Traditional field-testing practices evaluate the average insulation condition of high voltage substation equipment by measuring line frequency dissipation factor, which represent the dielectric losses of the system

1 Hz dissipation factor – The new trend for insulation condition assessment

ABSTRACT

The dielectric frequency response has evolved into a definitive analysis to determine the condition of the insulation system. The analysis of the NB DFR tests spectrum provides valuable pieces of information that can be used for the diagnostics of high voltage equipment. A case study has been conducted for a 10 MVA, 69/13.09 kV Dyn1 two-winding transformer that is tested in the field after OLTC repairs and before re-energization.

KEYWORDS:

case study, dielectric frequency response, dissipation factor, power factor

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Dielectric frequency response has evolved into a definitive analysis to determine the condition of the insulation system

Introduction

Traditional field-testing practices evaluate the average insulation condition of high voltage (HV) substation equipment by measuring line frequency (50/60 Hz) dissipation factor (DF) (or power factor (PF)), which represent the dielectric losses of the system. The DF (or PF) test result is frequency and temperature-dependent. Other factors, such as geometrical design, aging, moisture, and contamination, will also influence the measured values.

Throughout an electrical asset's service life, line frequency DF may not change, may slightly increase or sometimes may even slightly decrease. Research shows that even a 'good' line-frequency DF is not always representative of a 'good' insulation system [1], and the final assessment, in the hands of asset managers and operations managers, has always had a degree of uncertainty.

So naturally, these questions follow: How does one confirm the good condition of transformer insulation? What is this new trend for DF/PF field testing? What have we learned from almost a century of using DF/PF technology in the field?

The answer: we have learned a lot and it is time to move forward to innovative solutions that will bring reliable, safe, and efficient operation of the electrical system, together with peace of mind for decision-makers and asset owners. Proper assessment of insulation should consider at least one additional DF value obtained at a frequency different from 50 or 60 Hz. This additional measurement should be carried out at a frequency with enough sensitivity to truly validate the results or contradict 'good' line-frequency PF/DF results when the overall condition of the insulation system is not suitable for continuous operation.

This document introduces the new era of insulation DF/PF testing, and the benefit of testing insulation DF at line frequency (50 or 60 Hz) and 1 Hz. The information is supported using a real field example where a 1969 vintage transformer goes through routine testing after completing on-load tap changer (OLTC) maintenance.

> A 10 MVA, 69/13.09 kV Dyn1 two-winding transformer is tested in the field after OLTC repairs and before re-energization

Testing at frequencies different from 50 or 60 Hz

For many years, the common approach to insulation diagnostics in the factory and field has been looking at the dielectric losses at line frequency or a frequency very close to it. As an AC test, the use of a power source capable of increasing the voltage from the line supply value up to 10 or 12 kV provides additional advantages for field users. HV excitation current testing and stepped voltage DF/PF testing (tip-up test) are of important use in the field.

In the last 25 years, dielectric frequency response (DFR) has evolved into a definitive analysis to determine the condition of the insulation system. DFR is a very practical tool used to determine the moisture concentration in the solid insulation and the conductivity of the liquid insulation using a wide spectrum of frequencies for accurate estimation. The spectrum of frequencies used by DFR is typically from 1 kHz down to 1 mHz, and this range is temperature dependent.

To simplify the work in the field, the experience gathered over the last two decades has been fundamental to improving and modifying the way the dielectric dissipation factor is carried out. The unique option to test line frequency (50 or 60 Hz) and 1 Hz as a verification frequency is the safe way to detect insulation degradation without the need for additional trending and potentially inaccurate temperature correction tables. Testing at line frequency and 1 Hz is a proactive way to validate insulation test results and the best way to avoid dealing with doubtable misleading results. The reason for selecting 1 Hz is directly related to the direct characteristic of the loss factor (ε”) where, by definition, it will vary inversely proportional to the frequency value. It is also clear (see Fig. 1) that for ‘good’ condition insulation, the frequency range in the decade from 10 to 100 Hz is almost linear, and greater sensitivity is observed at frequencies below 10 Hz.

It is better to see the use of 1 Hz in practical field examples in the next section.

Field Experience

A 10 MVA, 69/13.09 kV Dyn1 two-winding transformer is tested in the field after OLTC repairs and before re-energization. The overall insulation, as well as HV bushings, are tested using line-frequency and 1 Hz dissipation factor.

Overall transformer line frequency dissipation factor (LF DF) tests:

The losses measured at 30 °C for the low voltage winding-to-ground (CLG) and high voltage winding-to-ground (CHG) insulation systems were higher than those measured for the interwinding, or high voltage winding-to-low (CHL), insulation system of the transformer. To normalize DF results to 20 °C, the Individual Temperature Correction (ITC) algorithm is used [2]. The temperature-corrected (i.e., 20 °C equivalent) LF DF test results for CLG and CHG insulation components were within acceptable limits (< 0.5 %), and even within limits established for new transformers. However, the CHG LF DF test result (0.43 %) was approximately 1.8 times the CHL LF DF result (0.24 %) (Table 1).

Based on recent experiences using Narrowband Dielectric Frequency Response (NB DFR) testing and successes in finding hidden issues not observed by LF DF tests [3], an NB DFR test was carried out. An NB DFR test is the measurement of % PF or % DF at different frequencies from 1 Hz up to 505 Hz.

In addition, the testing specialist performed 10 kV C1 (main bushing insulation capacitance) LF DF tests on the transformer’s high-side winding bushings (Table 2) at 30 °C. The H3 bushing produced elevated LF DF test results (measured and temperature-corrected) that were notably greater than results for the sister bushings mounted on the same transformer. Accordingly, the individual temperature-corrected LF DF test results for bushings H1 and H2 earned the bushings good (G) ratings, while the individual temperature-corrected LF DF test result for bushing H3 resulted in an aged (A) assessment, as displayed in Table 2.

The test results also display an interesting anomaly in the ‘individual temperature

Table 1. Overall transformer LF DF test results - initial condition

Transformer overall test									
Test No.	Insul test	Test mode	Test V	Capacitance [pF]	% DF	% DF 20 °C	Corr. fac.	mA	WATTS
1	CHG + CHL	GST-GND	10	5,957.29	0.29	0.30	1.04	22.38	0.65
2	CHG	GSTg-RB	10	2,160.56	0.41	0.43	1.04	8.10	0.32
3	CHL	UST-R	10	3,789.61	0.23	0.24	1.04	14.27	0.32
4	CHL'			3,796.73				14.27	0.32
5	CLG + CHL	GST-GND	7	10,899.93	0.33	0.34	1.04	41.05	1.34
6	CLG	GSTg-RB	7	7,111.37	0.38	0.40	1.04	26.79	1.02
7	CHL	UST-R	7	3,771.11	0.23	0.24	1.04	14.20	0.32
8	CHL'			3,788.56				14.26	0.32

Table 2. C1 test results for the high-side bushings, including 10 kV LF DF and 250 V NB DFR results, measured and temperature-corrected via the ITC method

Transformer bushing C1 test									
		% DF at 60 Hz			% DF at 1 Hz			% DF at 505 Hz	
Designation	C1 [pF]	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C
H1	265.55	0.26	0.27	G	0.39	0.29	G	0.28	0.33
H2	267.29	0.28	0.29	G	0.64	0.4	G	0.31	0.35
H3	266.51	1.1	0.65	A	14.4	7.92	I	0.43	0.49

correction' values. A temperature-correction (TC) factor is used to determine a test specimen's 20 °C equivalent LF DF value when the specimen is power factor tested at a non-20 °C temperature.

An ITC factor is a TC factor that is unique to every test specimen as it is based on the specimen's specific insulation condition. Note that the ITC factor for bushing H3 (~0.6) is different from the ITC factors determined for bushings H1 and H2 (~1.04). The non-uniformity that exists in these ITC factors is a clear indication that the H3 bushing has a different insulation condition than H1 and H2 bushings.

For a detailed description of the ITC algorithm, please refer to [2].

Transformer bushing C1 test investigation

ITC factors are far more accurate than TC factors accessed in a look-up table. To underscore the problem with temperature-correction look-up tables, consider the following:

1. If the end-user had relied on correction tables, the TC factor would have been determined based on the average of the ambient and bushing temperatures. This would have resulted in a TC factor close to unity for all three bushings – valid for bushings H1 and H2 but not for H3.
2. Bushing H3 would have been removed in this scenario due to a > 1 % DF value. However, had the bushing been tested at 10 °C instead of at around 30 °C, its measured and temperature-corrected DF test results by look-up tables may have been low enough to pass acceptance criteria as a normal, service-aged unit.

Given the LF DF test results, the utility performed NB DFR tests on the high-side bushings. 1 Hz and 505 Hz measurements from this testing are provided in Table 2. These tabular results affirm the good condition and rating of bushings H1 and H2 but escalate the assessment of the H3 bushing to an investigate rating.

NB DFR test results for bushing H3 (the blue trace in Fig. 1) revealed the following two worrisome electrical characteristics, and the utility replaced the bushing.

A bushing in good condition will have an ITC temperature-corrected DF value ≤ 1 % at 1 Hz. The ITC temperature-corrected 1 Hz DF test result of bushing H3 was 7.92 % (Table 2).

The test results also display an interesting anomaly in the 'individual temperature correction' values, i.e. the temperature-correction factor used to determine a test specimen's at 20 °C

NB DFR tests on the high-side bushings conducted with the frequency from 1 Hz and 505 Hz affirm the good condition and rating of bushings H1 and H2 but not for the H3 bushing

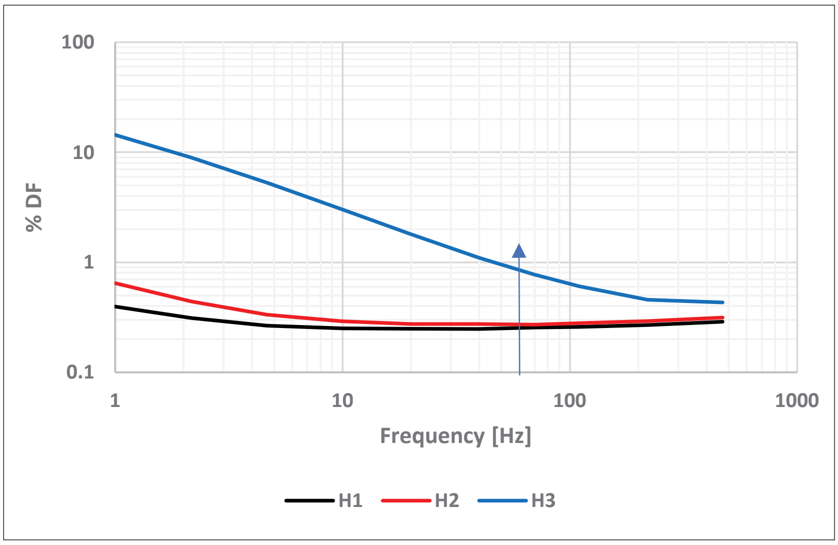

Figure 1. NB DFR measured test results for the high-side 69 kV bushings

Table 3. Pre-installation C1 test results for new H3 replacement bushing, 10 kV LF DF, and 250 VAC NB DFR

Transformer bushing C1 test									
		% DF at 60 Hz			% DF at 1 Hz			% DF at 505 Hz	
Designation	C1 [pF]	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C
H3 - replacement	232.43	0.22	0.22	G	0.31	0.22	G	0.26	0.3

After replacing the H3 bushing, the utility repeated the overall LF PF tests on the transformer to observe the good effects of the H3 bushing replacement on the overall HV winding insulation test characteristics

The 10 kV LF DF test result, 1.1 % (Table 2), and the LF DF test result at 250 V, a typical NB DFR test voltage, taken from Fig. 1, 0.8 %, are different. This implies a voltage dependence of the LF DF test results.

Before installing in the transformer, LF DF and NB DFR testing were performed on the H3 replacement bushing to confirm its integrity. LF DF and NB DFR test results indicated the bushing's good (G) condition (Table 3) (Fig. 2). The response in the 1 to 505 Hz spectrum is quite a linear, showing no degradation of the insulation.

After replacing the H3 bushing, the utility repeated the overall LF PF tests on the transformer to observe what effect the H3 bushing replacement had on the overall HV winding insulation test characteristics (Table 4). A notable improvement was noted.

With the problem corrected in the overall winding insulation test results, the utility

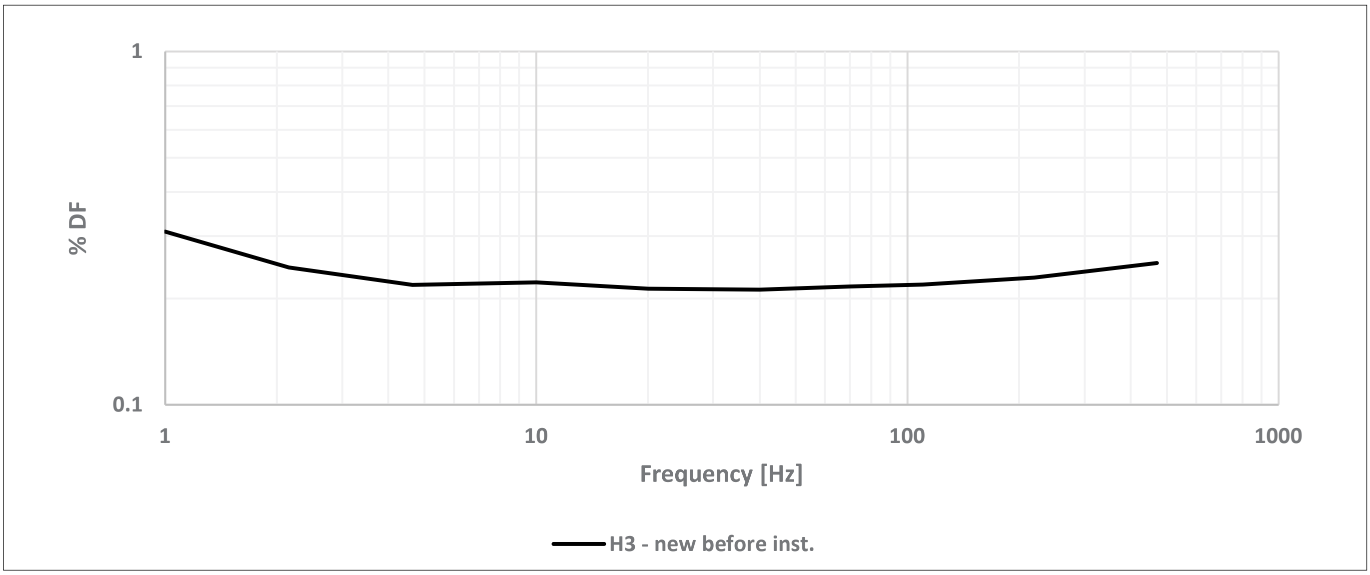

Figure 2. Pre-installation NB DFR test results for H3 replacement bushing

Table 4. 10 kV overall transformer LF PF test results after H3 bushing replacement

Transformer overall test									
Test No.	Insul test	Test mode	Test V	Capacitance [pF]	% DF	% DF 20 °C	Corr. fac.	mA	WATTS
1	CHG + CHL	GST-GND	10	5,922.59	0.25	0.26	1.04	22.25	0.55
2	CHG	GSTg-RB	10	2,125.91	0.30	0.31	1.04	7.97	0.23
3	CHL	UST-R	10	3,789.61	0.23	0.24	1.04	14.27	0.32
4	CHL'			3,796.68				14.27	0.32
5	CLG + CHL	GST-GND	7	10,899.93	0.33	0.34	1.04	41.05	1.34
6	CLG	GSTg-RB	7	7,111.37	0.38	0.40	1.04	26.79	1.02
7	CHL	UST-R	7	3,771.11	0.23	0.24	1.04	14.20	0.32
8	CHL'			3,788.56				14.26	0.32

Table 5. Post-installation C1 test results for H3 replacement bushing, 10 kV LF DF, and 250 VAC NB DFR

Transformer bushing C1 test									
		% DF at 60 Hz			% DF at 1 Hz			% DF at 505 Hz	
Designation	C1 [pF]	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C
H3 - new / mounted	231.4	0.24	0.35	G	0.26	0.24	G	1.1	1.22

staff then complemented their now routine procedure with a 10 kV LF DF test at 26 °C on the installed H3 replacement bushing (Table 5).

The 10 kV measured LF DF test result for the H3 replacement bushing was acceptable. However, the ITC temperature-corrected LF DF result is ~ 1.5 times the measured value, while the 1 Hz measured and ITC temperature-corrected results are nearly the same, but the 505 Hz DF test result is both non-typical and notably higher than the 505 Hz DF test results for the H1 and H2 bushings.

NB DFR tests for the installed H3 replacement bushing revealed a non-typical response, with uncharacteristically high losses in the high-frequency range (blue curve in Fig. 3).

The data indicate that might be a problem with the connection integrity of the bushing flange to the grounded tank. To verify the suspected grounding problem, the testing specialist applied a ground strap to the bushing flange and repeated the LF DF and NB DFR tests (Table 6). A significant improvement was observed in the LF DF test results and the dielectric response with the ground strap in use (green curve in Fig. 3).

It should be noted that the field test specialist had no prior experience with detecting poor flange grounding. When presented with the probable cause of this 505 Hz anomaly, the specialist used a multimeter and measured the resistance between the tank ground and bushing flange with no notice of a resistance issue. Only with the use of a four-terminal low resistance test instrument was the specialist able to detect a 'before and after' difference. This underscores the exceptional sensitivity of an NB DFR test to insufficient bushing grounding.

Repeated test showed that there was still a problem on the high-frequency side of the spectrum of the NB DFR test results for H3 replacement bushing, which indicate that there may be a problem with the grounding

The NB DFR curves of the original H3 bushing, the H3 replacement bushing before installation, after installation with poor grounding, and finally in its 'as left' condition after restoring a good ground connection are shown in Fig. 5. This provides a striking visual reminder of how bad the original bushing was, how

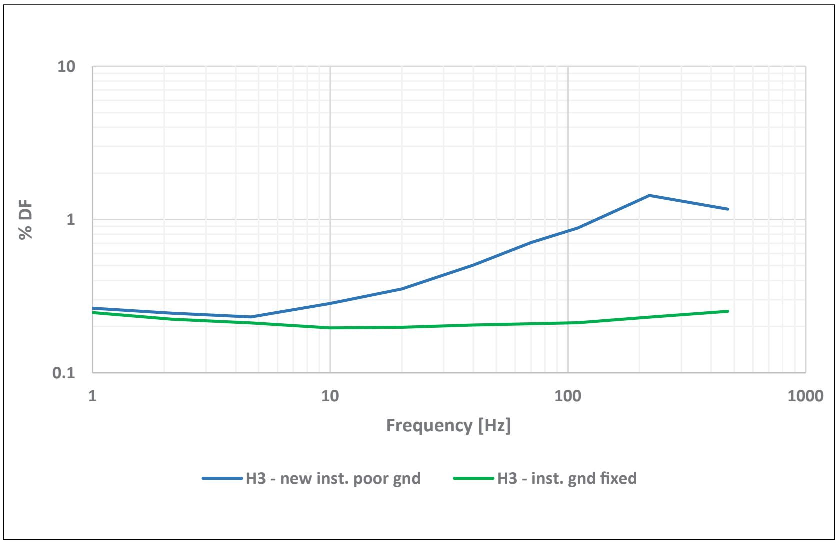

Figure 3. Ground effect on the NB DFR test results of H3 replacement bushing

Table 6. Post-installation C1 test results for H3 replacement bushing, before and after grounding correction, 10 kV LFDF and 250 V NB DFR

Transformer bushing C1 test									
		% DF at 60 Hz			% DF at 1 Hz			% DF at 505 Hz	
Designation	C1 [pF]	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C	IR	Measured	Corr. ITC 20 °C
H3 - new / mounted	231.4	0.24	0.35	G	0.26	0.24	G	1.1	1.22
H3 - grounded	231.8	0.22	0.22	G	0.24	0.22	G	0.28	0.31

practical NB DFR is for post-installation verification, and what the DFR curve for a bushing in good condition should look like.

Conclusions

- LF DF testing is the primary approach to evaluating HV insulation. Significant differences between UST and GST measurements may require further investigation. Bushings constitute part of the overall GST measurement of a transformer and, therefore, may be a factor in an elevated winding-to-ground LF DF test result. Megger recommends always testing bushings equipped with a test tap or potential tap.
- Temperature-correction look-up tables are not accurate for bushings with compromised insulation. The only reliable way to access the true, equivalent value of LF DF at 20 °C is to determine the test specimen's ITC factor, as explained in [2].
- An advantage of NB DFR is definitely time. Testing from 1–505 Hz should take approximately 3 minutes.
- NB DFR in the range from 1 Hz to 505 Hz confirms both early and advanced degradation in bushing insulation.
- After a bushing installation, NB DFR testing is recommended good practice as a verification procedure to detect poor grounding.
- DF test results at 1 Hz and 505 Hz for bushings, in particular, carry significant meaning and it is the "new trend" for transformer and bushing insulation testing.

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After fixing the poor connection with the ground on the H3 bushing, and after repeating the NB DFR test, the results were good as expected for the healthy condition

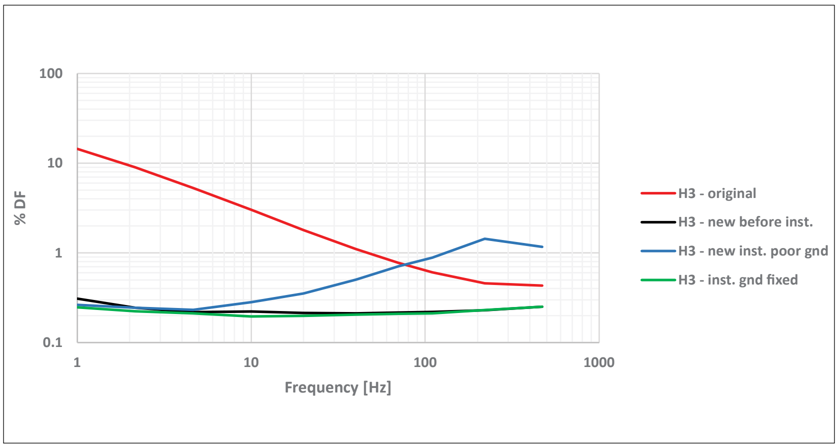

Figure 4. H3 bushing NB DFR test curves from 'as found' to 'as left'

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