

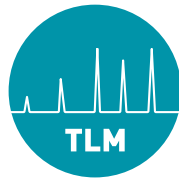


TRANSFORMER-LIFE-MANAGEMENT  
CONFERENCE

Continuous condition monitoring and protection of high  
voltage transformers by

**Dr. Jörn Peuser**  
B2 electronic






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CONFERENCE

Continuous condition monitoring and protection of high  
voltage transformers by



**b2 electronic GmbH**  
High Voltage



**Continuous condition monitoring  
and protection of high voltage  
transformers by direct sensor  
monitoring of oil aging**

Dr. rer. nat. Jörn Peuser, Dr.-Ing. Manfred R. Mauntz

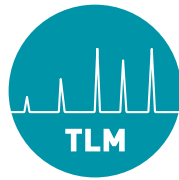
TLM 2015 – 27. / 28. October 2015 – Dubai



**Content**

1. Transformer oil and Motivation
2. Basic sensor concept and physical principle
3. Self-learning, adaptive temperature compensation
4. Online measurement and interpretation
5. Applications





## TRANSFORMER-LIFE-MANAGEMENT CONFERENCE

# Continuous condition monitoring and protection of high voltage transformers by

## Transformer oils / insulating oils

### Mineral oil based transformer oils:

- classical, unadditivated transformer oils
- Oils with Inhibitors, e.g. good oxidation stability

### Synthetic transformer oils:

- Silicon oil
- synthetic ester

### Transformer oils / insulating oils

- Insulate against possible voltage breakdowns, and more compact
- prevent corrosion,
- Remove heat by cooling
- Remove heat by cooling polarities of cellulose ( $\epsilon = 5.1$ )  $\rightarrow$  most water in the cellulose protect the insulation and
- Ester (up to 0.01% water reduction) significantly higher water dissolving power due to their molecular polar structure than mineral oil

**$\rightarrow$  Mineral oil: 44 ppm H<sub>2</sub>O at 20 ° C**  
 **$\rightarrow$  Ester: 2700 ppm H<sub>2</sub>O at 20 ° C**



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## Transformer oils / insulating oils

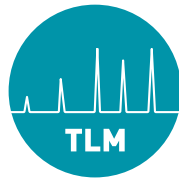
### To do so we need:

- an excellent resistance to aging
- a low dissipation factor  $\tan \delta$
- very good cold flow ability
- good corrosion protection properties



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# Continuous condition monitoring and protection of high voltage transformers by

## The 4 important measurements - online

- Temperature 24/7
- The loss angle  $\tan \delta$  24/7
- The water in insulating oils 24/7
- Breakdown voltage of the insulating oils 24/7

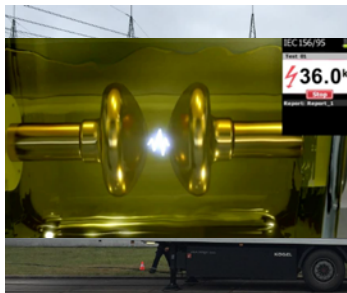


Figure source: b2 electronic GmbH - Riedstraße 1 - 6833 Klaus - Vorarlberg/Österreich, 2014



BA60, BA75,  
BA80, BA100

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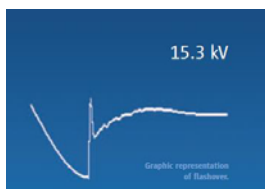
## One important measurement - BDV



<5 $\mu$ s - Ultra fast  
switch-off time



Highest level of RFI/EMC  
Shielding and rugged  
metal design!



Glas vessel – recommended by standard



Low weight and  
very compact design

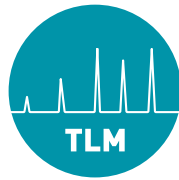


Comprehensive test reports

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Continuous condition monitoring and protection of high voltage transformers by

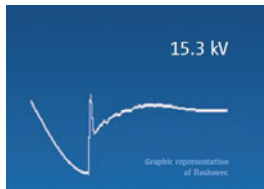
One important measurement - **BDV**



<5µs - Ultra fast switch-off time



Highest level of RFI/EMC Shielding and rugged metal design!



Glas vessel – recommended by standard



Low weight and very compact design



Comprehensive test reports



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**BA**

Portable Breakdown Analyzer



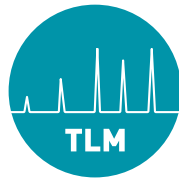
Very bright - colour display

IEC 60156:95	BA80	Withstand Test	BA80	IEC 60156:95	BA80
	Gap 2.5 mm		80 kV rms		Pause 1:20 str last 65.9kV
	Count 6			Test 1:	5.4kV
	Rise 2.0 kV/s			Test 2:	> 80 kV
	Voltage 80 kV			Test 3:	41.1kV
	Start Test			Test 4:	> 80 kV
	Main Menu			Test 5:	65.9kV
	3:16 PM	36 °C	3:00 Stop	41 °C	6 / 6 Stop



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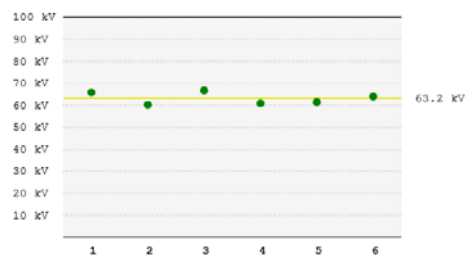
# Continuous condition monitoring and protection of high voltage transformers by



### Comprehensive test reports

TEST END 2008-01-01 11:02 all values (zms)

Mean	63.2 kV
Std. Dev.	2.5 kV
Range	6.5 kV
Oil Temperature	26 °C
Test Frequency	60 Hz



- Print-out (not BA60) - internal printer
- PDF -, Text - and XML-file
- Printout also from external printer (via PC)



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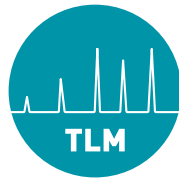


### PC Software „BA Control Center



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## TRANSFORMER-LIFE-MANAGEMENT CONFERENCE

# Continuous condition monitoring and protection of high voltage transformers by

## BA

### Portable Breakdown Analyzer



- Bluetooth
- USB
- Printer (not BA60)
- Mains supply
- Battery (not BA60)
- 12V
- Comprehensive accessories

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## Transformer oil ages over time

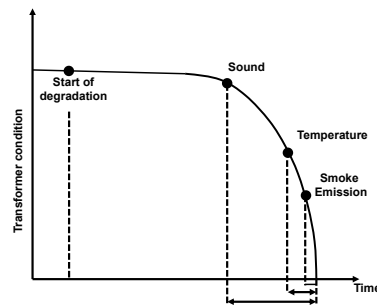
The process of degradation and products of contamination in the oil change the conductivity in insulating oils:

- contamination during the assembly
- formed acids
- aldehydes and peroxides

This results in the formation of sludge

Sludge:

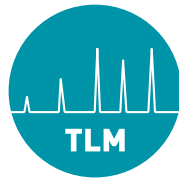
- attacks the cellulose insulation
- inhibits oil flow
- traps heat inside the transformer



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# Continuous condition monitoring and protection of high voltage transformers by

## Transformer oil ages over time

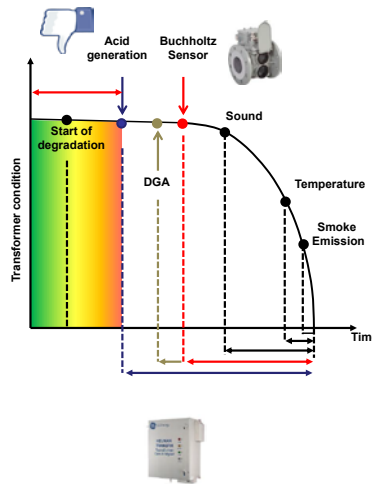
The process of degradation and products of contamination in the oil change the conductivity in insulating oils:

- contamination during the assembly
- formed acids
- aldehydes and peroxides

This results in the formation of sludge

Sludge:

- attacks the cellulose insulation
- inhibits oil flow
- traps heat inside the transformer



← No detection! →

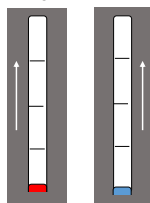


13

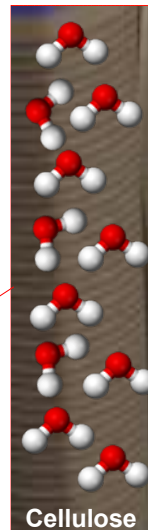
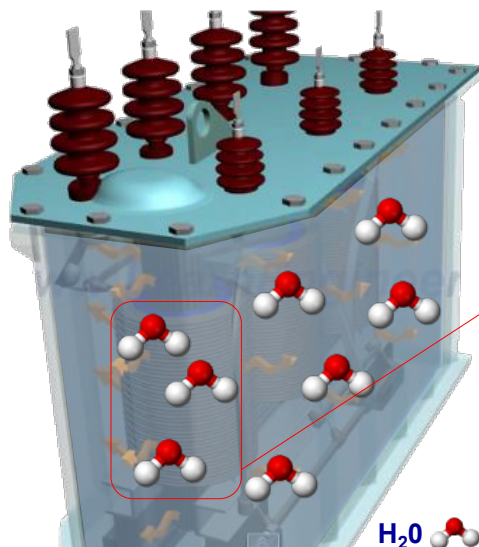
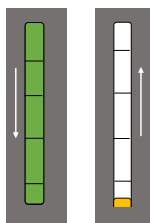
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## Model humidity in HV transformers

Temperature °C      Humidity ppm



BDV kV      Tan delta



Oil

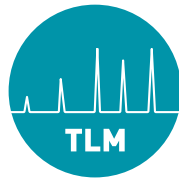
H<sub>2</sub>O

Cellulose



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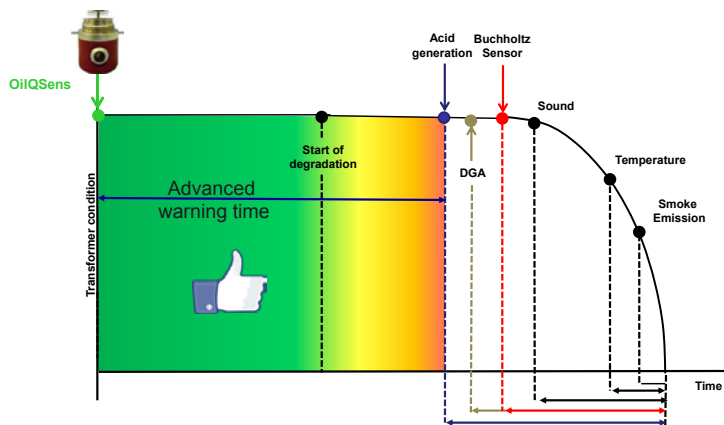




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# Continuous condition monitoring and protection of high voltage transformers by

## Transformer oil ages over time



OilQSens® provides an advanced warning time!

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## Measurements and Calculations

### • Measurements:

- electrical conductivity  $\kappa$
- relative permittivity  $\epsilon_r$
- temperature T



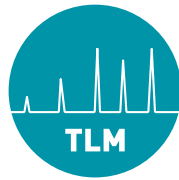
### • Calculations:

- Dissipation factor  $\tan \delta$  by electrical conductivity  $\kappa$  and relative permittivity  $\epsilon_r$
- Breakthrough voltage by electrical conductivity  $\kappa$  and relative permittivity  $\epsilon_r$
- Humidity estimation by relative permittivity  $\epsilon_r$
- Temperature compensation of all measured values

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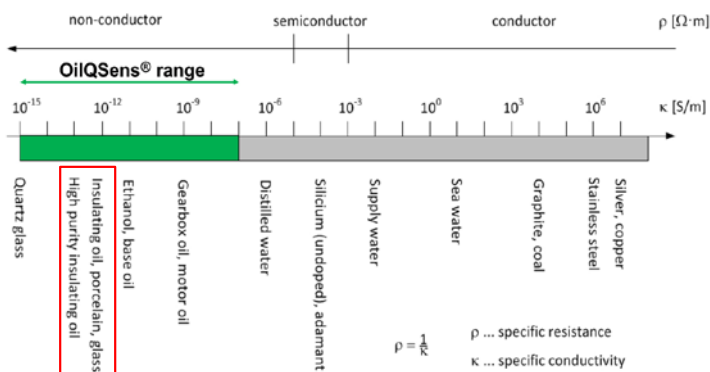
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Continuous condition monitoring and protection of high voltage transformers by

OilQSens® sensitivity: electrical conductivity  $\kappa$



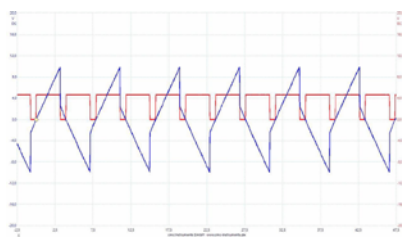
OilQSens® combines an excellent high sensitivity with low noise and a broad detection range!



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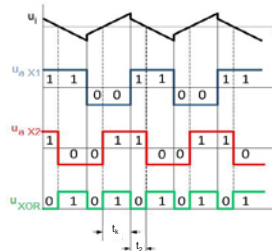
OilQSens® basic sensor concept



$$\kappa = \frac{R_1}{R_2} \cdot \frac{l}{A} \cdot \frac{C}{t_k} = \text{const.}$$

$$\varepsilon_r = (t_x - t_2) \cdot \frac{\kappa}{2\varepsilon_0}$$

$$u_i = \frac{-1}{R_x C_l} \int_0^T u_A(t) dt$$



A direct measurement of AC observables (RC circuit) is inaccurate: Oil has a very high resistance R (several GW), and a very low capacity C which leads to high uncertainties, errors and a low resolution, which is necessary to follow the effects in oil.

OilQSens® approach:  $\kappa$  and  $\varepsilon_r$  are determined by a precise time measurement with a very high accuracy and repeatability based on an integrating measurement technique with a high time/bandwidth product.



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## Continuous condition monitoring and protection of high voltage transformers by

### Loss factor $\tan \delta$ , rel. humidity

Loss factor  $\tan \delta$  out of electrical conductivity  $\kappa$  and permittivity  $\epsilon_r$ ,  
with dielectric constant  $\epsilon_0$ , angular frequency  $\omega = 2\pi f$

loss factor  $\tan \delta$  :  $\tan \delta = \frac{\kappa}{\epsilon_r \epsilon_0 \omega}$   $\rightarrow \tan \delta_{TC} = \frac{\kappa_{TC}}{\omega \epsilon_0 \epsilon_{rTC}}$

relative humidity rH:  $rH = a_0 \cdot \epsilon_r + b_0$   $\rightarrow rH_{TC} = a_{0TC} \cdot \epsilon_{rTC} + b_{0TC}$

*TC -> temperature compensated*

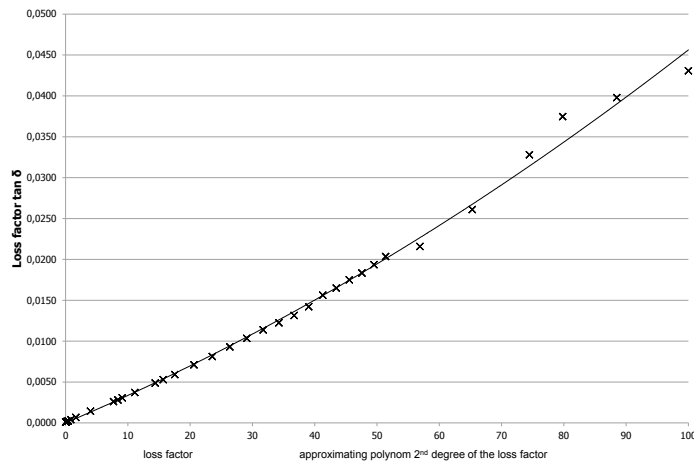
**TC: Standard 90°C or .... °C?**



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### Loss factor $\tan \delta$ as a function of the proportion of aged oil



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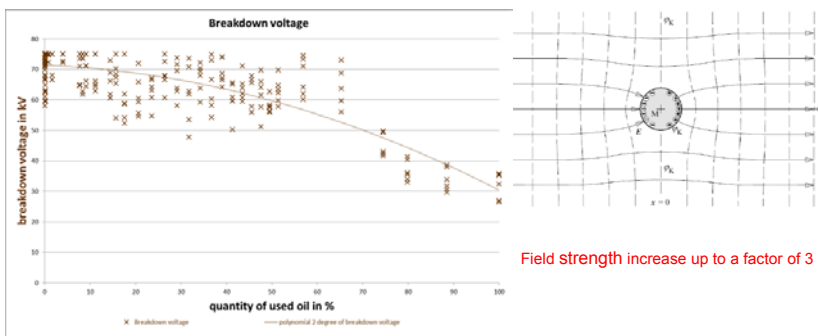
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Continuous condition monitoring and protection of high voltage transformers by

Breakdown voltage and conductivity as a function of the mixing ratio of new and used transformer oils

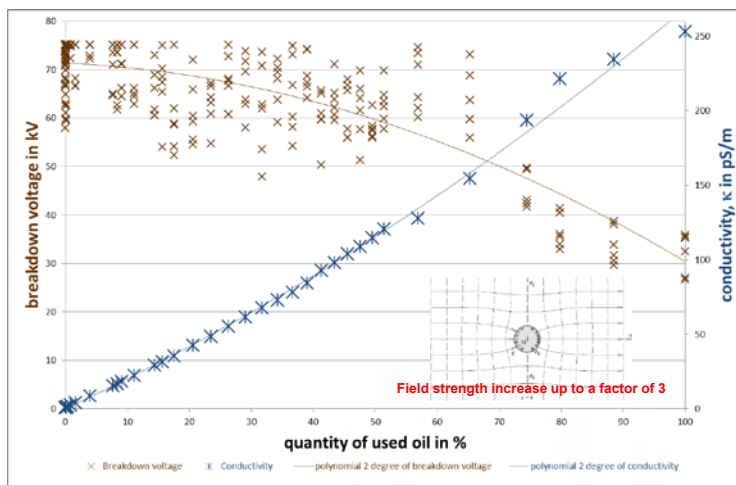


Source: Küchler, A.: Hochspannungstechnik, Grundlagen – Technologie – Anwendungen, VDI-Verlag, Düsseldorf, 3. Auflage, 2009

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Breakdown voltage and conductivity as a function of the mixing ratio of new and used transformer oils



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Continuous condition monitoring and protection of high voltage transformers by

Measured transformer oils

Oil name	Conductivity $\kappa$ [pS/m]	Permittivity $\epsilon_r$
Meguín J10	0,8817	2,199572
Trafolube 1	1,5126	2,161324
Trafolube 2	1,7033	2,176118
Starke & Sohn 1	0,1056	2,173823
Starke & Sohn 2	0,0542	2,170717

Even down to very low conductivities, they can be measured with a very high precision.

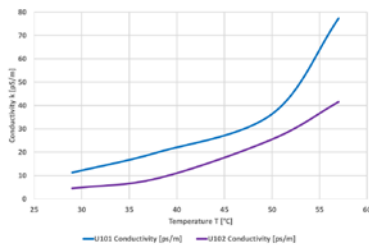


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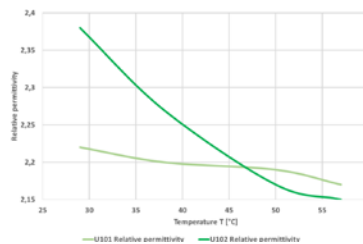
Temperature dependency of  $\kappa$  and  $\epsilon_r$

Increase of temperature results in



← increase of the conductivity  $\kappa$

decrease of the relative permittivity  $\epsilon_r$  →



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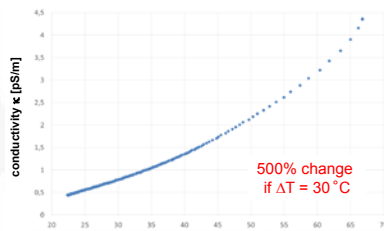
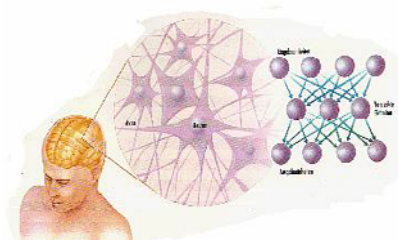
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Continuous condition monitoring and protection of high voltage transformers by

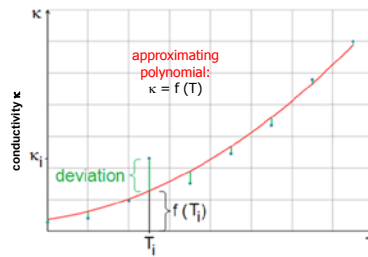
Adaptive temperature compensation of  $\kappa$  and  $\epsilon_r$  based on neuronal network



approximating polynomial:

$$\kappa = \kappa_{T_0} + a\Delta T + b\Delta T^2 + c\Delta T^3$$

\*Gaussian least squares method with risk function



Source: U. Lämmerl: WI Projekt – Neuronale Netze, University of Technology, Business and Design, Wismar 2010

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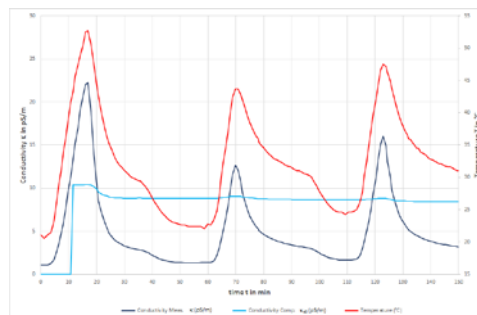
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The measured values – after temperature compensation



..... the conductivity  $\kappa$  of the oil increases with temperature. The type of pollution and its temperature dependence cannot be assumed to be known .....

Here we see how efficient the self-learning adaptive temperature compensation algorithm is working .....



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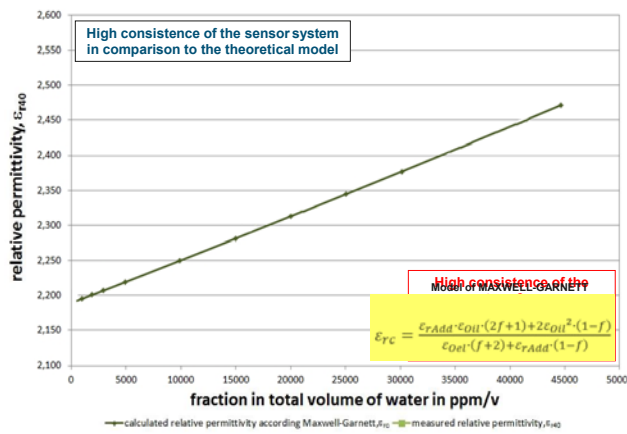
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Course of the measured dielectric permittivity  $\epsilon_{rTC}$  with the calculated dielectric permittivity  $\epsilon_{rC}$



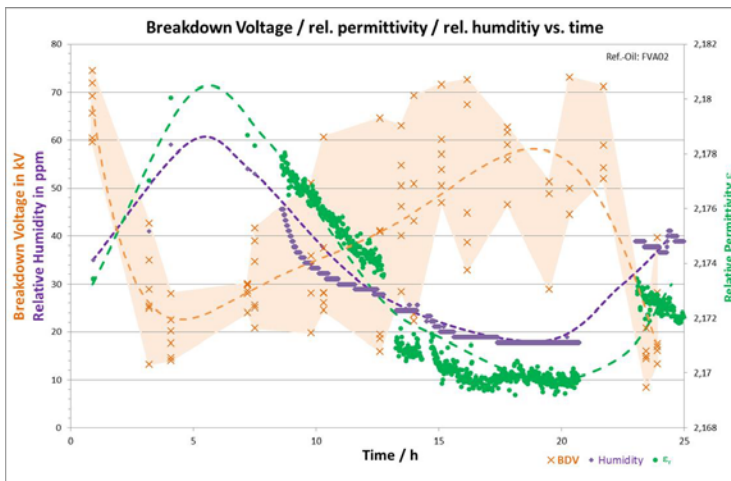
Source: Maxwell-Garnett, J.: Effective medium models for the optical properties of inhomogeneous media, Philosophical Transactions of the Royal Society of London, Vol. 203, 1904



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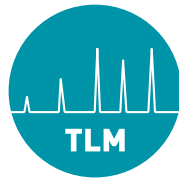
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BDV, permittivity and moisture vs. time



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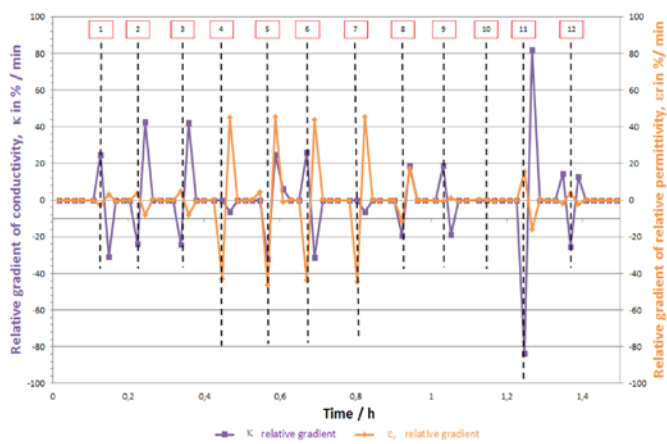
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Continuous condition monitoring and protection of high voltage transformers by

Simulation of partial discharge in transformers



#	BDV [kV]
1	89,8
2	67,8
3	72,3
4	82,5
5	89,0
6	84,3
7	80,8
8	80,9
9	87,1
10	92,8
11	75,3
12	89,3

1–12 BDV measurement



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Application example:

Monitoring of an oil regeneration plant



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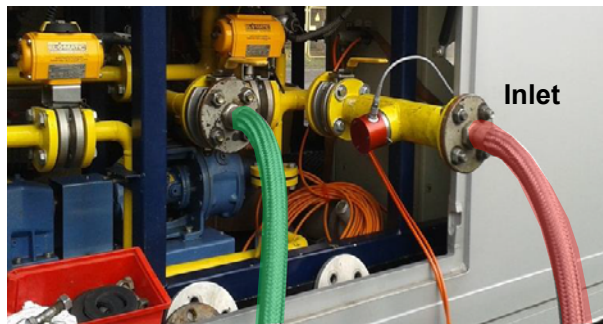




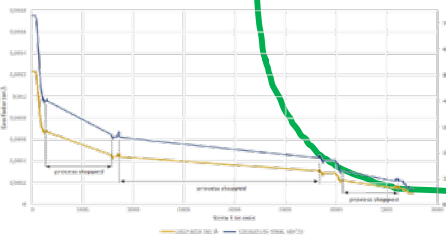
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Continuous condition monitoring and protection of high voltage transformers by

Application: oil regeneration plant



Filtration  
Vacuum drying

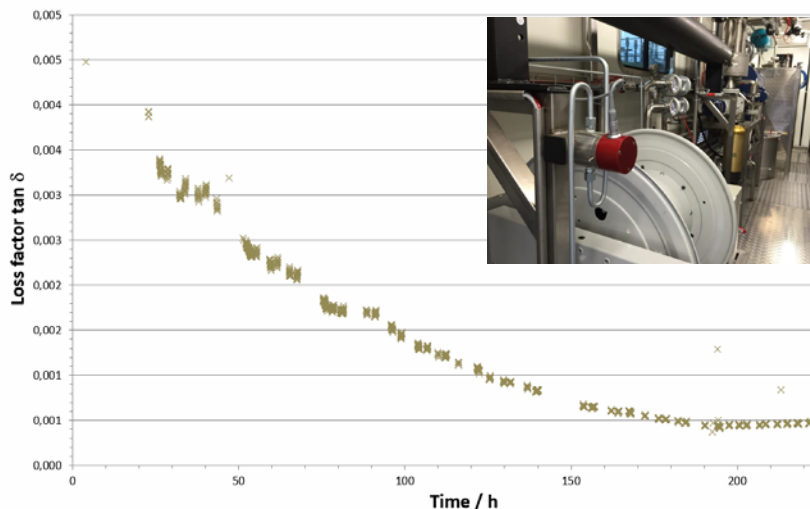


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Loss factor  $\tan \delta$  and conductivity  $\kappa$  vs. time

Loss factor  $\tan \delta$  [ @ T = 40°C ]



Loss factor  $\tan \delta$ :  $\tan \delta = \frac{\kappa}{\epsilon_r \epsilon_0 \omega}$

- Measured @ 40° C
- Compensated @ 90° C
- Laboratory @ 90° C



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**Continuous condition monitoring and protection of high voltage transformers by**

**Server – Interface via Internet Browser / E-Mail**



**Kundensensoren**    xxxxx

Leistungsname	Hardware	Firmware	Alte
800-0-003	CMCWARE V1.2	2010-10-27	Bestimme Lücken
			AS.008
			Sensordaten

**Sensordaten SN**    xxxxx

Januar 2014												
Mo	Di	Mi	Do	Fr	Sa	So						Index
1	2	3	4	5	6	7	8	9	10	11	12	1
13	14	15	16	17	18	19	20	21	22	23	24	2
27	28	29	30	31								3

Empfangszeit	T in °C	c in Ab/°C	d (sekunden)	w in µS/m	u (sekunden)
08.01.2014 23:36:33	40,310782	2,380022	2,383169	759,849623	788,734293
08.01.2014 23:50:14	40,310782	2,379961	2,384927	759,834453	787,683758
08.01.2014 23:46:32	40,310782	2,379983	2,383209	760,273933	789,093893
08.01.2014 23:36:30	40,489313	2,379798	2,384929	759,212717	787,339323
08.01.2014 23:21:08	40,467843	2,379712	2,384728	759,215479	787,083126
08.01.2014 23:11:25	40,310782	2,379739	2,384991	759,278889	787,528332
08.01.2014 23:01:43	40,310782	2,379903	2,384406	759,798172	788,772984
08.01.2014 22:52:01	40,467843	2,379781	2,384946	759,879139	787,41667
08.01.2014 22:42:19	40,467843	2,379887	2,384418	758,762363	787,030006
08.01.2014 22:32:36	40,446378	2,379989	2,384878	759,021539	786,730823
08.01.2014 22:22:53	40,424908	2,380474	2,384609	759,31776	787,439843
08.01.2014 22:13:11	40,403444	2,380263	2,383478	759,466155	787,232678
08.01.2014 22:03:28	40,414174	2,380032	2,383469	758,17814	786,093263
08.01.2014 21:53:45	40,437131	2,379977	2,384424	758,739382	786,683773
08.01.2014 21:44:02	40,478379	2,380663	2,385085	759,956489	788,448024
08.01.2014 21:34:20	40,425842	2,380098	2,386173	759,966182	788,610089

**Automatic email notification (incl. graphs):**

**Automatic Alarm Notification from Sensor:**  
**T12-WS-0072 E-Mail-Interval: 4 hour(s).**  
 20. Februar 2015 23:30

**T12-WS-0072**

	measured	lower limit	upper limit	rel. gradient [% / 1 min.]
$\epsilon_r$	1.000000	3	3	0
$\epsilon_r$ TC	1.044955	3	3	0
K [pS/m]	0.005354	1	10	-16,287
$\epsilon_r$ TC [pS/m]	0.032438	1	10	2,851
T [°C]	22,568778	20	70	0



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**Overview interfaces**



- Serial (RS232):**  
9-pin SUB-D
- Network (LAN / WLAN):**  
Ethernet / IEEE 802.11 b/g with IEEE 802.11i encryption
- Optional communication:**  
RS232/USB Adapter, RS232/Profibus
- Software:**  
WSens®/SW

**Web based decentralized Conditioning Monitoring System:**  
 Measuring signal transmission to web server,  
 Data query / presentation via Web browser



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## Continuous condition monitoring and protection of high voltage transformers by

### Conclusion and outlook

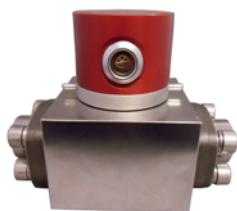
- Online measurement **24/7** of the
  - loss angle  $\tan \delta$
  - breakdown voltage
  - water in insulating oils



- Remote monitoring of HV transformers **24/7**



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