Using DFR to determine dissipation factor temperature dependence

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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 optimise the use of the power network.

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), was introduced more than a decade ago and has been thoroughly evaluated in a number of research projects and field tests with good results. DFR data in combination with mathematical modelling of the oil-paper insulation is proven as an excellent tool for moisture assessment. Since the modelling theory contains influence of temperature, DFR and modelling can be used to calculate the temperature dependence of the insulation system.

The condition of the insulation is an essential component of the operational reliability of electrical power transformers, generators, cables and other high voltage equipment. Transformers with high moisture content cannot sustain higher loads without risk. Bushings and cables with high dissipation factor at high temperature can explode due to “thermal runaway”. 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 or cable means substantial cost savings.

Traditional dissipation factor measurements

The most common insulation diagnostic test involves measuring capacitance and power factor at 50/60 Hz. Most tests are done at 10 kV (or sometimes lower, depending on the voltage rating of the component), and at operating temperature, but there are also tests with variable voltage (tip-up/step-up testing) as well as tests where power factor versus temperature is measured. Analysis is based on (historical) statistics and comparison with factory values. Since insulation properties depend on temperature, temperature compensation has to be used for measurements not performed at 20°C. This is normally achieved by using temperature correction table values for certain classes of devices [1].

In IEEE 62-1995, typical power factor measurement values for transformers and bushings are categorised.

Typical power factor temperature corrections are shown in Fig. 1. It is obvious that the given values are approximate guidelines only. IEEE 62-1995 states: “The power factors recorded for routine overall tests on older apparatus provide information on the general condition of the ground and inter-winding insulation of transformers and reactors. They also provide a valuable index of dryness, and are helpful in detecting undesirable operating conditions and failure hazards resulting from moisture, carbonisation of insulation, defective bushings, contamination of oil by dissolved materials or conducting particles, improperly grounded or ungrounded cores, etc. While the power factors for older transformers will also be <0,5% (20°C), power factors between 0,5% and 1,0% (20°C) may be acceptable; however, power factors >1,0% (20°C) should be investigated.”

Dielectric frequency response measurements

The first field instrument for DFR measurements was introduced 1995 [2]. Since then the numerous developments of the technology have taken place and several international projects/reports define dielectric response measurements together with insulation modelling as the preferred method for measuring moisture content of the cellulose insulation in power transformers [3,4,5]. In DFR tests, capacitance and dissipation factor are measured. The measurement setup is

![Fig. 1: Typical power factor temperature corrections.](image1)

![Fig. 2: DFR/FDS test setup.](image2)
Moisture assessment

The capability of DFR to measure dissipation factor as function of frequency, gives the user a powerful tool for diagnostic testing. Moisture assessment is one example. High moisture levels in transformers is a serious issue since it limits the maximum loading capacity (IEEE Std C57.91 – 1995) and the aging process is accelerated. Accurate knowledge of the actual moisture content is necessary in order to make decisions on corrective actions, replacement/scraping or relocation to a different site in the network with reduced loading.

Using DFR for moisture determination is based on a comparison of the transformers dielectric response to a modelled dielectric response (master curve). A matching algorithm rearranges the modelled dielectric response and delivers a new curve that reflects the measured transformer. The moisture content along with the oil conductivity for the master curve is presented. Only the insulation temperature (top oil temperature and/or winding temperature) needs to be entered as a fixed parameter.

Two different transformers are shown in Fig. 6. The two units have the same 0.7%, 50/60 Hz dissipation factor, characterised by IEEE 6 – 1995 as “warning/alert” status calling for “investigation”. The investigation is done as moisture analysis using MODS.

The two transformers are very different and maintenance measures for the two would also be different. Transformer 1 has good oil but needs drying. Transformer 2 has low moisture but needs oil change or regeneration.

Bushing diagnostics

Aging/deterioration of high-voltage bushings is a growing problem and manufacturers as well as utilities and test system providers are suggesting and testing various methods for detecting bushing problems before they turn into catastrophic failures. This includes on-line monitoring as well as off-line diagnostic measurements [6,7]. Traditional 50/60 Hz dissipation/power factor testing may give an indication of aging/high moisture content, especially if performed at various temperatures as shown in Fig. 7, [8] and Fig. 8, [10]. As seen in...
Fig. 7, dissipation factor values at lower temperatures are quite similar from very low to moderate moisture content. A significant change is not seen until measuring at about 50°C.

The “bad” bushing in Fig. 8 can be compared with bushing data in Fig. 7. Estimated moisture content is about 4%.

Increased dissipation factor at higher temperatures is a good indicator of bushing problems. Catastrophic bushing failures (explosions) are often caused by what is called “thermal runaway”. A high dissipation factor at higher temperatures result in an increased heating of the bushing which in turn increases the losses causing additional heating which increases the losses even further and the bushing finally explodes.

Individual temperature correction (ITC)

DFR measurements and analysis together with modelling of the insulation system includes temperature dependence. A new methodology (patent pending) is to perform DFR measurements and convert the results to dissipation factor at 50/60 Hz as a function of temperature. This technique has major advantages in measurement simplicity. Instead of time consuming heating/cooling of the bushing and doing several measurements at various temperatures, one DFR measurement is performed and the results are converted to 50/60 Hz tan delta values as a function of temperature. A result of the technique is shown and compared with the classical results presented by Blodget [9] in Fig. 9.

The method is based on the fact that a certain power factor measurement at a certain frequency and temperature corresponds to a measurement made at a different temperature at a different frequency. The conversion calculations are based on Arrhenius’ law/equation, describing how the insulation properties are changing over temperature. The relationship is depicted for three different activation energies in Fig. 10. Applying this technique on real-world DFR measurements on bushings gives results as shown in Fig. 11. Two bushings, "OK" and "bad" are compared with manufacturer’s values from Fig 7, [6]. The "bad" bushing is estimated to have about 4% moisture and should be considered “at risk”.

Temperature correction tables such as in IEEE/C57.12.90 give average values assuming “average” conditions and are not correct for an individual transformer or bushing. This was confirmed in field experiments and some utilities try to avoid applying temperature correction by recommending performing measurements within a narrow temperature range [11]. Examples are shown in Figs. 12 and 13. Power factor was measured at 10 kV on four transformers and three bushings of different age, condition and at various temperatures. Temperature dependence is very different for the transformers and bushings and using standard temperature correction tables will not give correct values for the 20°C reference value.

With DFR and the technique for converting data to temperature dependence, it
is possible to do accurate, individual temperature compensation. For a “good” component, the temperature dependence is weak. When the component gets older and/or deteriorated, the temperature correction factor becomes much larger, i.e. the temperature correction is a function of aging status. This is in line with several projects and studies [8,10]. Examples of individual temperature correction for bushings are shown in Fig. 14.

Manufacturer’s table data is only valid for as-new bushings. As soon as the bushing starts to show deterioration, the temperature dependence increases. “Bad” bushings have a very large temperature correction.

Individual temperature correction for transformers is more complex compared to “single-material” components e.g. bushings. The oil-paper insulation activation energy constant $W_a$ in Arrhenius’ law, for oil impregnated paper is typically 0.9 – 1 eV, while for transformer oil $W_a$ is typically around 0.4 – 0.5 eV.

Individual temperature corrections for transformers of various ages are shown in Fig. 15. Transformer data is summarised in Table 2.

As seen in the figure, each transformer has its individual temperature correction. New units have a “negative” correction for slightly elevated temperatures and will show dramatically different results if the standard table are used. Aged transformers show the same behaviour as the standard tables but with a much stronger temperature dependence compared to the average IEEE values.

Experimental results

Oil impregnated Kraft paper

Samples of Kraft paper with various moisture contents was measured at different temperatures [13]. Results for dry paper, moisture content <0.5% is shown in Fig. 16.

Using DFR technique to estimate temperature dependence based on measurements at one temperature only, gives the results shown in Fig. 17. As seen in the diagram, the calculated temperature dependence matches very closely to the actually measured dissipation factors.

Transformers

DFR measurements on a distribution transformer at various temperatures are shown in Fig. 18. As expected the moisture analysis (moisture in paper insulation) show the same values independent of insulation temperature (insulation temperature was estimated as winding temperature, measured as winding resistance).

Oil and paper insulation must be treated separately when modeling a transformer to estimate temperature dependence. This is described in Fig. 18. Combining the modeling results and converting to temperature dependence gives the temperature curves in Fig. 20. Also for this insulation system containing two different temperature dependent materials, the conversion gives results very close to the actual measured tan delta values.

Bushings

An Asea/ABB GOB OIP bushing, used but expected to be in good condition, has been measured at different temperatures. Tan Delta and DFR measurements were performed at three temperatures; Indoor at 22°C, outdoor at -8°C and in a heated chamber at 42°C. Results are shown in Table 3.

Calculated temperature corrections using DFR results are presented together with the manufacturer’s average temperature correction data in Fig. 20.

For the specific bushing, individual temperature correction (ITC) both at 22°C and 42°C fits very well with manufacturer’s data, indicating a bushing in normal condition.
Discussion

The temperature dependence of the dissipation factor of an insulating material needs to be considered when comparing measurement results with previous tests or factory values. Historically this has been done by the use of average temperature correction tables. Results are disappointing and many asset owners try instead to perform diagnostic measurements at a specific (usually room) temperature range.

The new method of using frequency data and calculate/model the temperature dependence of the actual component offers an alternative to waiting for the correct 20°C temperature and then do the test. It gives the possibility to have correct 20°C reference values and also to make a correct comparison to previously measured non-corrected data at other insulation temperatures.

How accurate the individual temperature correction can be is a valid question. As presented in this paper, using standard tables can easily give power factor errors of ±30 to 100% or more. The IFI examples presented show good correlation between the calculated and actually measured dissipation factor at various temperatures. However, envisioning a standard method used for a large population of components of various design and makes, a certain variation is anticipated. Preliminary tests with various temperatures demonstrate that the inaccuracy for ITC is in the order of ±50 – 100% or more.

Summary and conclusions

Dielectric Frequency Response (DFR/FDS) measurement is a technique/methodology for general insulation testing and diagnostics. In comparison with standard 50/60 Hz dissipation factor measurements, DFR measurements provide the following advantages:

- Capability of determining individual temperature correction of measured 50/60 Hz dissipation/factor at various temperatures to values at a reference temperature, 20°C.
- Capability of estimating dissipation/factor at operating temperature in order to assess risk of thermal runaway catastrophic failure.
- Capability of comparing test results from a new measurement at a different temperature to another measurement from a new measurement at a certain reference temperature, 20°C.
- Capability of estimating the moisture content of oil-immersed cellulose insulation in power transformers and bushings.
- Capability of investigating increased dissipation/factor in power components.

The insulation properties are very important for determining the condition of a power system component. Knowing the condition helps to avoid potential catastrophic failure and identifying “good” units and decide upon correct maintenance can save significant money due to postponed investment costs.

References


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