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. The new computational tools and the continuous research by individuals in the academic, public, or private sector have created better materials capable of withstanding demanding service conditions, saving space, and minimizing energy losses. As manufacturing technology advances at this rapid pace, testing methodologies must evolve to keep pace. Advances in power electronics and computer technology lead to more accurate, reliable, portable, and user-friendly instruments in the field.

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 that focus their resources on keeping up with the latest technological developments for design, construction, operation, testing, maintenance, and even post-mortem investigations of power and distribution transformers. IEEE, NETA, CIGRE, and IEC are the best references in this area.

Starting with a transformer’s factory acceptance testing (FAT) and continuing through its service life, mechanical, dielectric, thermal, and electromagnetic parameters are evaluated. Once the transformer has passed the FAT, it is ready for shipment to a new site, where a testing crew will commission the unit before energization. The next step is to continue to follow the standards.
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 handles all matters related to the application, design, construction, testing, and operation of transformers, reactors, and other similar equipment.

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 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 (Figure 1).

The new guide for diagnostic field testing of fluid-filled power transformers, regulators, and reactors was balloted and approved by RevComm in 2013. The work was led by Jane Verner (Chair), Loren Wagenaar (Vice Chair), Kipp Yule (Secretary), and supported by many members of IEEE who 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
- Corrosive Sulfur

Current transformers:
- Ratio
- Polarity
- 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 regarding these new additions:

- Annex D (informative) Dew Point Test
- Annex E (informative) Furan Testing
- Annex F (informative) Frequency Response Analysis
- Annex G (informative) Dielectric Frequency Response
- 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.

For now, focus is on transformers where the electro-mechanical and dielectric condition can be evaluated and traced for better diagnostics and interpretation of results. In 2012, a new working group was created within the IEEE Transformer Committee to develop a guide for DFR analysis, PC57.161, which is currently under development.

**CIGRE**

Founded in 1921, the Council on Large Electric Systems (CIGRE) is an international nonprofit association that joins forces with experts all over the world to improve electric power systems of today and tomorrow. Of course, the transformer topic is covered by several technical brochures dedicated to particular areas of interest in the scientific and operational fields.

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 (Figure 2). In this publication, frequency response techniques in time and frequency domains are grouped together with partial discharge (PD) testing as advanced electrical diagnostic techniques.

**Figure 2: CIGRE 445 - Electrical Tests and DGA Diagnostics Matrix**

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 document is an excellent reference describing the principles of FRA, the 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. As before, CIGRE provided a well-developed document, describing the transformer dielectric response model, the best testing practices, and guidelines for the interpretation of results.

**IEC**

Founded in 1906, the International Electrotechnical Commission (IEC) is the world’s leading organization for the preparation and publication of international standards for all electrical, electronic, and related technologies.
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 as well as suggestions on formatting the data resulting from the test.

IEC 60046-18 also includes several annexes. Annex A covers the measurement lead connections. This is sometimes critical, especially when the operator is not applying an adjustable ground braid to the transformer bushing. On subsequent attempts to generate the transformer signature, replicating the high-frequency band is almost impossible. The shortest distance between the bushing terminal and the bushing’s bottom flange is recommended and addressed by CIGRE in Technical Brochure 342.

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 clearly understood before it can be chosen for the most 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 or frequency domain spectroscopy (FDS) is a test to evaluate the overall condition of the transformer’s insulation. This overall insulation evaluation allows the user to identify:

- 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 linear single-input/single-output (SISO) system can be described with an impulse response \( h(t) \) or its transfer function \( H(j\omega) \) (Figure 3).

In the case of power transformers, the electromagnetic phenomena is well described by different laws (Faraday, Lenz, Ampere); by simple inspection, it is easy to understand that 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 4).
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 into the other end. The output voltage is measured in magnitude and phase. This information allows for interpretation and measurement of the effective impedance of the winding at that specific frequency.

The frequency sweeps from 20Hz up to 2MHz. Instruments available in the field have frequency bands starting from very low values up to frequencies beyond 20Mhz. 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 the transformer design. IEEE and IEC have set reference boundaries on the frequency response to identify the different sections of the transformer (Figure 5).

A good grounding connection practice allows for accurate and repeatable readings (Figure 6). Make sure the ground braid connection to the bushing’s bottom flange is solid and that the flange is grounded. Sometimes, oxidation or paint do not allow a good connection to ground, and error messages will come out of the unit not sensing the expected voltage.

One important thing to emphasize regarding an SFRA measurement is that it provides a very clear scan of the electromechanical construction, but interpretation may always be validated with a different testing technique (Table 1).

### Table 1: Correlation of SFRA with Other Testing Practices

<table>
<thead>
<tr>
<th>SFRA Mode</th>
<th>Transformer Characteristic</th>
<th>@ 60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit</td>
<td>Looks at winding and core characteristics</td>
<td>Similar to excitation current test</td>
</tr>
<tr>
<td>Short Circuit</td>
<td>Looks at winding</td>
<td>Similar to leakage reactance</td>
</tr>
<tr>
<td>Capacitive Inter-Winding</td>
<td>Looks at capacitance between windings</td>
<td>Similar to capacitance test</td>
</tr>
<tr>
<td>Inductive Inter-Winding</td>
<td>Looks at inductance of both windings</td>
<td>Similar to TTB</td>
</tr>
</tbody>
</table>

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. The simple example of a two-winding transformer shows the three electrodes needed to complete testing: HV, LV, and ground (Figure 7). An excitation ac signal is applied to one electrode in a wide range of frequencies — typically from 1kHz down to 1mHz — and current is measured.
on the other electrode. 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.

A two-winding transformer can analyze the following:
• 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

The response is a combination of a two-material complex dielectric system. For the majority of power transformers, the complex insulation is composed of liquid insulation (mineral oil) and solid insulation (cellulose). The dielectric response of these two materials 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 8. Moisture in the solid insulation is only 1% and the conductivity of the oil is $1 \times 10^{-13}$ pS/m. Temperature of the insulation system in this example is 20°C.

For interpretation of 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 and briefly described below in Figure 9.

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 ($\sigma$) of the liquid insulation. The information indicates the overall condition of the insulation and is a simple but powerful tool for coordinating and prioritizing necessary actions to be taken on a transformer.

Note that DFR is not an invention of the last millennium; it was developed in the mid 1990s and continues to evolve. Because it has a proven effectiveness in the field, its applications grow every day. No doubt, part of this development is the use of a multi-frequency measurement system capable
of reducing the testing time by almost 40% in the frequency domain. Testing time is critical for end users who are limited to fast testing procedures before re-energizing a transformer in the field, or as part of a planned shut-down for maintenance purposes. Furthermore, if the transformer was under load but de-energized and set for testing, a long DFR testing time may incur insulation thermal changes that will affect accuracy of the results — the lower the frequency, the longer the time needed to complete the testing procedure.

A correlation between temperature and the minimum frequency to complete the test has been recommended for end users. This allows acquisition of sufficient data to estimate moisture content in the solid insulation and conductivity of the liquid insulation. Interestingly, factors other than temperature influence the response — 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 five to 60°C with very high accuracy.

CONCLUSIONS

Technology is moving rapidly. Great advances in power electronics, telecommunications, and nanomaterials opened new opportunities to explore the condition of critical components installed in the electric energy system in more detail.

As technology advances, new testing techniques are being developed, and the international community needs to comprehend the benefits and limitations of these techniques. The different institutions working worldwide to provide best practices and guidelines rely on the knowledge and experience of transformer manufacturers, academics, researchers, field users, and instrument manufacturers who work together for the best interests of the technical community.

New technologies must be tested and tried in the field before they are brought to the attention of international committees for developing the necessary recommendations based on actual facts and real needs of end-users. 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.

More discussion regarding these advanced technologies is needed. A great amount of information has been gathered and published by the most relevant technical publications worldwide and international standards organizations, so use this to keep transformer diagnostics tools up-to-date.