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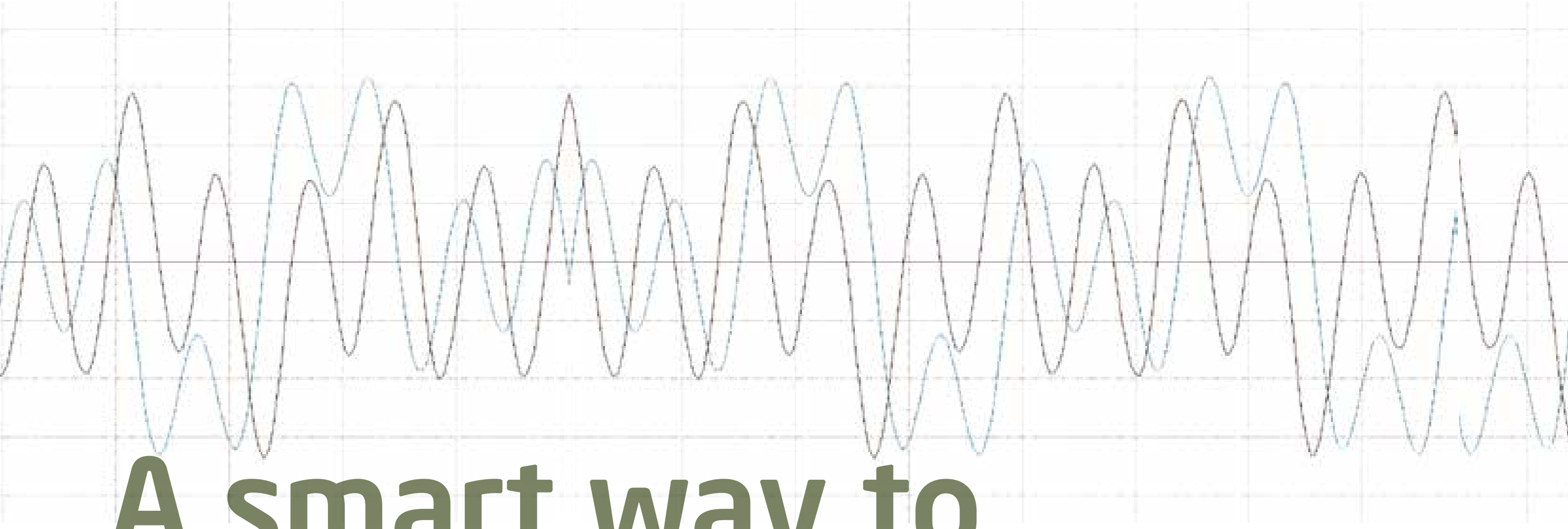

A smart way to minimize test time for transformer dielectric measurements

ABSTRACT

Dielectric response measurements for the moisture and oil conductivity assessment of transformers are well understood, internationally accepted and growing in use. Of the two principal dielectric response methods, an AC method called Dielectric Frequency Response (DFR, also Frequency-Domain Spectroscopy, FDS) is preferred due to its robustness against noise. The time requirement of a DFR measurement is lengthy compared to that of other electrical test methods. An earlier approach to accelerate test time combined DC (time domain) and AC (frequency domain) test methods. This article discusses the limitations inherent to that approach and presents today's multi-frequency test solution that minimizes test time for DFR measurements without compromising accuracy.

KEYWORDS

measurement time, Frequency-Domain Spectroscopy (FDS), Polarization-Depolarization Current (PDC), Dielectric Frequency Response (DFR), moisture in transformers

Introduction

The dangers of water in insulation systems are well known and fuel the need and desire to know the moisture content in power apparatus, such as transformers.

To this end, there are a variety of methods to estimate moisture contamination. Today there is greater general understanding of the advantages of (and a subsequent growing use of) dielectric response measurements, such as FDS and PDC, over the use of conventional methods, such as the application of equilibrium curves to the measured moisture content in an oil sample, to determine the moisture contamination of cellulosic insulation.

The primary challenge with dielectric response methods is to discriminate between the agents (moisture, temperature, oil conductivity, insulation construction, and conductive aging byproducts) that affect the response so that the resultant moisture estimation is reliable. A first step towards accomplishing this is to obtain the dielectric response of a system across a reasonable (large enough) frequency range, which is ideally defined differently and practically, depending on the asset and test conditions.

The measurement time to obtain such a response (and the subject of this article) can easily surprise when compared to other electrical field tests, and has influenced past approaches towards executing Dielectric Frequency Response (DFR) measurements. While one noted approach, which combines AC and DC test methods, achieves its objective of reducing test length, it is

”Dangers of water in insulation systems, such as accelerated aging, a decrease in breakdown strength and bubbling, fuel the need to know the moisture content in transformers

not a universal solution. A primary limitation (Table 1) is the combined method's sensitivity to electromagnetic interference that is present in varying degrees in most substations. While the combined approach had yielded an improvement over the time requirements of a traditional FDS measurement (Table 3), now, by using a multi-frequency technique for measuring the lowest frequencies, the preferred FDS method is a better choice.

> In an old or severely deteriorated transformer, the moisture content in paper can be greater than 4 %, but there are no practical ways to directly measure it; instead, indirect measuring methods are utilized

Moisture assessment and dielectric response analysis

Moisture accelerates aging of cellulose, decreases dielectric breakdown strength, and can fail a transformer at high temperatures by causing bubbles to form from the evaporation of the water inside the cellulose. Moisture detection is important to asset managers who, driven by cost pressures, are tasked with extending the life of expensive assets such as transformers and with shifting maintenance from time-based to condition-based strategies. Moisture detection also carries implications for system operators who may otherwise unwittingly cause a transformer winding failure through emergency switching and loading if these activities result in an increase in temperature that exceeds a wet transformer's bubble inception temperature.

During manufacture, the cellulose insulation in the transformer is carefully dried out before it is impregnated with oil. The moisture content in the solid insulation of a new transformer is typically targeted to be less than 0.5 % by weight. As the transformer gets older, the moisture content will typically increase around 0.05 % per year for a sealed conservator transformer and by approximately 0.2 % per year for free-breathing transformers. In an old and/or severely deteriorated transformer, the moisture content can be greater than 4 %. The aging process of the insulation is directly related to moisture content. The recommended approximate percent by weight of water in solid insulation according to IEEE C57.106-2002 depends on the transformer voltage class as follows:

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

The sources for moisture contamination teach that you do not have to live in a wet area to have a wet transformer and include:

- moisture ingress from the atmosphere via leaks or inadequate breathing devices
- insulation surface moisture introduced during assembly/commissioning and/or maintenance
- residual moisture from insufficient drying during the manufacturing process, and
- moisture generated from the ageing of cellulose and oil

There are no practical ways to directly measure moisture in transformer paper insulation so most available tools utilize indirect measuring methods, whereby properties of insulation that can be related to moisture content are measured. Of these indirect methods, the ones that have been traditionally applied in the industry to assess water contamination of the paper insulation (e.g. moisture in oil measurements and use of equilibrium charts) only provide accurate assessments if moisture equilibrium has been achieved. During the normal operation of a transformer, wherein the temperature inside the transformer varies throughout the day, moisture equilibrium between paper and oil will rarely be attained since the time constants of thermal and moisture dynamic processes are very different [1]. In extreme cases (e.g. a shipping damaged transformer seal), the resulting moisture ingress may be notably far from a state of equilibrium in the transformer during ensuing tests, resulting in a very inaccurate assessment of water in paper by traditional measurements [2].

In large part due to the inaccuracies associated with most other methods, dielectric response methods have emerged as attractive alternatives. These electrical test methods (based on models) are non-intrusive, very reliable tests with high repeatability. There is no need to wait for equilibrium, no inaccuracies due to the sampling and handling of oil, and they can be performed as part of the suite of electrical tests planned during a maintenance outage. This carries the advantage that the

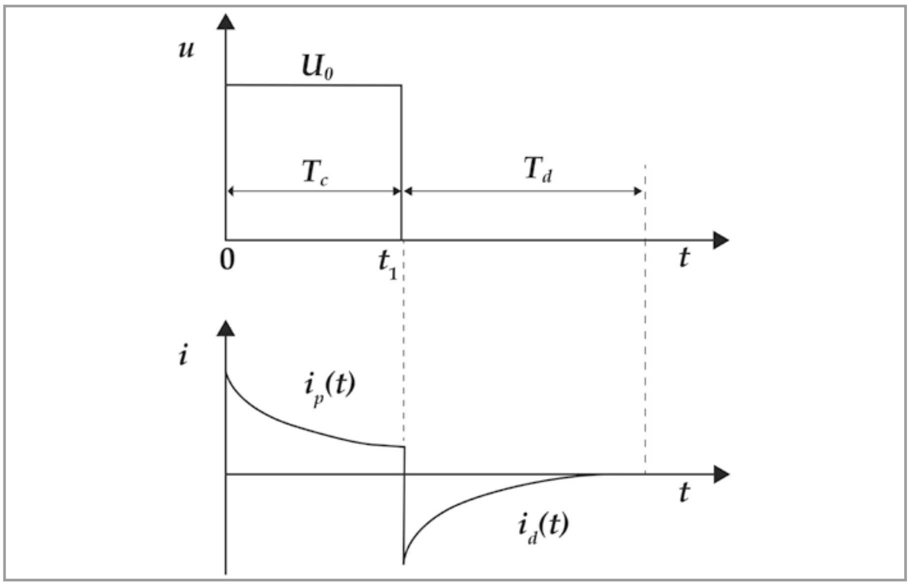

Figure 1: Polarization and Depolarization Current (PDC) response

results are immediate upon completion of the test. Dielectric response testing is typically performed on the interwinding insulation system(s) of a transformer since this is the area where most of the solid insulation is located and, therefore, where most of the water will be found. In the case of power transformers constructed with an interwinding shield, measurements must instead be performed on the winding to ground insulation.

Dielectric response methods

The dielectric response of an insulation system can be measured and represented either in the time domain or the frequency domain.

Polarization – Depolarization Current (PDC)

The measurement performed in the time domain is called the polarization and depolarization current (PDC) method. Here a step DC voltage is applied to a fully discharged transformer and the polarization current (pA) is measured and recorded over time. The insulation system is then shorted and the depolarization current is measured (Fig. 1). These measured charging and discharging currents are compared against laboratory models for interpretation. The results can be transformed from the time domain into the frequency domain if desired for comparison to FDS results, and vice versa. Transformation to the frequency domain is performed, for example, when the PDC method is combined with the FDS method. In such cases, only the polarization current (hereafter referred to as PDC) is measured to acquire very low frequency information while FDS measurements are performed to acquire high frequency dielectric characteristics.

Dielectric Frequency Response (DFR) or Frequency Domain Spectroscopy (FDS)

A Dielectric Frequency Response test (DFR, also known as Frequency-Domain Spectroscopy, FDS) records the electrical response of an insulation subjected to an AC voltage at successive frequencies that range, as a practical example, from 1 kHz to 1 mHz, which is suitable for most transformers. The tan delta or power factor (and the complex capacitance) is calculated and plotted against frequency.

A typical dissipation factor/power factor plotted versus frequency is given in Fig. 2. Moisture influences the low and high frequency areas. The linear, middle section of the curve reflects oil conductivity. Insulation geometry conditions determine the "knee points", which are located to the left and right side of the steep gradient.

As temperature or moisture increases, the dielectric response curve shifts to the right. Conductive aging byproducts, such as acids, will also cause the curve to shift right. In the end, as either high levels of water or high levels of acids in a transformer are a problem, discriminating between the two is principally useful to optimize the ensuing corrective maintenance activity. The influence of temperature, on the other hand, needs to be accounted for and hence is the most important input value that the tester must provide.

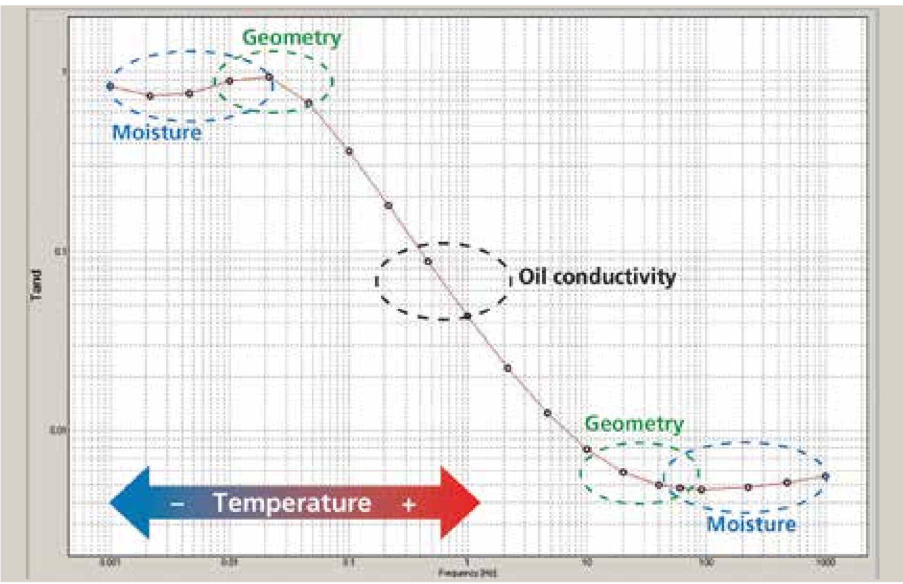

Figure 2: Typical shaped dielectric response curve [3]

Moisture determination is based on a comparison of the transformer's measured response to a modeled dielectric response. The insulation model is the internationally recognized X-Y model described in guides such as CIGRE TB 254 and 414 [3]. Compensation for aging byproducts in order to improve the accuracy of the moisture estimation in a moderately to severely aged transformer is approached differently between manufacturers with debate about the validity of the approaches. For the user, a very wet transformer or a very aged unit poses risk and warrants action. When a lengthy drying of the transformer seems eminent, a supplemental extended oil analysis that includes assessing the content of low molecular weight acids (LMWA) is a pragmatic and relatively unimposing recommended step.

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> Moisture determination is based on a comparison of the transformer's measured response to a modeled dielectric response

Advantages and disadvantages of each method

Under ideal conditions, the results of PDC and FDS methods are comparable. Their advantages and disadvantages, therefore, are of particular interest.

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As given in Table 1, the single advantage of the PDC method over the FDS method is its shorter measurement times for very low frequencies. In fact, the longer measurement time at low frequencies is the only shortcoming of a conventional FDS measurement. For example, it takes nearly 17 minutes to complete one sinusoidal cycle at 1.0 mHz. Since more than one full cycle is required to obtain a data point, measuring times at low frequencies, where several data points are of interest, start to add up. Measurements in the very low frequencies are important because this is one of the regions where moisture content is clearly indicated.

There are several disadvantages of the PDC method including, most notably, the measurement's susceptibility to power system interference. This time-based method also carries the disadvantage of a limited frequency range as measurements do not contain any information at higher frequencies due to the finite rise time of the DC pulses. For certainty in the PDC measurement, discharge may be needed first as the transformer must be fully discharged before application of a DC pulse, and finally, if to be used in the combined PDC plus FDS method, conversion of the PDC data is necessary.

These shortcomings (of the PDC method) highlight the strengths of the FDS method, which include robustness against noise, a wide frequency range, no data conversion, and no discharge necessary.

Interference

The time domain method with applied DC voltage (PDC) is particularly vulnerable to electromagnetic interference because very small currents are measured. It is not possible, for example, to separate a leakage current (high loss insulation) from an interference DC current and the resulting DFR response will have significant errors at low frequencies. Low AC interference in levels of micro-Ampere and DC interference in nano-Ampere can affect a PDC measurement.

AC and DC interference is common in a substation environment. Examples include transients and corona, high frequency switching noise (as in an HVDC station), induced AC at line frequency (50/60 Hz) plus harmonics, low frequency interference caused by slowly varying DC current, and induced DC, such as corona discharge.

In an effort to illustrate characteristic magnitudes of interference that may exist in a substation environment, AC and DC interference levels were recorded from 100 and 12 randomly selected measurements, respectively, and plotted in Fig. 3 [4].

Table 2 summarizes statistical characteristics of this data. The median value of AC interference at line frequency (i.e., the "middle" value of the 100 results above) is 0.24 micro-Ampere. Considering the micro-Ampere senstivity of a polarization current measurement, the ninety percentile and maximum values of AC interference are particularly significant at 166 and 1600 micro-Ampere, respectively.

Table 1. Advantages and disadvantages of PDC versus FDS dielectric response methods

	ADVANTAGES	DISADVANTAGES
Time domain (Polarization-Depolarization Current, **PDC**, measurements)	▪ Shorter measurement time for very low frequencies	▪ More sensitive to AC interference (micro-amperes) ▪ More sensitive to DC interference (nano-amperes) ▪ Limited frequency range (PDC only) ▪ Discharge before measurement may be needed ▪ Data conversion necessary (combined PDC + FDS method only)
Frequency domain (Dielectric frequency response, **DFR**, also Frequency Domain Spectroscopy, **FDS**)	▪ Less sensitive to AC interference (milli-amperes) ▪ Less sensitive to DC interference (micro-amperes) ▪ Wide frequency range ▪ No discharge necessary ▪ No data conversion	▪ Longer measurement time for low frequencies

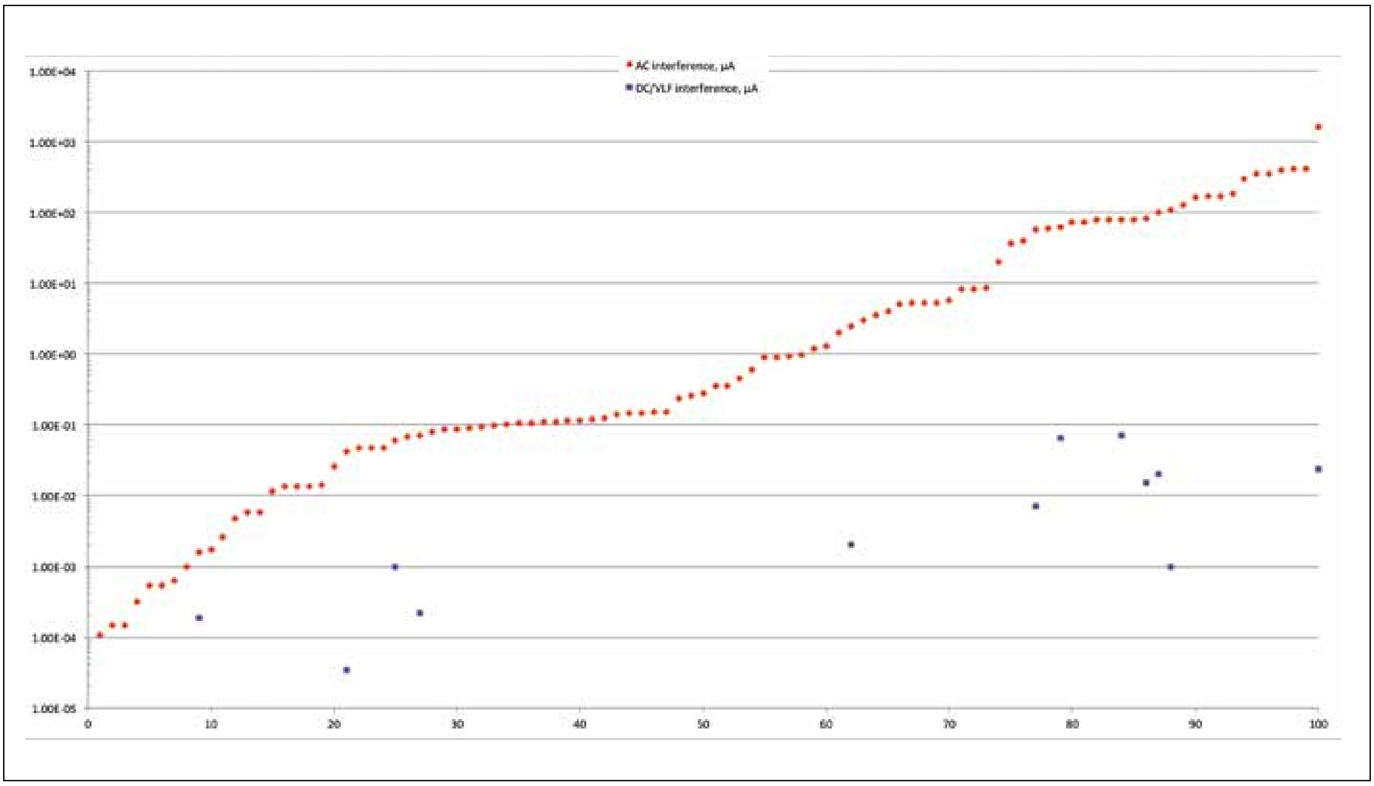
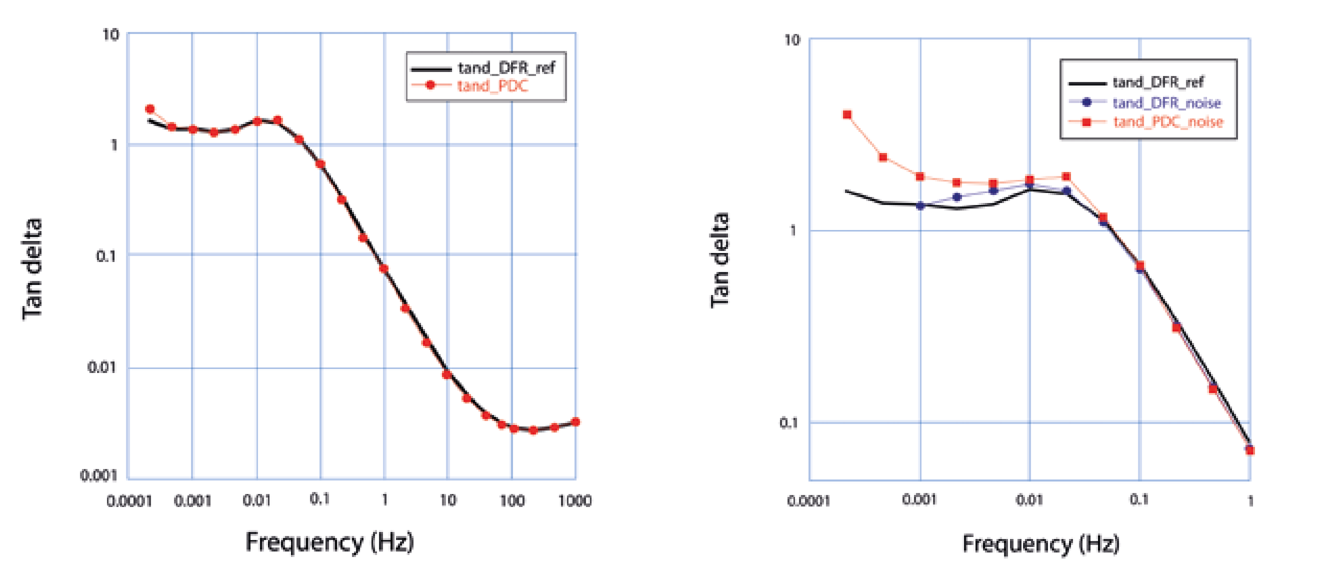


Figure 3. Levels of interference recorded from randomly selected measurements

To illustrate the effect(s) of interference on a polarization current measurement, through a Fourier transformation into frequency domain, compared to that on an FDS measurement, dielectric response measurements were performed in an environment with undetectable interference (Fig. 4a) and then repeated

Table 2. Statistical characteristics of data in Fig. 3

Type of interference	50 % median value	90 % percentile	Max value
Power frequency AC	0.24 µA	166 µA	1600 µA
DC	4.5 nA	62 nA	70 nA



(a) no interference

(b) 10.0 nA DC interference

Figure 4. Sensitivity of the PDC method to low level interference [4]

Accelerating the measurement time is nowadays possible with pure FDS method by using a multi-frequency test signal at low frequencies

in the presence of 10.0 nano-Ampere DC interference (Fig. 4b). With DC interference, the dielectric characteristics measured using a polarization current method change, resulting in a modeling error of 0.5 % using the PDC method. The measurements in the FDS method are practically unaffected.

Accelerating the measurement time of a DFR test

The single weakness of the FDS method is its measurement time at very low frequencies, for example, less than 1 Hz. Historically, dielectric response measurement times using a pure FDS test approach may have been several hours or more, for example, depending on the condition of the asset being tested and the temperature.

Consequently, in earlier attempts to accelerate measurement time, and despite the shortcomings of the PDC method, a test approach was developed that combines DC (time domain via a polarization current measurement) and AC (frequency domain, FDS) methods. This PDC plus FDS approach uses the measurement of polarization current in the low frequency range (e.g. 1.0 Hz – 0.1 mHz) and transforms these results into the frequency domain, and uses FDS for the higher frequency measurements (e.g. 1.0 kHz – 1.0 Hz), which are done rather quickly.

In ideal test conditions, the PDC plus FDS test approach achieves its objective of minimizing test time without compromising the moisture assessment. However, if interference is present in the testing environment, the results may be skewed, and ensuing efforts to investigate and perhaps repeat the measurement in pure FDS may consume any time savings. If using this method, one should be prepared to quantify interference present during the measurement for assurances of the test's accuracy.

In order to accelerate measurement time in all test conditions with best accuracy, today's approach accesses the advantages of a pure FDS method by using a multi-frequency test signal at low frequencies. The conventional FDS approach entails use of a single frequency test signal per measurement with each successive and lower frequency measurement taking progressively increasing time. This new, multi-frequency test solution reduces the cumulative measurement time by measuring multiple sinusoidal oscillations simultaneously and using Discrete Fourier transformation to separate the individual oscillations in the frequency domain. It is important to choose the correct frequencies to ensure they are orthogonal to eliminate influence from the neighboring frequencies [5]. The time savings of multi-frequency FDS is similar to the combined method but eliminates the concerns of interference affecting accuracy. Table 3 provides a comparison of measurement times using different dielectric response test approaches.

Conclusion

Efficient and reliable moisture assessment of power assets is of great interest to many in the power industry. Dielectric response tests have gained international acceptance as a standard method for moisture assessment. The two principal dielectric response methods are Dielectric Frequency Response (DFR, or also Frequency Domain Spectroscopy, FDS) and the Polarization-Depolarization Current (PDC) methods. Both methods, FDS and PDC, have advantage(s) and disadvantage(s) but FDS is the preferred choice for onsite measurements due to its robustness against noise.

The single and notable disadvantage of an FDS measurement is its cumulative measurement time at low frequencies, where moisture information is significant. A past approach to accelerate test time was to combine PDC and FDS methods, whereby a polarization current measurement was used to obtain low frequency measurements and FDS was used for higher frequency measurements.

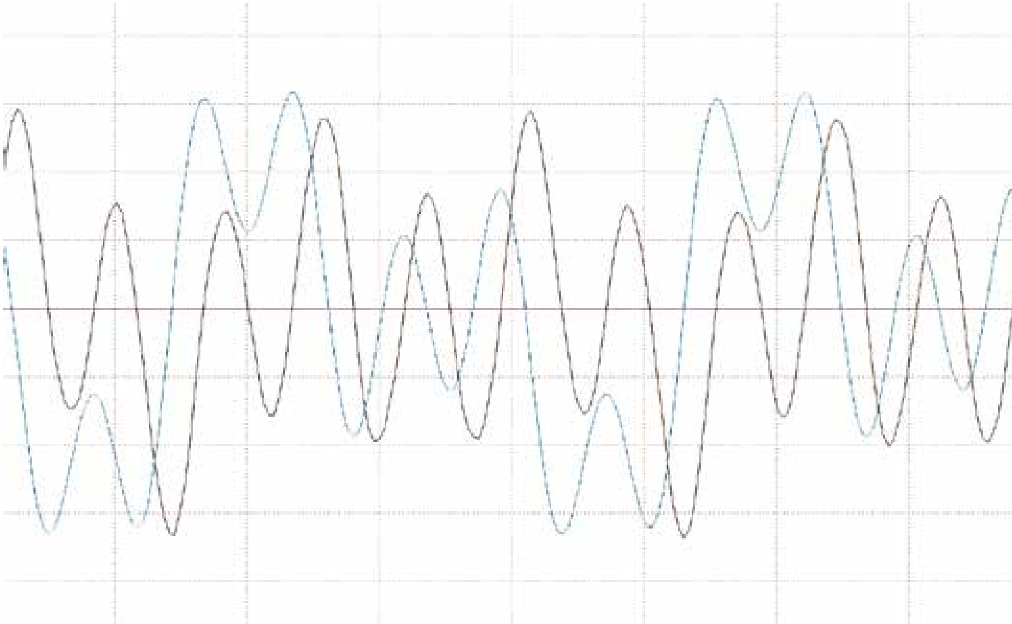
Both methods, FDS and PDC, have advantage(s) and disadvantage(s) but FDS is the preferred choice for onsite measurements due to its robustness against noise

Table 3. Comparison of measurement times using different dielectric response test approaches

Method	Frequency range			
	1 kHz - 1 mHz	1 kHz - 0.5 mHz	1 kHz - 0.2 mHz	1 kHz - 0.1 mHz
Multi-frequency FDS	22 m	43 m	1h44	3h25
FDS	51 m	1h25	4h08	5h31
FDS+"PDC"	24 m	40 m	1h30	2h54

The problem with this combined test approach is related to the PDC method's primary weakness, that is, its susceptibility to interference. AC interference in the micro-Ampere range and DC interference in the nano-Ampere range may skew polarization current test results necessitating the quantification of interference levels in the substation to guarantee the accuracy of the measurement. Keeping to a pure AC measurement (i.e. FDS) is a major advantage when performing dielectric response tests in a substation environment with AC and DC interference. Also, a pure FDS approach eliminates concerns associated with a polarization current measurement regarding discharging the test object between tests.

Today's approach for accelerating DFR test time is to use a test signal at low frequencies that contains a combination of frequencies. This new multi-frequency FDS test method significantly reduces the measurement time in the low frequency range and consequently the total measurement time. It is also best suited to provide reliable moisture assessments in a test environment with interference.



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In 2007 he returned to the power industry business as Marketing and Sales Manager for Pax Diagnostics, specializing in test systems for SFRA (Sweep Frequency Response Analysis) and FDS/DFR (Frequency Domain Spectroscopy/Dielectric Frequency Response Measurements) in transformers, generators and cables. In October 2008 Pax Diagnostics was acquired by Megger and Matz is now working as Director – Transformer Test Systems.
Matz Ohlen has presented/written a number of papers/articles on Measurement Techniques, Signal Analysis and Test and Maintenance of Power System Components for international conferences/publications. He is member of IEEE and holds several patents within the field of transformer testing.