A novel approach to DFR measurement speed and fidelity

An introduction to DFR

DFR (Dielectric Frequency Response), also known as FDS (Frequency Domain Spectroscopy), is a measurement technique in which capacitance and losses (dissipation factor/tan delta or power factor) are measured over multiple frequencies to assess insulation condition in test objects, such as power transformers, bushings, and current transformers (CTs). DFR technology is a long-established test procedure in laboratories that, in an innovative effort by Megger, was adapted for field use through the IDAX range of instruments.

In power transformers, bushings, and CTs, issues are often not visible under ‘convenient’ test conditions, such as at ambient temperature and when using line frequency test sources. Rather, problems are magnified at higher temperatures or closer to the operational limits of the objects. DFR measurements, comprised of many individual tan delta or power factor measurements, are primarily a function of insulation system geometry, aging by-products, moisture, liquid insulation conductivity, frequency, and temperature. Using knowledge about the relationship between the different factors, measured data can be matched to a reference model of the test object, and factors such as moisture content in solid and liquid insulation, oil conductivity, and tan delta (power factor) can be assessed. The IDAX incorporates reference models for several test objects and insulation systems, ranging from dual material model power transformers to single material model bushings.

In the calculations, ITC (Individual Temperature Correction) - another important Megger innovation - is used to determine DFR results at a desired reference temperature based upon the DFR test data measured at the test object temperature. The IDAX software incorporates ITC corrected frequency sweeps specifically designed for the assessment of power transformers, as well as bushings and instrument transformers. The IDAX DFR method is now part of international guides and standards, e.g., Cigre TB 254, Cigre TB 414, Cigre TB 445, Cigre TB 775, IEEE C57.152-2013, and IEEE C57.161-2018.

Traditional approach

Traditionally, DFR has been performed by applying a pure sinusoidal AC voltage of several discreet frequencies, one at a time, then measuring the AC response and calculating the tan delta value (power factor) and capacitance for each frequency. The network frequency is generally avoided to eliminate interference.

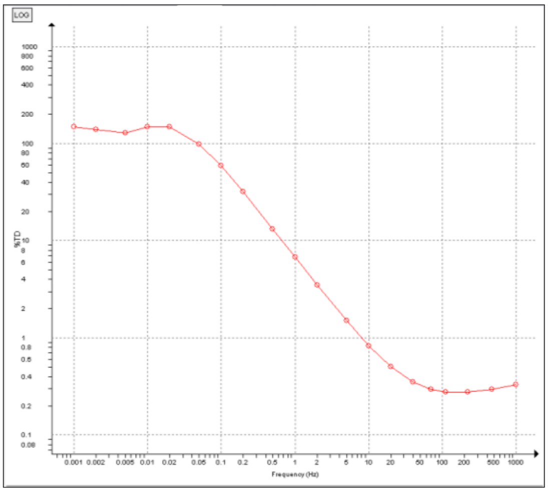

Figure 1: DFR frequency sweep of a transformer, 20 data points collected from 1000 Hz to 1 mHz

This technique is the simplest to use and to integrate, but the drawback is the time needed for a complete set of measurements, especially if the test object condition requires use of the very lowest frequencies. At least a full sinusoidal cycle is needed for measurement at each frequency. The IDAX also adds some time for initialisation and stabilisation for each measurement frequency, so the times needed for a full cycle at each frequency, and in total, are:

Frequency	**Time, one cycle [h:min:s]**	**IDAX total test time [h:min:s]**
1 Hz	0:00:01	0:1:16
0.1 Hz	0:00:10	0:1:49
10 mHz	0:01:40	0:4:56
5 mHz	0:03:20	0:8:36
2 mHz	0:08:20	0:17:46
1 mHz	0:16:40	0:36:06
0.5 mHz	0:33:20	1:12:46
0.2 mHz	1:23:20	2:44:26
0.1 mHz	2:46:40	5:47:46
50 µHz	5:33:20	11:40:00*
20 µHz	13:53:20	29:10:00*
10 µHz	27:46:40	58:20:00*

Table 1: DFR test times, traditional approach.

The frequencies in the µHz range (marked *) are approximations as this option is not used due to the sheer impracticality of performing a measurement that lasts hours on end.

Measurements at frequencies higher than 1 Hz are, of course, also made. A typical sweep is from 1 kHz down to 1 mHz; however, the addition of the higher frequencies to the test time is negligible and has been left out from the table.

Stop frequency

The most important aspect of completing a DFR measurement in as short a test time as possible is to select a proper stop frequency. The typical DFR curve for a power transformer is affected by parameters such as moisture, oil conductivity, and temperature, as shown in Figure 2.

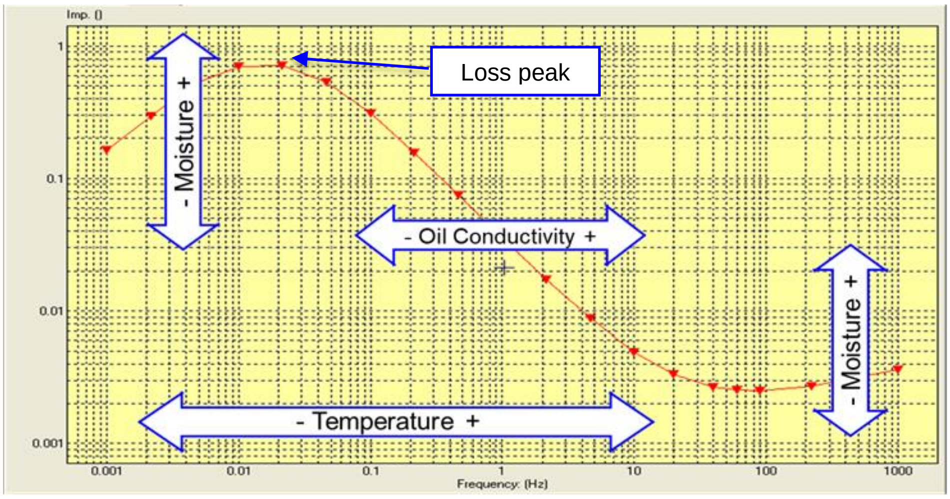

Figure 2: Effect of moisture, oil conductivity, and temperature in a DFR measurement

Ideally, for power transformers, DFR testing should be performed across a frequency span wide enough so that the loss peak in the lower frequency region is identified and that a few samples with losses lower than that peak are captured in the lowest frequencies. As can be seen in the graph, a higher temperature shifts the DFR curve to the right, effectively meaning that the peak moves to higher frequencies. This means that there is redundant data in the lowest frequency points, and these can be skipped. In IDAX 5.3, the recommended stop frequencies for two material test objects, such as power transformers, are:

Temperature [˚C]	**Stop frequency [Hz]**	**IDAX total test time [h:min:s]**
<20	0.5 mHz	1:12:46
≥20	1 mHz	0:36:06

Table 2: IDAX stop frequqncies and test times.

For instrument transformers, most errors can be detected using a frequency range of 1 kHz to 1 Hz (1 min 16 s), but to minimise the effect of interference and other disturbances, it is recommended to spend marginally more time on the actual measurement and use a frequency range of 1 kHz to 10 mHz (4 min and 56 s). Subsequently, the default stop frequency in the IDAX 5.3 for single material test objects is 10 mHz. Use of a higher measurement voltage, as provided by the VAX020 or the IDAX322 (2 kV peak) is also recommended to increase the signal-to-noise ratio.

Multi-tone measurements

To reduce the time needed for a full DFR sweep at the lowest frequencies, Megger in 2012, with the IDAX 5.0, released the multi-tone concept in which an AC voltage of three frequencies is applied simultaneously to the test object. The frequencies used are a base frequency (f0), two times the base frequency (2 × f0), and five times the base frequency (5 × f0). Since the frequencies used are orthogonal and in a linear system, the separate frequencies can be resolved in the input end of the IDAX by use of signal processing.

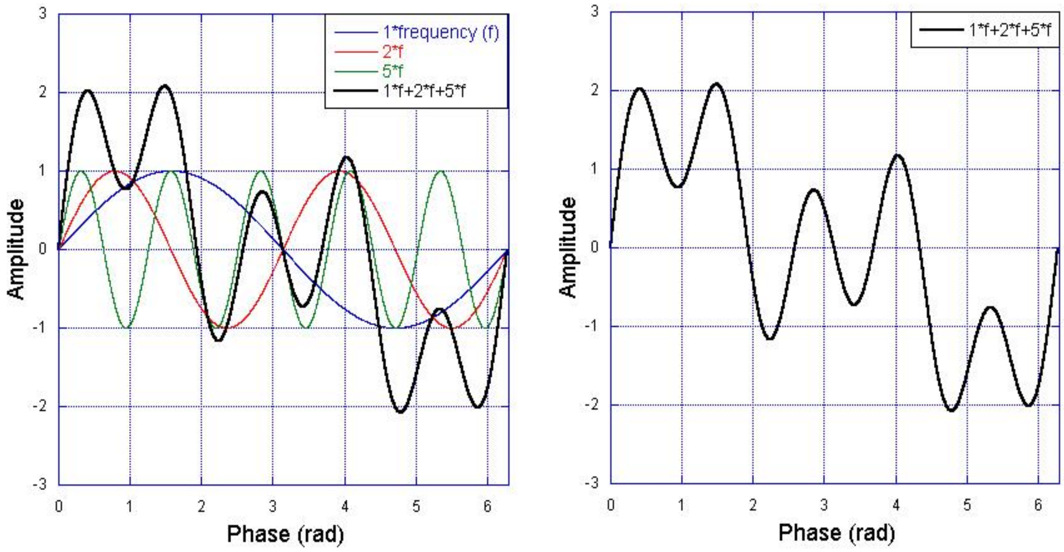

Figure 3: IDAX multi-tone output signal

In practice, the IDAX multi-tone measurements means that for measured frequencies, the 2x and 5x frequencies can be skipped as they are measured simultaneously with the base frequency. Table 1 then can be modified as below, showing significant time savings:

Frequency	Time, one cycle [h:min:s]	Total time, traditional approach [h:min:s]	Total time, multi tone [h:min:s]
1 Hz	0:00:01	0:1:16	0:1:16
0.1 Hz	0:00:10	0:1:49	0:1:49
10 mHz	0:01:40	0:4:56	0:4:56
~~5 mHz~~	0:00:00	0:8:36	0:5:51
~~2 mHz~~	0:00:00	0:17:46	0:12:16
1 mHz	0:16:40	0:36:06	0:23:16
~~0.5 mHz~~	0:00:00	1:12:46	0:42:31
~~0.2 mHz~~	0:00:00	2:44:26	1:43:56
0.1 mHz	2:46:40	5:47:46	3:26:36

Table 3: Time savings by IDAX multi tone measurements.

The IDAX multi-tone measurements are the fastest and most accurate way to measure DFR in any asset without the use of approximations in time to frequency domain transformations.

DFR combined with PDC

In some cases, it may be desirable to measure DFR at an even lower stop frequency than what is practical with the traditional or multi-tone approach. This may be due to the type of test object, inconclusive or hard to interpret data from a normal DFR sweep (for instance, in moderately aged power transformers, 2 - 3 % moisture where the loss peak in the DFR curve is not identified), or simply due to personal preference.

To address this need, a method of combining data (DFR) from the frequency domain (acquired by applying discreet, sinusoidal frequencies) and the time domain (PDC, by sampling a signal over time) has been introduced into the marketplace.

The base of the measurement is still the frequency domain data but by measuring the lowest frequencies, down to 0.1 µHz, in the time domain, a full frequency sweep equivalent can be completed in a much shorter time than if only discreet frequencies had been used.

The time domain data is Fourier transformed (i.e., the frequency content is calculated) and fitted to the frequency data and reference model so that moisture content or other values can be calculated. In this process, however, it is necessary to apply approximations and predictions as a Fourier transform, by definition, is done from zero to an infinite frequency and that amount of data simply is not available in a limited time.

Despite being a time saving measurement technique, the use of DFR in combination with PDC thus has the built-in risk of introducing measurement artifacts due to the approximations and predictions used. The artifacts are, in most cases, obvious, but in some cases, they may be hard to discern from actual problems spotted in the test object and there is a significant risk that the time saved by using DFR with PDC is consumed in full by other, more difficult troubleshooting. In the worst case, incorrect conclusions may be drawn regarding the status of the test object, which can become very costly.

Dual domain modelling

To overcome the drawbacks of the existing combination of DFR and PDC data, Megger, in the IDAX 5.3, has introduced a novel approach of achieving measurements at lower stop frequencies in acceptable test times.

Instead of transforming limited measurement data from the time to frequency domains, as the currently marketed method does, this new method utilises dual reference models for data matching; one in the frequency domain (as previously used by the IDAX) and another one in the time domain. The new time domain reference model has been achieved by Fourier transformation of the frequency domain model and, since the model spans nearly the entire frequency range from zero to infinity, the risk of introducing artifacts is minimised.

Measurement data can thus be fitted to two models; frequency domain data is matched against the frequency domain model, and time domain data against the time domain model. The resulting data is plotted in a range equivalent to the combined frequency range.

This means that, in combination with the previously introduced multi-tone technology, Megger now offers the fastest and most accurate method for DFR and PDC measurements for all test objects. Measurement times for the lowest frequencies are:

Frequency	**Time, one cycle [h:min:s]**	**IDAX total test time, traditional approach [h:min:s]**	**IDAX total test time, dual domain modelling [h:min:s]**
0.5 mHz	0:33:20	1:12:46	
0.2 mHz	1:23:20	2:44:26	
0.1 mHz	2:46:40	5:47:46	0:18:58 (1000 s)
50 µHz	5:33:20	11:40:00*	0:35:57 (2000 s)
20 µHz	13:53:20	29:10:00*	1:26:52 (5000 s)
10 µHz	27:46:40	58:20:00*	2:51:45 (10 000 s)

Table 4: Time savings by IDAX dual domain modelling. * Estimated times

Discussion

The IDAX now provides methods and algorithms for the fastest and most accurate results both for frequency and time domain measurements. Which method to use is ultimately up to the user, but the IDAX will support them all.

The selection of a proper stop frequency remains very important as the collection of data at lower frequencies than required by the temperature conditions is both time consuming and unnecessary.