TRANSFORMER TESTING TECHNIQUES AND STANDARD DEVELOPMENT

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Transformer manufacturers and field operators have always benefitted when new technologies are applied during design, manufacturing, commissioning, and operational processes that improve the quality and reliability of electrical apparatuses.

As technological advances and new testing methodologies become more readily available to transformer testing personnel, how can we keep up with this avalanche of new and promising alternatives, which at first glance seem to solve all our diagnostic problems? One way is by following the activities of national and international regulatory institutions. IEEE, NETA, CIGRE, and IEC are the best references in this area.

IEEE STANDARD C57.152-2013

IEEE is the world's largest professional association dedicated to advancing technological innovation and excellence for the benefit of humanity. The IEEE Transformer Committee met in Dallas in 2007 to revise the existing guide for routine testing in the field, IEEE 62, *Guide for Diagnostic Field Testing of Electric Power Apparatus — Oil-Filled Power Transformers, Regulators, and Reactors* (R2005). At the time, a vast number of old and new testing methodologies and practices were used in the field but were not covered by the IEEE 62 standard. It was logical to create a new or revised guide under the C57 standard series. The C57 standards already contained other transformer-related guidelines administered and supervised by the IEEE Transformer Committee.

The new guide for diagnostic field testing of fluid-filled power transformers, regulators, and reactors was balloted and approved by RevComm in 2013. The working group led by Jane Verner (Chair), and supported by many members of IEEE, dedicated long hours in revisions and contributions to the new guide.

The comparison between IEEE 62 and IEEE C57.152 brings something else to this discussion. The new Diagnostic Test Chart complements the old one, keeping the existing practices and adding those methods not considered previously. A comparative analysis shows the following methodologies were added to the new guide: Windings — Frequency Response Analysis (FRA); Insulating liquid — Furan Analysis and Corrosive Sulfur; and Current transformers — Ratio, Polarity, and Resistance.

IEEE C57.152 (Chapter 5) also considered the importance of providing a maintenance chart where the end user could select the testing practices recommended (REC), as-needed (AN), and optional (OPT) for different stages during the service life of the transformer: commissioning, in-service, after protection trip due to system fault, or after protection trip due to internal fault. In this chart, induced voltage and dielectric frequency response (DFR) are listed as optional techniques.

Not only are more testing methodologies listed in the new maintenance and diagnostics charts, but also included are new annexes developed to complement the guide:

- Annex D (informative) Dew Point Test
- Annex E (informative) Furan Testing
- Annex F (informative) Frequency Response Analysis (published guide IEEE C57.149)
- Annex G (informative) Dielectric Frequency Response (developing guide IEEE PC57.161)
- Annex H (informative) Other methods to verify polarity from previous field test guide revisions
- Annex I (informative) Particle Count
- Annex J (informative) Bibliography

Only general information about FRA and DFR was included in annexes F and G because when C57.152 was close to being published, other working groups were developing specific guidelines for the advanced diagnostic techniques of SFRA and DFR. Frequency response techniques have been used in the field for over 20 years. Researchers worldwide have found SFRA and DFR useful not only in transformer diagnostics, but also in other electrical apparatuses in the field.

CIGRE

CIGRE 445, the guide for transformer maintenance, provides a diagnostics matrix where a line is drawn to differentiate basic electrical testing from advanced electrical testing. Frequency response techniques in time and frequency domains are grouped together with partial discharge (PD) testing as advanced electrical diagnostic techniques.

CIGRE pioneered publishing guidelines dedicated to the frequency response methods. In 2008, CIGRE published Technical Brochure 342 — *Mechanical Condition Assessment of Transformer Windings Using Frequency Response Analysis (FRA)*. This is an excellent reference on the principles of FRA, suggested best practices for making repeatable measurements, and guidance for interpretation.

CIGRE also undertook a large project to investigate the frequency response of the dielectric components inside the transformer, publishing Technical Brochure 414 — *Dielectric Response Diagnoses for Transformer Windings* in 2010. CIGRE's well-developed document describes the transformer dielectric response model, the best testing practices, and guidelines for the interpretation of results.

IEC

Prepared by Technical Committee 14, the IEC 60046 standards series covers technical areas related to transformers. Standard IEC 60046-1 (2011) is the latest revision available for power transformers and IEC 60046-18 Ed. 1 (2012) addresses the methodology, best practices, and minimum requirements for measuring equipment and formatting the data resulting from the SFRA test.

IEC 60046-18 also includes several annexes. Annex A covers the measurement lead connections. Annex B covers factors influencing FRA measurements, including residual magnetization, use of different liquids and the level of liquid filled in the tank, temperature, and others. It also includes a few examples of confirmed damages in the windings detected by the FRA test. Annex C covers the applications of FRA, and Annex D provides examples of measurement configurations.

TRANSFORMER ADVANCED DIAGNOSTICS BY FREQUENCY RESPONSE TECHNIQUES

The objectives and scope of each frequency response method must be understood before it can be chosen for the appropriate application.

Frequency response analysis or sweep frequency response analysis (SFRA) is a comparative test to evaluate the electro-mechanical condition of the transformer. Deviations between frequency responses indicate mechanical and/or electrical changes in the active part of a transformer.

Dielectric frequency response (DFR) or frequency domain spectroscopy (FDS) tests the overall condition of the transformer's insulation, identifying:

- The percentage of moisture concentration in the solid insulation
- The conductivity or the dissipation factor of the liquid insulation corrected to 25°C
- The thermal behavior of dielectric parameters at specific frequencies, determining an accurate power factor / dissipation factor correction not based on table correction factors but on the individual dielectric response of the unit under test (UUT)
- The presence of contaminants creating a distortion of the dielectric response (also called non-typical dielectric response)

A deeper look at each technique is helpful to understand their advantages.

Sweep Frequency Response Analysis

According to control theory, the behavior of a single input, single output (SISO) system can be described with an impulse response h(t) or its transfer function H(jw) (Figure 1).

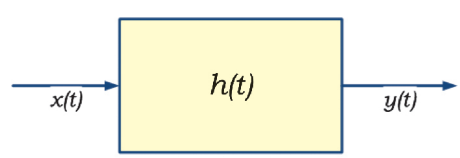


Figure 1: *SISO — Representation of a Transfer Function in Time and Frequency Domains*

In the case of power transformers, the physical structure of the winding can be represented in the electric language by an RLC complex circuit with multiple series and parallel combinations of these components (Figure 2).

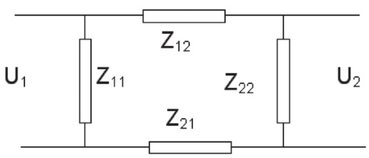


Figure 2: *Simplified Diagram of the Winding Configuration*

The ac input signal applied to one end of the winding at one specific frequency passes through the complex electric circuit of the winding, and the output voltage is measured in magnitude and phase at the other end.

The frequency sweeps from 20Hz up to 2MHz. Typically, a 2MHz upper limit is sufficient for power transformers, and a clear and repeatable response of the magnetic circuit can be obtained from 20Hz up to approximately 2kHz, depending on transformer design. IEEE and IEC have set boundaries on the frequency response to identify different sections of the transformer (Figure 3).

SFRA measurement provides a very clear image of the electromechanical construction, but interpretation may always be validated with an additional testing technique. The chart at the right shows the correlation of SFRA with other testing practices.

Dielectric Frequency Response

This technique is already used by many utilities and transformer manufacturers, which have greatly benefited from the vast amount of information gathered from the unique and individual dielectric response of the transformer insulation.

The testing procedure is quite similar to that applied for power factor or dissipation factor testing. The main difference is the wide-frequency band used by DFR — typically from 1kHz down to 1mHz. The test is carried out at low voltage (200Vp) for transformer testing. For environments with high interference, a voltage amplifier increases the signal-to-noise ratio. The use of a voltage amplifier is fundamental for the analysis of bushings and instrument transformers.

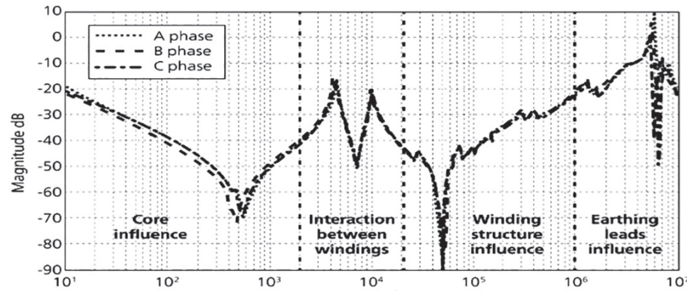


Figure 3: *Frequency Response Analysis — IEEE C57.149*

In a two-winding transformer, DFR can analyze the following insulating areas:

- CHL — capacitance between HV and LV windings (i.e. inter-winding capacitance)
- CHG — capacitance between HV winding and ground
- CLG — capacitance between LV and ground
- Bushing C1 and C2 capacitances, but only if test tap is available in the bushing
- Only oil sample DFR

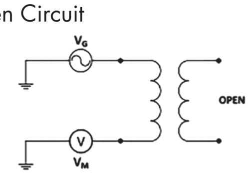
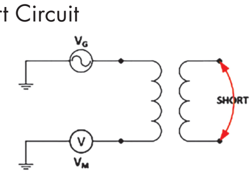
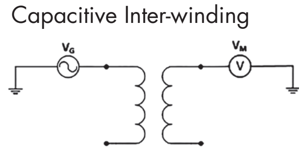
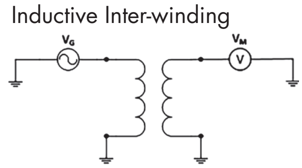
SFRA mode	Transformer Characteristic	@ 60 Hz
Open Circuit 	Looks at winding and core characteristics	Similar to eExcitation current test
Short Circuit 	Looks at winding	Similar to leakage reactance
Capacitive Inter-winding 	Looks at capacitance between windings	Similar to capacitance test
Inductive Inter-winding 	Looks at inductance of both windings	Similar to TTR

Figure 4

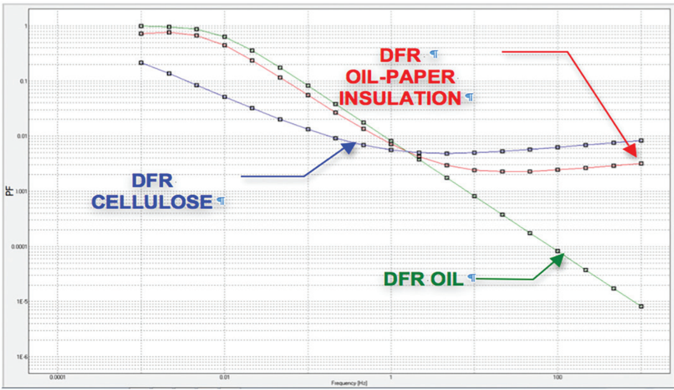


Figure 5: *DFR of a Transformer's Liquid-Paper Insulation (X=20, Y=20, %mc=1%, s=1E-13 pS/m, T=20°C)*

The dielectric response provides an in-depth understanding of the insulation system and allows differentiation between the condition of the liquid insulation versus the condition of the solid insulation.

An example of a transformer in excellent condition is presented in Figure 5. Moisture in the solid insulation is only 1 percent, and the conductivity of the oil is 1x10-13 [S/m]. Temperature of the insulation system in this example is 20°C.

For interpreting DFR results, the XY model explains the relationship between the solid insulation, the liquid insulation, and the system geometry. The XY model is well described in CIGRE 414.

Following the XY model and using mathematics to match the readings to those in a well-developed database, users can determine the moisture concentration in the solid insulation and the conductivity (s) of the liquid insulation.

The DFR method continues to evolve. Part of this evolution is the implementation of a multi-frequency measurement system capable of reducing the testing time by almost 40 percent in the frequency domain only. Testing time is critical for end users. Testing personnel should be aware of DFR best testing practices such as thermal stability of the specimen and preferably not-too-cold insulation temperatures where, inevitably, the prolongation of testing time runs to very low frequencies.

The thermal effect shifts the dielectric response to higher frequencies at higher temperatures and to lower frequencies at lower temperatures. This phenomenon led to another application: identification of the thermal behavior of dielectric parameters such as Power Factor and Dissipation Factor. In other words, DFR opened the door for transition from the frequency domain into the temperature domain of the insulation system, including using it for an accurate individual temperature correction of power factor values at line frequency or beyond it to reference values at 20°C, or any other temperatures from 5 to 60°C with very high accuracy.

CONCLUSIONS

As new testing techniques are developed, the international community must comprehend the benefits and limitations of these techniques.

The international committees go through a process that may take several years before a new guide is created and published. This is the only way to compile into one document the knowledge and experience of the entire technical community involved in this honorable activity.

SFRA is one of the most important tools for diagnosing potential mechanical problems in transformer windings. DFR is clearly gaining more importance within the utilities by providing a complete overview of the dielectric system inside the transformer, allowing end users to identify water contamination issues within the solid insulation or high conductivity in the liquid insulation.

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