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Continuous Monitoring of Power Transformer Solid Insulation Dry-out Process – Application of Dielectric Frequency Response

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Author	D. Robalino, P. Werelius
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Keywords	Oil-paper insulation; moisture; transformer; Dielectric Frequency Response (DFR); Frequency Domain Spectroscopy (FDS); Dry-out; Vacuum.
Abstract	Power and distribution transformers are some of the most important components of the energy system, and the aging of these devices during normal operation is inevitable. From the beginning of the manufacturing process, a strict control over the quality of materials used for the construction and assembly of transformers is implemented. Special attention is given to the solid insulation components in order to minimize exposure to the environment where they might be contaminated. After completion of assembly of the active part of the transformer, the windings and core are subjected to different dry-out processes to dry the solid insulation without affecting the life expectancy parameters defined by the degree of polymerization of the cellulose. Throughout the life of the transformer and due to the normal aging effect, several byproducts will evolve within the insulation system, and field operators will encounter the challenge of re-conditioning the insulation system of the transformer removing as much as possible these aging byproducts on-line or off-line. A variety of methods are available; selecting the right method should be the first decision. The dryout process must later be evaluated, and remaining moisture in the insulating system requires accurate estimation before the transformer is put back on service. In this work, factory and field dry-out processes are continuously monitored using Dielectric Frequency Response (DFR), analysis and validation is carried out comparing results against other available methods. On-line DFR application is demonstrated to optimize the dry-out process, providing valuable information regarding process efficiency.

Email	diego.robalino@megger.com

Spectroscopic dispersion of dielectric permittivity in oil-paper insulation and; thus, its associated energy absorption regions are investigated in the frequency range between $1\bullet10^{4}$ and $1\bullet10^{-4}$ Hz.

The processes of polarization and conduction are evident and are used by many researchers, manufacturers and utility operators to describe the condition of complex insulation systems integrated in critical high voltage (HV) components of the electrical infrastructure [1]. Due to long and positive experience, the combination of mineral oil and pressboard is widely used in transformer manufacturing.

Dielectric Frequency Response (DFR), also known as Frequency Domain Spectroscopy (FDS,) is a powerful tool that can determine the electrical/dielectric properties of solid and liquid materials by means of measuring the complex electrical impedance of the system Z(ω) and; therefore, the complex dielectric permittivity, affected by chemical and physical factors including moisture, temperature and pressure. Complex dielectric permittivity as a function of frequency is defined in [2] as

$$\hat{\varepsilon}(\omega)=\varepsilon'(\omega)-i\varepsilon''(\omega) \qquad (1)$$

Where:
$\omega=2\pi f$ – is the angular frequency,
f – frequency [Hz],
ε' – is the real permittivity, and;
ε'' – is the dielectric loss factor.

From the real and imaginary components of the complex permittivity, dissipation factor can easily be derived [3] as

$$\tan\delta(\omega)=\varepsilon''(\omega)\big/\varepsilon'(\omega) \qquad (2)$$

It is important to notice that most of the development and application of DFR for oil-paper insulation condition assessment had been developed since the early 1990's because new spectrometers have been manufactured allowing faster and more accurate dielectric response along the required wide frequency range. The benefit of using this wide frequency range is, of course, the ability to observe at low frequencies an increasing loss due to charge-conduction and electrode polarization in the material.

The fact that moisture is one of the byproducts generated in transformers as part of the normal cellulose insulation aging is well known. There is no need to emphasize the negative effect that moisture has on the dielectric properties of the insulation system. Many authors worldwide had investigated moisture behavior in insulation material and its effects in power transformers [4]. The amount of moisture in oil is not as great as that present in the solid insulation. Understanding that fact and recognizing the limitations of technical field and factory personnel in estimating moisture concentration in the solid insulation by methods that are merely estimation of moisture concentration by means of indirect testing procedures not capable to determine the "bulk" moisture concentration.

It is paramount to select the most suitable non-destructive and non-invasive method to estimate moisture concentration in solid insulation. Field users and manufacturers of power, distribution and instrument transformers are aware of moisture presence and relay now more and more on the DFR method. As of now, this technique has been applied as an advanced diagnostics tool looking at the insulation condition when high power factor values are encountered.

An extension to the application of DFR in factory and field is discussed herein. Dry-out process is part of the transformers' manufacturing process. In the field, aging transformers are tested and if high moisture concentration is detected, the next rational approach is to decide whether the transformer remains in service or needs to be removed from operation and be subjected to field dry-out process. DFR is shown in this document to be a simple tool to be used for factory quality assurance/quality control (QA/QC) of the dry-out process as well as an effective tool to monitor the dry-out process and its effectiveness in the field.

II. FACTORY DRY-OUT AND APPLICATION OF DFR

A. Factory Dry-out

It is extremely important for manufacturers and end users to have a dry transformer when leaving the factory premises. Regardless of the size or application of the transformer, dry-out of solid insulation is a fundamental and complex part of the manufacturing process. Due to the high number of hydroxyl groups, the cellulose molecule is very hydroscopic and these polar groups attract and bind water molecules.

At the manufacturing stage, the solid insulation is exposed to different ambient conditions which allow the ingress of moisture not only on the surface of the solid insulation but also in the inner layers. In order to properly dry the active part, power transformer manufacturers typically use a controlled steam drying system based on vapor-phase equipment. This known method for drying active parts of large power transformers and reactors units increases speed and efficiency of the treatment, maintaining their durability.

Several techniques are applied in the manufacturing floor to dry-out the active part of a transformer. In most cases, the manufacturer will infer the value of moisture concentration in the solid insulation by means of measurements performed on the liquid or gaseous medium. Without insulating liquid present, the analysis is carried out from the dew point test measuring relative humidity, temperature and pressure of the gas [5]. This is a clear example of inferring moisture content only of the surface insulation.

When the solid insulation is immersed in oil, measurements of relative saturation at the final stage of the temperature rise test procedure are conducted expecting moisture equilibrium between the surface of the solid insulation and the liquid medium surrounding it. Now, the main interest for manufacturers is not only to determine surface moisture concentration but "bulk" moisture concentration. This is the area where dielectric response methods become a better tool for QA/QC control.

B. Factory Dry-out Monitoring with DFR

A very good estimation of moisture concentration has been achieved in vertical ovens where the dry-out process is exclusively thermal. Several units are set in the oven for different times. The time specified to keep the unit inside the oven is mainly established based on average estimation.

For this experimental example, the active part of a distribution type transformer (see Fig. 1) Dyn1, voltage rating 12.5kV – 4160Y/2400 V, 60 Hz, design impedance 5%, 5 MVA, core and coil approximated weight 6000 kg, was tested prior to ingress in the oven. Results are shown in Fig. 2.

Fig. 1 Location of the experimental 5 MVA transformer's active part inside the oven

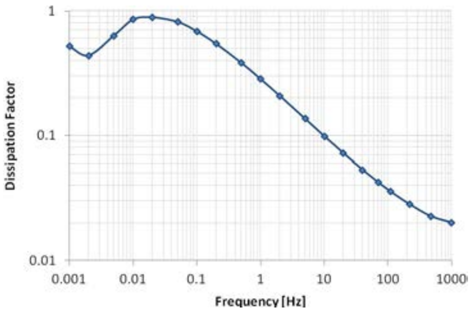

Fig. 2 Dielectric response of the active part of a 5MVA transformer before dry-out process

The dielectric response obtained from the active part of the transformer with the equipment IDAX 300 and analyzed with the software (SW) IDAX 5.0 indicates that the initial condition prior to dry-out is a moisture concentration of 4.6%.

The process now is subjected to thermo dynamical effects where a constant heat energy source is applied on the dielectric material expecting a variation on the dielectric response due to a decrease in moisture concentration. A low voltage sinusoidal signal is applied in intervals while the temperature of the insulation system will increase trying to reach maximum value at approximately 120°C. The variation of the response in the first 12 hours at 2h intervals can be observed in Fig. 3.

In the first 12h interval we can clearly observe the effect of a continuous increase of temperature together with a change of the response in the area of the low frequencies and of course reduction of surface moisture.

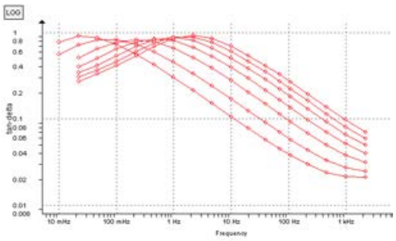

Fig. 3 Dielectric response changes observed during the first 12h interval of the dry-out process

The second 12h interval presented in Fig. 4 is mainly steady, no significant changes of the dielectric response are observed due to a more stable thermal effect and minor variations of moisture concentration in the cellulose. At this interval, the continuous monitoring process shows a close to isothermal process with no significant variation of the losses within the dielectric material. The cellulose material because of its manufacturing process and organic nature is not giving up moisture from the inner layers yet.

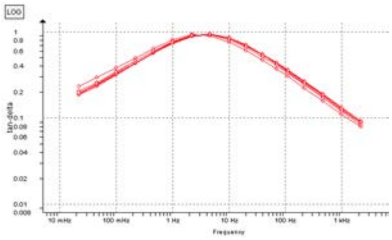

Fig. 4 Dielectric response changes observed during the second 12h interval of the dry-out process

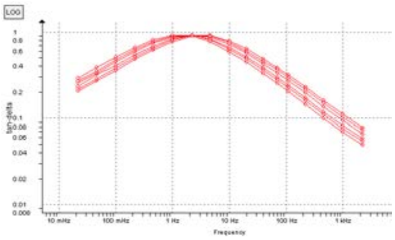

Fig. 5 Dielectric response changes observed during the third 12h interval of the dry-out process The third 12h interval shows in

Fig. 5 slight decrement of the dissipation factor value in the higher frequency band, even under almost constant temperature. At this point it can be observed that the cellulose starts slowly modifying its dielectric response due to minor moisture reduction at almost constant temperature.

The changes of the dielectric response presented in Fig. 6 correspond to the last 18h of the process. It is observed a steady decrease of dissipation factor values in the frequencies above the resonance point (between 300 mHz and 1 Hz). In general the unit was kept in the oven for

54h. The moisture concentration measured at the last reading is <2%. The time decided by the manufacturer to keep the unit in the oven was to be around only 48 hours.

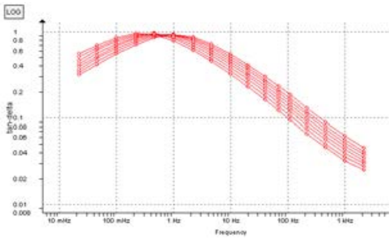

Fig. 6 Dielectric response changes observed during the last 18h interval of the dry-out process

The information provided in these figures must be correlated with a simple chart showing the process thermal profile and the moisture concentration variation as a function of time. This simplified chart is presented in Fig. 7.

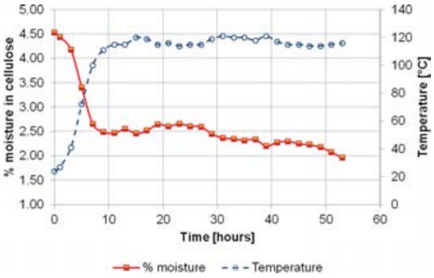

Fig. 7 Temperature of the solid insulation and %moisture concentration recorded as a function of time during the 54h dry-out process.

This is not the end of the overall dry-out process for this experimental unit. After extraction of the active part from the oven, the factory team is ready to tank it, final clamping, adjustments and fixation work, to seal it and apply vacuum for another 12h. This transition time from the oven to the vacuum process allows exposure of the insulation to the ambient and possible re-adsorption of water from the air at the solid insulation surfaces.

III. FIELD DRY-OUT AND APPLICATION OF DFR

A. Field Dry-out

As a matter of fact, there are several mechanisms applicable for field dry-out of power transformers. A simple way to differentiate the efficiency of the mechanism is by understanding the velocity of the process and this is well summarized in is based on the mechanism applied and a reference to this is shown in Fig. 8 as presented in [6].

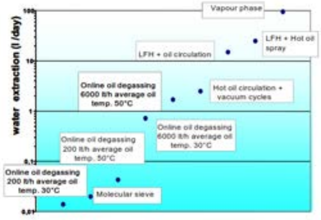

Fig. 8 Field dry-out mechanisms. Drying velocity from 3% down to 1.5% moisture.

From all the processes listed in Fig. 8, once the insulating system of a power or distribution transformer has been declared wet, and then the combination of heat and vacuum is a typical and quite efficient approach used by field operators to minimize the amount of moisture in the cellulose. Nonetheless, this stage has been mistaken many times and people in the field have tried to reduce the moisture in the cellulose by reduction of moisture in the liquid insulation. The problem now is to accurately monitor the process as it is applied on the transformer.

In the field, heat is applied by means of hot oil spray or hot oil recirculation and fast removal. The process also performs filtration, dehydration and degasification of the liquid insulation. A typical setup for an off-line dry-out system including heat and vacuum is presented in Fig. 9.

For hot oil spray method, the oil level can usually be reduced to less than 10% of the total oil volume. Heated oil at temperatures greater than 70°C is pumped into the transformer and the process continue until oil returning to processor at ≥ 50°C. The use of tarps and/or thermal blankets is usually recommended to help retain heat inside the transformer throughout the dry-out process.

If using flooded hot oil circulation, pump the oil out once temperature is achieved and apply vacuum.

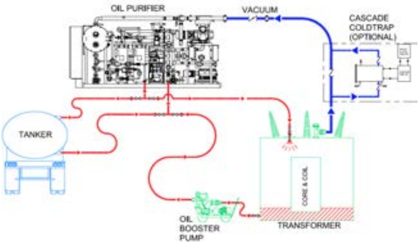

Fig. 9 Typical setup for field off-line dry-out process

B. Field Dry-out monitoring with DFR

The field dry-out process is even more challenging than the process in factory. The reason is due to the unknown aging condition of the solid insulation material. In the field final dry-out may not expect completion of the process with low levels of moisture concentration. Tensile strength of the cellulose decays with aging and some devices may not tolerate prolonged high vacuum processes without severe damage of the insulation.

To illustrate the process, an old 5MVA transformer, nominal voltage 69/12.5kV, Dyn1 was removed from operation due to a high power factor value (0.9% @ 20°C) encountered during a routine testing procedure. The first logical approach was to carry out DFR test on the unit to identify the source of the problem. The dielectric response of this unit is presented in Fig. 10. The DFR analysis confirmed the presence of 3.5% moisture in the cellulose and insulation liquid conductivity value of $1.5 \bullet 10^{-12}$ S/m. The engineering team together with the field operations team decided to take this unit temporarily off-line for dry-out process with heat and vacuum.

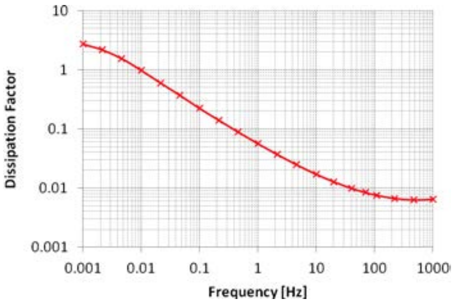

Fig. 10 Dielectric response of a 5MVA transformer in the field with moisture content of 3.5% before dry-out process

The dielectric response measured during the first 24 hours of the field process is presented in Fig. 11.

A fast change of the shape of the dielectric response is clearly observed in the first 6 hours of vacuum process, between t=0h and t=6h, after bringing the temperature up to ~65°C.

Measurements performed at every six-hour intervals resemble the same shape of the response obtained after six hours of vacuum and describe a continuous decay of dissipation factor along the whole dielectric spectrum.

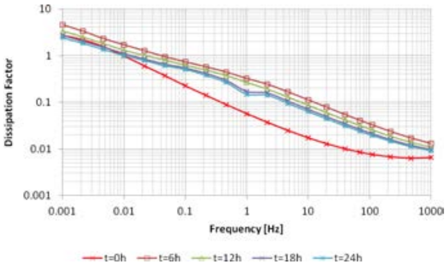

Fig. 11 Dielectric response of the 5MVA transformer put under vacuum dry-out for 24 hours.

The model for vacuum assumes constant conductivity value of $1 \bullet 10^{-17}$ S/m and relative permittivity of the surrounding medium equal to unity.

The first 24 hours show a clear variation of the dielectric response and therefore a clear expected change in the condition of the solid insulation material. Now, looking at the next 30h of the vacuum process in Fig. 12, it is obvious that the process is not being efficient and that there is no improvement in the condition of the solid insulation.

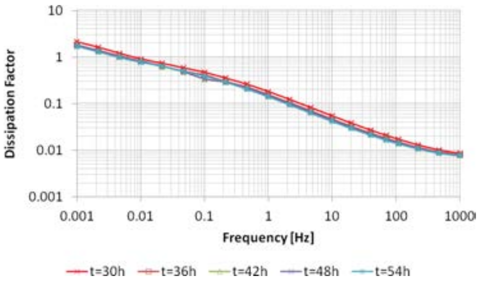

Fig. 12 Dielectric Response of a 5 MVA transformer during vacuum dryout. Interval from 30 to 54h

Once the process is observed to have low or non efficiency, this is a clear indication for the operators to re-heat the core and windings and initiate a new vacuum cycle. The moisture content in this unit was finally left at 2.6%. In order to validate the results, the unit was re-tested after two weeks of operation. The DFR results indicated a total of 2.6% moisture concentration in the cellulose ratifying the readings performed during dry-out and under vacuum.

IV. DISCUSSION AND CONCLUSIONS

It is undeniable that the dielectric response and therefore the complex permittivity (***Ê***) of the cellulose under constant AC electric field is dependable of angular frequency (ω) , temperature (T) and moisture content in the cellulose [7][8].

It has been clearly demonstrated that factory measurements could be carried out providing manufacturers with the advantage of determining the efficiency of the process, the breakout point when the cellulose allows extraction of not only surface moisture but also from inner layers. It is obvious for manufacturers if the unit needs to remain in the process or if it can be moved to a next stage in the system.

The application of DFR technique in the field to estimate the percentage moisture concentration in cellulose during dry-out process is relevant. It has demonstrated to show the point where the process reduces efficiency and slows down the moisture extraction. This alone, gives the operator guidelines to improve the process, continue as is or stop the process declaring completion of the dry-out process.

The surface of cellulose insulation is not a good indicator for the moisture inside the solid insulation. Ideally, side samples should be taken and tested by Karl Fisher titration. Although this is not feasible for all manufacturers and very time consuming if it has to be sent to a laboratory. Moreover, the manufacturer has to wait for results and is not able to take immediate decisions during the dry-out process itself. Therefore, laboratory analysis is not practical.

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