21, rue d'Artois, F-75008 PARIS
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HV and EHV BUSHING CONDITION ASSESSMENT – FIELD EXPERENCE

ISMAIL GÜNER
Hydro Quebec
Canada

DIEGO M. ROBALINO
Megger
USA

PETER WERELIUS
Megger
Sweden

SUMMARY

HV and EHV bushings are used on transformers, shunt reactors and circuit breakers to provide a solid connection between the bus and the internal components typically immersed in a different insulation media. Bushings are designed to transmit electric energy through a grounded barrier, and if allowed to deteriorate, may explode with considerable violence and cause extensive damage to adjacent equipment, power outages, soil contamination, and injuries to personnel working in the proximity.

As reported in CIGRE TB 642 [1], windings, tap changers and bushing related failures were the major contributors to transformer failure. It is also noted also that 17% of transformer breakdowns are caused by bushing failure often followed by explosion, tank rupture, fire and potentially human harm. In order to minimize the failure risk of HV bushings, their materials, design and construction have evolved. To date, the insulation system in HV and EHV bushings is mainly oil-impregnated paper (OIP) and resin-impregnated paper (RIP); in lesser quantities, resin-bonded paper (RBP). The design of HV and EHV bushings takes into account the impact of the shunt reactor, transformer or circuit breaker where it will be mounted during service.

This document describes the experience acquired in the field testing OIP EHV bushings with methods such as capacitance (C) and power factor/dissipation factor (PF/DF) measurement and more advanced testing techniques, including dielectric frequency response (DFR), and dissolved gas analysis (DGA) to better assess the "real" condition of a bushing insulation system. Utility operators and manufacturers gain from field experiences where the use of assertive testing techniques, troubleshooting and root cause analysis derive in practical, technically sound and economical decisions to continue with the operation of the equipment, change the operational conditions, implement additional investigation or remove the unit from service.

DFR has been used mainly by manufacturers, researchers and utilities to determine the moisture concentration in the solid insulation. The benefits presented by this non-destructive

and non-intrusive technique, based on low energy measurements of C and PF/DF in a wide frequency band, enabled a broad visualization of the unique dielectric properties of complex insulation systems. DFR has proven to be a practical tool to determine the moisture concentration in the solid insulation, the contamination in the liquid insulation, and the presence of contaminants creating a distortion on the typical dielectric response. Also, DFR allows individual temperature correction of measured PF/DF from any temperature to a normalized value (typically 20°C) without the use of average/generic tables. Therefore, advanced users have been able to use DFR not only for diagnostics but also for troubleshooting [2].

DGA is a widespread method, also applicable for bushings' condition assessment [3]. DGA provides end-users with fundamental information about an active electric or thermal fault condition affecting the concentration of gases dissolved in the liquid insulation.

Case studies from the field, presented herein, provide a reference for test execution in the field and the practicality of DFR and DGA to identify risk of failure of EHV bushings and the potential correlation between these two advanced diagnostics techniques. Best practices to perform these measurements in the field, especially when encountering high EMI environments, are also included. HV DFR in the frequency domain provides a complete dielectric response with a higher signal to noise ratio and valuable data can be acquired to be used by asset managers, maintenance and operations staff to better prioritize maintenance activities and/or replacement of units with increased risk of failure.

KEYWORDS

Bushings, OIP, dielectric frequency response, frequency domain spectroscopy, dissolved gas analysis, interference, DFR, FDS, DGA.

BACKGROUND

Condenser type bushings have been used for the past 50 years in high and extra-high voltage systems. They are produced in three types of technology: RBP (resin bonded paper), OIP (oil impregnated paper), and RIP (resin impregnated paper). Capacitance (C) and power factor/dissipation factor (PF/DF) for OIP and RIP bushings are permanent parameters until a disturbance occurs, making them favorable for condition diagnostics when properly interpreted. Throughout this paper, the findings on OIP condenser type bushings are elaborated.

Hydro-Québec (HQ) had U-type 735kV bushings mounted on single phase shunt reactors. Due to catastrophic failures, the decision of replacing them with specially designed OIP-type bushings adapted to the existing reactors was taken many years ago. Since 2012, three out of these 45 replacement bushings failed in service, causing major explosions and collateral damages in important substations. HQ considered necessary to set a 150-meter radius security perimeter around all the reactors that have the same model of OIP bushing. HQ restricted access to these areas until the root cause of failure is declared with certainty. The consulted manufacturer and the specialists from HQ concluded that the bushing had a certain degradation of insulation prior to failure. It became paramount for the HQ asset management team to identify a reliable testing methodology, besides routine practices, capable to determining potential risks of operation before catastrophic failure occurs.

With the impact of aging on power system infrastructure, changing economic climate and increased demand for electricity, utilities are forced to invest wisely in new infrastructure. A procedure should be implemented as a set of testing practices corroborating one each other and helping asset managers to decide if the bushing must be put under continuous monitoring, should be repaired, or definitely removed from the operation area and replaced. The data provided in [1] reflects the concern of utility operators and justifies any measure taken to minimize hazardous operation. The number of transformers failed due to bushing failure is presented in Figures 1 and 2.

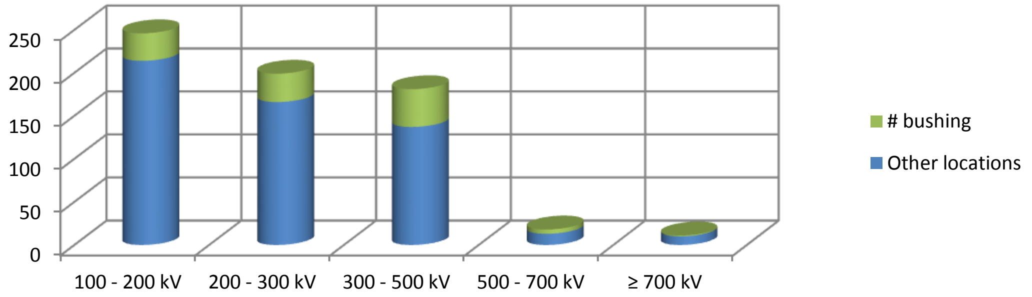


Figure 1 Number of transformers failed due to bushing failure and other causes with respect to voltage class [1].

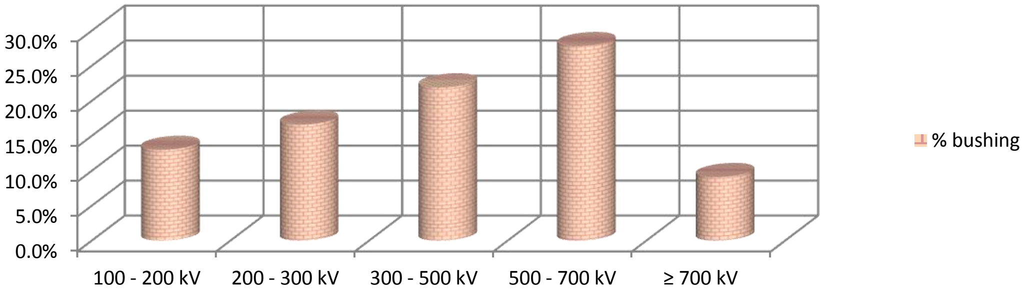


Figure 2 Percentage of transformer failed due to bushing failure with respect to voltage class [1]

Together, C, PF/DF, Dielectric Frequency Response (DFR) and Dissolved Gas Analysis (DGA) provide a wide set of information regarding the dielectric condition of the insulation system. The successful application of DFR in oil-immersed power and distribution transformers to evaluate moisture concentration in the solid insulation, conductivity of the liquid insulation, contamination in the form of non-typical responses and the ability to move the information from the frequency domain into the thermal domain suggests this to be a tool to be used for bushing and instrument transformer diagnostics [4].

BUSHING FIELD TESTING

In the scope of root cause and failure analysis, HQ made DFR measurements on 800kV OIP bushings of which 24 are presented in this document. Correlations between dielectric frequency responses and DGA results were analyzed. From the utility stand point, the disadvantage of DFR measurement on bushing failure analysis is the offline reactor time that can go up to 4 hours including disconnection from the network. A proper test set-up is crucial for correct interpretation of DFR results.

Capacitance and line frequency (50/60Hz) PF/DF on HV and EHV bushings are mentioned in the international standards [5] [6] [7] as part of the design and routine testing procedures for bushings. The specimen, as stated in the cited references, shall be dry and clean and the ambient condition should be ideal for testing (10 - 40°C). In this work, the field experience showed good results down to 5°C which was the lowest temperature at which DFR tests were carried out.

In order to facilitate the bushing diagnostic, one layer (usually the last or the second last layer) is made accessible externally at an electrode commonly referred to as the capacitance/test tap. Capacitance C_1 is measured between the HV conductor and the test tap, and capacitance C_2 is measured between the test tap and the grounded flange.

The following measurement procedure should be used [8]:

a. Measure the bushing's PF/DF
b. Determine the bushing's temperature
c. Obtain the appropriate correction factor corresponding to the bushings temperature

Since the measured PF/DF value is temperature dependent, test results should be normalized to a temperature base (20°C) using temperature-correction factors available from manufacturers or obtained by measurement of the dielectric response of the insulation system and later converted from the frequency domain into the thermal domain [9]. Table correction factors obtained from generic sources are average at best and therefore are subject to error [10].

If the PF/DF measurement of a bushing increases from 1.5 to 2 times from its initial reading, then the test frequency should be increased or the bushing should be removed from service. If the power factor/dissipation factor measurement triples the initial test reading, then the bushing should be removed from service [5]. For OIP bushings, a limit of 0.5% DF at line frequency is considered as per [11].

Bushing capacitance is compared with both nameplate and previous tests in assessing bushing condition. This is especially important for capacitance graded bushings where an increase in capacitance of 5% or more over the initial/nameplate value is cause to investigate the suitability of the bushing for continued service. The manufacturer should be consulted for guidance on a specific bushing. There are many reasons why insulation power factor and/or capacitance may increase over the life of a bushing. Nevertheless, PF/DF and capacitance tests at line frequency may not be conclusive (and sometimes even misleading). The use of DGA and DFR becomes advantageous and rational to complement field routine testing practices.

THE LEARNING CURVE

The application of DFR on MV and HV bushings has been discussed in the literature but EHV substations brought a new challenge to the typical practice. In the field, DFR is carried out at low voltages, typically 140Vrms, with the objective to measure the dielectric parameters of the insulation under test. Although, the major challenge for this method was to overcome the EMI of EHV and UHV substations. Valuable field experience reported in [12] helped establishing measurement guidelines.

First of all, the DFR test was carried out on OIP bushings where previous DF readings indicated a fairly good condition. The objective here was to verify effectiveness of the method and to visualize the dielectric response of a unit in good dielectric condition. Nevertheless, at this early stage, the first challenge had to be overcome. Tests were performed at 140Vrms obtaining a distorted response due to external noise/interference. Using a voltage amplifier, the test voltage was increased until a satisfactory response was obtained at 1400Vrms. Results are presented in Figure 3.

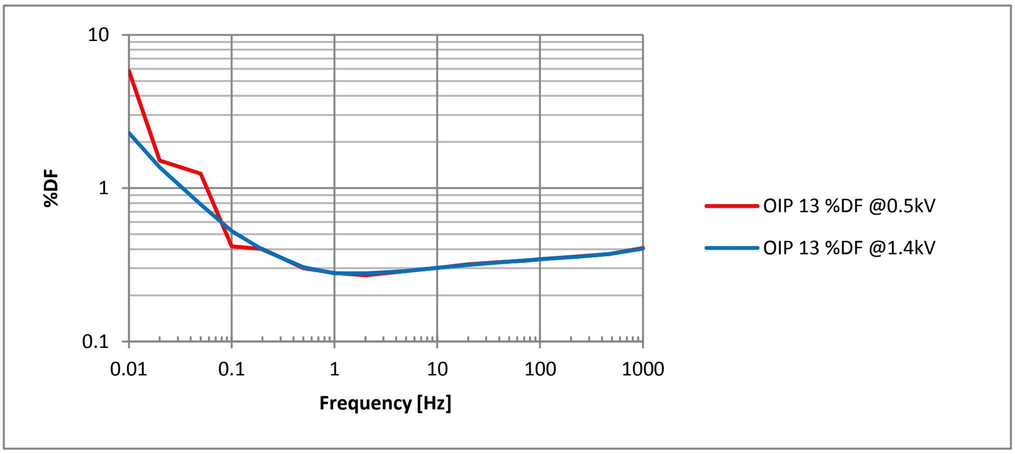


Figure 3 OIP 800 kV 1986 OIP 13 DFR at different voltage levels

The experience reported of HV DFR testing on power transformers [12] confirmed that the 800kV bushings can be tested in the field using HV DFR (1400V_{rms}) within a satisfactory frequency range from 1kHz down to 10mHz with minimum distortion under EMI.

The learning process is followed by a comparative analysis between sister units. The specimens OIP 13 and OIP 14 were tested at 17°C and 20°C to minimize the thermal effect on the dielectric response. A similar dielectric and thermal response was identified and it is presented in Figure 4 and Figure 5 respectively.

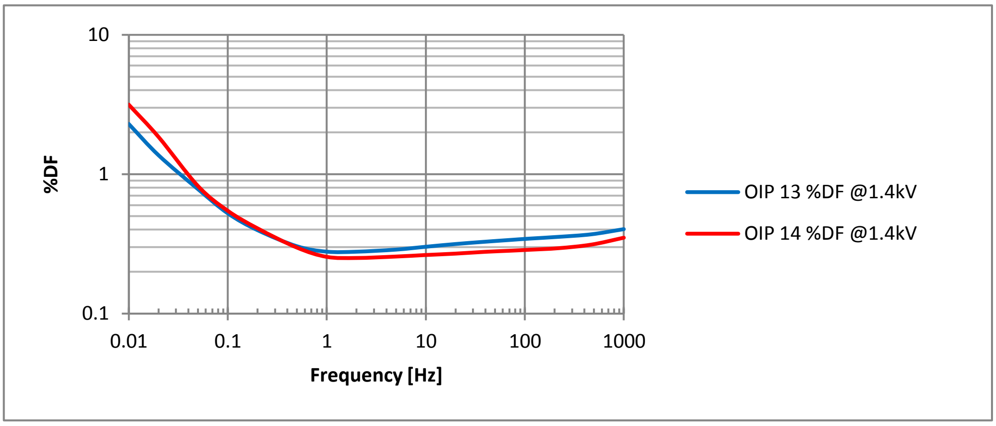


Figure 4 DFR of sister bushings OIP 13 (17°C) and OIP 14 (20°C)

The results of the analysis of OIP 13 and OIP 14 using their dielectric response are compiled in Figure 6. The overall condition of both bushings is good even though a discrepancy exists in the line frequency %DF. For the reader, these are good examples showing the dielectric response of bushings in good condition at a temperature of 20°C or very close to it.

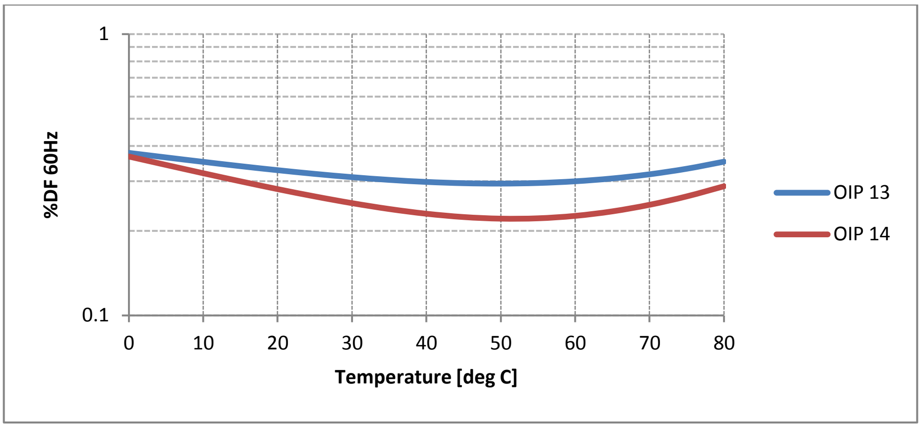


Figure 5 Individual Temperature Correction for bushings OIP 13 and OIP 14

The specimens OIP 1 and OIP 2 are tested in the workshop at only 140Vrms. In a warehouse, for a horizontal measurement, the bushing must be lifted above ground to a point where the measurement has no influence due to ground proximity; and, if the bushing is tested in a vertical position, keep the shield of the test cable at some distance not to influence on the response.

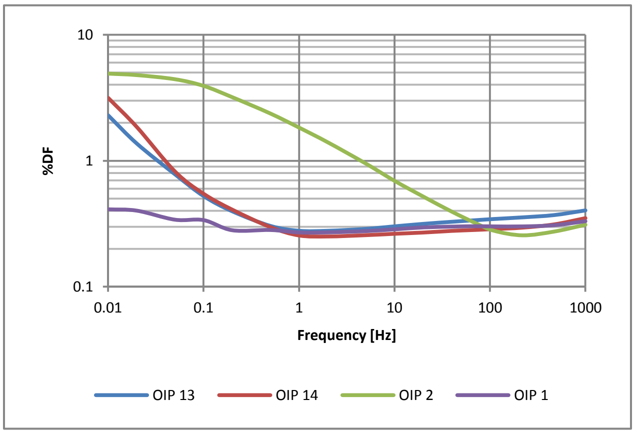
DFR	**Specimen**	**Condition**	**%DF @ 20C**			
			60 Hz	**10 Hz**	**1 Hz**	**0.1 Hz**
	OIP 13	good	0.32	0.29	0.28	0.57
	OIP 14	good	0.28	0.26	0.25	0.73
	OIP 2	bad	0.31	0.61	1.58	3.57
	OIP 1	good	0.30	0.29	0.27	0.32

Figure 6 Benchmark OIP bushing DFR reference data with respect to % moisture concentration and %DF different frequencies corrected to 20°C using Individual Temperature Correction (ITC)

The obtained responses of OIP 1, 13 and 14 show a flat response from 1kHz down to approximately 1Hz. Only, a graphic representation of the response is worthless without the ability to normalize the response to a reference temperature, in this case 20°C using the Individual Temperature Correction (ITC) algorithm described in [9]. In Figure 6 the %DF of line frequency, 10Hz, 1Hz and 0.1Hz tests normalized to 20°C have been included.

On a second instance, the test carried out in the field of a bushing mounted on the reactor should be similar to the test carried out on a stand-alone bushing. The capacitance tap allows measurement of the capacitance and dissipation factor of the bushing itself, despite the fact that the bushing could be connected to a transformer winding that has a ground capacitance significantly higher than the capacitance of the bushing.

EXPERIMENTAL WORK

Additional measurements were carried out in the field to better understand the effect of external factors on the DFR measurements. It is important to mention that while performing DFR testing, the frequency selection should contemplate frequencies different from line frequency values and its harmonics. Any values close to 2nd, 3rd, or higher harmonics will create a disturbance in the measurement. Avoiding these frequencies eliminates the problem of spikes in the frequency response. On a reactor, the terminals of the line bushing and the neutral bushing (H_0 disconnected from neutral bus) should be shorted. Not shorting the winding terminals together sometimes gives some resonance-alike response at higher frequencies.

HV DFR measurements on EHV bushings provided smooth responses down to 5mHz. The focus at this point is to be able to determine the condition of the EHV bushing without the need to run into very low frequencies. For bushings, extending the DFR test to very low frequency has limited value. A wide range, from 1kHz down to 10mHz certainly gives valuable information, for an accurate correction to normalized temperature values and to observe non-typical dielectric responses due to contamination or partial discharge (PD) activity. The use of a guard on the surface of the bushing is a common practice to avoid the path for surface currents that may affect DFR measurements. The effect of a guarded connection during PF/DF measurements of C_1 in the bushing is still a technique that requires further investigation.

From the tests carried out, it is observed that %DF at line frequency even normalized to 20°C does not provide a direct indication to differentiate a good bushing from a bad one. Looking at the information gathered from 24 specimens, %DF at line frequency and properly corrected to 20°C remains in the range between 0.2 and 0.5%. In a good scenario, %DF of 10Hz, 1Hz and 0.1 Hz corrected to 20°C by means of the ITC algorithm also reside in this region [9]. The faulty systems clearly deviate from this zone as presented in Figure 7.

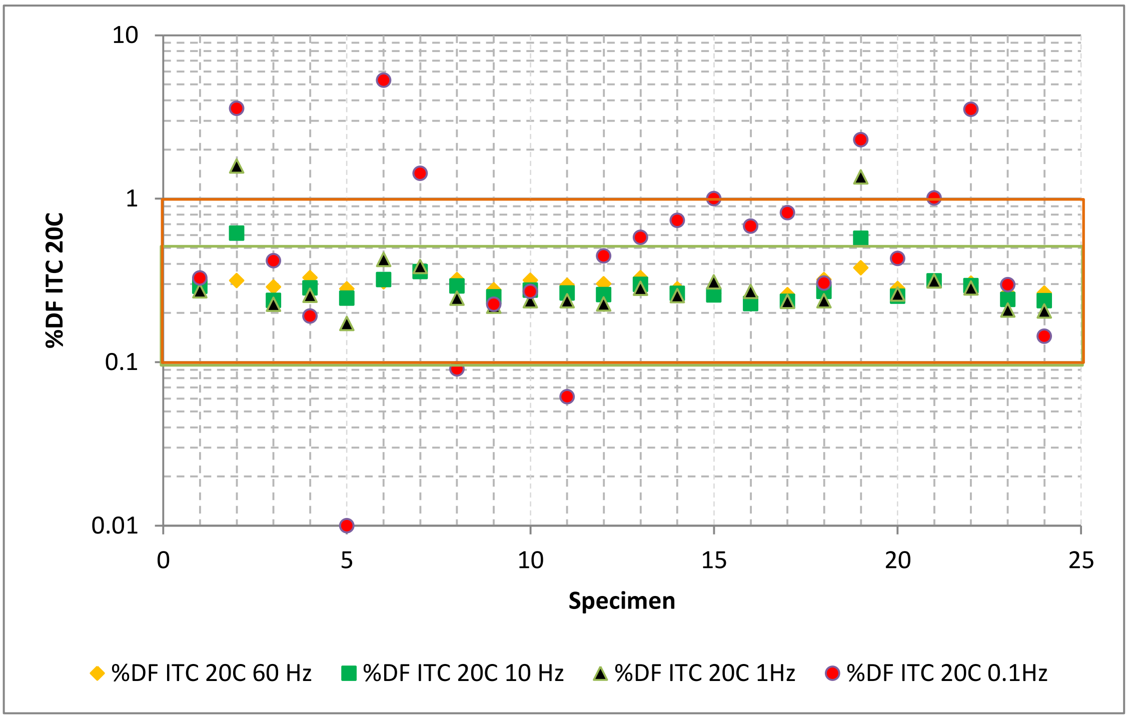


Figure 7 %DF corrected to 20°C at 60, 10, 1 and 0.1 Hz of 24 OIP bushings

Figure 8 DGA results and acceptance limits

In Figure 7, a differentiation has been made. Values obtained between 0.1% and 0.5% are considered to be typical of good condition bushings, a second boundary corresponding to an aging condition of the insulation system with increased losses was set up to 1% and results observed above the 1% upper limit or below the 0.1% lower limit are indicators of potential bad condition. As the DFR application is becoming more practical in the field and the challenges are being overcome, it is time to put together the DFR results with the DGA parameters obtained in the laboratory. A correlation between DFR and DGA will serve as the primary indication of risk of failure.

Table 1 summarizes the findings obtained in the experimental work. In this table, the word indicator DFR is a measurement obtained in the range greater than 1% and less than 0.1% DF. In the DGA measurements, indicator is a measurement obtained beyond the limits suggested by industry general practice (line on each graph in Figure 8).

Table 1 Summary of Indicators of DFR and DGA

Sample	**Indicator DFR**		**Indicator DGA**						
	1Hz	**0.1Hz**	H_2	**CO**	CO_2	C_2H_2	CH_4	C_2H_6	C_2H_4
OIP 2	X	X	X			X	X	X	
OIP 5		X							
OIP 6		X							
OIP 7		X							
OIP 8		X							
OIP 11		X							
OIP 17						X			
OIP 19	X	X	X			X	X	X	
OIP 21		X							
OIP 22		X							

From Table 1 OIP 2 & OIP 19 show DFR and DGA indicators suggesting potential risk of failure. The complete dielectric response of these bushings is presented in Figure 9.

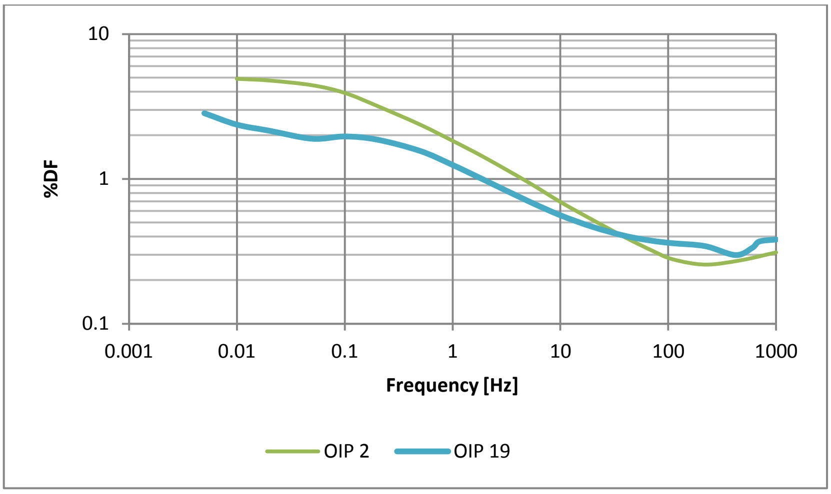


Figure 9 DFR of OIP 2 & OIP 19

Solid particles of carbon and hydrocarbon polymers (X-wax) are byproducts of partial discharge activity. When the X-wax is present in sufficient quantity, it can increase the dissipation losses in the paper-oil insulation hence reduce dielectric strength of insulating oil.

[3]. Two OIP bushings that showed abnormal DFR results were dismantled and inspected. X-wax residues were observed on the solid insulation in both cases.

In OIP 2, the response shows high conductivity of oil produced by PD or x-wax concentration. In the response of OIP 19 an unusual behavior of the response in the frequency band between 10Hz and 10mHz is observed. The “hump” is an indication of contamination or degradation of the insulation.

CONCLUSIONS

The learning curve in this section is a good reference for field users. In EHV and UHV environments the use of HV DFR is paramount to overcome the effect of external EMI on the DFR measurement. In this particular project a DFR instrument with 140Vrms output voltage together with a voltage amplifier capable to boost the voltage output to 1400Vrms was used. The instrument together with the amplifier was capable to measure from 1kHz down to 5mHz with satisfactory accuracy. It is recommended to perform DFR down to at least 10mHz.

HV dielectric frequency response can be used to detect other problems, beside high moisture content in OIP bushings. Therefore, a reference DFR response from the manufacturer is recommended for utilities during design reviews.

The use of line frequency PF/DF was not sufficient to detect insulation degradation in the investigated OIP EHV bushings. The study determined that reliable indicators were found to be %DF at 1Hz and 0.1Hz but because of the thermal effect, these values can only be analyzed if properly corrected to a reference temperature (20°C) by the individual temperature correction algorithm based on the unique dielectric response of the bushing.

Solid particles of carbon and hydrocarbon polymers (X-wax) are byproducts of partial discharge activity. Field experience and inspections showed that DFR technique can be used in order to detect presence of X-wax when conventional insulation tests at power frequency can fail to do so.

Further research is to be conducted to enhance the correlation between DFR and DGA and to investigate the sources of the non-typical responses. However, for end users, a method to differentiate between good or bad bushing insulation is imperative and DFR is an alternative to minimize DGA sampling in bushings and prevent catastrophic failure.

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