TranSCoM Online™ – Breakdown voltage (BDV)

Pilot installation report

Electrica Transilvania Nord S.A – Substation Cluj Centru, RO

by

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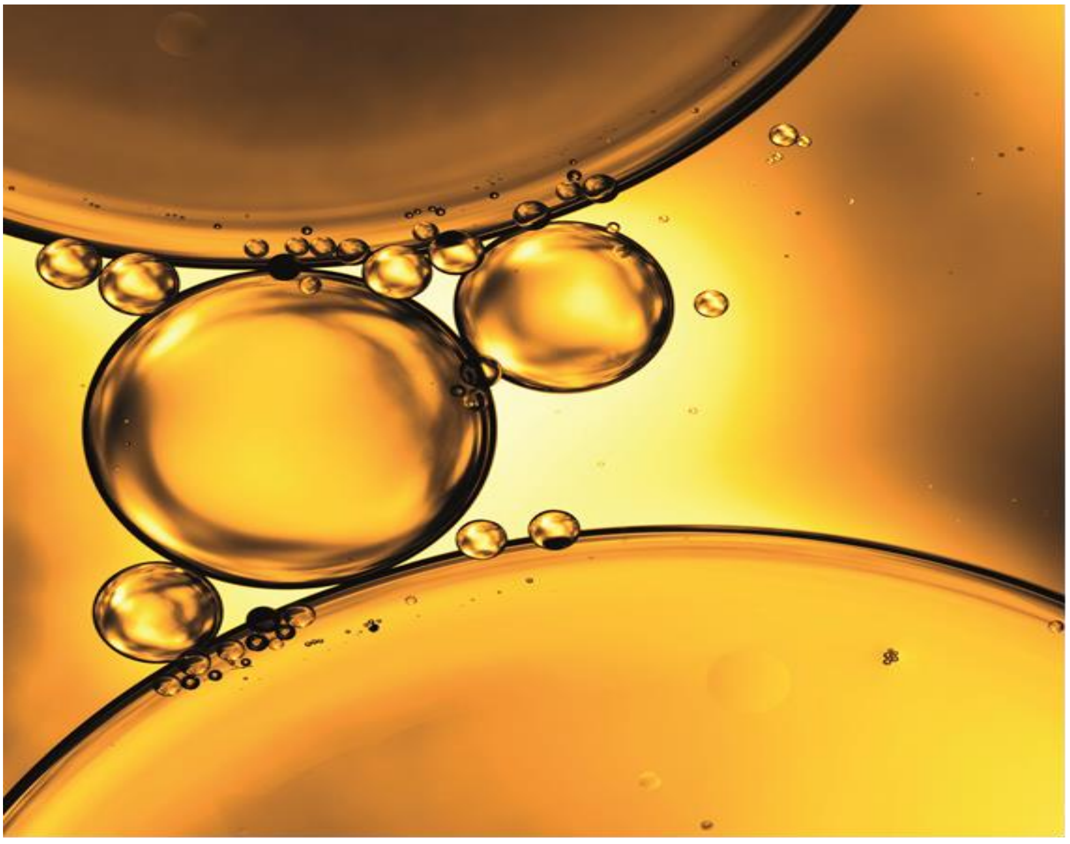

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1. Breakdown voltage (BDV) measurements

A complete Transformer Control and Monitoring system (TraCoMo) is being developed by A. Eberle GmbH & Co KG. The TraCoMo system will include, among other features, tap changer monitoring, dissolved gas analysis and bushing monitoring. A schematic overview is shown in the figure 1.
The subcomponent of the TraCoMo responsible for the evaluation of the breakdown voltage

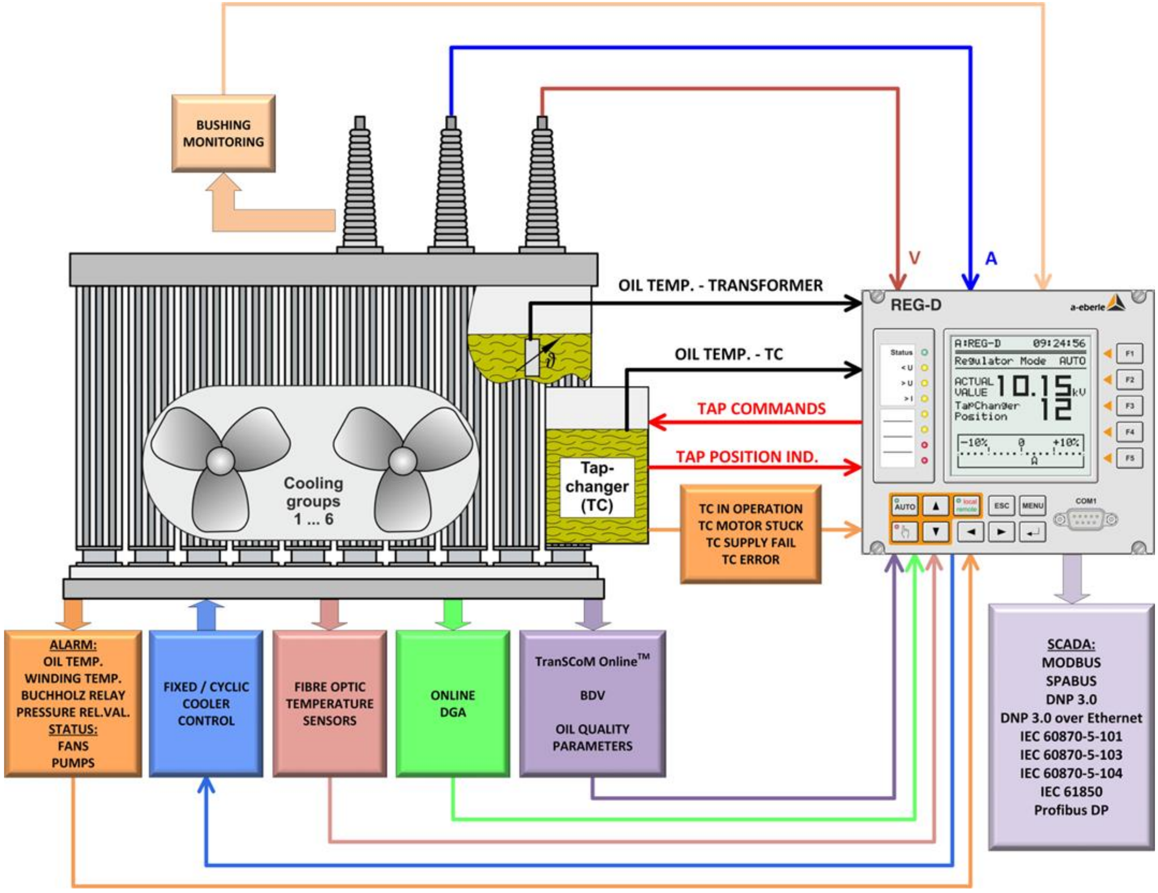


Figure 1: schematic overview of the TraCoMo system

(BDV), the TranSCoM Online, is currently under development in partnership with Yucoya Energy Safety GmbH. The TranSCoM Online which was installed at a transformer in Romania is the main focus of this report.

The BDV expressed in kV is an important indicator related to the quality of the transformer oil, which is the weakest part of the insulation inside a transformer, its interactions with the paper insulation in the presence of loads, and, of course, aging.

When discussing TranSCoM Online and BDV measurements the immediate questions are: What is BDV? Why measure it? Why online?
The answers are briefly summarized below.

The BDV is a measure of the oil's ability to withstand electric stress. The pressing customer need is the determination of this dielectric strength of the transformer oil to assure that the electrical stresses of an operating transformer are always below the insulating oil's dielectric strength. Otherwise, a safe operation of a transformer cannot be guaranteed.

In order to measure the BDV of an oil, the oil is commonly filled into a test cell which contains two electrodes as shown in figure 2. The voltage between these two electrodes is then raised until a conducting pathway between the electrodes forms, i.e., a breakdown of the insulating oil occurs. The voltage at which this breakdown occurs is the BDV.

Figure 2 below shows a breakdown in a test cell.

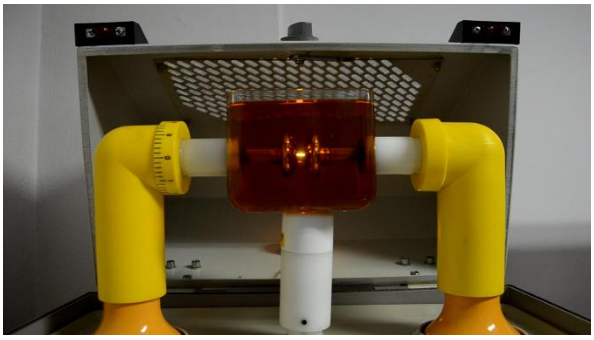


Figure 2: dielectric breakdown in a test cell (BAUR)

Unfortunately, the BDV is influenced by the dynamic interplay of many factors such as humidity, gas and particle concentration, and the electric field distribution. Thus, individual BDV measurements according to established methods differ immensely and no individual measurement is sufficient to determine the dielectric strength of an oil.

As an example of this issue four series of six BDV measurements, according to IEC 60156, of an oil sample with very high acidity (0.53 mg KOH/g) and high water content (50 ppm) is shown in table 1. Of these four series three yield a low BDV which would probably lead to a careful evaluation of the current transformer safety. However, the third series resulted in a BDV of 64.2 kV and would suggest that the oil is fine and the transformer can be kept in operation. This example clearly illustrates that a series of just six measurements is not enough for a reliable assessment of the oil's dielectric strength. Even if one follows the commonly accepted standard procedure, that is, a BDV measurement according to IEC 60156, one can easily end up with an acceptable BDV for an unacceptable oil. This could have severe consequences for a transformer in operation.

	First series	Second series	Third series	Fourth series
#1	43.8	45.1	54.5	41.8
#2	36.0	46.6	53.4	30.4
#3	37.4	47.3	72.1	28.8
#4	43.7	41.4	81.1	31.6
#5	33.2	36.1	55.7	30.1
#6	35.5	39.6	68.5	30.0
Mean	**38.3**	**42.7**	**64.2**	**32.1**

Another problem with the BDV measurement according to IEC 60156 is that the measurements are performed at 20 °C. Transformers at normal loads operate at temperatures of about 60 °C. It is well known that the water solubility of oil increases strongly with increasing temperature which leads to different BDV values at higher temperatures as figure 3 shows. Thus, the temperature has a strong effect on the BDV and, consequently, the analysis in the lab at a lower temperature might have little relevance for an assessment of the transformer condition. This also explains why a very low BDV in the lab does not rule out safe operating conditions of a transformer at higher temperatures.

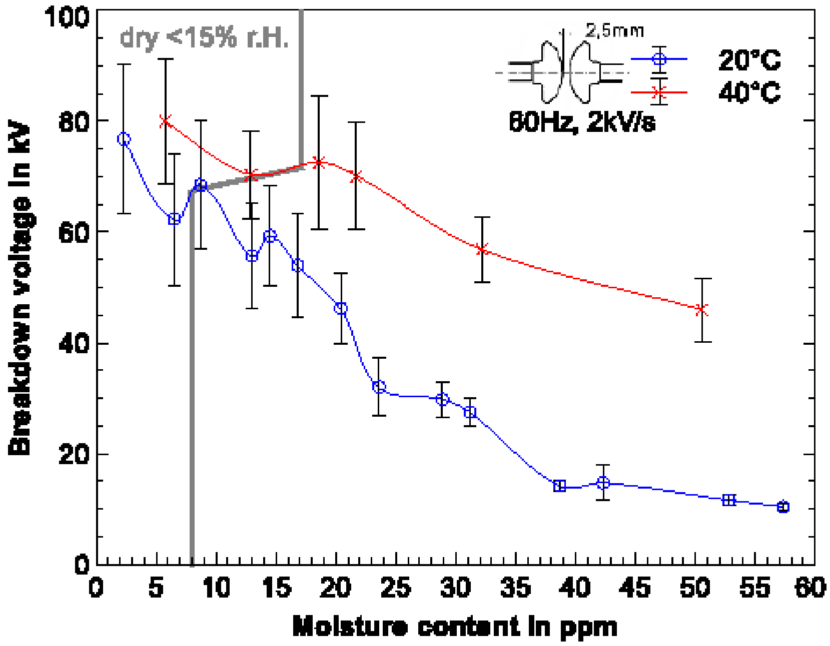


Figure 3: BDV for an oil at 20°C (blue) and 40°C (red) for different water contents. [1]

Obviously, what is really needed is an assessment of the transformer oil condition during its operation and this cannot be provided by occasional lab analyses.

There are two possible solutions to this problem of non-representative and contradictory BDV measurements:

The first is to measure the BDV directly on site with appropriate equipment. This method is preferred to a lab analysis because the oil will represent the real operating situation of the transformer oil. Yet, the issues with the unreliability of the measurement remain and, of course, such a measurement would also only give information about one particular moment and would not reveal the dynamical changes during normal operation.

The alternative solution implemented by TranSCoM Online is an online measurement of a large number of oil parameters from which the overall safety status of the transformer and the BDV can be deduced by a sophisticated statistical analysis. To this end, a device containing several sensors, most importantly an ultrasound and humidity sensor, is connected to the top and bottom oil valves of the transformer and monitors the sensor parameters of the transformer oil continuously. This way the system is able to recognize changes and trends of the oil's properties and to determine when conventional lab analysis should be performed to ensure safe operating conditions.

The need for multiple sensors stems from the fact that the BDV of an oil cannot be deduced unambiguously from single parameters. An example of the high variability of the BDV for oils that are comparable in total acid number and water content is shown in figure 4.

As the histogram shows, the measured BDV values (according to IEC 60156) for oils of over 200 different transformers that have the same water content (3 ppm) and same total acid number (0.03 mg KOH/g) span a wide range from 35 to 85 kV. So, this strongly indicates that the BDV cannot be simply deduced from these two commonly measured parameters and that a multivariate approach incorporating many variables is needed.

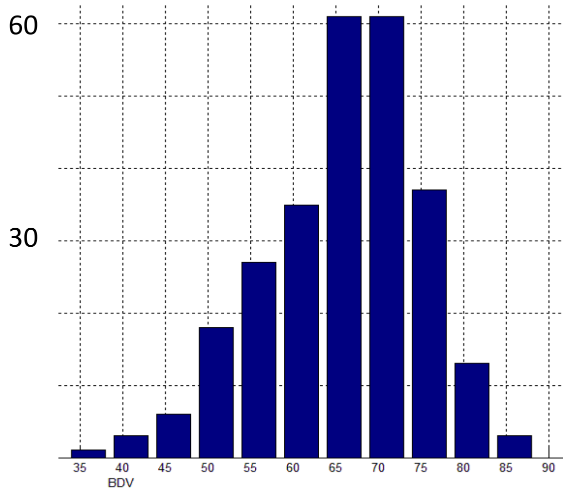


Figure 4: BDV of different oils with the same water content and total acid number. [3]

2. Device functional principles

As stated in the last section a dependable evaluation of the transformer oil is not achievable by single measurements of individual parameters. That is why an extendable multi-sensor architecture was employed in the TranSCoM Online to gain sufficient data of the oil. Since the TranSCoM Online is continuously gathering data it is also possible to investigate short-term dynamics of the transformer oil which allows for a thorough and reliable analysis of possible safety issues.

The TranSCoM Online device relies on several sensors to deliver a reliable assessment of the oil's quality and the BDV:

- ultrasound
- humidity
- temperature
- oil color

The central sensor of the TranSCoM Online is the ultrasound sensor which measures phase shifts and signal amplitudes of the sound waves for twenty frequencies between 595 kHz and 944 kHz.

Molecular acoustics is the underlying science that involves the study of the mechanisms of the propagation of sound energy by molecules in liquids and gases. The main focus of molecular acoustics is on speed and attenuation of sound. These parameters are affected by the molecular structure of the liquid under investigation and, thus, contain information about the composition of the liquid.

Phases and amplitudes of sound are measured by the ultrasound sensor. From the phase shifts and amplitudes the speed of sound and attenuation coefficients can be calculated. So, for each of the twenty frequencies two values are obtained, resulting in forty ultrasound parameters for each measurement. This multitude of ultrasound parameters can be understood as the ultrasonic fingerprint of the oil under investigation. Different oils or changes in the oil over time can be identified by changes in the ultrasonic parameters.

The obtained ultrasound parameters are then related to reference measurements of the oil by multivariate data analysis. Instead of just looking at one parameter multivariate analysis uses all parameters at the same time to get a prediction with higher precision. The general concept behind TranSCoM Online's evaluation is shown schematically in figure 5.

Quite simply, the larger the number of relevant variables that are measured the better the predictive powers of the multivariate model and the higher the certainty of safe operating conditions of a transformer will be. For this reason, TranSCoM Online also includes a humidity sensor and a camera to generate more robust results.

The humidity sensors of the TranSCoM Online is capable of determining the relative humidity of the oil and its temperature. It is a well-established fact that the BDV of transformer oil decreases with increasing humidity of either paper insulation or transformer oil [2]. Hence, the humidity sensor is a centerpiece of the TranSCoM Online and provides important data for a sound BDV determination and transformer monitoring.

During normal operations, the transformer will heat up and cool down in cycles. Water from the paper insulation will migrate to the oil when the temperature rises and migrate back to the paper when it decreases again. This implies that the water content in the oil changes continuously. This can also lead to a dangerous situation when the transformer oil cools rapidly and the water has not enough time to travel back to the paper insulation. In that case, the BDV of the oil would drop sharply and might reach a very low value. Such a situation could be easily identified and avoided with the TranSCoM Online.

It should also be kept in mind that this continuously changing water content of the oil makes it hard to draw oil samples under the same conditions. The humidity data can also be used to better time the drawing of representative oil samples for which the TranSCoM Online also provides two easy to use connectors.

Additionally, TranSCoM Online employs a small camera to determine the color of the oil. The color of the oil gives a quick indication of the oil status, but it must be handled with care. Oil becomes darker as it ages and the BDV tends to be lower for darker oils. The presence of particles, free water or dirt will lead to a cloudy appearance of the oil.

The current TranSCoM Online system uses the ultrasound parameters, humidity, temperature and oil color to evaluate the oil's BDV or, better said, safety status.

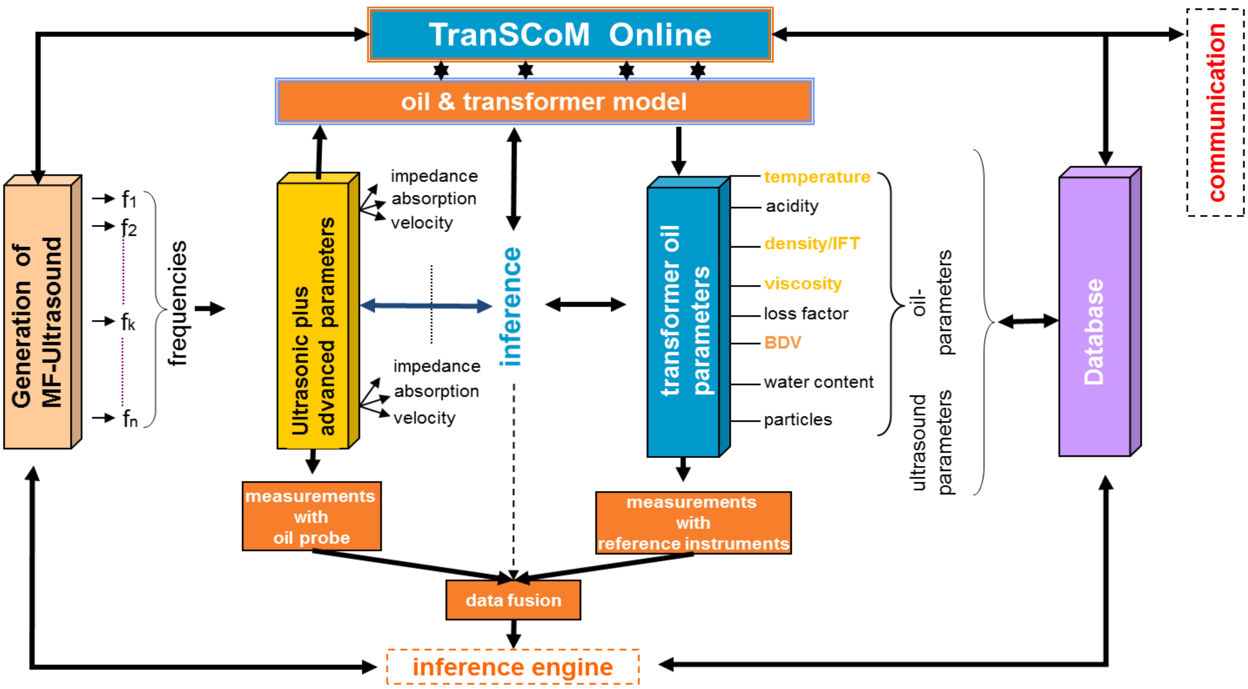


Figure 5: schematic of TranSCoM Online's evaluation and learning process

3. TranSCoM Online™ System Components

3.1 Hardware

The interior of the TranSCoM Online system is shown on the right in figure 6. The top and bottom oil sampling points of the transformer are connected to the device as shown in figure 8. There are also two additional connectors which can be used to draw oil samples.

Figure 6: interior of the TranSCoM Online

The oil is circulated by an oil certified pump (figure 7), similar to one used in heating systems. The valves at the lower part of the device are used during the filling procedure as well as during the drawing of oil samples via the bayonetted hydraulic connectors.

Figure 7: oil pump

The system is appropriately protected via an independent breaker (figure 9) from the transformer power panel (figure 10) to which it is connected.

The electronic parts taking the measurement and delivering the computation of BDV are connected for remote monitoring and control via an LTE-4G-3G-GPRS modem (also shown in figure 9), which uses a conventional pay as you go data card form the local mobile provider.

A camera and light source placed on the side of the electronic control block is optically monitoring the oil quality via a captured image using a transparent window installed in the oil flow path (figure 11).

Figure 8: top and bottom oil connectors

The degassing valve (figure 12) provided at the unit top has been employed to remove all air remained in the system to avoid aeration through the transformer tank. In principle, this valve can also be used to draw oil samples.

Appropriate connector hoses based on hydraulic oil pipes have been adapted to fit the unit as well as the transformer to which it will be connected.

Figure 9: breaker and GPRS modem

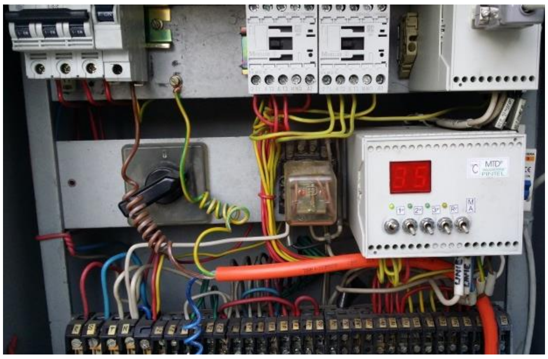


Figure 10: on-site power supply

Figure 10: transparent window for optical control

Figure 13: connector hoses

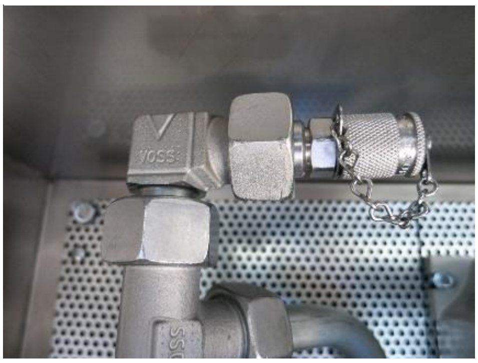


Figure 12: degassing valve

All devices are powered to appropriate voltages by the electronic box, the adapters pugged in and the convertor located under the electronic box.

3.2 Software

The software that controls all the sensors was implemented in Python and runs on a Raspberry Pi that is integrated into the main electronics box which also includes the electronics for the ultrasound sensor.

The standard measurement protocol that the software follows is the following:

When the program starts, the Raspberry Pi switches on an LED that illuminates the transparent oil window. A picture of the oil is taken by a small camera and the color of the oil is determined.

Next, the program starts the pump and keeps it running for two minutes to ensure that there is fresh oil from the transformer inside the TranSCoM Online system.

After stopping the pump the program waits for twenty seconds to ensure that the oil in the system is completely at rest.

For the next two minutes the program reads the measured data of the ultrasound sensor and humidity sensor, i.e., amplitudes, phases, temperature and relative humidity. These measurements are saved in a CSV file which can also be downloaded for further analysis.

When the measurements are done, another pumping cycle starts and the procedure just described starts again. After ten such cycles which last about one hour in total, the camera takes another picture of the oil.

Of course, the duration of pumping and measuring cycles can be adapted at will. The software can also be customized to, e.g., include features such as an automatic e-mail alert if the BDV of the transformer oil is too low or the humidity too high.

The most important part comes after the measurements are done.

Statistical methods are used to deduce oil parameters like the BDV from the ultrasound parameters, relative humidity, colour and temperature of the oil.

In the current version, the system needs a few days to gather enough data to allow for a calibration of the data model.

In the future, when reliable data of a sufficient number of oils has been gathered, advanced machine learning algorithms will be developed to enable a dependable evaluation of the current oil status that can also indicate when a thorough lab analysis of the oil is necessary.

3.3 Remote Monitoring via InSYS Modem

The INSYS modem pay as you go Vodafone SIM card had to use the following login details for a proper dial-out:

- APN: live.vodaphone.com
- User: live.vodaphone.com
- Password: vodaphone

4. Pilot site location selection and delivery

Together with the end customer Electrica Transilvania Nord a site survey has been conducted to determine the pilot unit location. The transformer selected is part of the substation Cluj Centru.

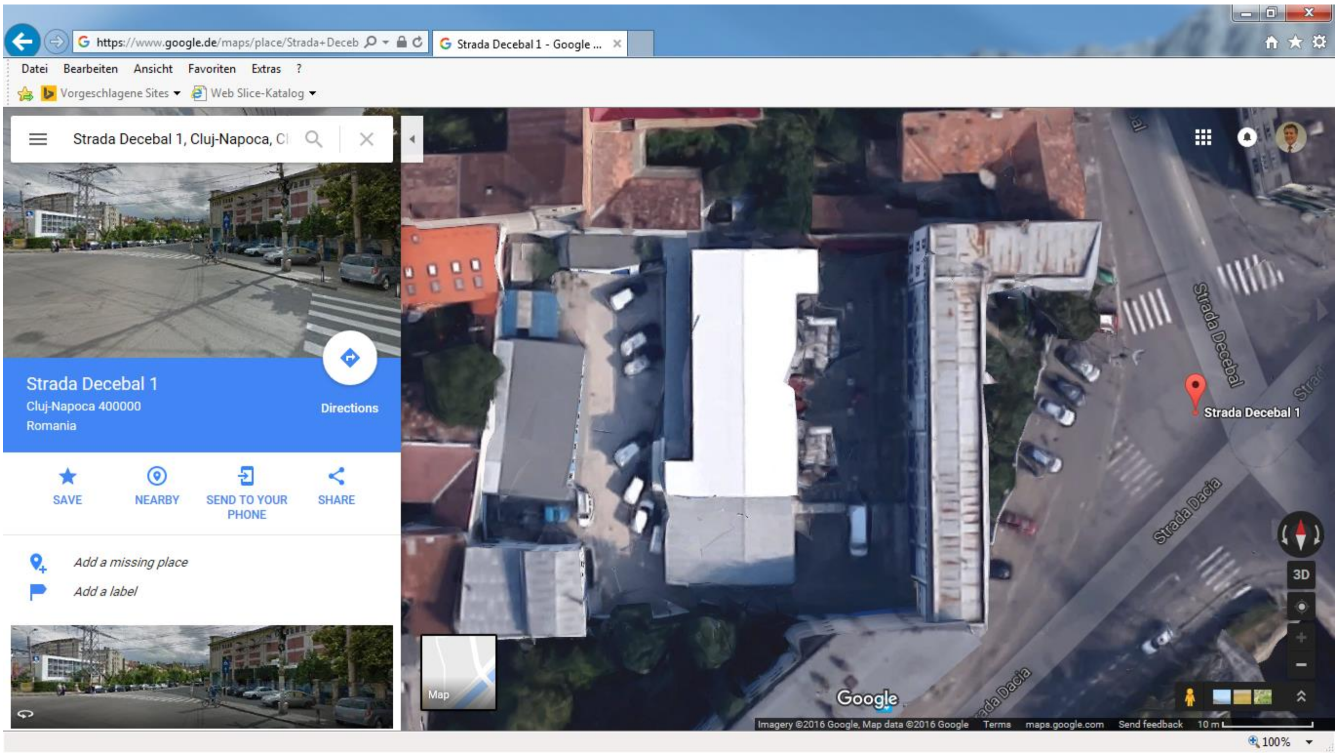


Figure 114: pilot site location

This is an original Romanian transformer manufactured by Electroputere, Craiova. The selection of this 20 MVA transformer (110 kV to 10 kV) was motivated by the risks associated due to its age, type of loads, ability to replace it and location of service.

The items surveyed after its down-selection were:

- Adjustment and adaptation of the oil pipes to the transformer
- Connectivity of the 230 VAC power supply
- Communication options:
  - Connectivity
  - Data storage
  - Logging
  - Location of the GPRS/3G/4G modem antenna
- Customer software expectations:
  BDV (in kV) trends
  Statistics
  Temperature profile

Oil samples of the transformer oil were drawn and stored in appropriate recipients (figures 15 and 16) for first oil-tuning of the TranSCoM Online system. The oil samples were delivered to Yucoya Energy Safety GmbH. The preliminary lab analysis report (figure 17) revealed the following oil characteristics:

Figure 16: containers in transport box 1

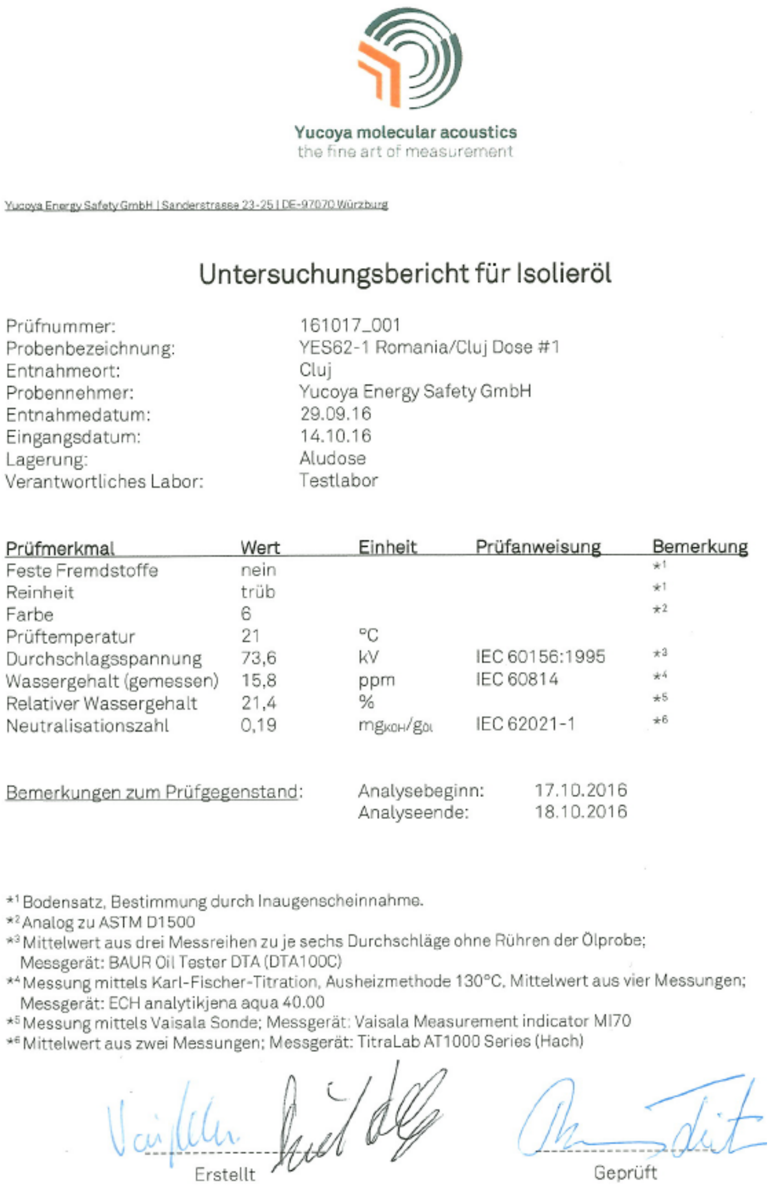
Figure 15: standard aluminum can 1

- Color 6
- Test temperature 21°C
- Water content 15.8 ppm
- Relative water 21.4 %
- Neutralization number 0.19 mg_{KOH}/g_{oil}
- BDV 73.6 kV

The preliminary installation date was set to November 14th.

The system has been delivered from Wurzburg (the effective cabinet) and Bucharest (via the A. Eberle Romanian partner Eneroptim) just in time for the install to take place on November 14th. The system has been assembled and completely installed on site.

The customer made all efforts to deploy appropriate personnel and to satisfy the installation requirements. This involved the mounting on site of the chassis/stand, the connectivity to the transformer oil (top and bottom) valves, the connectivity to power and the provision of a laptop required for setting up the INSYS modem.


Yucoya molecular acoustics
the fine art of measurement

Yucoya Energy Safety GmbH | Sanderstrasse 23-25 | DE-97070 Würzburg

Untersuchungsbericht für Isolieröl

Prüfnummer:	161017_001
Probenbezeichnung:	YES62-1 Romania/Cluj Dose #1
Entnahmeort:	Cluj
Probennehmer:	Yucoya Energy Safety GmbH
Entnahmedatum:	29.09.16
Eingangsdatum:	14.10.16
Lagerung:	Aludose
Verantwortliches Labor:	Testlabor

Prüfmerkmal	Wert	Einheit	Prüfanweisung	Bemerkung
Feste Fremdstoffe	nein			*1
Reinheit	trüb			*1
Farbe	6			*2
Prüftemperatur	21	°C		
Durchschlagsspannung	73,6	kV	IEC 60156:1995	*3
Wassergehalt (gemessen)	15,8	ppm	IEC 60814	*4
Relativer Wassergehalt	21,4	%		*5
Neutralisationszahl	0,19	$mg_{KOH}/g_{Öl}$	IEC 62021-1	*6

Bemerkungen zum Prüfgegenstand: Analysebeginn: 17.10.2016 Analyseende: 18.10.2016

*1 Bodensatz, Bestimmung durch Inaugenscheinnahme.
*2 Analog zu ASTM D1500
*3 Mittelwert aus drei Messreihen zu je sechs Durchschläge ohne Rühren der Ölprobe; Messgerät: BAUR Oil Tester DTA (DTA100C)
*4 Messung mittels Karl-Fischer-Titration, Ausheizmethode 130°C, Mittelwert aus vier Messungen; Messgerät: ECH analytikjena aqua 40.00
*5 Messung mittels Vaisala Sonde; Messgerät: Vaisala Measurement indicator MI70
*6 Mittelwert aus zwei Messungen; Messgerät: TitraLab AT1000 Series (Hach)

Erstellt Geprüft

Figure 127: lab analysis report

5. Installing the TranSCoM Online system

The TranSCoM Online installation consisted of the following steps (equivalent to the Westnetz Wesel transformer, which means that no shutdown of the transformer was necessary!):

- Connection of TranSCoM Online to both valves (top and bottom) to enable oil circulation
- Connection to the transformer control box/power supply followed by proper grounding
- Enabling oil flow into system (from top) into the measuring cell (with the system oil outlet at the bottom closed)
- Degassing of the system's measuring branch via the degassing valve (upmost top unit point)
- Employing the same procedure for the oil return branch
- Repetition of these steps until there was no gas in the measuring system (visible control)
- Power connectivity of the measurement and control box (which orders the start circulation of oil and measuring process)
- Connection to Yucoya server via the INSYS modem
- Enabling the on-site data acquisition/transmission

Figure 18: TranSCoM Online mounted on a stand and connected to the transformer

The site deployment allowed for a neat arrangement where the device has been installed and connected to the transformer with cables and hoses provided. Its accessibility is very good both for taking oil probes as well as for further tests and upgrades.

Figure 19: Connection to top and bottom oil

Figure 20: Simple access to interior of TranSCoM Online

6. BDV, Humidity Monitoring Results

Once the TranSCoM Online system is connected to the transformer and the software is running, the graphical user interface (figure 21) will appear and show diagrams of the measured (active water and temperature) and statistically inferred values (moisture, BDV, density, IFT).

One record of measurement parameters (stored in a CSV file) consists of the following sequence:

time stamp [s]
temperature [°C]
active water
ultrasound parameters (velocity, amplitudes, phases)
current breakdown voltage BDV [kV]
water content Wc [ppm]
Density [kg/m3]
IFT [mN/m]
Ultrasound parameters

The values (see figure 21) read by the system were comparable to the results of laboratory determinations which was expected since the data models were optimized to reproduce the determined values:

- Water content 13.5 ppm
- Relative water 20 %
- Density 889,39 kg/m3
- BDV 74.56 kV
- IFT 30.79 mN/m

It needs to be emphasized that the good agreement of infered values and results from laboratory analysis can only be expected if the data model is carefully adapted to the current transformer oil.

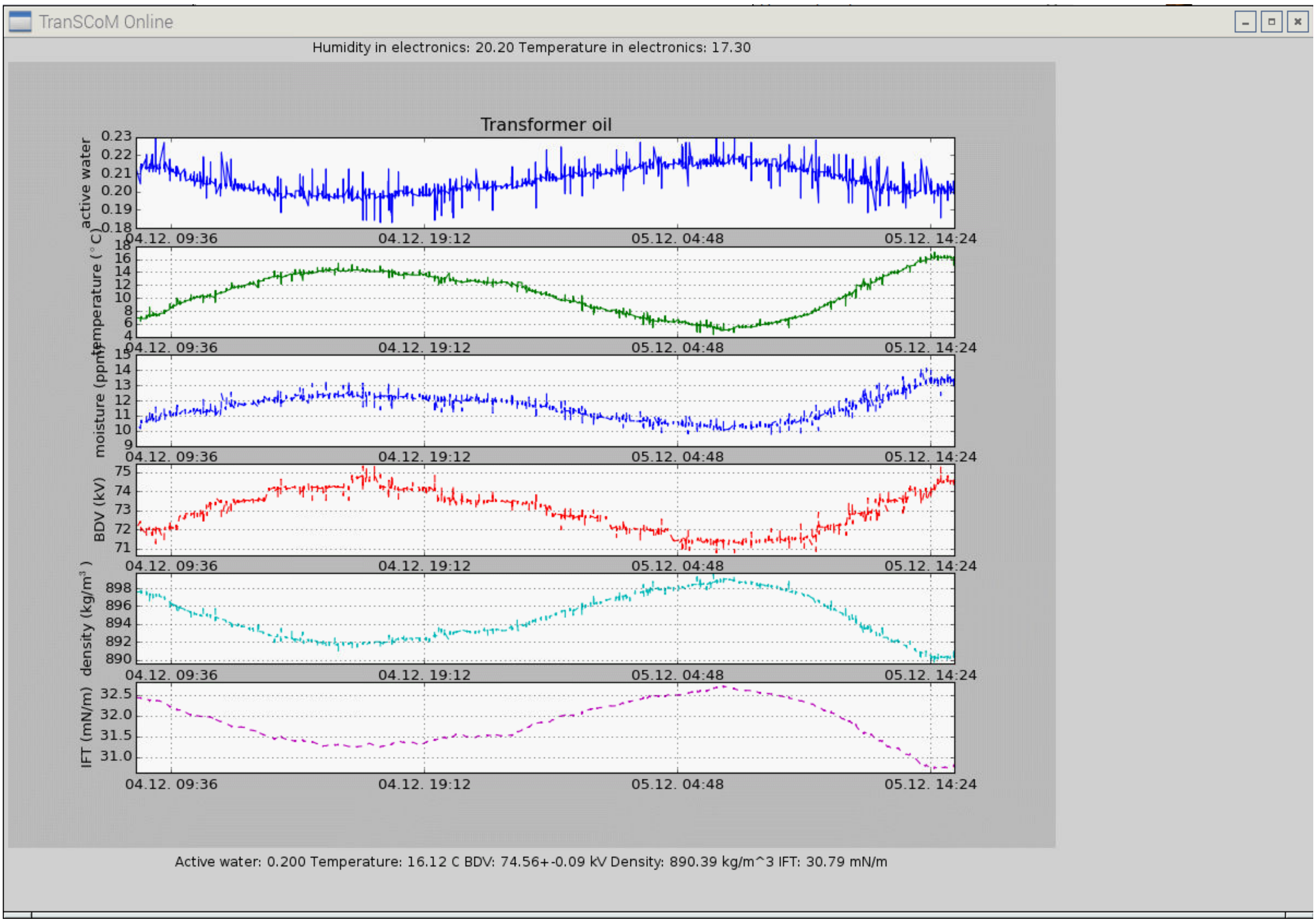


Figure 21: graphical user interface of the TranSCoM Online. The line at the bottom gives the mean values of the last ten measurements.

7. Conclusions

TransCoM Online, an online transformer monitoring system, has been installed at a transformer of Electrica Transilvania Nord in Cluj. The system works as a bypass which is connected to top and bottom oil connectors of the transformer. It uses ultrasound and humidity sensors as well as a camera to statistically infer oil parameters like the breakdown voltage, moisture, density and IFT.

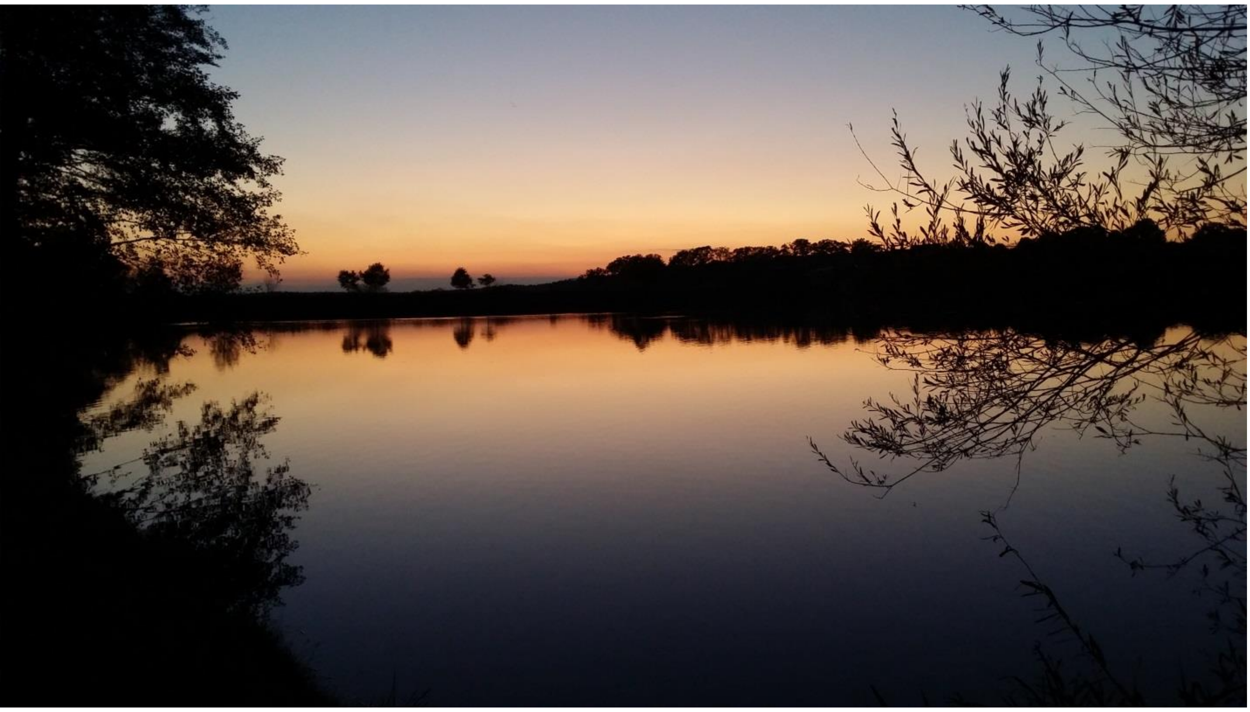
8. References

[1] M. Jovalekič, S. Tenbohlen, J. Harthun, C. Perrier, “Performance of alternative insulating liquids at low temperature”, *ETG-Fb. 140: Grenzflächen in elektrischen Isoliersystemen* – Beiträge der 4. ETG-Fachtagung, 12.11.13 – 13.11.13, Dresden, Germany.

[2] K. Miners, "Particles and Moisture Effect on Dielectric Strength of Transformer Oil Using VDE Electrodes", *IEEE Transactions on Power Apparatus and System*, vol. PAS-101, pp. 751-756, March, 1982.

[3] T. Fritsch, F. Wirner, S. Lech, J. Füser, "Transformer oil BDV online monitoring“, ieema 2nd TRAFOTECH Workshop 2016, India Habitat Centre, New Delhi, 22.11.16 – 23.11.16, New Delhi, India.

Notes



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