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A STUDY OF OIL-PAPER INSULATION VOLTAGE DEPENDENCY DURING FREQUENCY RESPONSE ANALYSIS

D. M. Robalino[1*], J. Cheng[2], P. Werelius[3] and R. Alvarez[4]
[1]Megger, USA
[2]Megger, China
[3]Megger, Sweden
[4]Universidad Nacional de La Plata, Argentina
*Email: <diego.robalino@megger.com>

Abstract: People often believe that power factor/dissipation factor testing at power frequency (50/60 Hz) usually exhibits a flat response as a function of test voltage if the insulation is in good condition. Dielectric Frequency Response, DFR is the extension of power factor testing except that the measurement is performed from 1 kHz down to typically 1 mHz. It is a very useful tool for evaluating the moisture content in solid insulation of HV and EHV components such as power transformers, bushings, instrument transformers and PILC cables. The voltage dependent phenomenon also called "the Garton effect", caused by paper absorbing electric charges in oil is investigated. The application of DFR in HV and EHV substations required a conceptual analysis of the phenomenon to better interpret the condition of the insulation system while increasing the signal to noise ratio to minimize the effect of surrounding interference. As a result of this work, authors provide practical recommendations regarding test voltages and frequency ranges to be used under high interference environments. The wide application of the method is supported with experimental field data.

1. INTRODUCTION

Line-frequency power factor/dissipation factor testing is one of the most common routine practices in factory and field to determine the condition of the insulation in complex MV, HV and EHV electrical equipment.

Manufacturers, researchers, service companies and field operators have been using capacitance (C) and power factor/dissipation factor (PF/DF) metering technology for almost 80 years looking at results obtained at line-frequency values (50/60Hz). The instrumentation used for this test has improved gradually as power electronic components became more efficient and lighter, but the testing practices in the field faced challenges of increasing voltages and higher electromagnetic interference (EMI) environments at the substations.

In this paper, authors focus particularly on the advanced method to diagnose oil-paper insulation systems based on the dielectric response. The dielectric response method involves measurement of dielectric parameters such as capacitance (C), permittivity (ε), power factor (PF) and/or dissipation factor (DF) as a function of frequency. The frequency range of the dielectric response starts at 1000 Hz and typically stops at 1 mHz, depending on the temperature of the insulation under test. One of the advantages of this method is the capability to discriminate between the properties of the cellulose and the liquid insulation [1]. As a result, the percentage moisture content (%mc) of the solid insulation and the conductivity (σ) or %DF of the liquid insulation can be obtained.

Nevertheless, due to the wide spectrum of frequencies used for the measurement sequence, the applied voltage in most cases does not exceed 140 V_{rms}. This voltage level, much lower than the traditional 10 kV line-frequency measurement, faces a new challenge: the signal-to-noise ratio is extremely low, especially at low frequencies. The way to overcome this challenge is to increase the signal-to-noise ratio by boosting up the test voltage. The effect of such approach is discussed throughout this document.

2. THE DIELECTRIC RESPONSE

The dielectric response might be obtained in the time or frequency domains.

In the time domain, the most common test is the insulation resistance (IR) test. For IR test, the instrument applies a DC voltage and leakage current is measured. Only one minute is required for IR test and 10 minutes for polarization index (PI) test. The PDC method is an extension of IR testing except that the test time is longer, typically 10,000 (ten thousand) seconds.

In the frequency domain, line-frequency power factor (PF) or dissipation factor (DF or tan δ) instrumentation allows for a quick test at voltages up to 12 kV (for portable field application). The test is intended to measure dielectric losses in the insulation and not to overstress the insulation. Therefore, test voltages should not exceed the specimen's rated voltages.

An application of the line-frequency PF/DF test is the tip-up test or line-frequency power factor at different voltages. The power factor tip-up is defined as the difference in the power factor measured at two voltages. Its application has been well investigated specially in dry type HV insulation where the increase of PF/DF was originally attributed to the increase of the electrical conductivity of the walls of the cavities subjected to partial discharges and also of the resistivity of the solid insulation material [2]. The power factor component arising from the dielectric losses generally changes very little with voltage; however, with some defects in the solid insulation, such as uncured resin sections or contamination due to ionic impurities, significant space charge losses may arise leading to an increasing or decreasing PF/DF value with voltage [3].

Dielectric Frequency Response (DFR) also known as Frequency Domain Spectroscopy (FDS) is an advanced application of the line-frequency PF/DF method. During DFR test, the insulation system is subjected to a low sinusoidal voltage of 140V_{rms} and measurements are carried out at different frequencies starting from 1 kHz down to typically 1mHz if the temperature of the insulation is around 20°C. Figure1 is an example of the DFR response of a liquid filled power transformer.

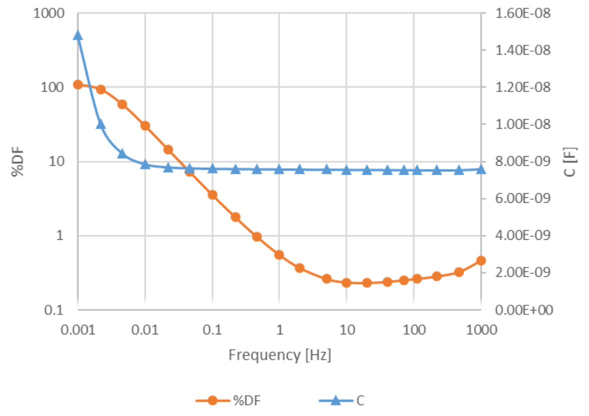


Figure 1: Dielectric frequency response of the inter-winding insulation of a liquid-filled two-winding transformer

3. SUBSTATION INTERFERENCE

As part of the study presented in [4], DFR readings, taken in 88 randomly selected substations, provided average reference values of AC and DC interference. The line-frequency AC interference was found to range between 0 – 100 μA, and DC interference ranged between 0 – 50 nA. The main concern during DFR testing is the effect of the low frequency interference and DC interference, affecting specifically the low frequency DFR measurements. As a matter of fact, environmental conditions will also influence the measurement. Under high ambient relative humidity, the DC and low frequency interference is more active as compared to dry environments.

The problem in hand is almost negligible when testing inter-winding power transformer insulation using a UST (ungrounded specimen test) mode. Although, a full DFR test will involve GST (grounded specimen test) and/or GST-guard mode where the measurement is more sensitive to the noise influence.

The technology available nowadays makes use of noise suppression algorithms and filters to mitigate the effect of noise. These algorithms certainly improve the quality of measurements but the challenge in the field increases when low capacitance specimens (i.e., bushings, HV instrument transformers and HVDC transformers) require advanced diagnostics. This is easy to visualize because the capacitive current is a direct function of voltage and frequency as described below:

$$I_c = \omega \cdot C \cdot V = 2\pi \cdot f \cdot C \cdot V \tag{1}$$

Figure 2 depicts the influence of noise on the dielectric response measurement on C1 of three bushings mounted on a two-winding power transformer with a capacitance value of approximately 300 pF.

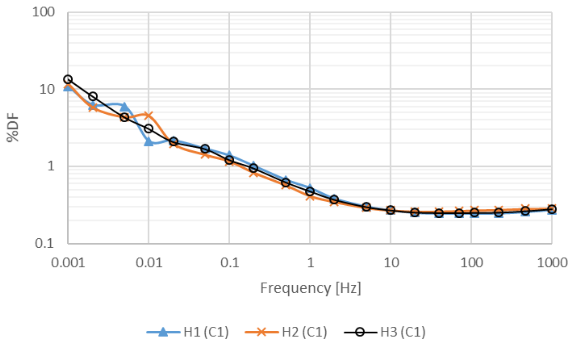


Figure 2: Low Voltage DFR measurement on C1 for three POC type bushings

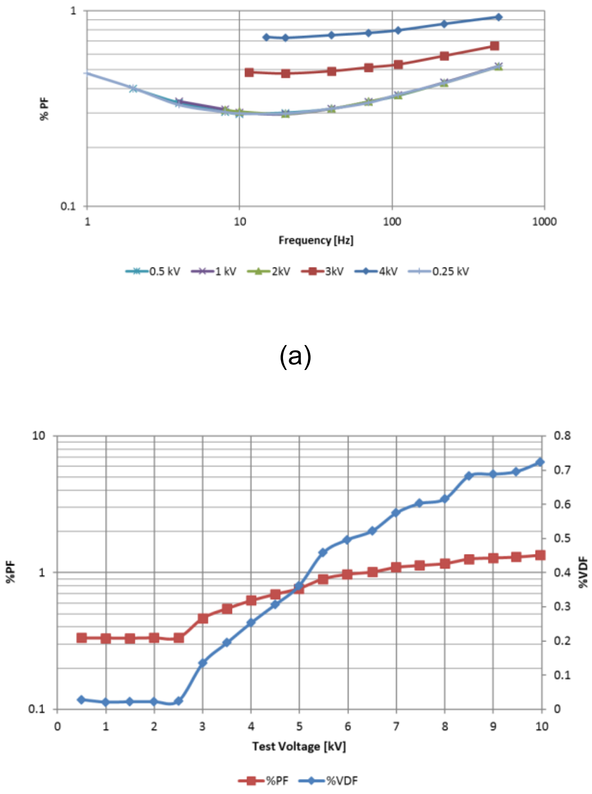
As observed in the example of Figure 2, the influence of noise is not constant (not even of the same polarity). The test on the C1 capacitance of H1 and H2 show greater influence of the surrounding interference as compared to H3. The very low frequencies below 10 mHz are the ones mainly affected. All frequencies above 10 mHz show a smooth response.

4. VOLTAGE DEPENDENCE

The voltage dependence phenomenon in solid insulation during line-frequency PF/DF test is well described in [3] and [5]. The losses measured in the insulation system when a line-frequency (50/60Hz) signal is applied, is a composite of dielectric losses which are constant with voltage and power loss due to discharges. Mathematically this can be expressed as the total conductance of the system in (2)

$$G = \omega C_0 \tan\delta_0 + \frac{2f}{V_m}\sum_{0}^{1/f} \Delta Q_i \sin \omega t_i \qquad (2)$$

Based on (2), if no discharges occur, the amount of charge increase on the electrodes or conductors as a result of internal discharges *(ΔQ_i)* equals zero. To visualize this effect, a narrow band DFR test at different voltage levels carried out on epoxy type MV equipment is presented in Figure 3.



(a)

(b)

Figure 3: (a) DFR obtained from MV epoxy-type insulation specimen at different voltages; (b) Tip-up test and measured % voltage dependence factor.

Figure 3(a) shows the effect of the applied voltage on the solid insulation along a frequency sweep. Important to notice here that even in a solid insulation system, the DFR at 0.5, 1 and 2 kV overlap perfectly one on top of the other.

In Figure 3(b) the tip-up test shows the discharge inception voltage at about 2.5 kV. This effect is also observed using the so called percentage voltage dependence factor (%VDF) representing the distortion of the measured current with respect to its fundamental. The distortion in the measured current signal, as represented in Figure 4, implies that the insulation system has lost its linearity.

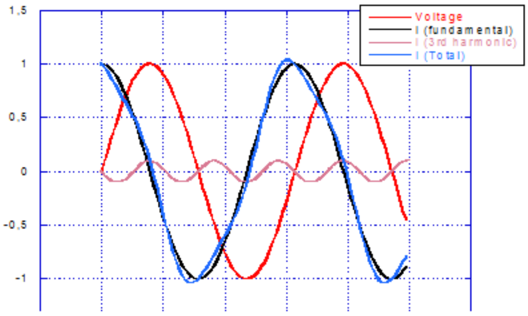


Figure 4: Applied Voltage and measured current through a voltage dependent insulation system

Therefore, the %VDF can be calculated in a similar way as the total harmonic distortion (THD) of the measured current signal:

$$\%VDF = \frac{\sqrt{\sum_{h=2}^{k} I_h^2}}{I_1} \cdot 100\% \qquad (3)$$

Transformer liquids behave like weakly dissociated electrolytes and display a linear ohmic response when exposed to low voltages. Considering the use of voltages greater than 140 V_{rms}, users should take into account the effect that this may have on the low frequencies of the dielectric response. In [6] Garton describes the effect of different magnitudes of an alternating electric field on the dielectric loss of films of insulating liquids in porous impregnated insulation.

The Garton effect is described as the charge accumulation occurring at the interface between paper and oil insulation due to the differences of electrical properties of each material. The accumulation speed is proportional to the field strength that is perpendicular to the interface and the ion accelerating time. In the frequency domain, the alternating electric field changes its polarity regularly and when the electric field strength is high and the charging period is short, the charge accumulation at the interface could be neglected.

As a result, when the frequency response reaches very low frequencies and the charging period increases, the charge accumulation will take place and the non-linearity effect is observed.

5. THE EFFECT ON THE FREQUENCY DOMAIN RESPONSE

First of all, the analysis of the dielectric response in the frequency domain (as mentioned in section 2), provides the following information:

- Percentage moisture concentration in the solid insulation;
- Conductivity and/or dissipation factor of the liquid insulation;
- Individual temperature correction of PF or DF from any temperature value to a normalized comparative temperature based on the unique and individual condition of the insulation system; and,
- Identification of non-typical responses, resulting from contamination of the insulation system.

Figure 5 describes the regions within the frequency spectrum of the DFR measurement that correspond to each of the materials and mathematical modelling parameters.

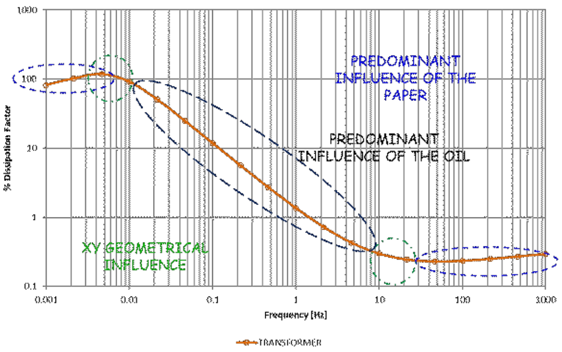


Figure 5: Frequency response of liquid filled power transformer showing the different areas of influence of paper, liquid and XY geometrical modelling parameters

From the experimental work presented in [7], capacitance and loss factor are influenced mainly by the increase of electric field in the frequencies between 1 and 5 mHz. Frequencies between 1 kHz down to 5 mHz have none or negligible effect. This particular statement is verified testing OIP bushings in factory at $140V_{rms}$ and $1400V_{rms}$ without the influence of external interference, and results are presented in Figure 6.

Two high voltage bushings are tested simultaneously in factory using the same excitation signal. The nonlinear effect is observed to influence the frequency domain response at ~ 10 mHz. Down to this frequency, the %mc is verified with the modelling software and results are summarized in Table 1.

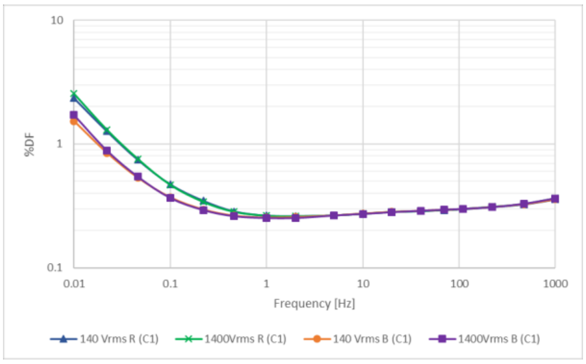


Figure 6: DFR measurement at different voltages of two similar OIP bushings R & B tested simultaneously in factory (~20°C) without interference.

Table 1. DFR analysis on bushings R & B

Test Voltage	140Vrms		1400Vrms	
Dielectric Characteristics	***%DF @60Hz & 20°C***	***%mc***	***%DF @60Hz & 20°C***	***%mc***
Bushing R	0.299	0.44	0.299	0.47
Bushing B	0.3	0.41	0.3	0.42

Table 1 shows no discrepancy in the analysis of the conditions of R & B bushings tested with LV and HV DFR.

Finally, the work presented in [8] summarizes the experience of the authors testing EHV bushings mounted on 745 kV reactors. The use of LV DFR yield only distorted curves and the only alternative was to boost up the signal-to-noise ratio using a DFR amplifier with 1400 V_{rms} output signal.

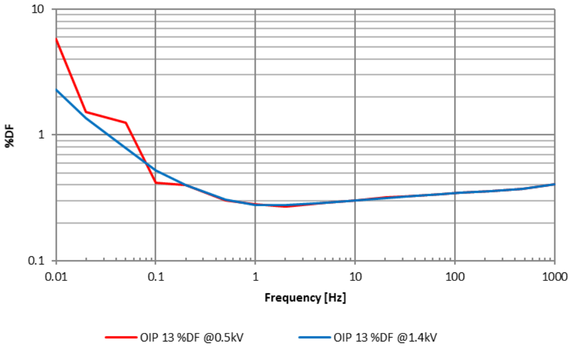


Figure 7: DFR test on OIP 800 kV bushing at $500V_{rms}$ and $1400V_{rms}$ in the field

The only way to obtain a realistic and accurate response of the EHV bushings required the use of HV DFR. Without it, the response will be misleading and the effect of the AC and DC interference in the substation could create an uncertain bias in the modelling reference curve that would yield to erratic diagnostics.

6. CONCLUSIONS

The complex insulation system of liquid filled power transformers and bushings is of organic origin and thus, susceptive to aging and degradation. DFR has demonstrated in the last 20 years (first field portable unit for DFR was brought to the market in 1997) the capability to provide valuable information not observed before with line-frequency PF/DF test.

This paper clearly identified the effect of the magnitude of the voltage applied to the insulation system under test and the possible sources of non-linearity.

In the higher frequency range, power losses due to discharges will affect the linearity of the response.

In the frequencies below 5 mHz, the dielectric loss of films of insulating liquids in porous impregnated insulation affects the linearity of the response.

In that regard, authors recommend to:

- Perform DFR UST measurements on power and distribution transformers on the inter-winding capacitance at low voltage (140V_{rms}) in the frequency range between 1 kHz and typically 1 mHz (at ~20°C). For lower temperatures, lower frequencies may be needed.
- Perform DFR UST measurements on low capacitance specimens (i.e. bushings C1) with LV DFR in factory down to 2 mHz (at ~20°C). In the field, it may be necessary the use of HV DFR and test at 1400V_{rms} to overcome the effect of noise. In order to avoid the effect of non-linearity at very low frequencies, the HV DFR test should run down to 5 mHz or when the harmonic distortion of the measured signal is observed.
- HV and EHV Bushings do not require very low frequencies to be analysed as the dominant material is paper.

REFERENCES

[1] S. M. Gubanski, et al., “Dielectric Response Diagnoses for Transformer Windings,” CIGRE 2010

[2] R. Goffaux, “On the nature of dielectric loss in high voltage insulation”, IEEE Transactions Electrical Insulation, Vol. EI-13, No. 1, 1978.

[3] IEEE Std. 286-2000 (R2012). “IEEE Recommended practice for measurement of power factor tip-up of Electric machinery Stator Coil insulation”.

[4] J. Skoldin, P. Werelius, M. Ohlen, “Dielectric Frequency Response Measurement Technology for Measurements in High Interference AC and HVDC Substations”. 2011 TechCon Asia-Pacific, Sydney, Australia

[5] T. W. Dakin, “The Relation of Capacitance Increase with High Voltages to Internal Electric Discharges and Discharging Void Volume”. AIEE Transactions. Part III, Issue 3, 1959

[6] C. G. Garton, “Dielectric loss in thin films of Insulating Liquids” Proceeding Institution Electrical engineering, Vol. 88, 1941, p. 103-120.

[7] J. Cheng, P. Werelius, D. Robalino, D. Wang, “The nonlinear behaviour of the transformer insulation system”, IEEE Proceedings of the Conference on Electrical insulation and Dielectric phenomena, 2013

[8] I. Güner, D.M. Robalino, P. Werelius, “HV and EHV bushing condition assessment – Field experience” CIGRE – IEC 2016 Colloquium on EHV and UHV (AC & DC), Montreal, 2016.