Maintenance & Diagnosis Strategies

for

High Voltage Substations

Robin Fischer, 28 April 2004

Diagnosis of Substation Equipment

- Power Transformers
- Instrument Transformers
- Switch-Gears Breakers
- Coils / Reactors
- Capacitors

Situation European and North American Utilities

Keywords

- Liberalization / Privatization of Electrical Market
- Globalization
- World-wide Economic Crisis

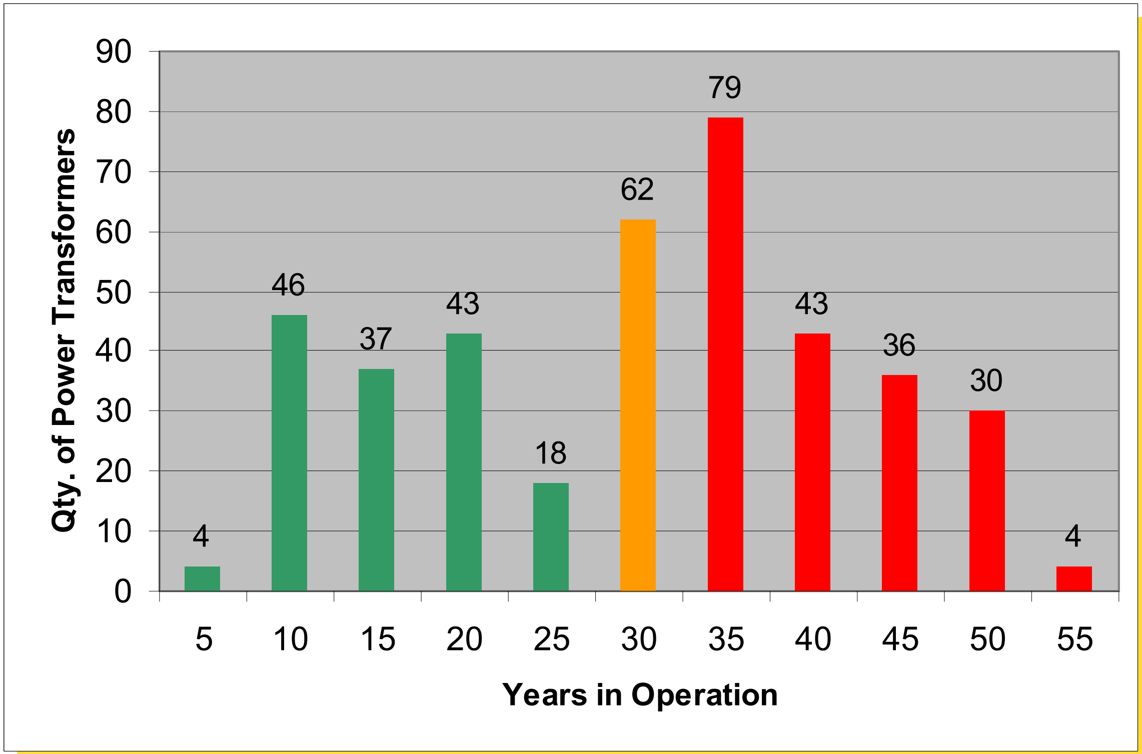
Situation European and North American Utilities

Effects

- Competition / Market Demand
  - low price for energy
  - reliability of supply
  - power quality

- Utilities have implemented Cost Reduction Plans
  - minimum maintenance work
  - minimum investments
  - extension of lifetime of substation equipment
  - avoiding catastrophic failures

Situation European and North American Utilities



e.g. a German Utility:

48 % of Power Transformers have reached critical lifetime (> 35 years)!

Only 32 % are uncritical (< 20 years)

Replace or Operate ?

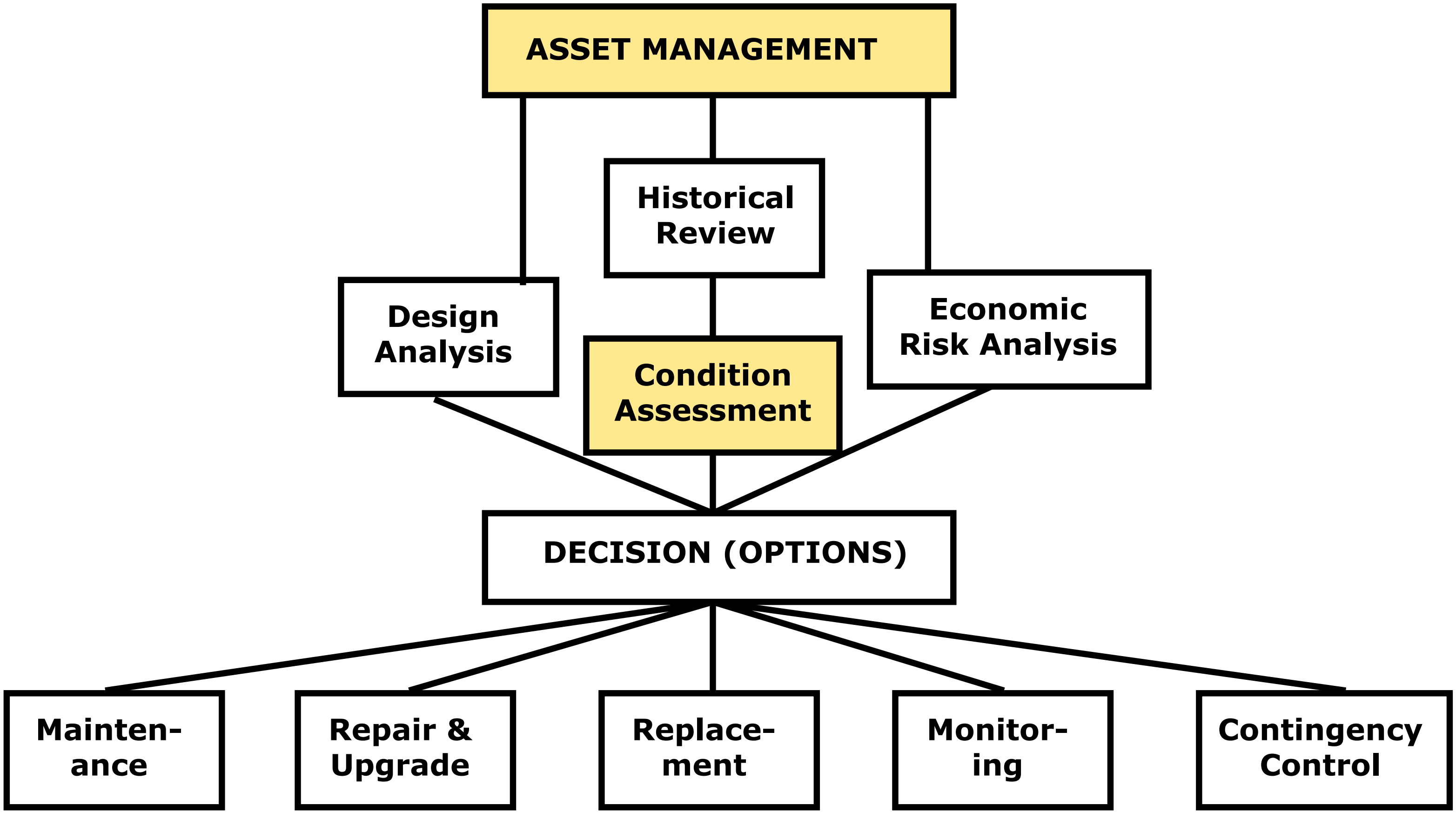
Costs:

- New unit including interest, depreciation and installation
- Maintenance
- Diagnosis
- Refurbish / Repair
- Outage (loss of revenue)

Benefits:

- Failure reduction
- Savings from less no load and load losses
- Improved reliability (transformer and power system)
- Scrap value (copper, core and tank)

Diagnosis


ASSET MANAGEMENT
Historical Review
Design Analysis
Economic Risk Analysis
Condition Assessment
DECISION (OPTIONS)
Mainten-ance
Repair & Upgrade
Replace-ment
Monitor-ing
Contingency Control

Diagnosis

- **CM:** Corretive Maintenance
  ➔ repair after failure

- **TBM:** Time Based Maintenance
  ➔ replace after a specific time

- **CBM:** Condition Based Maintenance
  ➔ evaluate condition of equipment
  ➔ repair just before a defect occurs

Condition Based Maintenance CBM

- **Identify high risk** equipment where deteriorated insulation condition represents a high failure probability.
- Condition-based maintenance is more profitable than traditional scheduled maintenance as the **resources are spent only on equipment with identified or suspected defects**. Scheduled maintenance on healthy equipment can even result in maintenance-introduced defects!
- **Risk-based maintenance** is a further improvement in terms of cost-reduction compared to CBM, as economic risk is an important criterion in the maintenance planning.
- Economic risk due to forced **outages can be reduced** either by reducing failure probability or by minimizing the consequences.

Condition Based Maintenance CBM

Typical Failures and Failure Rates (R_N) on Power Transformers:

Voltage Level	Units	Failure Rate
134 kV	3'674	0.35%
245 kV	419	1.19%
420 kV	258	2.33%
ϕ 245 ...420 kV	677	1.63%

CIGRE 1998

Trafo - Component	Failure Rate
Tap Changer	40%
Winding + Core	35%
High Voltage Bushing	14%
Transformer Tank	6%
Accessories	5%

CIGRE 1983

Condition Based Maintenance CBM

CM or CBM ? – Example of Cost Calculation

Assumption:

Costs of a 54 MVA Transformer	600 kUSD	
Costs of Repair after dramatic Failure	300 kUSD (replac. Winding)	
Costs for not delivered Power	21 kUSD / day	
Costs of Diagnosis Instruments	120 kUSD	
Quantity of maintained Transformers	10	
Manpower for Diagnosis Measurements	1 day / 2 persons	
Detection Rate (d_N):	Winding+Core	70 %
	Tap Changer	70 %
	Bushing	70 %
	Accessories	90 %

Condition Based Maintenance CBM

CM or CBM ? – Example of Cost Calculation

Calculation:

Probability of Failure without Diagnosis $f_0 = 1.63\% / \text{Year}$

Probability of Failure with Diagnosis $f = f_0 \times (r_N \times (1-d_N))$

$f = f_0 \times (40\%x30\%+35\%x30\%+14\%x30\%+5\%x10\%) = 0.51\% / \text{Year}$

Saving in „Risk“ $S = f_0 - f =$ **1.12 % / Year**

Reduction of failure probability by 1/3rd

d_N: Detection Rate (per Component)
r_N: Risk (per Component according CIGRE)

Condition Based Maintenance CBM

CM or CBM ? – Example of Cost Calculation

Calculation, continued :

Savings for Repair:
S = 1.12 % / Year x 300 kUSD = 3.4 kUSD / year

Savings for not delivered Power :
S = 1.12 % / Year x 20 days x 21 kUSD / day = 4.6 kUSD

Total Savings: 8 kUSD / Year / Transformer

Condition Based Maintenance CBM

CM or CBM ? – Example of Cost Calculation

Calculation, continued :

Costs for Manpower / 1 yearly measurement:
C_{MAN} = 2 x 1 KUSD = 2 kUSD

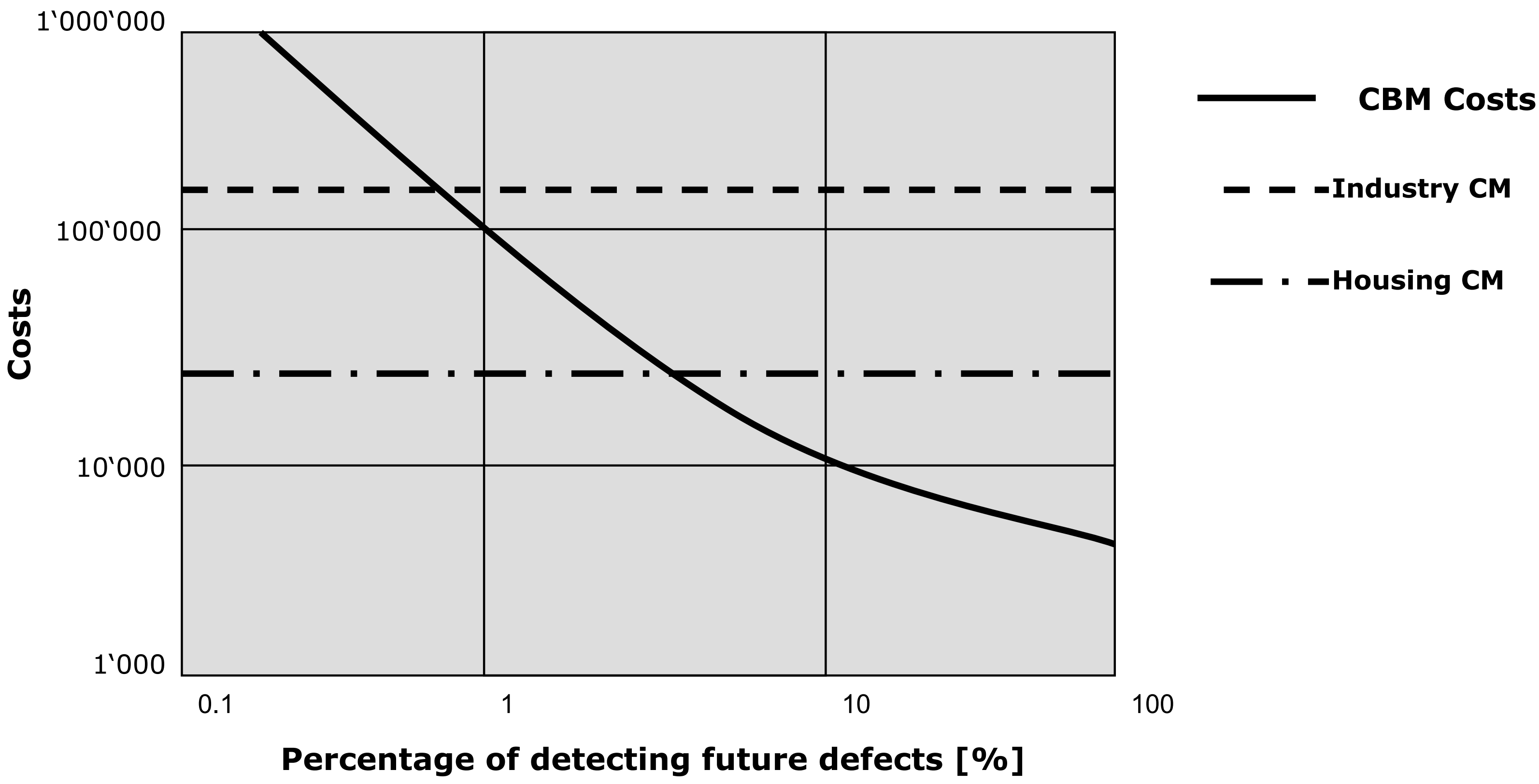
Costs for Investments:
C_{INV} = 120 kUSD / 10 * / 6 ** = 2 kUSD / Year

Total Costs:4 kUSD / Year

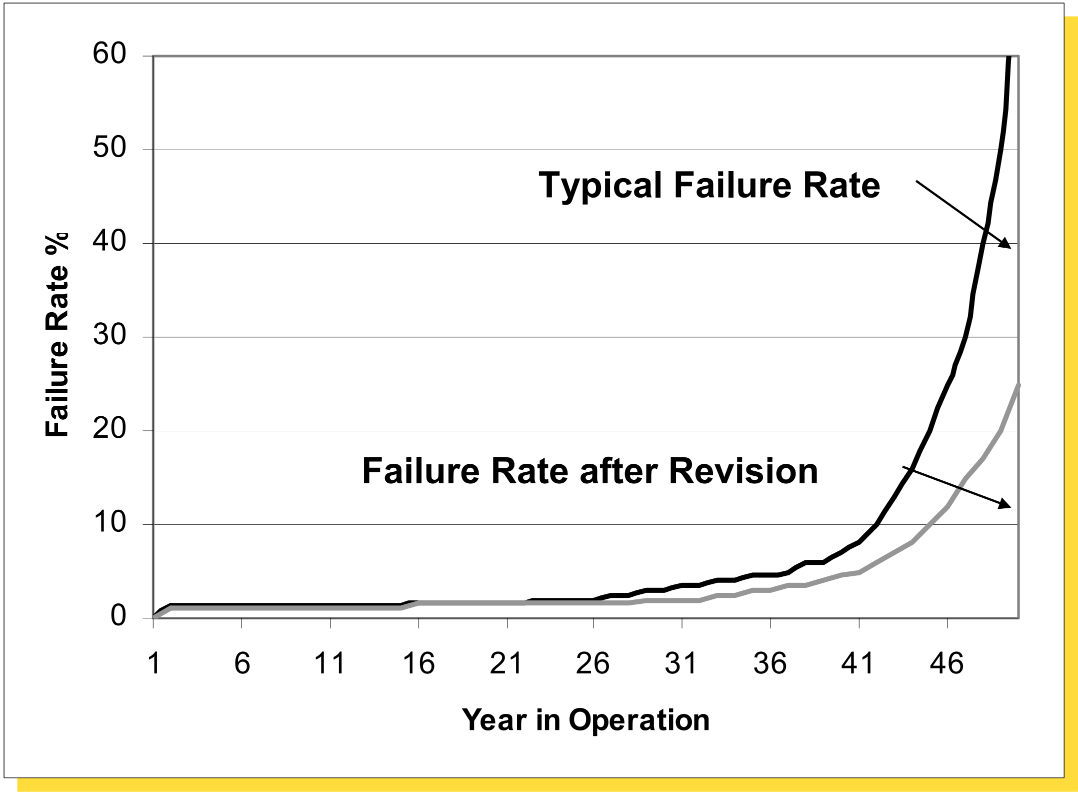
<u>Profit:</u> **8 kUSD / Year – 4 kUSD / Year = 4 kUSD / Year / Transformer**

* 10 maintained transformers
** 6 years write-off period for measurement equipment

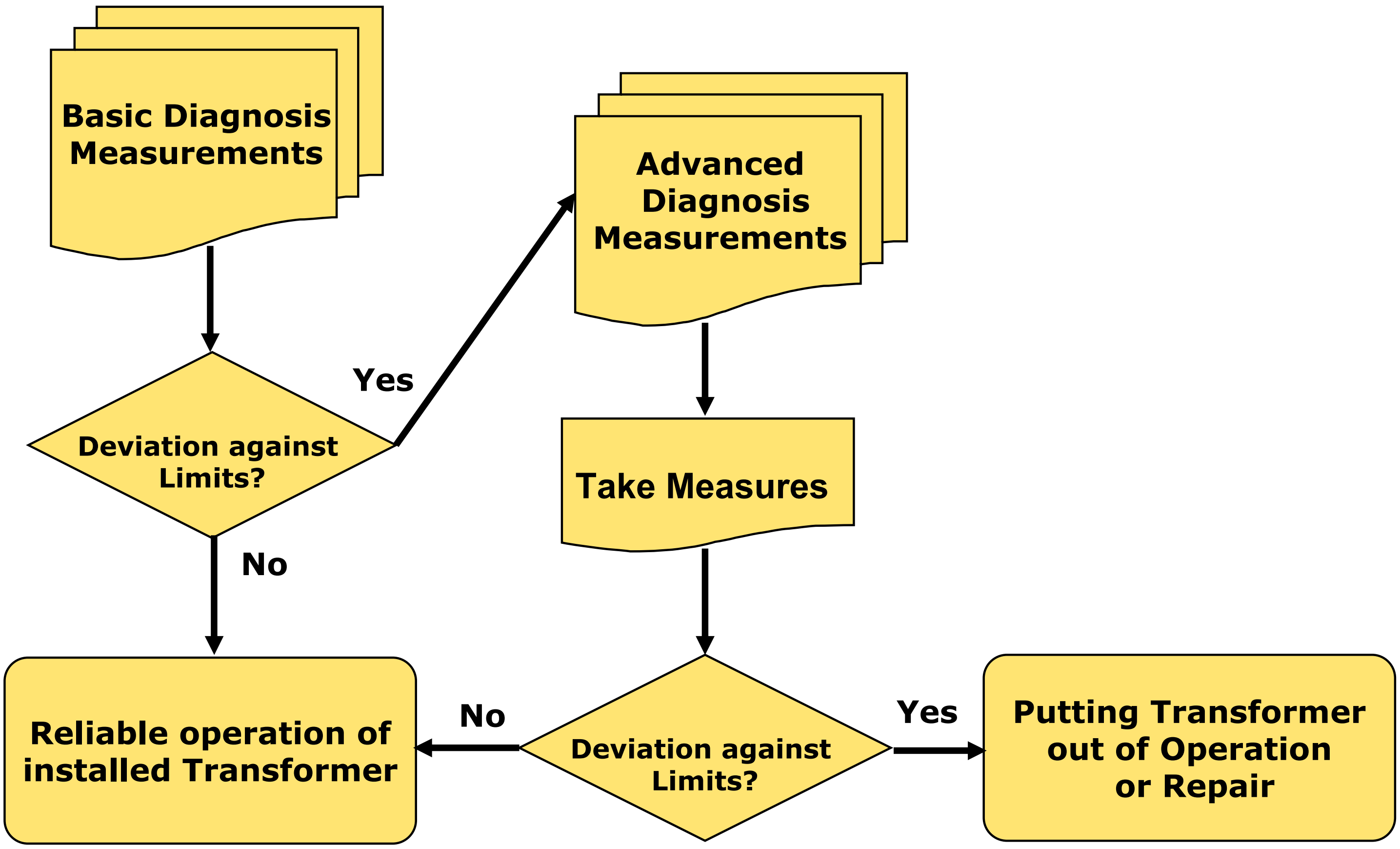
Condition Based Maintenance CBM



Condition Based Maintenance CBM



Condition Based Maintenance CBM



Diagnosis on Power Transformers

Basic diagnostic Tests during regular Maintenance work:

- Dissolved Gas Analysis
- Winding Resistance
- Transformer Turns Ratio
- Power Factor or c & tan d including
  Short circuit Impedance Measurement
- Oil Breakdown Voltage

Advanced diagnostic Tests for critical Transformers:

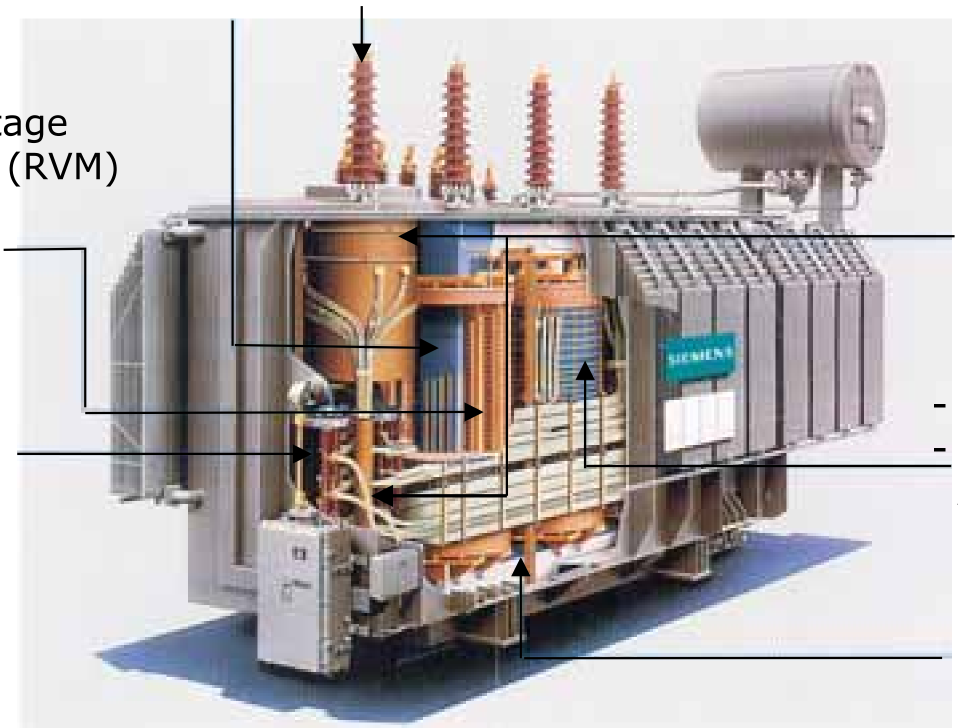
- Frequency Response Analysis (FRA)
- Dielectric Response Measurement (RVM)
- Partial Discharge acoustic Detection
- Field Induced Test with Partial Discharge Measurement
- Noise and Vibration Measurement

Diagnosis on Power Transformers

- Power Factor C & tand,
- Partial Discharge (acoustic, electrical – UHF)

- Recovery Voltage Measurement (RVM)

Isolation-resistance



- Winding Resistance
- Turns Ratio

- Short Circuit Impedance
- Frequency-Response Analyses (FRA)

Dissolved Gas (DGA)
Oil Breakdown Voltage

Diagnosis

Results from Diagnostic Test:

- Multiple Diagnostic Tests will give correct Information about the Condition of the Device. There is no way to get a „***Red***“ or „***Green***“ decision out of one Diagnosis Measurement!
- Comparison between different Measurements from same Device over a time period e.g. 5 years. Evaluation of the Deviation (Trend-Measurement). Is there an increase of the Deviation?
- Comparison between Measurements on similar Devices. Decision: Which device is worse?
- Comparison between three Phases of same Device. Is any Phase different from the others?
- Comparison between a Measurement and Research results achieved in a Laboratory

Measurements and Diagnosis Tools

for

High Voltage Substations

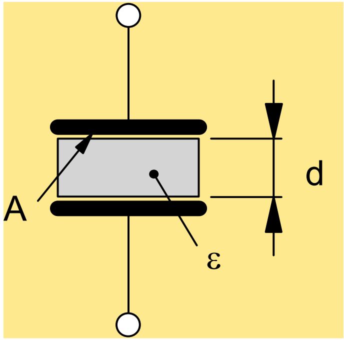
Measurements and Diagnosis Tools

Examples for Measurements:

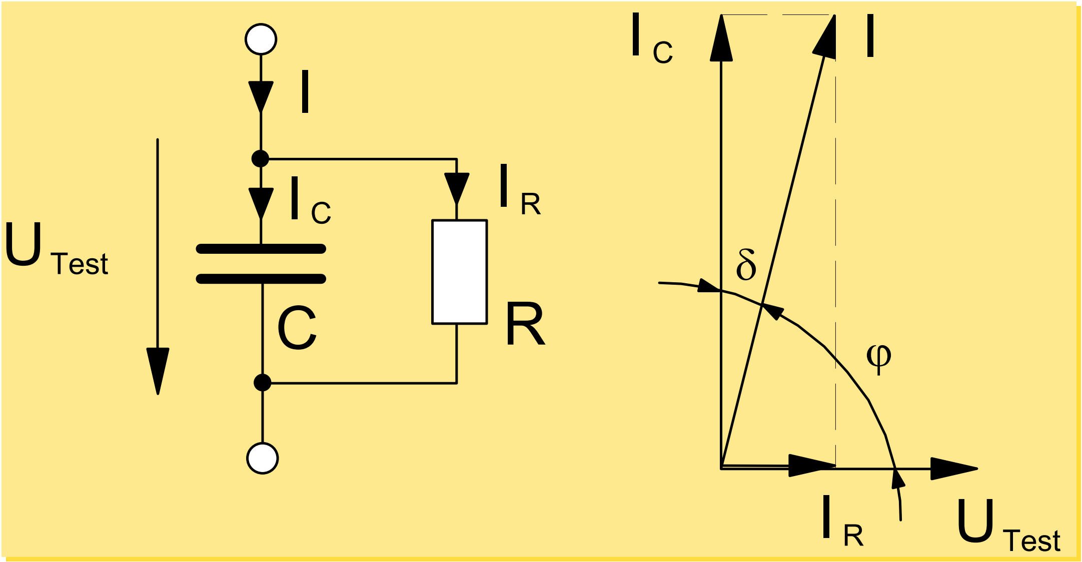
- C & tan δ
- Winding Resistance
- Transformer Turns Ratio
- Recovery Voltage
- Breakdown Voltage in Oil

C & tan δ Measurement

Oil-Paper Insulation



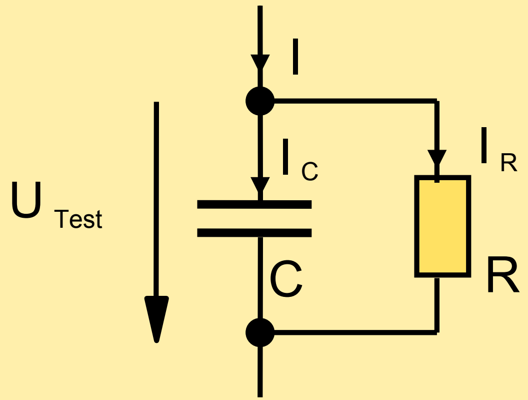
Equivalent Electrical Diagram



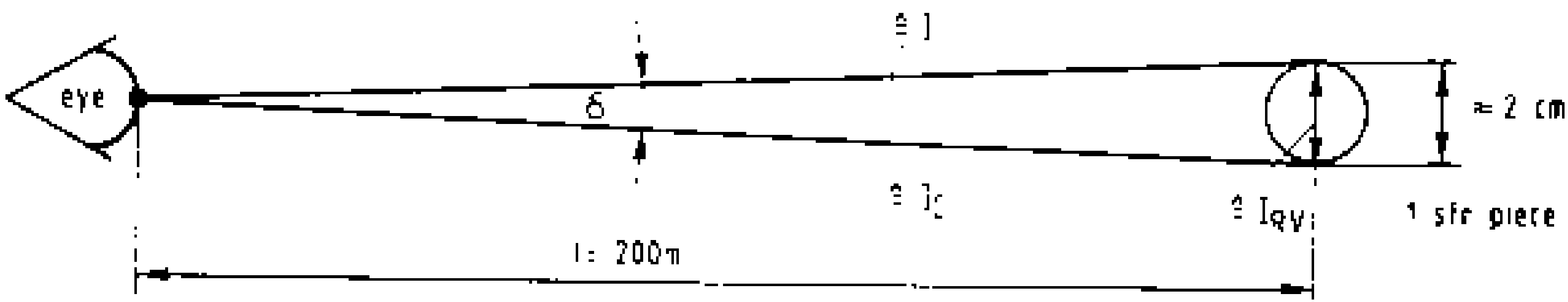
Measured Quantity

$$\tan\delta = \frac{I_R}{I_C} = \frac{P}{Q}$$

C & tan δ Measurement



$$\tan\delta = \frac{I_R}{I_C} = 1\cdot 10^{-4} = \frac{10\mu A}{100mA} = \frac{0.02m}{200m}$$



C & tan δ on Bushings

Some Data's form a world-class Bushing Manufacturer:

- delivered 600'000 Bushings over the last 30 years
- 80 % paper-insulated Bushings are older than 25 years
- periodical monitored only 3'000 to 4'000, typically only for 245 – 735 kV
- expected Lifetime approx. 40 years for paper-insulated Bushings

Recommendation:

- periodical c & tan d measurement

245 kV Bushing	max. deviation in Capacitance	+ 13 %
	max. tan d	< 1 %
420 kV Bushing	max. deviation Capacitance	+ 9 %
	max. tan d	< 0.9 %

C & tan δ Measurement

Power Transformers	tanδ new	tanδ old	Capacitance range
Dry design	$1 \bullet 10^{-2}$	$5 \bullet 10^{-2}$	500pF ... 5nF
Oil design	$1 \bullet 10^{-3}$	$1 \bullet 10^{-2}$	500pF ... 5nF

Bushings	tanδ new	tanδ old	Capacitance range
Various designs	$1 \bullet 10^{-3}$	$5 \bullet 10^{-2}$	50pF ... 1nF

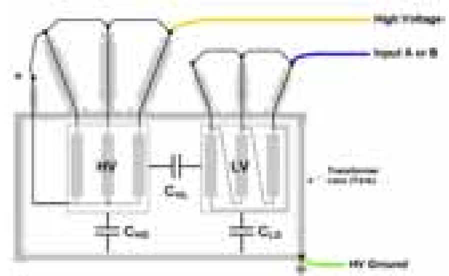
Transformer Oils	tanδ new	tanδ old	Capacitance range
Different types	$1 \bullet 10^{-4} \ldots 1 \bullet 10^{-3}$	$1 \bullet 10^{-3} \ldots 1 \bullet 10^{-2}$	Depends from test cell

midas[2880] Features

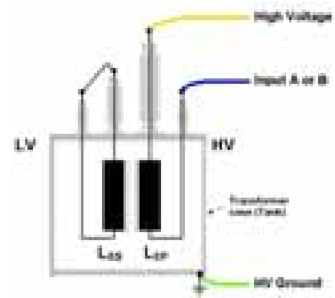
- ☑ **Dissipation Factor (tanδ)** and **Power Factor (cosφ)** Testing to analyse condition and quality of high voltage insulation systems
- ☑ **Additional measuring capabilities** like Quality Factor, Frequency, Voltage, Current, Power, Losses, Impedance, Inductance, Reactance, Capacitance
- ☑ Built-in high voltage supply up to **15kV, 3kVA**
- ☑ **Rugged, reliable and safe** construction
- ☑ **State-of-the-art** integrated PC with embedded Windows XP™ based touch screen user interface
- ☑ **Manual and Automatic** (Sequencer) test operation.
- ☑ Measurement **at local power-line frequency** based on Adaptive Dynamic Noise Suppression "ADNS" (patent pending)
- ☑ **Highest Accuracy** by using a built-in gas-insulated standard capacitor as internal reference

midas 2880 Applications

- **Transformers**
  Power Transformers, Distribution Transformers, Instrument Transformers

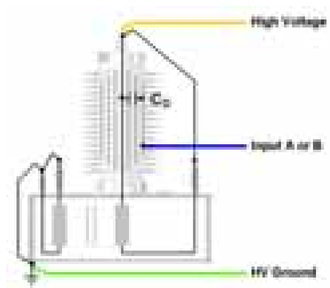


tan Δ

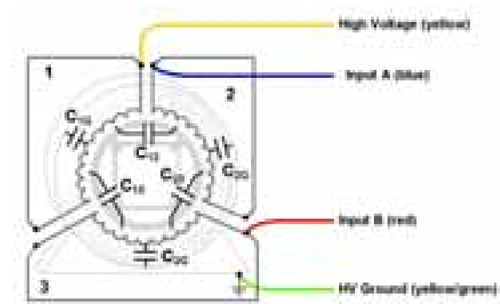


Short Circuit Impedance

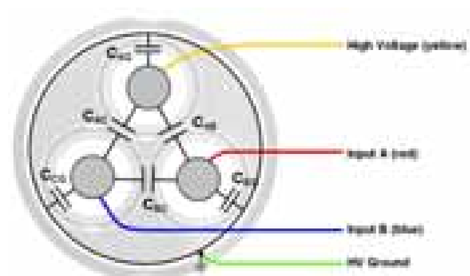
- **Bushings**



- **Rotating Maschines**



- **Cables**



- **Capacitors, Liquid Insulation, Surge Arrestors, Circuit Breakers**

midas 2880 Hardware

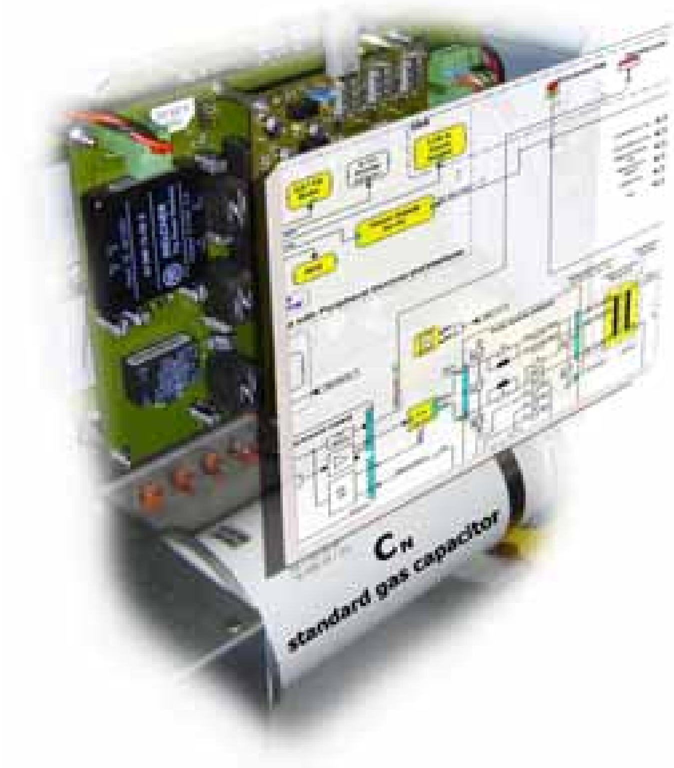
Shortest Measurement Time
• All-in-one-piece for shortest measuring set-up time in the market

Handy Mechanical Design
• Easy one-man transportation and loading
• Rugged construction and large pneumatic wheels

Easy to operate
• Self explanatory graphical user interface
• Large 12.1” colour display and the **touch screen** for test planning, preparation, execution and first assessment with just a finger tip
• Equipment is sealed against environmental influences

Wide Range of Application
• Unique built-in 15kV and 3kVA high voltage high power source which allows measurements on high capacitive loads
• Testing of generators with 25 kV nominal voltage according to IEC 60034
• Test of biggest class of power transformers in shortest time

midas 2880 Hardware



Highest Accuracy

- Highest accuracy on the market.
- **Built-in standard gas capacitor as reference** guarantees highest long term stability
- Independence of the temperature, air pressure and humidity
- All calibrations are done automatically as part of the self-test at boot-up

Advanced Interference Suppersion

- Adaptive Dynamic Noise Suppression "ADNS" for advanced interference suppression method (patent pending)
- **Measurements at real power frequency** as recommended IEEE/ANSI 56.12.90.
- No frequency modulation beside the actual power frequency is needed.

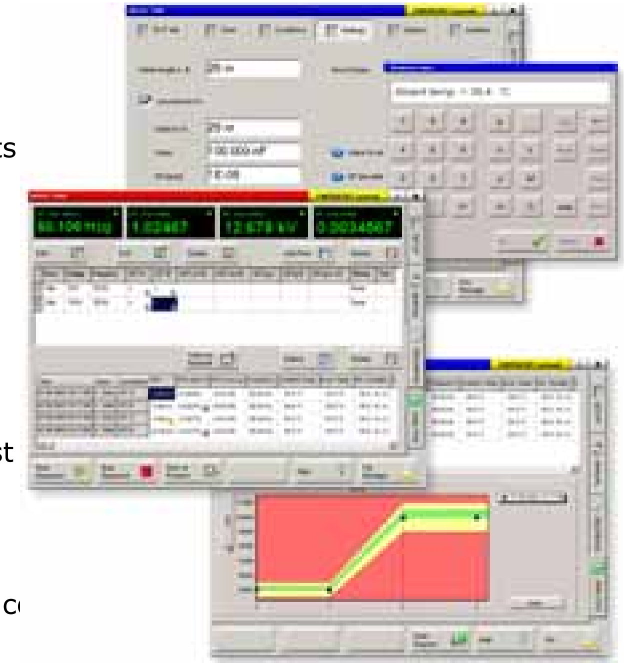
Latest Technology

- Real-time eletronic compensation by using newest integrated high speed data bus technology
- Integrated PC running under embedded Windows XP™ gives the most powerful tool

Tettex INSTRUMENTS

HUBBELL High Voltage Test Business

midas 2880 Software



Manual Mode

The manual test mode provides quick measurements without lots of definitions or pre-settings

Sequence Mode

Automatic test mode provides complete automated test sequences

Analysis Function

Immediate on-site assessment to compare the latest measurements with stored data sets

Setup

Set all configuration values, DUT Info, temperature c limits, etc.

Reporting and data handling

Measurement results and test object data can be saved in XML or ASCII text and transfered to a PC via floppy, Ethernet or a USB memory stick.

Condition Based Maintenance

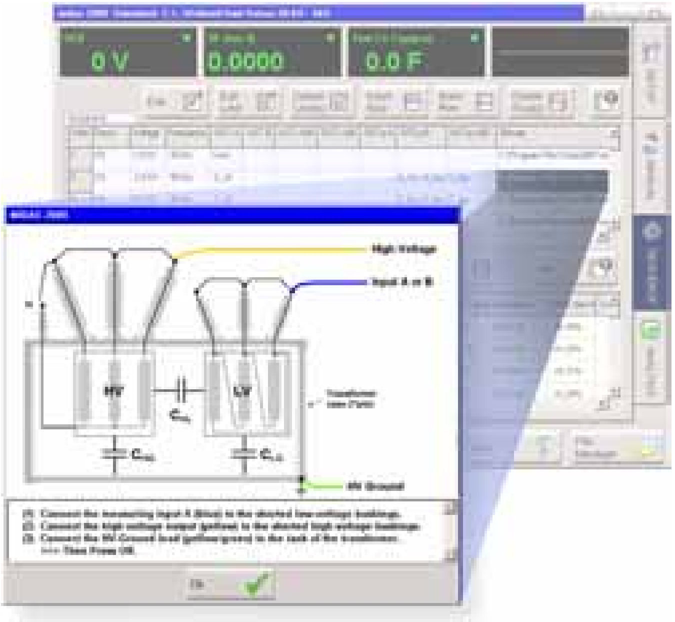
Large-scale development of knowledge rules to support decisions about asset endurance, is possible with knowledge based platforms “KSANDR”

midas 2880 Software

Automatic Measurement (Sequence Mode)

Executable test sequences (step macros) can be defined with

- **Set-ups**: Set all configuration values, DUT Info, temperature correction function, limits, serial numbers, etc.
- **Test Levels**: Set the desired different test levels (voltage and frequency)
- **Connections**: Set the different connections, e.g. USTg A&B.
- **Recorded Values**: E.g. Tan Delta@20°C, Voltage, Frequency, PF, Insulation Temperature, etc.
- **Test Instructions**: Guided test, e.g. rewiring of the test object
- **Pass/Fail Levels**: Limits can be set absolute or relative (based on reference measurements)



Tettex INSTRUMENTS

High Voltage Test Business

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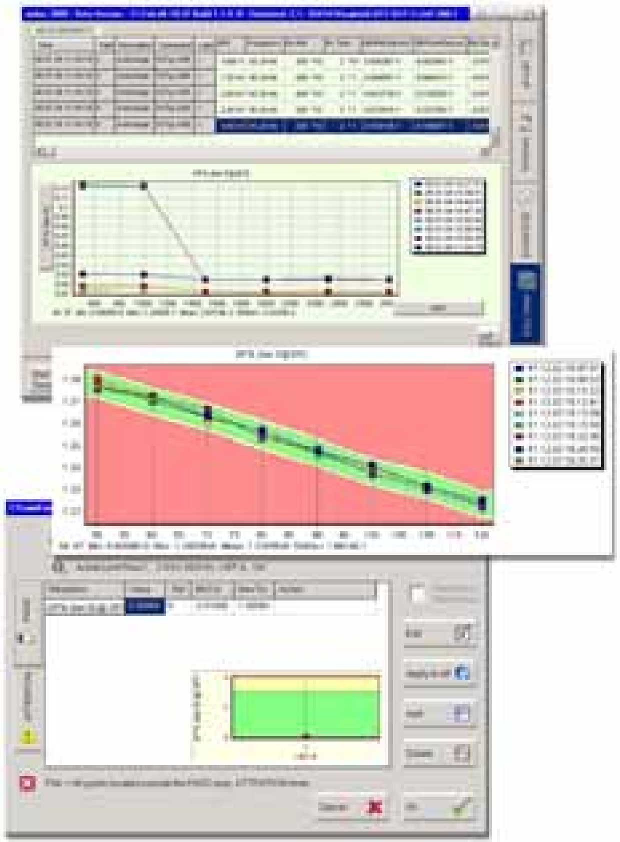
Analysis Function

- **Immediate on-site assessment** compare the latest measurements with stored data sets using the analysis diagram.
- **Comparisons** of measurements captured at different voltages, different frequencies
- **Trending analysis**
- **Pass/Fail** criteria are shown in the diagram as a green pass band, a yellow "Attention" band and a red "failed" section
- **Free definable axis** of the analysis diagram for almost any dependency



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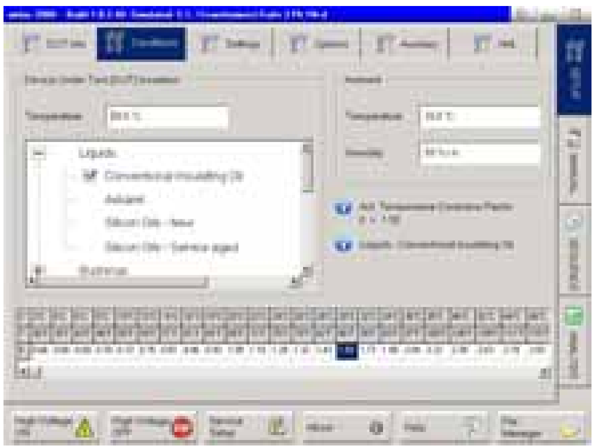
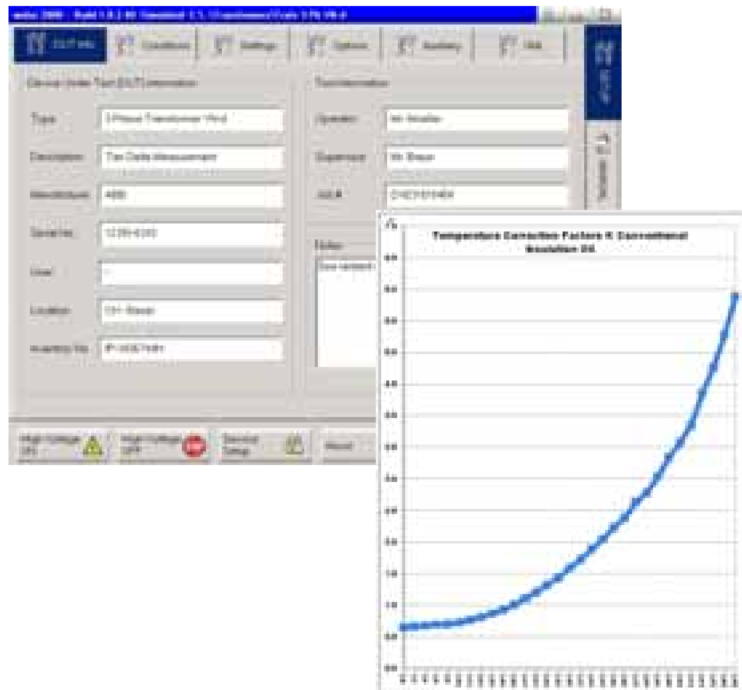
Setup

Set all configuration values, type of DUT, insulation type, temperature correction function, limits, work order, serial numbers, test personal, location, etc.





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Reporting and data handling

All measurement results and test object data can be saved in XML, which allows an easy transfer to database applications. For printing the test report and for further processing of the data (e.g. with MS EXCEL™) you can safe it as XML or ASCII text file as well and then transfer the data to a PC using floppy, Ethernet or a USB memory stick.

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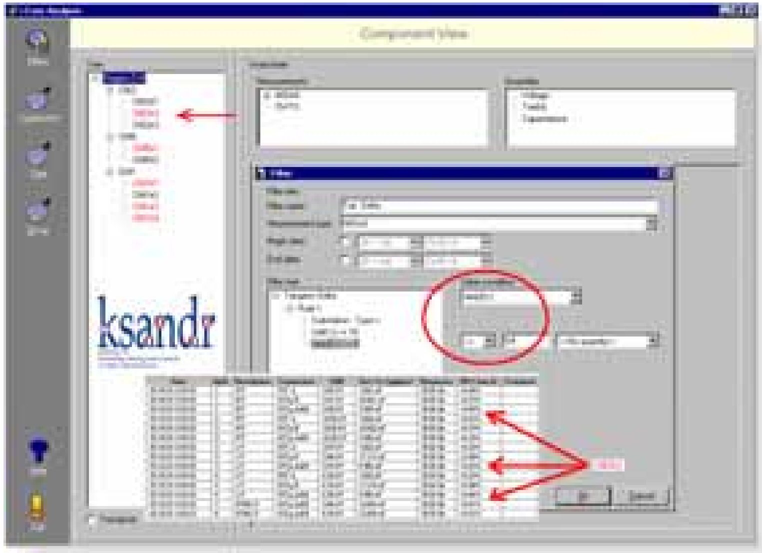
Condition Based Maintenance

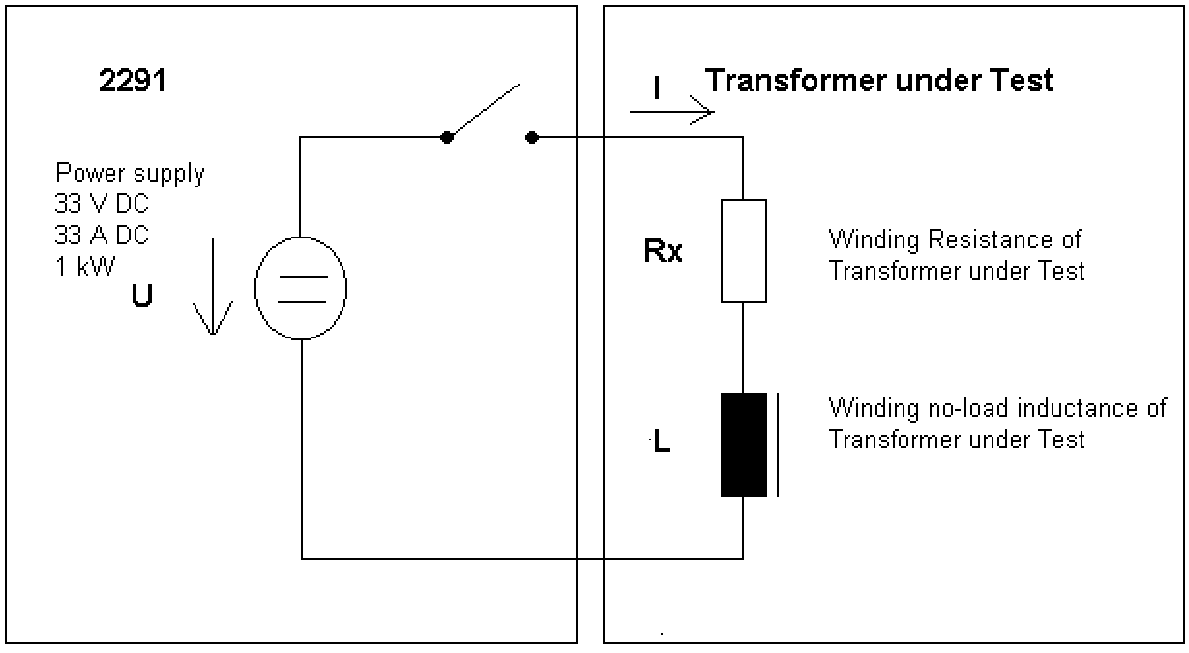
Gaining knowledge about asset (medium- and high voltage equipment) performance from condition measurements (e.g. tanδ values), databases and experts is essential for the implementation of a risk strategy. Large-scale development of knowledge rules to support decisions about asset endurance, is possible with knowledge based platforms e.g. KSANDR, a mutually applied expert database, designed for the collection of local condition measurements, generates decision rules based upon a lager population than just the local user. Membership to this non-profit, independent organisation is open to all willing to share data and experience regarding asset performance.



Winding Resistance Measurement

Why?

- Identification of short circuited windings



Electrical Equivalent Diagram

Winding Resistance Measurement

Formula

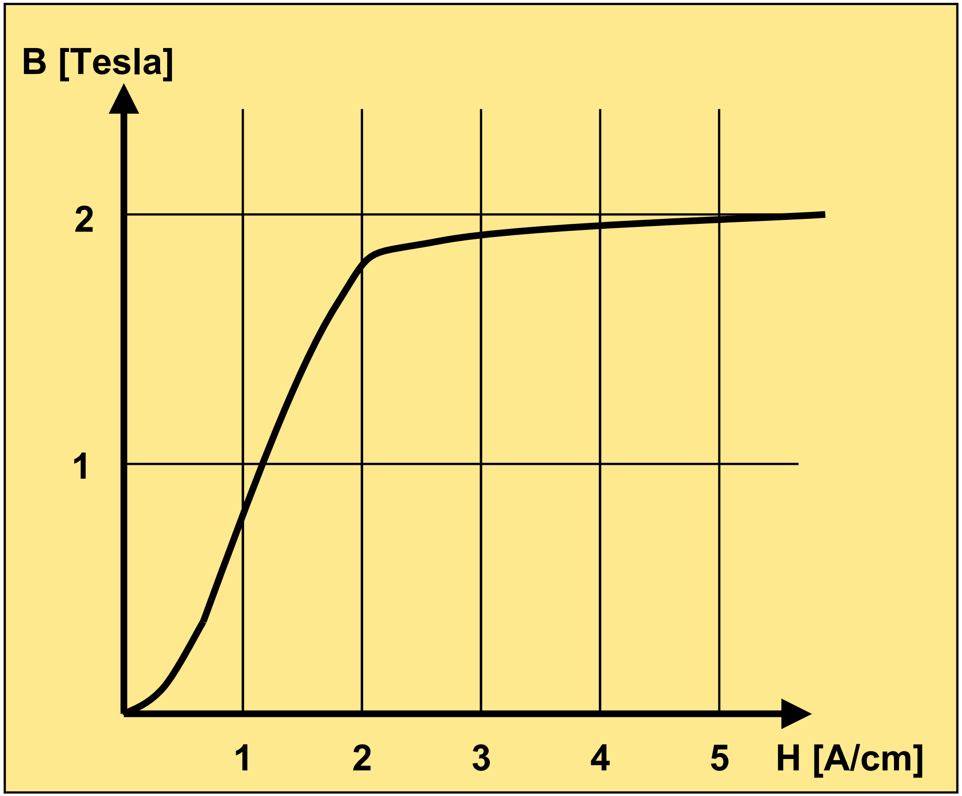
$$i = \frac{U_0}{R} \cdot \left(1 - e^{-\frac{t}{\tau}}\right)$$

$$\tau = \frac{L(i)}{R}$$

$$i_\infty \cong 4 \ldots 8 \cdot \tau$$

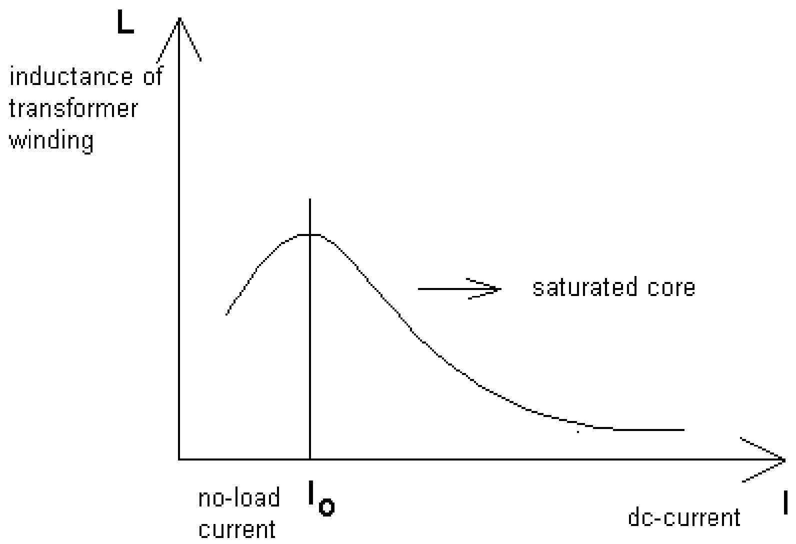
$$H = (i)$$

$$L \approx \frac{d(B)}{d(H)}$$

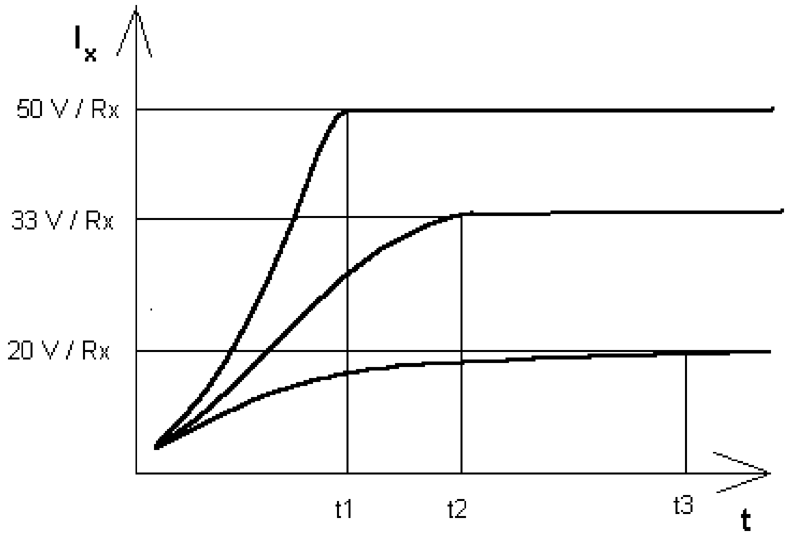


Winding Resistance Measurement

Issue – Core Saturation



Step 1: Saturation of the Core



Step 2: Supply of Measuring Current

Winding Resistance Measurement

Specification for Resistance Measurement Meter
e.g. Power Transformer 145 MVA - 245 kV - 0.15 % x I_o

Requirements:

- To avoid heating of the measured winding measurement current should be less than 10 % of nominal current of winding

$$I_{DC} < 0.1 \times I_N < 34\ A$$

- To saturate the transformer core measurement current should be 20 % more than the nominal no-load current

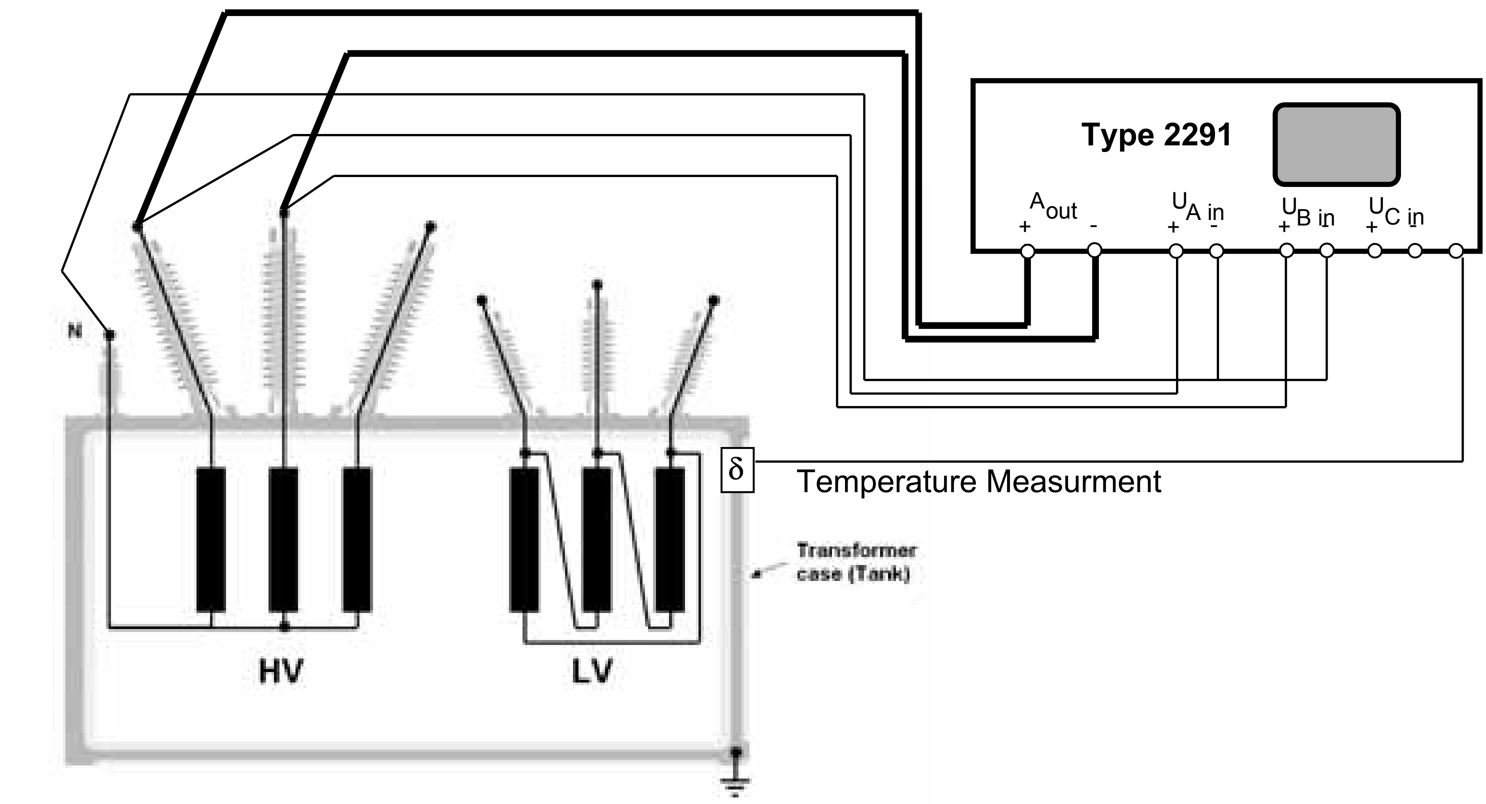
$$I_{DC} > 1.2 \times I_o > 5\ A$$

- DC measuring voltage should be as high as possible, but weight and input power supply of measuring instrument has to be considered

e.g. 1 kVA = 33 A x 33 V
2.5 kVA = 50 A x 50 V

Winding Resistance Measurement

Measurement on Power Transformer

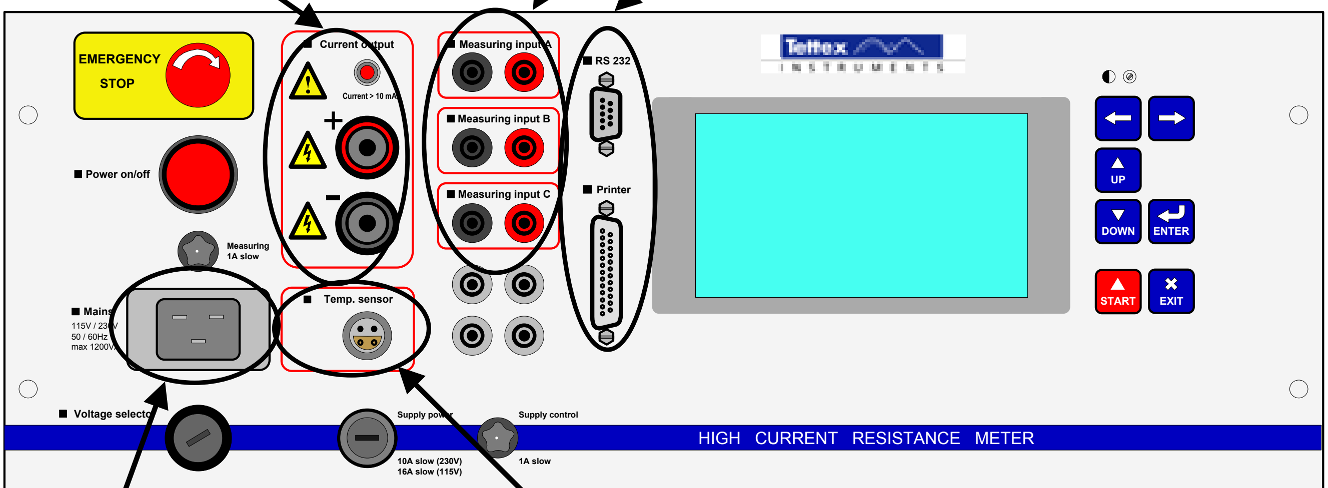


Winding Resistance Measurement
Typ 2291

3 Voltage Measuring Channels

Current Output
max. 33 A, 33 V

Interfaces for
Remote control & Printer

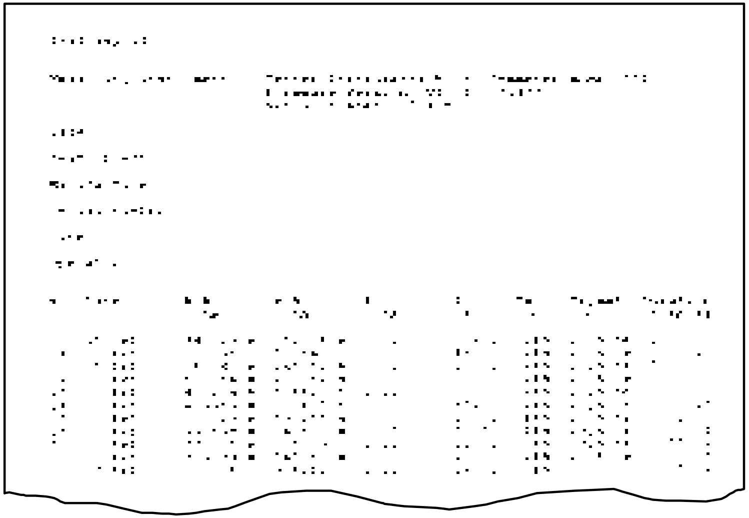


Main Power
115 / 230 V
50 / 60 Hz

Temperature Probe

Winding Resistance Measurement

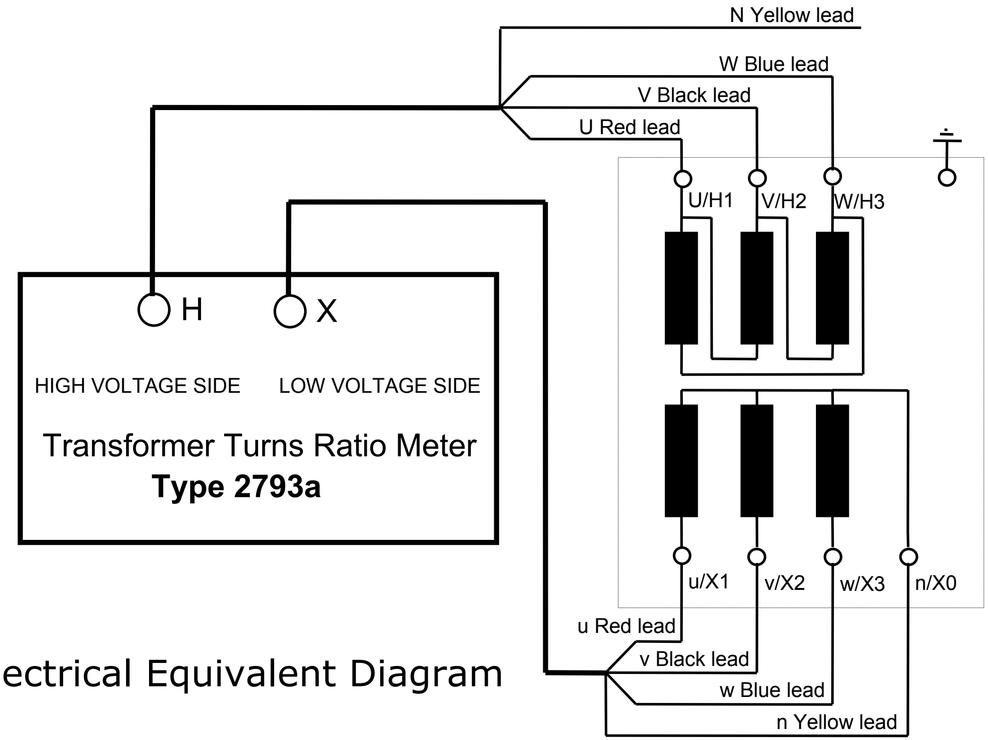
- **Highest accuracy**:
  0.05 % rdg +/- 0.05 % FS
- Powerful voltage and current output for fast and stable measurements (1 kW, 2.5 kW).
  Typical measuring time: 30 s – 2 min
- Discharge circuit and software features for safe operation
- **Automatic resistance measurement** at different tap changer positions
- **Temperature measurement** with probe, automatic temperature compensation
- **Remote control** for integration into host computer test report generation on printer



Transformer Turns Ratio Measurement

Why?

- Identification of turns faults
- Location of incorrect or defective Taps
- Incorrect Designation of Terminals/ Nameplates



Electrical Equivalent Diagram

Transformer Turns Ratio Measurement

Step 1:
Connect Measuring Cables to Transformer
(4 wire primary / secondary)

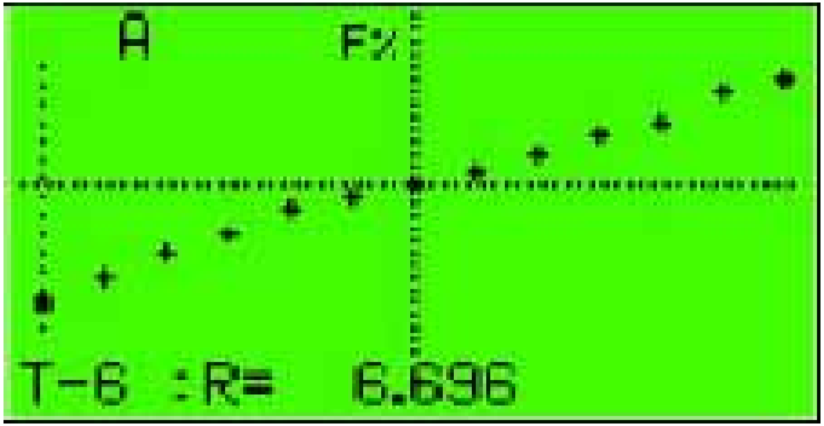
Step 2:
Choose Configuration, 18 configurations possible

Yn : Yn	Δ : Δ	Y : Y	CT : CT
Yn : Y	Δ : Yn	Y : Yn	I : I
Yn : Δ	Δ : Y	Y : Δ	III : III
Yn : Z	Δ : Z	Y : Z	
Yn : Zn	Δ : Zn	Y : Zn	

Step 3:
Set Tap Positions and Run Test

Transformer Turns Ratio Measurement

Step 4:
Get Results



Transformer Turns Ratio Measurement

Step 5:
Print Test Report

Test Report
****

S/N : 147999
Firmware : 2793a, 2.06
Date : 27,Jan 02 11:07

Transformer Information
Primary Voltage : Yn 120.00 kV
Secondary Voltage : Yn 3.000 kV

Vector Group : 0
Taps : -1... +1
Test Voltage : 100 V

Nominal Voltage Ratio : 40.0
Nominal Turn Ratio : 40.0

Additional Info
Type : Cooper 3 Phase
Serial Number : 100973276
Operator : M.S.
Location : New Kensington
Remarks : New Installation
Standard : ANSI Standard

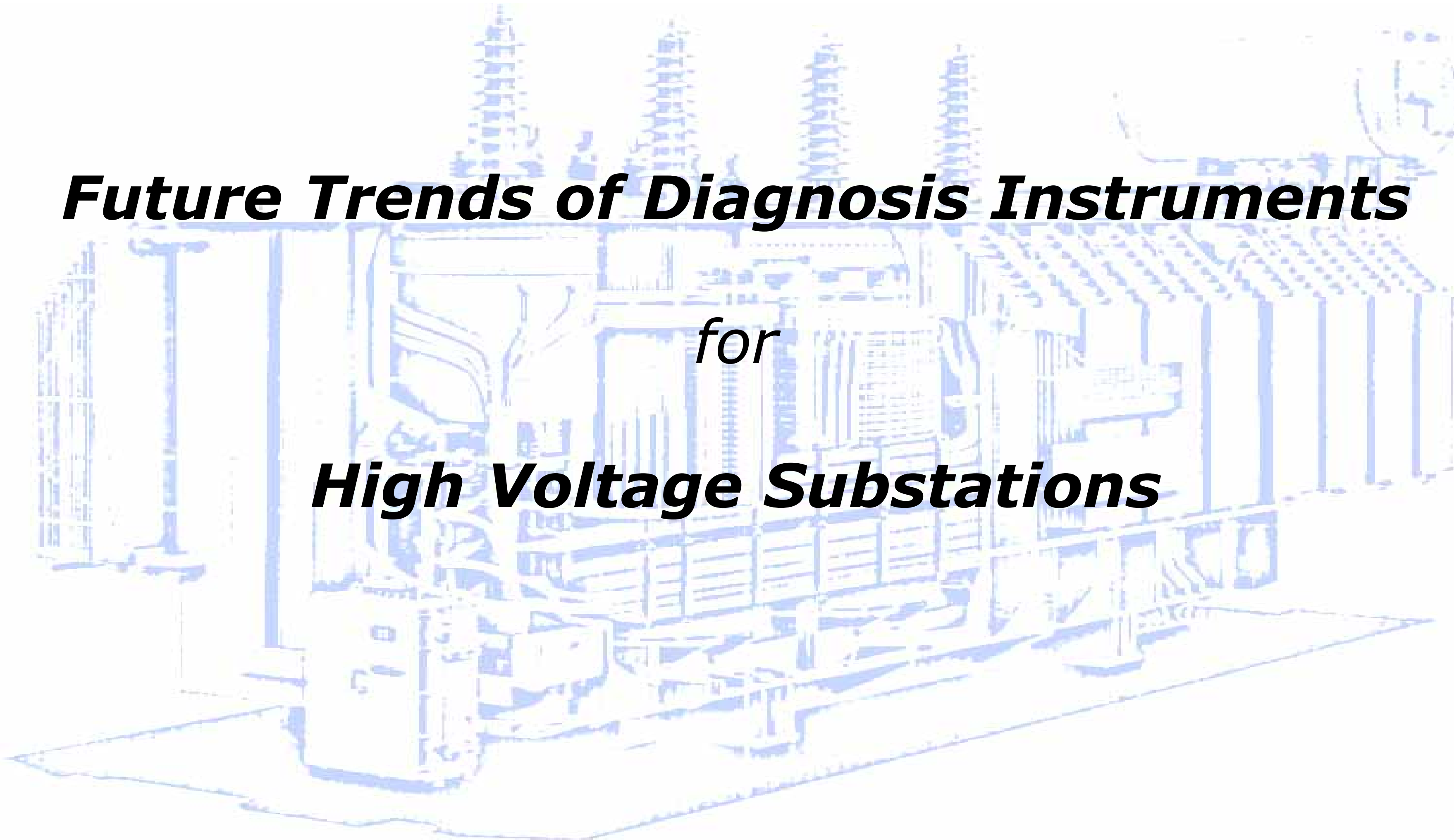
Tap	Phase	Prim	Sec	TRatio	I [mA]	Phase	Diff	%
-1	A	H1-N	X1-n		40.03	3.5	-0.0	0.08%
-1	B	H2-N	X2-n		40.02	2.7	-0.0	0.05%
-1	C	H3-N	X3-n		40.03	3.5	-0.0	0.08%
-0	A	H1-N	X1-n		40.03	3.5	-0.0	0.08%
-0	B	H2-N	X2-n		40.02	2.7	-0.0	0.05%
-0	C	H3-N	X3-n		40.03	3.5	-0.0	0.08%
+1	A	H1-N	X1-n		40.03	3.5	-0.0	0.08%
+1	B	H2-N	X2-n		40.02	2.7	-0.0	0.05%
+1	C	H3-N	X3-n		40.03	3.5	-0.0	0.08%

Transformer Turns Ratio Measurement

- Allows **fully automated testing of three-phase** power transformers as well as CT's and PT's
- Measures turns ratio in broad range from 0.8 to 13'000 and provides an unbeaten **accuracy of up to 0.05 %**
- Graphic display of ratios with up to **41 tap changer positions**. Faulty taps could easily be detected by the operator. Discharge circuit and software features for safe operation
- Displays turns ratio as well as voltage / current ratio. Allows to enter the nominal turns ratio, voltage ratio and current ratio, difference from nominal values are displayed and could be stored for printing out on test report or transferred to the office computer

Oil Breakdown Tester
Type OC60E

- **Preprogrammed** with standard test profiles according to ANSI, IEC
- Ability **to program and store custom** test profiles. **Test Results** - The user can determine whether or not to save the test results for later download, via RS232 port, and report generation
- Test sequences **are easily upgradeable** when standards change
- **Safe and Easy** - The interlocked HV section and the integrated controller allow operators to test safely and easily
- **Sturdy and Reliable** - The OC series oil testers have a long and trouble free life; proven by over 40 years of industry wide use.



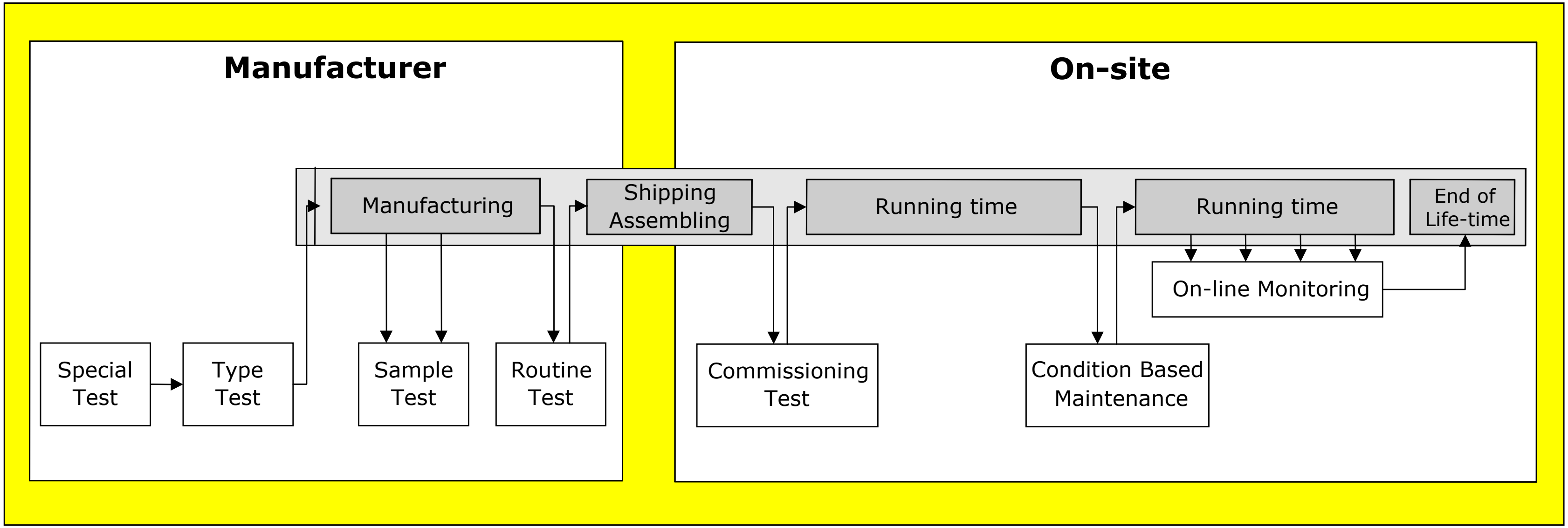
Future Trends of Diagnosis Instruments

for

High Voltage Substations

Diagnosis Future Trends

- Measurement results, fingerprints, trending information, etc., collected over the life-time of high voltage equipment helps to minimize risk of unexpected catastrophic outages



Diagnosis Future Trends

- Online monitoring systems for old, high risk and failure prone equipment comes will gain importance. Online monitoring systems will allow to operate the equipment to their nominal limits, and beyond.

- Only several measured quantities give an exact picture of the condition of a high voltage equipment. Different kinds of measurement stored in one data base give the possibility to correlate the measurements from different methods and/or between identical or similar equipment.

- Interpretation rules implemented in software tools should help the maintenance engineer to draw conclusion from the measurement results. An automatic decision given by an „expert software" („***Green*** – ***Yellow*** – ***Red*** Decision") should be achievable.