

Dielectric Frequency Response:

A New IEEE Guide for Field Test on Power and Distribution Transformers

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Since the invention of the transformer, the design, quality and efficiency of this magnificent machine has been improved thanks to the development of electromagnetic materials, computer design algorithms, insulation materials, cooling systems, structural design, etc. Nowadays, a vast number of transformers operate worldwide aiming to provide reliable and safe operation under the most cumbersome environmental and operational conditions.

Even though the materials, design and manufacturing processes have improved, the most common insulation system is a combination of liquid insulation, cellulose and impregnated in oil cellulose. These components of the overall insulation system go through an inevitable aging process that leads to the end of the service life of power and distribution transformers. One can expand this statement into other components with similar insulation construction such as bushings and instrument transformer with oil-impregnated paper insulation.

The Institute of Electrical and Electronic Engineers (IEEE) Standards Association approved the publication of IEEE C57.161-2018 – “Guide for Dielectric Frequency Response Test”. The work was developed within the IEEE Transformers Committee and the Dielectrics Sub-committee. A needed document for a non-intrusive and

non-destructive testing method to better understand the condition of the insulation system of power and distribution transformers.

Introduction

During the last two decades, other technical references presented the development of DFR (Dielectric Frequency Response) a.k.a. Frequency Domain Spectroscopy (FDS), aiming specifically to its application for power and distribution transformers with oil-impregnated paper insulation. CIGRE Technical Brochures 254, 414 and 445 as well as IEEE Std. C57.152 addressed the importance, the research carried out and the benefits of the method as applied to power and distribution transformers.

In the IEEE Transformer Committee, a Task Force was initially formed to recommend (or not) the need to develop a guide describing the application of DFR on oil-impregnated transformers. From the initial step of forming the Task Force to the publication of the guide, the contribution and participation of specialists, end-users, testing equipment manufacturers, transformer manufacturers and academia made possible the production of a practical and comprehensive guide for the use of DFR technology and interpretation of transformer's insulation dielectric response in the frequency domain.

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DFR References

As mentioned previously, since the beginning of the use of insulation materials, a method to determine an acceptable condition for its use in electrical applications was required. The dielectric response of any insulation material can be obtained in the time domain or in the frequency domain. Time domain dielectric response has been in place for over 100 years and the typical "Insulation Resistance" test became, by far, the easiest and most practical approach to understand the condition of the solid insulation.

The complex impedance of the dielectric system is measured at different frequencies and the dielectric response is finally plotted as percentage dissipation factor, permittivity or capacitance as a function of frequency.

Nevertheless, around the mid-1900s, the frequency domain response was greatly studied and the definition of dielectric losses at power or line frequency (50/60 Hz) turned to be a great success for transformer manufacturers, end-users and testing service companies. Nevertheless, technology evolved and with that, electronic components and control devices opened the door to a wider band frequency spectrum to analyze different insulation materials.

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The practical application of DFR in the field generated the interest in the industry and international organizations took lead on the investigation of this "new technology" revolutionizing the testing practices in the field.

In 2002, CIGRE developed the Technical Brochure 254 – "Dielectric Response Methods for Diagnostics of Power Transformers". This report from the Task Force (TF) D1.01.09 focused on three dielectric response techniques:

- Return Voltage Measurements (RVM)
- Dielectric Spectroscopy in Time Domain (PDC)
- Dielectric Frequency Domain Spectroscopy (FDS)

To summarize the text of this document, the TF concluded that all three methods reflect the same fundamental polarization and conduction phenomena in transformer insulation and that the definition of moisture in the solid insulation by time domain and

frequency domain responses required mathematical modelling and good understanding of dielectric properties of the insulation system components.

In 2010, CIGRE continued the work and published the Technical Brochure 414 – "Dielectric Response Diagnoses for Transformer Windings". In this document, CIGRE combines the practical experience acquired with the mathematical modelling approach to determine best testing practices. The document covers the fundamentals of the X-Y model, measurement configurations, test performance and maybe the most important part, case studies and comparative analysis using Karl Fisher Titration (KFT) to validate the moisture estimation

in the solid insulation by dielectric response methods.

Considering the great acceptance of the technology in the field, the CIGRE Working Group (WG) A2.34 incorporates dielectric response methods in time and frequency domain in section 5.1.3 in the Technical Brochure 454 published in 2011. Dielectric response methods are included as "Special or Advanced Measurements". DFR or FDS is an advanced testing technique used in the field to determine the water content in the solid cellulose insulation of oil-paper insulation, insulation failures, and contamination of insulation. Moisture content in the solid insulation derived from field testing, mathematical modelling and data base source is compared against limits given for dry, moderately wet and extremely wet insulation given in IEC 60422. As a reminder, IEC 60422 states that the determination of the water content in the paper of a transformer by the measurement of the water in oil has been frequently described, but practical results are often not in line with the theoretical predictions. All calculations and correlations of the water content in oil and the water content in the oil/paper-system depend on the equilibrium state between the insulating oil and the oil/paper system and vice versa.



In the North American world, the IEEE Transformer Committee revised the document IEEE 62 Part 1 – “Guide for Diagnostic Field Testing of Electric Power Apparatus – Oil filled Power Transformers, Regulators, and Reactors”. One of the fundamental reasons to revise this document was the application of new testing techniques not described in this document and considered important for the current requirements of manufacturers and end-users especially in the field. It is interesting to notice that IEEE 62 (R2005) provided in section 6.3.12 two tables with general guidelines for interpreting data expressed in percent saturation of water in oil and in percent moisture by dry weight of paper.

The work carried out by the IEEE transformer committee ended up with the publication in 2013 of the IEEE Std. C57.152 – “Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators and Reactors”. The amount of information put together in this document is difficult to describe in just a few lines, but this guide added the Informative ANNEX G introducing to the IEEE references the Dielectric Frequency Response Method. Annex G provides a brief description of the DFR method and its interpretation for oil-paper insulation systems in power transformers. Enough about history. Let us focus now on the recently published guide for DFR testing.





IEEE Guide for Dielectric Frequency Response Test

The continuous work of IEEE and its members is well reflected in the guide for dielectric frequency response test applicable for liquid-immersed transformers. The guide includes a thorough description of the DFR method, a comparative analysis between line-frequency power factor and the dielectric response in a wide frequency spectrum, recommendations for instrumentation, procedures for performing the tests, and guidelines for interpretation of the data. The application of DFR allows testing in factory and in the field.

After a general overview, Section 4 introduces the DFR method. DFR is a non-intrusive and non-destructive off-line testing technique performed in the frequency domain to determine the moisture content of the transformer's solid insulation and the conductivity of the liquid insulation. This paragraph covers one very important characteristic of the dielectric response; it can discriminate between the effect of moisture or contamination in the liquid or solid insulation.

In Section 4, some important facts are described. First, DFR as any other dielectric response method depends on the unique dielectric properties of the material, the electric field and the



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temperature of the specimen at the time of the test. Second, DFR follows the same measurement principle as line – frequency power factor test, but the excitation signal applied by DFR instruments varies frequency in the range from 1 kHz down to 1 mHz (typical range at 20°C). The complex impedance of the dielectric system is measured at different frequencies and the dielectric response is finally plotted as percentage dissipation factor, permittivity or capacitance as a function of frequency.

After a clear understanding of the behavior of the materials under an alternating excitation signal in a wide frequency spectrum, different factors affecting the dielectric response are described. One of the most important factors to take into account is the presence of EMI in the surrounding test area.



The modelling algorithm requires specific information to evaluate the condition of the insulation system. The normally fixed information is:

- a. Liquid Insulation relative permittivity ϵ_r
- b. Thermal activation energy for solid and liquid insulation
- c. Temperature of the insulation under test

The outcome of the test will provide:

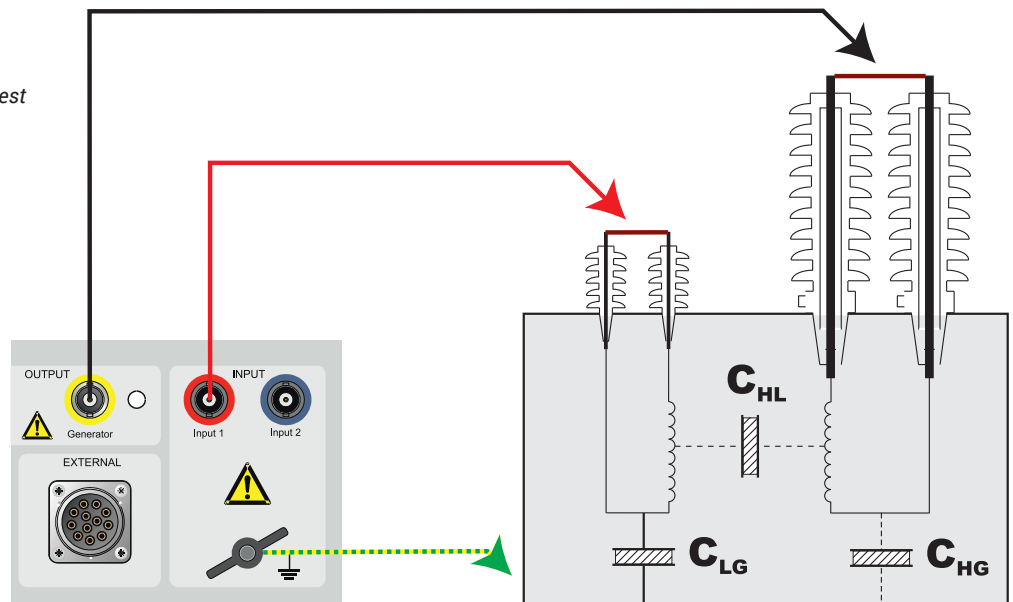
- a. Liquid insulation conductivity (σ)
- b. Moisture in solid insulation (m)

Besides the modelling part, it is important to understand that the test is performed in the field following the same instrument-to-object hook up principles as those used for power factor / dissipation factor testing at line frequency. Figure 1 shows the hook up diagram of the DFR test set to a commonly used two-winding transformer.

Section 5 provides the best practices and configurations to perform the test in the field.

As any other electrical test, the very first recommendations are related to safety. For many readers, safety is not just a best practice but also a life style. Therefore, local and federal regulations required to perform the test as well as safety instructions provided by the test set manufacturer must be followed. One more advantage of DFR is that the test involves a LV excitation signal typically $\leq 140 V_{RMS}$.

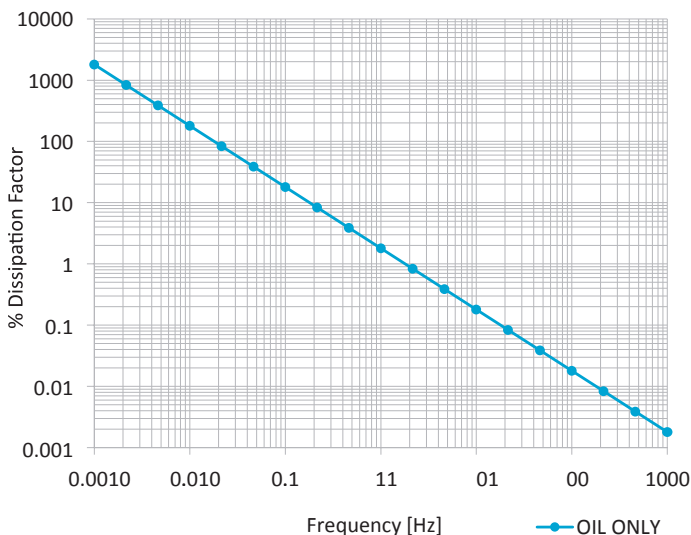
Figure 1. Hook up diagram between a DFR test set and a two-winding transformer





In the field, working conditions might not be optimal. Section 5 provides guidelines to minimize the effect of external factors on the test performance as well as the measurement configurations. At this stage, the reader should be aware that the most accurate estimation of moisture in the solid insulation is related to the test between windings in a UST (ungrounded specimen test) test mode. In a two-winding transformer, the capacitance of interest is the inter-winding insulation between high and low voltage windings represented in Figure 1 as C_{HL} . Other insulation systems, between high voltage winding and ground (C_H) or between the low voltage winding and ground (C_L) are susceptible to the influence of bushings and sometimes other components inside the transformer such as tap changers. Nevertheless, the GST measurements are often taken to identify non-typical responses related to contamination or degradation of the insulation system.

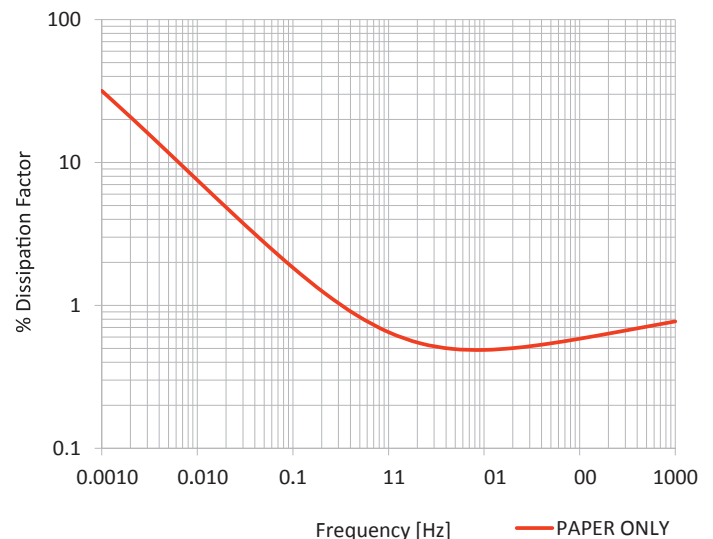
Figure 2. DFR of mineral oil (left); DFR of paper only (right)



Section 6 provides the guidelines to generate the test report, including an example of the report.

Maybe the most important part of the guide is without a doubt Section 7 – Measurement Analysis and Interpretation. In this section, the guide provides the differences between the dielectric response of liquid and solid insulation graphically represented in Figure 2. The liquid insulation dielectric properties can be described by a simple parallel RC-circuit, the capacitance representing the liquid permittivity and the resistance the liquid conductivity. The dielectric properties of solid insulation are more complex, both capacitance and losses vary with frequency in a manner that cannot be described by a simple parallel or series RC-circuit.

After a clear understanding of the behavior of the materials under an alternating excitation signal in a wide frequency spectrum, different factors affecting the dielectric response are described. One of the most important factors to take into account is the presence of EMI in the surrounding test area.



Overcome the effect of noise (EMI) on the measurement signal, the use of a voltage amplifier is considered as optional in the field, especially for low capacitance specimens and tests at temperatures close to zero degrees Celsius.

The Annexes included in the document cover:

- A. Dielectric Frequency Response Analysis – Theory and validation
- B. Non-moisture related factors influencing the DFR measurements
- C. Examples of typical measurement challenges
- D. Bibliography

Closing Note

This article is a brief summary of a well-developed document provided by IEEE and its members. Authors consider imperative for asset managers, utility operators, transformer manufacturers and testing service providers to acquire this document and follow the guidelines given. The article is co-authored by Dr. Roberts Neimanis, Product Manager at Megger Sweden.