> **The effort for standardization of the DFR test on different applications emphasizes the interest of advanced diagnostics among power system operators**

HV instrument transformer condition assessment

Dielectric Frequency Response

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> **Failure of instrument transformers may result in explosions and damage to other devices in the vicinity and risk for operations staff**

ABSTRACT

No matter how big or small your substation is, instrument transformers stand vigilant in the electric system, protecting and controlling. In order to satisfactorily accomplish this task, industry, academia, and instrument transformer manufacturers have worked with international standard associations such as IEC, IEEE and NETA to compile the theoretical fundamentals of operation, specifications by class of accuracy, and suggested testing methods to ensure safe and reliable operation of current and potential transformers under innumerable conditions.

Due to their durability, robustness, size, cost or time-consuming testing practices, instrument transformers in the field are not always a top priority. Nonetheless, failure during operation, lack of accuracy and unexpected activation of major protective devices usually result from poor maintenance and inefficient IT testing practices.

Dielectric frequency response provides a reliable method to assess the insulation condition of instrument transformers from manufacturing to service life in the field. The guidelines and references provided in this article allow asset managers, substations operation staff, and testing specialist to apply and interpret results from this method as it is applied to MV and HV instrument transformers.

KEYWORDS

current transformer, potential transformer, dielectric frequency response, frequency domain spectroscopy, diagnostics, standardization

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1. Introduction

The electrical industry is increasingly demanding every day. The addition of distributed generation, alternative backup systems, renewable energy sources, extra-high voltage transmission lines, AC/DC conversion stations and many more technologies into the power grid makes it more complex and sensitive to transient changes. Current transformers (CTs) and voltage/potential transformers (VTs/PTs) are instrument transformers (ITs) used for protection, control and metering applications; they silently serve the power grid by creating an interface between high-energy components and low-energy supervisory devices where human intervention is expected.

Despite design considerations, instrument transformers are subjected to mechanical, electrical, dielectric and thermal stresses just like any other component in the substation infrastructure. Therefore, the electromagnetic circuit and the dielectric components of the instrument transformer must be carefully tested to assure integrity of the instrument transformers and accuracy of the information transferred to metering and supervisory devices.

Proactive maintenance and informative diagnostic procedures avoid dealing with the aftermath of high energy explosions in the field. Regardless of the application, whether related to metering or protection, generation, transmission or distribution, HV instrument transformers' hermetical design and low volume of liquid insulation limit the ability for broad understanding of their internal insulation system.

For over twenty years, dielectric frequency response (DFR) has been used in the field and its application on oil-paper impregnated (OIP) instrument transformers is acquiring more and more acceptance in the industry and field. It is therefore relevant and pertinent to explain the benefits DFR provides to the reliable operation and sustainability of the electric grid.

2. Dielectric frequency response

During the last two decades, the development of DFR, also known as Frequency Domain Spectroscopy (FDS), has found wide acceptance with 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.

IEEE recently published the document IEEE C57.161 "Guide for Dielectric Frequency Response Test". The contribution and participation of specialists, end-users, testing equipment manufacturers, transformer manufacturers and academia has been derived in a practical and comprehensive guide for the use of DFR technology.

The dielectric response of oil-paper insulation in frequency domain is obtained using a low voltage sinusoidal signal (140 Vrms) in a wide spectrum of frequencies typically from 1000 Hz down to 1 mHz. The use of an alternate electric field allows acquisition of a unique dielectric signature of the insulation system in terms of a complex permittivity ε as a function of frequency.

$$\varepsilon = \varepsilon'(\omega) - j\varepsilon''(\omega)$$

Where:

$\varepsilon'(\omega) = \varepsilon_r + \chi'(\omega)$- is the real part of the complex permittivity and represents the real capacitance of the dielectric material

$\varepsilon''(\omega) = \frac{\sigma}{\omega\varepsilon_0} + \chi''(\omega)$- is the imaginary part of the complex permittivity and represents the losses in the dielectric material.

The ratio of the imaginary to real component of the complex permittivity is called the dissipation factor or tangent delta.

$$tan(\delta) = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)}$$

The applied voltage and the current through the insulation are measured. The capacitance and loss at each frequency are then calculated from the ratio of current to voltage and the phase difference between the current and the voltage known as the angle φ. Therefore, $\delta = 90^o - \varphi$ represents the angle between the total current and the capacitive current vectors.

The results are represented as a log-log plot of the real and imaginary parts of the permittivity (or capacitance) or the dissipation factor versus frequency as shown in Figure 1.

Throughout the service life of any instrument transformer, the dielectric response is expected to change due to aging, degradation, water contamination and possible internal contamination. Continuous assessment by means of oil sampling in instrument transformers is not possible and; consequently, off-line testing is required.

2.1. DFR hook-up diagrams for instrument transformers

Those involved in assessing the insulation condition of HV instrument transformers need to consider the following:

a. DFR in OIP type insulation is used mainly to determine:
  - The percentage of moisture concentration in the solid insulation
  - The conductivity of the liquid insulation

b. DFR, as any other dielectric testing procedure, is temperature dependent and insulation temperature is critical for the analysis.
  - Instrument transformers have no temperature indicators mounted on them
  - Winding temperature might be

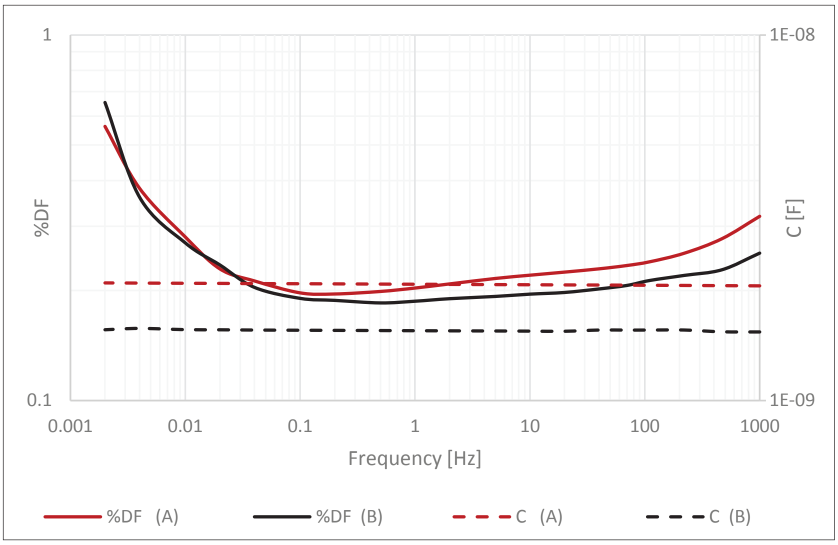

Figure 1. DFR on EHV CTs – exceptional dryness of solid insulation (<0.4 %) and the finest condition of liquid insulation

estimated by multi-point measurement externally
- Winding temperature might be established by winding resistance measurement

c. DFR for estimation of moisture should use the capacitive region of the instrument transformer where the majority of the solid insulation resides.
- Overall insulation for HV current transformers
- High-to-ground insulation on HV VTs. Typically, an electrostatic shield is installed in between the HV and LV windings
- Verify with the manufacturer the material used for the HV insulation. Typically, kraft non-thermally upgraded paper is used, but one may encounter ITs built with thermally upgraded paper

d. DFR measurement might be affected by high noise and interference in the substation [1]. Especially when the specimen under test is of low capacitance and the test needs to cover very low frequencies.
- In the event of testing in EHV substations or under environmental conditions increasing the interference on the measurement circuit, it is compulsory to use a voltage amplifier to improve signal-to-noise ratio. The HV DFR system runs at 1400 V_{RMS}.
- Because of the construction of instrument transformers, at temperatures close to 20°C, the required frequency band is 1000 Hz down to 5 mHz. Even at very low temperatures, close to 0°C, the lowest frequency for the sweep may not need to be less than 1 mHz.

Therefore, the suggested connections to test a HV CT using DFR technology are shown in Figure 2. The test mode is GSTg-RB defined as "grounded specimen test" (GST) with guard on red and blue leads.

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The value of capacitance sometimes differs from values taken in factory. Keep in mind that factory test is typically a UST test (ungrounded specimen test) or what is also known as a two point test, but in the field, the unit is solidly connected to the ground and the test is purely GST where stray capacitance bias might be observed.

If a CT with test tap is tested, the measurement connection is directly to the test tap in UST mode as shown in Figure 3.

For inductive type HV voltage transformers, the connections are as shown in Figure 4.

2.2. DFR on instrument transformers throughout their service life

Instrument transformers' active part is assembled in factory following rigorous

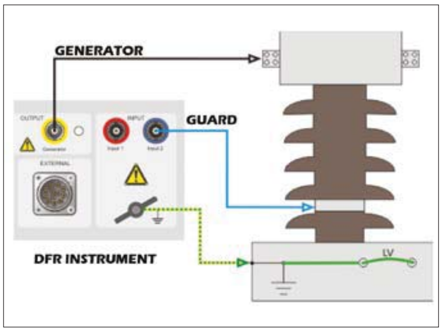

Figure 2. Hook-up diagram for DFR test on a HV CT without test tap

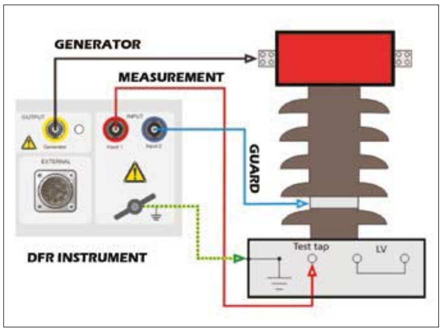

Figure 3. Hook-up diagram for DFR test on a HV CT with test tap

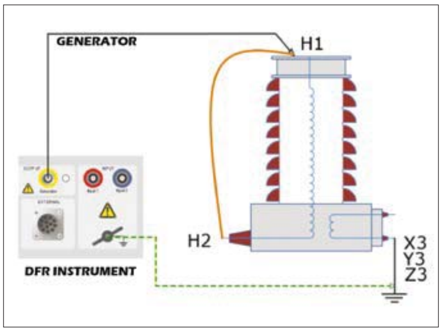

Figure 4. Hook-up diagram for DFR on a HV VT

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procedures based on precise engineering specifications aiming to achieve the highest quality standards. In this manufacturing process, the instrument transformer is tested in factory before the dry-out process to determine the percentage of moisture content in the solid insulation.

In factory, the active part of the instrument transformer can be tested using DFR and the moisture content can be determined before the dry-out process. It is complicated for factory to test every single unit before the oven, but the test can be certainly carried out on selected specimens out of a group of units of similar design.

Before the dry-out, the percentage of moisture content in the solid insulation typically fluctuates between 4 % and 6 %. The dielectric response of an IT before the dry-out is observed in Fig. 5.

During the process, depending on the manufacturing installation, the active part goes into a drying chamber for thermal dry-out. Later the IT is fully assembled and set for vacuum dry-out. Every stage can be evaluated using DFR as shown in Fig. 6. %DF Thermal corresponds to the dielectric response after the thermal dry-out process, and %DF Vacuum corresponds to the dielectric response after the vacuum process.

The dielectric response is influenced by the temperature of the insulation system at every stage of the dry-out process. Nowadays, the analysis of the dielectric response is improved with the application of the "Individual Temperature Correction" (ITC) algorithm [2] which allows analysis of the dielectric response obtained at any temperature and normalized to one reference

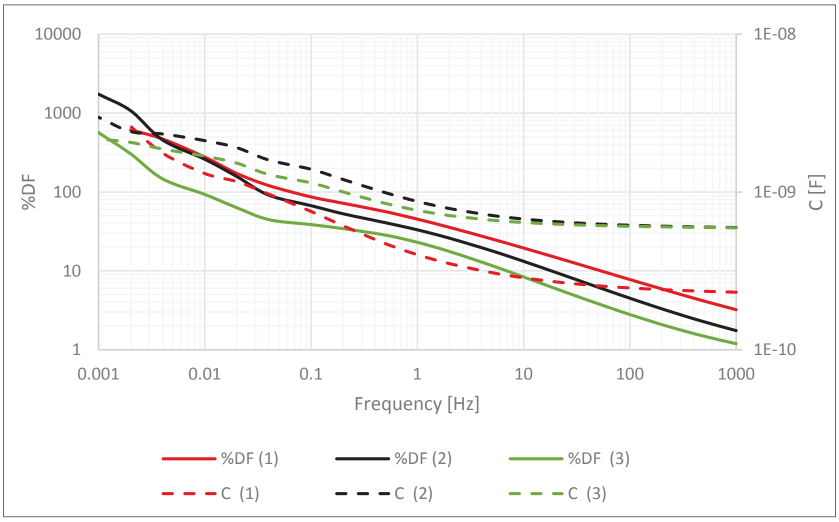


Figure 5. DFR on instrument transformers before dry-out. Moisture content >4 %

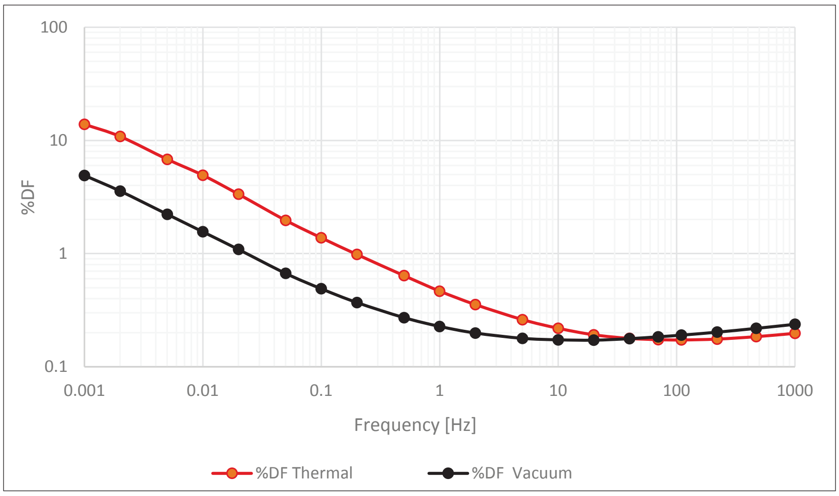
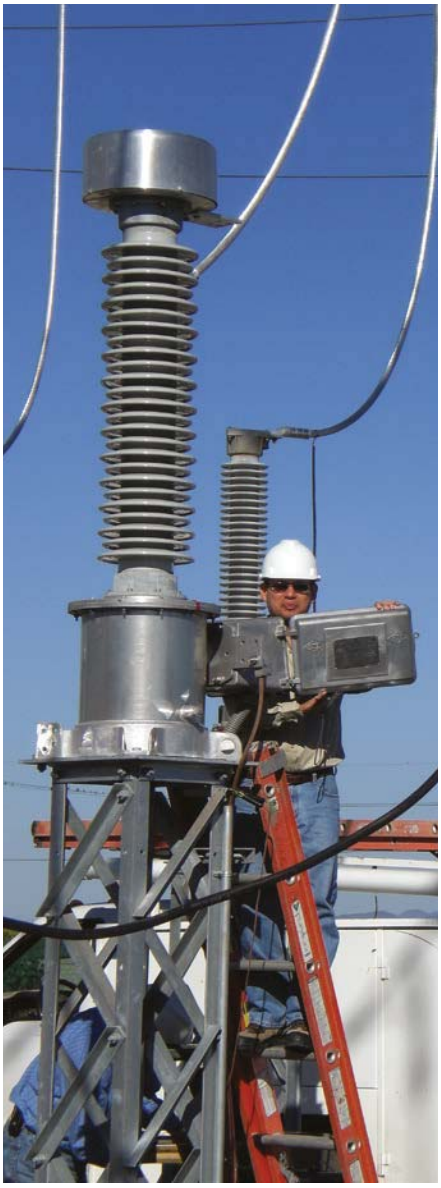


Figure 6. DFR test during dry-out process in factory. ~0.8 % moisture after thermal process and ~ 0.6 % moisture after vacuum process



temperature (20°C) as presented in Fig. 7. Therefore, ITC opens a new chapter in instrument transformer diagnostics based on a normalized dielectric response at 20°C where different frequencies could be used for analysis and interpretation of results. From here, the most sensitive is 1 Hz.

Conclusion

IEEE recently published the "Guide for Dielectric Frequency Response Test" as applied to power and distribution transformers immersed in oil. A research group is working now on the development of the guide as it applies to OIP bushings. The effort for standardization of the DFR test on different applications emphasizes the interest of advanced diagnostics among power system operators.

Failure of instrument transformers with OIP insulation may result in explosions and damage to other devices in the vicinity and risk for operations staff.

Throughout this article, the benefits of dielectric frequency response and individual temperature correction has been briefly summarized. DFR allows not only the determination of the percentage of moisture content in the solid insulation of instrument transformers but also atypical responses are indicative of contamination or degradation of the insulation system.

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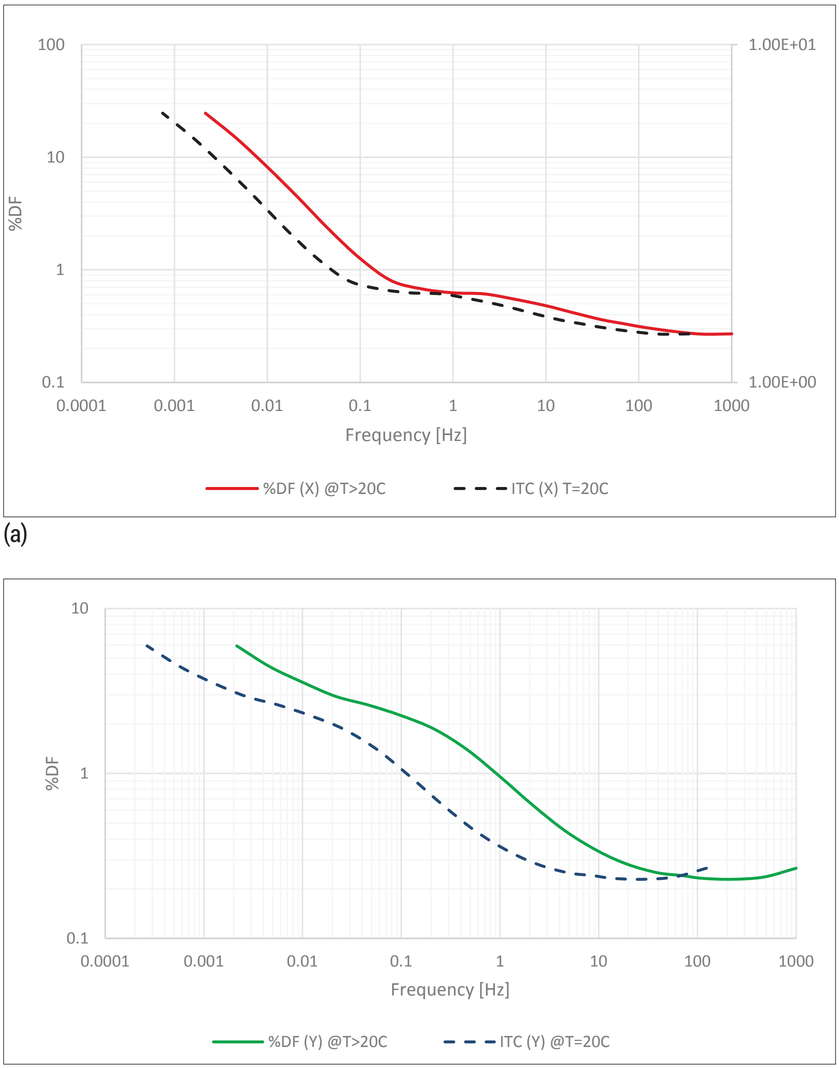
> **Atypical DFR responses are indicative of contamination or degradation of the insulation system**



(a)

(b)

Figure 7 (a) i (b). Application of ITC to normalize entire dielectric response at temperature other than 20°C

Author

Diego Robalino currently works for Megger North America as Principal Engineer, where he specializes in the diagnosis of complex electrical testing procedures. While doing research in power system optimization with a focus on aging equipment at Tennessee Technological University, Robalino received his electrical engineering PhD from that institution. Robalino has over 20 years of involvement in the electrical engineering profession with management responsibilities in the power systems, oil and gas, and research arenas. He is a Senior Member of the IEEE, member of the IEEE/PES transformers main committee and a certified Project Management Professional with the PMI. He is an active member of the IEEE/DEIS Electrical Insulation Conference, author and co-author of multiple technical articles related to power, distribution and instrument transformer condition assessment.