Misleading line frequency insulation results on a contaminated transformer

Megger

CASE STUDY

On a contaminated transformer

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Background information:

A 1978 vintage, 20 MVA, 69/13.09 kV, Dyn1 transformer, operating for a major North American utility, was taken out of service to repair a pump in the cooling system. The technical maintenance team completed the required repairs and conducted a complete protocol of routine commissioning tests, including a 10 kV line frequency (LF) power factor (PF) test.

Investigation:

- The insulation condition of the transformer was evaluated in the field after pump repairs.
- The overall capacitance and line frequency power factor (LF PF) test at 10 kV was performed using Megger's DELTA4000 power factor (dissipation factor) test set.
- The LF PF test results obtained at 30 °C top oil temperature (TOT), and then properly corrected to their 20 °C equivalent values using the individual temperature correction (ITC- https://transformers-magazine.com/magazine/2139-individual-temperature-compensation-power-transformer/) method, are presented in Figure 1. Traditional analytic guidelines suggest that these temperature-corrected LF PF test results are indicative of an insulation in acceptable condition. Modern learning, however, cautions that LF PF test results alone no longer provide a sufficient screen.
- Accordingly, as part of the power factor test, 1 Hz PF was also measured and corrected to 20 °C equivalent values (Figure 1). The 1 Hz PF test results are much greater than those recommended for service-aged transformers, as flagged by the software with an Investigation [I] rating.

Transformer Overall Test — Test Mode: Line Frequency + 1Hz | ITC | View Individual Temp. Correction Factors

Multiple Test

Test No.	NB DFR	Insulation Tested	Test Mode	Connections (Click image for detailed connection information)	60Hz TEST kV	60Hz Cap (pF)	Equivalent@10 kV mA	Equivalent@10 kV Watts	POWER FACTOR % Measured	POWER FACTOR % @ 20°C	IR	%VDF	1Hz POWER FACTOR % Measured	1Hz POWER FACTOR % @ 20°C	1Hz IR
1		$C_{HG} + C_{HL}$	GST-GND		10.0	9,543.5	35.9	1.5820	0.44	0.36	G	0.04			
2		C_{HG}	GSTg-RB		10.0	2,465.9	9.30	0.4782	0.52	0.39	G	0.04	11.7	4.25	I
3		C_{HL}	UST-R		10.0	7,064.5	26.6	1.1125	0.42	0.39	G	0.04	10.6	3.54	I
4		C_{HL}'		Test 1 Minus Test 2		7,077.6	26.6	1.1038			Valid				
5		$C_{LG} + C_{HL}$	GST-GND		7.00	19,361.3	73.0	3.1756	0.44	0.34	G	0.04			
6		C_{LG}	GSTg-RB		7.00	12,296.6	46.3	2.0625	0.45	0.35	G	0.03	10.6	3.56	I
7		C_{HL}	UST-R		7.00	7,063.4	26.5	1.0979	0.41	0.34	G	0.04			
8		C_{HL}'		Test 5 Minus Test 6		7,064.8	26.6	1.1131			Valid				
9		C_{HG}'		C_{HG} Minus H Bushings		1,653.9	6.24	0.2262							
10		C_{LG}'		C_{LG} Minus L Bushings											

Figure 1: Transformer overall LF and 1 Hz PF test (PowerDB screen shot)

- The C1 insulation systems of the HV bushings were also tested. The conditions during testing were:
  - Ambient temperature (TA) = 15 °C
  - Transformer top oil temperature (TOT) = 30 °C
  - Bushing temperature (Tavg = (TA + TOT)/2) = 22.5 °C
- All HV bushings' line frequency power factor (LF PF) test results were higher than desired, with power factor values double or nearly triple the nameplate values. These test results warrant investigation.
- An additional diagnostic clue that something is amiss with these bushings is their temperature sensitivity. The typical variation of LF PF between 20 and 22.5 °C should be close to zero. For example, bushing H2 measures 0.72 % PF at 22.5 °C. At a mere 2.5 °C difference, the expectation is that bushing H2 would also measure approximately 0.72 % PF. However, ITC reveals very different dielectric behaviour (Figure 2) of these bushings, i.e., an extreme temperature sensitivity.

Bushing C1 Test						
60Hz						
Test No.	Dsg.	TEST kV	POWER FACTOR %			Δ %PF @ 20°C
			Measured	@ 20°C	IR	
11	H1	10.0	**1.04**	**0.88**	**I**	**0.60**
12	H2	10.0	**0.72**	**0.63**	**I**	**0.34**
13	H3	10.0	**0.73**	**0.64**	**I**	**0.35**

Figure 2: HV bushings LF PF values (DF or tangent delta) - measured and corrected by ITC

- In Figure 2, the column Δ%PF refers to the difference between nameplate and measured %PF values corrected to 20 °C.
- As done with the overall PF testing performed on the transformer, 1 Hz PF test results were collected for the bushings as well (Figure 3).

Bushing C1 Test					
1Hz					
Test No.	Dsg.	TEST kV	POWER FACTOR %		
			Measured	@ 20°C	IR
11	H1	0.25	**15.1**	**12.3**	**I**
12	H2	0.25	**8.77**	**7.12**	**I**
13	H3	0.25	**9.69**	**7.92**	**I**

Figure 3: HV bushings 1 Hz PF (DF or tangent delta) - measured and corrected by ITC

- Not surprisingly, the 1 Hz PF test results confirmed the need to investigate all HV bushings.
- The asset owner ultimately decided to replace the HV bushings.
- The transformer oil was drained and the HV bushings were removed from the unit. Figure 4 shows a layer of contamination on the bottom section of the bushings.

Figure 4: HV bushing removed from the transformer – surface contamination on its lower insulator

- Based on these findings, the owner decided to filter the oil to ensure the removal of all in-tank particulates.
- New bushings were installed and tested. Excellent LF (Figure 5) and 1 Hz PF (Figure 6) values were obtained. Test conditions were:
  - Ambient temperature (TA) = 12 °C
  - Transformer top oil temperature (TOT) = 37 °C
  - Bushing temperature (Tavg = (TA + TOT)/2) = 24.5 °C

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Bushing C1 Test					
60Hz					
Test No.	Dsg.	TEST kV	POWER FACTOR %		
			Measured	@ 20°C	IR
11	H1	10.0	0.24	0.25	G
12	H2	10.0	0.24	0.25	G
13	H3	10.0	0.24	0.25	G

Figure 5: New HV bushings LF PF (DF or tangent delta)

Bushing C1 Test					
1Hz					
Test No.	Dsg.	TEST kV	POWER FACTOR %		
			Measured	@ 20°C	IR
11	H1	0.25	0.11	0.19	G
12	H2	0.25	0.14	0.18	G
13	H3	0.25	0.10	0.12	G

Figure 6: New HV bushings 1 Hz PF (DF or tangent delta)

- With the HV bushings replaced, the oil filtered, and under similar test conditions, the overall LF PF test was carried out and results show clear improvement (Figure 7).

Transformer Overall Test					
60Hz					
Test No.	Insulation Tested	TEST kV	POWER FACTOR %		
			Measured	@ 20°C	IR
1	$C_{HG} + C_{HL}$	10.0	0.43	0.31	G
2	C_{HG}	10.0	0.36	0.26	G
3	C_{HL}	10.0	0.45	0.33	G
4	C_{HL}'				Valid
5	$C_{LG} + C_{HL}$	7.00	0.48	0.33	G
6	C_{LG}	7.00	0.51	0.34	G
7	C_{HL}	7.00	0.45	0.33	G

Figure 7: Overall LF PF (DF or tangent delta) results after HV bushings replacement.

- As with the LF PF values, 1 Hz PF test results did improve as shown in Figure 8, but assessment indicates that the unit requires further investigation. Why would the 1 Hz PF values still be high after HV bushings replacement and oil filtering?.
- To answer this question, the asset owner requested a definitive analysis of the transformer's insulation system using the IDAX300 test instrument to obtain a complete dielectric frequency response (DFR).

Transformer Overall Test

1Hz

Test No.	Insulation Tested	TEST kV	POWER FACTOR % Measured	@ 20°C	IR
1	C_{HG} + C_{HL}				
2	C_{HG}	0.25	10.8	1.75	A
3	C_{HL}	0.25	13.6	2.19	I
4	C_{HL}'				
5	C_{LG} + C_{HL}				
6	C_{LG}	0.25	13.7	2.29	I
7	C_{HL}				

Figure 8: 1 Hz PF results after HV bushings replacement

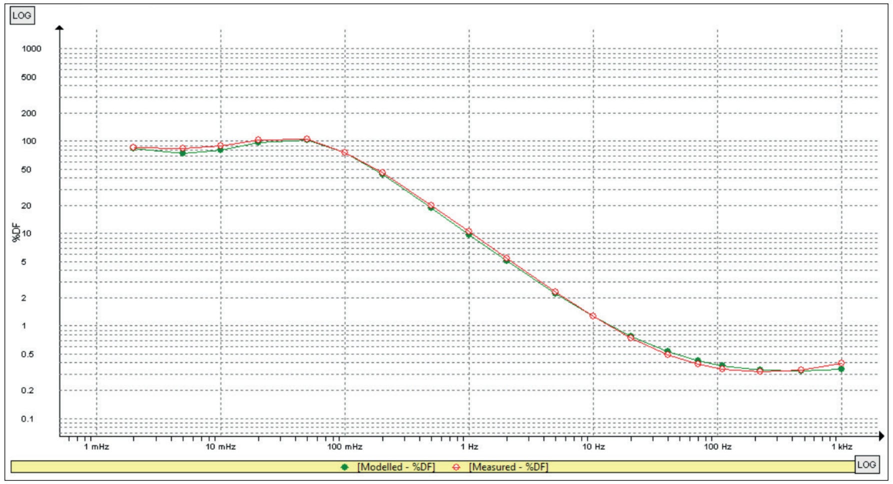

Figure 9: Dielectric Response after oil processing

- Full-spectrum DFR shows that the interwinding solid insulation contains a typical % moisture (1.7 %) for a service-aged transformer but the liquid insulation reports high conductivity (11.8 pS/m).
- Further internal inspection of the unit revealed that the tank walls and paper insulation retained contamination in areas making it difficult to remove. It was recommended to flush the core coil assembly several times to remove contamination. Samples were taken and sent to the laboratory for analysis.
- It is important to mention that historical DGA data (Figure 10) did not alarm the operator. In the Duval Triangle 1, values fluctuated within T1 and T2 regions. T1 and T2 are part of the six basic types of faults or stresses in transformers, identifiable with the Duval Triangle 1. T1 corresponds to thermal faults < 300 °C, and T2 correponds to thermal faults between 300 and 700 °C.

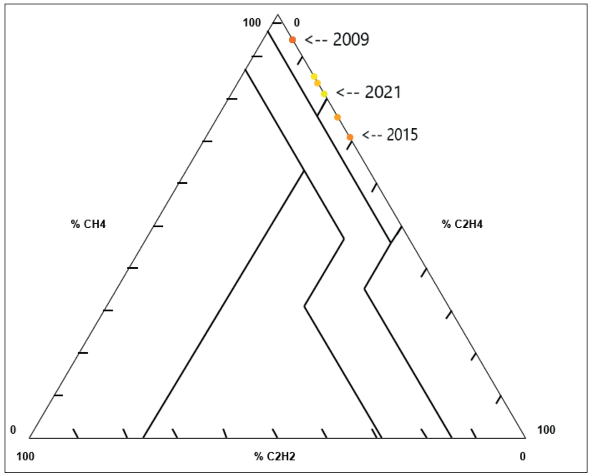

Figure 10: DGA identified fault condition from 2009 to 2021 for the 1978 transformer of this case study

Misleading line frequency insulation results on a contaminated transformer

Takeaways:

- Line frequency PF (DF or tangent delta) measurements by themselves may or may not reflect the true condition of the insulation system inside a transformer.
  - It is fundamental practice to record a benchmark signature of the dielectric condition of a power transformer before any maintenance work is carried out.
  - Look beyond the information provided by LF PF. 1 Hz (as demonstrated in this case study) and 500 Hz complement LF PF. Practical references are now available to assess 1 Hz and 500 Hz PF test results.
- A full-spectrum analysis (DFR) with IDAX300 is the definitive method to determine the condition of solid and liquid insulations.
- For a service-aged transformer, the recommended maximum limit of moisture is < 2 % and the recommended limit for liquid insulation conductivity is < 37 pS/m.
- Surface contamination of the solid insulation and tank walls must be analysed in the laboratory. Sediments and particles must be properly identified to better understand the source of such material.
- Be proactive, not reactive, and and make sure that you are equipped with the right tools to make the right decisions

Benefits:

- The main concern is always safety. Proper screening of the electrical assets that personnel work around is paramount in reducing risk of unexpected failure(s) and collateral damage. In this case, a thorough screen identified a transformer that may have suddenly failed due to dielectric breakdown, overheating or thermal runaway.
- While lab results must confirm, the likely source of contamination is the compromised pump. Even flushing the transformer several times may not guarantee a residual-free environment for the liquid and paper insulation. The significantly better screening tool of 1 Hz PF and a full DFR test will provide some perspective about the success of a flushing remedy. Should conductive contaminants remain, however, the transformer design is invalid and the asset owner assumes elevated risk of failure. In this event, the transformer may need to be replaced as soon as possible. Alternatively, this transformer may be derated with some manufacturer guidance, and, for example, be used or relocated to an area where load will not exceed 50 % of rated capacity.

Product Reference:

DELTA

- Dedicated capacitance and PF/DF test instrument (also exciting current):
- Narrowband DFR (NB DFR: 1 - 505 Hz)
- Individual Temperature Correction (ITC)
- Voltage Dependence Detection (VDD)

TRAX + TDX

- A multi-functional tester for transformer and substation equipment.
- Narrowband DFR (NB DFR: 1 - 505 Hz)
- Individual Temperature Correction (ITC)
- Voltage Dependence Detection (VDD)

IDAX + VAX

- Megger’s DFR test instrument (IDAX) and voltage amplifier (VAX)
- Provides analysis of moisture content, oil conductivity, and PF/DF; also performs NB DFR
- When coupled with the VAX or by upgrading to the IDAX322, an HV 1.4 kV rms output assures speed and reliability in high-interference environments.
- A culmination of >20 years’ experience in the design of DFR test equipment and expertise in the subject area

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