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TRANSFORMER RELIABILITY
THROUGH MOISTURE CONTROL

MOISTURE-RELATED DIAGNOSTICS & INTERPRETATION

IN POWER TRANSFORMERS

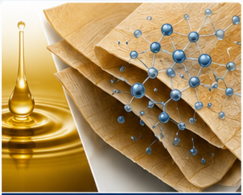
MEASUREMENT. ASSESSMENT.
INTERPRETATION. ACTION.
FOR LONG-TERM RELIABILITY.

UNDERSTAND MOISTURE
The primary driver of insulation aging and failure risk.

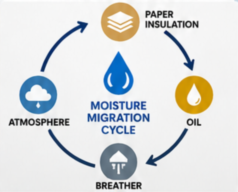
MEASURE ACCURATELY
Using internationally accepted methods and advanced tools.

INTERPRET INTELLIGENTLY
Convert data into meaningful insights and risk assessment.

TAKE THE RIGHT ACTION
Implement moisture management for reliable, longer asset life.



MOISTURE IN OIL & PAPER
Continuous equilibrium and migration



DYNAMIC BY NATURE
Affected by temperature, load and environment

DATA TO DECISIONS
Integrated diagnostics for better asset health decisions

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WHY MOISTURE MATTERS

Moisture is one of the most influential factors affecting the performance, reliability and life of power transformers.

Typically **95–99%** of the total moisture mass in an aged transformer insulation system resides within cellulose insulation (paper and pressboard), while only a small fraction is dissolved in the oil.

HOW MOISTURE AFFECTS TRANSFORMER INSULATION

ACCELERATES CELLULOSE AGING
Moisture promotes hydrolysis, reducing the degree of polymerization (DP) of cellulose and waakening mechanical strength.

REDUCES DIELECTRIC STRENGTH
Higher moisture content lowers breakdown voltage and increases the risk of dielectric failure.

INCREASES DIELECTRIC LOSSES
Moisture increases the dissipation factor (tan δ), leading to overheating and reduced efficiency.

PROMOTES BUBBLE FORMATION
Under high temperature and load, moisture causes bubble generation which can lead to partial discharges and insulation damage.

ENHANCES CHEMICAL DETERIORATION
Moisture accelerates oxidation and the formation of acids and sludge, degrading oil and paper insulation.

INCREASES FAILURE RISK
The combined effect of moisture, temperature and aging significantly increases the probability of faults, outages and catastrophic failure.

KEY ENGINEERING FACT

Moisture not only accelerates insulation aging but also reduces dielectric strength, increases dielectric losses, promotes bubble formation under overload conditions, and increases the probability of premature transformer failure.

References:
IEC 60422:2024 | IEEE C57.91:2011 | CIGRÉ TB 349:2008

THE MOISTURE → AGING → FAILURE CHAIN

1. **MOISTURE** — Enters through breather, leaks or handling.
2. **CELLULOSE HYDROLYSIS** — Moisture reacts with cellulose, breaking chemical bonds.
3. **REDUCTION IN DP** — Degree of Polymerization (DP) decreases, insulation weakens.
4. **LOSS OF MECHANICAL STRENGTH** — Paper and pressboard become brittle and less resilient.
4. **REDUCED DIELECTRIC MARGIN** — Lower breakdown voltage and higher dielectric losses.
6. **INCREASED FAILURE RISK** — Higher probability of faults, outages and asset failure.

Moisture is a silent degrader. It cannot be seen, but it can be measured, interpreted and managed.
Early detection and effective moisture management are the keys to long-term transformer reliability.

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WHERE IS THE MOISTURE?

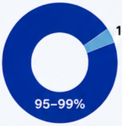
OIL vs PAPER INSULATION

Moisture is not uniformly distributed in a transformer. Understanding its location and behavior is essential for accurate assessment and effective management.

KEY TAKEAWAY

More than 95–99% of the total moisture mass in an aged transformer insulation system resides in the cellulose insulation (paper and pressboard), while only a small fraction is dissolved in the oil.

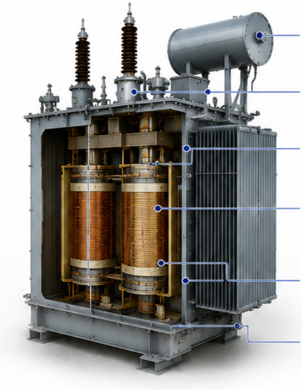
TYPICAL MOISTURE DISTRIBUTION IN AN AGED TRANSFORMER



Moisture Location	Typical Share
Cellulose Insulation (Paper & Pressboard)	95–99%
Oil (dissolved water)	1–5%
Other (gaps, interfaces, etc.)	< 1%

Values are typical for aged transformers in normal service conditions. Distribution varies with temperature, load, and history.

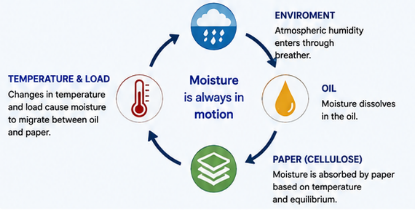
TYPICAL MOISTURE LOCATIONS INSIDE A TRANSFORMER



WHY DOES PAPER HOLD MOST MOISTURE?

- Cellulose is hygroscopic in nature and has high affinity for water molecules.
- Fiber structure provides vast internal surface area for moisture adsorption.
- Moisture migrates from oil to paper at lower temperatures and returns to oil at higher temperatures.
- Oil can hold only limited moisture based on temperature and its saturation capacity.
- Over time, moisture accumulates in paper and drives aging and loss of life.

MOISTURE MIGRATION – A CONTINUOUS CYCLE



IMPORTANT

Oil moisture measurement is only an indication — it does not represent the total moisture in the insulation system. A complete assessment requires understanding the equilibrium between oil, paper and ambient conditions.

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THE MOISTURE MIGRATION CYCLE

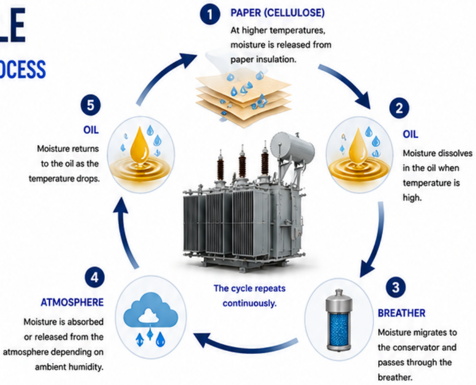
A CONTINUOUS & DYNAMIC PROCESS

Moisture is not static inside a transformer. It continuously moves between paper insulation, oil, and atmosphere based on temperature, humidity, and load conditions.

KEY MESSAGE

Moisture will always find equilibrium. The goal is to control the cycle and keep the insulation system as dry as possible.

THE MOISTURE MIGRATION CYCLE



FACTORS INFLUENCING MOISTURE MIGRATION

TEMPERATURE
Higher temperature drives moisture out of paper and into the oil.

RELATIVE HUMIDITY
High humidity increases moisture absorption through the breather.

LOAD
Higher load increases temperature and accelerates moisture movement.

SEASONAL CHANGES
Moisture levels typically rise in humid seasons and fall in dry seasons.

BREATHER CONDITION
Poor or saturated breather allows moisture ingress into the oil.

TYPICAL DAY / NIGHT MOISTURE MOVEMENT

DAY (HIGH TEMPERATURE)

PAPER — Moisture moves from paper to oil → OIL

- Temperature rises
- Paper releases moisture
- Oil moisture increases
- Moisture migrates to conservator
- Breather releases moisture to atmosphere

NIGHT (LOW TEMPERATURE)

PAPER — Moisture moves from oil to paper → OIL

- Temperature drops
- Oil holds less moisture
- Moisture returns to paper
- Paper moisture increases
- Cycle continues

WHAT THIS MEANS

- Moisture is never constant.
- Single measurements can be misleading.
- Trends over time tell the real story.
- Moisture control must address the full cycle.

ENGINEERING IMPLICATIONS

MONITOR TRENDS, NOT JUST VALUES
Track moisture (ppm, %RS, paper moisture) over time to understand real behavior.

TEST ACROSS SEASONS
Test in different climatic conditions to capture the full migration behavior.

CORRELATE WITH TEMPERATURE & LOAD
Always interpret moisture data with temperature and loading information.

MAINTAIN BREATHERS & SEALS
Ensure breathers are effective and gaskets, seals are leak-free.

CONTROL THE CYCLE NOT JUST THE OIL
Effective moisture management targets the entire insulation system.

IMPORTANT NOTE: If the moisture migration cycle is not controlled, the paper will remain high in moisture for longer periods, accelerating aging, reducing dielectric strength and increasing the risk of failure.

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MOISTURE DIAGNOSTIC TOOLS & METHODS

MEASURING WHAT MATTERS. UNDERSTANDING WHAT IT MEANS.

A combination of complementary diagnostic tools is required to accurately assess moisture, insulation condition and aging in power transformers.

No single test gives the complete picture.
A multi-parameter approach delivers the most reliable assessment of moisture and insulation health.

KEY DIAGNOSTIC TOOLS – WHAT THEY MEASURE

TOOL / METHOD	MEASURES	TYPE	DIRECT PAPER ASSESSMENT	ONLINE CAPABLE
Karl Fischer (KF) Titration (IEC 60814)	Moisture in Oil (ppm)	Chemical	✗	✗
Online Moisture Sensor	Moisture in Oil (ppm)	Electrical / Capacitive	✗	✓
Water Activity Sensor	Water Activity (aw) / %RS	Electrical / Capacitive	✗	✓
FDS (Frequency Domain Spectroscopy)	Paper Moisture (%)	Dielectric Response	✓	✗
PDC (Polarization / Depolarization Current)	Paper Moisture (%)	Dielectric Response	✓	✗
Furan (2-FAL) (IEC 61198)	Cellulose Aging Indicator	Chemical	✓	✗
Methanol (IEC 62953)	Early Cellulose Degradation	Chemical	✓	✗
DGA (IEC 60567)	Dissolved / Free Fault Gases	Gas Analysis	✗	✓*
CO / CO_2 (IEC 60599)	Cellulose Degradation Products	Gas Analysis	✗	✓*

** Online capability depends on the type of online monitoring system installed.*

DIAGNOSTIC PYRAMID – FROM BASIC TO ADVANCED

COMPREHENSIVE ASSESSMENT
- Predict remaining life & risk (FDS/PDC, Furans, DGA, CO/CO_2)

AGING & CHEMISTRY
- Understand aging rate (Furans, Methanol, Acidity, IFT)

ELECTRICAL PERFORMANCE
- Evaluate dielectric condition (BDV, tan δ, Resistivity)

MOISTURE STATUS
- Assess moisture level & risk (%RS, aw, Ppm)

BASIC MOISTURE MEASUREMENT
- Measure moisture in oil (Karl Fischer)

Move up the pyramid for deeper insight.
Each level builds confidence in decision making and risk management.

STRENGTHS & LIMITATIONS

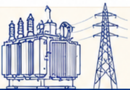
STRENGTHS
- Multiple tools provide a complete view
- Trends reveal the real condition
- Advanced tools assess paper moisture directly (FDS/PDC)
- Enables accurate risk assessment
- Supports proactive maintenance

LIMITATIONS
- Single tests can be misleading
- Oil moisture ≠ Paper moisture
- Temperature strongly influences moisture readings
- Some tests require offline sampling
- Advanced tests require expertise

SELECT THE RIGHT COMBINATION

Combination	Best for
Oil Moisture (ppm) + %RS + BDV + DGA	Routine monitoring & condition tracking
Furans + Methanol + Acidity + IFT + DGA	Aging assessment
FDS / PDC + Oil Moisture + %RS + Aging Markers	Detailed insulation assessment
All Parameters Integrated + Trend Analysis	Critical assets & risk-based decision making

> “The right tools, used together and interpreted correctly, turn data into **actionable insights** and **extend transformer life.**



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MOISTURE-RELATED DIAGNOSTICS & INTERPRETATION IN POWER TRANSFORMERS

RELATIVE SATURATION (%RS) vs OIL MOISTURE (ppm)

WHY CONTEXT MATTERS

Oil moisture in ppm depends on temperature. Relative Saturation (%RS) shows how close the oil is to holding maximum moisture at that temperature. %RS is often a more meaningful indicator of the insulation system's moisture condition.

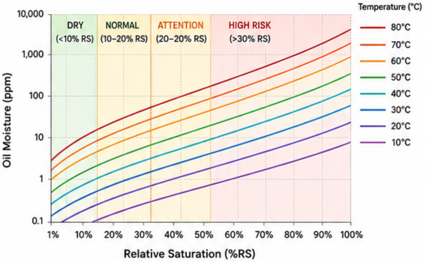
KEY MESSAGE

The same ppm value can mean the oil is very dry at low temperature, but very wet at high temperature.

Always interpret oil moisture with temperature using %RS.

OIL MOISTURE (ppm) vs RELATIVE SATURATION (%RS)

Relationship between oil moisture (ppm) and %RS at different temperatures (based on IEC 60814 & CIGRÉ TB 349 typical equilibrium data) for mineral oil.



Example: 20 ppm at 20°C ≈ 6% RS (Dry) 20 ppm at 60°C ≈ 32% RS (High Risk)

INTERPRETING %RS – GENERAL GUIDELINES (Mineral Oil)

%RS Range	Moisture Condition	Typical Interpretation	Action
< 10%	Dry	• Insulation system is dry • Good moisture margin	Continue monitoring
10 – 20%	Normal	• Acceptable for most transformers in service • Continue trending	Monitor trend
20 – 30%	Attention	• Moisture level increasing • Paper moisture likely elevated • Risk of accelerated aging	Investigate & manage
> 30%	High Risk	• Insulation is wet • High risk of cellulose aging, PD, and dielectric issues	Take corrective action

Note: *Limits are guidance values. Critical assets, high temperature, poor oil condition, or high ambient humidity may require lower thresholds.*

WHY %RS IS OFTEN BETTER THAN PPM

Accounts for temperature
Oil holds more moisture at higher temperatures.

Reflects proximity to saturation
Shows how close the oil is to its maximum moisture holding capacity.

Better indicator of paper moisture
High %RS usually means high paper moisture.

Improved risk assessment
More reliable for trend analysis and decision making.

FACTORS THAT INFLUENCE %RS AND PAPER MOISTURE

TEMPERATURE
Higher temperature increases oil moisture capacity and drives moisture from paper to oil.

RELATIVE HUMIDITY
High ambient humidity increases moisture ingress through the breather.

LOAD
Higher load increases temperature and accelerates moisture migration.

SEASONAL EFFECT
Day/night and seasonal variations cause continuous moisture cycling.

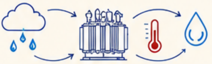
BREATHER CONDITION
Saturated or blocked breathers increase moisture ingress.

BEST PRACTICES

- Always measure oil moisture with temperature.
- Calculate %RS for every measurement.
- Track trends over time, not just single values.
- Correlate %RS with load, temperature and paper moisture estimation.
- Address moisture ingress and control the moisture migration cycle.
- Use %RS along with other diagnostics (BDV, DGA, Furan, Methanol, Acidity) for complete assessment.

In transformer insulation systems, context is everything.

Measure smart. Interpret right. Manage moisture proactively.



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MOISTURE-RELATED DIAGNOSTICS & INTERPRETATION IN POWER TRANSFORMERS

ESTIMATING PAPER MOISTURE FROM OIL MEASUREMENTS

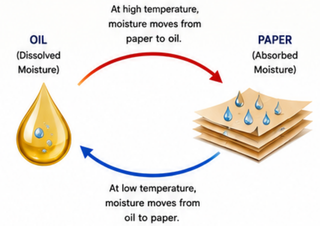
WHY PAPER MOISTURE IS THE REAL DRIVER

More than 95–99% of the total moisture in an aged transformer insulation system is in the solid cellulose (paper/pressboard). Oil and paper are in equilibrium: moisture migrates between them based on temperature and humidity.

KEY MESSAGE

Oil moisture tells part of the story. Estimated paper moisture tells the truth about insulation aging and risk.

OIL–PAPER EQUILIBRIUM RELATIONSHIP



Moisture equilibrium depends on temperature, oil type, cellulose type, aging and history.

METHODS TO ESTIMATE PAPER MOISTURE

Method	Input Parameters	Description	Typical Use
Equilibrium Charts (IEC 60422)	Oil moisture (ppm) Temperature (°C) Cellulose type (mineral oil)	Use equilibrium charts or equations to estimate paper moisture at operating temperature.	Routine assessment
Oommen Equation	Oil moisture (ppm) Temperature (°C)	Empirical equation widely used in industry.	Quick estimation
Koch Equation	Oil moisture (ppm) Temperature (°C)	More accurate for higher temperature range.	Better accuracy
Advanced Models	Oil moisture (ppm) Temperature (°C) Oil type, DP, history	Software-based models (CIGRÉ, lab tools) using multi-parameter correlation.	Detailed analysis

Note: Results are estimates. Use trends and multiple diagnostics for final decision making.

INTERPRETING ESTIMATED PAPER MOISTURE

Estimated Paper Moisture (%)	Moisture Condition	Typical Interpretation	Action
< 2.0%	Dry	• Insulation is dry • Low aging rate	Continue monitoring
2.0 – 3.0%	Moderate	• Acceptable for most transformers • Monitor trend and operating conditions	Monitor trend
3.0 – 4.0%	Wet	• Moisture level elevated • Aging rate increases • Risk of dielectric and mechanical degradation	Investigate & manage
> 4.0%	Very Wet	• High moisture in paper • Rapid aging and PD risk • High failure probability	Take corrective action

Typical ranges based on IEC 60422, CIGRÉ TB 349 and industry experience. Actual limits may vary with transformer design and service conditions.

FACTORS AFFECTING OIL–PAPER EQUILIBRIUM

TEMPERATURE
Higher temperature shifts equilibrium toward more moisture in oil.

RELATIVE HUMIDITY
Higher humidity increases moisture in the system.

OIL TYPE & CONDITION
Different mineral oils have different moisture capacities. Oxidation products affect equilibrium.

CELLULOSE TYPE & CONDITION
Paper grade, aging (DP), and additives influence moisture absorption.

LOAD & THERMAL STRESS
Higher load increases temperature and drives moisture migration.

SEASONAL VARIATION
Seasonal humidity and temperature cause continuous changes in equilibrium.

PRACTICAL EXAMPLE

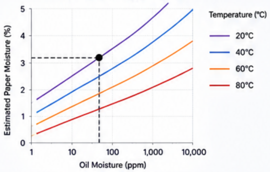
Given:

- Oil Moisture = 25 ppm
- Operating Temperature = 60 °C
- Mineral Oil
- Equilibrium chart (IEC 60422)

Estimated Paper Moisture:

≈ 3.2%

Oil Moisture vs Estimated Paper Moisture (Mineral Oil – Typical Curve)



Use charts or equations consistently and track trends over time. Rising paper moisture is a leading indicator of insulation aging.

Paper moisture is the best indicator of the insulation system's health and remaining life. Estimate it. Track it. Manage it.

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WATER ACTIVITY (a_w)
UNDERSTANDING MOISTURE AVAILABILITY

WHY a_w MATTERS

Water activity (a_w) indicates how much "free" water is available to participate in chemical reactions and accelerate aging. It is a powerful indicator of insulation aging risk, often more meaningful than ppm alone.

KEY MESSAGE

Two transformers with the same ppm can have very different aging risk depending on a_w. Lower a_w = lower risk. Higher a_w = higher risk.

WHAT IS WATER ACTIVITY (a_w)?

Water activity is the ratio of the vapor pressure of water in the oil to the vapor pressure of pure water at the same temperature.

$$a_w = \frac{P_{\text{water in oil}}}{P_{\text{pure water}}} \qquad (0 \le a_w \le 1)$$

a_w is unitless and directly relates to the availability of moisture for chemical reactions in cellulose insulation.

WATER ACTIVITY RISK SCALE

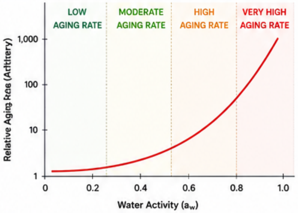
As a_w approaches 1.0, moisture is more available for reactions, accelerating cellulose degradation and aging.

RELATIONSHIP BETWEEN a_w, %RS & PAPER MOISTURE

Parameter	Low (Good)	Medium (Caution)	High (Risk)	Very High (Severe)
Water Activity (a_w)	< 0.20	0.20 – 0.40	0.40 – 0.60	> 0.60
Relative Saturation (%RS) (Mineral Oil)	< 10%	10 – 35%	35 – 70%	> 70%
Estimated Paper Moisture (%)*	< 1.0%	1.0 – 2.5%	2.5 – 4.0%	> 4.0%
Aging Rate	Very Slow	Slow to Moderate	Moderate to High	High to Severe
Condition	Excellent	Good	Concern	Critical

** Estimated for kraft paper insulation in mineral oil. Actual values may vary based on oil type, temperature and paper condition.*

IMPACT OF a_w ON CELLULOSE AGING



Cellulose aging rate increases exponentially as a_w rises above 0.5.

TYPICAL a_w VALUES IN SERVICE TRANSFORMERS

GOOD CONDITION — a_w < 0.20
- Dry insulation system
- Low moisture availability
- Minimal aging risk

NORMAL CONDITION — a_w 0.20 – 0.40
- Acceptable moisture level
- Aging rate under control
- Continue monitoring

CAUTION — a_w 0.40 – 0.60
- Moisture becoming active
- Aging rate increasing
- Investigate & manage

POOR CONDITION — a_w 0.60 – 0.80
- High moisture availability
- Significant aging risk
- Take corrective action

SEVERE CONDITION — a_w > 0.80
- Very high moisture activity
- Rapid aging & failure risk
- Immediate action required

FACTORS THAT INFLUENCE a_w

TEMPERATURE
Higher temperature increases a_w for the same moisture content.

RELATIVE HUMIDITY
Higher ambient humidity increases moisture ingress and a_w.

OIL TYPE & CONDITION
Different oils hold moisture differently; oxidation increases a_w.

BREATHER CONDITION
Saturated or blocked breathers increase moisture and a_w.

LOAD & THERMAL STRESS
Higher load increases temperature and drives moisture migration.

BEST PRACTICES

- Measure a_w along with ppm and %RS for meaningful assessment.
- Track a_w trends over time, not just single readings.
- Correlate a_w with estimated paper moisture and other aging indicators.
- Take action when a_w is consistently above 0.5.
- Maintain oil and breather in good condition.
- Reduce moisture ingress and manage moisture proactively.

Water activity reveals the "availability" of moisture for aging.
Monitor a_w, understand the risk, and act before aging accelerates.

Moisture Availability (a_w) + Cellulose (Paper) = Aging Risk

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DISSIPATION FACTOR (tan δ)
A SENSITIVE INDICATOR OF INSULATION CONDITION

WHY tan δ MATTERS

Dissipation factor (tan δ) measures dielectric losses in the insulation system. It increases with moisture, aging, contamination, and insulation deterioration.
It is one of the most sensitive tests for evaluating insulation condition.

KEY MESSAGE

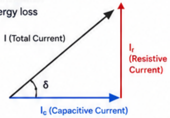
A low tan δ indicates a healthy, dry insulation system. An increasing tan δ warns of moisture ingress, aging, or contamination.

DISSIPATION FACTOR (tan δ) EXPLAINED

When AC voltage is applied to insulation, the current has two components:

- Capacitive current (I_c): charges the insulation
- Resistive current (I_r): represents energy loss

$$\tan\delta = \frac{I_r}{I_c}$$



tan δ is the ratio of energy loss to stored energy.
Higher tan δ = higher energy loss = poorer insulation condition.

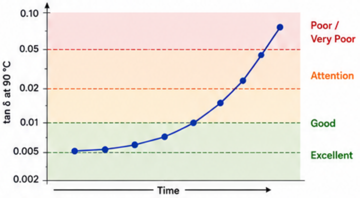
Measure tan δ over a wide frequency and temperature range for accurate interpretation.

INTERPRETING tan δ VALUES (Mineral Oil)

tan δ at 90 °C (approx.)	Insulation Condition	Typical Interpretation	Action
< 0.005	Excellent	• Dry insulation • No active aging	Continue monitoring
0.005 – 0.01	Good	• Normal condition • Acceptable dielectric losses	Monitor trend
0.01 – 0.02	Attention	• Moisture may be increasing • Early aging indicators	Investigate & manage
0.02 – 0.05	Poor	• Significant moisture • Aging / contamination	Take corrective action
> 0.05	Very Poor	• Severely degraded • High risk of failure	Immediate action required

Note: Values are indicative for new to aged mineral oil.
Refer to IEC 60247 & IEEE C57.152 for detailed guidance.

tan δ TREND OVER TIME – WHAT IT TELLS US



- Stable low tan δ → Healthy insulation
- Gradual increase → Moisture ingress / early aging
- Rapid increase → Accelerated aging / high risk
- Very high tan δ → Severe deterioration / failure risk

FACTORS AFFECTING tan δ

TEMPERATURE
tan δ increases with temperature. Always compare at the same reference temperature (usually 90 °C).

MOISTURE
Increased moisture is the primary cause of tan δ increase.

CONTAMINATION
Sludge, particles and oxidation products increase dielectric losses.

AGING
Cellulose aging and degradation increase tan δ.

ELECTRICAL STRESS
Overloading and partial discharges deteriorate insulation and increase tan δ.

OIL TYPE & CONDITION
Different oil types and oxidation levels show different tan δ behavior.

BEST PRACTICES

- Measure tan δ at power frequency (50/60 Hz) and over a wide frequency range if possible.
- Always measure at the same reference temperature (90 °C).
- Track trends over time, not just single readings.
- Correlate tan δ with moisture (ppm, %RS, a_w) and paper moisture.
- Use tan δ along with BDV, moisture, DGA, Furan, and acidity for complete assessment.
- Investigate any consistent upward trend.
- Maintain oil and breather in good condition to control moisture.

A rising tan δ trend is an early warning.
Act early. Prevent failure.

Dissipation factor (tan δ) is a powerful early indicator of moisture, aging, and insulation deterioration. Monitor it consistently.
A small increase today can prevent a major failure tomorrow.

Moisture + Aging = Higher tan δ (Higher Risk)

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INSULATION RESISTIVITY (ρ)
A KEY INDICATOR OF INSULATION INTEGRITY

WHY RESISTIVITY MATTERS

Insulation resistivity indicates how strongly the insulation opposes the flow of direct current (DC). It is highly sensitive to moisture, temperature, contamination, and aging.

Low resistivity increases leakage current, reduces dielectric strength, and accelerates insulation degradation.

KEY MESSAGE

High resistivity = Dry, clean, healthy insulation.
Low resistivity = Moist, contaminated, or deteriorated insulation.

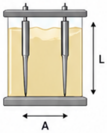
WHAT IS INSULATION RESISTIVITY?

Resistivity (ρ) is the inherent property of the oil insulation material to resist the flow of DC.
It is calculated as:

$$\rho = \frac{R \times A}{L}$$

Where:

- ρ = Resistivity (Ω·m)
- R = Measured resistance (Ω)
- A = Area of electrode (m^2)
- L = Distance between electrodes (m)



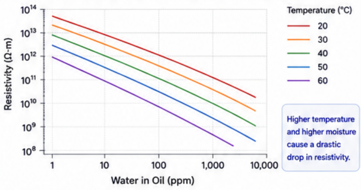
ⓘ Resistivity decreases exponentially with increase in moisture and temperature.

INTERPRETING RESISTIVITY VALUES (Mineral Oil at 25 °C)

Resistivity (Ω·m)	Insulation Condition	Typical Interpretation	Action
$> 1 \times 10^{12}$	Excellent	• Very dry and clean oil • Very good insulation condition	Continue monitoring
$1 \times 10^{11} - 1 \times 10^{12}$	Good	• Acceptable condition • Normal for most in-service transformers	Monitor trend
$1 \times 10^{10} - 1 \times 10^{11}$	Attention	• Moisture increasing • Possible contamination • Aging may be progressing	Investigate & manage
$< 1 \times 10^{10}$	Poor	• High moisture or contamination • Severe aging risk • High leakage current	Take corrective action

Note: Values are indicative for new to aged mineral oil. Actual limits may vary based on oil type, temperature, test cell, and industry standards (IEC 60247, IEEE C57.152).

EFFECT OF MOISTURE & TEMPERATURE ON RESISTIVITY



Resistivity can drop several orders of magnitude with small increases in moisture and temperature.

FACTORS AFFECTING RESISTIVITY

MOISTURE
The primary factor. Even small moisture increase causes resistivity to drop sharply.

TEMPERATURE
Higher temperature reduces resistivity.

CONTAMINATION
Particles, sludge, and oxidation products create conductive paths.

OIL TYPE & CONDITION
New oil has higher resistivity. Oxidation and aging reduce resistivity.

AGING
Aging increases polar compounds and acids, reducing resistivity.

BREATHER CONDITION
Saturated or damaged breathers increase moisture and reduce resistivity.

BEST PRACTICES

- ✔ Measure resistivity at a controlled temperature (preferably 25 °C).
- ✔ Ensure test cell is clean, dry, and per standard (IEC 60247 / ASTM D1169).
- ✔ Use short test time and stabilize before taking reading.
- ✔ Track trends over time, not just single readings.
- ✔ Correlate resistivity with moisture (ppm, %RS, a_w) and tan δ.
- ✔ Investigate sudden drops – check for moisture ingress, contamination or oil degradation.
- ✔ Maintain oil and breather system in good condition.
- ✔ Take action early to prevent insulation deterioration.

ⓘ Resistivity tests are highly sensitive to test technique and equipment. Use calibrated instruments and follow standard procedures.

CORRELATION WITH OTHER MOISTURE / AGING PARAMETERS

Parameter	High Moisture	Low Resistivity	High tan δ	Low BDV	High Paper Moisture	Interpretation
Moisture (ppm / %RS)	↑	↓	↑	↓	↑	Wet insulation, higher aging & failure risk
Water Activity (a_w)	↑	↓	↑	↓	↑	Moisture available for reactions
Paper Moisture (%)	↑	↓	↑	↓	↑	Paper aging accelerated
Temperature (°C)	↑	↓	↑	↓	↑	Thermal stress increases moisture effects
Aging Indicators (Furan, Acidity)	↑	↓	↑	↓	↑	Advanced aging of insulation

↑ Increase ↓ Decrease BDV = Breakdown Voltage tan δ = Dissipation Factor a_w = Water Activity

THE BIG PICTURE

Low resistivity rarely occurs in isolation. Always evaluate in combination with moisture, dielectric, and aging indicators for accurate diagnosis.

⚠ Resistivity is a powerful indicator of insulation health. **Monitor it consistently,** understand the trend, and **act before** insulation performance is compromised.

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BREAKDOWN VOLTAGE (BDV)

A DIRECT MEASURE OF OIL DIELECTRIC STRENGTH

WHY BDV MATTERS

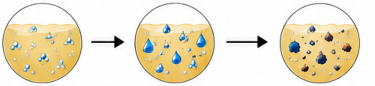
Breakdown Voltage is the voltage at which the oil fails to insulate and allows electrical discharge between electrodes. Moisture, contaminants, and aging reduce BDV and increase the risk of internal insulation failure.

KEY MESSAGE

High BDV indicates strong insulating oil.
Low BDV indicates moisture, contamination, or aging—higher risk of flashover and failure.

HOW MOISTURE & CONTAMINATION AFFECT BDV

Clean, Dry Oil	Moisture Ingress	Contamination & Aging
Strong molecular structure	Water disrupts molecular structure & reduces intermolecular attraction	Sludge, acids, polar compounds further weaken dielectric strength
High BDV	BDV Decreases	BDV Severely Decreases



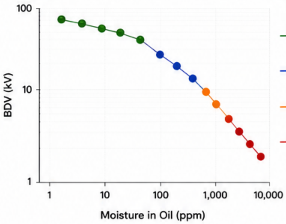
Moisture is the primary cause of low BDV in service transformers.

INTERPRETING BDV VALUES (Mineral Oil)

BDV (kV)	Condition	Typical Interpretation	Action
> 60	Excellent	• Dry, clean oil • Good dielectric strength	Continue monitoring
40 – 60	Good	• Acceptable condition • Normal for most in-service transformers	Monitor trend
30 – 40	Caution	• Moisture may be increasing • Contamination possible	Investigate & manage
20 – 30	Poor	• High moisture or contamination • Risk of dielectric failure	Take corrective action
< 20	Very Poor	• Severely contaminated / wet • High flashover risk	Immediate action required

Note: Values based on IEC 60156 (2.5 mm gap, 60 Hz). Actual limits may vary with oil type, test cell, temperature, and standards.

TYPICAL RELATIONSHIP: MOISTURE vs BDV



BDV decreases exponentially as moisture increases.

FACTORS THAT AFFECT BDV

MOISTURE
Even small moisture increases drastically reduce BDV.

PARTICULATE CONTAMINATION
Particles act as conductive bridges and initiate discharge.

CHEMICAL CONTAMINATION
Acids, sludge, and oxidation products reduce dielectric strength.

TEMPERATURE
Higher temperature lowers BDV.
Always correct to standard temperature (20–25 °C).

OIL TYPE & AGING
Aging and oxidation reduce BDV over time.

TEST CELL & PROCEDURE
Gap distance, electrode shape, stirring, and test method affect results.

BEST PRACTICES

- Use calibrated BDV tester as per IEC 60156.
- Ensure oil is well conditioned and test cell is clean and dry.
- Maintain consistent test gap (2.5 mm) and stirring.
- Test at controlled temperature (20–25 °C).
- Take multiple readings and report the average.
- Correlate BDV with moisture (ppm, %RS), tan δ, resistivity, and visual inspection.
- Track BDV trend over time, not just single values.
- Investigate sudden drops immediately.

BDV is one of the most immediate indicators of moisture ingress and contamination.

TYPICAL BDV RANGE BY OIL TYPE (at 20–25 °C)

Oil Type	Typical Good Condition BDV (kV)
Mineral Oil (New)	> 70
Mineral Oil (In Service)	40 – 70
High Grade New Oil	> 75
Reclaimed / Reprocessed Oil	> 50
Poor / Contaminated Oil	< 30
Severely Degraded Oil	< 20

QUICK REFERENCE

BDV < 30 kV usually indicates excessive moisture or contamination.
Confirm with moisture test and take action before failure risk increases.

ACTION PLAN FOR LOW BDV

1. **INVESTIGATE**
   - Check moisture (ppm, %RS)
   - Check oil appearance
   - Check other diagnostics (tan δ, resistivity)
2. **IDENTIFY CAUSE**
   - Moisture ingress
   - Contamination
   - Aging / Oxidation
3. **TAKE ACTION**
   - Vacuum dehydration
   - Filtration / Oil reclamation
   - Seal leaks & dry breather
4. **RETEST & CONFIRM**
   - Re-test BDV
   - Verify improvement
   - Continue monitoring
5. **TRACK TREND**
   - Trend BDV over time
   - Ensure long-term reliability

High BDV protects. Low BDV warns.
Measure accurately. Interpret correctly. **Act before failure.**

OIL ACIDITY (TOTAL ACID NUMBER – TAN)

A CRITICAL INDICATOR OF OIL & INSULATION HEALTH

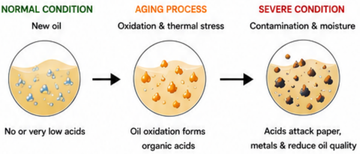
WHY ACIDITY MATTERS

Acidity in transformer oil comes from oxidation and decomposition of oil and paper insulation. Acids accelerate cellulose aging, corrode metal parts, and reduce oil dielectric strength. High acidity indicates advanced aging and contamination.

KEY MESSAGE

Low acidity = healthy oil & insulation system.
Rising acidity = oil oxidation, paper degradation, and increased risk of failure.

HOW ACIDITY FORMS IN TRANSFORMER OIL



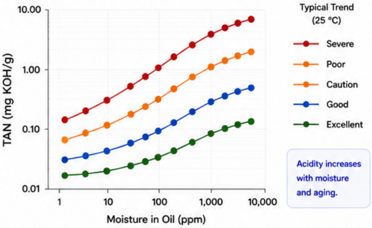
Moisture, oxygen, high temperature, and catalysts accelerate acid formation.

INTERPRETING ACIDITY LEVELS (TAN)

TAN (mg KOH/g)	Condition	Typical Interpretation	Action
< 0.10	Excellent	• Very low acidity • Oil and insulation in good condition	Continue monitoring
0.10 – 0.30	Good	• Acceptable acidity • Normal aging	Monitor trend
0.30 – 0.60	Caution	• Acidity increasing • Insulation aging progressing	Investigate & manage
0.60 – 1.00	Poor	• High acidity • Significant aging / contamination	Take corrective action
> 1.00	Very Poor	• Very high acidity • Severe aging / failure risk	Immediate action required

Note: Values are typical for mineral oil. Refer to IEEE C57.106 and IEC 60422 for test method and industry guidance.

TYPICAL RELATIONSHIP: ACIDITY vs MOISTURE



Control moisture to slow acid formation and extend insulation life.

FACTORS THAT INFLUENCE ACIDITY

MOISTURE
Promotes hydrolysis and acid formation.

TEMPERATURE
Higher temperature accelerates oxidation and acid generation.

OXYGEN
Oxidation occurs in presence of oxygen.

PAPER INSULATION
Degradation of cellulose produces acids.

CONTAMINATION
Sludge, metals, and impurities catalyze reactions.

ELECTRICAL STRESS
Partial discharges and arcing accelerate oil and paper degradation.

BEST PRACTICES

- Use calibrated TAN tester as per IEC 62021.
- Ensure oil sample is clean, dry, and properly handled.
- Maintain consistent testing temperature (25 °C).
- Track TAN trend over time, not just single readings.
- Correlate TAN with moisture, BDV, DGA, and tan δ.
- Maintain oil and breather in good condition.
- Reduce oxygen ingress (proper sealing, conservator care).
- Act early when TAN is in caution zone.

Rising TAN is an early warning of insulation aging. Early action prevents major degradation.

TYPICAL TAN RANGE BY OIL TYPE (at 25 °C)

Oil Type	Typical Good Condition TAN (mg KOH/g)
Mineral Oil (New)	< 0.03
Mineral Oil (In Service)	< 0.30
High Grade New Oil	< 0.02
Reclaimed / Reprocessed Oil	0.10 – 0.50
Poor / Contaminated Oil	> 0.60
Severely Degraded Oil	> 1.00

QUICK REFERENCE

TAN > 0.60 mg KOH/g indicates significant aging or contamination. Investigate and take action before insulation condition deteriorates further.

ACTION PLAN FOR HIGH ACIDITY

1. **INVESTIGATE**
   - Check TAN trend
   - Check moisture
   - Review DGA & BDV
   - Inspect for overheating or contamination
2. **IDENTIFY CAUSE**
   - Oil oxidation
   - Paper aging
   - Moisture ingress
   - Overheating
   - Chemical contamination
3. **TAKE ACTION**
   - Oil filtration
   - Vacuum dehydration
   - Oil reclamation
   - Replace breather
   - Repair leaks / seals
4. **RETEST & CONFIRM**
   - Re-test TAN
   - Verify improvement
   - Ensure moisture control
   - Continue monitoring
5. **TRACK TREND**
   - Trend TAN over time
   - Correlate with other tests
   - Ensure long-term reliability

Acidity is a silent killer of insulation. Monitor TAN regularly, understand the trend, and act before damage becomes irreversible.

INTEGRATING MOISTURE INDICATORS FOR ACCURATE DIAGNOSIS

WHY INTEGRATION MATTERS

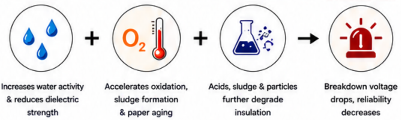
No single test tells the whole story. Moisture, aging, and contamination influence each other. Integrating multiple indicators provides a complete picture of insulation health and failure risk.

KEY MESSAGE

Correlate all available data, look for trends, and confirm with physical condition.

Integrate → Interpret → Act.

INTERACTION BETWEEN MOISTURE, AGING & CONTAMINATION



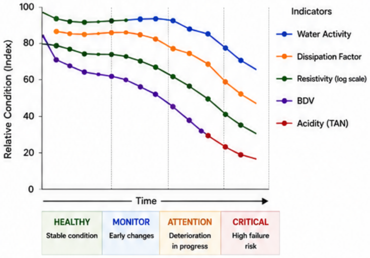
Managing moisture effectively breaks the chain of deterioration.

COMPREHENSIVE DIAGNOSTIC MATRIX

Parameter	Condition / Risk Level				
	Excellent (Low Risk)	Good (Monitor)	Caution (Elevated Risk)	Poor (High Risk)	Severe (Critical)
Water Activity (a_w)	< 0.20	0.20 – 0.40	0.40 – 0.60	0.60 – 0.80	> 0.80
Dissipation Factor (tan δ)	< 0.005	0.005 – 0.01	0.01 – 0.02	0.02 – 0.05	> 0.05
Insulation Resistivity (ρ, Ω-m)	$> 1 \times 10^{12}$	1×10^{11} – 1×10^{12}	1×10^{10} – 1×10^{11}	1×10^{9} – 1×10^{10}	$< 1 \times 10^{9}$
Breakdown Voltage (BDV, kV)	> 60	40 – 60	30 – 40	20 – 30	< 20
Oil Acidity (TAN, mg KOH/g)	< 0.10	0.10 – 0.30	0.30 – 0.60	0.60 – 1.00	> 1.00
Estimated Aging	Minimal	Low	Moderate	High	Severe
Recommended Action	Continue Monitoring	Monitor Trends	Investigate & Manage	Take Corrective Action	Immediate Action Required

Note: *Thresholds are typical guidelines. Use industry standards, asset condition, and experience for final interpretation.*

INSULATION HEALTH OVER TIME – EXAMPLE



Trending multiple indicators helps detect early warning signs and prevents unexpected failures.

KEY TAKEAWAYS

- Moisture is the primary driver of insulation aging and failure.
- Water activity (a_w) best indicates moisture availability.
- Dissipation factor (tan δ) shows insulation dielectric loss.
- Resistivity reflects insulation integrity and contamination.
- BDV shows overall dielectric strength of the oil.
- Acidity (TAN) indicates oil & paper degradation.
- Integrate all indicators, analyze trends, and act early.

BEST PRACTICES SUMMARY

- Sample oil correctly and avoid contamination.
- Use calibrated instruments and standard methods.
- Measure at controlled temperature (preferably 25 °C).
- Track trends over time, not just single readings.
- Correlate with ppm, %RS, paper moisture, DGA, Furan, and visual inspection.
- Set appropriate alarm thresholds for your fleet.
- Act before indicators enter high risk zone.
- Maintain oil and breather system in good condition.
- Document results and maintain diagnostic history.
- Review and re-assess after remedial actions.

Consistent monitoring and proactive management ensure reliable transformers and long service life.

RECOMMENDED ACTIONS BASED ON OVERALL ASSESSMENT

LOW RISK (Good)
- Continue routine monitoring
- Maintain oil & system
- Verify trends periodically

ELEVATED RISK (Caution)
- Investigate root causes
- Improve sealing & breathers
- Consider oil treatment / drying

HIGH RISK (Poor)
- Take corrective action urgently
- Dehydrate / recondition oil
- Address contamination & leaks

CRITICAL RISK (Severe)
- Plan outage and major intervention
- Vacuum dehydration / oil reclamation
- Component replacement if needed

Prevention is always more cost-effective than failure and unplanned outages.

Moisture management is transformer life management.

Monitor. Interpret. Act. Protect your assets.

Monitor + Interpret + Act = Reliable Transformer

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FURAN ANALYSIS (2FAL)

A POWERFUL INDICATOR OF PAPER INSULATION CONDITION

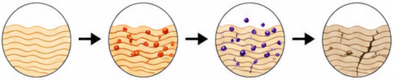
WHY 2FAL MATTERS

Furan compounds are formed when paper insulation breaks down due to overheating, electrical stress, and in the presence of moisture and oxygen. 2Furaldehyde (2FAL) is one of the most reliable markers for assessing the condition of paper insulation and estimating the degree of polymerization (DP).

KEY MESSAGE

2FAL reflects the degradation of paper insulation. Higher levels indicate aging and thermal stress. Track trends to assess insulation life.

HOW FURANS ARE FORMED



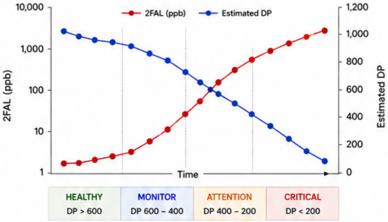
2FAL is more stable and more specific to paper insulation than other furans.

INTERPRETING 2FAL LEVELS IN OIL

2FAL (ppb)	Condition	Interpretation	Action
< 100	Normal	• New or well-maintained • paper insulation	Continue monitoring
100 – 250	Alert	• Early signs of aging • Monitor for trend	Monitor trend
250 – 750	Caution	• Moderate aging • Possible overheating in the past	Investigate & manage
750 – 1500	High	• Significant aging • Insulation life reduced	Take corrective action
> 1500	Severe	• Severe aging / damage • High risk of failure	Immediate action required

Note: Values are general guidelines. Use industry standards and asset condition for final interpretation.

TYPICAL 2FAL TREND vs ESTIMATED DP



Increasing 2FAL and decreasing DP confirm insulation aging. Act before DP reaches critical levels.

FACTORS THAT INFLUENCE 2FAL LEVELS

TEMPERATURE
Higher temperature accelerates paper degradation and furan formation.

MOISTURE
Moisture in paper and oil increases chemical reactions.

OXYGEN
Oxygen promotes oxidation and cellulose breakdown.

ELECTRICAL STRESS
Partial discharges and arcing accelerate insulation deterioration.

PAPER QUALITY
Lower quality paper degrades faster.

CONTAMINATION
Sludge, acids, and metals increase stress on insulation.

BEST PRACTICES

- Use calibrated furan analyzer as per IEC 61198.
- Sample oil correctly and avoid contamination.
- Track 2FAL trend over time, not just single readings.
- Correlate 2FAL with DP, moisture, DGA, and TAN.
- Maintain oil and breather in good condition.
- Control moisture and temperature.
- Act early when 2FAL enters caution zone.
- Document results and review diagnostic history.
- Plan maintenance based on trend and risk.

Trend analysis is key. A small increase today may lead to major problems tomorrow.

ESTIMATING DP FROM 2FAL

2FAL (ppb)	Estimated DP (Approximate)
< 100	> 1,000
100 – 250	600 – 1,000
250 – 750	400 – 600
750 – 1500	200 – 400
> 1500	< 200

QUICK REFERENCE

2FAL > 750 ppb or DP < 400 indicates significant insulation aging. Investigate and take action.

ACTION PLAN BASED ON 2FAL LEVELS

1. **INVESTIGATE**
   - Check 2FAL level
   - Review trend & DP
   - Check moisture and temperature
2. **IDENTIFY CAUSE**
   - Overheating
   - Electrical stress
   - Moisture ingress
   - Oxygen exposure
3. **TAKE ACTION**
   - Improve cooling
   - Dry out insulation
   - Repair leaks
   - Improve sealing
4. **RETEST & CONFIRM**
   - Re-test 2FAL & DP
   - Verify improvement
   - Continue monitoring
5. **TRACK & PLAN**
   - Track trend over time
   - Update risk assessment
   - Plan maintenance

2FAL tells the story of paper aging.

Monitor the trend, protect the insulation, and extend transformer life.

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MOISTURE–RELATED DIAGNOSTICS & INTERPRETATION IN POWER TRANSFORMERS

METHANOL & ETHANOL ANALYSIS

EARLY WARNING INDICATORS OF PAPER INSULATION AGING

WHY METHANOL MATTERS

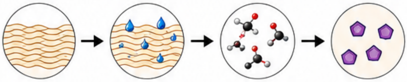
Methanol and ethanol are produced during the early stages of cellulose (paper) degradation, especially under hydrolytic conditions (moisture + heat). They often increase before furans, providing an earlier warning of insulation aging.

KEY MESSAGE

- Methanol is the earliest indicator of paper deterioration.
- It is more sensitive to moisture than furans.
- Tracking methanol trends helps prevent unexpected failures and extend transformer life.

HOW METHANOL & ETHANOL ARE FORMED

HEALTHY PAPER (NEW)	HYDROLYSIS BEGINS (MOISTURE + HEAT)	METHANOL & ETHANOL ARE RELEASED	ADVANCED AGING FURANS INCREASE
Strong cellulose structure	Water attacks cellulose chains and breaks glycosidic bonds	Methanol (CH_3OH) and ethanol (C_2H_5OH) are released into the oil	Further degradation produces furans (2FAL, 5HMF, etc.)



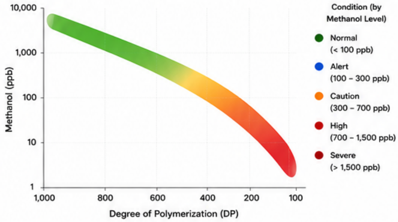
Methanol typically responds first, followed by 2FAL and other furans.

INTERPRETING METHANOL LEVELS IN OIL

Methanol (ppb)	Condition	Typical Interpretation	Action
< 100	Normal	• New or well-maintained • No significant hydrolysis	Continue monitoring
100 – 300	Alert	• Early stages of paper aging • Moisture ingress likely	Monitor trend
300 – 700	Caution	• Moderate hydrolysis • Insulation aging progressing	Investigate & manage
700 – 1,500	High	• Significant paper aging • Risk of strength reduction	Take corrective action
> 1,500	Severe	• Advanced aging • High risk of insulation failure	Immediate action required

Note: Values are general guidelines. Evaluate with trends, moisture, temperature, load, and other diagnostic indicators.

TYPICAL TREND: METHANOL vs DEGREE OF POLYMERIZATION (DP)



As DP decreases (paper ages), methanol increases.
Use together with 2FAL, moisture, and other diagnostics for accurate assessment.

WHY METHANOL RESPONDS EARLIER THAN FURANS

- Methanol is a primary product of hydrolysis in the early stage of cellulose breakdown.
- Furans form later, during advanced thermal and oxidative degradation.
- Methanol is more sensitive to moisture and temperature.
- Tracking methanol helps detect insulation degradation at an early, reversible stage.
- Early action reduces risk, extends life, and lowers maintenance cost.

BEST PRACTICES

- Use calibrated methanol analyzer as per IEC 62953.
- Take oil sample correctly and avoid contamination.
- Track methanol trend over time, not just single values.
- Correlate methanol with moisture, DP, 2FAL, DGA, and TAN.
- Maintain oil and breather in good condition.
- Control moisture and temperature.
- Act early when methanol enters caution zone.
- Document results and review diagnostic history.

Methanol is your "early warning system" for paper insulation aging.

REFERENCE: IEC 62953

IEC 62953 provides test methods for the determination of methanol, ethanol, 2FAL, and 2ACF in insulating liquids.

Key Points from IEC 62953:

- Applicable to mineral oil, ester, and synthetic esters.
- Methanol determination by GC–FID.
- Typical detection limit for methanol: ~1 ppb.
- Report results in ppb (µg/L).
- Combine results with other diagnostics for accurate interpretation.

QUICK REFERENCE

Rising methanol = Early paper aging due to moisture + heat.
Monitor the trend. Act early. Protect the asset.

COMPARISON: METHANOL vs OTHER PAPER AGING INDICATORS

Indicator	Source / Formation	Responds To	Stage of Aging Detected	Strength	Limitation
Methanol (CH_3OH)	Hydrolysis of cellulose	Moisture + Heat	Early (Initial aging)	Earliest indicator, highly moisture sensitive	Can be affected by sample handling (acid wash recommended)
Ethanol (C_2H_5OH)	Hydrolysis of cellulose	Moisture + Heat	Early to Mid	Supports methanol trend, more stable in oil	Lower concentration, less sensitive than methanol
2FAL	Degradation of cellulose	Heat + Oxidation	Mid to Advanced	More specific to paper aging	Responds later than methanol
DP	Polymer chain length	Moisture + Heat	Direct measure	Direct reflection of paper strength	Requires lab analysis

Use methanol for early detection, 2FAL for confirmation, and DP for condition assessment.

Methanol is the first whisper of paper aging.
Listen to the trend. Act early. Protect the transformer.

CH_3OH Methanol + Moisture + Heat = Reliable Transformer

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DGA INDICATORS RELATED TO MOISTURE & CELLULOSE AGING

WHY DGA MATTERS

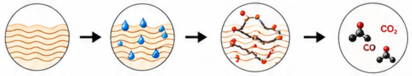
Dissolved Gas Analysis (DGA) provides valuable insight into both thermal faults and insulation (paper) degradation. Moisture accelerates cellulose breakdown, increasing gases such as CO and CO_2 at lower temperatures.

KEY MESSAGE

- CO, CO_2 and CO_2/CO ratio are key indicators of paper insulation aging.
- Moisture lowers the energy required for paper decomposition, increasing gas generation.
- Trend analysis is more important than single values.

HOW MOISTURE ACCELERATES CELLULOSE DEGRADATION

NORMAL DRY PAPER	MOISTURE INGRESS	ACCELERATED DEGRADATION	GAS GENERATION IN OIL



Stable cellulose structure	Water weakens hydrogen bonds in cellulose	Lower activation energy breaks cellulose chains at lower temperature	CO, CO_2 and other gases are released into oil

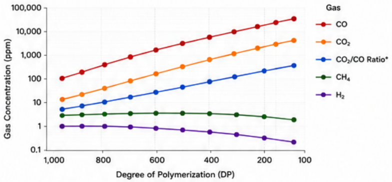
Moisture + Heat = Faster cellulose decomposition = More gases at lower temperature.

KEY DGA INDICATORS FOR PAPER AGING

Gas	Source	What It Indicates	Effect of Moisture	Key Points
CO (Carbon Monoxide)	Cellulose decomposition (low temperature)	Early stage paper degradation	Increases significantly	• Most sensitive indicator • Rises early
CO_2 (Carbon Dioxide)	Advanced cellulose decomposition	More severe paper aging	Increases greatly	• Higher at higher DP reduction • Correlates with aging severity
CO_2/CO Ratio	Balance of low and high temp. degradation	Severity and progression of aging	May increase or decrease depending on aging stage	• < 1 : Early aging • > 3 : Advanced aging
H_2 (Hydrogen)	Thermal faults (not paper)	Fault energy indicator	Not directly affected by moisture	• Helps distinguish fault from aging
CH_4 (Methane)	Low temperature thermal faults	Arcing/thermal faults	Not directly affected by moisture	• Combined with other gases

Note: Always use gas trends, not single samples. Consider load, temperature, oil type, and fault history for accurate interpretation.

TYPICAL TRENDS: GASES vs DEGREE OF POLYMERIZATION (DP)



EARLY STAGE (DP > 600)	DEVELOPING STAGE (DP 300 – 600)	ADVANCED STAGE (DP 150 – 300)	SEVERE STAGE (DP < 150)
Slight increase in CO	CO & CO_2 rise noticeably	High CO & CO_2, CO_2/CO increases	Very high gases, risk of failure

CO increases early. CO_2 rises later. Monitor both and the CO_2/CO ratio. Correlate with moisture and furans/methanol for accurate aging assessment.

INTERPRETING CO_2/CO RATIO

CO_2/CO Ratio	Interpretation
< 1	Early stage aging – CO dominates
1 – 3	Moderate aging – Balanced degradation
> 3	Advanced aging – CO_2 dominates

Use CO_2/CO ratio with DP, moisture, 2FAL, and methanol for better accuracy.

MOISTURE EFFECT ON GAS GENERATION

Higher moisture content in paper:

- Lowers activation energy of cellulose breakdown
- Increases CO and CO_2 generation at lower temperature
- Shortens time to reach critical DP
- Leads to faster deterioration and higher failure risk

A dry transformer ages slowly.
A wet transformer ages quickly.

REFERENCE: IEC 60599

IEC 60599 provides guidelines for the interpretation of dissolved and free gases in mineral oil-immersed transformers.

Key Points from IEC 60599:

- Use key gas method and ratio method.
- Consider both total gas concentration and individual gas behavior.
- CO and CO_2 are related to paper aging.
- Moisture accelerates aging and gas generation.
- Interpret with operating conditions and history.

Always apply engineering judgment.

DGA INTERPRETATION GUIDE FOR PAPER AGING (IEC 60599 – ADAPTED)

Condition	CO (ppm)	CO_2 (ppm)	CO_2/CO Ratio	Interpretation	Recommended Action
Normal / Good	< 200	< 2,000	< 1	No significant paper aging	Continue regular monitoring
Caution (Early Aging)	200 – 1,000	2,000 – 10,000	1 – 3	Early to moderate paper aging	Monitor trends, check moisture & furans
Alert (Developing Aging)	1,000 – 5,000	10,000 – 30,000	2 – 5	Advanced aging in progress	Investigate, take samples more frequently
Critical (Severe Aging)	> 5,000	> 30,000	> 3 – 5	Severe paper degradation	Take corrective action immediately

Note: Values are typical guidelines. Adjust based on transformer size, load, oil type, and operating temperature.

QUICK REFERENCE

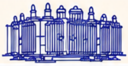
- CO = Early warning of paper aging
- CO_2 = Severity of aging
- CO_2/CO = Progression of aging
- Moisture = Aging accelerator
- Trend + Correlation = Accurate diagnosis

Measure. Monitor. Correlate. Act.
Protect your transformer.

ACTION PLAN BASED ON DGA & MOISTURE

1. **CHECK MOISTURE**
   - Measure ppm & %RS
   - Estimate paper moisture
2. **REVIEW DGA TRENDS**
   - CO, CO_2, CO_2/CO
   - Compare with previous results
3. **CORRELATE INDICATORS**
   - DGA + Moisture
   - 2FAL + Methanol
   - DP if available
4. **ASSESS RISK**
   - Determine aging stage
   - Identify urgency
5. **TAKE ACTION**
   - Dry out transformer
   - Improve sealing
   - Address root cause
6. **MONITOR & VERIFY**
   - Track improvement
   - Continue monitoring
   - Prevent recurrence

Moisture accelerates aging. DGA reveals the story.
Detect early. Interpret correctly. Act before failure.



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FREQUENCY DOMAIN SPECTROSCOPY (FDS)

ADVANCED MOISTURE ASSESSMENT OF PAPER INSULATION

WHY FDS MATTERS

FDS measures the dielectric response of insulation across a wide frequency range. It is highly sensitive to moisture in paper and provides direct estimation of paper moisture content, even in non-equilibrium conditions.

KEY MESSAGE

- FDS is the most reliable method for estimating moisture in paper insulation.
- Works in field conditions and does not require equilibrium.
- Detects moisture gradients and early deterioration.

HOW FDS WORKS

1. **APPLY AC VOLTAGE** – A small AC voltage is applied over a wide frequency range (typically 1 mHz to 1 kHz).
2. **MEASURE RESPONSE** – The instrument measures capacitance and dissipation factor (tan δ) at each frequency.
3. **ANALYZE SPECTRUM** – The dielectric spectrum reflects the polarization processes in oil, paper, and interfaces.
4. **ESTIMATE MOISTURE** – Advanced models translate the spectrum into paper moisture content (% by weight).

ⓘ FDS provides a direct, accurate, and non-destructive measurement of paper moisture.

FDS – KEY ADVANTAGES

DIRECT MOISTURE ESTIMATION
Provides direct % moisture in paper (no equilibrium needed).

HIGH ACCURACY
Typically ±0.2% moisture by weight.

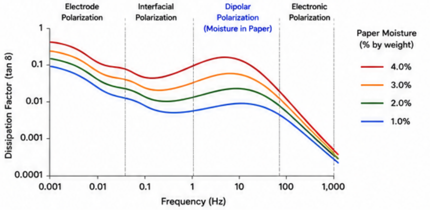
DETECTS NON-UNIFORM MOISTURE
More sensitive to moisture gradients than other methods.

WIDE TEMPERATURE RANGE
Compensates for temperature automatically.

EARLY WARNING
Detects moisture increase before other tests respond.

FIELD APPLICABLE
Fast test (10–20 minutes). No need to bring sample to lab.

TYPICAL FDS SPECTRUM (EXAMPLE)



ⓘ Higher moisture shifts the dipolar polarization peak upward and to lower frequencies.

INTERPRETING FDS RESULTS – PAPER MOISTURE RANGE

Paper Moisture (% by weight)		Condition
< 1.0%	Excellent	Dry paper insulation.
1.0 – 2.0%	Good	Normal operating range.
2.0 – 3.0%	Caution	Increasing moisture – monitor closely.
3.0 – 4.0%	High	High moisture – accelerated aging risk.
> 4.0%	Severe	Very high moisture – immediate action required.

Note: Limits may vary with transformer design, loading, and history. Use trend analysis for final assessment.

FDS vs OTHER MOISTURE ESTIMATION METHODS

Method	Equilibrium Required	Direct Paper Moisture	Accuracy	Sensitivity to Gradients	Field Applicable	Typical Uncertainty
FDS (IEC TS 60076-57-129)	No	✓	High	High	✓	±0.2% (typ.)
Equilibrium (IEC 60422)	Yes	✓	Medium	Low	✗	±0.5 – 1.0%
Karl Fischer (IEC 60422)	Yes	✗	High	Low	✗	±0.2 – 0.3%
Capacitance (IEC 60422)	Yes	✗	Medium	Low	✓	±0.5 – 1.0%
Polarization Index	No	✗	Low	Low	✓	Qualitative

ⓘ FDS provides the most accurate and reliable estimate of paper moisture in field conditions.

BEST PRACTICES FOR FDS TESTING

- Use calibrated FDS instrument as per IEC TS 60076-57-129.
- Ensure good grounding and proper test connections.
- Record oil temperature accurately.
- Take readings at multiple tap positions when possible.
- Correlate FDS results with %RS, 2FAL, methanol, and DGA.
- Track trend over time, not just single readings.
- Act early when moisture shows upward trend.

ⓘ FDS is most powerful when used as part of an integrated diagnostic approach.

IEC REFERENCE

IEC TS 60076-57-129:2015
Power transformers – Part 57-129: Guide for the interpretation of frequency domain measurements.

Key Points from IEC TS 60076-57-129:

- Provides procedures for FDS measurement and analysis.
- Describes models to estimate paper moisture.
- Applicable to mineral oil-immersed transformers.
- Provides guidance on accuracy, uncertainties, and reporting.

QUICK REFERENCE
FDS = Direct. Accurate. Reliable.
Measure. Interpret. Act.

TYPICAL FDS TEST CONDITIONS

Temperature Range	-20 °C to 90 °C
Oil Condition	Degassed, representative sample
Frequency Range	1 mHz to 1 kHz (typical)
Test Voltage	2 to 10 Vrms (typical)
Test Duration	10 to 20 minutes

ⓘ Follow manufacturer instructions and IEC TS 60076-57-129 for accurate results.

FDS reveals what other tests may miss.
Know the moisture in your paper. Protect your transformer.

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POLARIZATION DEPOLARIZATION CURRENT (PDC)

A POWERFUL TOOL FOR MOISTURE ASSESSMENT

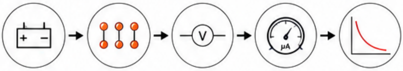
WHY PDC MATTERS

PDC measures the natural electrical response of insulation after DC polarization. Moisture in paper significantly affects depolarization currents, making PDC highly sensitive to moisture content and distribution in cellulose insulation.

KEY MESSAGE

- PDC is highly sensitive to moisture in paper insulation.
- Useful in both laboratory and field conditions.
- Complements FDS and other diagnostics.
- Detects moisture changes and migration over time.

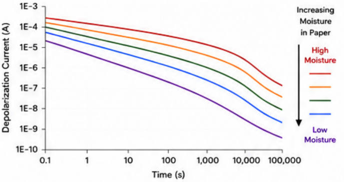
HOW PDC WORKS



APPLY DC VOLTAGE	POLARIZATION	REMOVE DC VOLTAGE	MEASURE CURRENT	ANALYZE RESPONSE
A DC voltage is applied for a fixed polarization time (typically 10 minutes).	Molecular dipoles in oil and paper align with the electric field.	The voltage is removed and the insulation begins to depolarize.	Depolarization current decays over time and is measured.	The shape and magnitude of the current reflect insulation condition and moisture.

ⓘ Moisture slows down depolarization, resulting in higher PDC values and slower decay.

TYPICAL PDC RESPONSE CURVES



ⓘ Higher moisture results in higher initial current and slower decay. Compare curves taken at the same temperature and polarization time.

PDC INDICATORS FOR MOISTURE IN PAPER

PDC INTERPRETATION (@ 20–30 °C)	INDICATION	MOISTURE LEVEL IN PAPER	TYPICAL %RS (Approx.)
Very Low PDC	Dry insulation	Very Low	< 15%
Low PDC	Low moisture	Low	15 – 30%
Moderate PDC	Moderate moisture	Moderate	30 – 60%
High PDC	High moisture	High	60 – 80%
Very High PDC	Very high moisture	Very High	> 80%

ⓘ PDC results must be temperature compensated and compared with reference curves or historical data.

PDC vs OTHER METHODS

Feature	PDC	FDS	Equilibrium (Karl Fischer)	RH / %RS (From Oil)
Field Applicable	Yes	Yes	No	Yes
Equilibrium Required	No	No	Yes	Yes
Direct Paper Moisture Estimate	Indirect (Good)	Direct (Excellent)	Direct (Excellent)	Indirect (Fair)
Sensitivity to Moisture	High	Very High	Very High	Moderate
Time to Result	20 – 30 min	20 – 30 min	Hours – Days	Minutes
Detects Moisture Migration	Yes	Yes	No	No
Best Use	Trend & Moisture Changes	Accurate Moisture Estimation	Laboratory Confirmation	Moisture Ingress Check
Standards	IEEE C57.12.00	IEC TS 60076-57-129	IEC 60422	IEC 60422

ⓘ PDC is ideal for field trending and early detection, while FDS provides the most accurate estimate.

FACTORS AFFECTING PDC RESULTS

TEMPERATURE	Higher temperature lowers current. Always temperature compensate.
MOISTURE	Higher moisture increases current and slows down decay.
OIL CONDUCTIVITY	High conductivity increases current. Use clean, representative oil sample.
POLARIZATION VOLTAGE	Use standard voltage (500 – 2,500 V) and consistent test time.
POLARIZATION TIME	Typical polarization time is 10 minutes.
SAMPLE HANDLING	Avoid contamination and air bubbles. Degas oil before testing.

ⓘ Consistent test conditions are essential for reliable comparison of PDC results.

BEST PRACTICES FOR PDC TESTING

- Use a calibrated PDC analyzer as per IEEE C57.12.00.
- Ensure proper grounding and shielding.
- Use clean, dry glassware and dry, filtered oil.
- Degas the oil sample before testing.
- Maintain constant test temperature (20–30 °C) or apply correction.
- Record full depolarization curve (at least up to 1,000 s).
- Compare with previous results under similar conditions.
- Use PDC in combination with FDS, DGA, furans, and oil tests.

ⓘ PDC is a trend tool. Focus on changes, not single values.

PDC APPLICATIONS

ROUTINE MONITORING
Track moisture changes over time.

MOISTURE MIGRATION STUDY
Assess drying progress and moisture movement.

DRYING VERIFICATION
Confirm effectiveness of drying processes.

FAILURE PREVENTION
Detect early moisture increase before risk becomes critical.

COMPLEMENT TO FDS
Use both for accurate and reliable diagnosis.

LIMITATIONS OF PDC

INDIRECT MEASUREMENT
Does not provide exact % moisture by weight.

AFFECTED BY CONDITIONS
Temperature, oil conductivity, and cell geometry influence results.

NEEDS EXPERIENCE
Interpretation requires knowledge and proper reference data.

NOT A REPLACEMENT
Use along with FDS, DGA, oil tests, and other diagnostics.

QUICK REFERENCE
Rising PDC = Rising Moisture = Rising Risk
Trend it. Act early. Protect your transformer.

PDC listens to what the insulation remembers.

Track the change. Understand the risk. Prevent the failure.

DC Polarize + µA Depolarize → Analyze = Protect

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INTERNATIONAL STANDARDS & DIAGNOSTIC LIMITS

International standards provide test methods, guidance, and interpretation limits for moisture and related diagnostics in power transformers.

KEY MESSAGE

- Follow standards for testing, interpretation, and reporting.
- Use multiple diagnostics together for accurate assessment.
- Trends are more important than single readings.
- Always consider transformer design, age, history, and operating conditions.

Always refer to the latest edition of the standards. National annexes and utility practices may apply.

IEC STANDARDS

- **IEC 60076-1** Power transformers – General
- **IEC 60076-2** Temperature rise
- **IEC 60422** Mineral insulating oils – Sampling and tests
- **IEC 60567** Oil – Determination of interfacial tension
- **IEC 60599** Mineral oil-immersed transformers – Interpretation of dissolved and free gases analysis
- **IEC 60770** Guide to the interpretation of gases in oil-immersed equipment
- **IEC 61198** Furan analysis (2FAL, 5HMF, 2ACF, 2FOL)
- **IEC 62953** Methanol and ethanol in insulating liquids – Test methods
- **IEC TS 60076-57-129** Frequency domain spectroscopy (FDS) for paper moisture measurement
- **IEC 60247** Measurement of relative permittivity, tan δ and resistivity of insulating liquids

IEEE STANDARDS

- **IEEE C57.12.00** General requirements for liquid-immersed distribution, power and regulating transformers
- **IEEE C57.106** Guide for acceptance and maintenance of insulating oil
- **IEEE C57.104** Guide for the interpretation of dissolved and free gases in oil-immersed transformers
- **IEEE C57.91** Guide for loading mineral-oil-immersed transformers
- **IEEE C57.157** Guide for the interpretation of furan analysis
- **IEEE C57.159** Guide for the interpretation of moisture in oil-immersed transformers
- **IEEE C57.12.90** Test code for liquid-immersed distribution, power and regulating transformers

CIGRÉ TECHNICAL BROCHURES

- **TB 349** Moisture Equilibrium and Moisture in Transformers
- **TB 445** Moisture in Transformers
- **TB 642** Transformer Reliability Survey
- **TB 761** Dissolved Gas Analysis – Interpretation and Diagnostic Techniques
- **TB 850** Evaluation and Management of Moisture in Transformers
- **TB 890** Ageing of Paper-Insulated Power Transformers
- **TB 951** Best Practices for Moisture Management

TYPICAL DIAGNOSTIC LIMITS & INTERPRETATION GUIDELINES (GENERAL REFERENCE)

Indicator	Measurement	Unit	Good / Normal	Caution / Alert	Poor / High Risk	Reference / Notes
OIL MOISTURE	Water Content (in oil)	ppm (mg/kg)	< 20	20 – 40	> 40	IEC 60422 Consider temp. and saturation
RELATIVE SATURATION (%RS)	Calculated from ppm and oil temperature	%	< 30%	30 – 60%	> 60%	IEC 60076-57-129 TB 445
PAPER MOISTURE (Estimated)	From %RS or FDS or other methods	% by weight	< 1.5%	1.5 – 3.0%	> 3.0%	TB 349, TB 850 IEC TS 60076-57-129
BREAKDOWN VOLTAGE (BDV)	2.5 mm gap	kV	> 60	30 – 60	< 30	IEC 60156 IEEE C57.106
ACIDITY (TAN)	Total Acid Number	mg KOH/g	< 0.10	0.10 – 0.30	> 0.30	IEC 62021-1 IEEE C57.106
FURANS (2FAL)	2-Furfuraldehyde	ppb	< 250	250 – 750	> 750	IEC 61198 IEEE C57.157
METHANOL (CH_3OH)	In oil	ppb	< 100	100 – 300	> 300	IEC 62953 Early warning indicator
CO (DGA)	Carbon Monoxide	ppm	< 350	350 – 1,000	> 1,000	IEC 60599 Moisture + ageing indicator
CO_2 (DGA)	Carbon Dioxide	ppm	< 2,500	2,500 – 10,000	> 10,000	IEC 60599 Cellulose degradation
CO_2/CO RATIO	Degradation ratio	–	< 1	1 – 3	> 3	IEC 60599 Ageing severity
DISSIPATION FACTOR (tan δ)	At 90 °C (typical)	%	< 0.5	0.5 – 1.0	> 1.0	IEC 60247 Moisture + ageing
INSULATION RESISTIVITY	@ 90 °C	GΩ·m	> 1	0.1 – 1	< 0.1	IEC 60247 Affect by moisture & temp.

These limits are general guidelines for mineral oil-immersed transformers. Adjust based on transformer design, class, age, and service conditions.

NOTES & CONSIDERATIONS

- Use trend analysis rather than single values.
- Consider load, temperature, and season.
- Compare with transformer history.
- Correlate moisture indicators with aging indicators (furans, methanol, DGA, DF).
- High moisture accelerates insulation aging and reduces dielectric strength.
- Always act before indicators reach high-risk levels.

QUICK REFERENCE
Moisture is controllable.
Aging is reversible (partially).
Failure is preventable.
Monitor. Interpret. Act.

APPLICABLE TO

- **Power Transformers** – All voltage classes
- **Distribution Transformers** – Oil-immersed
- **Shunt Reactors** – Oil-immersed
- **On-load Tap Changers (OLTC)**
- **Bushings & Accessories** – Oil-immersed

BEST PRACTICES FOR ACCURATE DIAGNOSIS

- Use calibrated and verified instruments.
- Sample oil correctly and avoid contamination.
- Record temperature and load at time of sampling.
- Apply multiple diagnostics for correlation.
- Use latest standards and guideline limits.
- Document all results and actions.
- Review and update maintenance strategy based on trends and risks.

Integrated diagnostics provide the best understanding of moisture, aging, and transformer health.

DIAGNOSTIC ACTION SUMMARY

1. **MONITOR** – Collect accurate data and establish trends. →
2. **INTERPRET** – Use standards and correlation of indicators. →
3. **ASSESS RISK** – Determine aging stage and failure risk. →
4. **ACT EARLY** – Reduce moisture. Mitigate aging. Prevent failure. →
5. **REVIEW & IMPROVE** – Track results. Improve strategy. Extend life.

Standards guide testing. Diagnostics reveal the truth.
Integrated interpretation leads to informed action and long transformer life.

MOISTURE DIAGNOSTIC DECISION TREE

A systematic approach to evaluate moisture, paper aging, and associated risks

START
Collect and review latest test data

1 CHECK OIL MOISTURE (ppm)

- Compare with IEC 60422 limits
- Consider temperature

Normal (≤ 20 ppm) → **Moisture in oil is normal** – Continue routine monitoring

High (> 20 ppm) ↓

2 CALCULATE RELATIVE SATURATION (%RS)

- %RS > 60% indicates risk of paper moisture
- Consider operating temperature

%RS ≤ 60% → **Monitor closely** – Investigate if rising trend or approaching 60%

%RS > 60% ↓

3 ESTIMATE PAPER MOISTURE (% by weight)

- Use equilibrium charts or FDS/PDC
- Compare with limits (< 1.5% good)

≤ 1.5% → **Paper moisture acceptable** – Continue monitoring

> 1.5% ↓

4 CHECK CELLULOSE AGING INDICATORS FURANS (2FAL)

- < 250 ppb: Good
- 250 – 750 ppb: Caution
- > 750 ppb: High risk

Caution (250 – 750 ppb) → **Investigate trend** – Check methanol, DGA and operating conditions

High (> 750 ppb) ↓

5 CHECK EARLY AGING INDICATOR METHANOL (CH_3OH)

- < 100 ppb: Normal
- 100 – 300 ppb: Alert
- > 300 ppb: High

Alert (100 – 300 ppb) → **Monitor trend** – Correlate with moisture and furans

High (> 300 ppb) ↓

6 REVIEW DGA INDICATORS

- CO, CO_2, CO_2/CO ratio
- Increasing trend indicates accelerated aging

Elevated → **Assess severity** – Correlate with moisture and temperature

High / Severe ↓

7 NEED ADVANCED DIAGNOSTICS? Consider FDS or PDC

- High uncertainty?
- Conflicting results?
- Critical asset?

No → **Continue enhanced monitoring** – Implement moisture management plan

Yes ↓

TAKE ACTION – MANAGE MOISTURE & RISK

- Address moisture ingress and sources
- Implement drying / dehumidification strategy
- Monitor more frequently
- Reassess after corrective actions
- Document all findings and actions

RISK LEVEL GUIDE

LOW	No immediate action
MODERATE	Monitor & Investigate
HIGH	Take Action
SEVERE	Immediate Action

KEY PRINCIPLES

- Moisture starts in the oil but threatens the paper.
- Moisture migrates to the paper.
- Paper deteriorates and ages.
- Multiple diagnostics reveal the true condition.
- Early detection and action prevent failure.

INTERPRETATION SEQUENCE

1. Check Oil Moisture (ppm)
2. Calculate %RS
3. Estimate Paper Moisture
4. Review Furans (2FAL)
5. Review Methanol
6. Review DGA Indicators
7. Consider FDS / PDC
8. Make Decision & Take Action

WHEN TO ESCALATE

- %RS consistently > 60%
- Paper moisture > 2.0%
- 2FAL > 750 ppb and rising
- Methanol > 300 ppb and rising
- CO or CO_2 high and rising
- CO_2/CO ratio increasing
- Conflicting test results
- Critical or high-value asset

MOISTURE MANAGEMENT GOAL

Keep moisture out.
Keep moisture low.
Keep your transformer healthy for decades.

MONITOR. INTERPRET. CORRELATE. ACT. PROTECT.

CORRELATE – UNDERSTAND – ACT

Moisture Enters → Moisture Migrates → Paper Ages → Diagnostics Reveal → Action Protects → Asset Lives Longer

FROM MOISTURE MONITORING TO MOISTURE MANAGEMENT

Protect the Paper. Protect the Transformer. Protect the Future.

Moisture is inevitable. What matters is how we manage it.
A proactive moisture management program extends transformer life, improves reliability, and reduces total cost of ownership.

THE MOISTURE CHALLENGE

Moisture Enters (Through Breathers, Leaks, Oil Fill, Humidity) → Moisture Migrates (To Paper via Concentration Gradient) → Paper Degrades (Insulation weakens, Aging accelerates, Risk increases)

THE MOISTURE JOURNEY

1. INGRESS
- Moist air through breathers
- Oil filling
- Leaks
- High humidity

2. MIGRATION
- Moisture moves from oil to paper
- Driven by temperature and %RS
- Not always immediately visible

3. ACCUMULATION
- Moisture builds up in paper
- Lowers dielectric strength
- Accelerates aging

4. DETERIORATION
- Cellulose breaks down
- Insulation weakens
- Risk of failure increases

5. ACTION
- Detect early
- Interpret correctly
- Act before failure
- Extend asset life

THE SOLUTION

CONTINUOUS MOISTURE MANAGEMENT

- Monitor continuously
- Interpret intelligently
- Mitigate moisture ingress
- Control moisture balance
- Preserve insulation
- Ensure reliability
- Maximize transformer life

CONTINUOUS MOISTURE MANAGEMENT STRATEGY

MONITOR
Use a combination of online and offline tools.
- Oil Moisture
- %RS
- FDS / PDC
- DGA
- Furans & Methanol
- TAN, IR, BDV

INTERPRET
Correlate indicators to understand true condition.
- Trend analysis
- Cross-correlation
- Consider load, temp, season
- Use standards & limits

MANAGE
Remove, block, or control moisture sources.
- Drying / Dehumidification
- Breather management
- Leak prevention
- Oil maintenance
- Sealing & gaskets

VERIFY
Confirm effectiveness and maintain.
- Follow-up testing
- Trend improvement
- Document actions
- Continuous improvement

SUSTAIN
Build a culture of reliability.
- Trailow-u,ß awareness
- Procedures
- Records
- KPIs & reviews

THE DRYTRANS APPROACH

DryTrans

Integrated Solutions for Moisture Management in Transformers

- Advanced Diagnostics
- Moisture Control Systems
- Oil Drying & Filtration
- Breather & Sealing Solutions
- Engineering & Advisory
- Lifecycle Asset Management

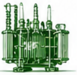
Detect. Manage. Protect.

REAL-WORLD IMPACT

UTILITY TRANSFORMER – 220 kV, 150 MVA

Challenge
High oil moisture (35 ppm), rising %RS (55%), 2FAL at 520 ppb and increasing.

Action
Online drying unit installed, breather replaced, seals improved, continuous monitoring.



Results (12 months)
- Oil moisture reduced to 12 ppm
- %RS reduced to 28%
- 2FAL reduced to 180 ppb
- Improved BDV and reliability
- Estimated life extended by 10+ years

GENERATOR STEP-UP TX – 400 kV, 300 MVA

Challenge
Moisture migration detected by FDS and rising CO/CO_2 ratio.

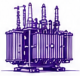
Action
Oil dehydration + paper drying using vacuum and hot oil circulation.

Results (12 months)
- Paper moisture reduced from 2.4% to 1.2%
- %RS reduced from 68% to 32%
- DGA stabilized
- No load tap changer issues
- Increased operational confidence

AGED TRANSFORMER – 132 kV, 75 MVA

Challenge
High methanol (420 ppb) and 2FAL (980 ppb), paper moisture 3.1%.

Action
Comprehensive moisture management program + seal replacement + oil rejuvenation.



Results (18 months)
- Methanol reduced to 210 ppb
- 2FAL reduced to 430 ppb
- Paper moisture reduced to 1.6%
- Significantly lower risk
- Asset life extended

THE BENEFITS OF EFFECTIVE MOISTURE MANAGEMENT

- Extends transformer life and insulation strength
- Reduces risk of unexpected failures
- Improves operational reliability and safety
- Reduces maintenance and failure-related costs
- Supports load growth and asset utilization
- Enhances return on investment
- Contributes to grid stability and sustainability

FINAL MESSAGE

“Moisture cannot be eliminated, but it can be managed.
Integrated diagnostics reveal the truth.
Timely action protects the insulation.
Smart moisture management saves assets, saves money, and powers a reliable future.”

REMEMBER

Moisture is silent.
Diagnostics speak.
Management protects.

Monitor. Interpret. Manage. Protect.

That’s the DryTrans Commitment.

Partner with DryTrans for a drier, stronger, and longer-lasting future.

CONTACT US

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MOISTURE ASSESSMENT & ANALYSIS DATA INPUT FORM

Provide Accurate Data.
Enable Accurate Diagnosis.
Support Smarter Decisions.

Please complete all applicable sections. Accurate and complete information helps us deliver a reliable moisture assessment, analysis, and interpretation report for your transformer.

1 CLIENT DETAILS

Company Name : ______

Contact Person : ______

Designation : ______

Phone : ______

Email : ______

Address : ______

Report Required By : ______ Date : ______

Purpose of Assessment : ______

2 TRANSFORMER DETAILS

Transformer ID / Name : ______

Manufacturer : ______

Serial Number : ______

Year of Manufacture : ______

Type : ______
(Power / Distribution / Generator Step-up / Other)

Voltage Rating (HV/LV) : ______ kV

Power Rating : ______ MVA

Frequency : ______ Hz

Transformer Oil Type : ______
(Mineral / Synthetic / Natural Ester / Other)

Tap Changer Type : ______
(OLTC / DETC / No Load / Fixed)

Phase : ☐ 1-Phase ☐ 3-Phase

Cooling Type :
☐ ONAN ☐ ONAF ☐ ODAF ☐ OFWF ☐ Other ______

Application
☐ Utility ☐ Industrial ☐ Oil & Gas ☐ Renewable ☐ Other ______

3 TEST RESULTS (Latest Sample)

A. OIL MOISTURE & CONDITION

Test / Parameter	Result	Unit	Test Method
Oil Moisture	(ppm)	ppm	IEC 60422
Relative Saturation (%RS)		%	IEC 60422
Oil Temperature (at sampling)		°C	—
Oil Acidity (TAN)		mg KOH/g	IEC 62021-1
Interfacial Tension (IFT)		mN/m	IEC 62937
Dielectric Breakdown Voltage (BDV)		kV	IEC 60156
Dissipation Factor (tan δ) @ 90°C		%	IEC 60247
Insulation Resistivity @ 90°C		GΩ·m	IEC 60247

B. PAPER / CELLULOSE AGING INDICATORS

Test / Parameter	Result	Unit	Test Method
Paper Moisture (Est.)	(% by weight)	%	Calc / FDS / Equil.
Furan (2FAL)		ppb	IEC 61198
Methanol (CH_3OH)		ppb	IEC 62953
Ethanol (C_2H_5OH)		ppb	IEC 62953
DP (Degree of Polymerization)		—	Calc (IEC 61198)

C. DGA (DISSOLVED GAS ANALYSIS)

Gas	Result (ppm)			Test Method
Hydrogen (H_2)		Carbon Monoxide (CO)		IEC 60599
Methane (CH_4)		Carbon Dioxide (CO_2)		
Ethylene (C_2H_4)		Oxygen (O_2)		
Ethane (C_2H_6)		Nitrogen (N_2)		

D. OPTIONAL / ADVANCED TESTS

Test / Parameter	Result	Unit	Test Method
FDS – Paper Moisture	(% by weight)	%	IEC TS 60076-57-129
PDC (at ___ °C)	(Value / Curve)	—	IEEE C57.12.00
Polarization Index (PI)		—	IEC 60076-3
Sweep Frequency Range		kHz	FDS / PDC
Sample Condition	(New / In Service)	—	—

Comments

4 PAST OIL CONDITIONING DATA

Date (dd/mm/yyyy)	Service Performed	Method / Equipment	Moisture Before (ppm/%RS)	Moisture After (ppm/%RS)	Oil Temp. (°C)	Duration (hours)	Remarks

5 MAINTENANCE HISTORY (Recent)

Last Major Overhaul : [dd/mm/yyyy]

Last Oil Replacement : [dd/mm/yyyy]

Last Drying / Filtration : [dd/mm/yyyy]

Last DGA : [dd/mm/yyyy]

Last Furan / Methanol Test : [dd/mm/yyyy]

Any Recent Faults / Alarms : ☐ Yes ☐ No

If Yes, Please Describe

______

6 OPERATING INFORMATION (At Time of Sampling)

Load : ______ % or ______ MVA

Top Oil Temperature : ______ °C

Ambient Temperature : ______ °C

Oil Level (if applicable) : ☐ Normal ☐ High ☐ Low

Breather Type : ☐ Silica Gel ☐ Molecular Sieve ☐ Other ______

Breather Condition : ☐ Good ☐ Saturated ☐ Unknown

Sampling Point : ☐ Main Tank ☐ Conservator ☐ Other ______

Sampling Method : ☐ Top Oil ☐ Bottom Oil ☐ Other ______

7 ADDITIONAL INFORMATION

Please provide any additional information that may help in analysis and interpretation.

______

8 OTHER COMMENTS / OBSERVATIONS

______

HOW TO SUBMIT

- Fill this form completely.
- Attach latest test reports (if available).
- Email to vishal@drytrans.com
- Our team will review and respond with a Moisture Assessment & Interpretation Report.

OUR COMMITMENT

Accurate data in.
Accurate diagnosis out.
Better decisions.
Stronger assets.

CONFIDENTIALITY ASSURANCE

All information provided will be treated as confidential and used solely for the purpose of moisture assessment, analysis, and recommendations.

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TRANSFORMER INSULATION MOISTURE ASSESSMENT REPORT

Integrated Diagnostics. Accurate Interpretation. Smarter Decisions.

1. CLIENT & TRANSFORMER DETAILS

Client Name	:	ABC Utility
Location	:	Abu Dhabi, UAE
Transformer ID	:	GT-01
Manufacturer	:	XYZ Transformers
Rating	:	220 MVA
Voltage Rating	:	220 / 132 kV
Year of Manufacture	:	2008
Transformer Type	:	ONAN
Oil Type	:	Mineral Oil
Tap Changer Type	:	OLTC
Application	:	Power Generation
Assessment Reference	:	DT-MAR-2026-001

2. MOISTURE RISK DASHBOARD

MOISTURE CONDITION	CELLULOSE AGING RISK	DIELECTRIC RISK	OVERALL MOISTURE RISK
HIGH	MODERATE	MODERATE	HIGH

OVERALL ASSESSMENT

HIGH RISK

IMMEDIATE ATTENTION RECOMMENDED

3. MOISTURE ASSESSMENT SUMMARY

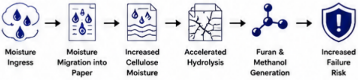
Parameter	Result	Unit	Status	Interpretation
Oil Moisture	28	ppm	●	Attention
Relative Saturation (%RS)	52	%	●	High
Estimated Paper Moisture	3.4	%	●	High
Furan (2FAL)	780	ppb	●	High
Methanol (CH_3OH)	290	ppb	●	Attention
CO	950	ppm	●	Attention
CO_2	6,500	ppm	●	Attention
Breakdown Voltage (BDV)	42	kV	●	Attention
Acidity (TAN)	0.12	mg KOH/g	●	Normal
Interfacial Tension (IFT)	32	mN/m	●	Normal
Dissipation Factor (tan δ @ 90°C)	0.45	%	●	Normal
Insulation Resistivity (@ 90°C)	1.2	GΩ·m	●	Normal

● Normal (Good) ● Attention (Monitor) ● High (Action Required)

4. KEY FINDINGS

- Elevated moisture content present within insulation system.
- Relative saturation indicates increased moisture availability.
- Estimated paper moisture above recommended range.
- Furan and methanol indicate active cellulose aging.
- Reduced dielectric margin observed.
- Moisture identified as primary degradation mechanism.
- No evidence of severe active electrical fault from available data.

5. MOISTURE PATHWAY INTERPRETATION



Moisture is the root cause that accelerates insulation aging and increases failure risk.

6. TRANSFORMER MOISTURE HEALTH INDEX

58
/100

FAIR CONDITION

Moisture Management Recommended

Assessment Category	Weight	Score (0-100)
Moisture Condition	30%	45
Paper Aging	25%	55
Dielectric Performance	20%	65
DGA Indicators	15%	75
Operating Conditions	10%	80
TOTAL	100%	58

7. RECOMMENDED ACTIONS

IMMEDIATE ACTIONS (0 – 3 MONTHS)

- Verify moisture trend with increased sampling.
- Inspect breather condition and replace if required.
- Check for oil leaks and moisture ingress sources.
- Verify sealing integrity of tank, conservator & bushings.
- Increase monitoring frequency.

MEDIUM-TERM ACTIONS (3 – 12 MONTHS)

- Implement moisture reduction strategy (drying/filtration).
- Correlate moisture with loading and temperature.
- Monitor paper aging indicators (furans, methanol).
- Perform dielectric tests to track improvement.

LONG-TERM STRATEGY (> 12 MONTHS)

- Establish continuous moisture management plan.
- Perform annual moisture assessment review.
- Track insulation aging progression over time.
- Optimize operating conditions to reduce stress.

8. ESTIMATED IMPROVEMENT POTENTIAL

Parameter	Current	Target	Expected Benefit
Oil Moisture	28 ppm	< 15 ppm	Improved insulation life
Relative Saturation	52 %	< 25 %	Reduced moisture availability
Paper Moisture	3.4 %	< 2.0 %	Lower aging rate
Furan Trend (2FAL)	Rising	Stabilized	Slower cellulose degradation
Dielectric Margin (BDV)	42 kV	> 60 kV	Improved dielectric strength
Overall Reliability	Moderate	High	Extended asset life

9. ENGINEERING CONCLUSION

Based on the available diagnostic information, the transformer insulation system exhibits elevated moisture levels and evidence of ongoing cellulose aging.

Moisture is identified as the dominant degradation driver.

Corrective moisture management actions are recommended to reduce insulation aging rate, improve dielectric performance, and support long-term asset reliability.

10. ASSESSMENT CONFIDENCE LEVEL

Available Data	Confidence	
Moisture Only	★☆☆☆☆	Low
Moisture + Oil Tests	★★☆☆☆	Medium
Moisture + Oil + Furans	★★½☆☆	Good
Moisture + Oil + Furans + Methanol + DGA	★★★★☆	High
Plus FDS / PDC	★★★★★	Very High

CURRENT ASSESSMENT CONFIDENCE

HIGH

11. METHODOLOGY REFERENCES

- **IEC 60422** – Mineral Insulating Oils – Sampling and Tests
- **IEC 60814** – Insulating Liquids – Selection and Maintenance
- **IEC TS 60076-57-129** – Guide for Moisture Equilibrium & Oil Treatment
- **IEEE C57.106** – Guide for Acceptance and Maintenance of Insulating Oil
- **IEEE C57.91** – Mineral Oil-Immersed Transformers – Guide
- **CIGRÉ TB 349** – Moisture Equilibrium and Moisture in Transformers
- **CIGRÉ TB 741** – Dissolved Gas Analysis – Interpretation and Diagnostic Techniques
- **CIGRÉ TB 761** – Moisture in Transformer, Insulation

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ESTIMATED WATER QUANTITY

IN TRANSFORMER OIL AND CELLULOSE INSULATION

Using T.V. Oommen Oil–Paper Moisture Equilibrium Curve

WHY THIS MATTERS

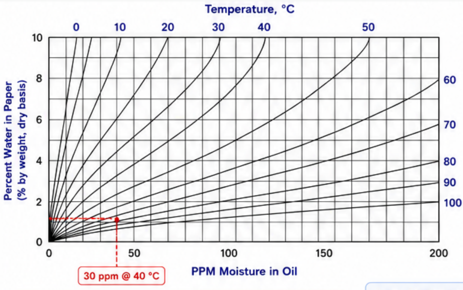
Oil moisture measurements alone do not indicate how much water is present in the transformer insulation system. Since most moisture resides in cellulose insulation, estimating the total water quantity helps assess insulation condition and moisture management requirements.

1. EXAMPLE INPUTS

Parameter	Value
Oil Volume (V_{oil})	60,000 L
Oil Moisture (C_o)	30 ppm
Oil Temperature (T)	40 °C
Oil Type	Mineral Oil
Oil Density (ρ_{oil})	0.89 kg/L
Estimated Dry Paper Mass (M_p)	6,000 kg (≈ 10% of oil volume)
Estimation Method	T.V. Oommen Curve

Note: Dry paper mass is assumed as approximately 10% of oil volume when manufacturer data is unavailable.

2. T.V. OOMMEN OIL–PAPER MOISTURE EQUILIBRIUM CURVE (MINERAL OIL)



From the T.V. Oommen curve: At 40 °C and 30 ppm in oil,

Estimated Paper Moisture ≈ **1.1 – 1.3 %** (by weight, dry basis)

Source: T.V. Oommen, "Moisture Equilibrium Curves – Use and Misuse", Doble Conference Proceedings, 2003.

3. WATER QUANTITY IN OIL

Step 1: Oil Mass (kg)

$$M_{oil} = V_{oil} \times \rho_{oil} = 60{,}000 \times 0.89 = 53{,}400 \text{ kg}$$

Step 2: Water in Oil (kg)

$$M_{water,oil} = \frac{C_o\ (\text{ppm}) \times M_{oil}\ (\text{kg})}{1{,}000{,}000} = \frac{30 \times 53{,}400}{1{,}000{,}000} = 1.602 \text{ kg}$$

Step 3: Convert to Liters

$$M_{water,oil}\ (\text{L}) = \frac{M_{water,oil}\ (\text{kg})}{\rho_{water}\ (\text{kg/L})} = \frac{1.602}{1.0} \approx 1.6 \text{ Liters}$$

Water in Oil ≈ 1.6 Liters

4. WATER QUANTITY IN PAPER (USING OOMMEN CURVE)

Step 1: Use Oommen curve estimate of paper moisture

At 40 °C and 30 ppm in oil, Estimated Paper Moisture ≈ 1.1 – 1.3 % (dry basis)

Step 2: Water in Paper (kg)

$$M_{water,paper}\ (\text{kg}) = \frac{M_p\ (\text{kg}) \times X_p\ (\%)}{100}$$

Where M_p = estimated dry paper mass

Estimated Paper Moisture (X_p)	Water in Paper (kg)	Water in Paper (L*)
1.1 %	66 kg	≈ 66 L
1.2 %	72 kg	≈ 72 L
1.3 %	78 kg	≈ 78 L

Step 3: Convert to Liters

$$M_{water,paper}\ (\text{L}) = \frac{M_{water,paper}\ (\text{kg})}{\rho_{water}\ (\text{kg/L})}, \quad \rho_{water} \approx 1.0 \text{ kg/L}$$

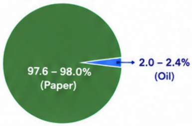
Water in Paper (Cellulose Insulation) ≈ 66 – 78 Liters

5. RESULTS SUMMARY

Total Water Quantity in Transformer Insulation System

Location	Water Quantity (Liters)
Oil	≈ 1.6 L
Cellulose Insulation (Paper)	≈ 66 – 78 L
TOTAL WATER (Approx.)	≈ 67.6 – 79.6 L

6. MOISTURE DISTRIBUTION (Approx.)



7. KEY ENGINEERING INSIGHT

Although oil moisture is measured in ppm, the majority of water in a transformer insulation system is stored in cellulose insulation.

Therefore, moisture assessment should focus on estimating paper moisture and total water inventory rather than oil moisture alone.

8. LIMITATIONS OF OOMMEN-BASED WATER ESTIMATES

Assumes approximate oil–paper equilibrium.

- Actual paper mass varies by transformer design.
- Moisture distribution is not uniform throughout insulation.
- Seasonal and loading variations affect moisture migration.
- Oommen curves are based on mineral oil; for ester fluids, different curves apply.
- FDS / PDC measurements provide higher confidence for direct paper moisture assessment.

9. IMPORTANT NOTE

Oommen equilibrium curves provide an engineering estimate of paper moisture based on oil moisture and temperature under approximate equilibrium conditions.

Operating transformers are dynamic systems and may not be in true equilibrium due to load changes, temperature gradients, oil circulation, and moisture migration.

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