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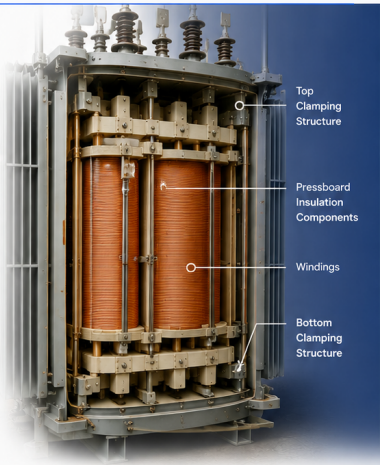
# MOISTURE, WINDING CLAMPING PRESSURE, AND THE SEARCH FOR THE OPTIMUM DRYNESS LEVEL

## Understanding Why Transformer Reliability Is About Balance, Not Maximum Drying

For decades, moisture has been viewed primarily as an electrical insulation problem. Excessive moisture in transformer insulation is known to reduce dielectric strength, accelerate cellulose aging, increase dielectric losses, promote partial discharge activity, and increase bubbling risk during overload conditions.

As a result, utilities often pursue drying programs with a simple objective: reduce moisture as much as possible.

**However, recent research has revealed that moisture influences more than just dielectric performance. It also affects the mechanical behavior of cellulose insulation and therefore the winding clamping pressure that maintains transformer structural integrity.**




This raises an important question:
**Should transformers always be dried to the lowest possible moisture level, or is there an optimum operating range?**

### WINDING CLAMPING PRESSURE – THE HIDDEN RELIABILITY PARAMETER

Power transformer windings are compressed between structural clamping assemblies. The purpose of this clamping system is to:

- Maintain winding geometry
- Prevent winding displacement
- Withstand electromechanical forces during short circuits
- Preserve insulation clearances throughout transformer life

**A loss of winding clamping pressure can increase the risk of:**

- Axial winding movement
- Radial deformation
- Buckling
- Short-circuit damage
- Reduced mechanical withstand capability

Recent work by Naranpanawe, Saha, and Ekanayake (IEEE APPEEC 2016) demonstrated that winding clamping pressure is strongly dependent on **both moisture content and temperature** because cellulose pressboard changes its dimensions and mechanical properties as moisture levels vary.

**In other words:**
**Moisture affects not only electrical insulation performance but also the mechanical behavior of the transformer insulation system.**

**KEY MESSAGE:** **Transformer reliability is about balance, not maximum drying.**

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# THE OPTIMUM MOISTURE RANGE FOR TRANSFORMER RELIABILITY

## Why Balance Matters More Than Maximum Drying

Moisture is essential in small amounts but harmful in excess. The goal is not to remove every last ppm of moisture, but to maintain the insulation system within an **optimum** moisture range that balances electrical performance, ageing rate, mechanical integrity and operational reliability.

Moisture, temperature and ageing interact continuously. Changing any one of these factors influences the others and the overall condition of the insulation system.

**Therefore, dehydration should be controlled, data-driven and transformer-specific.**

## MOISTURE IMPACTS MULTIPLE RELIABILITY DIMENSIONS

### ELECTRICAL PERFORMANCE

- Reduces dielectric strength
- Increases dielectric losses
- Increases partial discharge risk

### CHEMICAL AGING

- Accelerates hydrolysis
- Lowers DP
- Increases furan and methanol
- Increases acidity

### THERMAL & BUBBLING RISK

- Lowers bubble inception voltage
- Increases hot-spot temperature
- Reduces overload capability

### MECHANICAL INTEGRITY

- Changes pressboard dimensions
- Alters compression characteristics
- Influences winding clamping pressure

Moisture affects not only electrical insulation performance, but also the mechanical behavior of the transformer insulation system. This is a critical factor in long-term reliability.

## THE MOISTURE SPECTRUM – TOO WET, OPTIMUM, TOO DRY

### TOO WET
**High Risk**

- Accelerated insulation ageing
- Reduced dielectric strength
- High dielectric losses
- Higher bubble formation risk
- Increased partial discharge activity
- Corrosion and chemical reactions

### OPTIMUM MOISTURE RANGE
**Best Balance of Performance and Life**

**BEST BALANCE ACHIEVED**

- Stable dielectric performance
- Slower ageing rate
- Lower bubble risk
- Stable mechanical properties
- Better overall operational reliability

### POTENTIALLY TOO DRY
**Potential Concerns**

- Excessive cellulose shrinkage
- Changes in pressboard compression characteristics
- Changes in winding clamping pressure distribution
- Increased mechanical stress redistribution (especially in aged transformers)

## KEY TAKEAWAY

**The driest transformer is not always the most reliable transformer.**

**The most reliable transformer is the one maintained within an optimum moisture range for its age, design and operating conditions.**

## PRACTICAL MOISTURE TARGETS (PAPER MOISTURE %)

| TRANSFORMER CONDITION | TYPICAL PAPER MOISTURE RANGE | OBJECTIVE |
|---|---|---|
| New Transformers (Factory Condition) | 0.5 – 1.5% | Ensure excellent dielectric performance and low initial ageing rate |
| Healthy In-Service Transformers | 1.0 – 2.0% | Maintain optimal balance of performance, life and mechanical stability |
| Aging In-Service Transformers | 2.0 – 3.0% | Control ageing while maintaining mechanical integrity |
| Elevated Risk Zone (Too Wet) | > 3.0% | Take immediate action to reduce moisture content |

### WHY TARGETS VARY

Optimum moisture levels are not one-size-fits-all. They depend on:

- Transformer age and design
- Degree of polymerization (DP)
- Mechanical condition
- Operating temperature
- Loading profile
- Environmental conditions
- Sealing and ingress control

Paper moisture estimation using accurate oil testing methods (RS, $a_w$) is essential to determine when dehydration objectives are achieved.

## THE DRYTRANS PHILOSOPHY

### Controlled Dehydration. Not Maximum Dehydration.

DryTrans systems continuously remove excess moisture from the transformer and guide it to a healthier equilibrium state—where electrical, chemical, thermal and mechanical requirements are all in balance.

- Dehydrate the transformer to a safe and optimal level.
- Prevent moisture from re-entering the insulation system.
- Track moisture trends continuously.
- Make informed decisions based on data, not assumptions.
- Protect both electrical and mechanical integrity.

**A stable insulation system is a reliable insulation system. Controlled dehydration today ensures transformer reliability and asset value for decades.**

## KEY MESSAGE:

**Move from removing moisture blindly, to managing moisture intelligently.**

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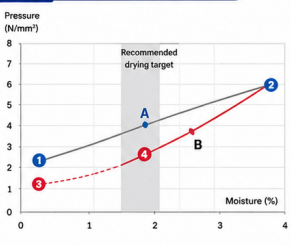
# FROM MOISTURE REDUCTION TO MOISTURE OPTIMIZATION

## Establishing Practical Dehydration Targets for Long-Term Transformer Reliability

Industry experience confirms that while excessive moisture is harmful, removing too much moisture—especially in aged transformers—can reduce winding clamping pressure disproportionately. The goal is to dehydrate to the right level and then maintain it.

### EFFECTS OF DRYING ON WINDING PRESSURE




Source: C. Krause (Weidmann), CIGRÉ Paper C101,
6th Southern Africa Regional Conference, 2009.

1. **Initial moisture and winding pressure (new transformer)**
   Winding pressure is relatively low at low moisture content.

A. **Moisture accumulates over time,**
   winding pressure increases accordingly.

2. **Critical moisture level is reached,**
   drying is initiated.

B. **Transformer is dried,**
   winding pressure declines disproportionately as moisture is removed.

3. If drying is continued to the initial moisture level, winding pressure becomes critically low, impairing the transformer's mechanical stability.

4. Correct drying target balances the benefits of moisture reduction and the risks of loss of winding pressure.

### KEY INTERPRETATION

- As moisture increases, pressboard swells and winding pressure rises.
- Drying reduces moisture and improves dielectric condition.
- However, excessive drying can lead to a sharper reduction in winding pressure.
- A practical drying target (typically around 1.5 – 2.0% paper moisture) provides the best balance between:
  - Electrical performance
  - Aging mitigation
  - Mechanical integrity

**THE OBJECTIVE IS NOT MAXIMUM DRYING.**
**THE OBJECTIVE IS OPTIMUM MOISTURE MANAGEMENT.**

Controlled dehydration ensures a stable insulation system that performs reliably under electrical, thermal and mechanical stresses throughout its service life.

### FACTORS THAT INFLUENCE THE OPTIMUM DRYING TARGET

**Transformer Age & Insulation Condition**
Older transformers with lower DP (degree of polymerization) may be more sensitive to large moisture changes.

**Degree of Polymerization (DP)**
Lower DP insulation is more prone to mechanical weakening and may require a higher target moisture.

**Mechanical Condition**
Existing compression level, historical short-circuit events and core-winding assembly condition.

**Operating Temperature**
Higher operating temperature increases moisture migration and affects the optimum equilibrium point.

**Loading Profile**
Load cycles influence temperature and moisture movement between oil and paper.

**Oil Quality & Sealing Condition**
Moisture ingress rate determines how quickly the transformer moves away from the optimum range.

### WHY CONTROLLED DRYING IS ESSENTIAL

- Reduces ageing rate and extends insulation life
- Improves dielectric strength and reliability
- Reduces risk of bubbling and partial discharge
- Maintains adequate winding clamping pressure
- Supports mechanical stability during fault conditions
- Preserves overall transformer integrity and asset value

> **The best drying level is the one that keeps the insulation system stable, not the one that removes every last molecule of moisture.**

### DRYTRANS INSIGHT

Every transformer is unique. The optimum moisture target should be determined based on real-time condition data and continuous monitoring—not assumptions.

### A PRACTICAL PERSPECTIVE

The data shows that a drying target in the range of 1.5 – 2.0% paper moisture (for most in-service transformers) provides an excellent balance between electrical performance, ageing control and mechanical integrity.

**Optimum moisture is not a fixed number.**
**It is a managed condition.**

### THE BOTTOM LINE

Move transformers from the "Too Wet" region to the "Optimum Moisture Range" and keep them there. This is the most effective path to long-term reliability and lower life-cycle cost.

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# KEY TAKEAWAYS & CONCLUSIONS

Transformer reliability is achieved by managing moisture intelligently—not by removing it completely.

### 1. MOISTURE IS A MULTI-DIMENSIONAL RELIABILITY FACTOR

Moisture impacts electrical performance, accelerates chemical aging, increases bubbling risk, and influences the mechanical behavior of cellulose insulation and winding clamping pressure.

### 2. OPTIMUM RANGE, NOT MINIMUM

Both excessive moisture and excessive drying create risks. The objective is to maintain the insulation system within an optimum moisture range that delivers the best balance of electrical, chemical, thermal and mechanical performance.

### 3. WINDING CLAMPING PRESSURE MATTERS

Moisture changes cause pressboard and cellulose to swell or shrink, directly affecting winding clamping pressure. This must be considered when setting dehydration targets, especially for aged transformers.

### 4. TEMPERATURE AND AGEING INFLUENCE EVERYTHING

Operating temperature and degree of polymerization (DP) alter how moisture behaves in the insulation system. Drying targets must be adjusted based on transformer age, condition and operating environment.

### 5. CONTINUOUS MONITORING IS ESSENTIAL

Moisture is dynamic. Continuous or periodic monitoring of moisture, temperature, and insulation condition enables data-driven decisions and helps confirm that dehydration objectives are achieved and maintained.

### 6. CONTROLLED DEHYDRATION CREATES LONG-TERM VALUE

Controlled dehydration reduces ageing rate, improves dielectric reliability, minimizes the risk of bubbles and partial discharge, and preserves mechanical integrity—ultimately extending transformer life and lowering life-cycle cost.

## THE DRYTRANS PERSPECTIVE

**We believe the future of transformer reliability lies in intelligent moisture management.**

- Remove excess moisture when needed.
- Achieve the optimum moisture range.
- Maintain that range over time.
- Protect electrical and mechanical integrity.
- Maximize reliability, minimize risk and reduce cost.

> The goal is a stable insulation system that performs reliably today—and continues to do so for decades.

## PRACTICAL ACTIONS FOR UTILITIES

**SET CLEAR TARGETS**
Define transformer-specific moisture targets based on age, condition and operating environment.

**MEASURE ACCURATELY**
Use reliable methods to estimate paper moisture (%), moisture in oil (ppm) and temperature.

**TREND AND ANALYZE**
Evaluate trends, not single data points. Understand moisture behavior under real operating conditions.

**CONTROL MOISTURE**
Use appropriate drying methods and maintain breathers, seals and oil quality.

**VERIFY AND VALIDATE**
Confirm when the optimum range is achieved and continue monitoring to maintain it.

**PARTNER WITH EXPERTS**
Work with experienced specialists who understand the science and the operational reality.

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