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On-Line diagnosis of Transformer Winding Insulation failures using Extended Park's Vector Approach

Presented by Paul Guy – Smart Grid Solutions

paul.guy@gridsolutions.com.au

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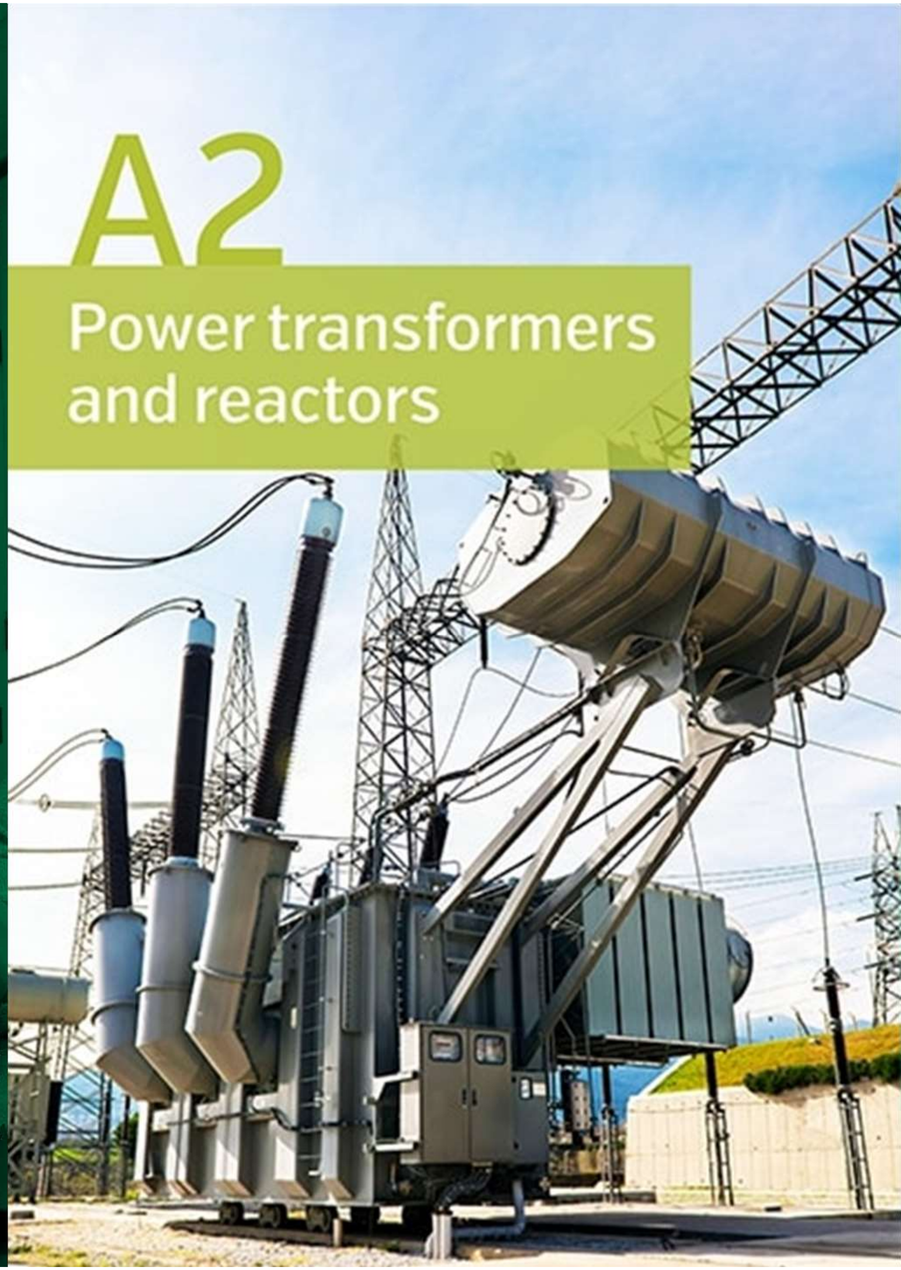
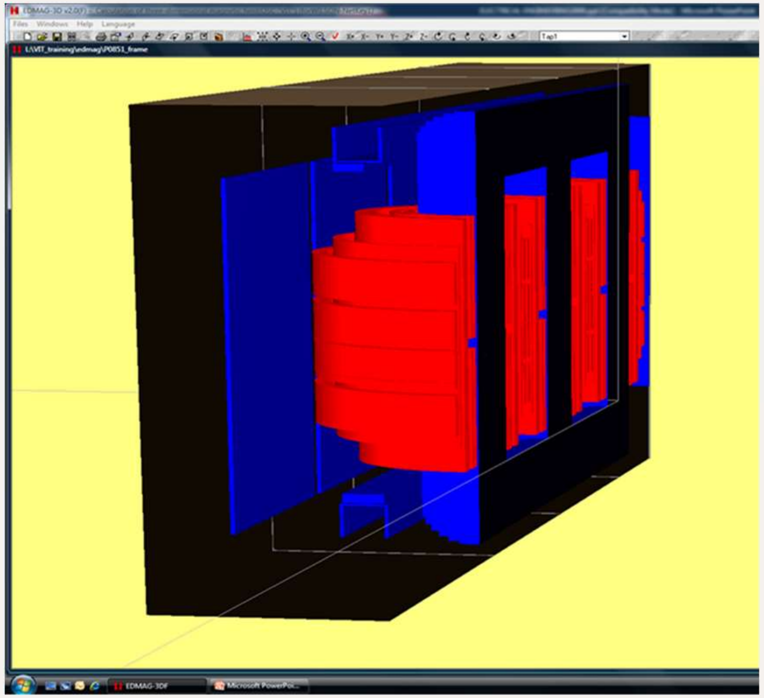


What would you consider to be the perfect on-line Power Transformer Condition Monitoring system?

Mechanisms of Typical Failures

Electromagnetic Circuit

- Experience has shown that defective/faulty conditions typically are attributed to the following abnormal states:
  - General overheating, namely, abnormal rise of the oil temperature due to cooling deficiency, poor distribution of oil flow, core overheating
  - Local core overheating associated with the main magnetic flux
  - Local core overheating associated with stray flux



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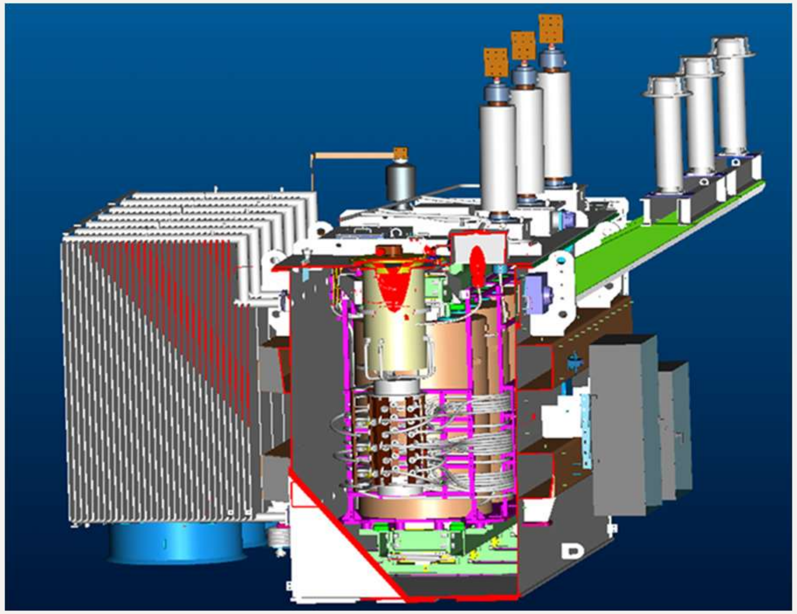
Mechanisms of Typical Failures

Current Carrying Circuit

- The following typical scenario of an equipment failure may be suggested:
  - Fixed connection: Local heating in places of poor joints, increasing contact resistance, oil overheating, pyrolytic carbon growth, gas generation, coking, impairment of heat exchange, melting the copper, or breakdown of oil due to severe contamination.
  - Movable (OLTC) connection: formation of film coating reducing the contact surface, increasing the contact resistance and temperature. A progressive rise of contact resistance results in the progressive rise of temperature, gas generation, irreversible degradation of the contacts, coking, open-circuit or short-circuit occurrences.



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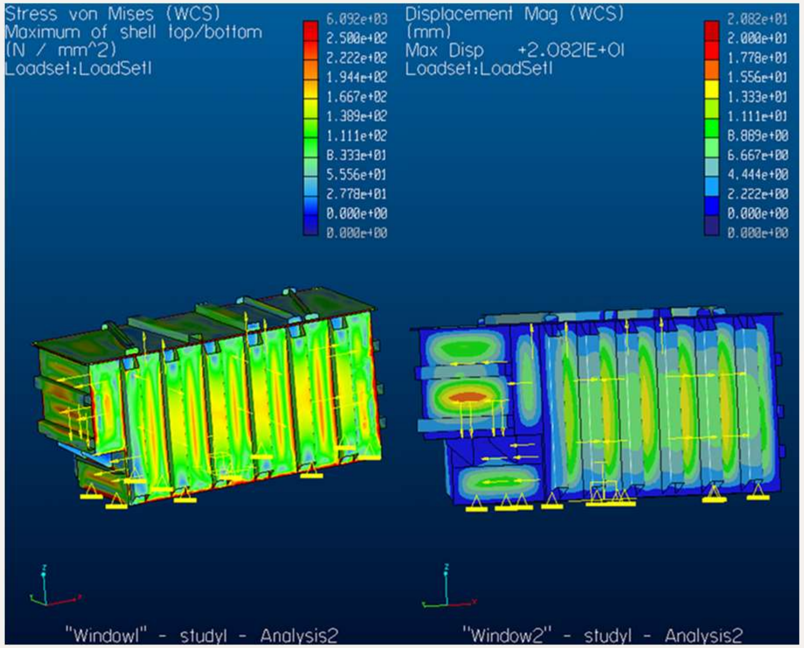
Mechanisms of Typical Failures

Mechanical Withstand Strength

The following typical scenarios of a transformer failure have been experienced:

- Loose clamping - Distortion of winding geometry ⇒ PD appearance ⇒ Creeping discharge progressing ⇒ Breakdown
- Distortion of winding geometry + Switching surge ⇒ Flashover between coils (sometimes with restoring withstand strength) ⇒ Gas evolution



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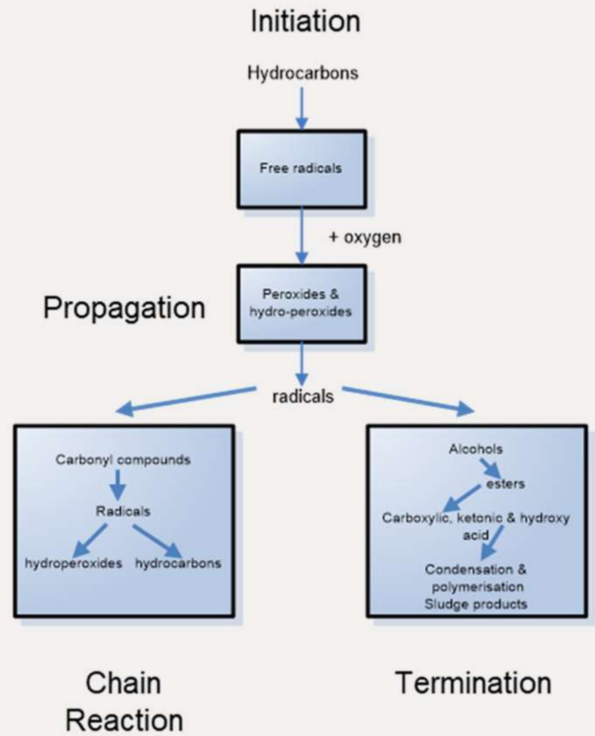
Mechanisms of Typical Failures

Dielectric System

It is possible to define two critical stages of dielectric withstand strength degradation:

- Defective condition: reduction of the initial withstand strength under the impact of the degradation agents. It results in appearance of usually non-destructive partial discharges (PD) at operating voltage and reduction in impulse withstand strength.
- Faulty condition: appearance of destructive PD, progressing surface discharges, and creeping discharge occurrence.



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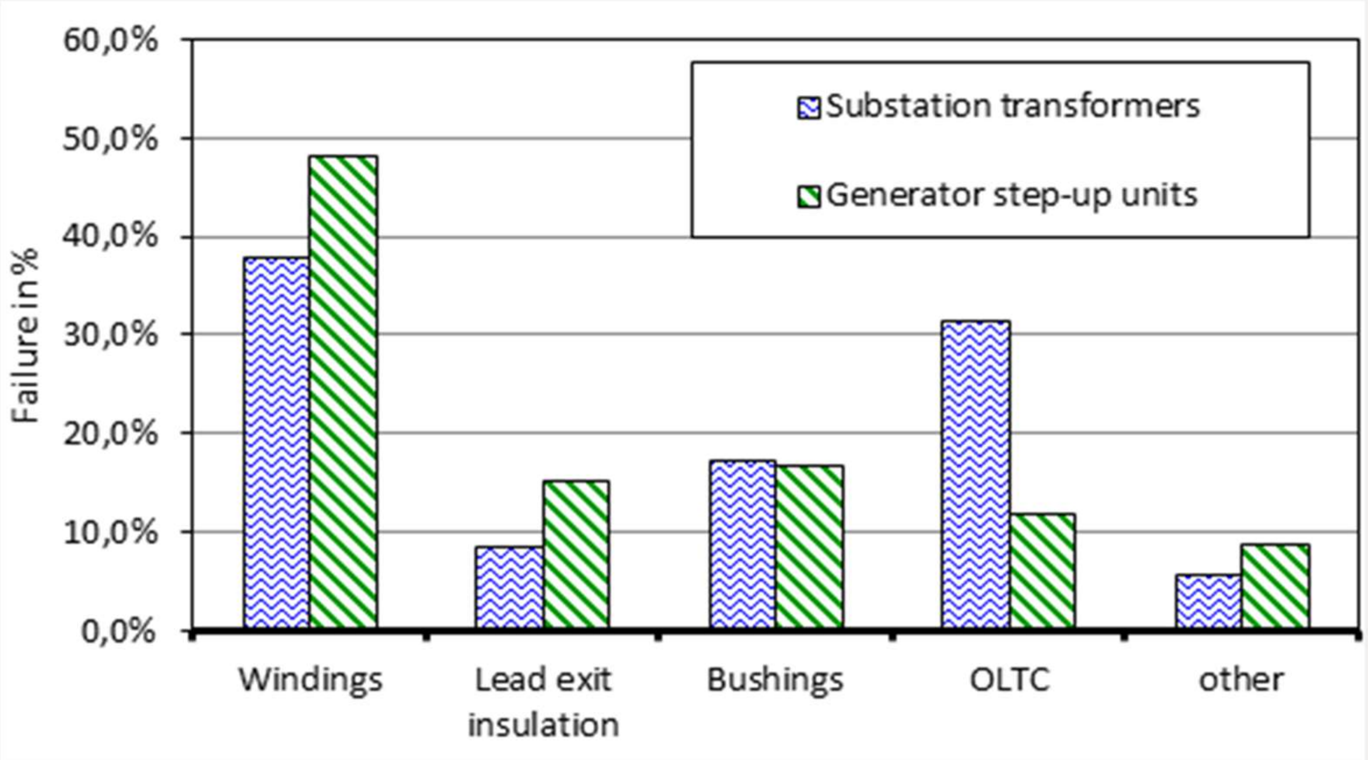
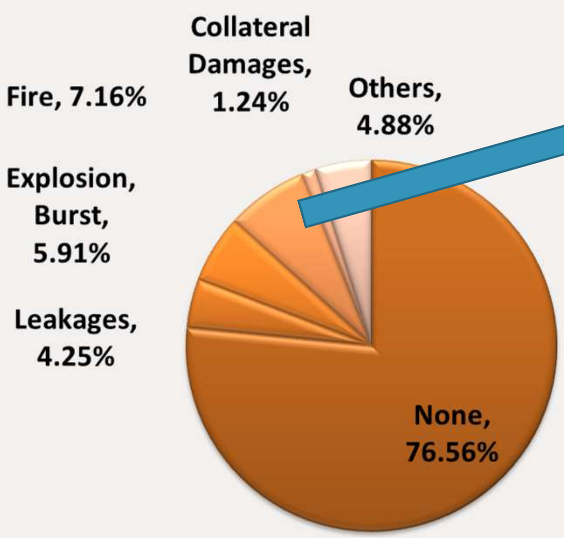
Failure Location dependant on Application (U>100kV)

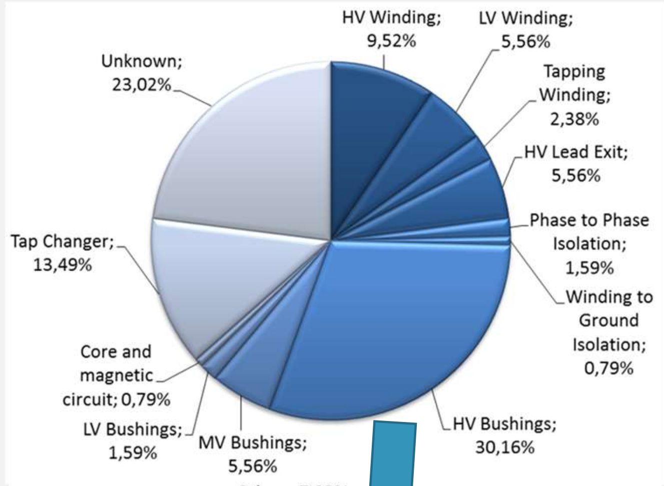


Failure location of substation transformers (based on 536 failures) and generator step-up units (based on 127 failures)

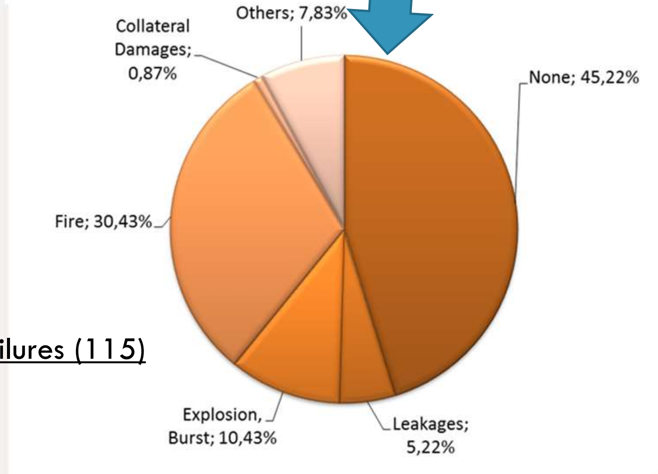
External Factors



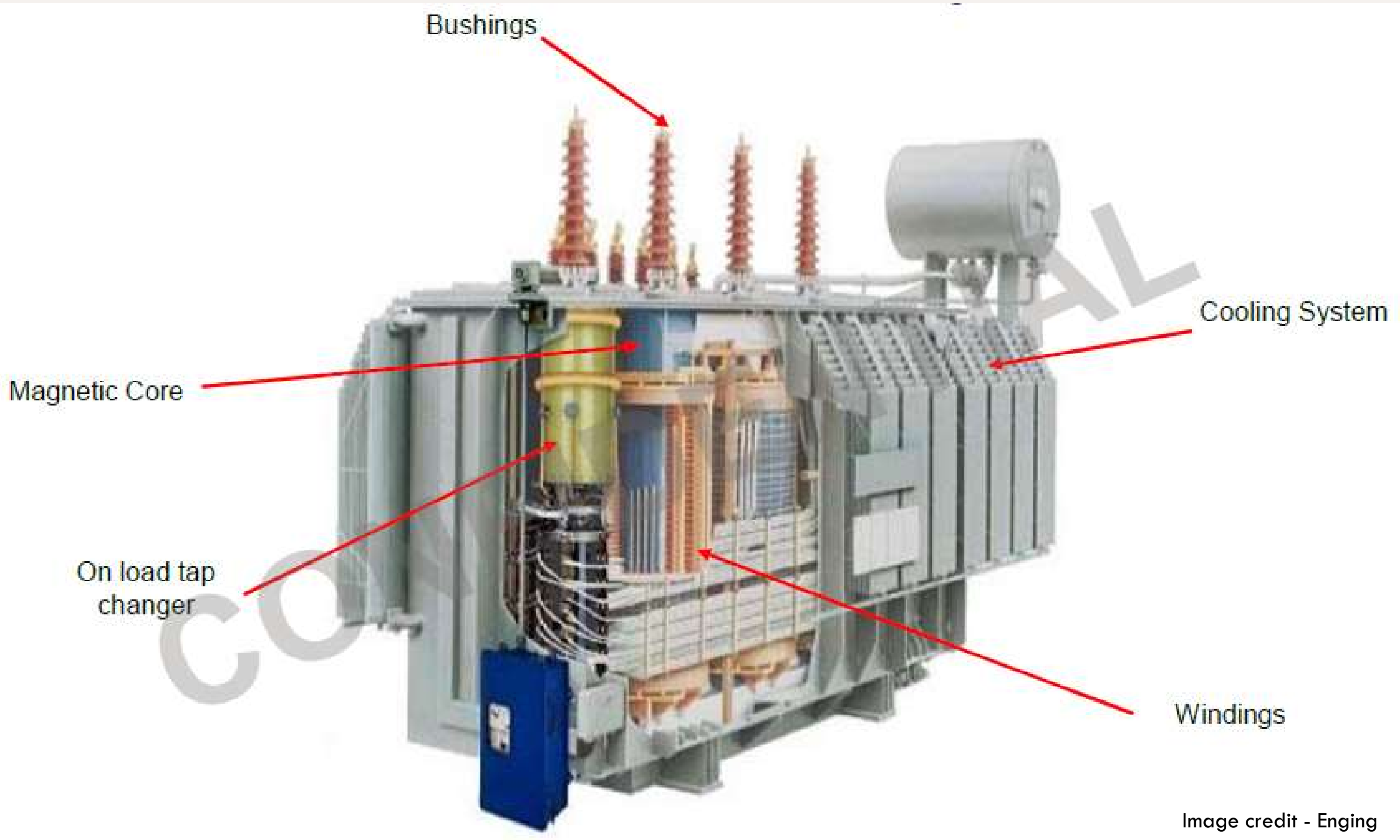
Failures with Fire or Explosion (126)



Bushing Failures (115)



Power Transformer Monitoring – Basic Concepts



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Condition Assessment Classification

Condition Assessment Classification	Description
Regular Visual Inspection	Identifies by your eyes, defects such as leaks etc. Unit can be energized or de-energized
Routine de-energized	Inspection & testing with normal test sets when the unit is out of service
Routine on-line	With unit in service e.g., testing (DGA), infrared scans etc.
Continuous on-line	Data available from installed IED’s such as DGA or bushing or OLTC monitors
Advanced	Deeper inspection & analysis such as FRA, DFR, unit out of service
Internal Inspections	With oil level lowered to expose the upper areas of the active part and lower portions of bushings & connections.
Inductive Reasoning	Domain, or tribal knowledge of certain makes of components and/or vintages units produced with issues, that time has revealed.

Measured On-line Continuous Values

Subsystem	Measured on-line continuous values (inputs)
Active Part (Tab. A.1)	- Rate of change and total gas (primarily H2) dissolved in the oil - 8 gases dissolved in oil (single measurement) - Load current transformer (3 phases) - Core ground current - Short-circuit current of the transformer (disturbance of the 3 phases - Peak voltage of the transformer surge - Primary / secondary / tertiary voltages (3 phases) - Winding temperature (thermal imaging) - Top oil temperature - Moisture (and temperature) in oil tank - Membrane rupture detector actuation - Partial discharges measurement (electric, UHF, acoustic)
Oil Containment and Preservation (Tab. A.2)	- Oil level sensor in the tank - Membrane rupture detector actuation - Moisture and temperature in oil - Ambient Moisture - N2 pressure level of the transformer
Cooling (Tab. A.3)	- Oil pumps motor current - Cooling system AC supply voltage - Forced pumps oil flow - Status of the oil pumps (on / off) - Transformer (3 phases) load current - Fans motor current - Ambient temperature - Winding temperature (thermal imaging) - Top oil temperature - Bottom oil temperature - Cooling / Fans status (on / off)
Bushings (Tab. A.4)	- Capacitance and tan-delta - Leakage current - Bushing voltage from capacitive coupler
OLTC (Tab. A.5)	- Status of the end of course (operation completion signal) - Actuation of command keys / buttonholes (event signal) - Motor driving current - Current accumulated in individual taps (load current) (load current) - Shaft torque curve of the engine switch (drive speed) - Tap position indicator - AC supply voltage - Number of accumulated changes on each tap - Total number of operations of the OLTC - RMS phase-to-earth transformer voltage (3 phases - primary / secondary / tertiary) - New position for the tap after switching (tap target) - OLTC Oil level - Oil temperature (diverter switch and compartment) - Gas sensor in insulating oil - Moisture content in the oil - Oil filter pressure - OLTC current (transformer winding)

Source: Table A.7
On-line Continuous Inputs

Cigré Technical Brochure TB 630

Thermal Monitoring

Temperature measurements are the basic data required for:

- General status of the transformer,
- Cooling control,
- Protection,
- Load-ability (Dynamic Rating of transformer),
- Ageing / insulation consumption.

Q_h	Relative Ageing Rate
92ºC	0.5
98ºC	**1.0**
104ºC	2.0
110ºC	4.0
134ºC	64

IEC 60076 part 7

A Typical Transformer Management System:

- Applies IEC transformer standards (e.g., IEC 60076) to determine thermal properties of a transformer
- Programmed with transformer factory test results (heat run, no-load/load losses, etc.) to define an accurate model of the transformer
- May also measure winding temperatures directly with fibre optic probes

Transformer Winding Direct Hot-Spot Monitoring

Inside Tank

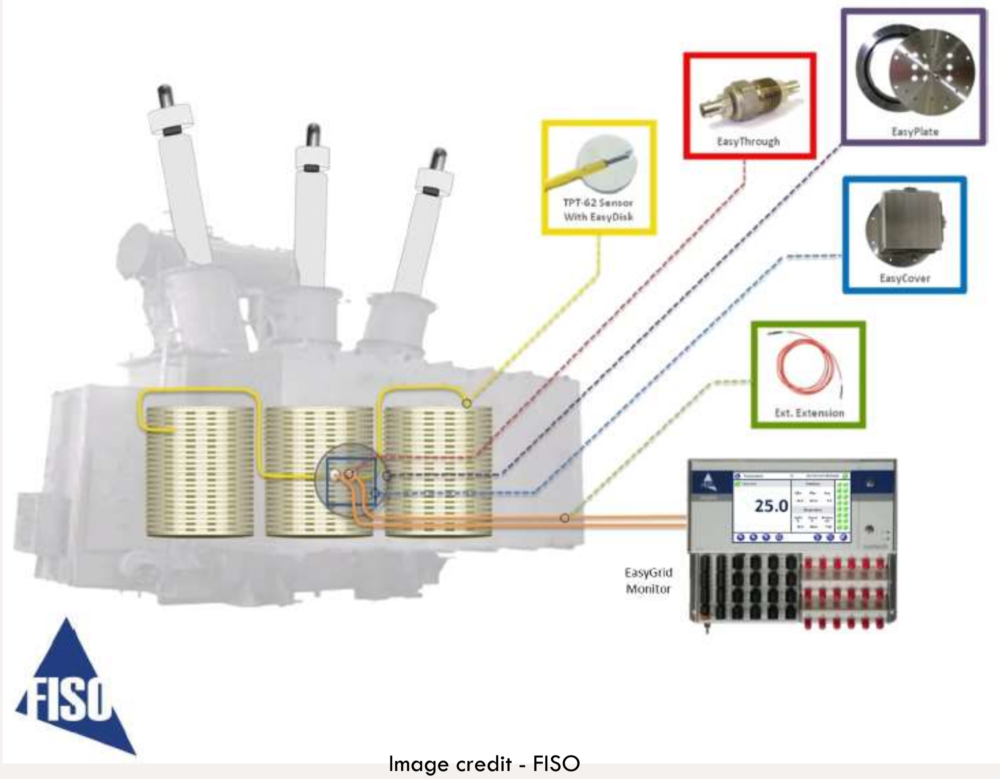
- Optical sensors are installed in the spacers of the winding
- Sensor cables brought to inside of tank wall interface

Tank Wall Interface

- SS316 plate is bolted to a flange on the wall. Gasket between to seal.
- Leak-proof optical feedthroughs (thick glass window inside) allow light to pass inside <-> outside

Outside the Transformer

- Fiber-optic extension cables are protected by a conduit and led into a control panel on the side of the transformer and connected to the monitor



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Tap Changer (OLTC) Monitoring

Able to monitor many properties online:

- **Drive/Energy Storage**
  - Motor CB trip
  - Motor energy monitor
  - Number of tap changes per day
- **Electrical Properties**
  - Counters for each tap
  - Record tap wear by I² for each tap
  - Reversing switch exercise
- **Thermal Properties**
  - Absolute temperature
  - Temperature differential

Image credit - MR

Fault Mechanisms and Diagnosis - Bushings

Partial breakdowns

- Measurement of capacitance
- Tan Delta measurement
- PD measurement

Voids, cracks

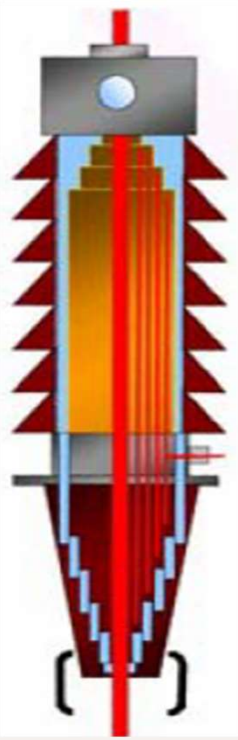
- Measurement of capacitance (RBP)
- PD measurement

Contact problems on measurement taps

- Tan Delta voltage sweep (tip-up test)

Ageing, moisture

- Dielectric response measurements
- Tan Delta



Voltage [kV]	No. of layers	% change
123	14	7.1
245	30	3.3
420	40	2.5
550	55	1.8

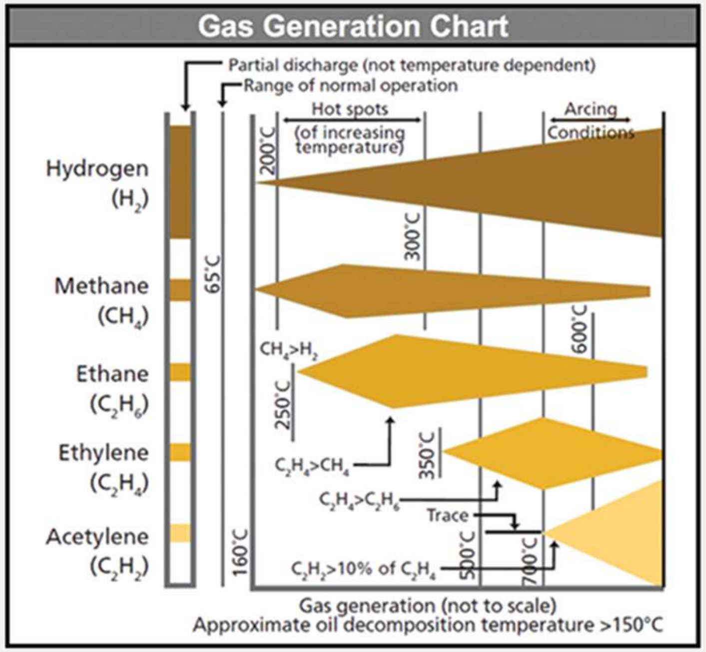
Bushing Diagnostic and Monitoring

Diagnostic methods	Periodic (off-line)	Continuous (on-line)
Capacitance	Yes	Yes
tanδ or PF (50/60 Hz)	Yes	Yes
FDS, PDC, RVM and R_{ins}	Yes	No
Winding resistance	Yes	No
Infrared scanning	Yes	Yes
PD measurement	Yes*	Yes*
DGA	Yes	No
Moisture in oil	Yes	No
Creepage current	No	Yes
Oil pressure	No	Yes
Transients	No	Yes

CIGRE WG A2.43: Transformer Bushings Reliability, Manila, 23.04.2018.

DGA Analysis

- Typical gases that appear in transformers are hydrogen (H2), methane (CH4), ethane (C2H6), ethylene (C2H4), and acetylene (C2H2). These gases begin to form at specific temperatures and dissolve within the insulation oil of a power transformer.



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Regular Electrical Tests

FM Global Property Loss Prevention Data Sheets - Transformers

2.1.2.2.6 Perform the off-line tests listed in Table 2 every three years.

Table 2. Routine Off-line Tests

Component	*Test*
Windings	Insulation resistance
	Winding resistance
	Polarization index
	Turns ratio
	Power factor/capacitance
Bushings	Power factor/capacitance
Core	Core insulation resistance
On load tap changer	Turns ratio
	Contact resistance
	Insulation resistance
	DGA
	Fluid screen test
	Motor current measurement
	Acoustic signature analysis

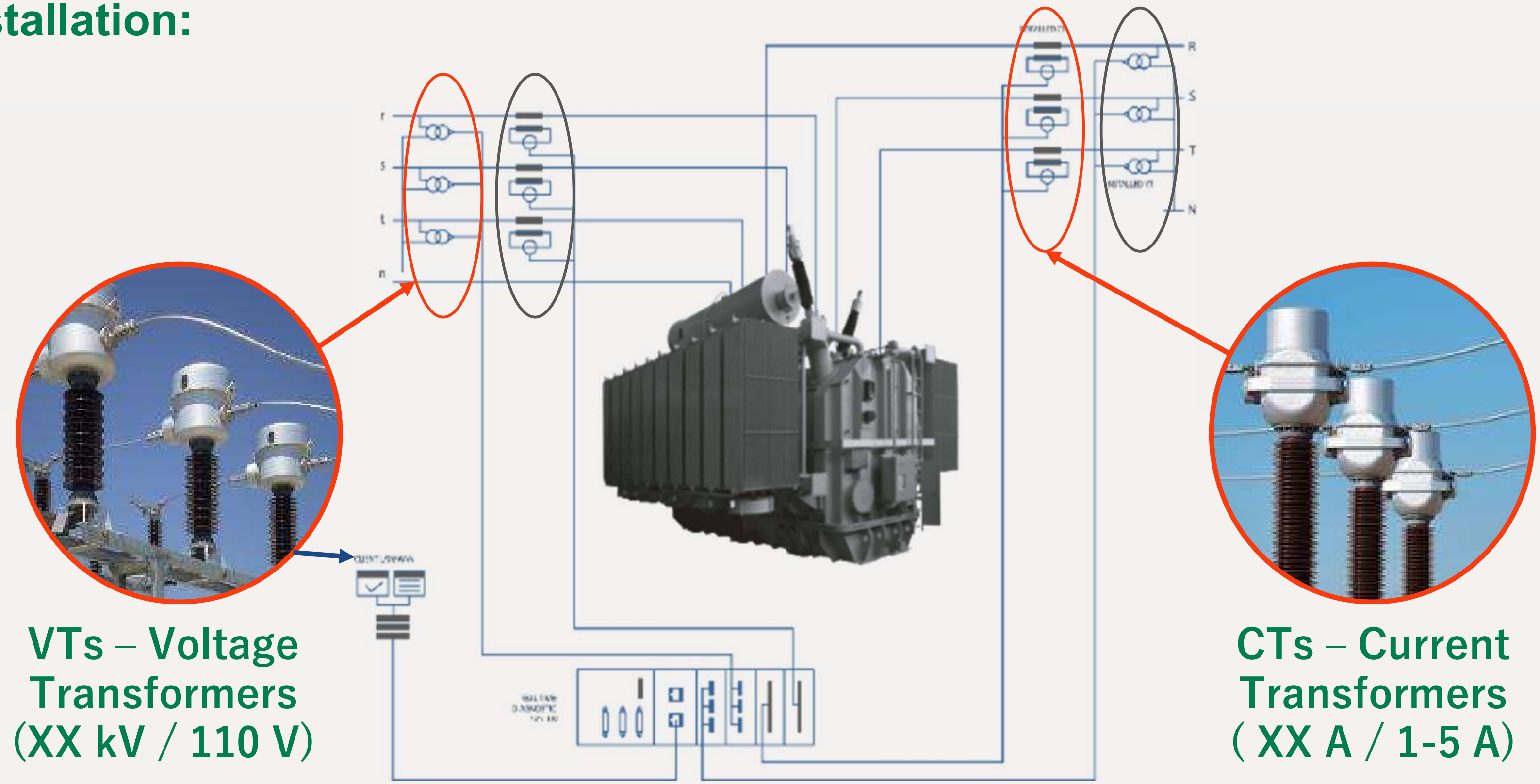
What if you could perform complimentary electrical tests online?

Online, in Real-Time and Non-Invasive Technique

- Mathematical model that allows the calculation of all of the transformer internal parameters
- Analysis of the magnetization current
- Analysis of the short-circuit inductance
- Analysis of the transformer turns ratio
- Analysis of the OLTC dynamic impedance

Diagnostic techniques based on electric analysis

Simple Installation:



VTs – Voltage Transformers (XX kV / 110 V)

CTs – Current Transformers (XX A / 1-5 A)

Extended Parks Vector Approach

- Parks Vector Approach on-line diagnosis is based on identifying the appearance of an elliptic pattern, corresponding to the transformer supply current Park's Vector representation, whose ellipticity increases with the severity of the fault and whose major axis orientation is associated to the faulty phase.

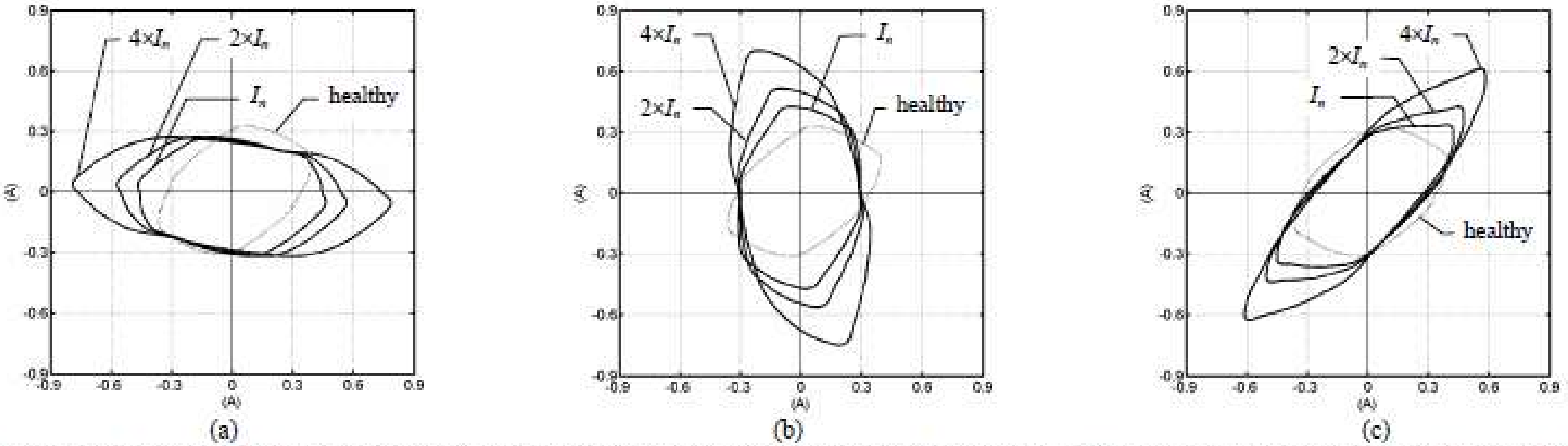


Figure 7.: Simulated on-load exciting current Park's Vector patterns for the case a *YNyn0* connection, rated load condition and two shorted turns in the primary winding, with several values of faulty current (in terms of the rated current of the affected winding, I_n), and for different faulty phases: (a) phase *R*; (b) phase *S*; (c) phase *T*.

Extended Parks Vector Approach

- With this approach, it can be difficult to discriminate between unbalanced loads and winding faults.
- To overcome this difficulty, an improved diagnostic technique has been implemented, which consists in the analysis of the on-load exciting current Park's Vector pattern, and therefore unaffected by the transformer's load conditions.
- Additionally, the on-load exciting current Park's Vector Approach enhances the severity of the fault, as compared to the former diagnostic technique.

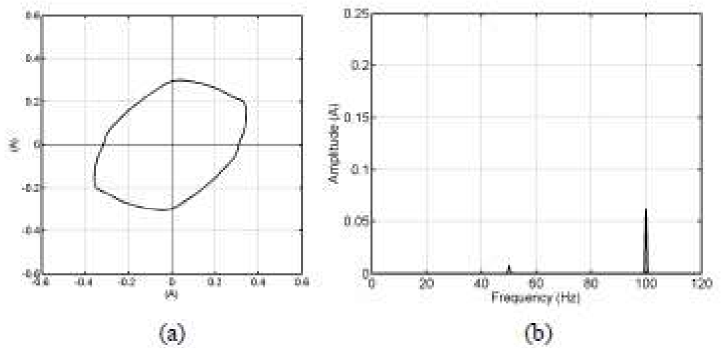


Figure 6. Simulated on-load exciting current Park's Vector pattern (a) and EPVA signature (b) for the case of an *YNyn0* connection, rated load and healthy operating conditions.

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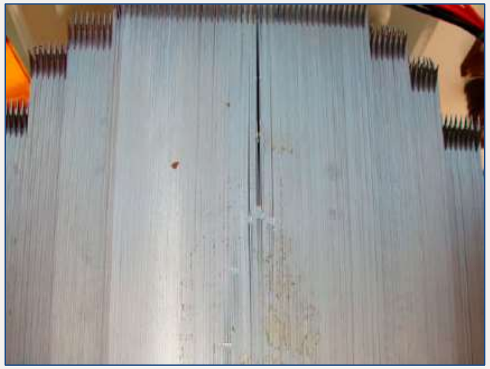
Using Three Methods of Fault Detection

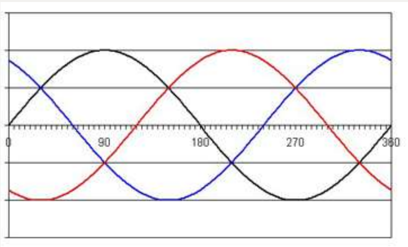
- Three diagnostic methods used to detect faults in power transformers:
- 1. **AOLEC** - Analysis of the On-Load Excitation Current allows the fault diagnosis of the windings / magnetic circuit of the power transformers. This method are perfectly adapted to the power transformers operating conditions used in the energy production, transmission and distribution (load variability, system immunity to possible disturbance in the electrical lines, etc.).
- 2. **MOTRAD** - In order to perform the faults discrimination between the windings, the magnetic circuit and, also, to detect faults in the on-load tap changer (OLTC) has been developed another diagnostic method called MOTRAD (MOdel-based TRAnsformer Diagnosis). the AOLEC and MOTRAD methods, working together, allow to detect, discriminate, locate and quantify the extension of the fault in transformer winding and ferromagnetic core.
- 3. **Sliding Window** - The method of the sliding window allows the inspection of the current signal in all tap transitions of the OLTC. This information gives the realistic data of the OLTC operating conditions at all tap transitions.

Diagnostic Principles – Excitation Current

- **What is the excitation current?**
  - Current needed by the transformer in order to create the magnetic field inside the core
  - Very small current, typically less than 1% of winding rated current
  - Measured by an offline test
- **What diagnostic information can provide?**
  - Compromised Insulation (interturn short-circuit faults, winding-to-ground insulation)
  - Core magnetic circuit abnormalities
  - On-load tap changer problems
  - Severe discontinuities, poor connections, and/or open-circuits



Diagnostic Principles – Excitation Current

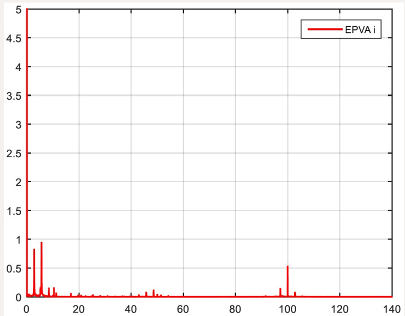


Primary and secondary current signals

$[I_{exc}] = [T][I_P] + [I_S]$
Excitation Currents

Three-phase Transform

FFT Algorithm



Spectral Analysis

Degradation Index

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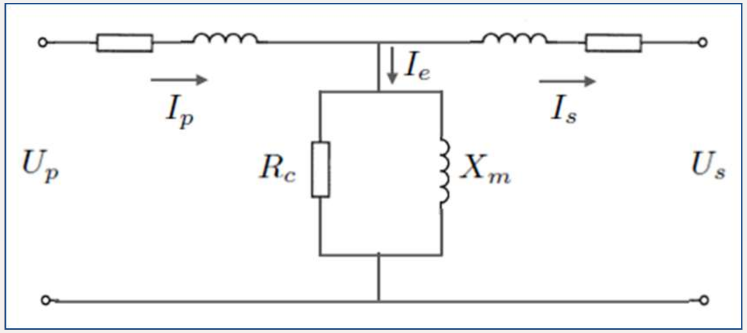
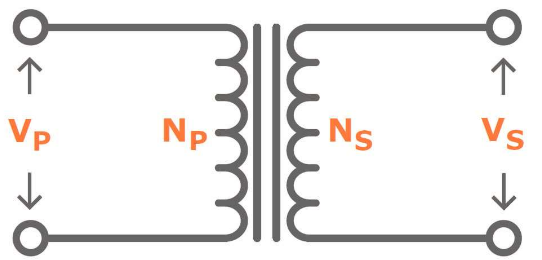
Diagnostic Principles – Mathematical Model

- **What is the transformer's mathematical model?**
  - Equivalent electric circuit that allows to model the transformer's behavior
  - Represented as a per phase model
- **What diagnostic information can provide?**
  - Real-time calculation of specific parameters
  - Allows to distinguish winding problems from core problems
  - Important for the calculation of other parameters (turns ratio and short-circuit inductance)
- **Fault Diagnosis:**
  - Winding/core – Exciting current and parallel impedance
  - OLTC – Exciting current and series impedance



Diagnostic Principles – Transformer Turns Ratio

- **What is the Turns Ratio?**
  - Evaluates the transformation ratio between primary/secondary sides
  - Comparison with the factory/nameplate data
  - Measured by an offline test



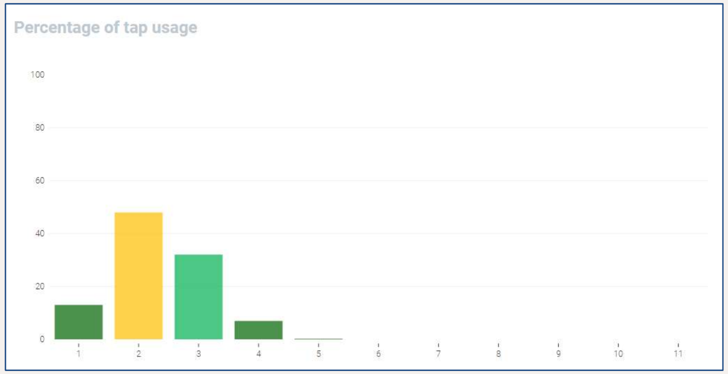
$$\text{Turns Ratio} = n = \frac{N_P}{N_S} = \frac{V_P}{V_S}$$

- **What diagnostic information can provide?**
  - Turn short-circuit due to insulation issues
  - Core magnetic circuit abnormalities
  - On-load tap changer problems
  - Severe discontinuities, poor connections, and/or open-circuits

Diagnostic Principles – Transformer Turns Ratio

- Calculation based on the voltage and current measurements
- Tap-changer operation profile (Variation according to each tap position)

- Calculation of OLTC tap usage
- Indication of which taps are subject to the greatest degradation



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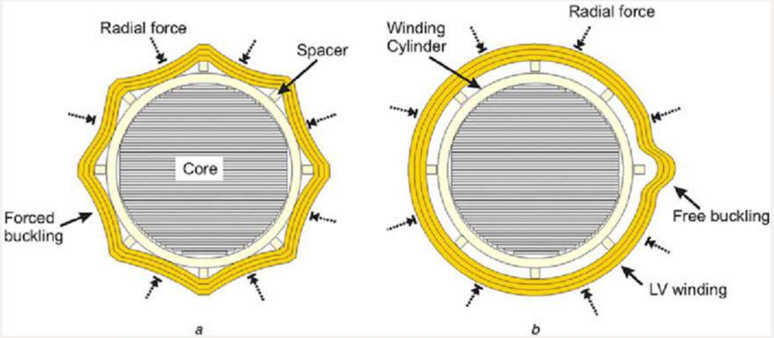
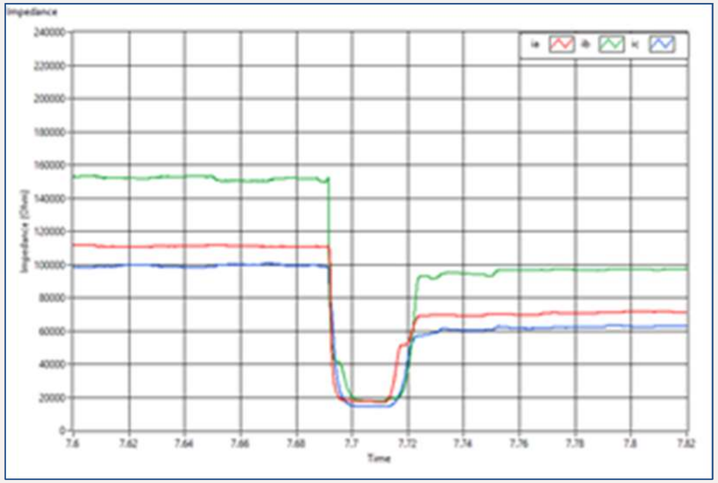
Diagnostic Principles – Short Circuit Inductance

- **What is the Short-Circuit Inductance/Leakage Reactance?**
  - Parameter related to the leakage magnetic flux inside the transformer (flux not fully contained in the core)
  - Sensitive to construction or physical variations
  - Comparison with the factory/nameplate data
  - Measured by an offline test
- **What diagnostic information can provide?**
  - Assessment of winding deformations or displacement
  - Variations related to the transformer physical structure
  - Should remain constant over time



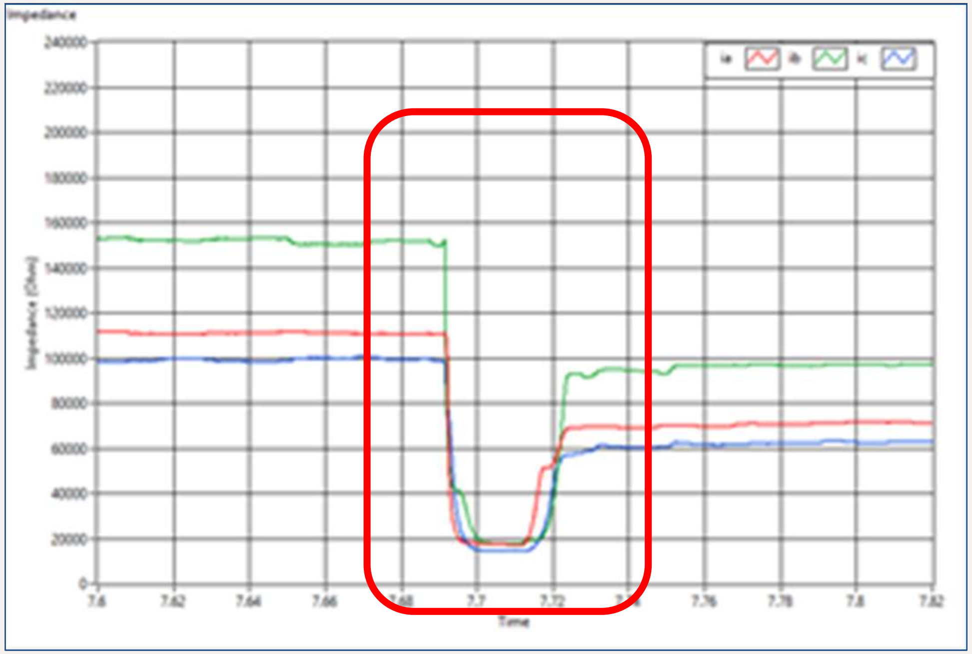
Diagnostic Principles – OLTC Dynamic Impedance

- **What is the on-load tap changer dynamic impedance?**
  - Proposed approach for online OLTC analysis
  - Impedance measurement during tap changer transient operation
  - Relates the winding voltage and the on-load excitation current

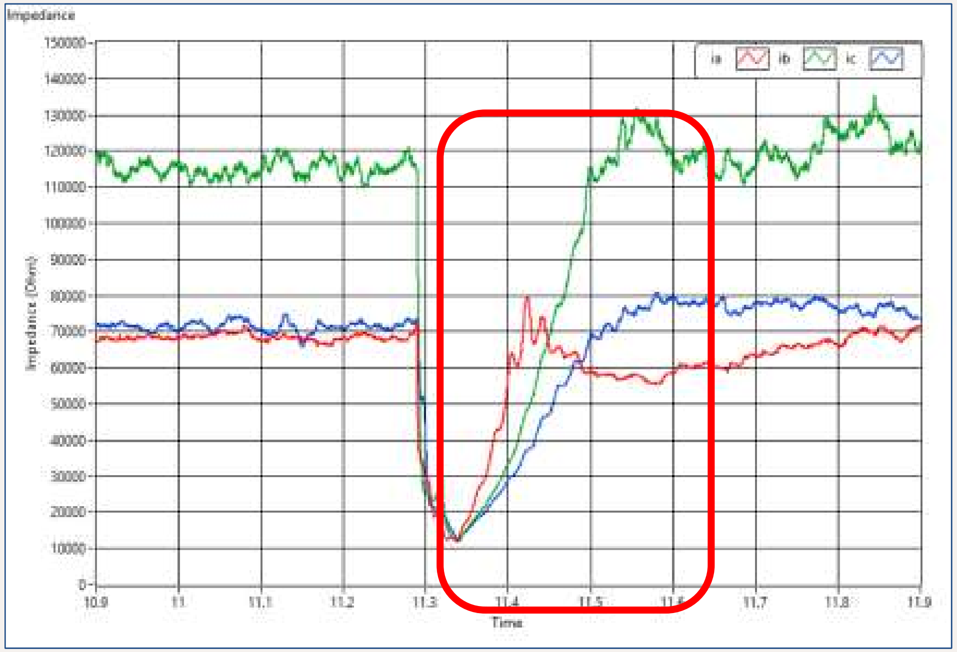


- **Why it is important? What diagnostic information can provide?**
  - Assessment of OLTC electrical problems
  - Detection of OLTC mechanical problems

Diagnostic Principles – OLTC Dynamic Impedance



Visible changes over time



Summary - Typical Failure Modes

	Common Failures	TRADITIONAL DIAGNOSTIC TECHNIQUE	DIAGNOSTIC TECHNIQUE
Windings	Oil / Paper discharges Hot spots Winding displacements	DGA Hot Spot Monitoring Offline Electrical Tests	☺ 😐
Core	Circulating currents	DGA Offline Electrical Tests	☺ ☺
Bushings (OIP)	Gassing / Explosion Cracks	Visual Inspection DGA PF & Capacitance test	😐
OLTC	Sparking Out of Synchronism Drive mechanism jammed	Visual Inspection Offline Electrical Tests	☺ ☺

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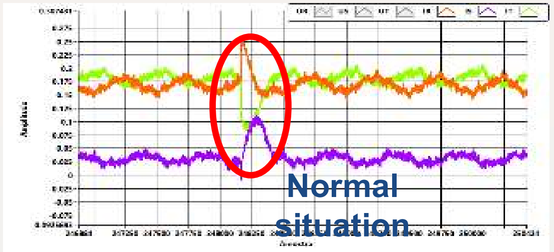
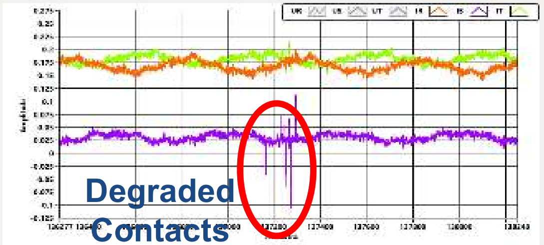
Case Study 1 – Distribution Substation

Problem: On Load Tap-Changer

- **Problem:**
  - The EMS TCM system detected a problem in the on-load tap changer between consecutive taps.
- **Problem Verified:**
  - Visual inspection confirms detected problem
  - The OLTC oil was changed and the on-load tap changer was put back into service
  - Replacement was scheduled for a more convenient date





Transformer:

- 31.5 MVA, 60 / 31.5 kV, 50 Hz, yn, date of manufacture: 2005

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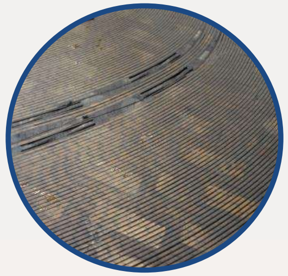
Case Study 2 – Hydroelectric Power Plant

Problem: Windings (interconnection with line)

- **Problem Verified:**
  - During the last 3 years of operation, there was an increase in the values obtained through the oil analysis.
  - The maintenance team made the decision to stop the transformer and send it to the factory (750 000 €).
  - EMS TCM indicated that the transformer was in good condition and that nothing wrong was happening in the insulation of the same.
- **Conclusion:**
  - The inspection revealed that the insulation of the windings were in perfect condition
  - The problem was in the oil, contaminated
  - The core was removed and was in good condition

Transformer opening - before core removal



windings' insulation, being in good condition

TRANSFORMER:

- 58 MVA, 10/240 kV, 50 Hz, Dyn11, shell core, date of manufacture: 1971

Opening of Winding's Insulation

Case Study 3 – Wind Farm

Problem: Windings

- **Problem Verified:**
  - A degradation was detected by EMS TCM system during the commissioning stage
  - Abnormal asymmetrical representation of transformer's intrinsic signature (overall stretched shape registered)
  - The degradation was pinpointed to be located in the windings of the transformer
  - Some current and voltage spikes were also detected which are related to transformer's abnormalities. It is possible to see spikes or larger variations due to inherent fast load variations and due to the degradation condition in this transformer.
- **Conclusions:**
  - The transformer has been normally operating over the last year with this detected winding problem
  - Permanent online remote monitoring of the transformer is being performed in order to permit additional analysis and build tendencies, allowing to evaluate the winding´s degradation evolution over time (level of severity) and thus plan a much more objective preventive/corrective maintenance.

Transformer:

- 38 MVA, 45 / 20 kV, Dyn 11, date of manufacture: 2011

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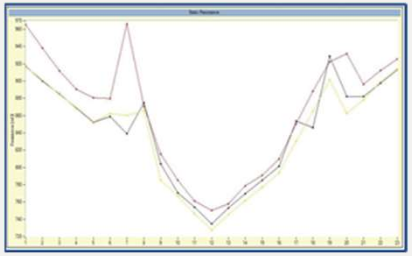
Case Study 4 – Distribution Substation

Problem: Bushing problem

- **Problem Verified:**
  - EMS TCM system detected a short circuit in windings, the fault was pinpointed to be located in the L3 phase of the windings.
  - Operational teams locally performed electrical analysis
  - Abnormal static ohmic resistance values registered in some taps
  - Deeper offline electrical analysis detected a fracture in a bushing



- **Conclusions:**
  - Transformer sent for repair and visual inspection proved a clear fracture in the bushing.
  - Degradation problems also detected in the selector´s contacts and diverter switch.
  - The early fault detection and alarm alert issued by EMS TCM system permitted to avoid a major failure in the transformer and consequent power loss of the substation (at least by 30%). Savings are calculated to be around € 400.000

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Thank You

Any Questions?

paul.guy@gridsolutions.com.au

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