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Condition Assessment of HVDC converter transformers at limited time of outage applied to the Fenno–Skan 1 transmission system

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SUMMARY

The high voltage direct current (HVDC) converter transformer is a key integral part of the HVDC electric power transmission system and one of the most important components in the system considering its complexity and size. The condition of a converter transformer is crucial for its successful operation and, as a consequence, for the reliability of the HVDC transmission system as whole. Repairing or replacing a converter transformer can be expensive and time-consuming. Therefore, utilities need to evaluate the condition of their converter transformers in order to maintain system reliability and to optimize asset management strategies.

In the present study we describe key points to consider when performing condition assessment of HVDC converter transformers and summarize activities included into the condition assessment project.

Specific for the project was that the service outage period of the Fenno-Skan 1 transmission system was so limited that the time for electric measurements was restricted to maximum one day per transformer. It was not even possible to completely disassemble external connections from the bushings of the Valve windings. Therefore, the scope of electric measurements was adjusted with the purpose to get most valuable diagnostic data within the given limitations. In the study we describe how this adjustment effected the results of condition assessment and which aspects of transformer condition were not possible to evaluate thoroughly.

As a result of this study, the grid owner got valuable information about condition status of the HVDC converter transformers as well as recommendations on how to keep them functioning properly. Suggestions were also given regarding the possibility to extend service lifetime of the units.

KEYWORDS

HVDC converter transformer, Condition assessment, Risk assessment, Diagnostics.

INTRODUCTION

The purpose of performing a thorough condition assessment of power transformers is to understand how well these assets perform after several years of services and to capture any signs of weaknesses or changes in performance that eventually would or could lead to a failure [1,2]. Understanding the condition of HVDC converter transformers is especially important since a failure of a converter transformer serving an HVDC link can lead to a failure of the entire link and imply a major loss for the power utility [3].

Condition assessment of HVDC converter transformers is similar to condition assessment of "conventional" inter bus (AC) power transformers. However, there is a number of significant distinctive features such as:

- HVDC transformers are specific in design as well as the operational stresses they face during operating life [4]. This leads to differences in failure distribution by component (see for example Figure 1) and influences the choice of methods utilized for condition assessment.
- Specifics of design and operational stresses may also lead to necessity to set specific thresholds for some diagnostic parameters (such as typical gas concentrations for DGA).
- If a converter station is served by a group of transformers identical in design (e.g., 3 or 6 single-phase units), then for many diagnostic methods, measurement results obtained on one unit may be used as a baseline for another one.
- Sometimes DC terminals are located inside the valve hall, while AC terminals are outside. If it is not possible to pull the test lead through the valve hall wall, the measurements which require connection to AC and DC terminals at the same time are not applicable.
- It is sometimes a problem to remove external connections from DC terminals which influences the choice of methods utilized for condition assessment.

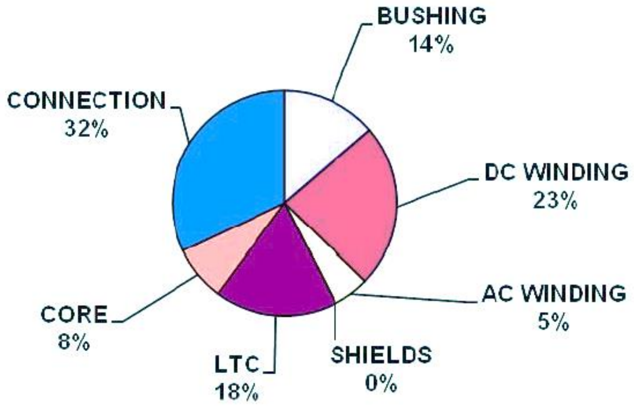


Figure 1. Failures of HVDC transformers by component 2003 -2012 [5]

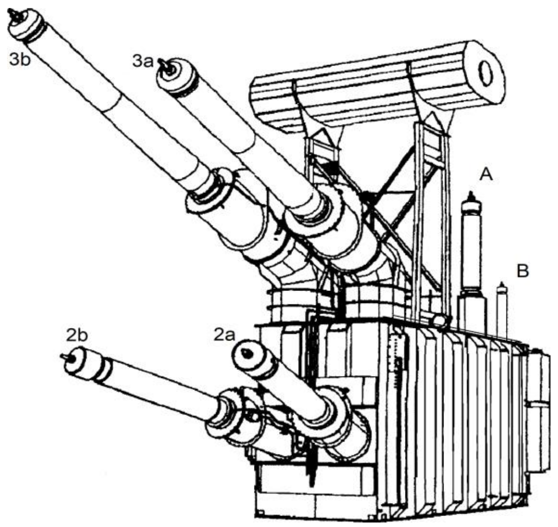
OBJECT

Fenno–Skan 1 is the HVDC transmission system between Dannebo in Sweden and Rauma in Finland. The transmission system has been in service since November 1989, and after more than 30 years of successful operation it has become necessary to evaluate operational risks of the converter transformers and make a strategic decision on the possibility of extending their expected service lifetime.

This motivated to perform condition assessment of the HVDC transformers. The present study is based on the transformer condition assessment project at Dannebo Converter Station carried out in 2020.

Dannebo Converter Station is served by three single-phase units whose condition has been investigated. A summary of the transformer data is given in Table 1.

Table 1. Transformer data

Manufacturer	Hitachi Energy (former ABB)	
Year	1988	
Cooling type	OFAF	
Number of phases	1	
Rated Frequency [Hz]	50	

Terminals	Rated voltage [kV]	Rated Power [MVA]	Rated Current [A]
A B (AC winding)	$405/\sqrt{3} + \frac{+18}{-7}$ x 1.25%	194,6	680 – 832 – 913
2a 2b (Y-connected Valve winding)	$161{,}4/\sqrt{3}$	97,3	1045
3a 3b (Δ- connected Valve winding)	161,4	97,3	$1045/\sqrt{3}$

METHODOLOGY

Modern diagnostic methods are available and may be applied for oil filled transformers and accessories. Some of them are listed in Table 2.

Table 2. Examples of diagnostic methods for oil filled transformers

Type		Method	Object
Chemical		DGA (Dissolved Gas Analysis)	Electrical and/or thermal fault diagnosis
		Oil condition tests	Determination of oil condition
Electrical	Basic	Turns ratio	Detection of winding short circuits and interruptions
		Winding resistance	Detection of bad contacts, winding short circuits and interruptions
		Insulation resistance	Estimation of insulation condition, indication on moisture ingress, contamination, aging, etc.
		Capacitance and dissipation factor (tan δ)	
		Excitation current	Problems associated with the core; indication of winding short circuits and interruptions
		Short-Circuit Impedance	Detection of winding short circuits and active part deformations

Table 2. Examples of diagnostic methods for oil filled transformers (continued)

Type		Method	Object
Electrical	Advanced	Sweep Frequency Response Analysis (SFRA)	Detection of winding short circuits and active part deformations – provides more accurate information than basic measurements
		Dielectric Frequency Response (DFR), also known as Frequency Domain Spectroscopy (FDS)	Estimation of insulation condition – provides more accurate information than basic measurements
		Partial discharges (PD)	Detection of weak spots inside the insulation system
Acoustic		Partial discharges (PD)	Detection of weak spots inside the insulation system
		Acoustic sound level	Acoustic noise level of a transformer
Others		Theoretical paper ageing calculation	Determination of paper aging rate
		Thermography	Detection of heat sources and hot spots
		Vibration signal analysis	Mechanical properties of active part, accessories
And other methods…			

The more diagnostic methods that are included in the transformer condition assessment, the more accurate result is expected. On the other hand, every additional method applied increase needed outage time, sometimes demands additional measuring equipment, special experts, preparational work, etc. which may dramatically increase complicity of the project and its costs. Therefore, a set of diagnostic methods for the particular condition assessment project is usually chosen on preparation stage, based on known condition related problems / fault condition indications. Choosing the methods to include in the scope it is necessary to consider:

- information on design and factory acceptance test (FAT) data of the actual transformer,
- historical condition assessment results and other service data,
- information about previous events in the grid,
- possible limitation factors for diagnostic measurements on site such as service outage time, level of external electromagnetic interference, ambient conditions, etc.

Since the project has been performed in close cooperation between the manufacturer of the transformers and the grid owner, all necessary data was available, so that it was possible to select the methods which provided most valuable diagnostic data for the particular units within given limitations.

Specific for the project was that the service outage period of the Fenno–Skan 1 transmission system was so limited that the time for electric measurements was restricted to maximum one day per transformer. It was not even possible to completely disassemble external connections from the bushings of the Valve windings, see the Figures 2 and 3 - only the bushings of the Line winding were freed from the external connections.

Figure 2. Valve winding bushings of three single-phase transformers

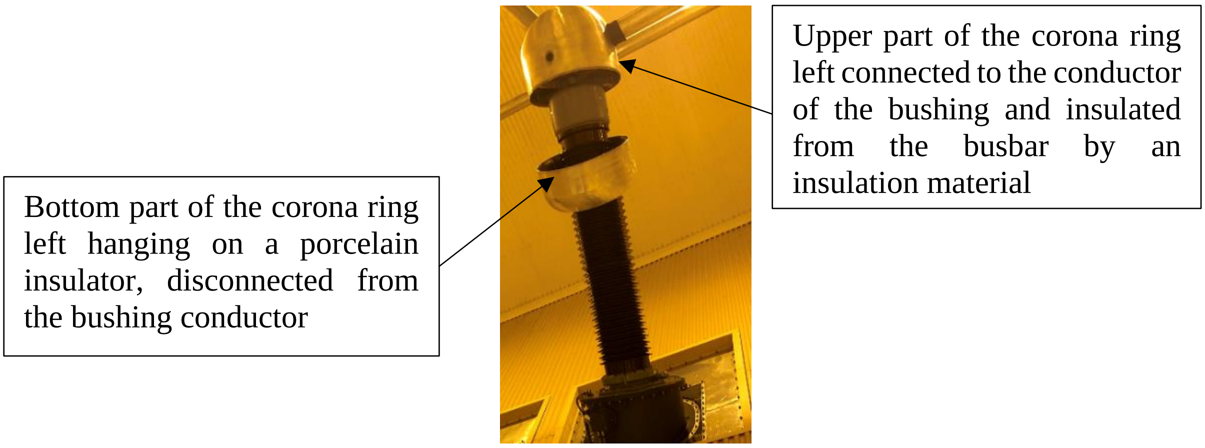


Figure 3. Setup of external connections of Valve winding bushings during the measurement

The methods chosen for the study were selected in a structured way, making it possible to capture faults in the active part, active part insulation, internal connections, on-load tap changer (OLTC), bushings of Line and Valve windings as well as cooling system. The following diagnostic methods were used: DGA, oil condition tests, winding resistance measurement, SFRA, capacitance and tan δ, DFR, and visual inspection. Condition of the bushings was evaluated using, among the other techniques, a combination of DGA and DFR which is recognized as the most sensitive diagnostic tool for the bushing insulation [6,7].

Inability to completely disassemble external connections from the bushings of the Valve windings put following limitation on the scope of condition assessment: oil sampling from the Valve winding bushings was not feasible; applied voltage to the Valve windings was limited to 0,2 kV; measured dielectric parameters of insulation of Valve windings and bushings for some transformers were not valid; SFRA traces of the Valve windings may have been influenced.

EXAMPLES OF THE MEASUREMENT RESULTS

Results from diagnostic methods applied were similar for all transformers. Hereunder examples of typical results from some methods are provided.

WINDING RESISTANCE MEASUREMENT

Temperature corrected values of winding resistance were within ± 2% of the FAT values which is acceptable. However, for the Line winding the values obtained on the tap changer positions 15 – 26 had slightly increased deviation from FAT (examples of measurement results of one of the units presented in Figure 4). Tap changer positions from 15 to 26 correspond to the change-over selector position which was not used in service for a long period. Therefore, slightly increased winding resistance at the tap changer positions 15 – 26 were interpreted as an early evidence of formation of an oxidation film on the surfaces of the change-over selector contacts.

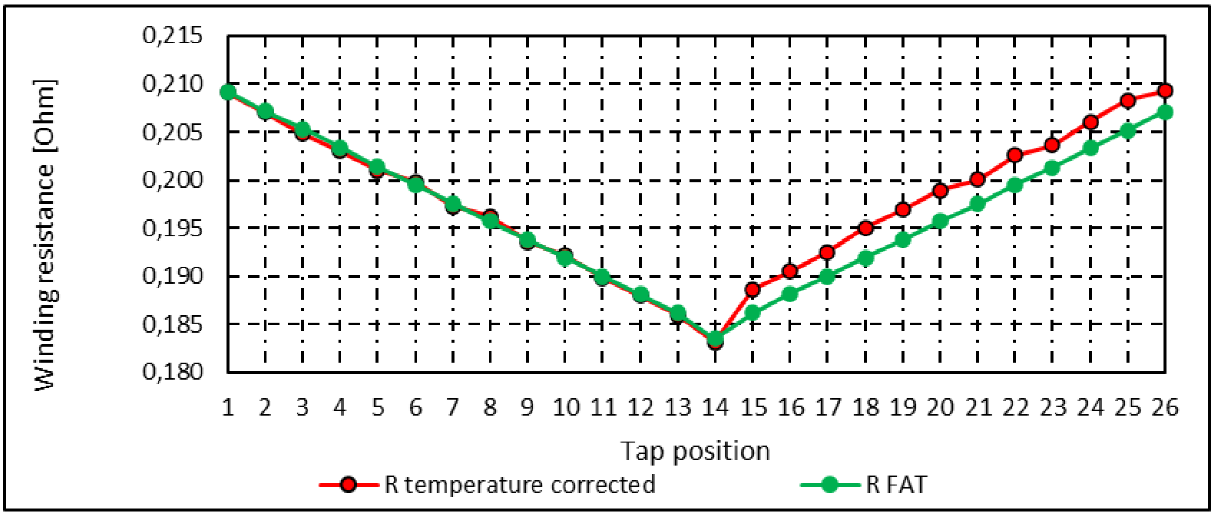


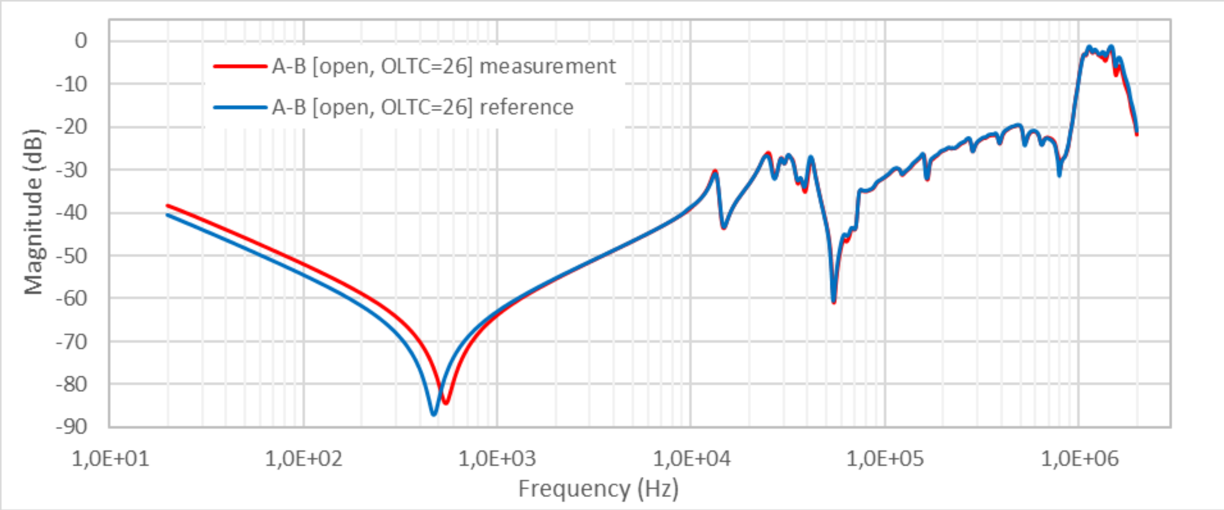
Figure 4. Winding resistance measurement results of the Line winding

SFRA

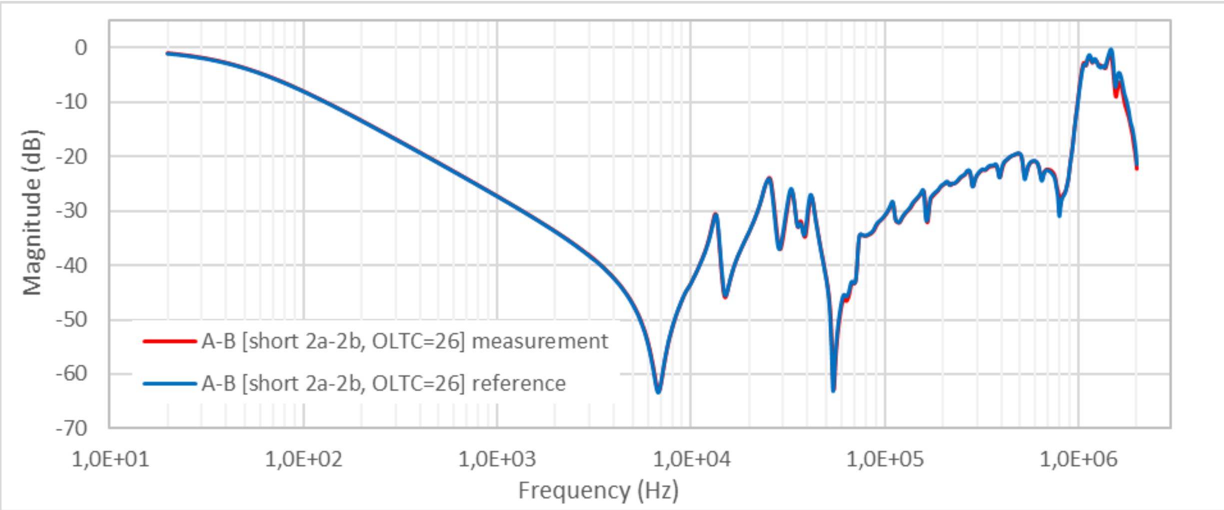
Measurement leads connections were arranged in accordance with IEC 60076-18, except when measuring Valve windings. Due to the setup of external connections of their bushings (Figures 2 and 3), measurement leads were connected to ribs of the corona rings.

Examples of measurement results of one of the transformers presented in Figures 5 – 8.

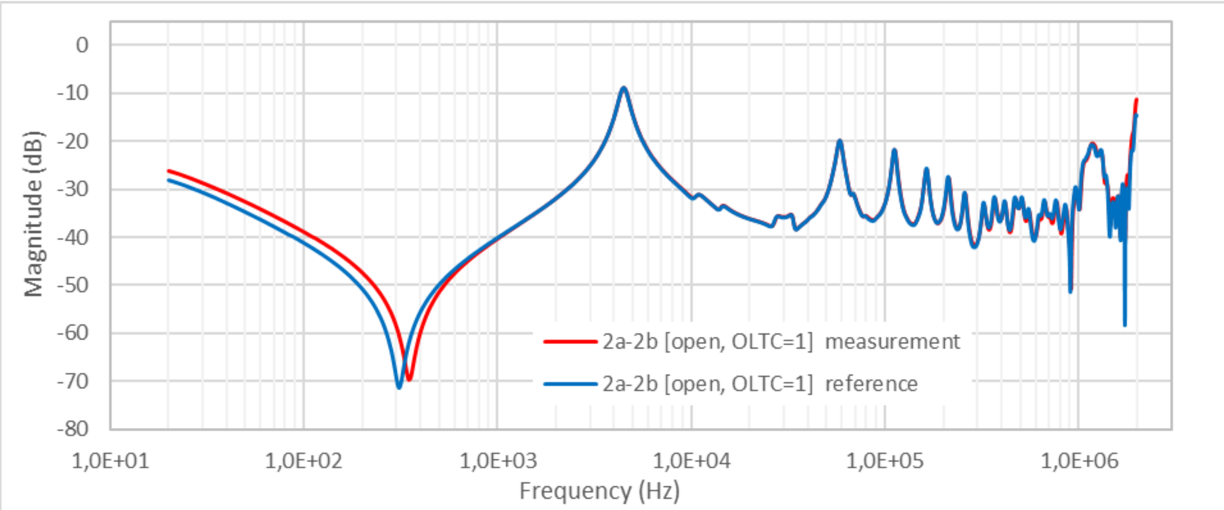
The comparison with the traces obtained from the units of identical design (sister unit) does not show any obvious sign of an active part damage. Disturbance in open-circuit configurations (Figures 5, 7 and 8) at frequencies below approx. 1 kHz are normal and caused by different remnant magnetization of the core.



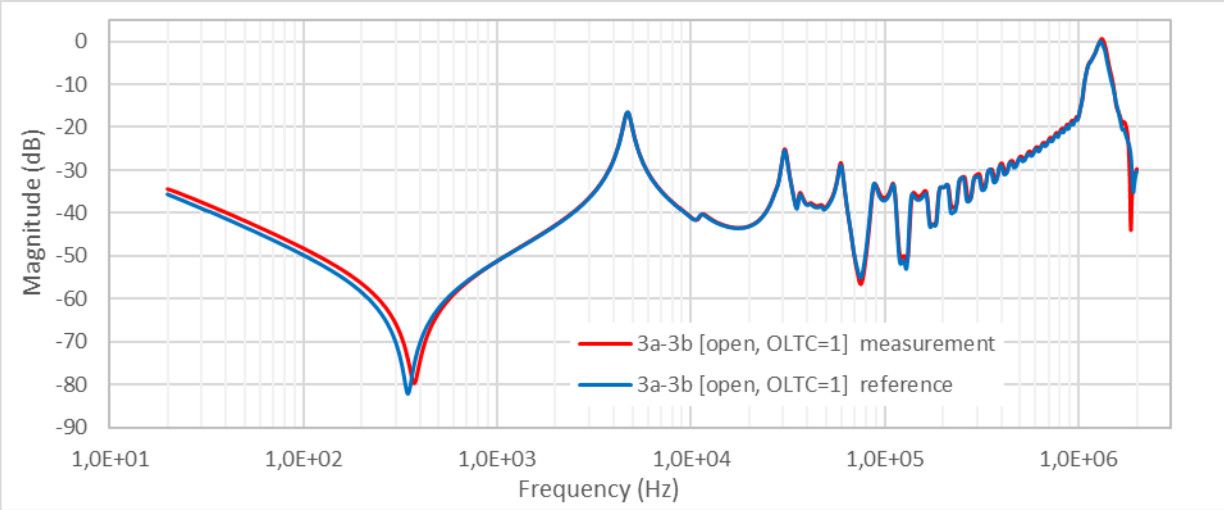
Figures 5. SFRA measurement result from Line winding, "open-circuit" test



Figures 6. SFRA measurement result from Line winding, "short-circuit" test



Figures 7. SFRA measurement result from Y-connected Valve winding, "open-circuit" test



Figures 8. SFRA measurement result from Δ- connected Valve winding, "open-circuit" test

Obtained SFRA traces may be used as a baseline for future diagnosis.

DFR

Due to the setup of external connections of Valve winding bushings (Figures 2 and 3), DFR measurement results of insulation of Valve windings and their bushings for some transformers were not valid. However, valid DFR results indicated acceptable insulation condition for all transformers. Moisture in cellulose estimation results were below 0,5 % for all units.

Example of frequency dependencies of both capacitance and dissipation factor obtained on Line winding insulation of one of the units is given in Figure 9. Comparison of the measured response with the reference obtained on a sister unit shows expected results, i.e., good fit between responses after temperature compensation (see Figure 9 (b)).

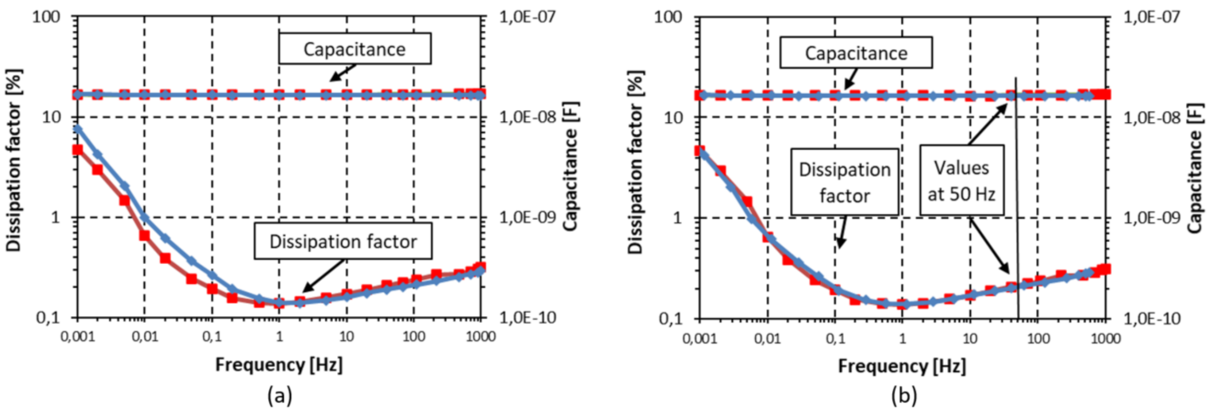


Figure 9. DFR response of Line winding insulation (red) compared with the reference response from a sister unit (blue): (a) before temperature compensation; (b) after temperature compensation – normalized to 20 °C

Responses of the bushings did not show abnormality. Example of a DFR response of a bushing of Δ- connected Valve winding is shown in Figure 10, with no deviation from the reference after temperature compensation.

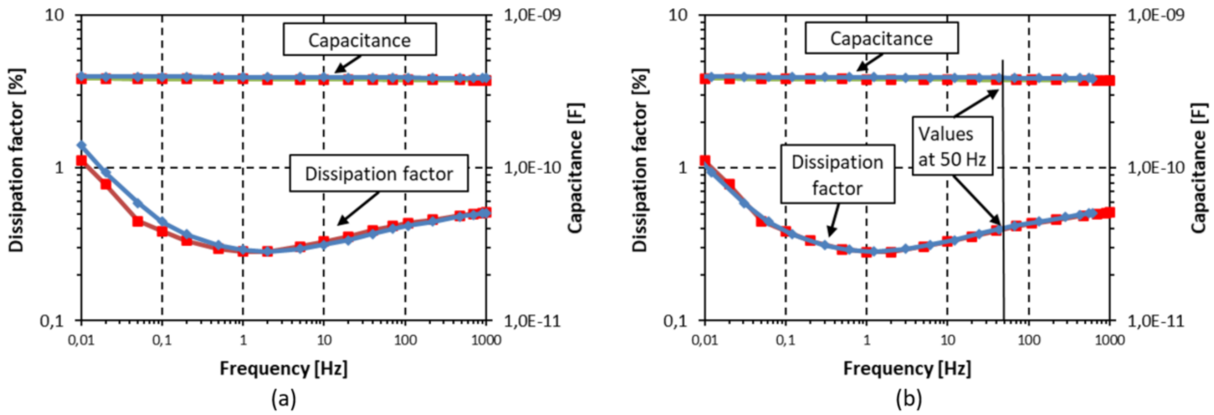


Figure 10. DFR response of a bushing of Δ- connected Valve winding (red) compared with the reference response from a sister unit (blue): (a) before temperature compensation; (b) after temperature compensation – normalized to 20 °C

DISSOLVED GAS AND OIL ANALYSIS

DGA analysis results do not indicate any abnormal condition of the main tank insulation of any transformer, see for example sum of hydrocarbons and carbon oxide results for one of the units in Figure 11.

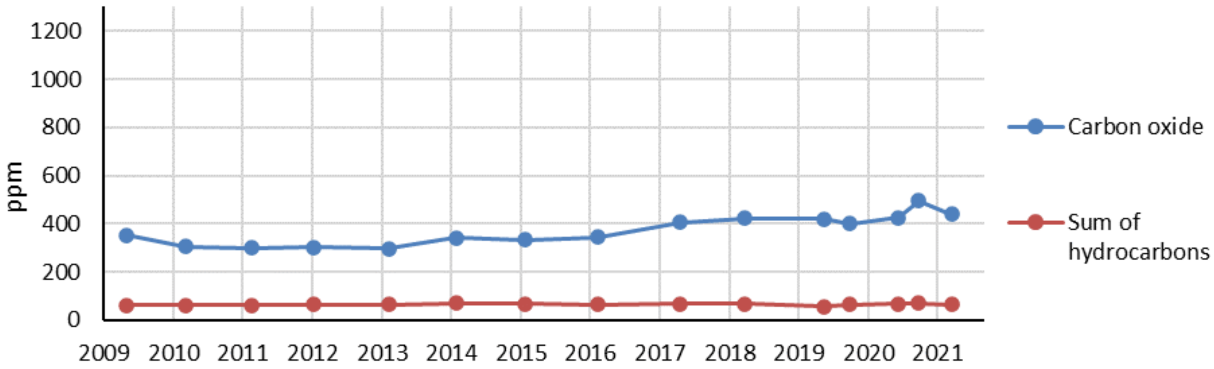


Figure 11. Sum of hydrocarbons and Carbon oxide 2009 - 2021

Oil analysis results do not indicate any fault condition, meanwhile in all units the metal passivator content has dropped below the level that is normally considered acceptable.

No problem of any Line winding bushing – all gas concentrations as well as moisture in oil content were within acceptable limits.

For on-load tap changers the findings are similar for all three transformers: the ratio of CH_4, C_2H_6, C_2H_4 and C_2H_2 (Stenestam ratio [8]) indicate an incipient hot run; also, the breakdown voltage is low and does not meet the requirement of IEC 60422.

Table 3. DGA results for OLTC of one of the transformers

Gas	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
Concentration values [μl/l]	18900	3800	1100	8780	5600	672	7560

RESULTS OF THE CONDITION ASSESSMENT AND RECOMMENDATIONS

Overall condition of the investigated converter transformers and in particular mechanical condition of the active part as well as condition of insulation system were found acceptable. Detected abnormalities summarized in Table 4 are similar for all transformers.

Table 4. Detected abnormalities and recommendations for remedial actions

Method indicated an abnormality	Detected abnormality	Recommendations for remedial actions to maintain short-term reliability
Winding resistance	Measured values are acceptable. Suspected early evidence of the formation of an oxidation film on the contact surfaces	The formed films are generally removed by switching the on-load tap changer (OLTC) through its full cycle thanks to the wiping action of the moving contacts
Oil analysis for the oil from the transformer main tank	The results do not indicate any abnormal condition. Meanwhile metal passivator content has dropped below the level that is normally considered acceptable	As a short-term solution, addition of more passivator is suitable. For continued long-term operation oil reclaiming or oil change may be more suitable alternatives
DGA and oil analysis for the oil from the OLTC	DGA results indicate an incipient hot run in the OLTC. Oil analysis shows that the breakdown voltage is low and does not meet the requirement of IEC 60422	The oil in the diverter switch tank should be changed. In connection with this, a service on the OLTC should also be performed (as well as checking the contacts). An alternative solution is to upgrade the diverter switches to a vacuum type
Visual inspection	Oil leakages and damaged paintwork detected	Eliminate the oil leakages, recover the paintwork

As these converter transformers have been in service for more than 30 years, ageing of the cellulose insulation is occurring and the key components facing ageing as well. This increases the risk of failure the older the units get.

Hence, to decide if the transformer paper insulation has enough resource for reliable operation during the next 20 years, it was recommended to perform estimation of the paper insulation aging rate. It can be based on calculations of hot spot temperature over transformers lifetime as well as on estimation of influence on the aging process of such factors as availability of oxygen, water content and the presence of acids in the oil [1].

If paper aging status is suitable, then to ensure transformers reliability for the upcoming 20 years, the manufacturer of the transformers has recommended:

- A replacement program for the transformer bushings. Dry insulated bushings are recommended for replacement;
- Upgrade OLTC diverter switches to a vacuum type;
- Replacement of gaskets;
- Replacement of transformer accessories which exceed expected lifetime (such as control cabinets, cabling, temperature indicators, pressure relay, Buchholz relay and others).

It is essential to continue performing regular maintenance on the transformers to reduce the risk of forced outages of the HVDC link.

CONCLUSION

The study provides an example of condition assessment of HVDC converter transformers. Valuable information about condition status of the transformers has been obtained during challenging limited conditions thanks to close cooperation between the manufacturer of the transformers and the grid owner as well as to the set of modern diagnostic tools applied (gas and oil analysis, SFRA, DFR, winding resistance, etc.).

The grid owner has received recommendations on how to improve short-term reliability of the transformers as well as how to keep them functioning properly. Suggestions were also given regarding the possibility to extend service lifetime.

If the paper aging does not cause limitations to the transformers, then, according to the manufacturer's recommendations, mainly by replacing all bushings as well as upgrading all OLTC diverter switches, the requirement of another 20 years lifetime could be fulfilled.

By replacing the oil-filled DC-bushings with the dry type, the risk of fire in the valve hall is reduced.

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