Measuring transformer oil parameters via multi-frequent ultrasound:

TranSCoM as a new innovative method providing increased safety for power transformers

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Abstract: Power transformers are the backbone of the upcoming Smart Grid. However: the aging of their components, especially of transformer oil and paper, will reduce their availability in near future dramatically. Currently mostly time-based maintenance schedule schemes for transformers are applied. But: State-based predictive maintenance schedules are urgently required to be able to cope with the changes due to aging processes. Presented is an absolutely new approach to transformer oil monitoring (both online and offline) which allows predictive maintenance resulting in prolonging the lifetime of power transformers in the grids. The measured parameters: physico-chemical properties of transformer oil via multi-frequency ultrasound spectroscopy (MFUS) which in turn was developed for the ultrasonic analysis of liquids in general. The oil parameters provided by the measurements include neutralization number (acid), moisture content (water) and – in future - further contaminants like particles, inhibitor content and gas-in-oil. Electrical properties like dielectric power factor or breakdown voltage are inferred by intelligent software tools. The measurements can be carried out in online or in offline mode. Results can immediately be used for the "health assessment" of the transformer with the difference to "normal" assessment methods that these are not based upon hard physico-chemical measurement data but only on statistical assumptions. The application to the transformer takes place in online mode by introducing a pair of ultrasound transducers into the transformer (and its oil) and sending the results to the net control centers. In offline mode oil samples are taken contamination-free and analyzed *in situ*, using different measurement scenarios. Thus, this technology provides a new fundamental approach to enhance the safety of the electrical energy supply - today and in the future.

I. **Introduction – problem statement**

There is a major misunderstanding concerning the importance of power transformers in the upcoming Smart Grid. Most of the Smart Grid concepts currently under discussion do not express much concern regarding power transformers as safety-critical active nodes of the Smart Grid. In reality, power transformers constitute the actual backbone of the existing Grid. Yet this backbone is now dramatically aging. For instance: in Germany, approx. 7850 power transformers worked in the 110kV- grid in 2008. A big sub-group of these transformers consisted of 3340 units aged between 31 and 45 years (in 2008). The age of another sub-group consisting of 1330 units was between 46 and 55 years. Both groups together consisted of 4670 units, what was 59,5% of the whole transformer population. According to recent studies published by CIGRÉ, the outages of power transformers due to failures (e.g. insulation) are increasing on a non-linear basis, beginning with the age of 30 service years {Tenbohlen, 2012}. As a consequence, the success of the *Energiewende* in Germany is really endangered, since most of its implicit burdens are imposed on the rapidly aging power transformers as the backbone of the Grids. Each power transformer in the Grids will thus suffer from strong fluctuations of electrical power fed into the Grid by renewable energy sources. These electrical load fluctuations are especially affecting the only protection means of the transformer: nonlinear aging of transformer oil. This problem remains as yet unrecognized; however, solving it will be crucial to a successful *Energiewende*.

The situation as it can be observed today: the world-wide electrical power supply is getting closer and closer to a **critical state** - and/or has already reached this state in different regions of the world. Widespread power failures (blackouts) take place ever more frequently. Transformer fires cause immense direct and collateral damage. In Germany, a nationwide blackout was avoided at the last possible second {Wetzel, 2012}. Due to excess wind power in the HV Grid "50 Hz" (which could not be transferred to the neighboring Grids due to power breakdown of an important grid-connecting substation) - the European UCTE-Grid was nearly facing the abyss. The current infrastructure of the worldwide electrical power supply cannot withstand these presently strict (and

in future perhaps even more strict) requirements which in many cases can lead to severe threats of the power supply for bigger areas.
The individual problems which are the driving forces of the general problem of energy supply safety: increasing power consumption and power trade, plus (above all) the integration of renewable energy sources into the existing Grids. On the other hand - the power supply companies cannot really afford even one loss of a transformer in the Grid at present, because the replacement time of a transformer reaches up to two years - and the cost for this replacement is high. Moreover, the collateral damage could be catastrophic, and the public image of the company would suffer in a way, which could never be accepted.

The existing Grid must still be used as long as possible - and at the same time, a new structure (the "**Smart Grid** "- must be attained, which can withstand the above mentioned strong requirements. That is an extremely difficult task. It can be compared with a flight across the oceans while changing its energy source and re-engineering the airplane itself during the flight. Moreover not even one severe mistake will be allowed to occur during the flight. The different fuels to be exchanged must reach for the full distance and the airplane has to make a safe landing – hopefully with all passengers aboard. Thus - the "mission" can only be accomplished, if the operating conditions of the transformers and their electrical isolation means are continuously monitored online.

The most important and on the long run the only real **protection means** of the transformer is the ***transformer oil***, which due to its changes during its lifetime provides concise information on the aging of the transformer along with the condition of its electrical insulation ability (of the oil and of the oil-impregnated Kraft paper, insulating the windings) which is affecting safety and reliability of the operation modes of the transformer. This monitoring is up to the moment carried out in most cases only through selective and sporadic laboratory analyzes of the oil parameters far from the actual state of the oil during continuous operation of the transformer in use.

The load fluctuations in the Grid are the reason for a much higher thermal variability in the transformers whose usage is currently pushed to the limits, especially in the vicinity of off-shore wind farms. The frequent variation of temperature causes a forced aging of the transformer oil - the only shield against electrical discharges within the transformer – and the paper. Transformer oil provides electrical insulation and is the only means of heat transport in the transformer. Lacking an integrated online-monitoring of transformers in the Grid only lab examinations of transformer oil are taking place – sometimes never, sometimes starting after 5-10 service years, sometimes in intervals from 1-2 years, if the transformer has reached a "critical age". But – taking an oil sample from a transformer at a certain time within a yearly or a half-yearly period provides no really significant information about the real safety state of the transformer or its insulation, respectively. So far, transformer-oil samples, taken in the traditional way, are only selective snapshots of the transformer safety state which will rapidly change more and more and in future even in shorter time intervals.

If for instance water content and acidity are determined by laboratory methods like Karl-Fischer and potentiometric titration, than one should also consider that the deterioration of paper produces acids as well, in this case low-molecular acids (LMAs) like formic acid which – under presence of water in paper - is dissolving and producing hydronium ions which turned out to be very aggressive against the paper structure {Liland, Lundgaard, 2004, 2008}. When an oil sample will be taken in this situation than the water content will be much higher and regarding the acidity (with different acids combined) much more different than when taking the sample at a reduced temperature. The reason for this is the following one. When temperature rises in the transformer due to heavier electrical load then water together with its dissolved acid contaminants from LMAs is migrating from paper into the oil and vice versa when temperature will fall again. Thus it is obvious that the water and acid content in transformer oil are not constant but changing with time according to the daily or weekly load life cycle of the transformer. In other words water content and especially acid content are time-dependent oil parameters, whereas on a middle-long time scale. Therefore it cannot be recommended to regard oil samples, taken in yearly intervals, as meaningful information about the real safety state of the transformer oil.

Under these circumstances a concise and continuous online-monitoring of power transformers in the Grids, which are intended to change into the "Smart Grid" by some "intelligence" to be implemented, is mandatory. Especially transformer oil devoted to guarantee electrical and thermal safety has to be monitored with much more focus than it is done in the current application. As a consequence, a condition monitoring has to be introduced, which must be based on hard physico-chemical measurement data, but applying a holistic standpoint, where it is possible, to detect with one measurement as much oil parameters as possible at the same time instant. The proposed Multi-Frequency Ultrasound Spectroscopy (MFUS) is the first of such holistic investigation methods, using physical ultrasound, where measurements based on ultrasonic frequency diversity are able to fulfill the above-stated strong requirements.

II. Description of the new method - molecular acoustics

The scientific basis of MFUS is molecular acoustics, which was applied as an advanced science of matter since the "fifties" in East and West, {Michailov, 1964}. Due to the culmination of political antagonisms between East and West 1962-1989 resulting in the "iron curtain", molecular acoustics developed in different ways in East and West. In the West there was only little interest to continue the strong tradition built up by {Herzfeld & Litovitz, 1959}, {Nozdrew, 1960}, {Schaaffs, 1963}, {Matheson, 1971}. Only a small group of scientists in Japan around Takagi (see {Oakley}) and in Taiwan around Kuo & Wu {Kuo, 1972, 1974} continued to work on this subject. A good overlook of the different working groups in East and West is given by {Oakley 2003} , whose verdict at the end of the description of the work done by Russian groups is a comprehensive but also sobering judgment of the sometimes stifling dependency of scientific progress from the stability of political systems: "*With the crumbling of the Berlin Wall and the subsequent passing of Communism in the former Soviet Union, the phenomenal output of the Kursk State Pedagogical Institute was abruptly halted. No studies were published in this area after 1989*.", see Oakley, p. 1507.

First of all, since most of the readers will not be familiar with the concepts of molecular acoustics, a very good readable and comprehensive definition and description of molecular acoustics science is cited from "The Great Soviet Encyclopedia", whose author was A.L. Poliakova, {Poliakova, 1979}

"*Molecular acoustics is a branch of physical acoustics in which the properties of matter and the kinetics of molecular processes are studied by acoustic methods. The main methods of molecular acoustics are the measurement of the speed of sound and sound absorption and of the dependence of these quantities on various physical parameters, such as the frequency of the sound wave, the temperature, and the pressure. Gases, liquids, polymers, solids, and plasma may be studied using methods of molecular acoustics.*

The development of molecular acoustics as an independent branch began in the 1930's, when it was established that dispersion of the velocity of sound takes place in many substances during the propagation of sound waves in them and that the absorption of sound is not described by the classical law, according to which the coefficient of absorption is proportional to the square of the frequency. These anomalies were explained on the basis of the study of relaxation processes, which made it possible to correlate certain properties of matter at the molecular level, and also a number of kinetic characteristics of molecular processes, with such macroscopic quantities as the speed and absorption of sound.

Such characteristics of matter as compressibility, the specific heat ratio, and the elastic properties of a solid can be determined from the speed of sound, and the values of shear viscosity, second *viscosity, and relaxation time can be determined from the absorption of sound. In gases the parameters that characterize the interaction of gas molecules during collisions are determined by measuring the speed of sound and its temperature dependence. In a liquid, the accuracy of the model used may be assessed and the interaction energy of the molecules determined in many cases by calculating the speed of sound on the basis of a given model of the liquid and comparing the results of the calculation with experimental data. The speed of sound is affected by the peculiarities of molecular structure, the force of molecular interaction, and the packing density of the molecules. For example, an increase in the packing density of molecules, the appearance of hydrogen bonds, and polymerization lead to an increase in the speed of sound, whereas the introduction of heavy atoms into the molecule leads to a decrease.*

In the presence of relaxation processes, the energy of translational motion of molecules - which they receive in the sound wave - is redistributed into internal degrees of freedom. In the process, dispersion of the velocity of sound appears, and the dependence of the product of the coefficient of absorption and wavelength on frequency has a maximum at a certain frequency, called the relaxation frequency. The extent of dispersion of the velocity of sound and the value of the coefficient of absorption depend on precisely which degrees of freedom are excited by the action of the sound wave, and the relaxation frequency, which is equal to the inverse of the relaxation time, is related to the rate of energy exchange among the degrees of freedom. Thus, an assessment of the character of molecular processes and a determination of the process that makes the main contribution to relaxation can be made by measuring the speed of sound and the absorption as a function of frequency and by determining the relaxation time. These methods may be used to study the excitation of the oscillatory and rotational degrees of freedom of molecules in gases and liquids, processes of molecular collision in mixtures of various gases, establishment of equilibrium during chemical reactions, rearrangement of the molecular structure in liquids, processes of shear relaxation in highly viscous liquids and polymers, and various processes of the interaction of sound with elementary excitations in solids.

The analysis of acoustic data is usually more difficult for liquids than for gases, since the relaxation region here generally lies at higher frequencies - which in turn require more complex measurements. The entire set of relaxation processes with a broad range of relaxation times may contribute to absorption and dispersion in highly viscous liquids, polymers, and certain other substances. Since the relaxation time depends on temperature and pressure, the relaxation region may be shifted in frequency by changing these parameters. For example: in a gas, an increase in gas pressure is equivalent to a decrease in frequency. This may be used conveniently in measuring the speed and absorption of sound if the relaxation frequency under normal conditions lies within the range of frequencies that is difficult to study experimentally. The study of the temperature dependences of the speed - and absorption of sound makes it possible to separate the contributions of various relaxation processes.

Ultrasound is usually used for research in molecular acoustics. In gases the range of frequencies is 10^4-10^5 hertz (Hz), and in liquids and solids, 10^5-10^8 Hz. This results both from the great development of radiation technology and ultrasonic techniques and the high precision of measurements in this frequency range and from the fact that work at lower frequencies would require very large volumes of the substance under study, whereas at higher frequencies the absorption of sound becomes so great that many acoustical methods become inapplicable."

After the crush of "real socialism" in East Europe only a small group of scientists in Poland passed on the baton of molecular acoustics research. They founded the Journal of Molecular and Quantum Acoustics {MQA} and held since 1972 in Ustron-Jaszowiec a yearly meeting called "Winter School of Molecular & Quantum Acoustics and Sonochemistry. A short overview is given by {Opilski, 2001}. A multiplicity of research on molecular acoustics has been done by scientists gathered within this network, to cite only a few like {Linde, 2002, 2006}. The scientists (and founders) of

Yucoya Energy Safety GmbH had strong personal connections to this network beginning from the "Nineties". They took up the baton again and developed "Multi-Frequency Ultrasound Spectroscopy" which is applicable to any liquid, in medical applications as well as in NDT (non-destructive testing). The application to transformer oil was the outcome of a long cooperation with A. Eberle GmbH & Co. KG and later with Micafluid AG as well. The first results were published 2011 at Transformers Conference, Torun, Poland, {Fritsch, 2011}. Already in 1984, the EPRI had investigated transformer oil {Howells, 1984}, because they wanted to know why some results of PD (Partial Discharge) measurements were differing so obviously. It turned out that transformer oil is not a "Newtonian liquid", as it was assumed up to then, but it was shown instead, that especially ultrasonic velocity not only depends from temperature, but also from frequency. Moreover it could be shown that humidity, viscosity and the temperature gradient of different gases, dissolved in oil (saturated), are changing with ultrasound velocity and vice versa. This was the proof, that transformer oil shows, dependent on the different contaminants like water, acids and gas in oil, a *dispersive* behavior. Therefore the ultrasound velocity is changing with frequency and is not a constant, as it is assumed for "pure" Newtonian liquids. Recent scientific investigations on the frequency dependency of ultrasonic velocity, like those from {Dukhin, 2009} and {Voleisiene, 2008} stating only small dispersions of ultrasound velocity, focused on other materials due to their research interest. So far, the findings of molecular acoustics, cited in the "definition" given by Poliakova, directly apply in the case of transformer oil. This gave a solid scientific foundation for the research activities from Yucoya Energy Safety GmbH. The major principles and the current results of the Multi-Frequency-Ultrasound Spectroscopy are given in the next paragraph.

III. TranSCoM technology

A. System Overlook

The system TranSCoM X applies multi-frequent ultrasound for the analysis of the transformer oil. The *novelty* is the fact that a very large number of different frequency-specific ultrasound measuring parameter data can be obtained when investigating the medium instead of only some few parameter data when using only one ultrasound frequency. Several hundred ultrasound parameters are thus gathered within one measuring sweep for about 300 frequencies. Carrying out a full frequency sweep and evaluation of ultrasonic parameters takes about two seconds at the moment. Current improvements of electronics will accelerate the speed of evaluation enormously. The multiplicity of ultrasound parameters carry information about the specific characteristics of the different substances (by-products of aging for instance) contained in the transformer oil. The knowledge about the characteristics of these substances is achieved by means of an intelligent evaluation of the ultrasound data with mathematical-statistical methods and by means of procedures from "artificial intelligence ".

The advantages of the TranSCoM Online! Under development (in comparison to other devices and procedures for monitoring transformer oil on the market) are:

- continuous determination of a multiplicity of oil parameters such as water content, total acid number, viscosity, breakdown voltage and in future interfacial tension, power factor, inhibitor content and gas-in-oil: with one measurement performed by one device,
- continuous determination of mixtures of different acids in oil, especially the discrimination between high-molecular acids (HMAs) and low-molecular acids (LMAs: current research project) – in future, as a result of academic cooperation,
- continuous monitoring of migration of water plus LMAs between oil and paper insulation (future research project) – in future, as a result of academic cooperation,
- estimation of DP-value from paper by LMA content in oil, indicating the degradation of solid paper insulation – in future, as a result of academic cooperation and
- all measurements are taking place during the continuous operation of the transformer.

B. Measurement Principle

The TranSCoM technology can be described as applied molecular acoustics. The frequency-dependency of the ultrasound attenuation (absorption) is well known in science. But during a research period of over 15 years it could be found out by the scientists of Yucoya Energy Safety that ultrasound velocity in several fluids is **not** a constant but instead is slightly changing with frequency even for low frequencies (1-10 MHz). Since ultrasound waves are compression waves, in liquids for instance it is assumed that changes in ultrasonic velocity in dependency from frequency will occur due to the presence of contaminants which cause frequency-specific delays or accelerations in the compression and/or the dilatation phases of ultrasonic wave propagation. Multi-Frequency Ultrasound Spectroscopy (MFUS) takes advantage from these changes by providing a broad frequency-dependent acoustical spectrum with a bundle of ultrasound parameters for the fluid in real-time. Thus it is possible to "grasp" fast reacting chemical processes for some dominant variables. On the other hand it is also easily possible to "grasp" processes only moderately changing in time but with a lot of variables involved. The aging of transformer oils for instance is such a process.

Within TranSCoM technology the "time-of-flights" (TOF) of ultrasound waves are calculated for 2 different but similar frequencies instead of a direct determination of ultrasound speed by distance and travelling time. Thus it is possible to determine the phase shifts of the signals in transmission mode of ultrasound transducers for these 2 frequencies. This allows the precise determination of the time-of-flight for this signal. Due to the application of under-sampling techniques, it was possible to achieve picoseconds-resolution. The amplitude at the receiver transducer is representing the attenuation of the signal while travelling through the oil. To achieve a broad frequency range with sufficient signal quality, three different transducers for different frequency bands (1-3 MHz, 3-7-MHz, 7-10 MHz) were integrated into one device (TranSCoM X-Lab). The acoustical fields of these ring transducers are shown in Fig. 1.

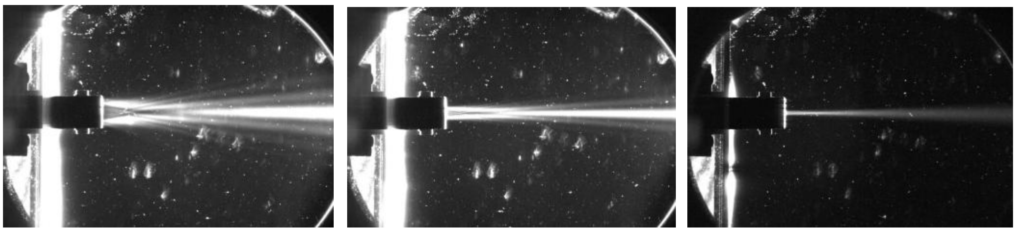

Fig. 1: Acoustical fields made visible in the "Schlieren chamber" for the three-ring transducers from left to the right, with a higher-frequency band (1-3 MHz, 3-7 MHz, 7-10 MHz) – TranSCoM X-Lab

For each of the three frequency bands there are 46 frequencies, each providing specific TOFs and attenuations. In the current version, *all* ultrasound parameters provided by the corresponding electronic device, the HiPer TransQM are used by software procedures on a host computer for evaluation purposes. The alternative would be to select specific frequencies which would be characteristic for certain substances and for their concentration in transformer oil. Yet in most cases these special frequency-substance relations are not known; however, they could be determined by a successive scientific investigation process. This will take its time.

So far the multiplicity of ultrasound parameters and the subsequent computational effort to extract useful information about the oil parameters in question from these high-dimensional data requires the application of sophisticated mathematical procedures coming from mathematical statistics, neural network and fuzzy logic theory. Needed is a reduction of dimensionality of the original raw data resulting in matching clusters of the corresponding oil parameter values stored in a common database. For this purpose, the parameters of the representative samples of transformer oil (plus the corresponding ultrasound parameter values) have been determined in a preceding step.

C. Measurement Process
The practical progression of the offline TranSCoM (X-Lab) measurement process is illustrated in Fig. 2. The oil from the transformer is led through a connecting device "Transformer Connect” (TC) into the MF-100S measurement cell for analysis. The ultrasound raw data received for 138 frequencies from the MF-3-AL ultrasound transducers are evaluated in the HiPer TransQM. The results are material-specific ultrasound parameters which are compared to those already saved in a database on a host computer.
The actual oil parameters are determined via a statistical inference engine associating them to the corresponding oil parameters, which in turn are saved in the same database. As a result, the graphical trend of oil parameter time evolution can be shown on a display screen. The oil circulation in the system "TC-TranSCoM” can occur as long as intended - and can also be repeated many times.

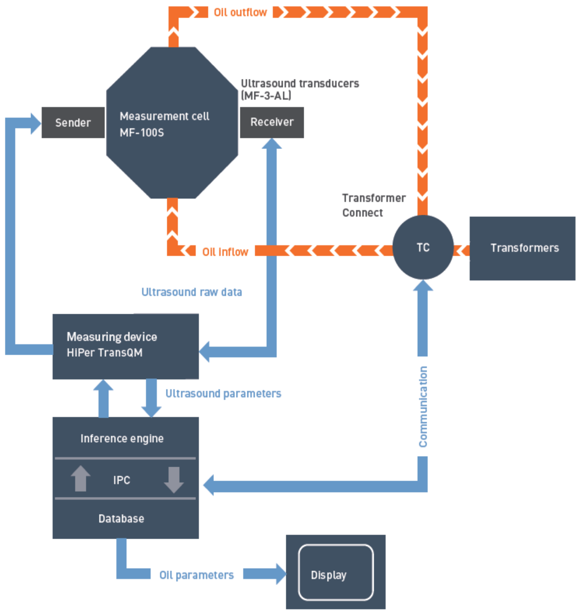

Fig. 2: The TranSCoM (X-Lab) system's measurement process (only applicable for offline measurements)

D. Results

Fig. 3: GUI for two of four oil parameters (water content and BDV), for a mixture of pure Shell Diala with Shell oil in service, which in turn was slightly modified by the injection of serviced Shell Diala – oil causing changes for all oil parameters.

IV. Conclusions and next steps ("Get me the Data” {Bush, 2012})
The TranSCoM technology is the correct answer to the common request for a broadband online monitoring of transformer oil. To prove its tremendous potential, it has to be seamlessly embedded in real transformer applications, especially in field tests. For this purpose, a new ultrasound probe is currently under development which will allow MFUS measurements *within* the transformer. The

evaluation of oil parameters can then be transmitted via Ethernet to Net Control Centres. This new approach “TranSCoM Online!” enables the safety assessment of the Smart Grid's backbone.

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