Industry NAVIGATOR

SUSTAINABLE DEVELOPMENT STRATEGIES FOR T&D

CONFERENCE 2025

EDF – Effective approach of transformers monitoring to improve sustainable fleet management

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EDF

EDF main generation transformers fleets + context

Hydro fleet ⇨ ≈ 800 power transformers / ≈ 100 monitored

Nuclear fleet ⇨ ≈ 310 power ODAF transformers / ≈ 230 to be monitored (No OLTC)

Surging demand for transformers worldwide: large impact due to ageing fleets renewal, increasing electrification projects (including renewable), labor shortages, supply chains (Covid-19 and others)

⇨ **Most of the power transformers are custom products** with little to no standardization and complex requirements (EU Ecodesign Regulation) + need for specific raw materials quality

⇨ **Each require extensive studies** and testing, and are unique or produced in very small batches

⇨ **Major equipment manufacturers' order books are full** for the next 3 to 7 years (!) and the same is true for accessories such as bushings (at least 1 year between order and delivery)

⇨ **Fleet assessment and life extension is more essential than ever in:**

⇨ **Sustainable & resilient production approaches to best prevent any major failure!**

Evolution with a new effective monitoring approach ☺

Offline fleet assessment + Online monitoring systems

Offline fleet assessment (≈ 1,800 transformers):

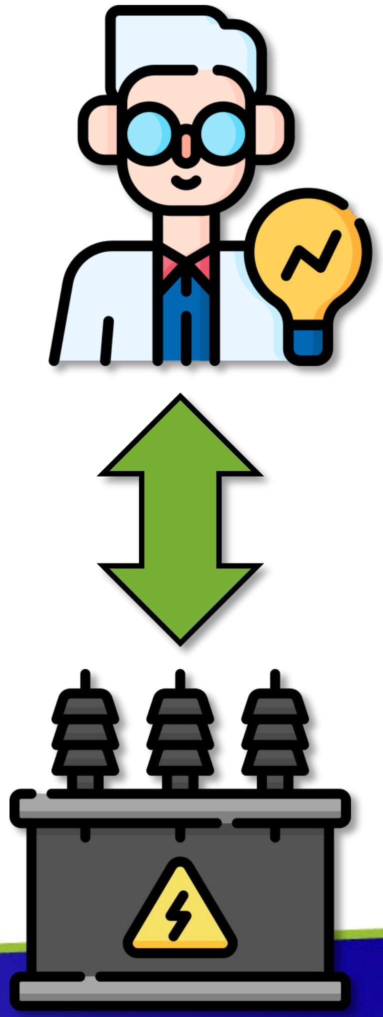
⇨ Inhouse database + tool to automatically assess all periodic oil analysis (+ bushings)
⇨ 3 health indexes automatic calculations: health, risk and confidence

Monitoring assessment (≈ 300 transformers to come), and / or:

⇨ **Thermal** (mid to long term evolutions)
Top oil + ambient temperatures + load + cooling stage (ODAF) = 1 measure / 10 min

⇨ **Dissolved Gas Analysis (DGA)** (short to mid term evolutions)
9 gases to perform fault identification = 1 measure / day to 1 measure / hour

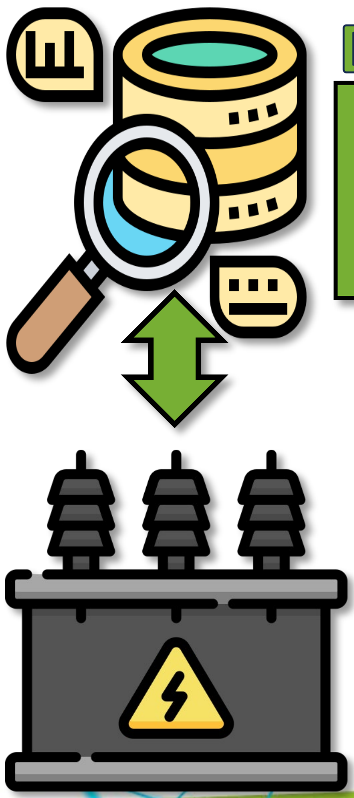
⇨ **Bushing monitoring** (very short to short term evolutions)
Capacitive currents + partial discharges + relative tan δ = 1 measure / hour



Effective monitoring approach: All about risks & actions

⇨ Convert complex data into ***risk levels*** and ***operational actions*** without requiring expert knowledge

⇨ The expert is in the software ☺



DATA

- Thermal
- DGA
- Bushing

RISK EVALUATION

- Loss of cooling efficiency
- High risk fault
- Missing layer

ACTION

- Clean coolers
- Reduce load
- Deenergize…

Designed to improve:

- ➢ Monitoring impact & efficiency
- ➢ Thus ⇨ reliability rate = no (less!) failures
- ➢ Thus ⇨ sustainable fleet management ☺

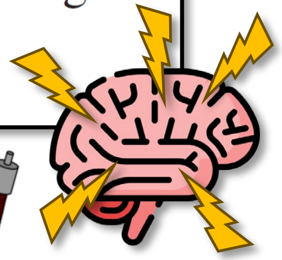
Thermal monitoring of ODAF transformers (1/2)

Based on extensive internal studies published by EDF
(Luc Paulhiac and Rémi Desquiens)

IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 37, NO. 5, OCTOBER 2022 4135

Dynamic Thermal Model for Oil Directed Air Forced Power Transformers With Cooling Stage Representation

Luc Paulhiac and Rémi Desquiens

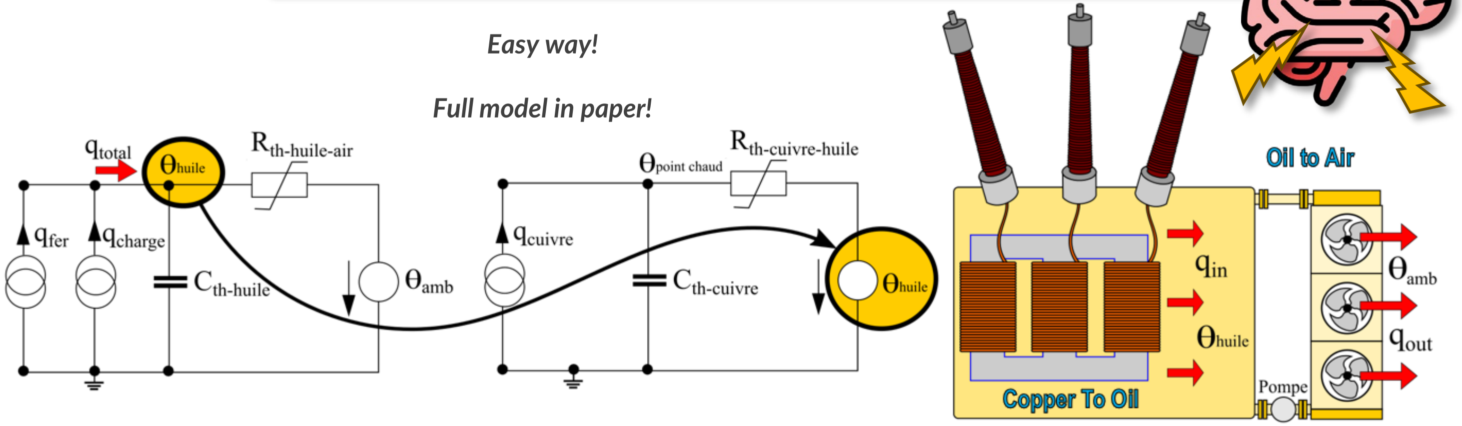


Uses of a “digital twin”:

- ➪ Optimize the cooling stages to minimize ageing
- ➪ Evaluate in operation thermal margins
- ➪ Estimate the loss of coolers’ efficiency
- ➪ Condition based maintenance of coolers
- ➪ Calculate emergency cooling capacity, etc.

Easy way!

Full model in paper!

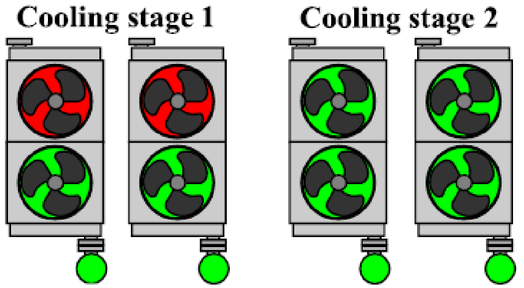


Inputs & outputs:

- ➪ Basic factory acceptance tests (FAT) data: no-load + load losses + heat run temperature rises.
- ➪ Operational parameters: top oil and ambient temperatures, load, cooling stages.
- ➪ Continuous model / measures comparison

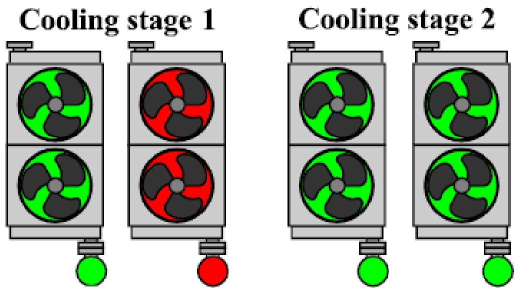
Thermal monitoring of ODAF Transformers (2/2)

Constant Oil flow / Fan modulation

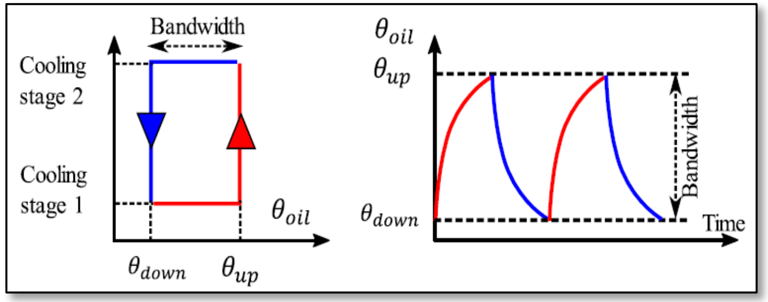


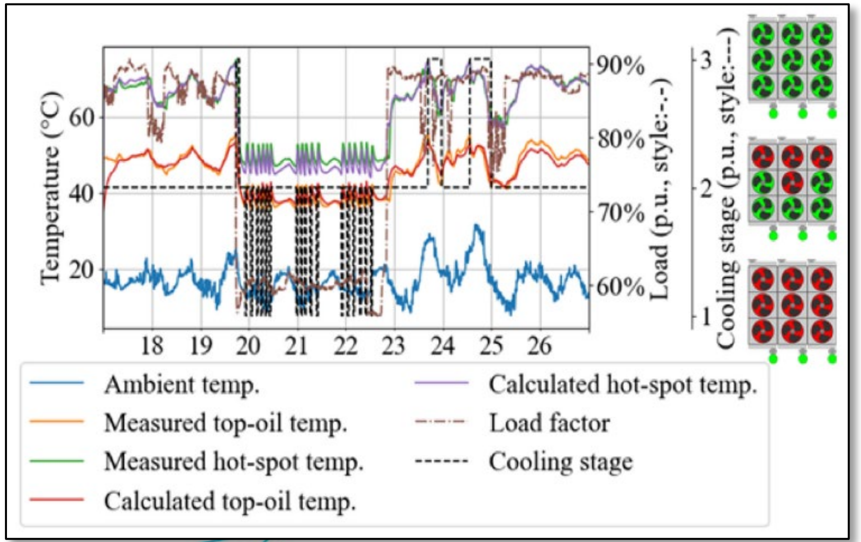
OR

Sub exchanger modulation



Hysteresis based regulation





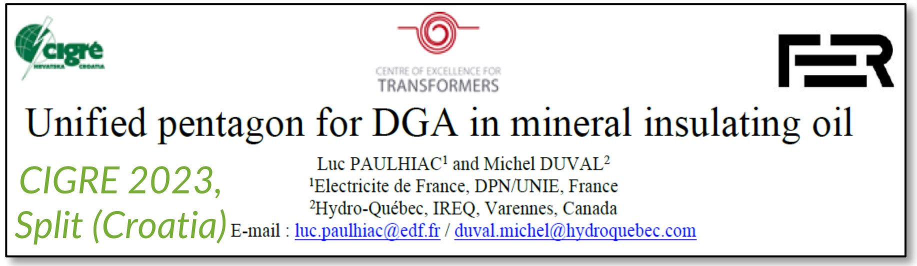
"Digital twin" = Online evaluation of normalized TopOil value (1 pu, 20°C)

Δ K	State	Actions
< 8	1: OK ☺	No actions required
8-16	2: Check	Clean filters with compressed air!
> 16	3: Bad ☹	State 2 + water cleaning + check thermal margins.

Example of poplar cottonwood blocking the finned tubes

Dissolved gas analysis monitoring (1/2)

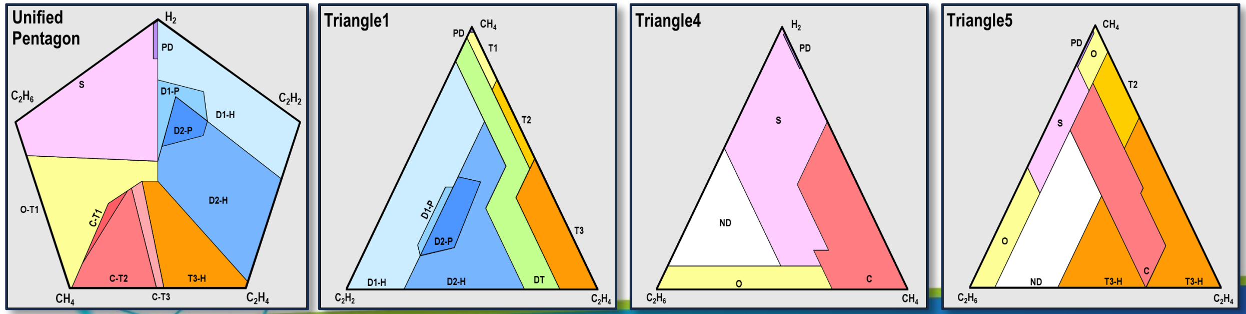
Based on research by Michel Duval (**Cigre TB-771**) and Luc Paulhiac
+ Ongoing publication Duval/Paulhiac in IEEE Access and in Cigre 2025-Montréal



CIGRE 2023, Split (Croatia)

Faults & severity: Not all faults are equal!

- ⇨ 11 types of faults
- ⇨ **Main fault** determined with a **pentagon**
- ⇨ **Secondary fault** determined with **triangles (1/4/5)**
- ⇨ **Severity** depends on the
  - ⇨ Fault **type** (dielectric / thermal)
  - ⇨ **Location** of the fault (paper / oil)

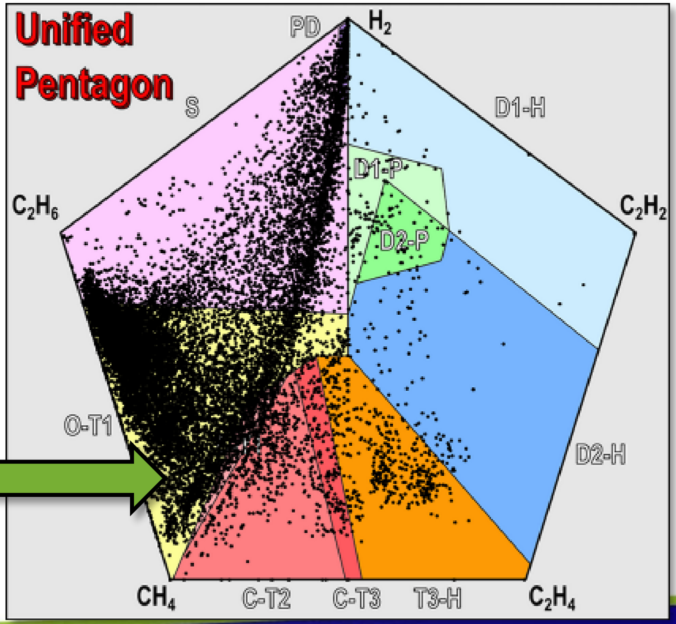


Fault Severity

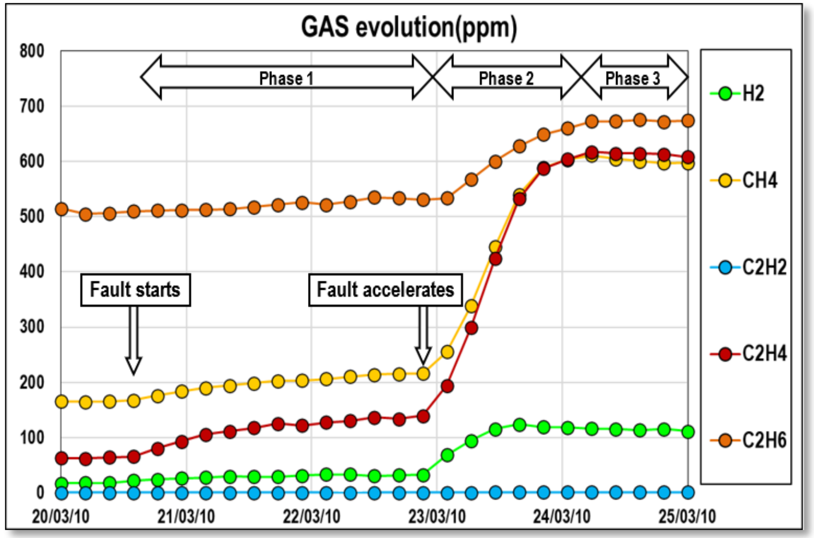
Fault Type	Severity Scale
S	Low
PD	Low
O-T1	Low
T3-H	Low
D1-H	Moderate
C-T1	High
C-T2	High
C-T3	High
D2-H	High
D1-P	Very High
D2-P	Very High

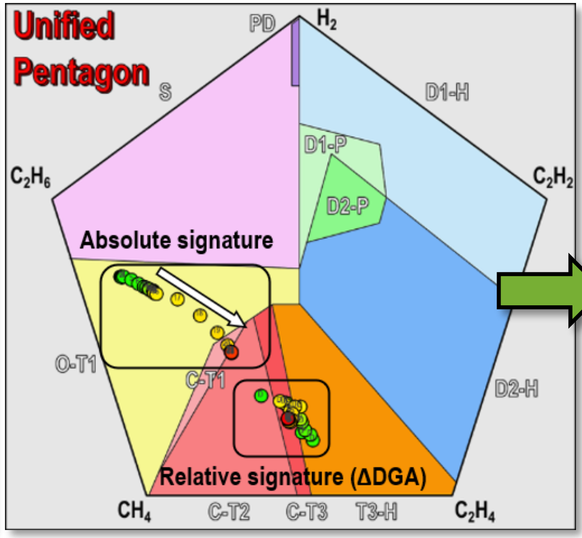
Most of the gassing are in S and O-T1 zones

EDF-data cluster (34,000 DGA)



Dissolved gas analysis monitoring (2/2)





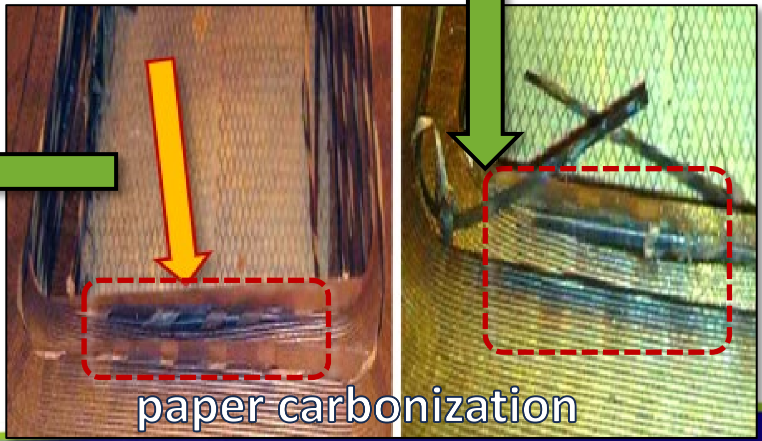
Sub Fault Type	Sub Fault Severity Scale	Associated Dominant Gas	Risk Scale for the Equipment: Dominant Gas Level = Low to Typical NO FAULT & Little to No gassing Activity If Dominant Gas CONS OR ROC < 90%	Dominant Gas Level = Typical to PF FAULT & Gassing Activity If Dominant Gas 90%< CONS OR ROC < PF	Dominant Gas Level = Pre-Failure State FAULT & Severe Gassing Activity If Dominant Gas CONC OR ROC > PF
S	Low	H_2 or C_2H_6	Low	Low to Moderate	High
PD		H_2			
O-T1		C_2H_6			
T3-H		C_2H_4			
D1-H	Moderate	C_2H_2	Low to Moderate	Moderate to high	Very High
C-T1	High	CH_4 or C_2H_4	Moderate to high	High	Very High +
C-T2					
C-T3					
D2-H		C_2H_2			
D1-P	Very High		High	Very High	Very High ++
D2-P					

Challenges:

- ⇨ Detect gassing evolutions = adaptation of the new method to online monitoring
- ⇨ Analyze relative signature
- ⇨ Adapt sampling frequency
- ⇨ Some faults evolve very fast, etc.

Risk and Proposed Action

Risk Scale		Action
Low	1.0	Normal business…
Low to Moderate	1.5	
Moderate	2.0	
Moderate to high	2.5	Increase sampling frequency (always use remote oil sampling ports). Examine faults more in depth. For thermal and especially "C" faults perform load variations to evaluate the effect on the gas production.
High	3.0	
High to Very High	3.5	
Very High	4.0	Install an online gas analyzer… Examine faults more in depth. Ask for an expert (and/or the vendor) to have a second look. Consider removing the transformer from operation (for further investigations) especially if the signature is rapidly moving toward faults associated to high or very high severity.
Very High +	4.5	
Very High ++	5.0	



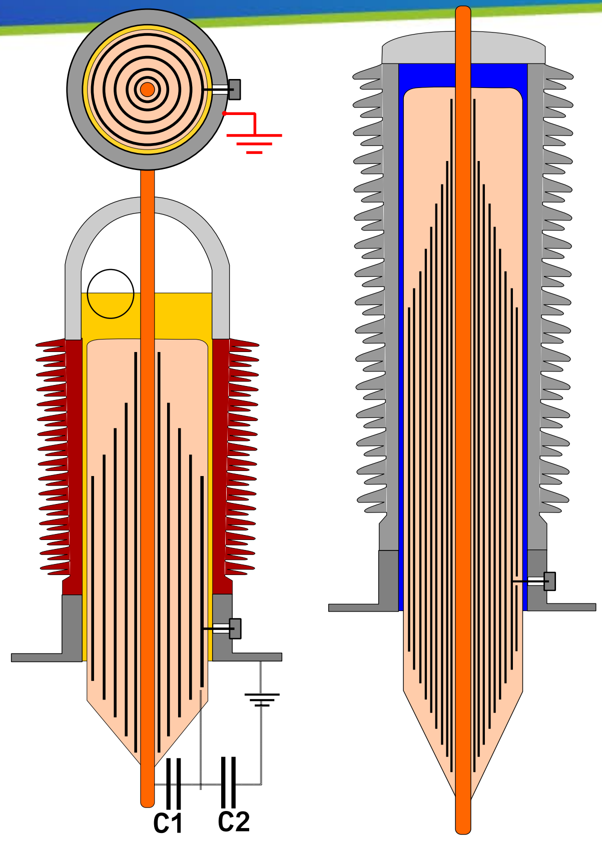
Bushing monitoring (1/2)

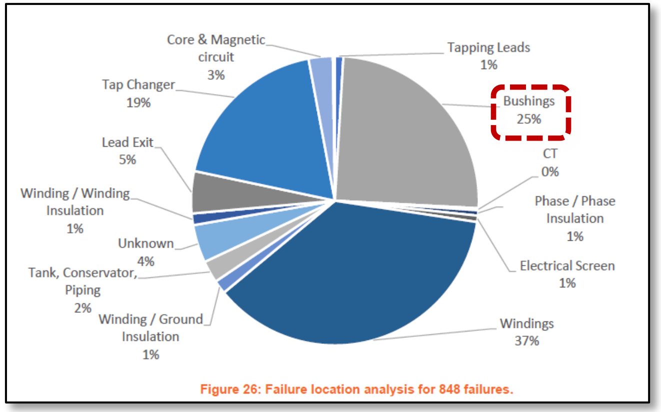
Bushings are a major SPV (single point of vulnerability) **:**

- ⇨ 25 % of transformers failures
- ⇨ More than 50 % of the fire cases

Monitoring based on:

- ⇨ Leakage currents (C1) ⇨ missing layers
- ⇨ Relative tan δ (without voltage references)
- ⇨ Partial discharges





CIGRE TB#939 AC Transformer Reliability
See Also TB#755 Bushing Reliability

Oil/SF6 RIP High Voltage Bushings on GIS Field Cases of Tests Onsite and Investigations

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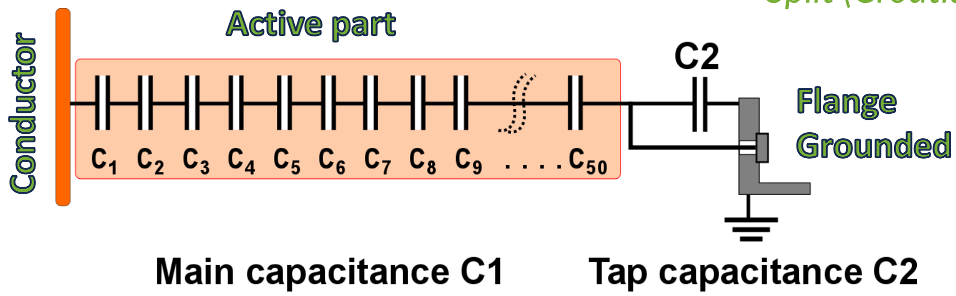
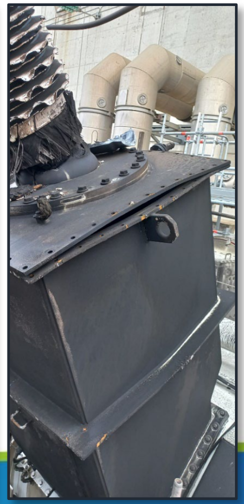




Bushing monitoring (2/2)

EDF has developed its own robust algorithms based on raw currents :

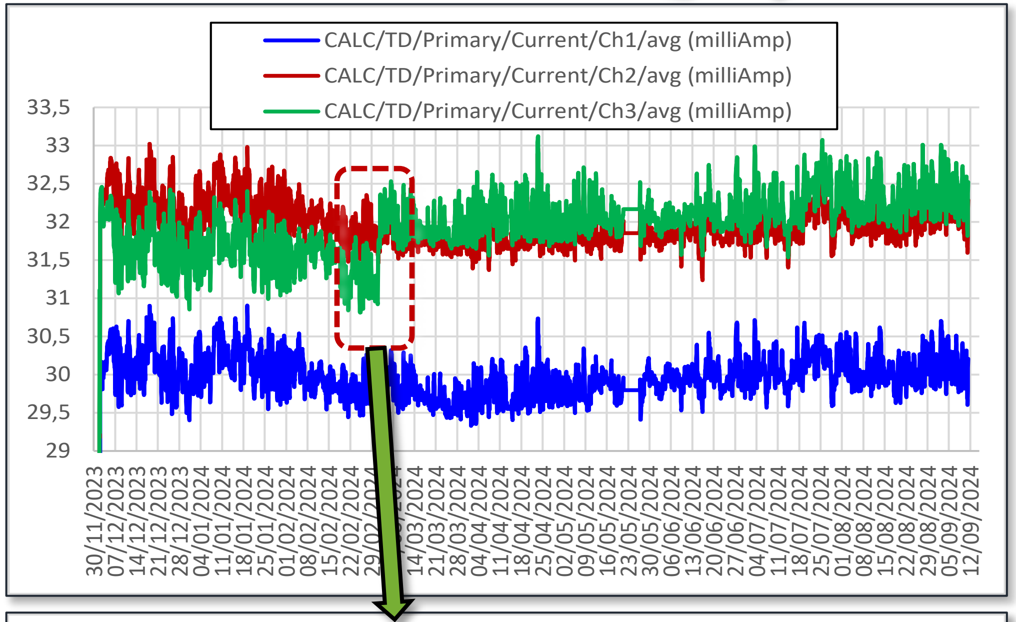
⇨ **Setting alarm thresholds** (neither too high nor too low) with commercial systems **is not easy**.

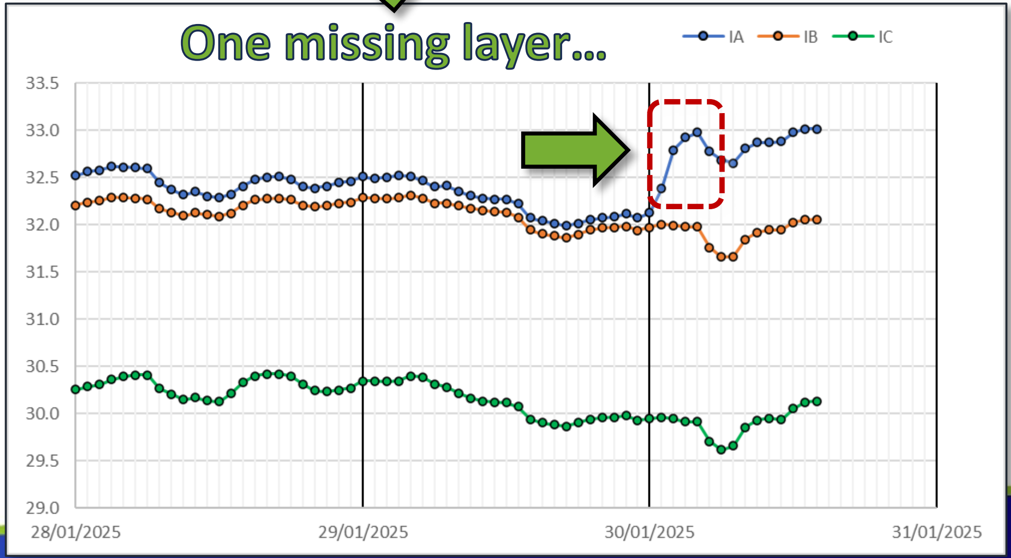
⇨ Given the lack of general theory regarding degradation kinetics, **it is essential to detect early stages of degradation** (**1 layer in short-circuit**) and to create robust detection means (without a false positive).

⇨ On a 400 kV HV bushing one missing layer corresponds to a sudden increase in leakage current of 2 % (0,7 mA over 30-32 mA).

⇨ Commercial software packages cannot reach this goal.

⇨ **Results** : already 2 online interceptions ⇨ removed from service.





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Conclusion

- ⇨ **Power transformers are the most critical assets in a switchyard**.

  Effective monitoring must address the primary sources of degradation and the associated risks.
- ⇨ **Thermal degradation** has long-term effects and can significantly reduce the transformer's lifespan if not detected and addressed.
- ⇨ **Dissolved gas analysis** (DGA) and **bushing monitoring**:

  Early detection through both offline and online measurements is crucial.

  There is no established theory to describe the degradation kinetics of bushings or the active parts of a transformer. Degradation processes can take months or just a few hours.
- ⇨ **Failures pose significant risks to personnel and can result in substantial financial losses**.

  Given the current supply crisis, failure is not an option!
- ⇨ Pressing need for software that can **convert complex data into risk evaluation**, and **appropriate operational actions** to make monitoring fully effective.
- ⇨ With no effective methods in current IEC/IEEE standards, EDF has developed its own algorithms ☺

Thank you for your kind attention

☺

Questions ?