Estimating moisture in Power Transformers

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Estimating moisture in Power Transformers

- How to Estimate and What to Do

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Abstract— **Modern technology and developments in signal acquisition and analysis techniques have provided new tools for transformer diagnostics. Of particular interest are dielectric response measurements where insulation properties of oil-paper systems can be investigated. Dielectric Frequency Response, DFR (also known as Frequency Domain Spectroscopy, FDS), was introduced more than 15 years ago and has been thoroughly evaluated in a number of research projects and field tests with good results. DFR data in combination with mathematical modeling of the oil-paper insulation is proven as an excellent tool for moisture assessment. The dryness of the oil-paper insulation systems in power transformers is a key factor in both their short and long term reliability since moisture has deleterious effects on dielectric integrity and insulation ageing rates. This paper gives a background to moisture issues in transformers, where it comes from, how it can be measured, how it can be addressed and how this can be used for decisions on maintenance and/or replacement.**

Keywords – moisture, power transformers, dielectric frequency response; DFR; frequency domain spectroscopy; FDS; power factor; dissipation factor

I. INTRODUCTION

With an aging power component population, today's electrical utility industry faces a tough challenge as failures and consequent repair and revenue loss may inflict major costs. Transformers have become one of the most mission critical components in the electrical grid. The need for reliable diagnostic methods drives the world's leading experts to evaluate new technologies that improve reliability and optimize the use of the power network.

The condition of the insulation is an essential aspect for the operational reliability of electrical power transformers, generators, cables and other high voltage equipment. Transformers with high moisture content have a higher aging rate and can not without risk sustain higher loads.

On the other hand it is also very important to identify "good" units in the aging population of equipment. Adding just a few operating years to the expected end-of-life for a transformer means substantial cost savings for the power company.

II. MOISTURE IN TRANSFORMERS

The insulation system of power transformers consists of oil and cellulose. Both materials generally change their dielectric properties during the life of the transformer and among factors contributing mostly to the degradation of transformer insulation moisture plays an important role. Presence of water in solid part of the insulation, even in small concentrations, increases its aging rate, lowers the admissible hot spot temperature and increases the risk of bubble formation. In addition, moisture reduces the dielectric strength of transformer oil as well as the inception level of partial discharge activity [1].

A. *Where is the water?*

When discussing moisture in transformers it is important to understand where the water resides. Consider the following example (typical values for a 300 MVA service aged power transformer at 50°C):

- The insulation in a power transformer consists of oil impregnated cellulose and oil.
- 60 tons of oil with water content of 20 ppm = 1.2 liter
- 10 tons of cellulose with 3% water content = 300 liter
- Almost all water is in the cellulose!

During normal operation at different loads and temperatures the water moves back and forth between oil and cellulose. Sometimes the water content in the oil is doubled, 40 ppm/2.4 liter. However the moisture in the cellulose remains almost the same, 299 liter. The average moisture content in the solid insulation is very constant!

B. *Moisture accelerates aging*

Aging of the cellulose insulation is directly related to the moisture content. Figure 1 describes life expectancy for the insulation at various temperatures and moisture content [3]. At 90°C, cellulose with 1% moisture has a life expectancy of about 12 years. At 3% moisture the life expectancy is only 3 years!

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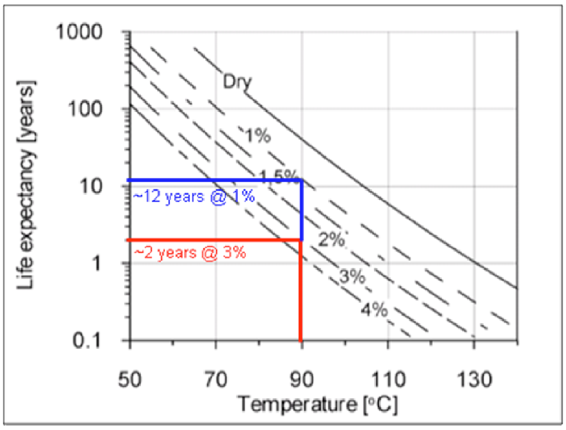

Figure 1. Life expectancy for cellulose at different temperature and moisture content [3]

C. Moisture limits the loading capability

A rise in temperature, especially at thick insulation layers, causes evaporation of adsorbed water with a high vapor and gas pressure within the inner layers of paper. This pressure may become high enough to create formation of vapor-filled cavities (bubbles) on the insulation surface with subsequent decrease of the dielectric strength [2].

Figure 2 describes limitation of load conditions due to moisture content [4].

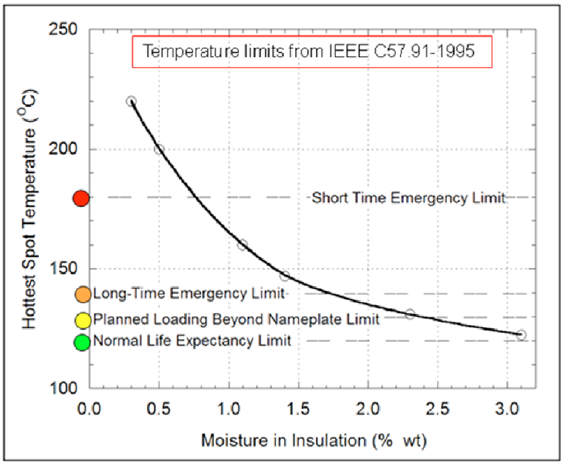

Figure 2. Recommended maximum loading limits (IEEE) as function of moisture [4]

D. Where does the water come from?

Transformers are dried during the manufacturing process until measurements or standard practices would yield a moisture content in the cellulosic insulation of less than 0.5% to 1.0% depending upon purchaser's and manufacturer's requirements. After the initial drying, the moisture content of the insulation system will continually increase. There are three sources of excessive water in transformer insulation [2]:

- Residual moisture in the "thick structural components" not removed during the factory dry-out or moistening of the insulation surface during assembly
- Ingress from the atmosphere (breathing during load cycles, site erection and/or maintenance/repair processes)
- Aging (decomposition) of cellulose and oil.

1) Residual moisture

Excessive residual moisture can remain in some bulky insulating components, particularly in wood and plastic or resin-impregnated materials, which need much longer drying times in comparison to paper and pressboard. Typically, these are supports for leads, support structures in the load tap changer (LTC), support insulation for the neutral coils of the winding, cylinders, core support insulation, etc.

Different insulation materials require different drying durations. The drying time is roughly inversely proportional to insulation thickness in square. However the structure of material is an important factor as well, e.g. pressboard featuring a high density requires longer drying time than low density pressboard. [2].

New transformers are generally dried to a moisture content < 1%. When drying larger transformers, the residual moisture may be as low as about 0.3%.

2) Ingress from the atmosphere

The main source of the buildup of water in transformers is the atmosphere and there are several mechanisms and occasions for moisture ingress.

- Exposure to humid air during site installation
- Leaking gaskets and faulty water traps may expose the inside of the transformer to moisture humid air
- Exposure to humid air during maintenance

3) Decomposition of cellulose

The aging of cellulosic materials leads to molecular chain scission and the formation of byproducts including water and furanic compounds.

Figure 3 describes several studies on how moisture is produced as a function of number of chain scissions. After five chain scissions a paper starting at a degree of polymerization of 1200 has ended up with a DP of 200 [2] (curves should only be considered as indicators on the order of magnitude of the water producing effect).

Typical increase of moisture in a transformer can be in the order of 0.05 – 0.2%/year pending design [2, 5]

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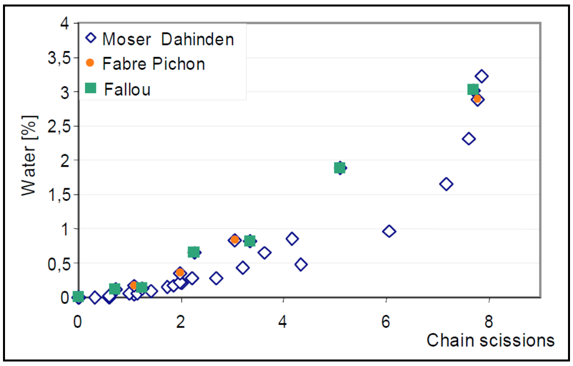

Figure 3. Produced water as a function of number of chain scissions [2]

III. STANDARDS AND RECOMMENDATIONS FOR MOISTURE

International standards and guides give some recommendations for moisture assessment. As an example IEEE C57.106-2002 recommended the following approximate percent by weight of water in solid insulation.

- < 69 kV, 3% maximum
- > 69 - < 230 kV, 2% maximum
- 230 kV and greater 1.25% maximum

Other standards and guides only give a classification of the moisture content. Figure 4 depicts moisture categories according to some standards and practices.

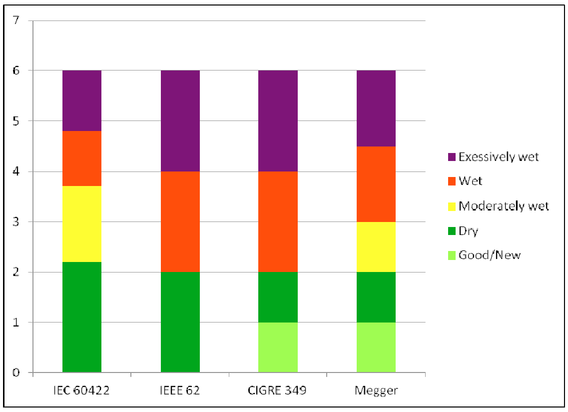

Figure 4. Moisture assessment examples

IV. MOISTURE MEASUREMENTS

There are several methods available to measure the moisture content in the solid insulation of the transformer.

Direct method

- Take paper sample from transformer and measure moisture content using Karl Fisher titration

Indirect methods

- Moisture in oil
  - Absolute values
  - Relative saturation
- Power frequency tan delta/power factor measurements
- Dielectric response measurements
  - Return Voltage Measurement (RVM) – DC method
  - Polarization-Depolarization Current measurements (PDC) – DC method
  - Dielectric Frequency Response measurements (DFR/FDS) – AC method

A. *Direct method – KFT on paper samples*

Karl Fischer titration allows for determining trace amounts of water in a sample using volumetric or coulometric titration. Its principle is to add a reagent (titre iodine) to a solution containing an unknown mass of water until all water reacts with the reagent. From the amount of reagent the mass of water can be calculated.

Several factors may affect the results of KFT analyses, e.g.:

- There is always ingress of moisture from the atmosphere during sampling, transportation and sample preparation. This happens particularly during paper sampling from open transformers
- Cellulose binds water with chemical bonds of different strengths. It is uncertain whether the thermal energy supplied releases all the water.
- Heating temperature and time certainly changes the released water.

To investigate the effect of these influences and to evaluate the discrepancies that may result from KFT analyses, a round robin test (RRT) was carried out among seven laboratories from four European countries [1]. It concentrated on analyzing the water content in paper relative to weight and the water content in oil relative to weight in three oil and paper samples according to the respective laboratory’s standard procedures. The obtained results revealed an unsatisfactory comparability between the laboratories, as shown below in Figure 5.

As seen in the figure the results show large variations. For sample A, containing little water, the comparability was worst. Moisture estimates varied between 1.0% and 2.0%.

Another issue for direct measurements of moisture in cellulose is the uneven distribution of moisture. In the “REDIATOOL” project [8], samples were taken from different parts of a transformer and analyzed for moisture. Results are presented in Figure 6. As seen in the figure the moisture distribution is very uneven between different parts and locations. To get a “true” result from KFT analysis of paper it is important to take many samples and average the results.

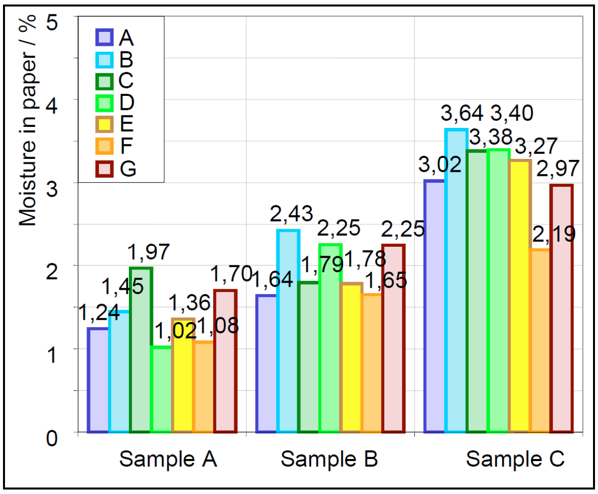

Figure 5. Moisture content in paper in % relative to weight as measured by seven laboratories [1].

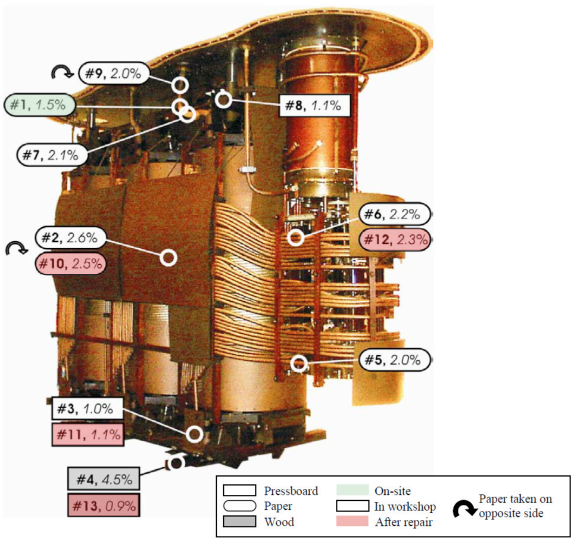

Figure 6. Moisture content estimated by means of KFT in samples of transformer solid insulation at different locations and sampling events [8]

Water content determination by means of dielectric response or other indirect methods is often calibrated by comparing them with evaluations based on KFT. However, as shown above, KFT results also suffer from a poor comparability between different laboratories. The user must therefore be aware of this fact, and understand that a deviation in the comparison does not necessarily point out weaknesses of the evaluated methods.

B. *Moisture in oil*

Measuring moisture levels in oil is probably the most common method for moisture assessment. Many operators of power transformers apply equilibrium diagrams to derive the moisture by weight (%) in cellulose from the moisture by weight in oil (ppm). This approach consists of three steps:

1. Sampling of oil under service conditions
2. Measurement of water content by Karl Fischer Titration
3. Deriving moisture content in paper via equilibrium charts .

The procedure is affected by substantial errors, e.g:

- Sampling, transportation to laboratory and moisture measurement via KFT causes unpredictable errors.
- Equilibrium diagrams are only valid under equilibrium conditions (depending on temperature established after days/months).
- A steep gradient in the low moisture region (dry insulations or low temperatures) complicates reading.
- The user obtains scattered results using different equilibrium charts.
- Equilibrium depends on moisture adsorption capacity of solid insulation and oil.

The influence of sampling, transportation and laboratory analysis has been evaluated in a round robin test carried out among seven laboratories [1]. The obtained results also here revealed an unsatisfactory comparability between the laboratories, as shown below in Figure 7.

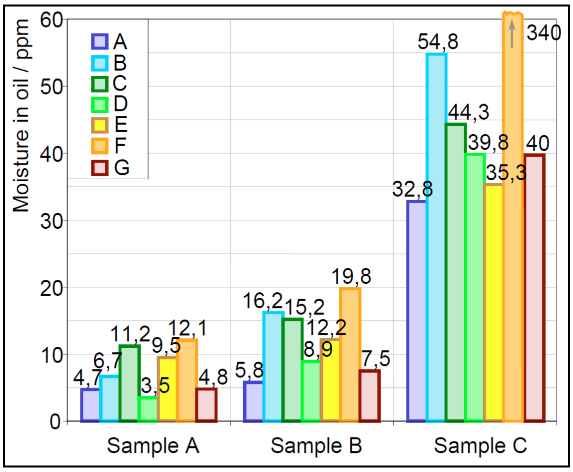

Figure 7. Moisture content in oil in ppm relative to weight as measuredby the laboratories [1]

For the drier samples A and B only a trend was recognizable; the results varied from 3.5 to 12.1 ppm for sample A and from 5.8 to 19.8 ppm for sample B. Systematic differences were obvious. It has to be mentioned that for the dry oils, the results also varied within one single laboratory and a standard deviation of 20% is not unusual.

The amount of water in the oil is used to derive moisture content in paper by using equilibrium charts. Several charts are available, below figure 8 shows "Oomen". Note the steep gradient the low moisture region that severely complicates reading.

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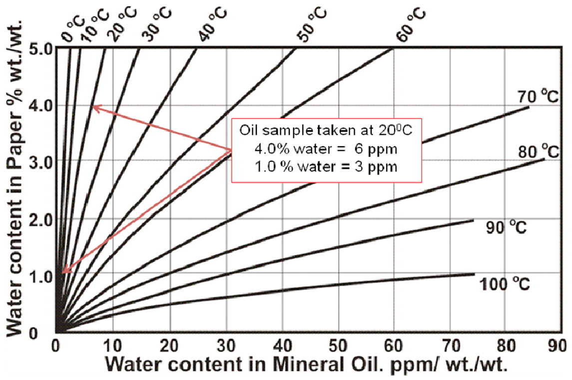

Figure 8. Equilibrium chart for moisture content in paper versus water content in oil at various temperatures.

One step to improve the method of using equilibrium diagrams is to use the *relative saturation* in oil (%) or *water activity* instead of the moisture by weight (ppm). In case direct measurements are performed with a probe mounted directly on the transformer this method removes the issues with sampling and transportation. Furthermore the moisture absorption capacity is less temperature dependent and oil aging and its influence on moisture saturation level becomes negligible, since it is already included into relative saturation [2]. However the method is still pending equilibrium and charts are pending material.

C. Power frequency tan delta/power factor measurements

Tan delta/Power factor measured at power frequency (50/60 Hz) shows the combined dissipation factor coming from losses in oil and cellulose. It is known that the measurement cannot discriminate a dry transformer with service aged oil from a wet transformer with new oil and the method is relatively insensitive to moisture levels < 2%.

Figure 9 describes the relation between power frequency tan delta values and moisture levels for a new and service-aged typical core-form transformer. At 0.3% power factor (20°C), the moisture may be from 0.5% to about 2% pending the condition of the oil.

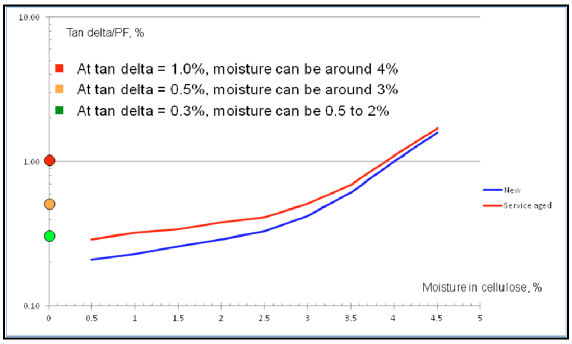

Figure 9. Tan delta (% @ 20C) vs moisture (%) for a new and service-aged typical core-form transformer

Furthermore it is also well-known that the standard tan delta temperature correction factors/tables (TCF) given in standards and many instrument manufacturers user manuals/recommendations, are incorrect for the individual transformer [9]. This adds an additional source of inaccuracy to the method.

D. Dielectric response measurements

Dielectric response measurements can be performed in time (DC) or frequency (AC) domain. The most common measurement techniques/methods are:

DC methods – Time domain

- Return Voltage Measurement (RVM); Voltage vs time
- Polarization-Depolarization Current Measurement (PDC); Current vs time

AC method – Frequency domain

- Dielectric Frequency Response Measurements (DFR/FDS); Capacitance and dissipation factor vs frequency

The different methods have been thoroughly investigated in several tests and experiments [7]. The dielectric response methods RVM, PDC and DFR/FDS where used to analyze the moisture content for different arrangements of insulation geometry at different temperatures by the corresponding software programs. Results were compared to KFT analysis.

The results of RVM analysis differed strongly, although the moisture content of paper was constant during all the measurements. Dependences on the oil conductivity as well as on the temperature and the insulation geometry appeared. Hence the RVM software used could not evaluate moisture in oil-paper-insulation systems well since the interpretation scheme used was inaccurate without taking into account the geometry and oil parameters.

Results of PDC analysis showed much smaller influence of insulation geometry and weaker temperature dependence. These influences were already compensated by the interpretation software used. With increasing oil conductivity the evaluated moisture content increased, although in reality it remained constant. Nevertheless, the simulation results were close to the level evaluated by Karl Fischer titration.

The DFR/FDS analysis provided the best compensation for insulation geometry. At the same time, the paper seemed to become drier with increasing temperature. This actually happens in reality because of moisture diffusing out of the paper, but not to indicated extent. The observed tendency rather reveals imperfect compensation for temperature variations. Similarly as for the other methods, an increased oil conductivity results in a slight increased of the estimated moisture content. For more details please see [7]

1) Dielectric Frequency Response Measurements

The first field instrument for DFR/FDS measurements of transformers, bushings and cables was introduced 1995 [9]. Since then numerous evaluation of the technology has been performed and as an example, several international projects/reports define dielectric response measurements together with insulation modeling as the preferred method for measuring moisture content of the cellulose insulation in power transformers [1], [6], [7].

In DFR tests, capacitance and dissipation/power factor is measured. The measurement principle and setup is very similar to traditional 50/60 Hz testing with the difference that a lower measurement voltage is used (200 Vpeak) and instead of measuring at line frequency 50/60 Hz, insulation properties are measured over a frequency range, typically from 1 kHz down to 1 mHz.

The results are presented as capacitance and tan delta/power factor versus frequency. Measurement setup is shown in Fig 10 and typical DFR results from measurement on transformers in different conditions in Fig 11.

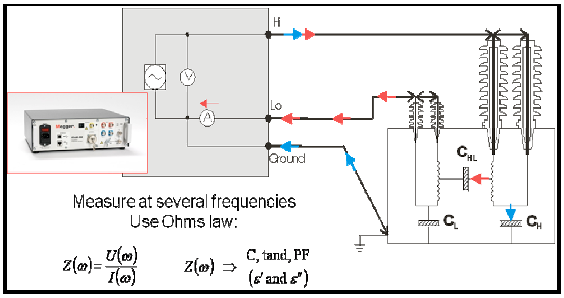

Figure 10. DFR/FDS test setup

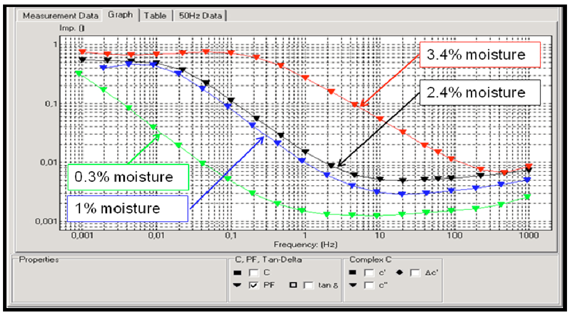

Figure 11. DFR measurements on four different transformers at different temperatures with moisture content ranging from 0.3% to 3.4%

a) Moisture Assessment

The method of using DFR for determining moisture content in the oil-paper insulation inside an oil-immersed power transformer has been described in detail in several papers and articles elsewhere [1], [6], [7], [10] and is only briefly summarized in this paper.

The dissipation factor for an oil/cellulose insulation plotted against frequency shows a typical inverted S-shaped curve. With increasing temperature the curve shifts towards higher frequencies. Moisture influences mainly the low and the high frequency areas. The middle section of the curve with the steep gradient reflects oil conductivity. Fig 12 describes parameter influence on the reference curve.

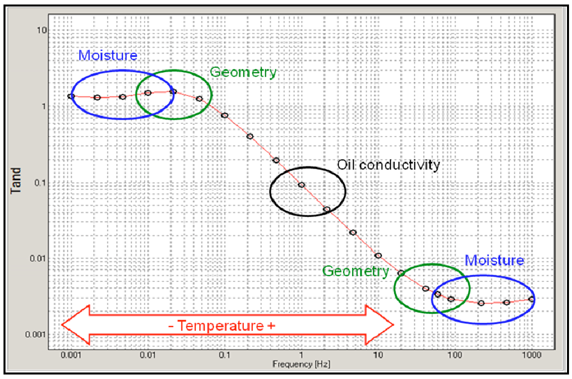

Figure 12. Parameters that effects the dissipation factor at various frequencies

Using DFR for moisture determination is based on a comparison of the transformers dielectric response to a modeled dielectric response (reference curve). A matching algorithm synthesizes a modeled dielectric response and delivers a reference curve that reflects the measured transformer. Results are displayed as moisture content along with the temperature corrected power frequency tan delta and oil conductivity. Only the insulation temperature (top oil temperature and/or winding temperature) needs to be entered as a fixed parameter. Figure 13 depicts results after insulation analysis/assessment.

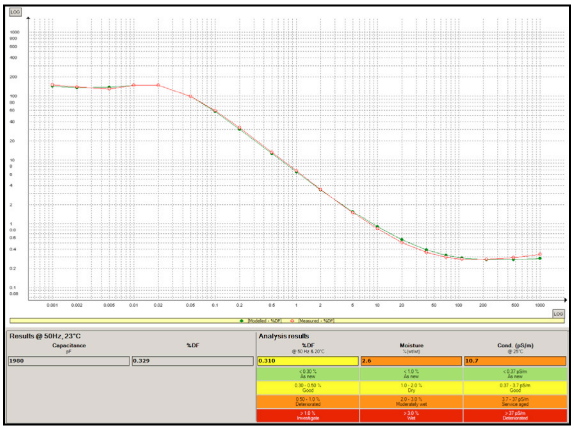

Figure 13. DFR insulation analysis/assessment

2) Comparing DC and AC techniques/methods

DC and AC measurements can be performed at low or high voltage and it is also possible to combine techniques by mathematically convert time domain data to frequency domain data and vice versa [11]. When selecting a suitable method for field measurements it is important to consider how sensitive the instrument is to substation interference.

A summary is presented in Table I. AC methods are generally more robust in high-interference conditions. DC methods and in particular low voltage DC measurements are very sensitive to DC interference from e.g. corona. The interference will add to the measured polarization current which the analysis SW will interpret as increased moisture in the insulation.

TABLE I. NOISE SENSITIVITY FOR DIFFERENT DIELECTRIC RESPONSE MEASUREMENT METHODS

Interference signals	DFR Measurement Technologies		
	Low Voltage DC	Low Voltage AC	High Voltage AC
AC (50/60Hz + harmonics)	Sensitive	Not sensitive	Not sensitive
DC/VLF	Very sensitive	Sensitive	Not sensitive

V. TRANSFORMER DRYING

Transformer drying is an important maintenance action in today's aging transformer fleet and several reports and publications describe the issues related to drying [11], [12], [13] (it is not the intention of this paper to cover details on the different processes, the interested reader is recommended to study the references).

The different methods for drying can be summarized as follows:

Two major techniques are used:

- Drying the insulation by drying the oil – Field
- Drying the insulation with heat and vacuum – Field and factory

Drying the oil can be performed with:

- Molecular sieves
- Cellulose filters
- Cold traps
- Combined oil regeneration and degassing

Drying the insulation can be performed with:

- Vacuum and heat
- Pulsation drying through oil circulation
- Hot oil spray drying
- Low frequency heating
- Vapour phase drying

All methods can remove water out of the transformer insulation. However the efficiencies in the different techniques vary to a very large extent. See Figures 14 and 15 describing water extraction capacity and the time needed for drying a 400 MVA transformer with 14 ton insulation from 3% down to 1.5% moisture.

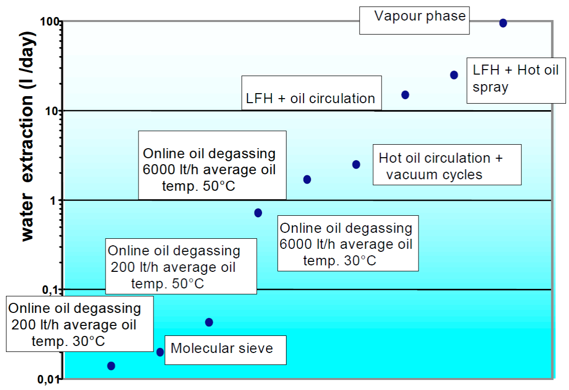

Figure 14. Drying velocity from 3% down to 1,5 % average humidity

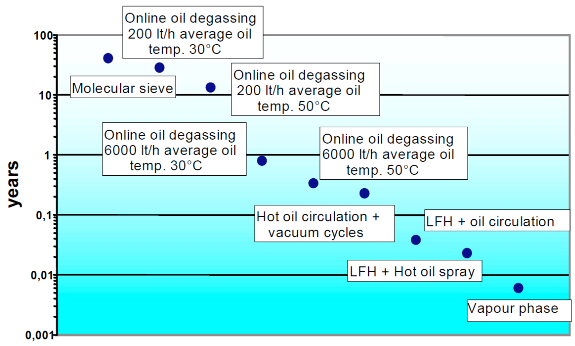

Figure 15. Drying time to dry a 400 MVA transformer with 14 ton insulation from 3% down to 1,5 % average humidity [13]

VI. FIELD EXPERINCES

A. Maintenance based on water in oil analysis

TABLE II. MOISTURE IN SOLID INSULATION BASED ON WATER IN OIL ANALYSIS COMPARED TO DFR ANALYSIS

Transformer	Type	% moisture in insulation (from oil analysis)	% moisture in insulation (from DFR)	Oil Cond (pS/m)
1	Core	**2.5**	0.9	0.38
2	Core	**1.8**	0.9	0.49
3	Core	**1.4**	0.9	0.41
4	Core	**2.8**	0.7	1.3
5	Shell	*Not available*	**1.2**	**1.5**
6	Core	**3.5**	**2**	**3.0**
7	Shell	**3.3**	1	0.30

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A utility had selected seven transformers for oil regeneration and drying. The decision was based on water in oil measurements. Before processing the service company suggested DFR measurements to verify status before treatment [14].

Tables II show results from oil tests and DFR measurements. Out of the seven transformers selected only 1 or 2 needed treatment! This is an example of how water in oil analysis tend to overestimate moisture in solid insulation

B. On-line oil regeneration and drying

In this example a 30+ year distribution transformer was selected for oil regeneration and drying. Transformer and process information:

- 25 MVA manufactured 1972
- 17 days of hot oil circulation with clay filtering (Fuller's earth)
- PF down from 0.4% to 0.3%
- Moisture in cellulose not significantly reduced. 3% before drying and 2.7% after drying
- Degraded oil significantly improved. Conductivity before regeneration 12.0 pS/m and 1.6 pS/m after filtering

DFR measurements before-after treatment is presented in Figure 16.

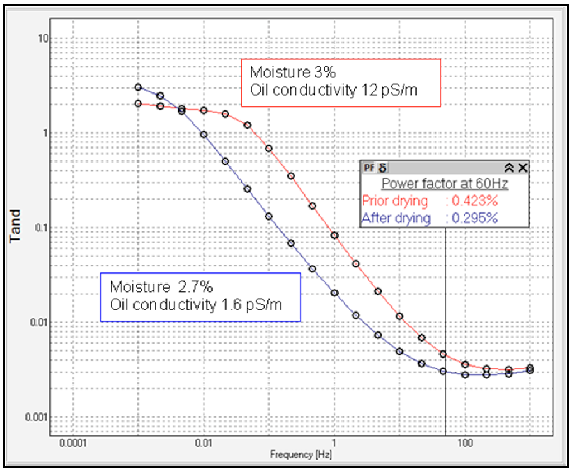

Figure 16. DFR measurements before-after oil regeneration and drying of a 25 MVA transformer [15]

VII. Summary and Conclusions

- Moisture is one of the the worst enemies of the transformer!
  - Limits the loading capability
  - Accelerates the aging process
  - Decreases dielectric strength
- The water/moisture in a transformer resides in the solid insulation, not in the oil
- Dielectric Frequency Response Measurement is a great technique for moisture assessment as it can measure:
  - Moisture content in the cellulose insulation
  - Conductivity/dissipation factor of the insulating oil accurately corrected to 25°C reference temperature
  - Power frequency tan delta/power factor, accurately temperature corrected to 20°C reference temperature
- Drying a power transformer can take from days to years pending drying process and technology

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