing or internal test tap contact issue	Yes	Yes	Yes

As seen in the table, Capacitance and Tan Delta measurements detect most defects. PD detection on bushings at site (whether online or offline) is not widespread, as there are concerns with PD detection capabilities and there are difficulties in PD interpretation. It is difficult to perform accurate PD measurements at sites in view of the high level of noise prevailing at sites. Thus, the main focus is still on Capacitance and Tan Delta measurements.

4. Capacitance and Tan Delta

Capacitance change

It is to be noted that an increase in capacitance with failure of one Capacitance segment depends on the number of foils, ie, the number of capacitor segments in the condenser core of bushing. In OIP bushings, a relatively higher number of foils are used when compared with RIP bushings. For example, typically, in 145 kV OIP bushings, 31 aluminium foils are used for condenser grading, whereas in 145 kV RIP bushings about 15 aluminium foils are used. With a Capacitance value of 300 pF, failure of one capacitor segment causes increase in Capacitance to 310 pF (300 x 31/30) in OIP bushings and increase in Capacitance to 332 pF (300 x 15/14) in RIP bushings. Thus, change in Capacitance due to failure of one Capacitance segment in RIP bushings is higher than that in OIP bushings.

As the kilovolt class keeps on increasing, the number of aluminium foils used for condenser grading also keeps on increasing. Thus, higher the kilovolt class, lower the change in Capacitance due to failure of one segment. Accurate data on number of foils should be asked for from the bushing manufacturer. When such data is not readily available, the limits of permissible change in Capacitance must be followed, as given in the table below (Refer CIGRE TB 755).

kV Class	OIP Capacitance Change (%)	RIP Capacitance Change (%)
72.5 kV	8.8%	12.0%
145 kV	4.8%	7.1%
245 kV	2.7%	4.2%
420 kV	1.7%	2.6%

It is found during measurements at site that the Capacitance values are lesser than factory test results (mentioned on bushing rating plate) by about 2 percent. Hence, the reference Capacitance value for future monitoring should always be based on values measured at the pre-commissioning stage.

Capacitance varies linearly with temperature and is mainly decided by variation of composite dielectric constant variation with temperature. The typical temperature coefficients of Capacitance of OIP, RIP, and RIS are 0.025 percent per degree Celsius for OIP and 0.04 percent per degree Celsius for RIP. If we consider, a bushing has a Capacitance value of 300 pF at 20 degrees Celsius, and if we estimate Capacitance at 50 degrees Celsius based on above temperature coefficients, in case of OIP bushings, the capacitance will be 302.3 pF; for RIP bushings, it will be 303.6 pF. Thus, during site measurements, we need to consider the temperature of insulation at the time of Capacitance measurement and change in capacitance caused by puncture of one foil segment and then decide health and status of bushing. When Capacitance is measured immediately after shutdown, CIGRE TB 755 has given a method of estimating average temperature of bushing,

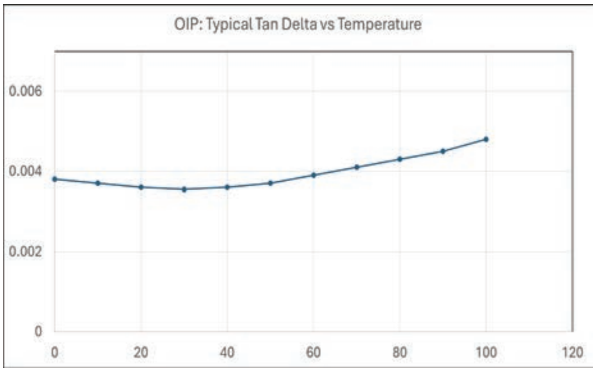
$$T(avg) = \frac{[T(f) \times H(oil)] + [0.5 \times H(air) \times \{T(f)+T(h)\}]}{H(oil) + H(air)}$$

- T(f): Temperature of mounting flange
- T(h): Temperature of head portion
- H(oil): Length of oil end of bushing
- H(air): Length of air end of bushing
- T(avg): Average bushing temperature.

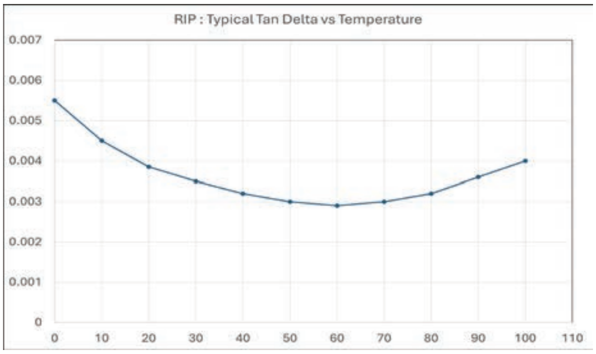
To summarise, it is necessary to measure Capacitance value at pre-commissioning stage and convert it to a standard reference temperature of 20 degree Celsius by using temperature coefficient of Capacitance for the relevant insulation system. During service, if it is necessary to measure Capacitance immediately after shutdown, measure temperatures of mounting flange, head portion; calculate the average temperature and convert Capacitance value to 20 degree Celsius. For evaluating health and condition of the bushing, the permissible change in Capacitance should be used, as recommended by the bushing manufacturer. As an alternate, the limits shared in the table above can be used.

Tan Delta change

The Air to Oil type bushings are mounted on the transformer tank and oil end part is immersed in hot oil inside the transformer, and thus, based on the transformer load conditions, the bushings in service are continuously exposed to temperatures of 60 degree Celsius to 90 degree Celsius 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 and RIP bushings and assess its performance at test bed and during service. Typical Tan Delta vs temperature characteristics of OIP bushings is shown in the graph below. As seen, there is a variation in Tan Delta when the temperature is increasing.



In case of RIP bushings, in view of the inherent resin material characteristics, higher Tan Delta variation (when compared with OIP) is observed with respect to temperature.



As seen from the above graph, Tan Delta varies with respect to temperature, and thus, for health or condition assessment, it is essential to convert the Tan Delta value to 20 degree Celsius as a standard reference temperature. It is essential that users seek the data of Tan Delta vs temperature (ie correction factor) from the bushing manufacturer and use it as a guidance for correcting Tan Delta measured at site temperature to Tan Delta at 20 degree Celsius. As mentioned in the above paragraphs, always consider the pre-commissioning value as a reference value for future monitoring. Assessment of insulation health based on change in Tan Delta is best defined in CIGRE TB 755. Refer to the table below.

Relative Change in Tan Delta (OIP)	Condition of Bushing
Up to 1.33	Good
1.34 to 1.66	Moderate
1.67 to 2.00	Severe
>2.00	Extreme

The pre-commissioning Tan Delta value is to be considered as 1.00 in above evaluation. The condition-based guidance is given below.

- Good: Good condition. All assessments at regular intervals.
- Moderate: Moderate change. Perform visual inspection, take additional measurement within a year. Continuous monitoring is suggested.
- Severe: Severe change. Perform visual inspection, take additional measurement within a month. Continuous monitoring is suggested. Consider removal from service.
- Extreme: Extreme change. Remove from service, or service may be prolonged for a short period (ie, a month) with continuous monitoring applied.

As seen above, it is best to monitor health of the bushing based on relative change, rather than absolute value. As an example, if Tan Delta measured at pre-commissioning is 0.0024 and when the relative change in Tan Delta is >2, ie, Tan Delta value is >0.0048, the condition should be assessed as extreme and immediate action taken. Some users wrongly consider 0.007 as a limit for taking remedial action.

It is also well known based on experience that, in case of RIP bushings, mainly capacitance monitoring is effective and Tan Delta based monitoring is usually not carried out as there is insignificant change in Tan Delta during service.

5. Dielectric Frequency Response (DFR)

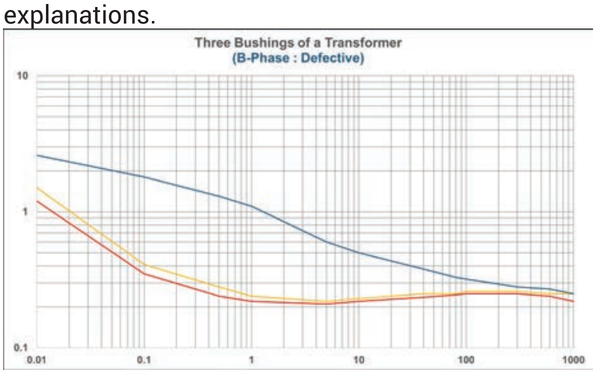
The Capacitance and Tan Delta measurements mentioned in section-4 refer to offline measurements carried out at rated frequency 50 Hz. Capacitance and Tan Delta measurements at 50 Hz need to be converted to a standard reference of 20 degree Celsius and the analysis depends on the relative increase of values and is judgmental. In OIP bushings, it is well known that moisture ingress is one of the major causes of bushing failure. The Tan Delta measurements at 50 Hz are found to be about the same value even if the moisture content is 0.5 percent or 2 percent. It is also revealed by technical papers and literature that moisture content in the OIP insulation can be revealed by measurements at Tan Delta at lower frequencies such as 1 Hz and few megahertz. The measurement of DFR (ie, measurement of Tan Delta at various frequencies) has become more popular as an effective health assessment tool. There are two types of DFR measurements, namely, narrow band (NB) DFR and wide band (WB) DFR. In NB DFR, measurements are carried out between 10 Hz and 400 Hz, and in WB DFR, measurements are carried out between 10 mHz and 1 kHz. The DFR measuring equipment also has a capability of converting all measured Tan Delta value to 20 degrees Celsius as a reference temperature. The moisture ingress in RIP bushings due to improper storage can also be effectively determined by NB DFR measurements. Aging or overheating, insulation contamination such as X-wax or tracking paths, and shorted Capacitance segments, result in increased oil Tan Delta (ie, oil conductivity) and which is detected by state-of-the-art DFR equipment. Indicative limits of Tan Delta have been given in CIGRE TB and are shared below.

Frequency	OIP Bushings		RIP Bushings	
	New	Aged	New	Aged
15 Hz	<0.5%	<0.7%	<0.6%	<0.7%
50 Hz	<0.4%	<0.5%	<0.5%	<0.5%
400 Hz	<0.5%	<0.7%	<0.6%	<0.7%

Experience is being gained by site engineers and data is also being generated. One such data-based information is that in RIP bushings, due to intrinsic properties of epoxy resin, the Tan Delta of new and healthy RIP bushings could be around 0.7 percent. In ISH-2021, Dr. Robalino and others proposed Tan Delta limits at 1 Hz for OIP bushings, which are reproduced below.

Condition	1 Hz Tan Delta at 20 degrees Celsius
As New	0.2 to 0.4%
Good	0.4 to 0.75%
Aged	0.75 to 1.25%
Investigate	>1.25%

In 2022, IEEE C57.12.200 (Guide for the Dielectric Frequency Response Measurement of bushings) has been published, which explains in detail the basics of use of DFR and case studies-based explanations.



Recently, experts have published a three-step approach for monitoring bushings, which is summarised below:

Step-1: 50 Hz Capacitance and Tan Delta testing

- Absolute Tan Delta limits, eg, double of pre-commissioning value.
- Tan Delta and its temperature dependence.
- Capacitance increase – puncture of capacitor segments.

Step-2: NB DFR

- 1 Hz and 10 Hz Tan Delta values indicative of moisture contamination.

Step-3: WB DFR. Tan Delta up to 0.01 Hz

- Percentage moisture content (or contamination content):
    - As New: 0.15% to 0.5% + good in service: 0.5% to 1.0%.
    - Average in service: 1.0% to 2.5% + investigate: >2.5%.
- Oil conductivity (pS/m):
    - As New: 0.001 to 0.37 + good in service: 0.37 to 3.7 + average in service: 3.7 to 37 + investigate: >37.

6. Dissolved Gas Analysis (DGA) of Oil Sample from OIP Bushings

Since the oil volume in bushing is relatively small, there are limitations on the tests which can be carried out on oil sample from bushing. Due to the critical sampling procedure, it is recommended to limit the oil sample volume. Thus, DGA of oil sample is the most preferred evaluation method, in view of low quantity of sample. It is recommended to carry out DGA of oil sample, when it is concluded that relative change in Tan Delta is more than 1.67 and Tan Delta at 1 Hz is more than 1.25 percent. The DGA results confirm action to be taken on OIP bushings. Given below are the typical limits of gas content (ppm) for new bushings and limiting values (ppm) for bushings in service:

Gas	Typical Limits for New Bushing	Limiting Values in Service
H2	<20 ppm	>140 ppm
CH4	<5 ppm	>40 ppm
C2H2	<2 ppm	>2 ppm
C2H4	<5 ppm	>30 ppm
C2H6	<5 ppm	>70 ppm
CO	<150 ppm	>1000 ppm
CO2	<300 ppm	>3400 ppm

Based on experience with similar rated bushings from same bushing manufacturer, users arrive at different limits for DGA when compared to above referred values.

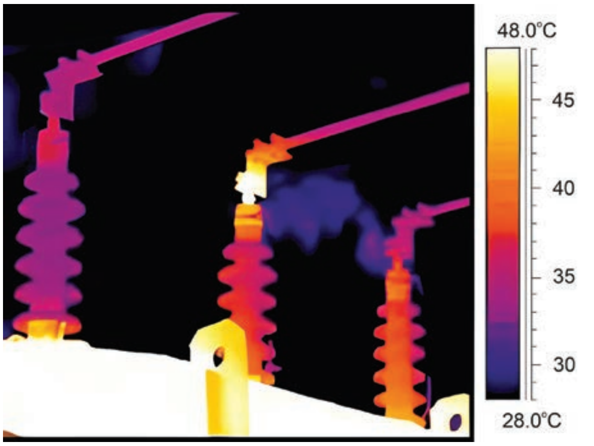
7. Thermography/Infrared Scanning

All bushings (OIP/RIP) confirming to dimensions as per IS12676 are provided with air end HV terminal of copper material, whereas the connection from transmission line or bus is made of aluminium alloy. Thus, bimetallic strip or sleeve is necessary to be used. If not used, it will result into bimetallic corrosion and reduction in contact area causing overheating.

In case adequate flexibility is not provided between rigid aluminium bus and HV terminal of bushing at higher ambient temperature or during carrying higher current, this will result in excessive force on HV terminal, causing loosening of terminal connector clamping on HV terminal, which will result in overheating.

The overheating at HV terminal needs to be detected and prevented from exceeding the thermal limits of OIP insulation (105 degrees Celsius) or RIP insulation (120 degrees Celsius). Thermography or IR scanning method is used for assessing temperature (overheating) of the HV terminal to terminal connector joints. Temperature difference is assessed between similar bushings and comparable bushings. Technical literatures have provided guidance as under, based on temperature difference.

Temperature Difference	Assessed Condition
<5 degrees Celsius	Normal condition
>5 degrees Celsius to <10 degrees Celsius	Caution-check and repair in next scheduled maintenance
>10 degrees Celsius to <35 degrees Celsius	Caution-prepone maintenance schedule for repairs
>35 degrees Celsius	Emergency – immediately remove from service for repairs



8. Online Monitoring System

Online condition monitoring systems are now being connected to test tap stem of bushings. Thus, the test tap stem of bushings is connected to earth through the components of online condition monitoring system. Hence, the following precautions need to be taken while configuring online condition monitoring system with test tap of bushings:

- Normally the bushings are provided with a test tap cap, which makes contact of test tap stem with mounting flange of bushing, ultimately connected to Earth.
- When online monitoring devices are to be connected to bushings, test tap cap is removed, and a test tap adopter is screwed on and fixed in place of test tap cap.
- For use of online monitoring system on bushings, a detailed drawing of the test tap adopter – a part of the online monitoring system – is to be shared with the bushing manufacturer for review and to ensure its suitability and compatibility.
- Test tap adopter must establish solid and firm contact with the test tap stem of the bushing to maintain connection to Earth through the components of the online monitoring system. The contact springs to ensure contact is adequate to carry impulse surge currents from test tap stem to earth.
- Test tap adopter should provide weatherproof sealing against the mounting flange while maintaining firm contact with the test tap stem.
- Adequate protection must be a part of either the test tap adopter, online monitoring device, or both, to safeguard the bushing from surge voltages on its test tap. Additionally, proper protection should be in place to prevent open circuiting of the test tap stem connection to earth.

9. Summary

At the start, we have described the insulation systems used in transformer bushings. A large

population of OIP bushings are still in service, and in India, RIP bushings are gaining popularity as they prevent explosive or catastrophic failures of bushings, and consequently, the catastrophic failure of transformers. The dielectric construction of OIP and RIP bushings is also briefly described.

The difference between bushings failure modes of OIP and RIP bushings is also described and how offline Capacitance and Tan Delta measurements detect the insulation degradation is detailed. Temperature dependence of Capacitance and Tan Delta has been discussed and explained in detail is the importance of correcting the Capacitance and Tan Delta to a reference temperature of 20 degrees Celsius. Reference values of percentage change in Capacitance due to one segment failure has been explained. Similarly, the relative change in Tan Delta with respect to pre-commissioning value and thereby detecting the condition of insulation is explained in detail.

DFR and its usage have been explained, and the indicative and proposed limits at 1 Hz have also been shared. DGA analysis limits for new and in-service bushings are explained.

Importance and popularity of regular use of thermography or infrared scanning is detailed and how to use the temperature difference between similar bushings is explained in above paragraphs.

Online monitoring systems are now being frequently installed, by connecting them to test tap of bushings. Precautions needed while configuring online monitoring systems with bushings are explained.

It is possible to prevent catastrophic or explosive failure of transformer bushings when the right data-based analysis is carried out, of Capacitance, Tan Delta measurements at rated frequency. The NB and WB DFR measurements should be adopted to further refine the judgement on dielectric health of bushings. DGA analysis of oil sample from OIP bushings should be used as a final confirmation of deteriorated health of OIP bushing, as indicated by DFR and rated frequency Capacitance and Tan Delta measurements.

10. References

[1] CIGRE: Doc No. 755 (2019) by Working Group A2.43 – Transformer Bushings Reliability.

[2] CIGRE: Doc No. 445 (2011) & Doc No. 642 (2015) by Working Group A2.37 – Transformer Maintenance & Transformer Reliability Survey.

[3] CIGRE: Doc No. 761 (2019) – Condition Assessment of Power Transformers.

[4] EIC-2025: Condition Assessment of Bushings using DFR by Dr. Peter Werelius (Megger), Lars Jonsson (Hitachi) and team.

[5] ISH-2021: Paper 1054 - Novel Approach for Insulation Condition Assessment of High Voltage Substation Equipment at 1 Hz by Dr. Diego Robalino & team (Megger)

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