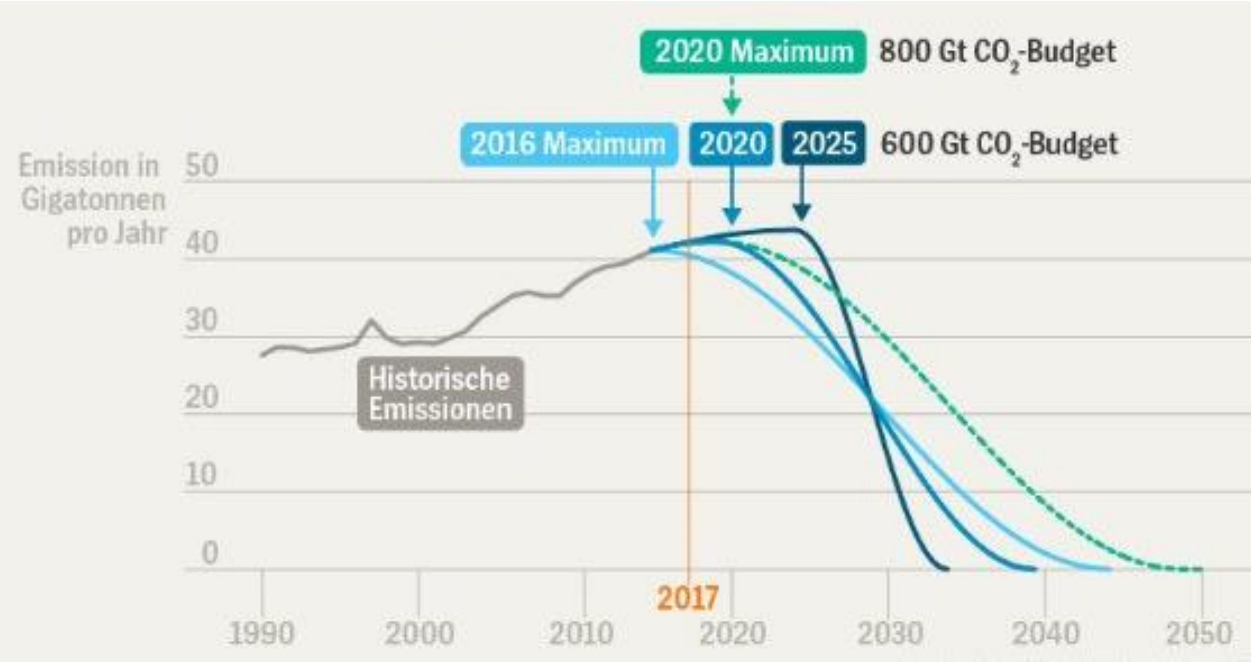
MASTER CLASS - ENERGY TRANSITION TO NET ZERO POWER SYSTEM – STRATEGIES AND PATHWAYS

Saving Resources by Condition Based Maintenance of Power Transformers

Speaker : *Prof. Stefan Tenbohlen,*
University of Stuttgart, Germany

Motivation

CO_2-Budget acc. to Paris agreement



CO_2-reduction in transmission and distribution by use of:

- New materials (SF_6-free, natural esters)
- Energy-efficient designs (reduction of losses)
- New operational schemes
- Higher reliability and resilience
- Longer lifetime

Contents

Analysis of AC Transformer Reliability

Tutorial of CIGRÉ WG A2.62

Stefan Tenbohlen, Germany

Motivation
Transformer Reliability Survey

- Accurate information about service experience of high voltage equipment is of significant value for both electric utilities and for manufacturers,
- It helps the manufacturers to improve their products,
- It provides important inputs for the utilities when buying equipment, when organizing maintenance and when benchmarking their performance,
- Statistical analysis of the past failure data can display useful features with respect to the future failure behavior,
- Equipment reliability data are also required when assessing the overall reliability of an electric power system,
- Furthermore, international standards applicable to high voltage equipment are being improved on the basis of service experience and reliability data.

STANDARDIZED FAILURE DATA COLLECTION

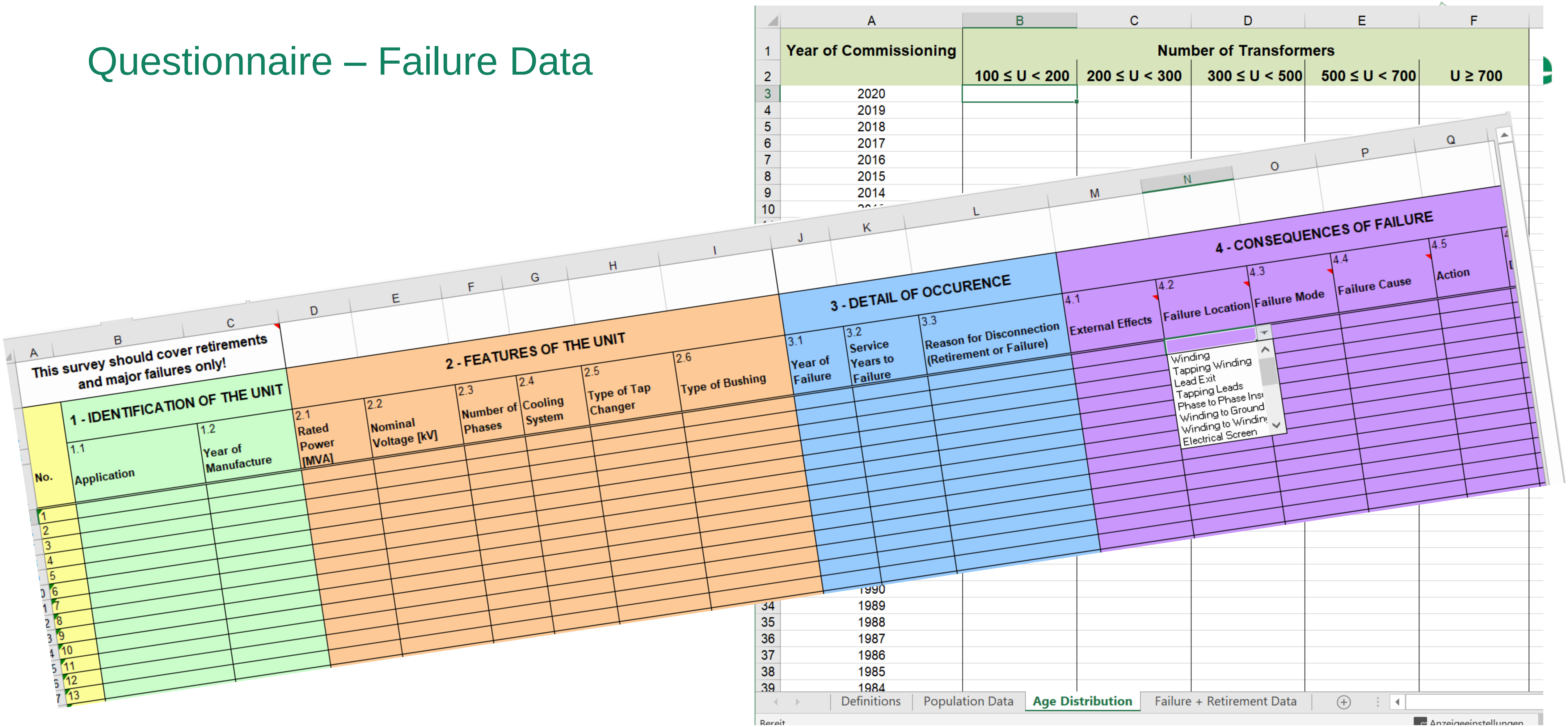
Definition of Major Failure

- Any situation which requires the equipment to be removed from service for a period longer than 7 days for investigation, remedial work or replacement is a major failure.
- Where repairs are required, these involve major remedial work, often requiring the transformer to be removed from its plinth and returned to the factory.
- A major failure would require at least the opening of the tank, including the tap changer tank or an exchange of bushings.
- Also a reliable indication that the condition of the transformer prevents a safe operation should be counted as a major failure if remedial work (longer than 7 days) is needed for restoring original service capability (e.g. detection of strong PDs).

Questionnaire – Failure Data

- *Identification of the unit:* application, type, construction type, year of manufacture.
- *Features of the unit:* rated power, rated voltage, number of phases, cooling system, type of oil, tap changer, tap changer arrangement, oil preservation system, over voltage protection.
- *Detail of occurrence***:** year of failure, service years to failure, loading immediately prior to failure.
- *Consequences of failure:* external effects, failure location, failure mode, failure cause, action taken and detection mode.

Questionnaire – Failure Data



See Cigre A2-Website!

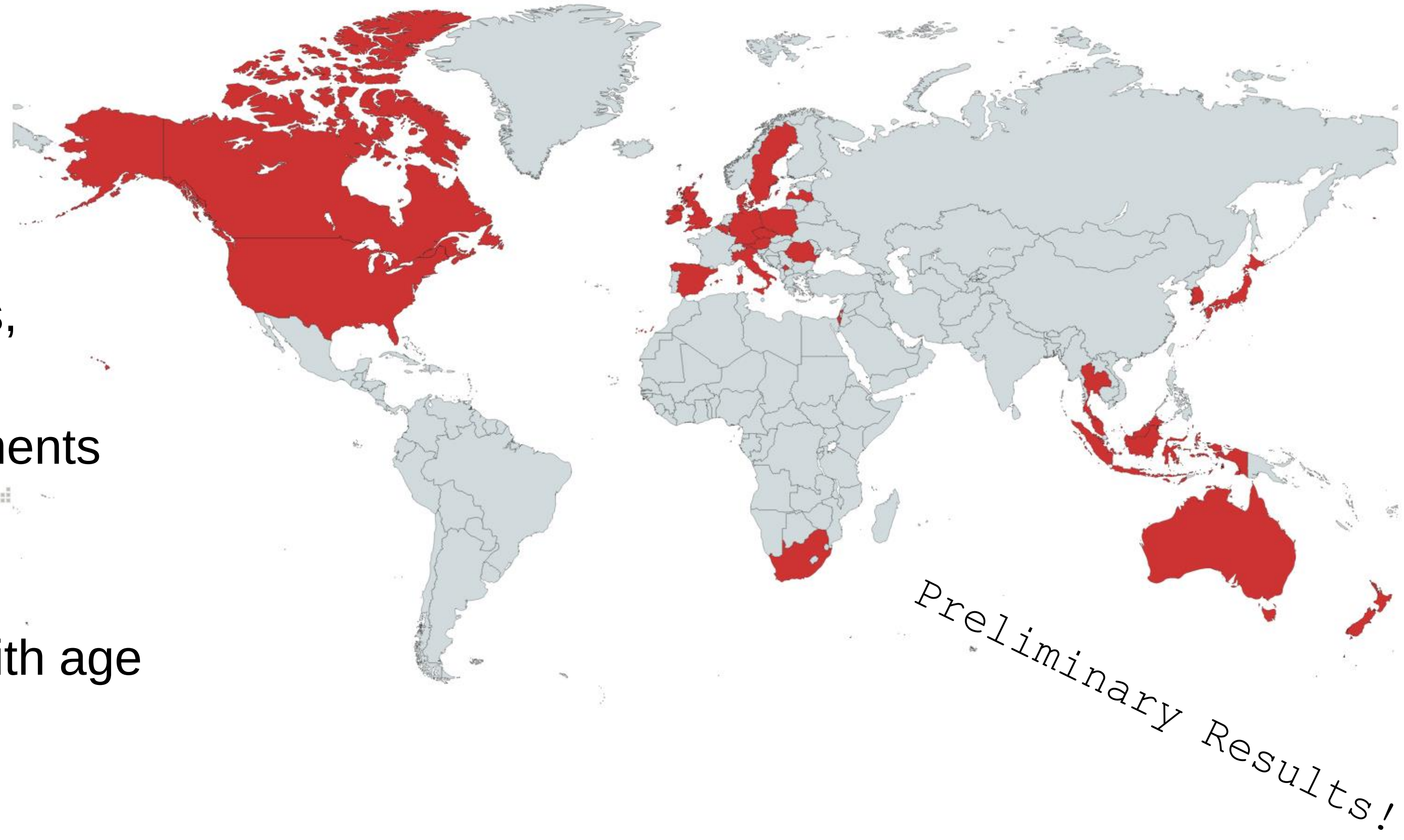
https://www.ieh.uni-stuttgart.de/aktuelles/news/CIGRE-working-group-A2.62/

- Failure Rate
- Failure Location
- Failure Cause
- External Effects
- Hazard Curve

RESULTS OF RELIABILITY SURVEY

Summary of Collected Data

- Data submitted by 53 utilities from 26 countries
- Population of 34254 transformers, 32931 substation transformers, 441 generator step-up transformers, 882 shunt reactor transformers
- 975 major failures and 1758 retirements
- Year of manufacture span from 1919 - 2020
- Almost all utilities submitted data with age distribution of population



Failure Rate

Number of failures divided by the number of transformers in service over a period of time.

Failure rate of a single population:

$$\lambda = 100\% \cdot \frac{n_1 + n_2 + \ldots + n_i}{(N_1 + N_2 + \ldots + N_i) \cdot T}$$

n_i is the number of failures in the **i-th year**
N_i is the number of transformers operating in the i-th year
T is the reference period (one year)

Failure rate of combined population:

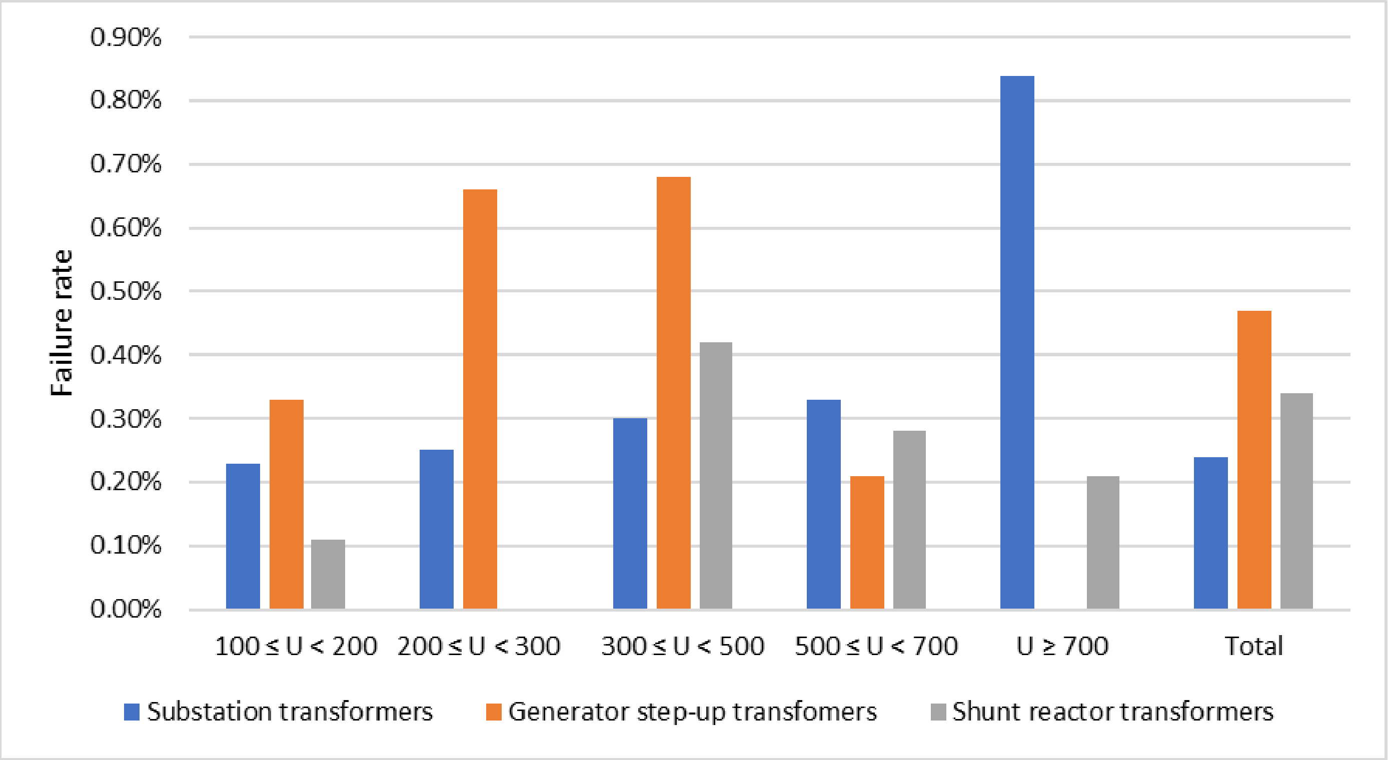
$$\lambda = 100\% \cdot \frac{n_1 + n_2 + \ldots + n_i}{N_1 \cdot T_1 + N_2 \cdot T_2 + \ldots + N_i \cdot T_i}$$

n_i is the number of failures by **i-th population**
N_i is the number of transformers of i-th population
T_i is the reference period of i-th population

Failure Rates

Preliminary Results!

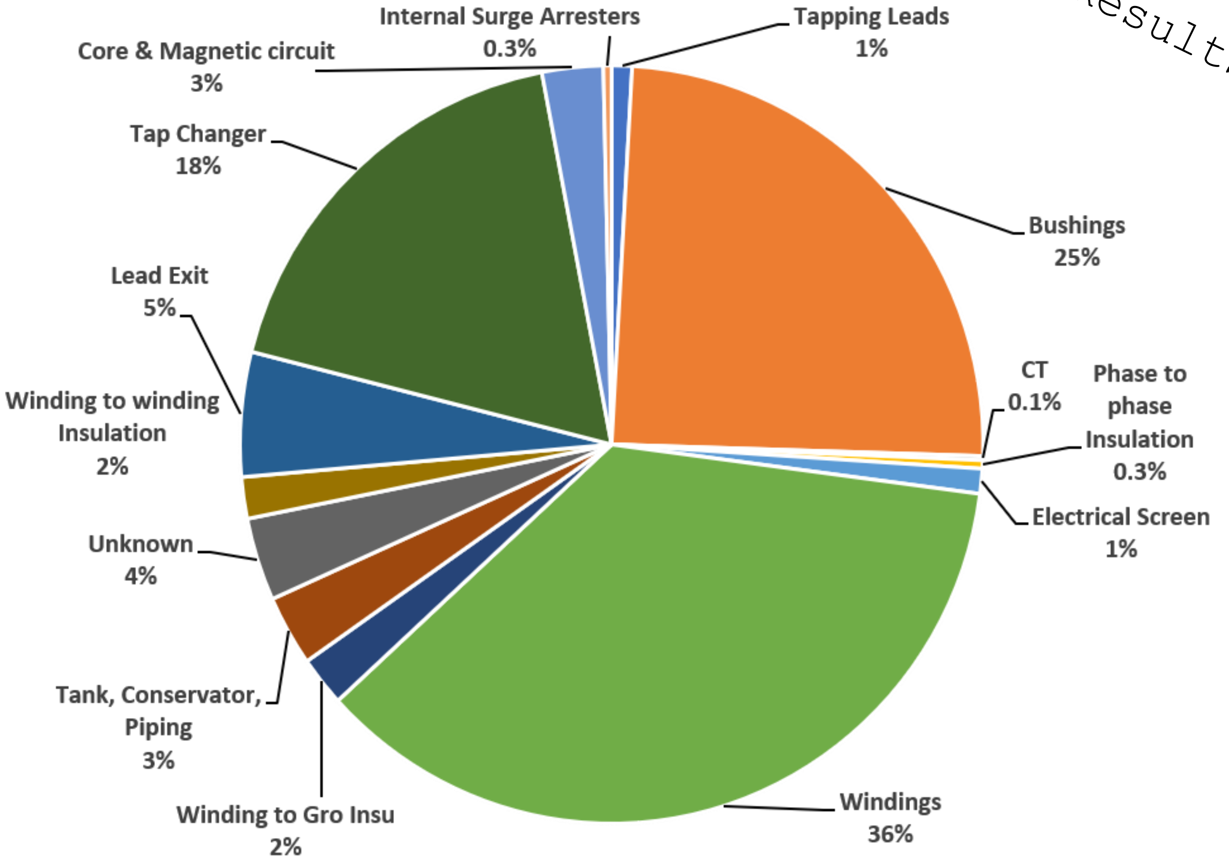
- Failure rate of all transformers in all voltage classes is below 1%.
- The failure rate of GSUs is higher in almost all voltage classes.
- Only 4 utilities have a failure rate higher than 1%.



Failure Location

Preliminary Results!

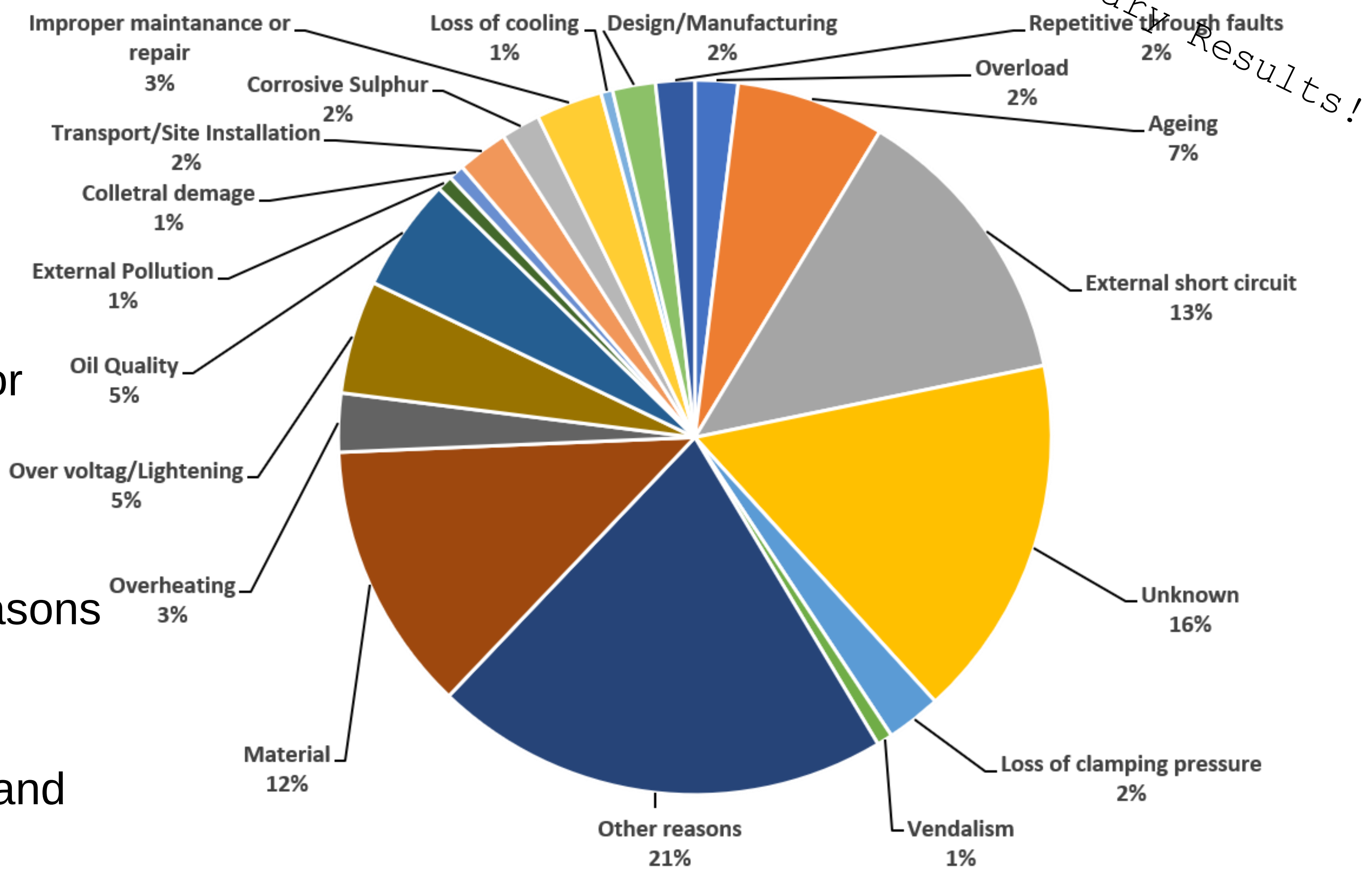
- Windings, tap changer, and bushing-related faults are the major contributors in all voltage classes
- Substation transformers
  - Windings, tap changers, and bushings are dominant failure locations
- Shunt reactors
  - Bushings, core & magnetic circuits, and lead exit
- Generator step-up units
  - Core & magnetic circuits and insulation



Failure location (based on 565 failures)

Failure Cause

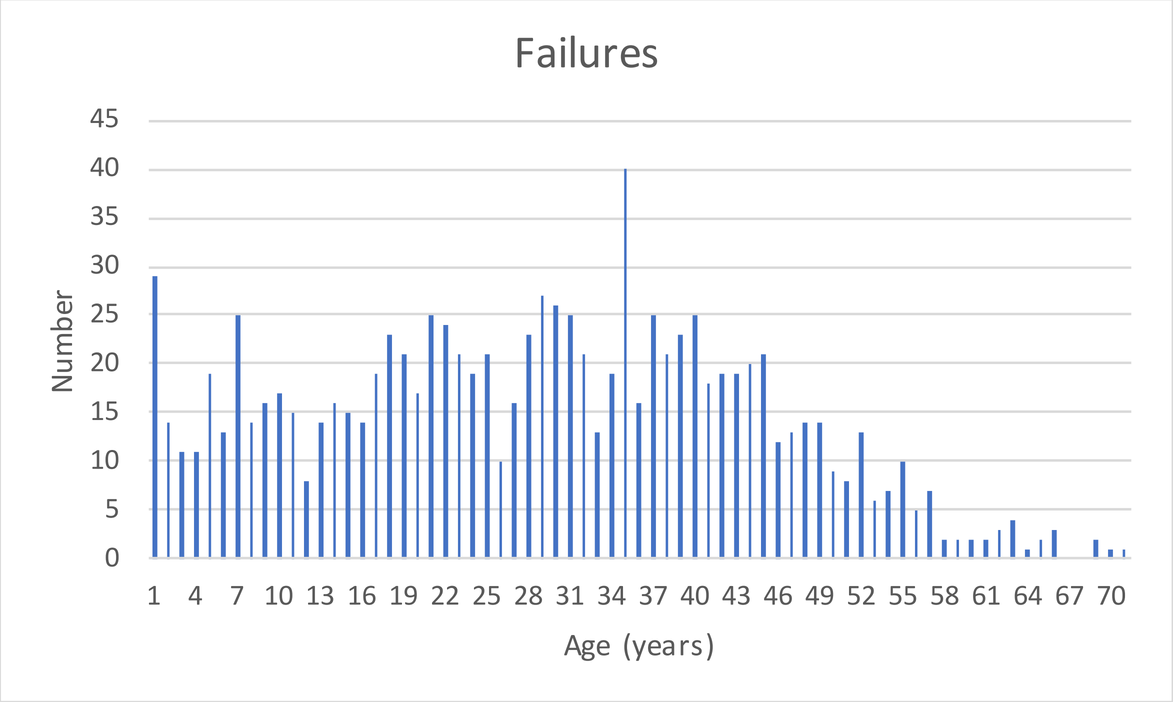
- Unknown, other reasons and external short circuits, are major causes
- Substation transformers
    - External short circuits, unknown and other reasons
- Shunt reactors and GSU transformers
    - Material, overheating, and other reasons

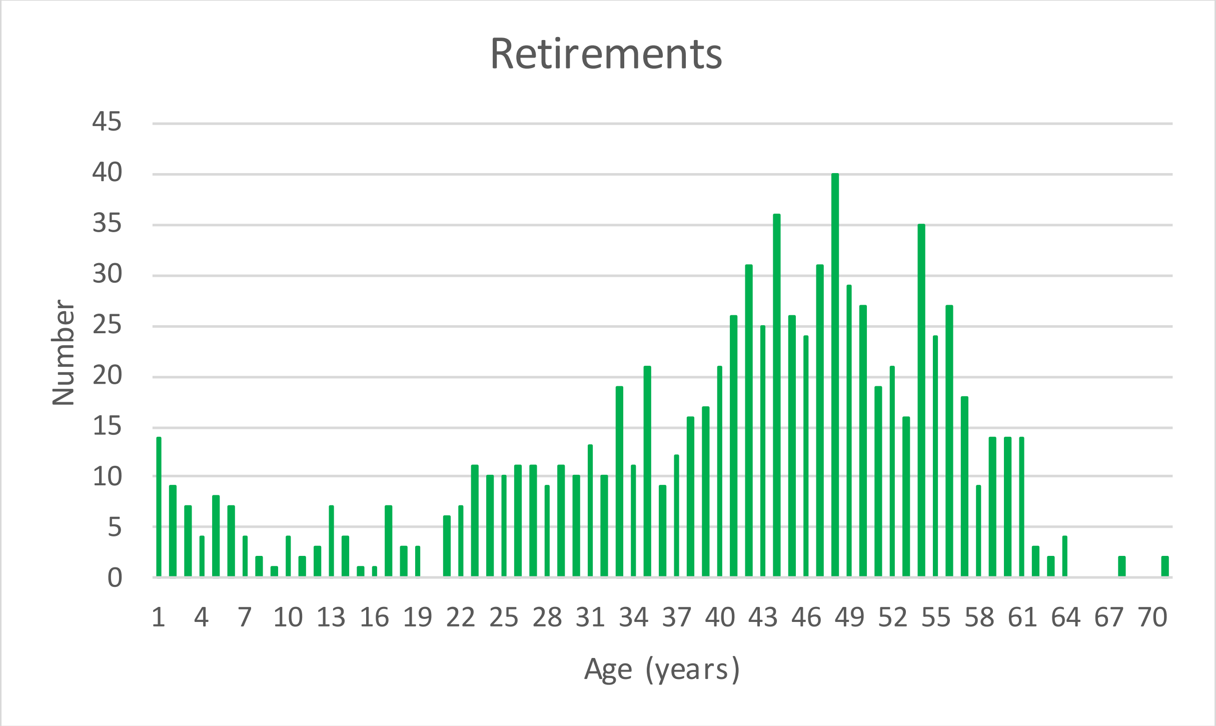


based on 565 failures

Number of Failures and Retirements dependent on Age

Preliminary Results!



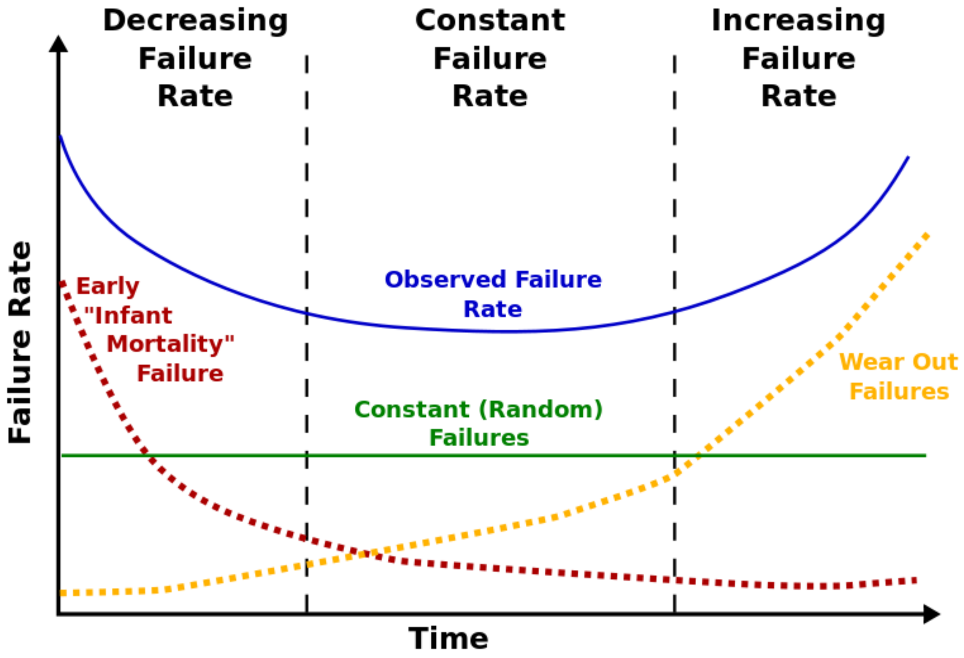


Definition – Hazard Function

$$h(t) = \frac{1}{N(t)} \cdot \frac{\Delta n(t)}{\Delta t}$$

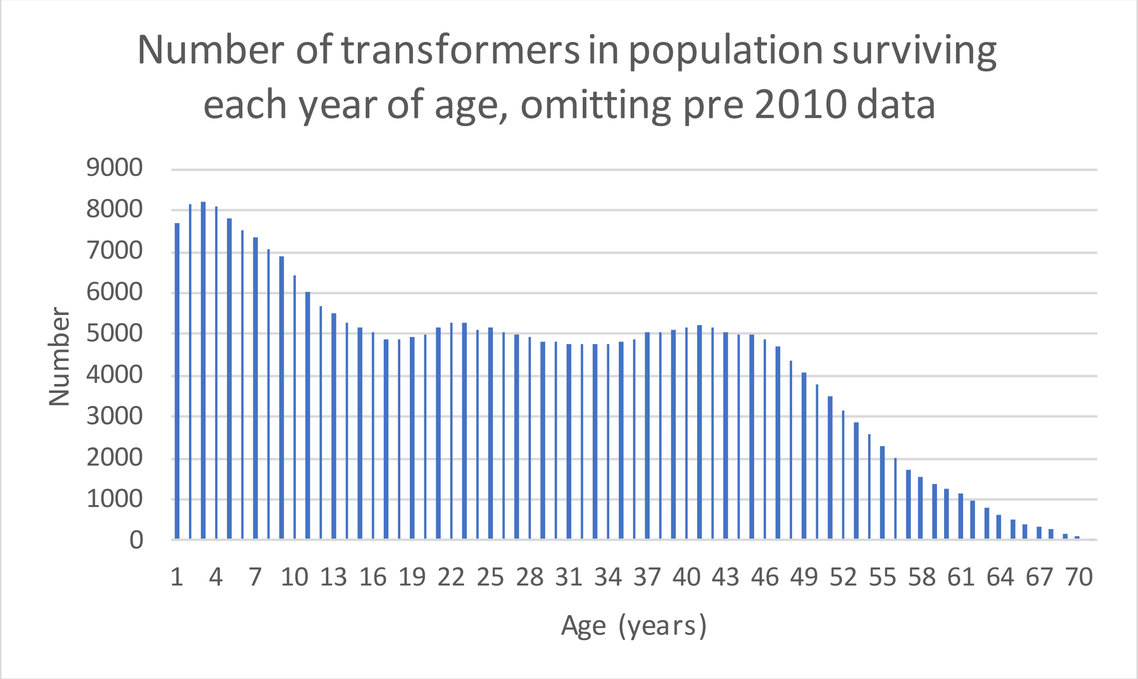
Δn(t) = Number of failures in time interval [t, t+Δt]
Δt = Length of time interval
N(t) = Population surviving at time t

h(t) is the instantaneous failure rate at age *t*, that is, in the short time Δt from *t* to *t*+Δt, a proportion $\Delta t \cdot$h(t) of the population *that reached age t* fails.

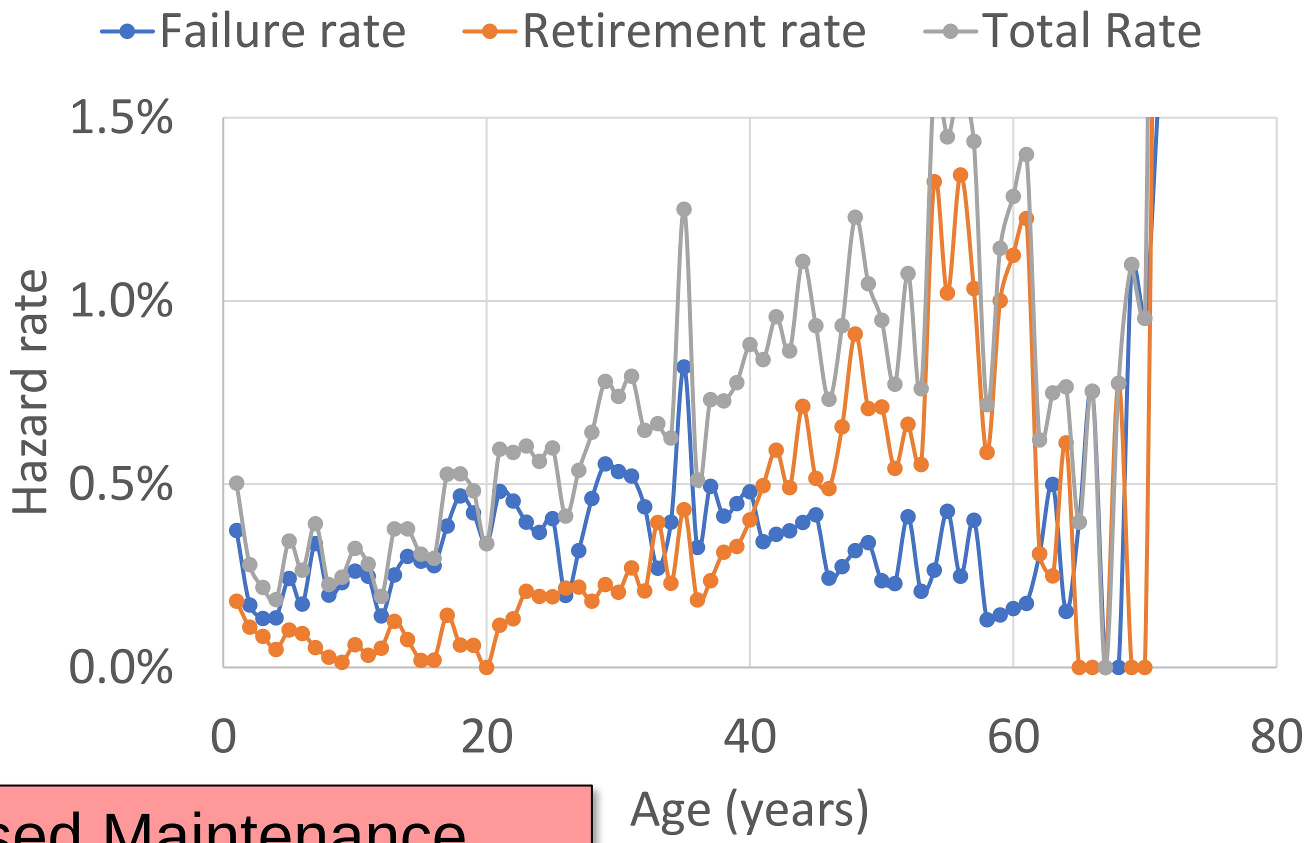


Number of Transformers-Years surviving Age T (considering 10 year failure interval)

Preliminary Results!



$$h(t) = \frac{1}{N(t)} \cdot \frac{\Delta n(t)}{\Delta t}$$



Condition based Maintenance instead of Time based Maintenance!

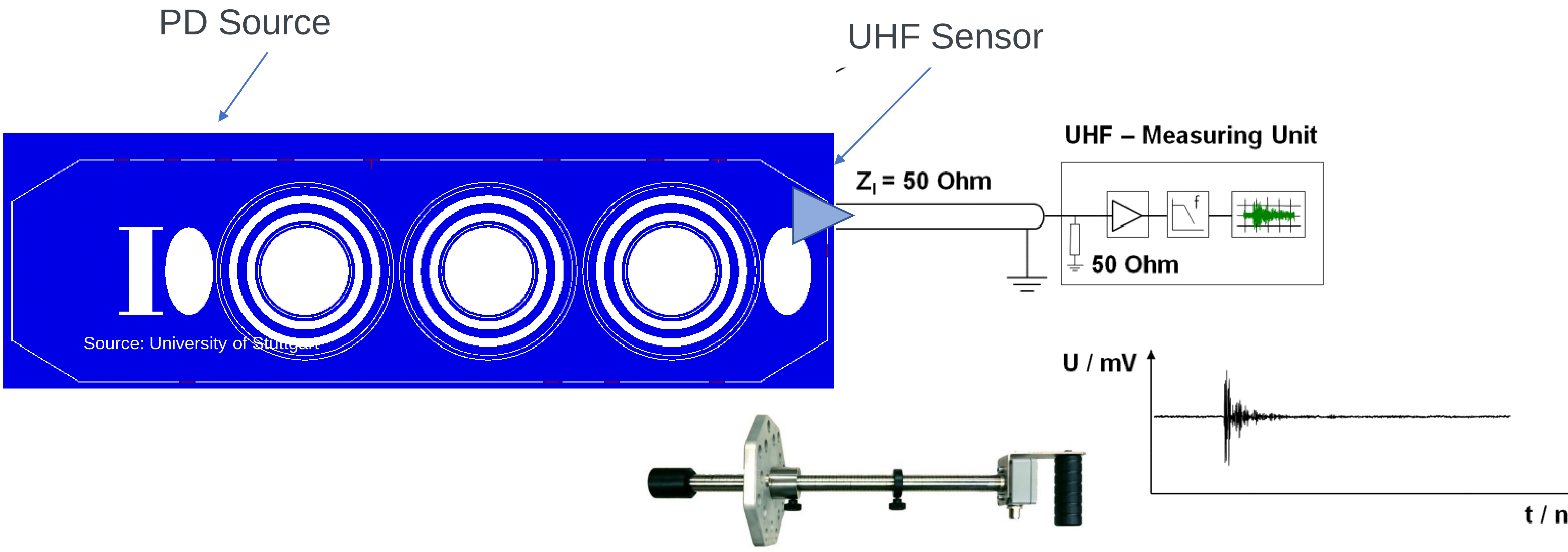
Condition Assessment Techniques

Method	Offline	Online	Monitoring	Offsite
Ageing of oil (e.g., color, moisture, and tan δ)	XXX	XXX	X [1]	XXX
Furan in oil analysis	XX	XX	-	XX
Gas-in-oil analysis (DGA)	XXX	XXX	XXX	XXX
Partial Discharges (IEC 60270)	XXX	X	X	XXX
Unconventional PD-measurement (e.g., UHF PD measurement)	XX	XX	XX	XX
Transfer function (FRA)	XXX	X	-	XXX
Dielectric diagnostic (PDC and FDS)	XX	-	-	XX
Thermal monitoring	-	-	XX	-
Degree of polymerization (DP-value)	-	-	-	XXX

XXX: generally accepted or standardized;
XX: accepted by different users;
X: under investigation or consideration;
-: not applicable.

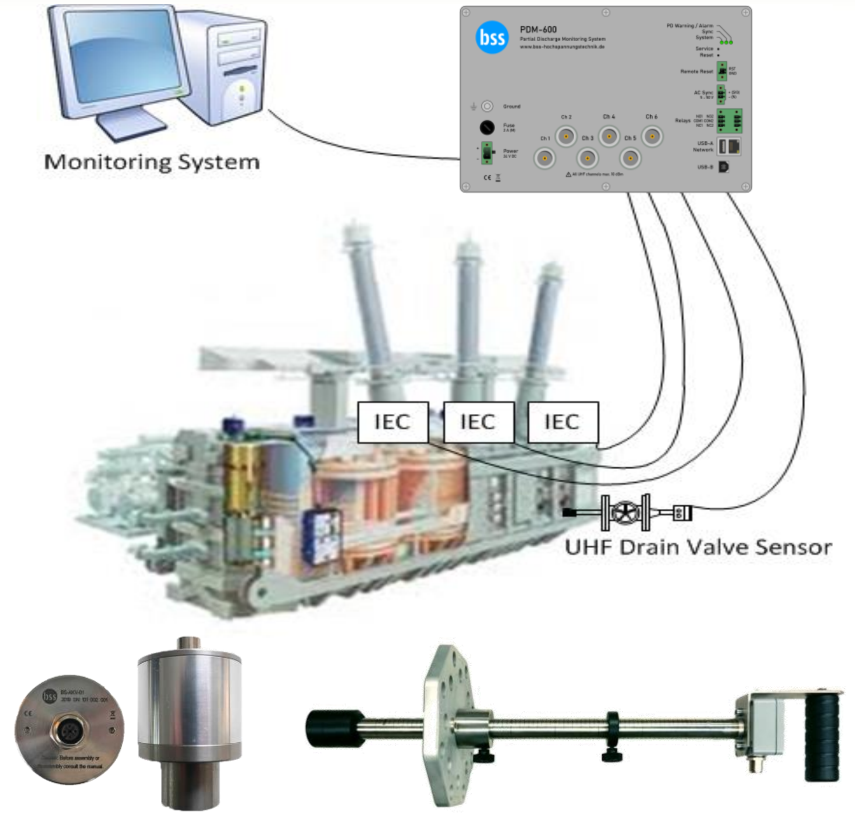
[1] moisture measurement

Principle of UHF PD Measurements in Power Transformers

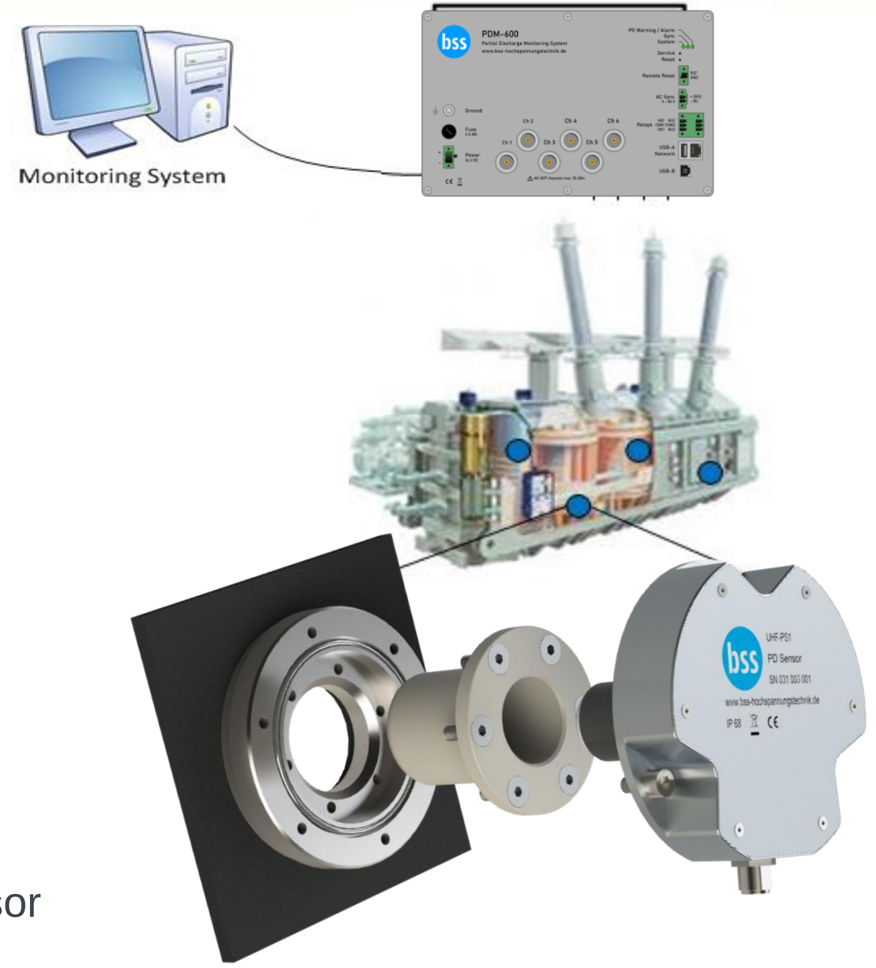


Drain valve UHF sensor

UHF PD Monitoring System



1 UHF-DN50/DN80 drain valve UHF PD sensor & 3 BS-PD bushing sensors for PD measurements according IEC60270



4 window-type UHF PD sensors UHF-PS1

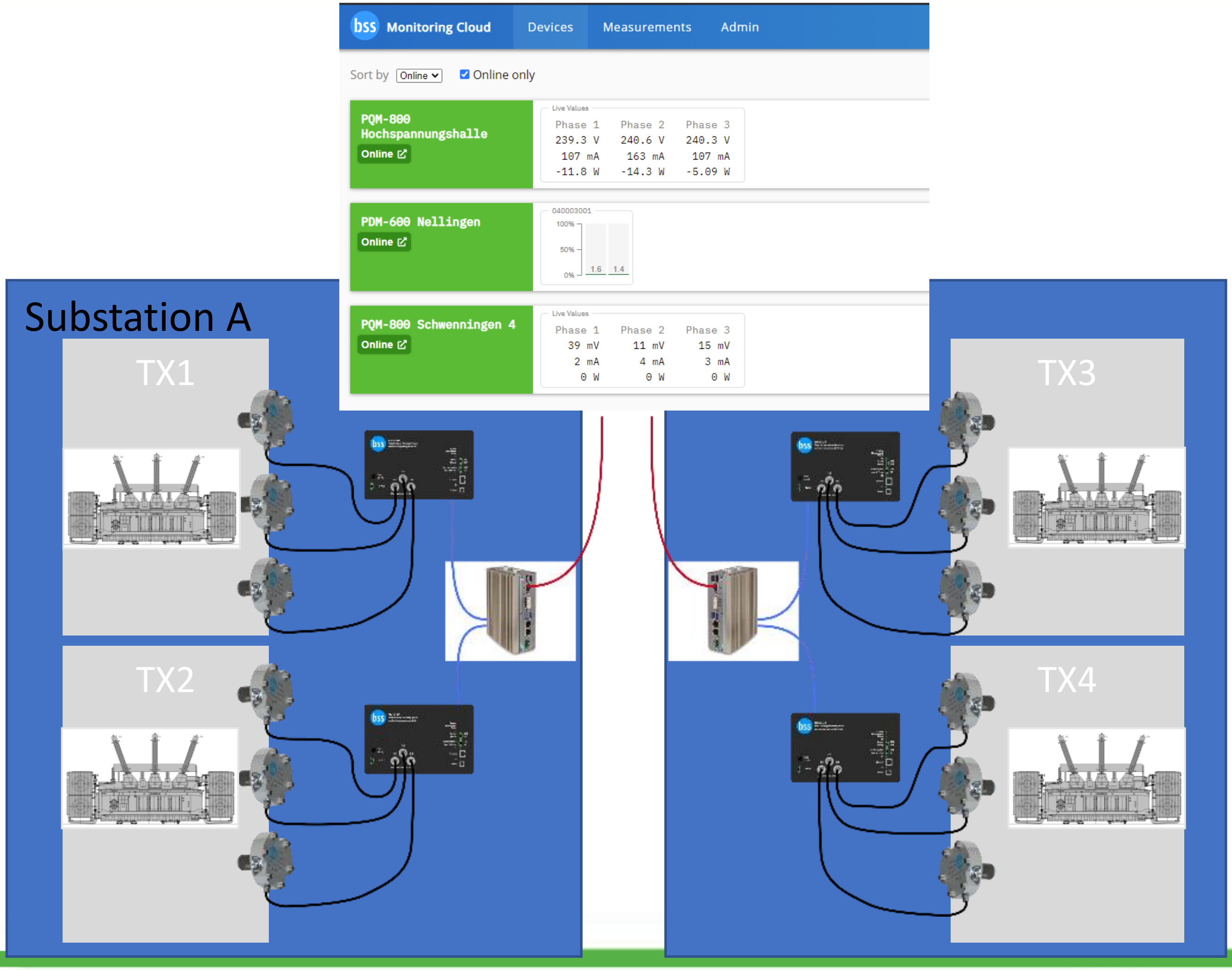
UHF PD Monitoring System PDM-600

www.bss-hochspannungstechnik.de

- From 1 up to 6 channels
- 220 MHz … 3 GHz frequency range
- 50 µV … 100 mV(at 50 Ω) input range
- Simultaneous measurement
- 70 dB dynamic range
- 12-bit vertical resolution
- 1° phase resolution in PRPD view
- UHF calibration possible (Cigré TB 861)

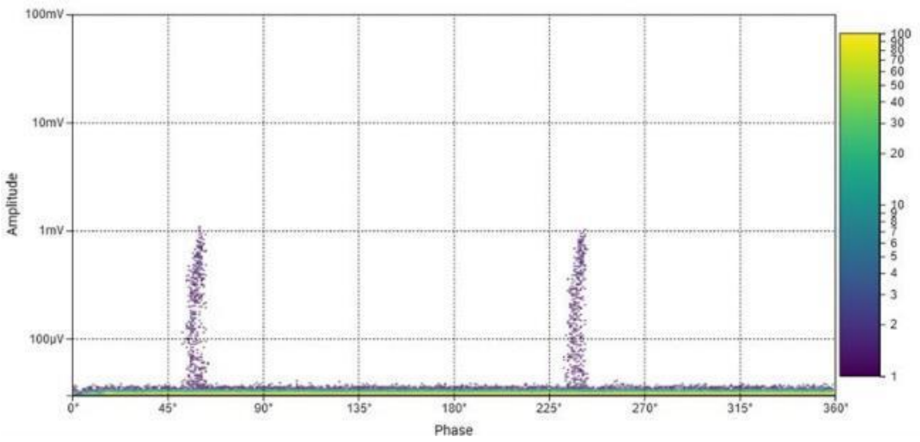
- Platform-independent web interface (GUI) with PRPDs, trends, etc.
- Historical PD data storage
- ModbusTCP, IEC61850, httpAPI, Relays

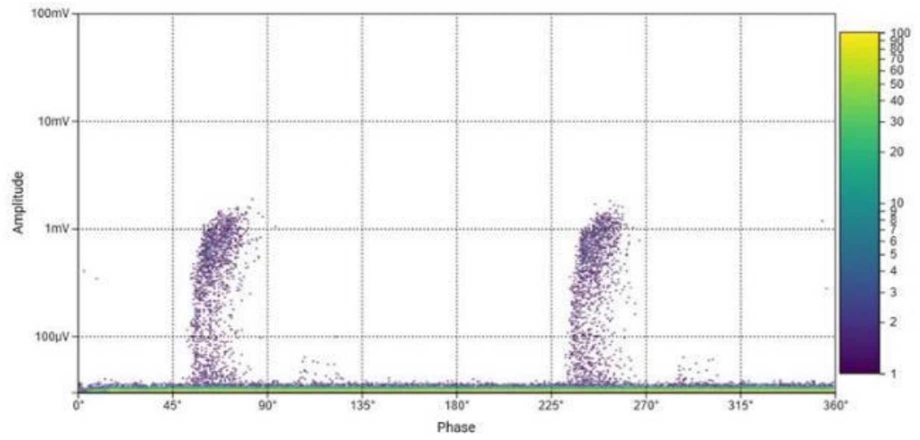
Use Case UHF PD Monitoring: Four 160 MVA Power Transformers



- 12 UHF-PS1 Sensors
- 4 PDM-600 with 3 channels each
- 2 MDPU Data Processing Units
- Upload to BSS Monitoring Cloud

Use Case UHF PD Monitoring: Four 160 MVA Power Transformers



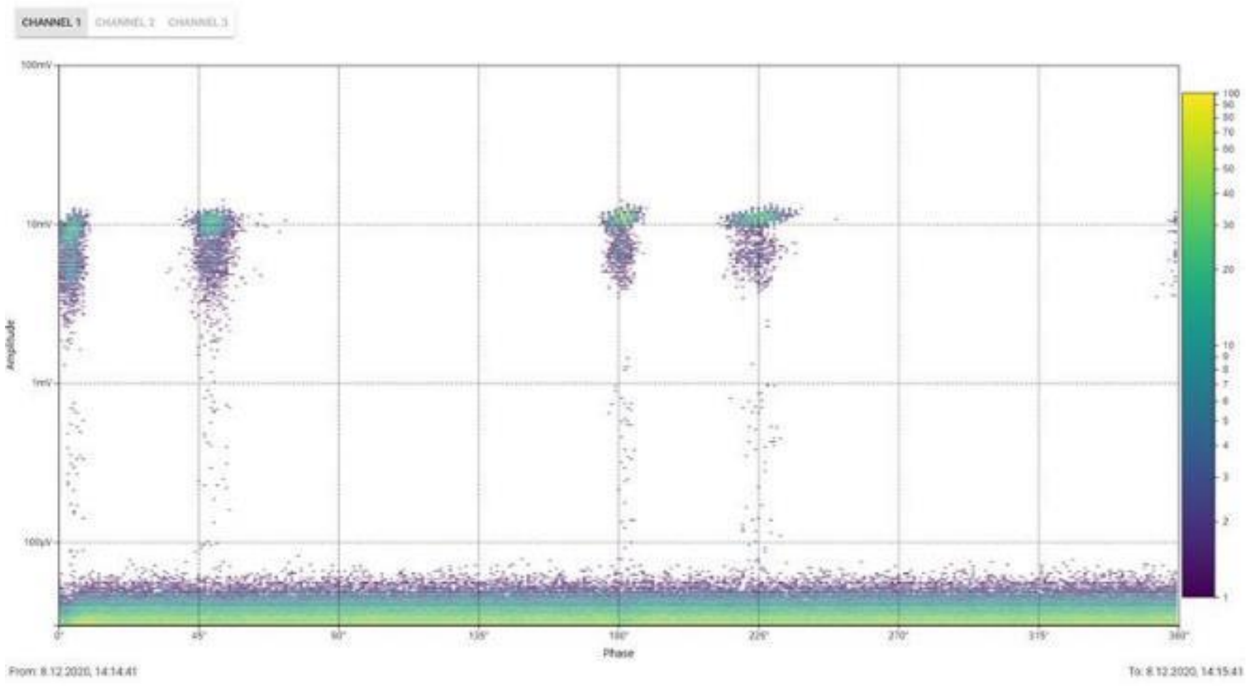


- Signals reached **PD warning** level (set to 1 mV in this case)
- PRPD shows sporadic patterns as shown in the first few hours after erecting
- Patterns disappeared after a few hours

➢ Likely caused by sporadically appearing and disappearing bubbles in oil

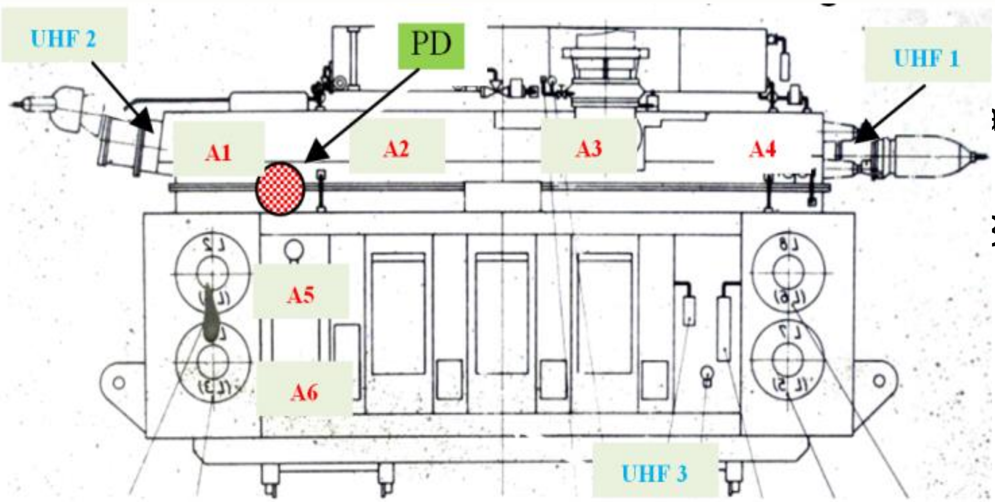
➢ **Uncritical for further operation**

Use Case UHF PD Monitoring: Four 160 MVA Power Transformers



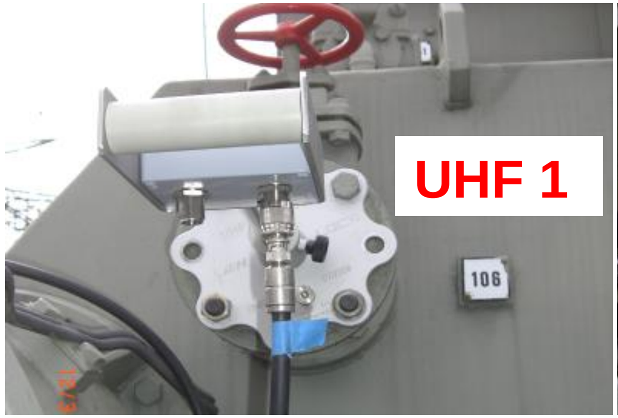
- **PD alarm** at transformer 2
- PD Level constantly > 10 mV
- Pattern indicates a bad contact or a floating potential
- Possible reasons: manufacturing problem, **transportation**, etc.
- **PD should be investigated further (e.g. localization) and should be fixed to avoid critical long-term damage**

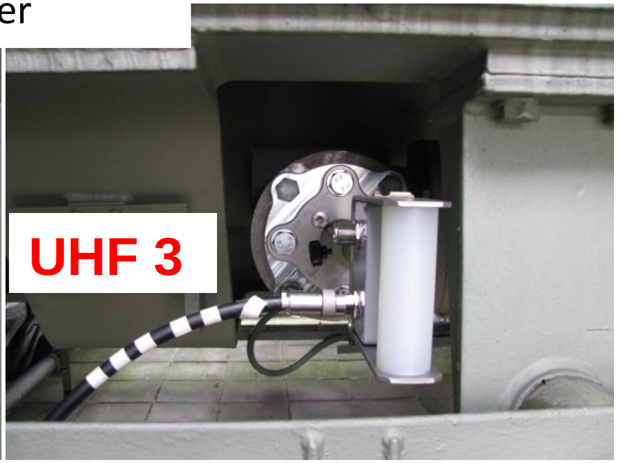
Use Case 2 – UHF PD Detection and Location

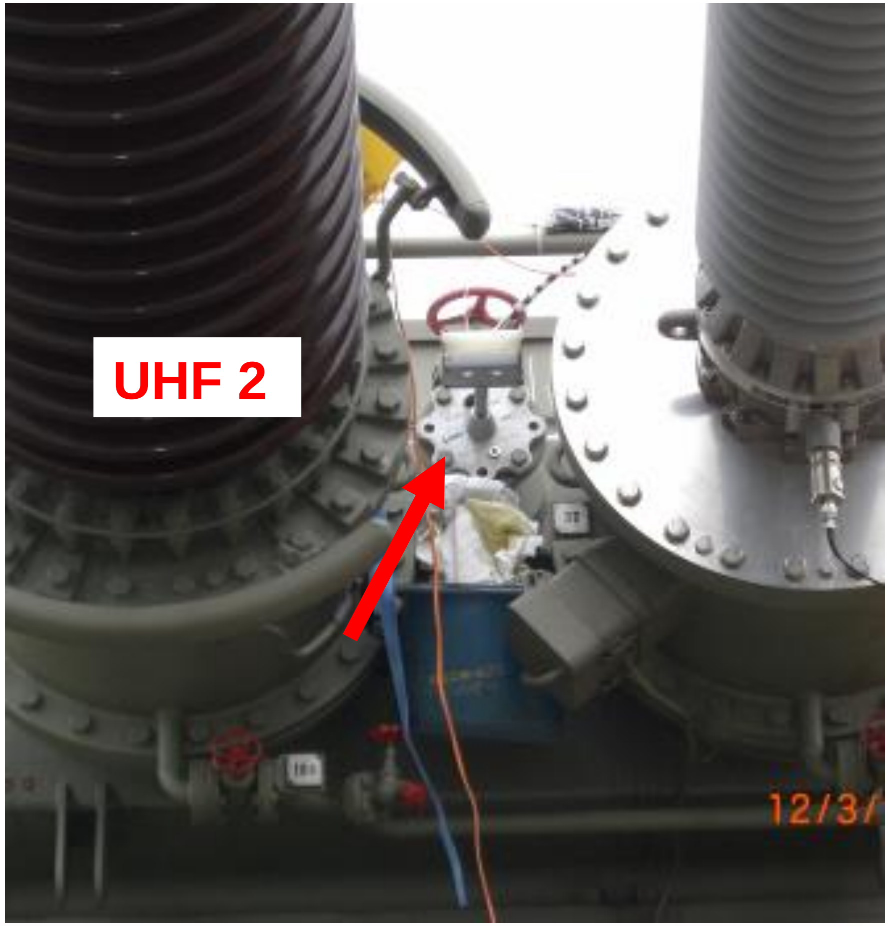


ase transformer
nstruction: 1966
30 kV

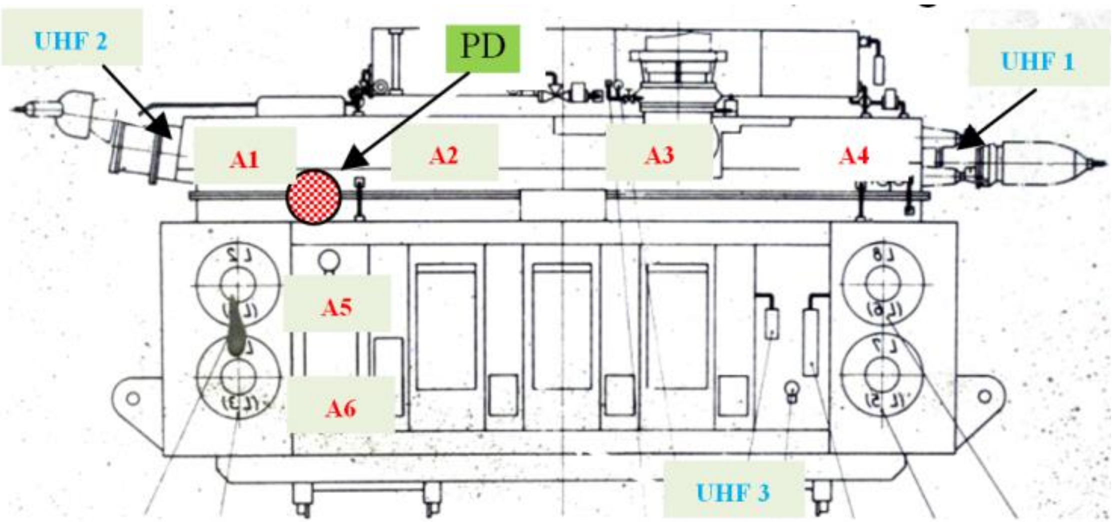
Positions of three UHF sensors at 333 MVA transformer



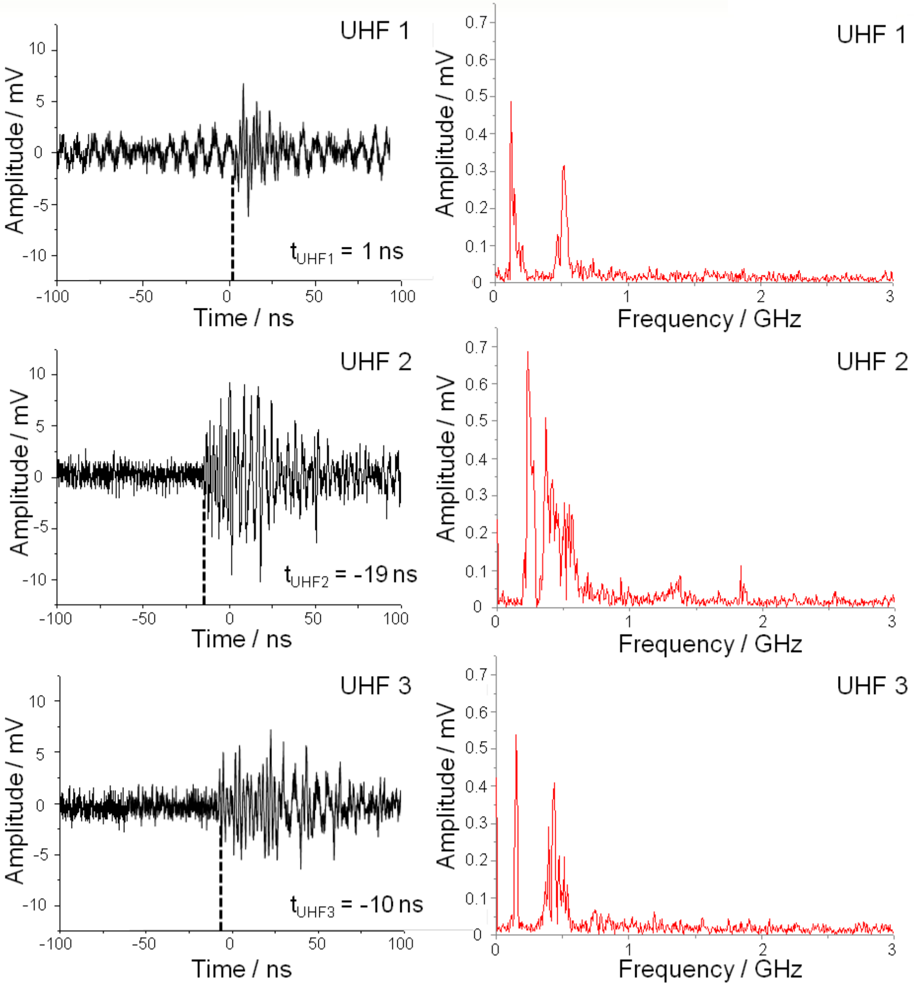




Use Case 2 – UHF PD Detection and Location

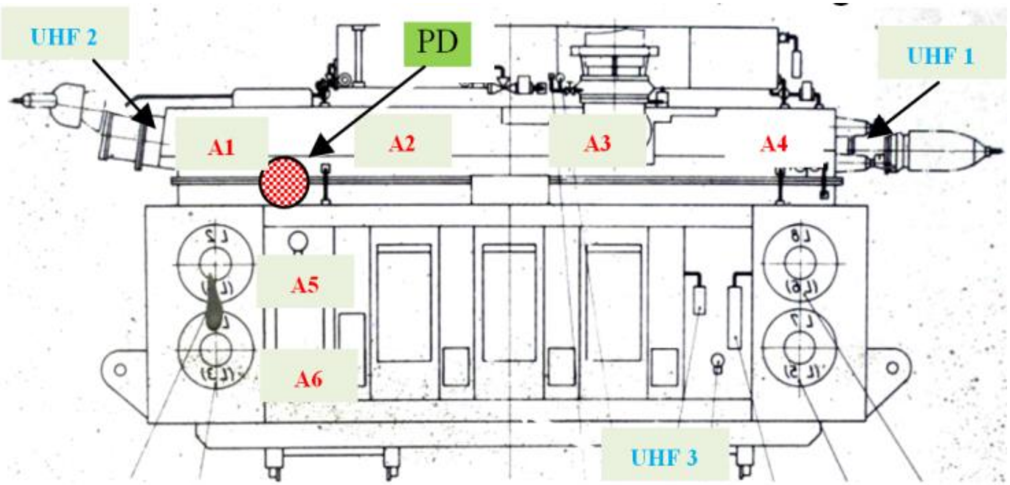


Positions of three UHF sensors at 333 MVA transformer



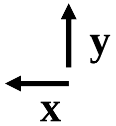
S. Coenen, S. Tenbohlen, Location of PD Sources in Power Transformers by UHF and Acoustic Measurements, IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 19, No. 6, 2012

Use Case 2 – PD Location Result



Position of PD → Onload Tap Changer

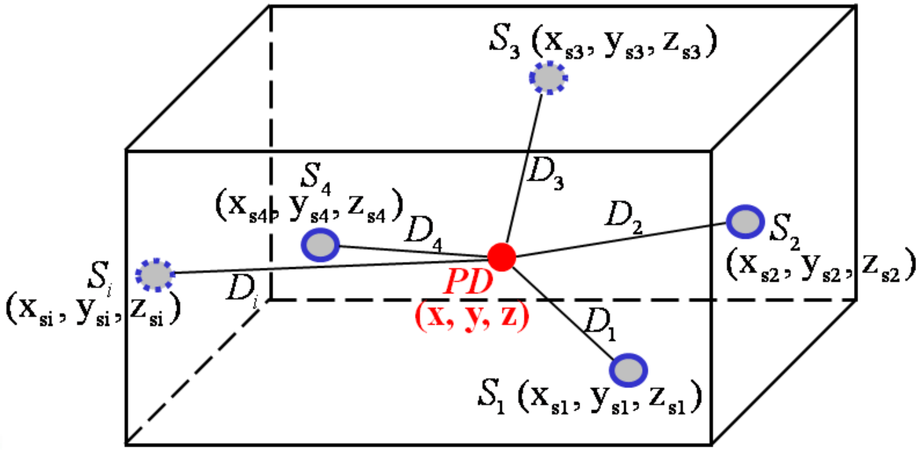
Piezo-electric Sensor



$$(x - x_{s1})^2 + (y - y_{s1})^2 + (z - z_{s1})^2 = (v_s \cdot T_{S1})^2$$
$$(x - x_{s2})^2 + (y - y_{s2})^2 + (z - z_{s2})^2 = (v_s \cdot T_{S2})^2$$
$$(x - x_{s3})^2 + (y - y_{s3})^2 + (z - z_{s3})^2 = (v_s \cdot T_{S3})^2$$

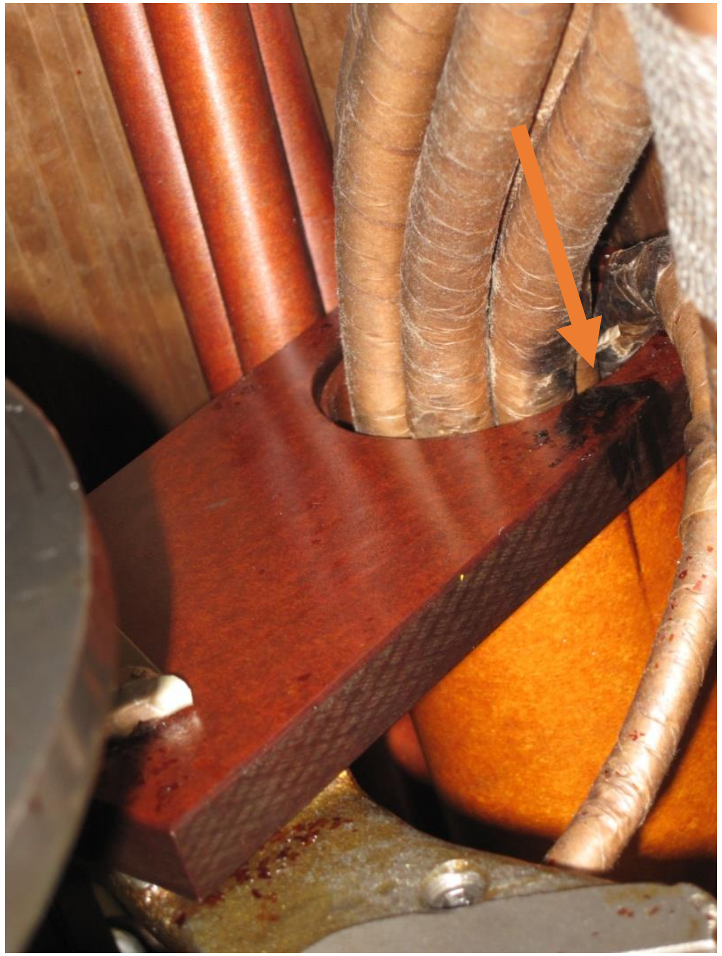
	X / cm	Y / cm	Z / cm
1	691	300	75
2	701	299	115
3	719	299	115
4	720	266	93
5	717	300	116

Localization accuracy: 40 cm



Use Case 2 – Repair in Factory





Conclusion

- CO_2-Reduction on T&D by new materials, higher efficiency, new operation schemes and higher reliability.
- A questionnaire was developed by which utility failure statistics can be collected in a standardized way.
- Failure rate of app. 0.5 %/a for power transformers.
- The hazard curve function for substation transformers does not show a distinct ageing behaviour -> CBM is necessary!
- About 50% of major failures occur in the windings.
- UHF partial discharge monitoring is helpful to prevent failure in the active part.

Outlook: Analysis of DTR failure for Indian DISCOMs

- Questionnaire for understanding the reasons for high DTR failure rate (12 – 15%) in India
- Analysis of DTR failure causes with classification of reasons
- Recommendations for measure(s) to reduce the DTR failure rate based on the analysis of selected DISCOMs with some guiding sequence for future study and give some references on measurements, maintenance, infrastructure etc. required for reducing the failure rate and increasing the life of DTR.

Sponsored by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)

Thank You

Member of University Transformer Research Alliance

MANCHESTER 1824 The University of Manchester
The University of Queensland Australia
Tsinghua University 1911
University of Stuttgart Germany
Xi'an Jiaotong University 1896