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Dielektrische Response Analysis (DFR) für Transformatoren und Durchführungen

Dipl.-Ing. Denis Denisov,
Megger GmbH

2002
B.Sc. in Elektrischer Energietechnik von der TU Nowosibirsk, Russland
2004
M.Sc. in elektrischer Energietechnik von der RWTH Aachen
2005-2008
Doktorand am Institut für Hochspannungstechnik der TU Stuttgart. Forschungsthema: Teilentladungsdiagnose an Kabelgarnituren im UHF-Band
2009-2012
Applikation & Enwicklungsingenieur für Teilentladungsmonitoring im Kabel bei SebaKMT, Baunach
2013 - jetzt
Business development manager bei Megger SebaKMT, Baunach

Megger

Dielektrische Response Analysis (DFR) für Transformatoren und Durchführungen

Dielectric Frequency Response Analysis for Power Transformers and Bushings

M.Sc.EE, Matz Öhlen, Megger Sweden, matz.ohlen@megger.com
Ph.D, Peter Werekius, Megger Sweden, peter.werelius@megger.com
M.Sc.EE, Denis Denisov, Megger Germany, denis.denisov@megger.com

Abstract

Dielectric Frequency Response, DFR (also known as Frequency Domain Spectroscopy, FDS), was introduced more than 20 years 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 in power transformers. Since the modeling theory contains influence of temperature, DFR and modeling can be used to calculate the temperature dependence of the insulation system. This paper gives a background to DFR, insulation modeling and how these tools can be utilized to improve understanding of insulation properties and in particular how this can be used for power transformer and bushing diagnostics.

1 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 and their bushings have become one of the most mission critical components in the electrical grid. 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 can not without risk sustain higher loads. Bushings and cables with high dissipation factor at high temperature can explode due to "thermal runaway".
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 or bushing means substantial cost savings for the power company.

2 50/60 Hz Dissipation Factor Measurements

A common insulation diagnostic test is measuring capacitance and dissipation factor at 50/60 Hz. This is the standard test performed whenever there is a need for investigating insulation properties. Tests are typically done at "any" temperature using a test voltage from about 30 V up to about 10 kV for field tests and up to nominal voltage in factory measurements. There are also tests with variable voltage (tip-up/step-up testing) as well as tests where tan-delta over temperature is measured. Analysis is based on standards, historical statistics and comparing factory values. Since insulation properties are pending temperature, temperature correction is commonly used for measurements not performed at 20° C, this is normally achieved by using temperature correction table values for certain classes of devices
In CIGRE TB 445 [1], IEEE C57.152 [2] and IEEE C57.19.01 [3], typical expected tan delta values for transformers and bushings are categorized.

TABLE I. TYPICAL TAN DELTA (50 HZ) VALUES

Power component	**Typical tan delta values @ 20° C insulation temperature**		
	"New"	**"Old"**	**Warning-alert limit**
Power transformers, oil insulated	0.2-0.4%	0.3-0.5%	> 0.5%
Bushings (OIP)	< 0.5%	< 1%	> 1%

Examples of temperature corrections for bushings and transformers (IEEE) are shown in Fig 1.

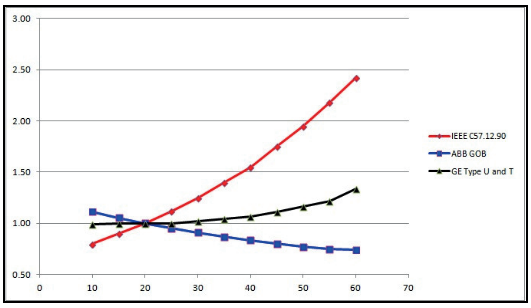

Figure 1. Typical dissipation factor temperature corrections (relative tan delta as function of temperature)

It is obvious that the given values are approximate guidelines only. IEEE C57.152 states; "*The power factors recorded for routine overall tests on older apparatus provide information regarding 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, carbonization 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% (20C), power factors between 0.5% and 1.0%***

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(20C) may be acceptable; however, power factors >1.0% (20C) should be investigated.” And moreover in IEEE C57.12.90-2006 [3]; ***“Experience has shown that the variation in power factor with temperature is substantial and erratic so that no single correction curve will fit all cases.”***

3 Dielectric Frequency Response Measurements

The first field instrument for DFR/FDS measurements of transformers, bushings and cables was introduced 1995 [4]. 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 [1,2,7-13].
In DFR tests, capacitance and dissipation/power factor is measured. The measurement principle and setup is similar to traditional 50/60 Hz testing but with the difference that instead of measuring at line frequency 50/60 Hz, insulation properties are measured over a frequency range, typically from 1 mHz to 1 kHz.
The results are presented as tan delta and capacitance versus frequency. Measurement setup is shown in Fig 2 and typical DFR results from measurement on transformers in different conditions in Fig 3.

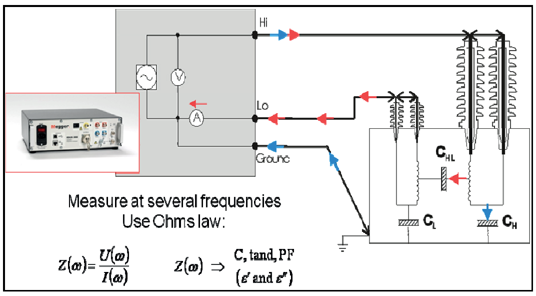

Figure 2. DFR/FDS test setup

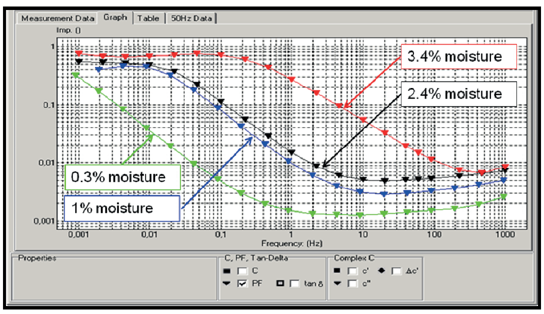

Figure 3. DFR measurements on four different transformers at different temperatures with moisture content ranging from 0.3 to 3.4%

4 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 is limiting the maximum loading capacity [9] and the aging process is accelerated. Accurate knowledge about the actual moisture content in the transformer is necessary in order to make decisions on corrective actions, replacement/scrapping or relocation to a different site in the network with reduced loading.
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 [5-8], 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 4 describes parameter influence on the reference curve.

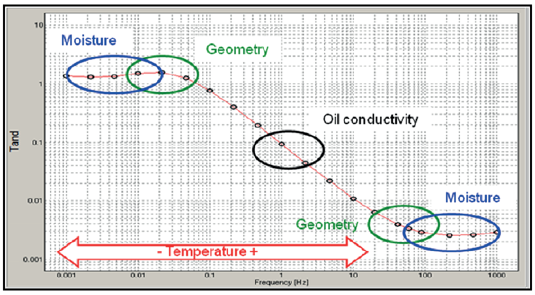

Figure 4. Parameters that effects the dissipation factor at various frequencies

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 rearranges the modeled dielectric response and delivers a new response curve that reflects the measured transformer. The moisture content along with the oil conductivity and 50 Hz tan delta at 25 and 20°C reference tempertures are calculated and preresented together with assessment guidelines in accordance with international standards and guides. Only the insulation temperature (top oil temperature and/or winding temperature) needs to be entered as a fixed parameter and the complete measurement and insulation assessment takes only 22 min at 20-30° C insulation temperatures

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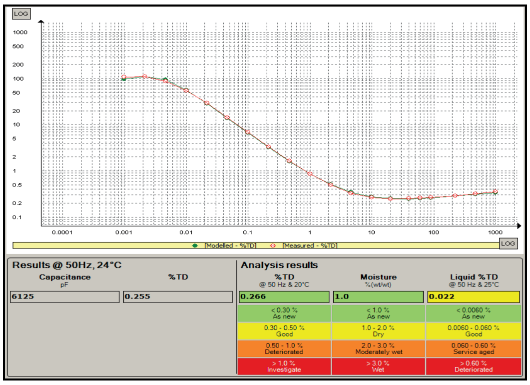

Figure 5. DFR insulation assessment and moisture analysis

Three different transformers are shown in Fig 6. The units have the same 0.5%, 50 Hz dissipation factor, typically characterized as “warning/alert” status calling for “investigation”. The investigation is done as DFR analysis assessing moisture content and oil conductivity.

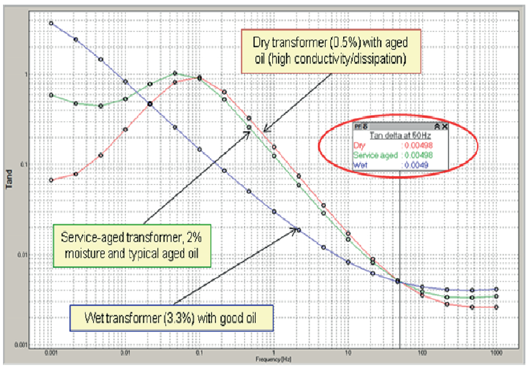

Figure 6. DFR analysis for three transformers with different oil quality and moisture content

The transformers are very different and maintenance measures for the would also be different. One transformer has good oil but needs drying, another has low moisture but needs oil change or regeneration, the third unit is a service aged distribution transformer with “normal“ values.

5 Individual Temperature Correction (ITC)

DFR measurements and analysis together with modeling of the insulation system includes also temperature dependence. A new methodology is to perform DFR measurements and convert the results to dissipation factor at 50/60 Hz as a function of temperature [12]. This technique has major advantages in measurement simplicity for bushings. 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. The method is based on the fact that a certain dissipation 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 relate to temperature.

$\kappa = \kappa_0 \cdot \exp(-W_a/kT)$

With activation energy W_a and Boltzmann constant k

The relationship is depicted for single-material insulation and three different activation energies in fig 7.

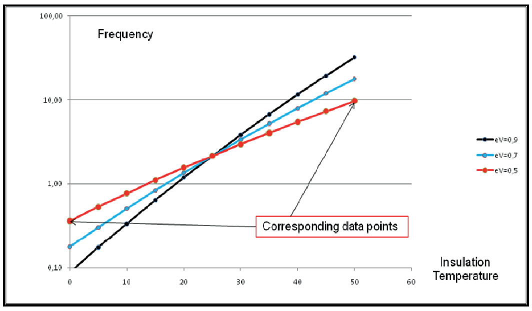

Figure 7. Relationship between power factor values at different frequencies taken at different temperatures.

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 is 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 Fig 8 and 9. Dissipation 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.

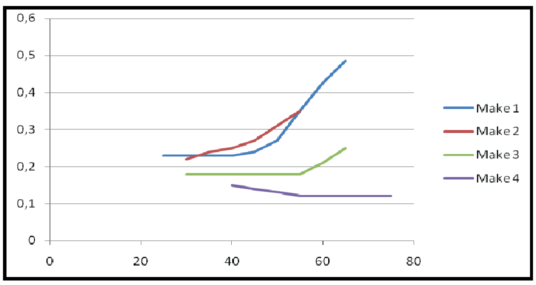

Figure 8. Tan delta values as function of temperature (°C) for four different transformers [11].

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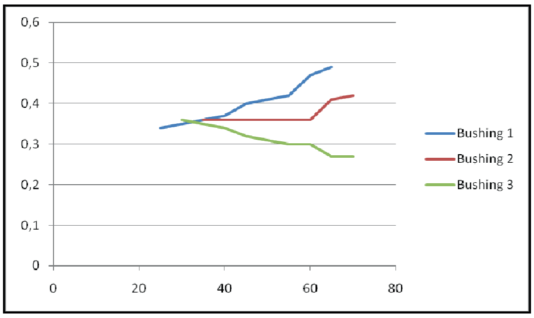

Figure 9. Tan delta values as function of temperature (°C) for three different bushings [10].

With DFR and the technique for converting data to temperature dependence, it is possible to do accurate, individual temperature correction. 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 dependence is a function of aging status. This is in line with several projects and studies [14-16]. An example of using the technique is shown in Figure 10 and 11. Samples of Kraft paper with various moisture contents was measured at different temperatures [15]. The dielectric response for dry paper, moisture content <0.5%, is shows in Figure 10.

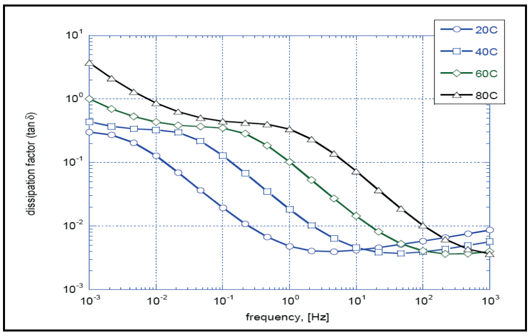

Fig 10. Dissipation factor as function of frequency for dry Kraft paper.

Using DFR technique to estimate temperature dependence based on measurements at one temperature only, gives the results shown in Fig 11. As seen in the diagram, the calculated temperature dependence matches very closely to the actually measured dissipation factors at different temperatures.

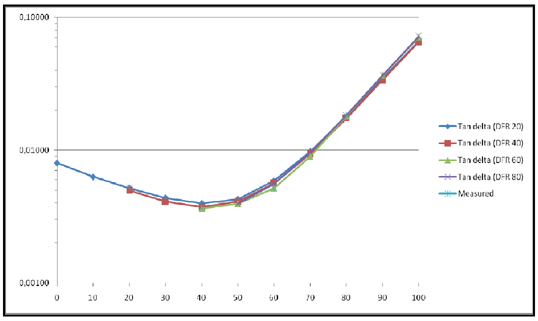

Fig 11. Tan delta at 50Hz for dry Kraft paper as function of temperature

Another example, applying individual temperature corrections for transformers of various ages is shown in Figure 12. Transformer data is summarized in Table II.

TABLE II. TRANSFORMER DATA

Manufacturer	Year	Moisture	Power (MVA)	Status
Pauwels	2005	0.4 %	80	New, at factory
Pauwels	2000	0.3 %	20	New, at utility
Westinghouse	1985	1.5 %	40	Used, spare
Yorkshire	1977	4,5 %	10	Used, scrapped

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

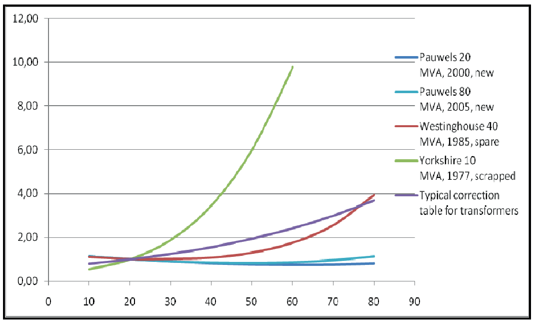

Fig 12. Temperature correction for transformers in various conditions

6 Bushing Diagnostics

Aging/deterioration of high-voltage bushings is a growing problem and manufacturers as well as utilities and various methods for detecting bushing problems are suggested to detect problems before they turn into catastrophic failures destroying a costly transformer. This includes on-line monitoring as well as off-line diagnostic measurements, see e.g. [1-4, 13-17].
50/60 Hz tan delta measurements are the most common insulation diagnostic test on bushings. C1 (UST) is a common test and as an example, CIGRE 445 [1] presents the following guidelines:

TABLE III. TAN DELTA VALUES FOR TYPICAL OIP BUSHINGS

Type	Tan delta @ 20°C		
	Typical new values	"OK" IEC60137	"OK" IEEE C57.19.01
RIP, resin impregnated paper	0.3-0.4%	< 0.7%	< 0.85%
OIP, oil impregnated paper	0.2-0.4%	< 0.7%	< 0.5%
RBP, resin bonded paper	0.5-0.6%	< 1.5%	< 2%

Test results are compared to nameplate values or previous tests. Increases or decreases from reference values are usually an indication of contamination and/or deterioration of the insulation system. Limits for the maximum permissible change tend to be manufacturer and type specific. A doubling of the initial dissipation/power factor value suggests either more frequent monitoring or replacement [1].
Measuring the bushings over temperature and in particular at high temperature gives further information about the condition of the insulation and indication of aging/high moisture content. See examples presented in Fig 13 [14]. Increased dissipation factor at higher temperatures is a good indicator of bushing problems. 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 may finally explode ("thermal runaway").

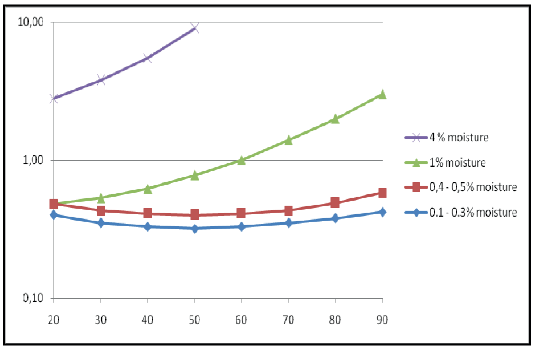

Figure 13. Dissipation factor (%) vs temperature for OIP bushings with various moisture content, [14]

6.1 GE type U – Accelerated Aging Tests

GE Type U bushings have exhibited a poor record of performance and provided utilities with major assets replacements. In a research project initiated by Ontario Hydro (Canada) and Pacific Gas & Electric (USA), an accelerated aging program was performed on six 155 kV Type U bushings and various diagnostic tests were performed on the bushings [18]. The bushings were subjected to simultaneous thermal and electrical aging. During the aging program a voltage of 66 kV (nominal line-to-ground voltage) was applied to the bushings. Thermal aging was accomplished by means of circulating power frequency current through the bushings, starting at 1200 A and slowly increasing to 2000 A. Two bushings failed (#3 and #4) at elevated current (1900 A) during the aging program.
The bushings were selected for test on the basis of tan delta (power factor) measurement results. Two units had low values, two units had high values and two had "intermediate" values. See Fig 14 for details. Nameplate tan delta is assumed to be 0.25%.
During aging, periodic and continuous diagnostic tests were performed. Tan delta, capacitance, DFR, PD, DGA etc. Parts of the results from the traditional test methods have been reported elsewhere [18].

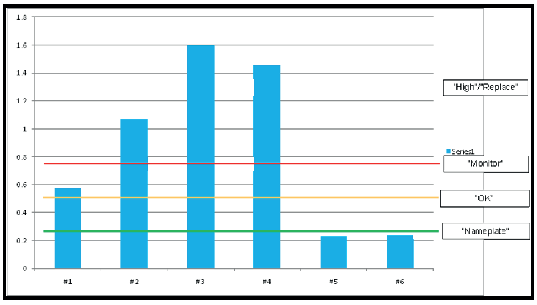

Figure 14. Dissipation factor (%) for the six GE Type U bushings at 20°C

6.1.1 DFR Measurements

DFR measurements were performed in the beginning of the program. The bushings were tested at various voltages (tip-up tests) and temperatures, see Table IV.
Low voltage DFR results are presented in Fig 14. The differences in dissipation factor between the bushings are much larger at low frequencies compared to 60 Hz values.

TABLE IV. DFR MEASUREMENTS ON GE TYPE U BUSHINGS

Bushing	"0A", ambient/21° C, measured @ kV						"1200A", ~ 50° C, measured @ kV						"1600A", ~ 65° C, measured @ kV					
	0.1	3	6	9	12	14	0.1	3	6	9	12	14	0.1	3	6	9	12	14
1 (M)	x							x	x	x	x	x	x	x	x	x	x	x
2 (M)	x							x	x	x	x	x	x	x	x	x	x	x
3 (H)	x		x		x								x	x	x	x	x	x
4 (H)	x																	
5 (L)	x		x		x		x	x	x	x	x	x	x	x	x	x	x	x
6 (L)	x		x		x			x	x	x	x	x	x	x	x	x	x	x

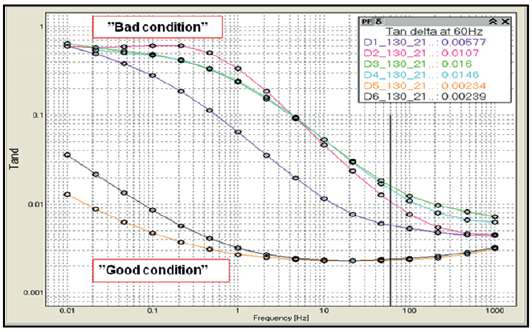

Figure 16. Tan delta vs frequency measured at 0.13 kV and ambient temperature

6.1.2 Temperature dependence

Using the technique described in section 5, we can use the DFR data to estimate temperature dependence. The results are shown in Fig 17 as tan delta temperature dependence for the six bushings.
Temperature dependence for bushings #5 and #6 corresponds to factory data indicating that these bushings are in good condition. The other bushings have stronger temperature dependence. Bushing #2, classified as M/"intermediate" has the same temperature dependence as the "bad" bushings #3 and #4 that failed during the accelerated aging test.

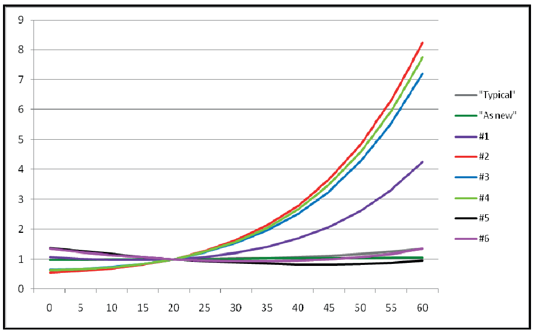

Figure 17. Tan delta temperature dependence (relative tan delta) for the six bushings (temperature on x-axis)

DFR measurements at three temperatures are presented for two bushings in Fig 18 and 19.

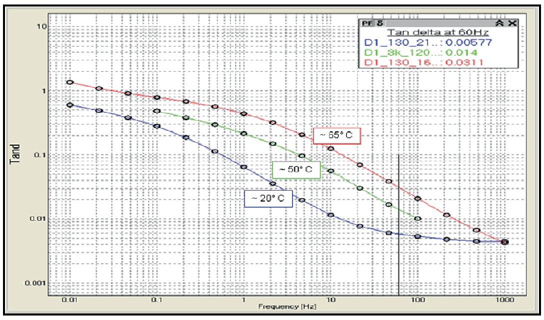

Figure 18. DFR measurement on bushing #1 at different temperatures

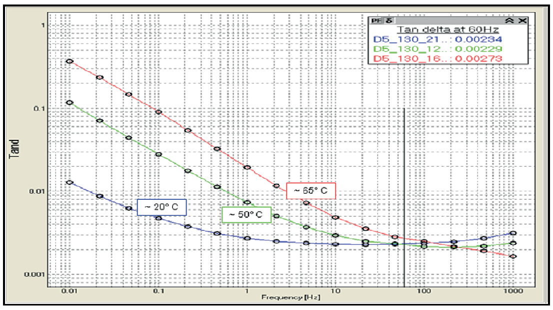

Figure 19. DFR measurement on bushing #5 at different temperatures

6.1.3 Tip-up measurements

Two tip-up results are shown in Fig 20 and 21.

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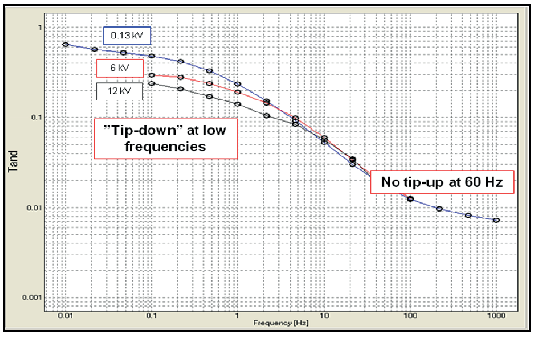

Figure 20. DFR tip-up measurement on bushing #3 ("bad").

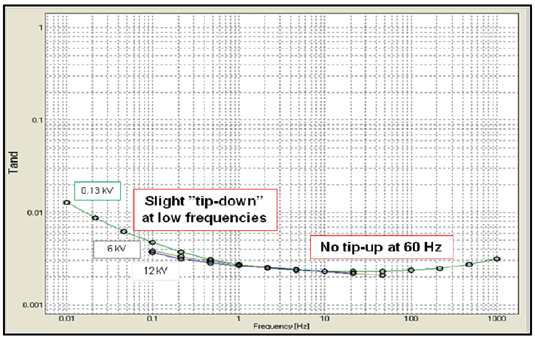

Figure 21. DFR tip-up measurement on bushing #5 ("good").

60 Hz tan delta values are almost independent of test voltage and not sensitive to aging effects. At lower frequencies there is a small "tip-down" effect.

6.1.4 Moisture assessment

The DFR measurements can also be used for moisture assessment using the same modeling technique as for oil-immersed power transformers. Results for the 6 bushings are presented in Table V.

TABLE V. MOISTURE ASSESSMENT OF GE TYPE U BUSHINGS

Bushing	Moisture content	Moisture classification (IEC)
1 (M)	2.5%	"Moderately wet"
2 (M)	3.0%	"Moderately wet"
3 (H)	3.3%	"Moderately wet"
4 (H)	3.2%	"Moderately wet"
5 (L)	0.8%	"Dry"
6 (L)	1.0%	"Dry"

7 Case studies

7.1 3 x Single-phase Power Transformer

Insulation measurements were performed on a 1000MVA GSU consisting of three separate single-phase units. Due to practical circumstances the test was split in two days resulting in one unit measured at 30°C insulating temperature and the other two at 8°C.

TABLE VI. TAN DELTA MEASUREMENT RESULTS

Phase	Insulation Temperature	Tan delta values		
		Measured	20°C TCF (IEEE C57.12.90)	20° C ITC
Blue	8	0.26	0.33	0.23
Red	8	0.24	0.30	0.22
White	30	0.19	0.15	0.20

The TCF (IEEE) corrected values show a large variation between white phase and the other two. Using ITC, all three phases comes out at about the same (low) value. A comparison between the standard TCF table and the individually measured temperature correction is shown in Fig 13.

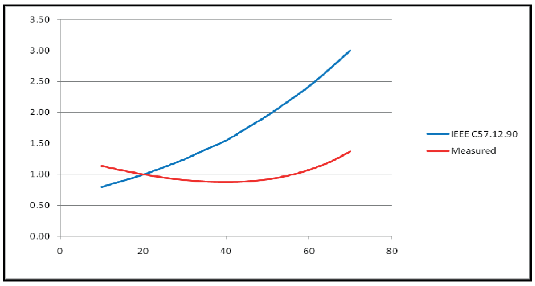

Figure 22. Individual tan delta temperature correction (ITC) compared to IEEE C57.12.90 temperature correction table (TCF)

This transformer in good condition (low tan delta values), has a very different tan delta temperature dependence compared to the "average transformer".

Moisture and temperature corrected oil conductivity based on DFR analysis, are presented in Table VII.
Red and white phase of the transformer have a moisture level of about 1% and oil conductivity around 0,4 pS/m. Blue phase have somewhat higher moisture, 1,4% and about twice the oil conductivity, around 0,8 pS/m.

TABLE VII. MOISTURE AND OIL CONDUCTIVITY RESULTS

Phase	Temperature	Moisture	Oil conductivity, pS/m	
			Measured	25° C
Blue	8	1.4%	0,34	0,78
Red	8	1.1%	0,14	0,33
White	30	0.9%	0,74	0,37

All values are "good", indicating a transformer with good insulation. However, it is an interesting fact that by using DFR and accurate temperature correction factors, the measurements and analysis indicate that the blue unit may have a faster aging pattern compared to the other two. This would not be possible to see with traditional tan delta testing.

7.2 GE Type U and T – Field Test

This is results from field testing a 324/26 kV transformer with HV GE type U and LV GE type T bushings. C1 DFR measurements on HV and LV bushings are presented in Fig 22 and 23. Insulation temperature was about 10°C.

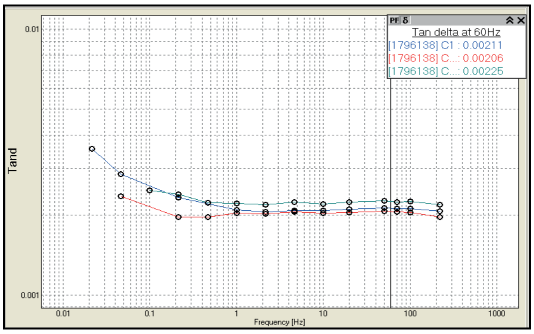

Figure 22. C1 DFR measurement on 220 kV GE type U bushings

Looking at the HV bushings results we can see that 60 Hz tan delta is low/as nameplate. Also the low frequency response is about the same as 60 Hz values, indicating low temperature dependence. Conclusion is that HV bushings are in good condition.
Looking at the LV bushings reveals a somewhat different situation. 60 Hz data differs between phases but are all within the 0.5% "OK" limit. However low frequency data differs, especially for X3, indicating higher temperature dependence.

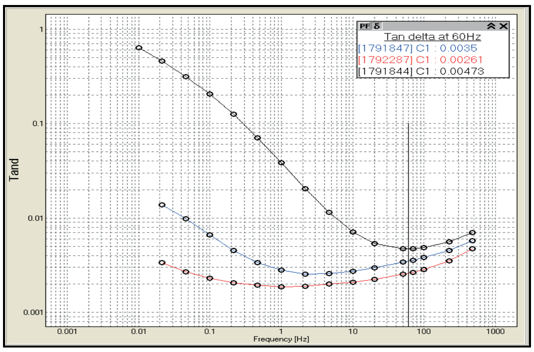

Figure 23. C1 DFR measurement on 26 kV GE type T bushings

Temperature dependence for the LV bushings are presented in Fig 24. We can see that X3 tan delta @ 20°C is > 0.5% and temperature dependence is rather strong. This bushing should be "closely monitored" or maybe replaced.

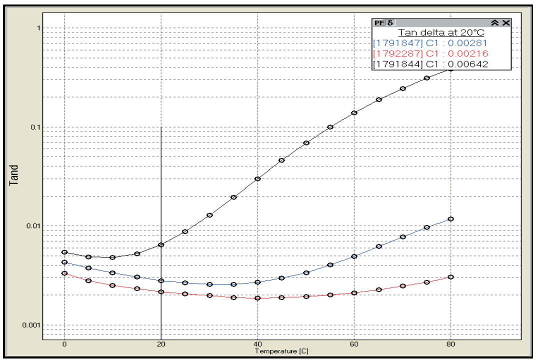

Figure 24. Tan delta temperature dependence, 26 kV GE type T bushings

8 Summary and Conclusions

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

- Capability of estimating the moisture content of oil-immersed cellulose insulation in power transformers and bushings
- Capability of performing individual temperature correction of measured 50/60 Hz dissipation factor at various temperatures to values at a reference temperature.
- Capability of estimating temperature dependence in an object and from measured dissipation factor at a certain temperature calculate the dissipation factor at a different temperature
- Capability of generally investigating causes for 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 failures, and identifying "good" units and decide upon correct maintenance, can save significant money due to postponed investment costs.

9 References

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