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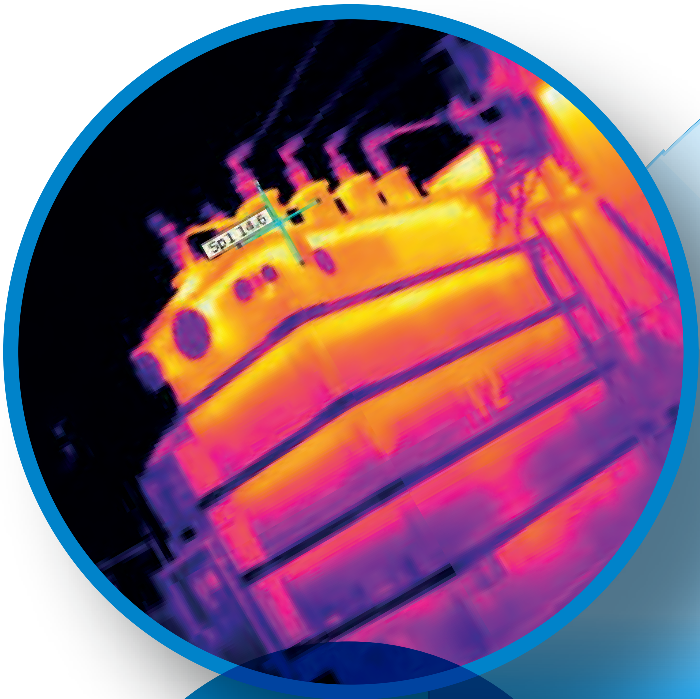
Flexible Networks
for a Low Carbon Future



Real Time Thermal Rating System

- Phase I Asset Condition Assessment

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0	2014-07-14	First issue	M.W. Louwerse	S. Meijer	J.M. Wetzer

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1 EXECUTIVE SUMMARY

Background

The Real-Time Thermal Rating (RTTR) project is part of SPEN's LCNF Tier 2 project: Flexible Networks for a Low Carbon Future. Flexible Networks for a Low Carbon Future will provide the network operators with economic, DNO-led solutions to increase and enhance the capability of the networks. Crucially, these will be capable of being quickly implemented and will help to ensure that the network does not impede the transition to a low carbon future.

SPEN's solution will aim to provide a 20% increase in network capacity through enhanced monitoring and analysis to precisely determine existing performance, and the deployment of novel technology for improved network operation – including flexible control and dynamic rating.

Scope of work and activities performed

SPEN selected 8 primary transformers to take part in the RTTR project: St. Andrews T1 and T2, Cupar T1 and T2, Ruabon T1, Whitchurch T1, Yockings Gate T1, Liverpool Rd. T1. In the context of the RTTR project DNV GL assessed the condition of each transformer and estimated its remaining life. The following activities were performed:

- collection and analysis of the available information
- detailed visual inspection
- thermo-graphic inspection
- online partial discharge measurement
- oil analysis (dissolved gasses, quality, corrosiveness, furanic compounds)
- estimation of the remaining life on the basis of:
    - furanic compounds in the oil
    - dynamic loading-guide calculation.

Conclusions

1) The estimated remaining lifetime of all 8 transformers that were part of the condition assessment is over 25 years.
2) The observations during the visual inspections, thermo-graphic surveys (IR), online partial discharge measurements (PD) and oil analyses can be summarized as follows:

Transformer	Visual	PD	IR	Oil
St. Andrews T1	Rust	OK	OK	OK
St. Andrews T2	Rust	OK	Hotspot on 33 kV terminal	OK
Cupar T1	Rust, sweating	OK	OK	OK
Cupar T2	Rust, sweating	OK	OK	OK
Ruabon T1	OK	Corona discharge in air	Peculiar temperature profile on radiators	Free water
Whitchurch T1	OK	OK	Hotspot on 33 kV-disconnectors	Free water PD-activity
Yockings Gate T1	Leaking cable box	OK	OK	OK
Liverpool Rd. T1	Sweating	OK	OK	PD-activity Corrosive

3) Pending mitigative measures to be implemented on Ruabon T1 and Whitchurch T1, DNV GL currently qualifies the following six transformers suitable for operating under over-loading conditions under careful dynamic loading:
    - St. Andrews T1 and T2
    - Cupar T1 and T2
    - Yockings Gate T1
    - Liverpool Road T1.

Recommendations

1) In addition to the normal maintenance regime, perform the following short-term actions (0-12 months):
    - Ruabon T1:
        - collect an oil sample from the main tank for analysis of the concentration of dissolved gasses and quality;
        - as the transformer is still under warranty, contact the manufacturer regarding the measured partial discharge activity as well as regarding the observed temperature profile of the radiators.
    - Whitchurch T1:
        - collect an oil sample from the main tank for analysis of the concentration of dissolved gasses and quality.
    - Liverpool Road T1:
        - collect an oil sample from the main tank for analysis of the concentration of dissolved gasses and quality.
        - on the basis of a risk assessment study (CIGRÉ Brochure 378, 2009), evaluate the necessity for corrective actions regarding the corrosiveness of the oil.
2) In addition to the normal maintenance regime, perform the following medium-term actions (12-24 months):
    - St. Andrews T1:

    - define and implement actions to correct/mitigate the observed rust.
- St. Andrews T2:
    - define and implement actions to correct/mitigate the observed rust;
    - define and implement actions to correct the observed hot-spot on a 33 kV-terminal.
- Cupar T1, Cupar T2:
    - define and implement actions to correct/mitigate the observed rust.
- Whitchurch:
    - define and implement actions to correct the observed hot-spots on 33 kV-disconnectors.
- Yockings Gate T1:
    - define and implement actions to correct the observed mass-leakage from the 33 kV-cable box.

3) In addition to the normal maintenance regime, perform the following long-term actions (24-60 months):
    - Cupar T1, Cupar T2 and Yockings Gate T1:
        - define and implement actions to correct/mitigate the observed sweating.

2 INTRODUCTION

2.1 Background

The Real-Time Thermal Rating (RTTR) project is part of SPEN's LCNF Tier 2 project: Flexible Networks for a Low Carbon Future. Flexible Networks for a Low Carbon Future will provide the network operators with economic, DNO-led solutions to increase and enhance the capability of the networks. Crucially, these will be capable of being quickly implemented and will help to ensure that the network does not impede the transition to a low carbon future.

SPEN's solution will aim to provide a 20% increase in network capacity through enhanced monitoring and analysis to precisely determine existing performance, and the deployment of novel technology for improved network operation – including flexible control and dynamic rating.

2.2 Scope of work and activities performed

This report describes the condition assessment of 8 primary transformers and any assets directly involved with a potential transformer real-time thermal rating (RTTR) system. The following 8 primary transformers were selected by SPEN to be part of the project:

- St. Andrews T1 and T2
- Cupar T1 and T2
- Ruabon T1
- Whitchurch T1
- Yockings Gate T1
- Liverpool Road T1.

In the context of the RTTR project DNV GL assessed the condition of each transformer and estimated its remaining life. The following activities were performed:

- collection and analysis of the available information
- detailed visual inspection
- thermo-graphic inspection
- online partial discharge measurement
- oil analysis (dissolved gasses, quality, corrosiveness, furanic compounds)
- estimation of the remaining life on the basis of:
  - furanic compounds in the oil
  - dynamic loading-guide calculation.

2.3 Outline

Chapter 2 describes the used techniques, equipment and methodologies used for the condition assessments. Chapter 3 presents the results of the site visit, the laboratory analyses and the condition assessments for the eight transformers. Finally, in chapter 4 the conclusions are drawn and recommendations are given.

3 TECHNIQUES, EQUIPMENT AND METHODOLOGIES

DNV GL has developed its own methodology to assess the condition and estimate the remaining lifetime of medium and high voltage equipment. This methodology is partly based on proprietary tools and methods and partly confirmative to (international) recognized standards and industry's best practices.

Our methodology comprises the following steps:

1) Data collection
2) Testing and analysis
3) Estimation of remaining life time
4) Interpretation of results
5) Merging and summarization of results

3.1 Data collection

As a first step, DNV GL requests information regarding the component under study. This information includes, but is not limited to the following:

- name plate data
- all available test reports (e.g. factory acceptance test, site acceptance tests,)
- maintenance and inspection data
- historical and/or representative loading data
- historical results of oil analysis
- failure and repair reports (if applicable).

3.2 Visual inspections

DNV GL engineers visually inspected the 8 transformers that were selected by Scottish Power.

The inspections were carried out according to a checklist containing the following aspects:

- name plate data
- ambient condition
- vegetation around the transformer bay
- coating / corrosion and deformation.
- breather and silica gel
- condition of bushings
- oil leakage, gaskets
- fans/cooling.

DNV GL analyzed the results of the inspections and made recommendations for maintenance purposes. The results of the inspection are provided in chapter 3.

3.3 Partial discharge measurements

A partial discharge (PD) is a local breakdown of a dielectric when being stressed with a voltage. In contrast to a full breakdown, a partial discharge only partially bridges the insulation medium.

Dielectric weaknesses are caused by irregularities in the isolation material, like inclusions, voids, cracks, moisture, floating particles, tip on a potential, cavity, contact noise etcetera. These weaknesses may cause breakdowns in time. Often, a breakdown will be preceded by partial discharges.

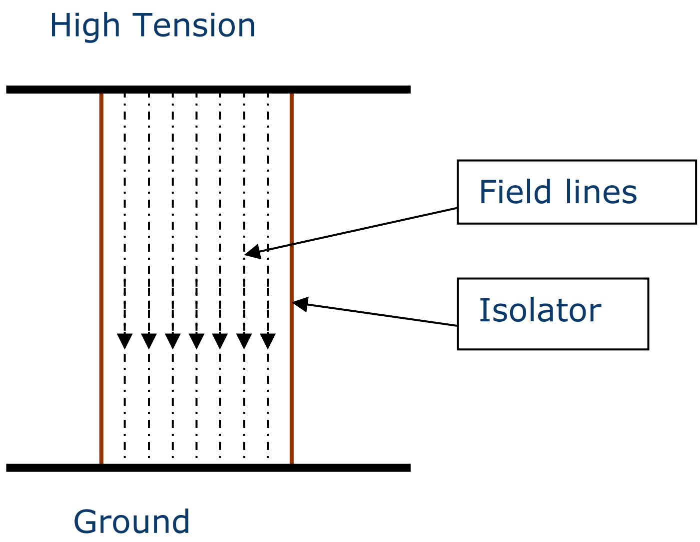


Figure 2.1 Simple example of an electrical field distribution in homogeneous insulation material

Figure 2.1 shows an example of insulating material when stressed by a voltage. In this figure it is shown that the field lines are evenly distributed implicating a linear field distribution inside the insulation medium (dielectric). The presence of an irregularity would distort the path of the field lines leading to a (local) non-linear field distribution. As an example of an irregularity, a void is used in figure 2.2. The equivalent circuit of a dielectric incorporating a void can be modelled as a capacitive voltage divider in parallel with another capacitor.

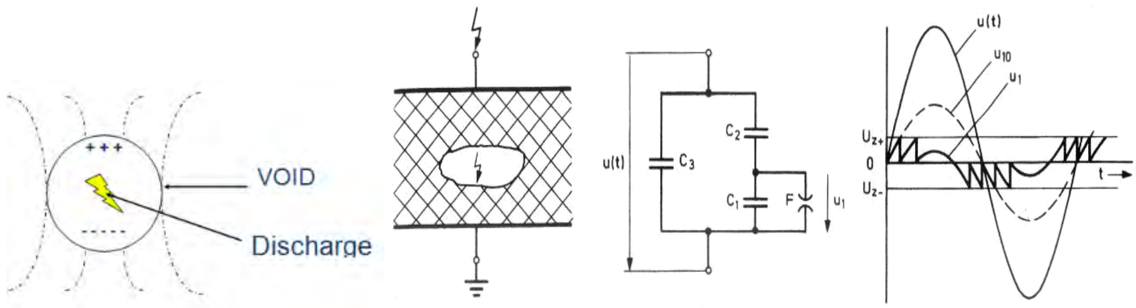


Figure 2.2 Bending of field lines due to a void and its equivalent circuit

Due to capacitive nature of a void, a charge builds up under the influence of the electrical field, resulting in a voltage across the void. As soon as this charge is large enough, and the voltage across the void exceeds the breakdown voltage, a discharge will take place.

Amongst other phenomena, partial discharges produce electromagnetic (EM) and acoustical waves.

3.3.1 UHF-methodology

The DNV GL-PD-MS system is a tool to detect partial discharges (PD) in HV equipment, such as circuit breakers, GIS, insulators and (oil-filled) power transformers. It can provide phase-resolved discharge patterns (PRPD) and time resolved discharge patterns (TRPD) from which the dielectric integrity of the insulation of the HV equipment can be assessed.

One of the detection methods used by the DNV GL-PD system is based on the propagation of electromagnetic waves. The technique used to detect the EM-waves emitted by partial discharges comprises a broadband antenna and a spectrum analyzer.

The sensor for on-line PD measurements on transformers is a broadband spiral-antenna mounted on a lance with gland seals (see figure 2.3). The sensor can be inserted into the transformer through an oil drain valve. Sensors to be used on switchgear and GIS are shown in figure 2.4.

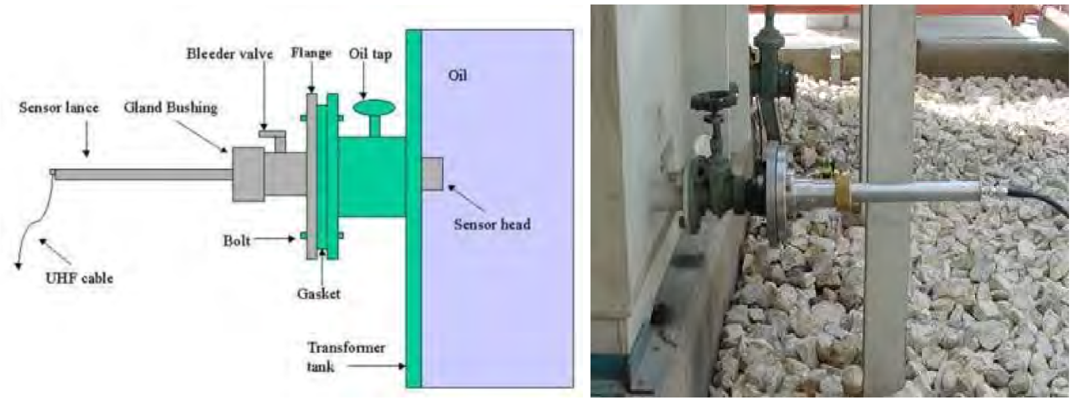


Figure 2.3 UHF-sensor inserted in a power transformer

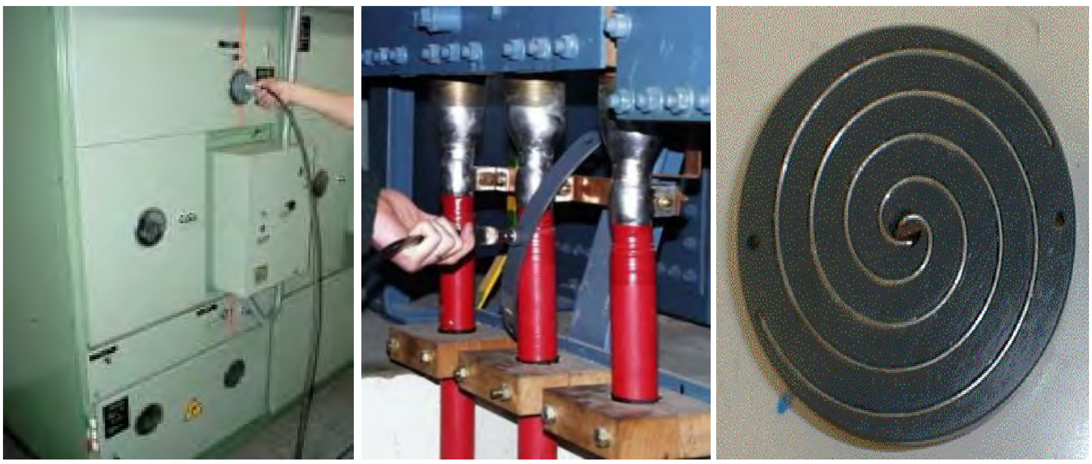
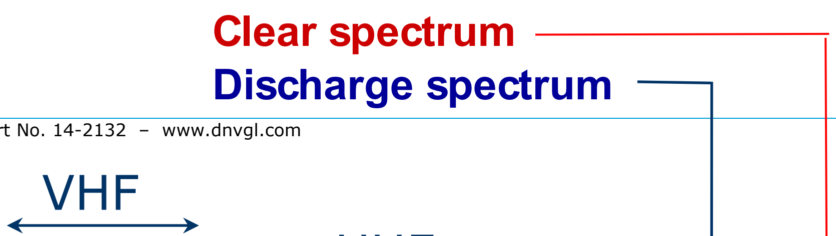


Figure 2.4 Example of externally applied UHF-sensor

The presence of partial discharge activity in the device under test (DUT) is assessed by comparing a reference spectrum (referred to as the background) and the spectrum measured close to the DUT as is shown in figure 2.5.



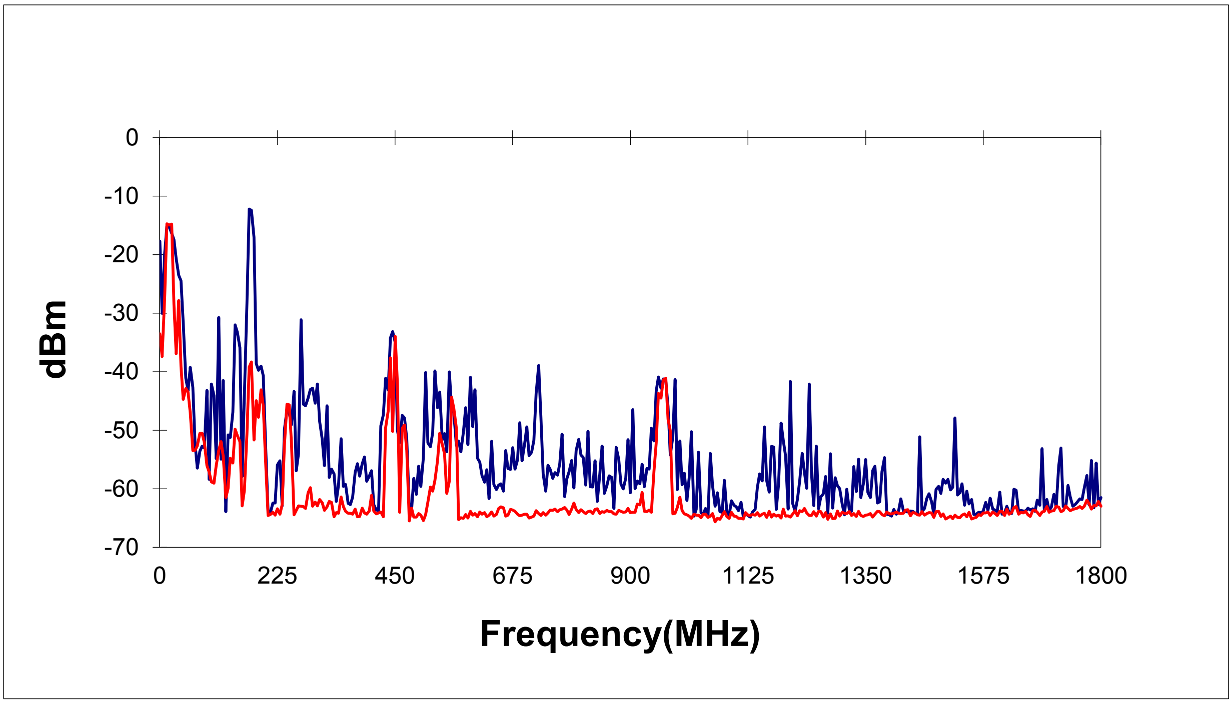


Figure 2.5 Two measured spectra

The red curve shows a spectrum of a clean environment. Up to a frequency of approximately 300 MHz is called VHF (Very High Frequency). In this area radio broadcasting can be found. From 300 MHz and above is called UHF (Ultra High Frequency). In this frequency area, only narrowband sources are present e.g. mobile telephone, television, et cetera. These signals will be considered as unwanted noise.

The blue curve shows the spectrum of the DUT. By comparing the blue and red curves, frequencies are selected for further analysis. The frequencies are chosen such that best signal to noise ratio is achieved, e.g., frequencies at which a profound signal is measured near to the DUT while very low signal is measured in the background. In the example of figure 2.5, a frequency between 270 MHz and 400 MHz, 650 MHz and 900 MHz and 1100 MHz and 1800 MHz would be suitable.

After suitable frequencies are detected, so-called point-on-wave (POW) measurements are performed to obtain time- and/or phase-resolved PD-patterns. These patterns provide information of the partial discharge activity (e.g. magnitude, intensity, correlation with voltage). In figure 2.6, several phase-resolved partial discharge patterns are depicted.

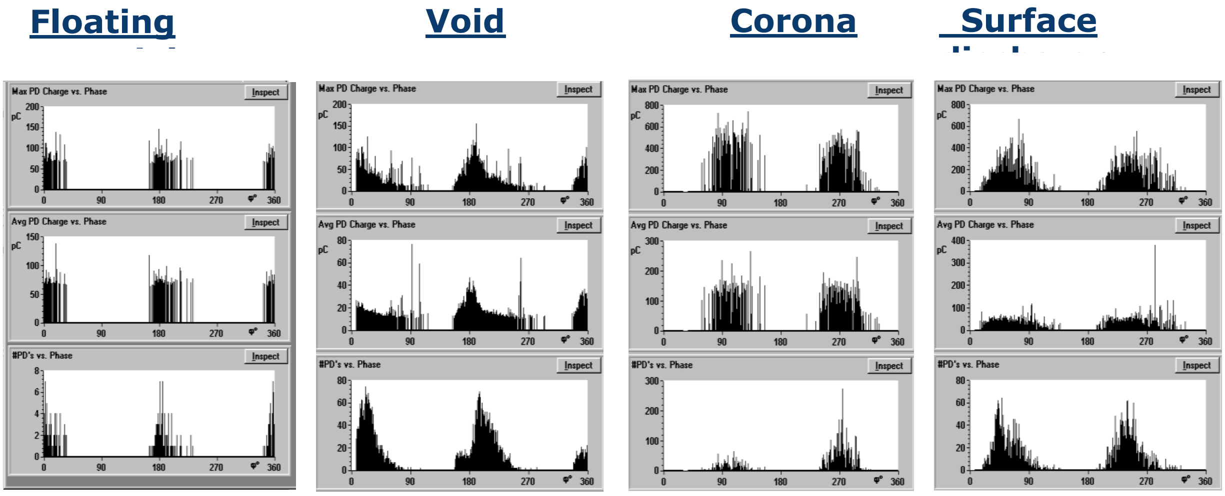


Figure 2.6 Examples of some PRPD measurements of different types of errors

3.3.2 Acoustic-methodology

DNV GL acoustic detection of partial discharge activity is based on the detection of ultrasonic vibrations in the range of 40 to 100 kHz by means of pre-amplified (60 dB) piëzo- electric sensors (resonance frequency 60 kHz).

Low frequency vibrations, which are usually generated by background noise, are filtered out. The DNV GL acoustic PD-detection system reshapes and amplifies the detected pulses by means of a logarithmic amplifier.

The PD-activity is stored and represented as both time- and phase-resolved patterns (see section 3.2.1).

Acoustic PD detection is suitable for oil filled components, which can usually not be diagnosed by means of UHF PD detection as the EM-waves do not propagate through metal cladding. Acoustic PD-measurements can be performed by external application of a sensor (see figure 2.7) on oil-filled transformer tanks, oil-filled cable terminations, or oil-filled switchgear.

Figure 2.7 Example of externally applied acoustic sensor

3.4 Thermal imaging

Thermal imaging uses infrared (IR) radiation to determine the associated temperature. Unlike X-ray technology which allows one to look inside of equipment, this method is primarily sensitive to heat that is radiated by the surface of the device under test. Hence, it may not provide conclusive proof about internal thermal faults deep(er) down. Thermal imaging is most effective in detecting thermal faults associated with loose or poorly fastened bolts, overheating of structural parts due to circulating currents or bad contacts inside bushings.

The determination of anomalies is based on the relative temperature difference across the surface of the device under test. For visual purposes, the hottest and coldest points are marked in contrasting colors and all temperatures in between are graded by color, thus providing a graphic display of the heat contours along the surface of the equipment.

3.5 Oil analyses

Oil samples of all 8 transformers (main tank – bottom) were taken by SPEN and subsequently analyzed by DNV GL in her oil laboratory in Arnhem, The Netherlands.

The following analyses are performed:

- dissolved gasses
- furanic compounds
- corrosive properties
- DBPC-content
- corrosive properties
- DBDS-content
- breakdown voltage
- color and appearance
- specific insulation resistance and power factor of insulation (tan(δ))
- contaminants
- acidity.

3.6 Remaining lifetime assessment

The remaining lifetime was assessed by two different methods:

1) Furanic compounds;
2) Dynamic loading guide calculations.

3.6.1 Method 1: Furanic compounds

Considering different ageing mechanisms, problems with the oil can often be solved by treatment or replacement of the oil. Thermal and dielectrical problems can often be solved by repair. However the aging of the insulating paper of a transformer is an irreversible process which results in the end of life of a transformer.

In practice, the end of the technical life of a transformer will be reached when the degree of polymerization (DP) of the insulating paper of the windings reaches a value lower than 250. New insulating paper has a DP value of approximately 1200.

The approach that DNV GL uses is to estimate the DP value of the insulating paper of the windings at a certain moment using the gas-in-oil analysis (DGA) and the determination of the 2-furfural concentration in the oil. This DP value has a certain inaccuracy (standard deviation, s.d.). With this estimated DP value, the remaining lifetime will be calculated based on a model that gives the decrease of the DP value as a function of time. A Monte Carlo simulation is used to incorporate uncertainties. The result is a failure rate as a function of the remaining life under the assumption that the average loading of the transformer will not change. It is up to the owner of the transformer to decide which failure rate is acceptable; mostly 5% or 10% is used.

Changing the load will result in a different outcome of the remaining life estimation. Decreasing or increasing the load will decrease or increase the hot-spot temperature and therefore affect the speed in which the paper will degrade and the DP value will reach a value of 250 or lower.

The consequence of reaching the DP value of 250 or lower will not be an immanent failure but the chance of a failure due to an extraneous event (e.g. transportation, a short circuit behind the transformer or switching on and off the current) will be unacceptable high.

For old transformers with insulating paper in the core, the ageing of this paper also contributes to the 2-furfural content of the oil. The confidential limits of the model are partly determined by this phenomenon.

DNV GL has determined a correlation between the DP value and the 2-furfural concentration, DP[fur]. DNV GL also determined a correlation between the DP value and the product of the 2-furfural concentration and the CO concentration, DP([fur]*[CO]). The first relation is especially for 2-furfural concentrations lower than 2 mg/kg. The second relation gives in general a better result for 2 furfural concentrations higher than 2 mg/kg.

For DGA as well as for the furfural analysis it is important to know what happened to the oil. Treatment of the oil to improve the thermal and/or the electrical properties often remove species which are used for the DGA as well as for the furfural analysis. The concentrations of most of the gases used for DGA decrease by oil treatment or oil replacement and increase again by production of these gases by thermal and electrical processes in the oil. The concentration of the 2-furfural however shows a different behaviour. The 2-furfural is produced in the paper and a part of the produced 2-furfural will move to the oil. There will be an equilibrium in which the concentration of 2-furfural of the paper is much higher than the concentration of 2-furfural in the oil. This is rather analogous to the behaviour of water where also the concentration of water in paper is much higher than the concentration of water in the oil. After a treatment or replacement of the oil only the relatively small amount of 2-furfural in the oil has been removed. Within a few years there will be a new equilibrium and the concentration of 2-furfural in the oil will be almost the concentration just before the oil treatment or replacement increased by the concentration which has been produced in the meantime.

So by applying this analysis the history of the transformer with respect to the oil always has to be kept in mind.

The 2-furfural concentration in the oil of some transformers was lower than the minimum detectable concentration of 0.1 mg/kg. To assess the DP-values, and from that the remaining life, a concentration of 0.1 mg/kg is used (worst case scenario). For these 2-furfural concentrations the DP-value is assessed to be around 550. This means that these transformers have used only a small part of their technical life time.

3.6.2 Method 2: dynamic loading guide calculations

The loading guide analysis is a KEMA software tool that uses algorithms stipulated by IEC 60076-7 ageing principles. The input parameters are statistically distributed according to pre-specified distributions. The output is the estimated failure rate as a function of the remaining lifetime, and is calculated by means of a Monte Carlo simulation (all values of the distributions of the input parameters are calculated so that a distribution of the output values is obtained). Figure 2.8 shows the input screen that is used for this analysis. For the analysis the following data is used, as indicated in figure 2.8:

1. Loading guide parameters:
    a. d(top oil): This is the top-oil temperature rise at rated load
    b. Loss ratio R: ratio between the load losses and the no-load losses
    c. H*gr: difference between hot spot temperature and top oil temperature
    d. oil exponent x, winding exponent y: parameters that account for the heat dissipation and distribution within the oil and windings of the transformer, depending on the type of cooling applied
2. Life expectancy for large power transformers. This is a value derived from manufacturer recommended values and / or database information
3. Historical loading and ambient temperatures
4. Future expected loading and ambient temperatures.

age	23			DP				ON.. Trafo	
Dpfur	526.6	stand. Dev	27	532.27	Tremfur	101.1615	number trials	1000	
DPfurCO	543.852	stand. Dev	40	539.8067	TremfurCO	105.6008			
DPend	250			Loading guide					
DPbegin	1200			dTtopoil	Loss ratio R	Oil exp x	Hgr	wind exp y	1
[fur]	0.2			52.00021319	12.256667	0.89859	25.9999843	1.6003358	
[CO]	600								
life expectancy	29.9988								2

		HISTORY						
	Tambient	Load K	period	Ths	Rel.ag.	Use	Tremhistory	3
1	24	0	4	29.09797	0.000349197	9.6999E-06		
2	27	0	2	32.09797	0.000493839	6.8589E-06		
3	30	0	0	35.09797	0.000698394	0		
4	33	0	0	38.09797	0.000987678	0		
5	36	0	0	41.09797	0.001396787	0		
6	39	0	0	44.09797	0.001975356	0		
7	42	0	0	47.09797	0.002793575	0		
8	45	0	0	50.09797	0.003950712	0		
9	48	0	0	53.09797	0.00558715	0		
10	51	0	0	56.09797	0.007901423	0		
101	24	1	0	102.0002	1.587437273	0		
102	27	1	1	105.0002	2.244975321	0.01559011		
103	30	1	1	108.0002	3.174874546	0.02204774		
104	33	1	0	111.0002	4.489950641	0		
105	36	1	0	114.0002	6.349749091	0		
106	39	1	0	117.0002	8.979901282	0		
107	42	1	0	120.0002	12.69949818	0		
108	45	1	0	123.0002	17.95980256	0		
109	48	1	0	126.0002	25.39899636	0		
110	51	1	0	129.0002	35.91960513	0		
	39.95455	0.5	144			0.39308563	50.4049	
					Real use	9.04096945		

		FUTURE						
	Tambient	Load K	period	Ths	Rel.ag.	Use	Tremfuture	4
1	24	1	22	102.0002	1.587437273	0.06063128		
2	27	1	81	105.0002	2.244975321	0.31569965		
3	30	1	82	108.0002	3.174874546	0.45197867		
4	33	1	67	111.0002	4.489950641	0.52226856		
5	36	1	54	114.0002	6.349749091	0.59528898		
6	39	1	73	117.0002	8.979901282	1.13807777		
7	42	1	117	120.0002	12.69949818	2.57958557		
8	45	1	65	123.0002	17.95980256	2.02671383		
9	48	1	13	126.0002	25.39899636	0.57324124		
10	51	1	2	129.0002	35.91960513	0.12472085		
	37.5	1	576			8.3882064	1.766668	

Figure 2.8 Example of the input screen for IEC Loading Analysis

The loading data is expressed as the factor K, which is the actual load divided by the rated load. The loadings have been divided in load-classes 0%, 10%, 20%,….120% rated load, and the corresponding ambient temperatures have been divided in ambient temperature-classes 24, 27, 30,….51 °C. The green marked parameters in figure 2.8 have certain statistical distributions. All parameters, except the load factor (K) and the ambient temperature, are assumed to have normal distributions.

In figure 2.8 the loading and ambient temperature data are depicted in row "Tambient" and row "Load K". The row "period" indicates the number of periods that this combination occurs.

The rows "Ths.", "Rel. ag." and "Use" calculate the corresponding hot spot temperatures, relative ageing and actual number of years that are consumed due to thermal ageing of the insulating paper. Finally, the remaining lifetime based on historical loading data and based on future expected data is calculated. The calculation of the remaining lifetime based upon the preceding input parameters yields the output curve depicted in figure 2.9. This figure shows the expected failure rate of the paper insulation as a function of the remaining lifetime of the transformer.

As shown in figure 2.9, there will be no significant paper deterioration due to thermal ageing for the next decades if the transformer will be loaded as under current and historical circumstances. The relatively low loading of this unit causes this result. However, in case this unit will be continuously loaded at 100% rated load from now on, the expected remaining lifetime will be less than 2 years.

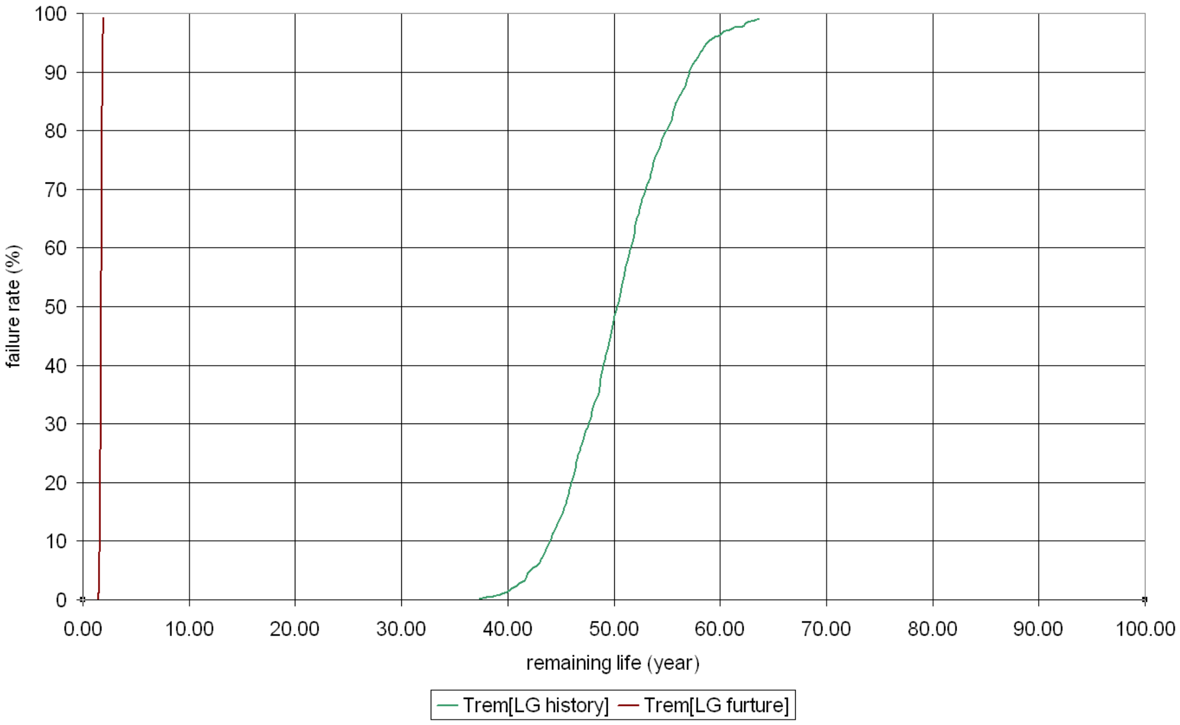


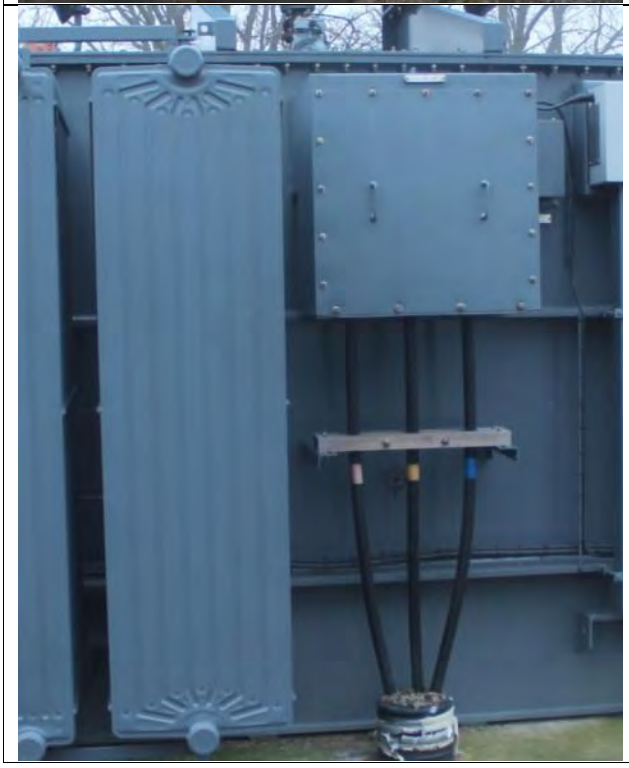
Figure 2.9 Example forecast failure rate based on Loading Simulation for a power transformer

4 RESULTS ASSET CONDITION ASSESSMENT

4.1 Whitchurch

4.1.1 Visual inspection

  	Overview pictures of transformer T1 at substation Whitchurch. Transformer installed in 2010. No severe signs of damage, leakage and deterioration.

 	Terminations of 33 kV feeding cables. New cables have been installed in 2010. Other components in the bay are older, but show no severe signs for deterioration or damage.
	33 kV cable termination box.

Conclusion

During the visual inspection, no severe signs of damage and deterioration have been observed. Transformer has been installed in 2010.

4.1.2 Partial discharge measurement

Frequency spectra

The recorded frequency spectra are shown in figure 3.1.

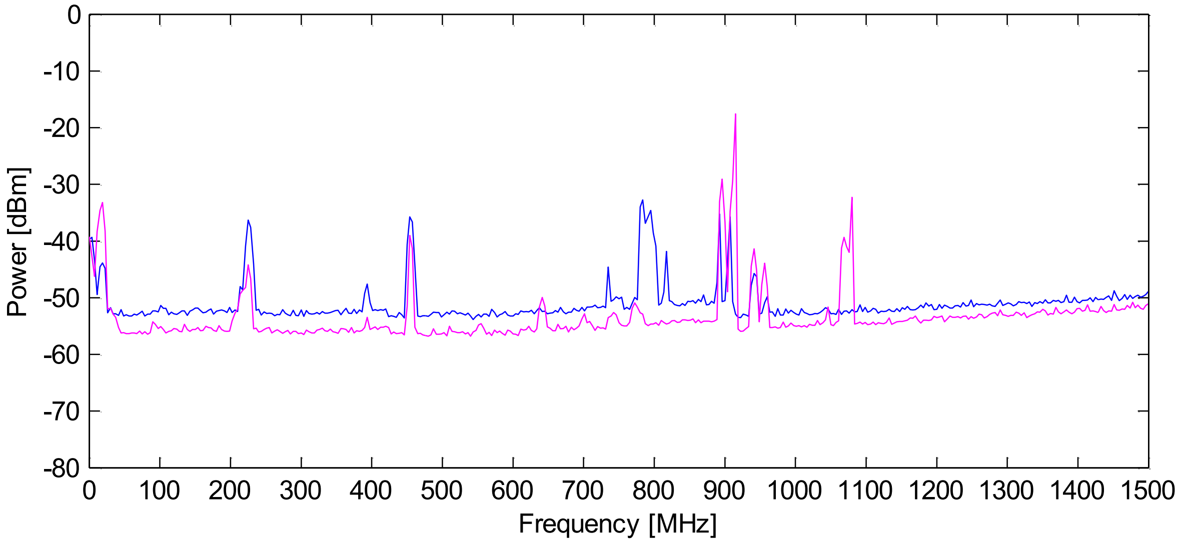


Figure 3.1 Frequency spectra of background (blue) and object (magenta)

Point-on-wave measurements

Based on a comparison between the two frequency spectra shown in figure 3.1, point-on-wave measurements were performed on:

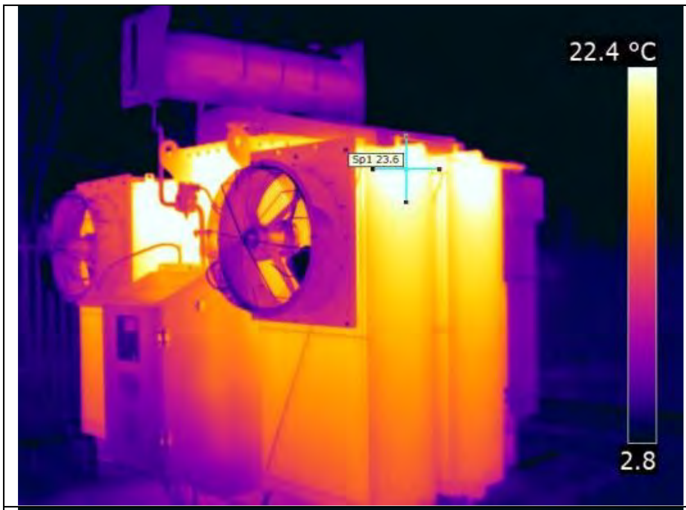
- 25 MHz
- 650 MHz
- 700 MHz
- 760 MHz
- 800 MHz
- 1125 MHz.

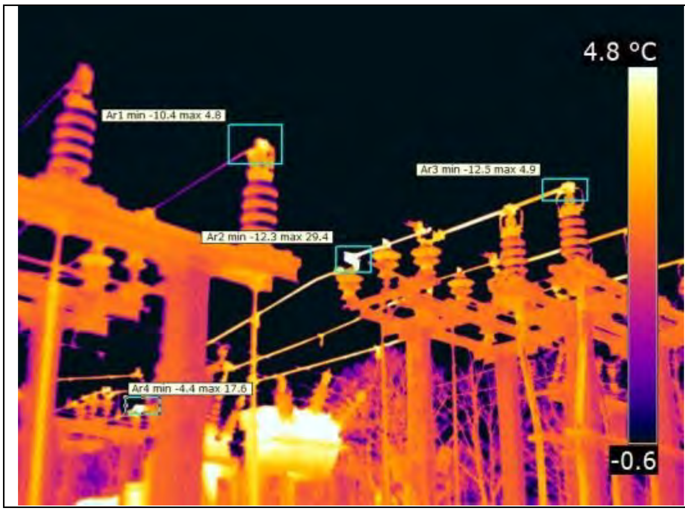
It was found that the detected signals are not generated by partial discharge activity within the object.

Conclusion

During the partial discharge measurements, no source of partial discharge activity was found within the transformer.

4.1.3 Thermal imaging

	No indication of thermal issues.
	No indication of thermal issues.
	No indication of thermal issues. Highest observed temperature on tank surface was roughly 25 °C.



In the 33 kV-switchyard, some minor hot spots were detected on the (rail-side) terminal of several disconnectors.

Conclusion

During the thermal imaging of the transformer, no observations were made that would suggest the presence of a thermal issue.

During the thermal imaging of the 33 kV-switchyard, some minor hot spots were detected on the (rail-side) terminal of several disconnectors. It is recommended to address these hot spots during the next scheduled maintenance/outage.

4.1.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.1.

Table 3.1 Results dissolved gas analysis

Gas	Result	
Hydrogen	**9.6**	µL/L
Methane	**1.1**	µL/L
Ethane	**<1**	µL/L
Ethylene	**4.3**	µL/L
Acetylene	**37.5**	µL/L
Propane	**<1**	µL/L
Propene	**1.8**	µL/L
Carbon-monoxide	**41**	µL/L
Carbon dioxide	**1200**	µL/L
N-butane	**1.2**	µL/L
Iso-butane	**1**	µL/L

Results physical properties

The physical properties are presented in table 3.2.

Table 3.2 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	< 0.1	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	0.066	%(m/m)
Corrosive properties	Non-corrosive	-
DBDS	< 5	mg/kg
Breakdown voltage	23	kV/2.5 mm
Color	0-0.5	-
Specific resistance (@ 90°C)	-	GΩ·m
Tan(δ) (@ 90°C)	-	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	Free water detected	-
Water content	40	mg/kg
Acidity	0.03	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates the presence of electrical discharges. Given that no electrical discharge activity was detected during the online partial discharge measurements (see section 3.1.2) may indicate that the activity occurs intermittently. Alternatively, leakage between the oil compartment of the on-load tap-changer and the transformer main tank cannot be excluded. DNV GL recommends to collect a new sample in June 2014 for analysis on dissolved gasses.

On the basis of the measured water content and the detection of free water, the oil fails to meet the requirements of IEC 60422. To verify the results, DNV GL recommends to collect a new sample immediately for the analysis of the physical properties.

4.1.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is smaller than the detection limit of 0.1 mg/kg and the age is 4 year. The DP value is assessed to be 545, the highest value which can be given by the model (worst case).

In figure 3.2, the assessment of the remaining life of this transformer is given. From this figure it can be seen that the expected remaining life is rather small. For a 5% failure rate, the remaining life is estimated at 14 years. This is because of taking a 2-furfural concentration of 0.1 mg/kg (worst case) after only 4 year of service. This concentration is very unlikely and is expected to be lower than the detection limit of 0.1 mg/kg. The model is only useful for young transformers if there is a measurable concentration of 2-furfural.

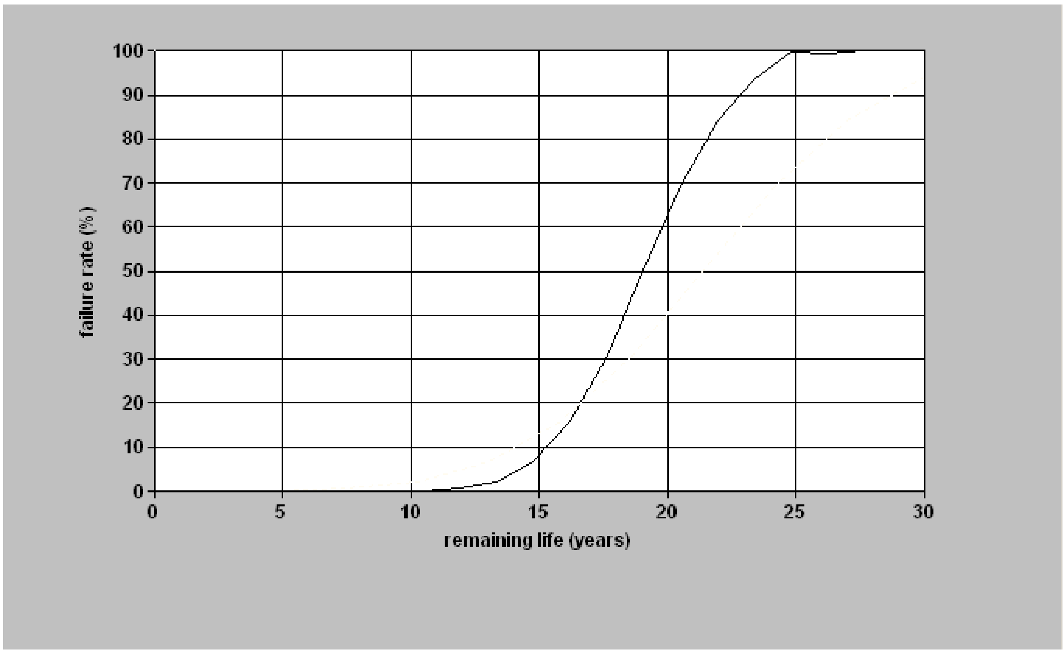


Figure 3.2 Assessed failure rate of transformer Whitchurch T1 (unrealistic)

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years;
- Loading equal to 1: > 29 years.

Conclusion

From the remaining life analysis follows no significant ageing. The transformer is still very young and therefore the results based on furanics, which is specifically developed for older transformers, gives low values. Based on the loading guide analysis, the expected remaining life is more than 29 years.

4.2 Liverpool Road

4.2.1 Visual inspection

 	Overview pictures of transformer T1 at substation Liverpool Road. No severe signs of damage and deterioration. Some oil sweating at the oil expansion tank.
	Some oil sweating at the expansion tank.

	11 kV cable termination box, no signs for deterioration, ageing and leakage.
	33 kV cable termination box, no signs for deterioration, ageing and leakage.

Conclusion

During the visual inspection, no severe signs of damage, deterioration and leakage have been observed. Some oil sweating at the oil expansion tank.

4.2.2 Partial discharge measurement

Frequency spectra

The recorded frequency spectra are shown in figure 3.3.

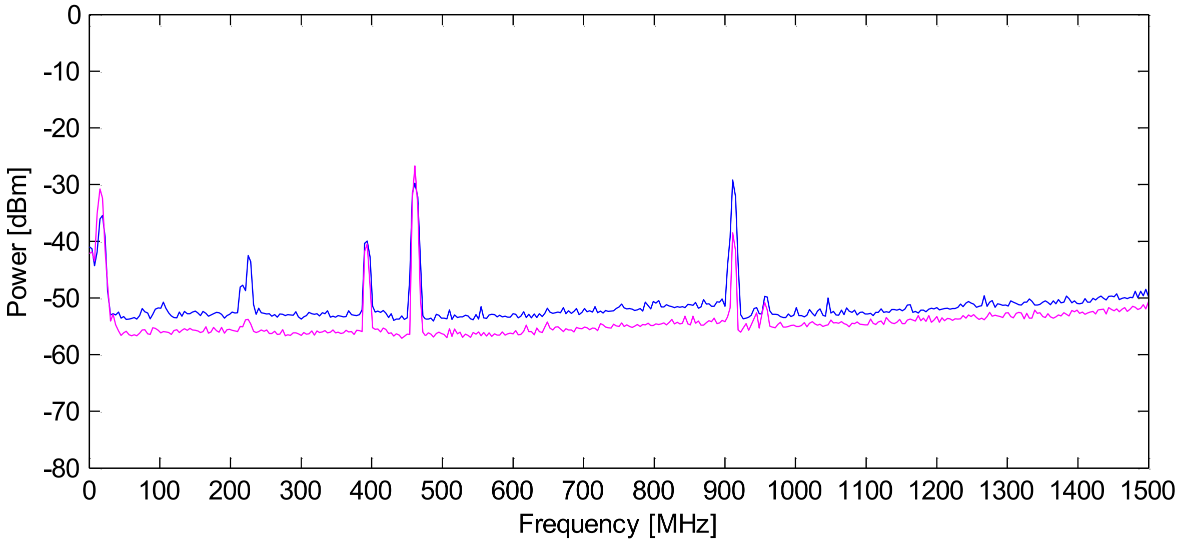


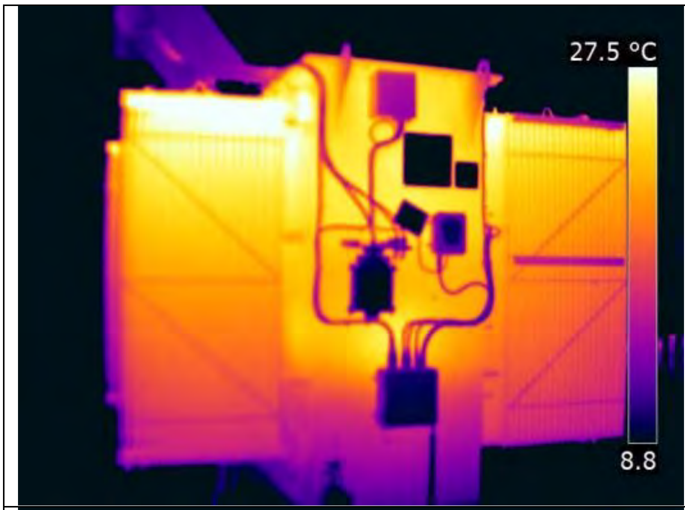
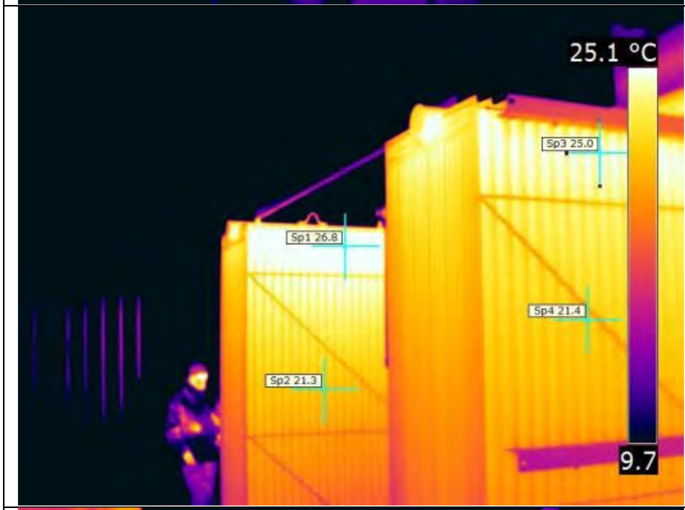
Figure 3.3 Frequency spectra of background (blue) and object (magenta)

Based on a comparison between the two frequency spectra shown in figure 3.3, it can be concluded that no source of partial discharge activity is present within the object.

Conclusion

During the partial discharge measurements, no source of partial discharge activity was found within the transformer.

4.2.3 Thermal imaging

	No indication of thermal issues.
	No indication of thermal issues.
	Highest observed temperature on tank surface was roughly 25 °C.

Conclusion

During the thermal imaging of the transformer, no observations were made that would suggest the presence of a thermal issue.

4.2.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.3.

Table 3.3 Results dissolved gas analysis

Gas	Result	
Hydrogen	**15.0**	μL/L
Methane	**6.1**	μL/L
Ethane	**31.1**	μL/L
Ethylene	**10.3**	μL/L
Acetylene	**89**	μL/L
Propane	**23.7**	μL/L
Propene	**7.3**	μL/L
Carbon-monoxide	**39**	μL/L
Carbon dioxide	**1350**	μL/L
N-butane	**8.7**	μL/L
Iso-butane	**< 1**	μL/L

Results physical properties

The physical properties are presented in table 3.4.

Table 3.4 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	< 0.1	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	< 0.05	%(m/m)
Corrosive properties	Corrosive	-
DBDS	131	mg/kg
Breakdown voltage	63	kV/2.5 mm
Color	0-0.5	-
Specific resistance (@ 90°C)	141	GΩ·m
Tan(δ) (@ 90°C)	56	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	None detected	-
Water content	26	mg/kg
Acidity	0.03	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates the presence of electrical discharges. Given that no electrical discharge activity was detected during the online partial discharge measurements (see section 3.2.2) may indicate that the activity occurs intermittently. Alternatively, leakage between the oil compartment of the on-load tap-changer and the transformer main tank cannot be excluded. DNV GL recommends to collect a new sample in June 2014 for analysis on dissolved gasses

The oil is found to be corrosive. DNV GL recommends to carefully evaluate the necessity of corrective actions on the basis of a risk assessment study according to CIGRÉ Brochure 378 (2009).

4.2.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is smaller than the detection limit of 0.1 mg/kg and the age is 13 year. The DP value is assessed to be 545, the highest value which can be given by the model (worst case).

In figure 3.4, the assessment of the remaining life of this transformer is given. From this figure it can be seen that the model predicts a rather high remaining life although the 2-furfural concentration is below the detection limit (compared to the results of the transformers Ruabon T1 and Whitchurch T1). For a 5% failure rate, the remaining life is estimated at 45 years.

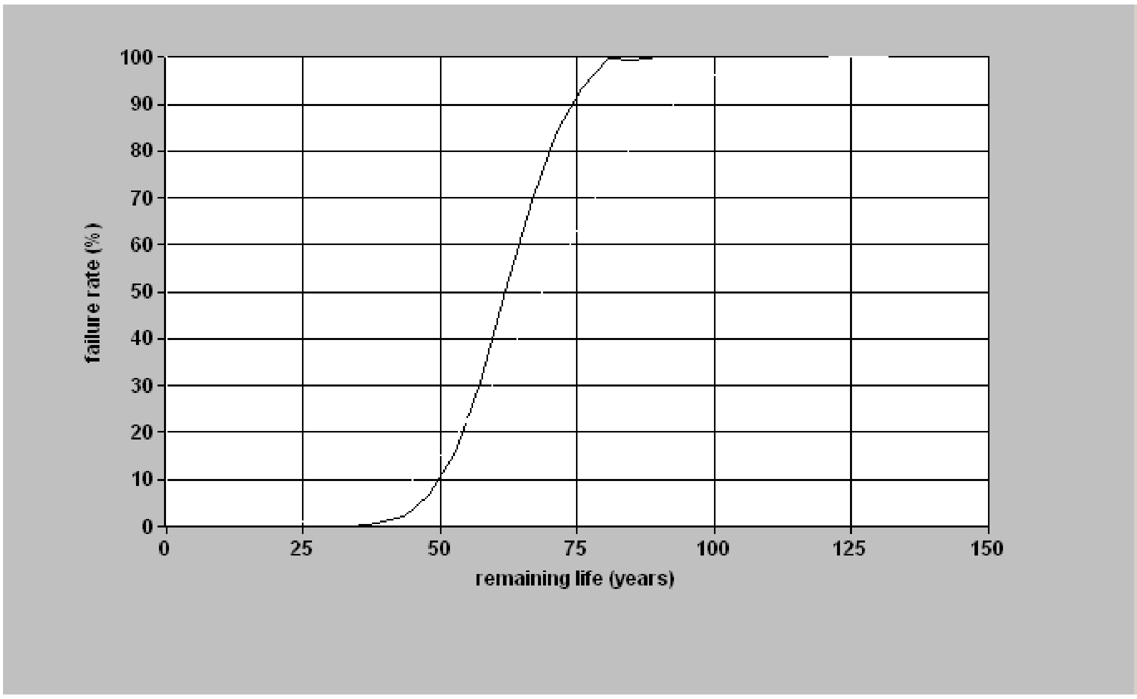


Figure 3.4 Assessed failure rate of transformer Liverpool Rd T1

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years
- Loading equal to 1: > 28 years.

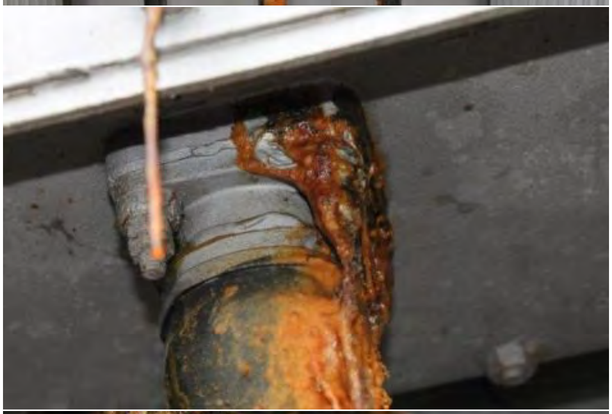
Conclusion

From the remaining life analysis follows no significant ageing. The different analysis methods indicate a remaining life of 28 years or longer.

4.3 Yockings Gate

4.3.1 Visual inspection

 	Overview pictures of transformer T1 at substation Yockings Gate. No severe signs of damage, deterioration and leakage, except for the middle phase of the 33 kV cable in the termination box.
	Some small rust spots were observed at different locations.
	Original 11 kV cables are still in operation. Cables terminate in termination box. Some signs of wear on the cable sheaths, no further signs of deterioration or leakage. New cable jointed in 2012 to enter the new switchgear.

	
  	New 33 kV incoming cables installed in ±2000. Severe signs of leakage of mass at the termination box, middle phase. Right phase shows some mass leaking.

Conclusion

During the visual inspection, no severe signs of damage, deterioration and leakage have been observed. Some small rust spots have been observed. Severe leakage of mass from the 33 kV cable termination box has been observed.

4.3.2 Partial discharge measurement

Frequency spectra

The recorded frequency spectra are shown in figure 3.5.

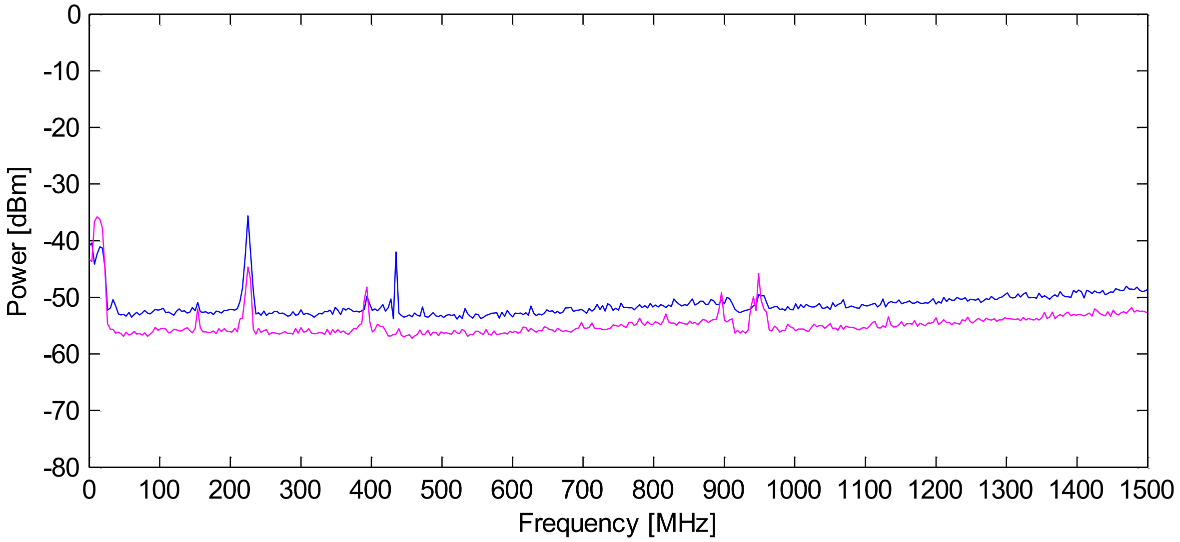


Figure 3.5 Frequency spectra of background (blue) and object (magenta)

Point-on-wave measurements

Based on a comparison between the two frequency spectra shown in figure 3.5, point-on-wave measurements were performed on:

- 35 MHz
- 140 MHz
- 200 MHz
- 415 MHz
- 850 MHz
- 995 MHz.

It was found that the detected signals are not generated by partial discharge activity within the object.

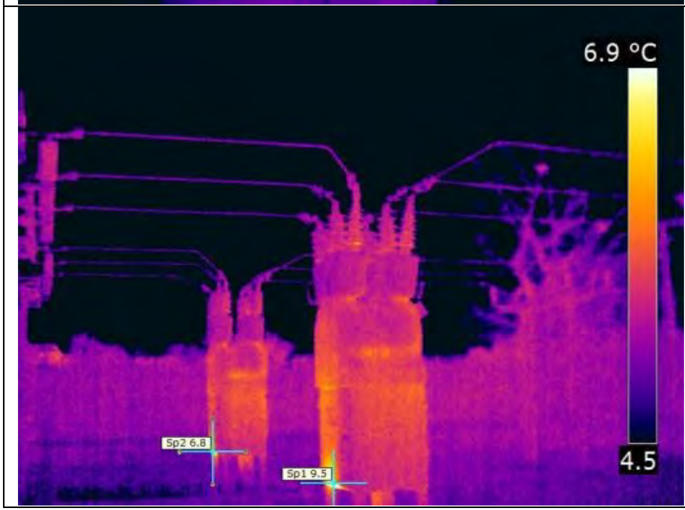
It is noted that in addition to the UHF-methodology, also partial discharge measurements by means of the acoustic methodology were performed. These measurements confirmed the results of the UHF-methodology as no indications of partial discharge activity were found.

Conclusion

During the partial discharge measurements, no source of partial discharge activity was found within the transformer.

4.3.3 Thermal imaging

	No indication of thermal issues.
	No indication of thermal issues.
	No indication of thermal issues.

	Highest observed temperature on tank surface was roughly 15 °C.
	No thermal issues were found in 33 kV-switchyard.

Conclusion

During the thermal imaging of the transformer, no observations were made that would suggest the presence of a thermal issue.

4.3.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.5.

Table 3.5 Results dissolved gas analysis

Gas	Result	
Hydrogen	**16.8**	µL/L
Methane	**3.7**	µL/L
Ethane	**4.2**	µL/L
Ethylene	**7.8**	µL/L
Acetylene	**< 1**	µL/L
Propane	**10.2**	µL/L
Propene	**39.8**	µL/L
Carbon-monoxide	**181**	µL/L
Carbon dioxide	**2510**	µL/L
N-butane	**21.1**	µL/L
Iso-butane	**3.2**	µL/L

Results physical properties

The physical properties are presented in table 3.6.

Table 3.6 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	0.22	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	< 0.05	%(m/m)
Corrosive properties	None-corrosive	-
DBDS	< 5	mg/kg
Breakdown voltage	52	kV/2.5 mm
Color	2.5-3.0	-
Specific resistance (@ 90°C)	4.6	GΩ·m
Tan(δ) (@ 90°C)	451	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	Some detected	-
Water content	13	mg/kg
Acidity	0.13	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates a normal aging process. DNV GL recommends to collect a new sample in January 2015 for the analysis on the concentration of dissolved gasses.

The physical properties of the oil meet the requirements of IEC 60422 and can be kept in service. DNV GL recommends to collect a new sample in January 2016 for the analysis of the physical properties.

4.3.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is 0.22 mg/kg and the age is 60 years. The DP value is assessed to be 523 (s.d. 27).

In figure 3.6, the assessment of the remaining life of this transformer is given. From this figure it can be seen that the expected remaining life is very high. For a 5% failure rate, the remaining life is estimated at 70 years.

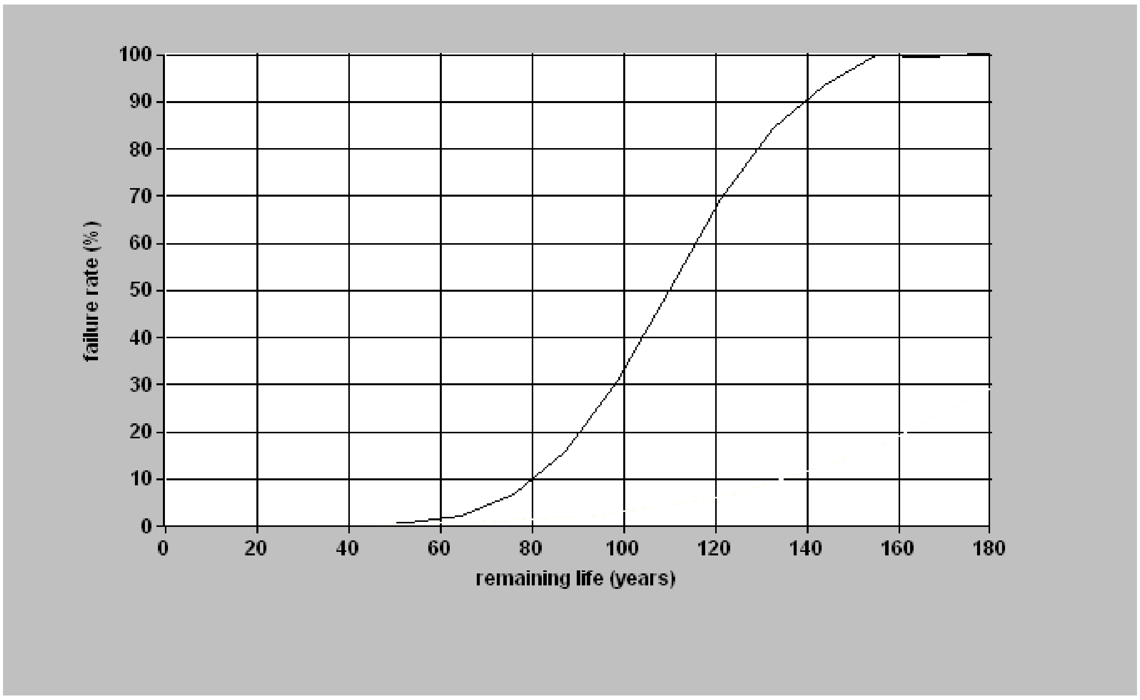


Figure 3.6 Assessed failure rate of transformer Yockings Gate T1

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years;
- Loading equal to 1: > 27 years.

Conclusion

From the remaining life analysis follows no significant ageing. The different analysis methods indicate a remaining life of 27 years or longer.

4.4 Ruabon

4.4.1 Visual inspection

	Overview pictures of transformer T1 at substation Ruabon. Transformer installed in 2013. No severe signs of damage, leakage and deterioration.

	Terminations of 33 kV feeding cables. New cables have been installed in 2013.
	Other components in the bay show no signs for deterioration or damage.
 	Some small rust spots were observed.

	11 kV cable termination box.
	33 kV cable termination box.

Conclusion

During the visual inspection, no severe signs of damage and deterioration have been observed. Transformer has been installed in 2013.

4.4.2 Partial discharge measurement

Frequency spectra

The recorded frequency spectra are shown in figure 3.7.

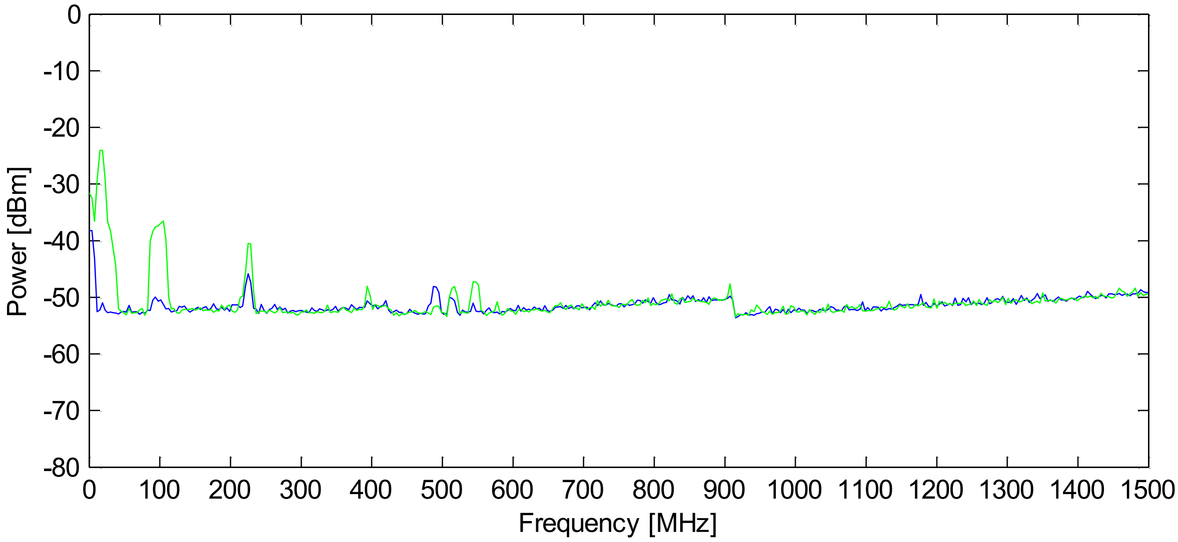


Figure 3.7 Frequency spectra of background (blue) and object (green)

Point-on-wave measurements

Based on a comparison between the two frequency spectra shown in figure 3.7, point-on-wave measurements were performed on:

- 35 MHz
- 105 MHz
- 245 MHz
- 385 MHz
- 505 MHz
- 565 MHz.

At 35 MHz, the following signal was recorded:

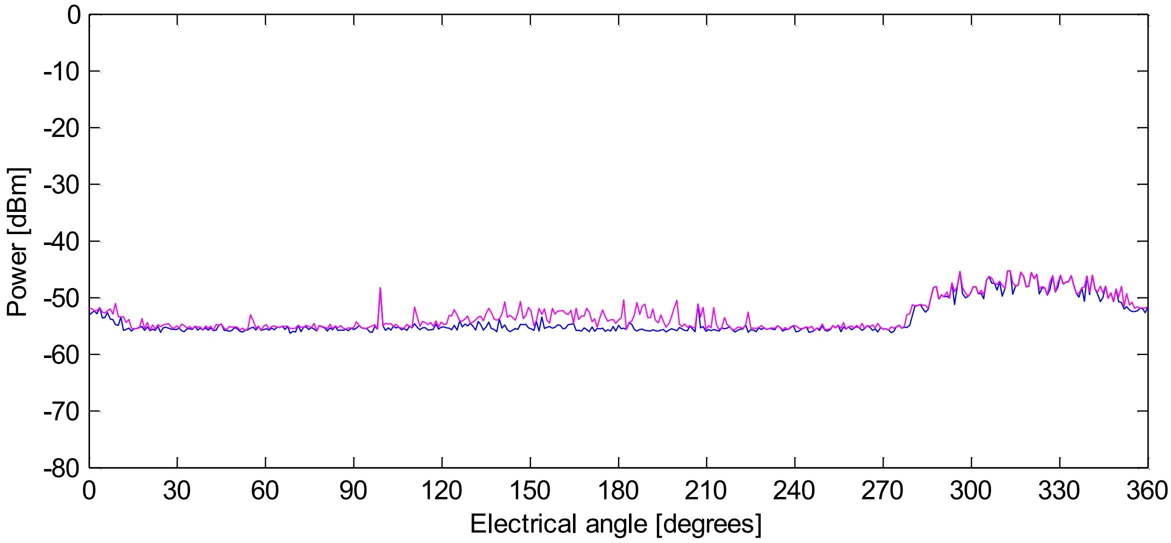


Figure 3.8 Point-on-wave measurement at 35 MHz after 30 seconds (blue) and 60 seconds (magenta)

The signal depicted in figure 3.8 is indicates the presence of partial discharge activity. Based on an evaluation of the signal, DNV GL concludes that the most likely origin is a corona discharge in air. As such, it is unlikely that the source of the partial discharge activity is inside the transformer. In an attempt to further localize the source of the partial discharge activity, the following additional measurements were performed:

- partial discharge measurements on the air-insulated 33 kV-switchyard by means of the UHF-methodology
- partial discharge measurements on the transformer by means of the acoustic methodology.

In none of the above-mentioned additional measurements, partial discharge activity was observed; hence, the location of the source could not be determined. Possibly, the 33 kV-cable terminations are involved; due to their position (enclosed within air insulated cable box) these could not be measured accurately.

Conclusion

During the partial discharge measurements, partial discharge activity was found. However, it is unlikely that the source of this activity is within the transformer. Instead, the most likely origin is a corona discharge in air. In spite of additional measurements, the location of the discharge activity could not be determined. Possibly, the 33 kV-cable terminations are involved.

Given the fact that the transformer is still under warranty, it is recommended to consult the manufacturer.

4.4.3 Thermal imaging

	Temperature difference between main tank and radiators is noticeable. Possibly, the difference is caused due to differences in emissivity of the surface: • main tank: painted steel • radiators: galvanized steel. However, it could not be unambiguously determined whether the observation was caused by another phenomenon, e.g. incorrect position of radiator valves.
	Highest observed temperature on tank surface was roughly 28 °C.
	

	No thermal issues were found in 33 kV-switchyard.
	No thermal issues were found in 33 kV-switchyard.

Conclusion

During the thermal imaging of the transformer, no observations were made that would suggest the presence of localized hot spots. However, a peculiar temperature difference was between main tank and the radiators was noted. As the main tank is made of painted steel while the radiators are made of galvanized steel, possibly, the difference is caused due to differences in emissivity of these surfaces: However, it could not be unambiguously determined whether the observation was caused by another phenomenon, e.g. incorrect position of radiator valves.

Given the fact that the transformer is still under warranty, it is recommended to consult the manufacturer.

4.4.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.7.

Table 3.7 Results dissolved gas analysis

Gas	Results	
Hydrogen	**17.6**	µL/L
Methane	**1.2**	µL/L
Ethane	**< 1**	µL/L
Ethylene	**1.7**	µL/L
Acetylene	**< 1**	µL/L
Propane	**< 1**	µL/L
Propene	**< 1**	µL/L
Carbon-monoxide	**101**	µL/L
Carbon dioxide	**580**	µL/L
N-butane	**1.5**	µL/L
Iso-butane	**2.1**	µL/L

Results physical properties

The physical properties are presented in table 3.8.

Table 3.8 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	< 0.1	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	0.10	%(m/m)
Corrosive properties	None-corrosive	-
DBDS	< 5	mg/kg
Breakdown voltage	8	kV/2.5 mm
Color	0-0.5	-
Specific resistance (@ 90°C)	-	GΩ·m
Tan(δ) (@ 90°C)	-	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	Free water detected	-
Water content	35	mg/kg
Acidity	0.03	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates a normal aging process. DNV GL recommends to collect a new sample in January 2015 for the analysis on the concentration of dissolved gasses.

On the basis of the measured water content and the detection of free water, the oil fails to meet the requirements of IEC 60422. To verify the results, DNV GL recommends to collect a new sample immediately for the analysis of the physical properties.

4.4.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is smaller than the detection limit of 0.1 mg/kg and the age is 1 year. The DP value is assessed to be 545, the highest value which can be given by the model (worst case).

In figure 3.9, the assessment of the remaining life of this transformer is given. From this figure it can be seen that the expected remaining life is very small. At 5% failure rate, the remaining life is 4 years. This is because of taking a 2-furfural concentration of 0.1 mg/kg (worst case) after only 1 year of service. This concentration is very unlikely and is expected to be lower than the detection limit of 0.1 mg/kg. The model is only useful for young transformers if there is a measurable concentration of 2-furfural.

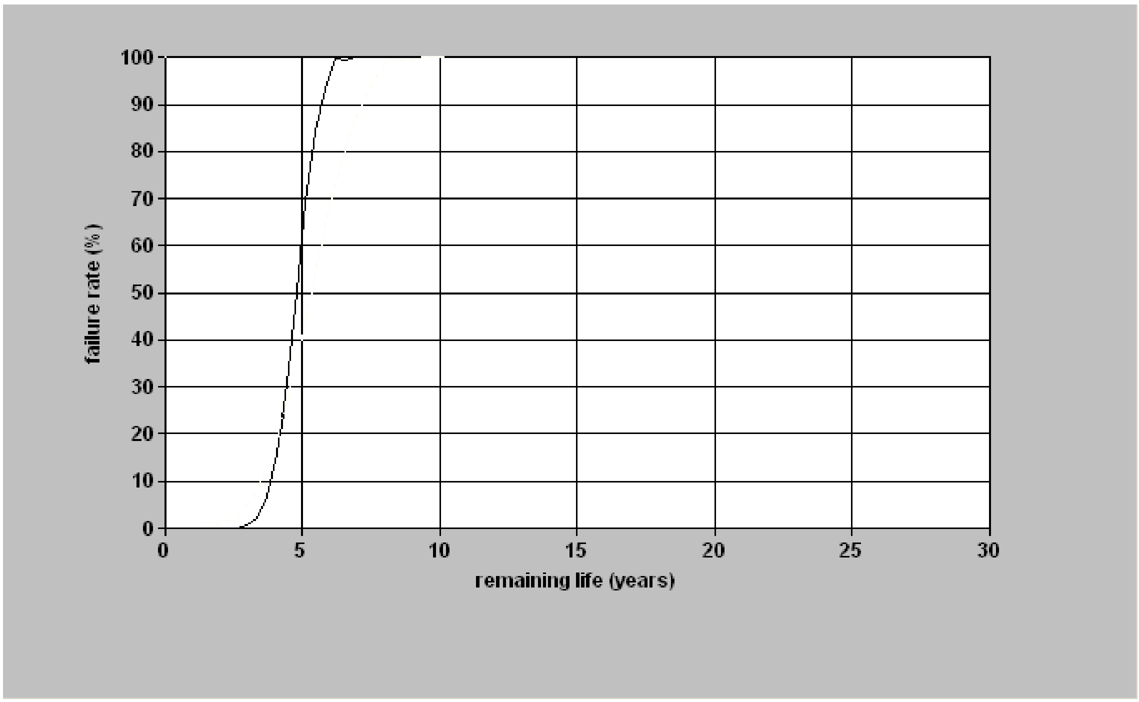


Figure 3.9 Assessed failure rate of transformer Ruabon T1 (unrealistic)

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years ;
- Loading equal to 1: > 29 years.

Conclusion

From the remaining life analysis follows no significant ageing. The transformer is still very young and therefore the results based on furanics, which is specifically developed for older transformers, gives low values. Based on the loading guide analysis, the expected remaining life is more than 29 years.

4.5 St. Andrews – Transformer 1

4.5.1 Visual inspection

	Overview picture of transformer T1 at substation St. Andrews. No severe signs of damage, deterioration and leakage.
	Picture of the tap-changer compartment. No severe signs of damage, deterioration and leakage.
	Picture of two 33 kV bushings. No signs of damage or deterioration on the 33 kV and 11 kV bushings.
	Rust was found on several locations on the radiators.

	Some small oil leakage or sweating was observed.
	Large spots with rust on the supporting construction of the radiators.
	Rust formation along the bottom plate of the transformer.
	11 kV cables have been replaced in 1988. Some wear on the terminations, but no signs of deterioration.

	33 kV incoming cables and disconnecting switches. Cables have been replaced in 2010. No severe signs of damage and deterioration on other components.

Conclusion

During the visual inspection, no severe signs of damage, deterioration and leakage have been observed. The rust formation on the radiators might need further attention.

4.5.2 Partial discharge measurements

Frequency spectra

The recorded frequency spectra are shown in figure 3.10.

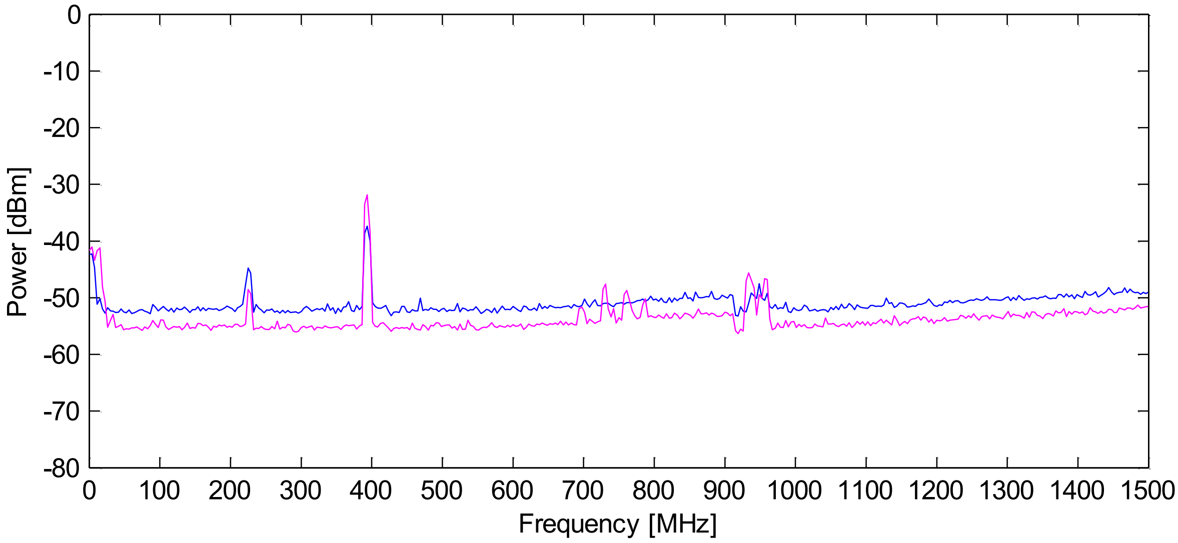


Figure 3.10 Frequency spectra of background (blue) and object (magenta)

Point-on-wave measurements

Based on a comparison between the two frequency spectra shown in figure 3.10, point-on-wave measurements were performed on:

- 20 MHz
- 40 MHz
- 115 MHz
- 260 MHz
- 700 MHz
- 770 MHz
- 825 MHz.

It was found that the detected signals are not generated by partial discharge activity within the object.

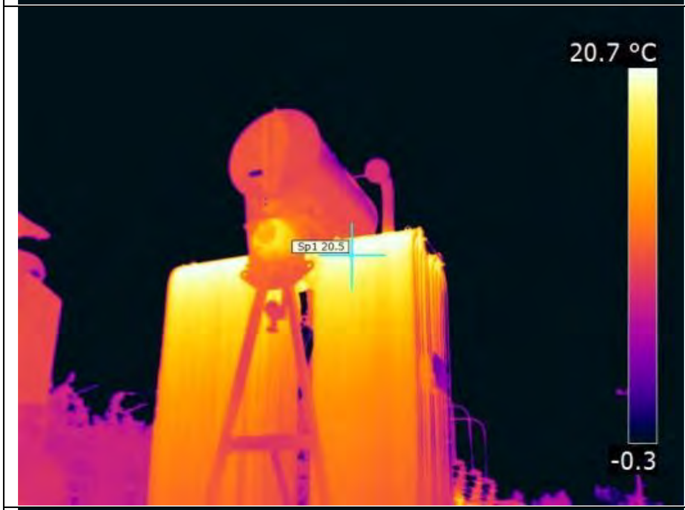
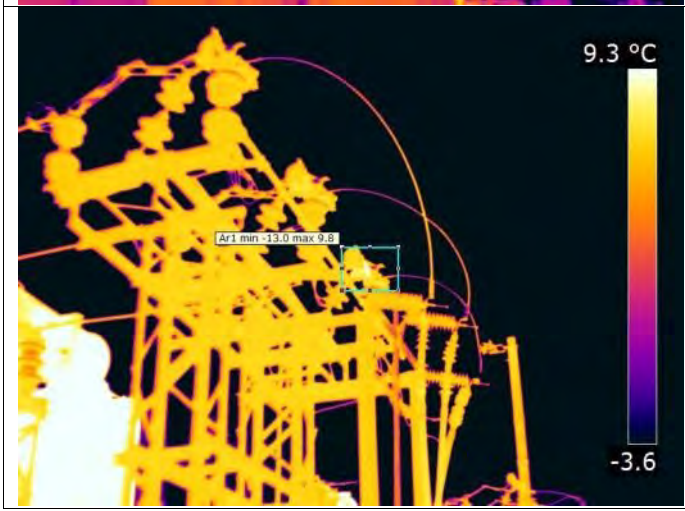
It is noted that in addition to the UHF-methodology, also partial discharge measurements by means of the acoustic methodology were performed. These measurements confirmed the results of the UHF-methodology as no indications of partial discharge activity were found.

Conclusion

During the partial discharge measurements, no source of partial discharge activity was found within the transformer.

4.5.3 Thermal imaging

	No indication of thermal issues.
	No indication of thermal issues.
	No indication of thermal issues.

<table>
<tr><td>
</td><td>No indication of thermal issues.</td></tr>
<tr><td>
</td><td>No indication of thermal issues.</td></tr>
<tr><td>
</td><td>No thermal issues were found in 33 kV-switchyard.</td></tr>
</table>

Conclusion

During the thermal imaging of the transformer, no observations were made that would suggest the presence of a thermal issue.

4.5.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.9.

Table 3.9 Results dissolved gas analysis

Gas	Date (dd-mm-yyyy)			Unit
	13-10-2009	08-10-2012	**25-02-2014**	
Hydrogen	38.2	14.2	**41**	µL/L
Methane	4.5	2.9	**2.6**	µL/L
Ethane	4.5	2.6	**3.6**	µL/L
Ethylene	4	2.3	**3.0**	µL/L
Acetylene	0	0	**< 1**	µL/L
Propane	-	-	**15.4**	µL/L
Propene	-	-	**33.1**	µL/L
Carbon-monoxide	118.6	111.2	**227**	µL/L
Carbon dioxide	2824.6	2766.3	**3190**	µL/L
N-butane	-	-	**22.4**	µL/L
Iso-butane	-	-	**28.1**	µL/L

Results physical properties

The physical properties are presented in table 3.10.

Table 3.10 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	< 0.1	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	< 0.05	%(m/m)
Corrosive properties	None-corrosive	-
DBDS	< 5	mg/kg
Breakdown voltage	66	kV/2.5 mm
Color	2.0 – 2.5	-
Specific resistance (@ 90°C)	16.5	GΩ·m
Tan(δ) (@ 90°C)	146	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	None detected	-
Water content	9	mg/kg
Acidity	0.15	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates a normal aging process. DNV GL recommends to collect a new sample in January 2015 for the analysis on the concentration of dissolved gasses.

The physical properties of the oil meet the requirements of IEC 60422. DNV GL recommends to collect a new sample in January 2016 for the analysis of the physical properties.

4.5.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is smaller than the detection limit of 0.1 mg/kg and the age is 48 years. The DP value is assessed to be 545 (s.d. 27), the highest value given by the model (worst case).

In figure 3.11, the assessment of the remaining life of this transformer is given. At 5% failure rate, the estimated remaining life is 170 years. From this figure it can be seen that the expected remaining life, even in the worst case, is very high.

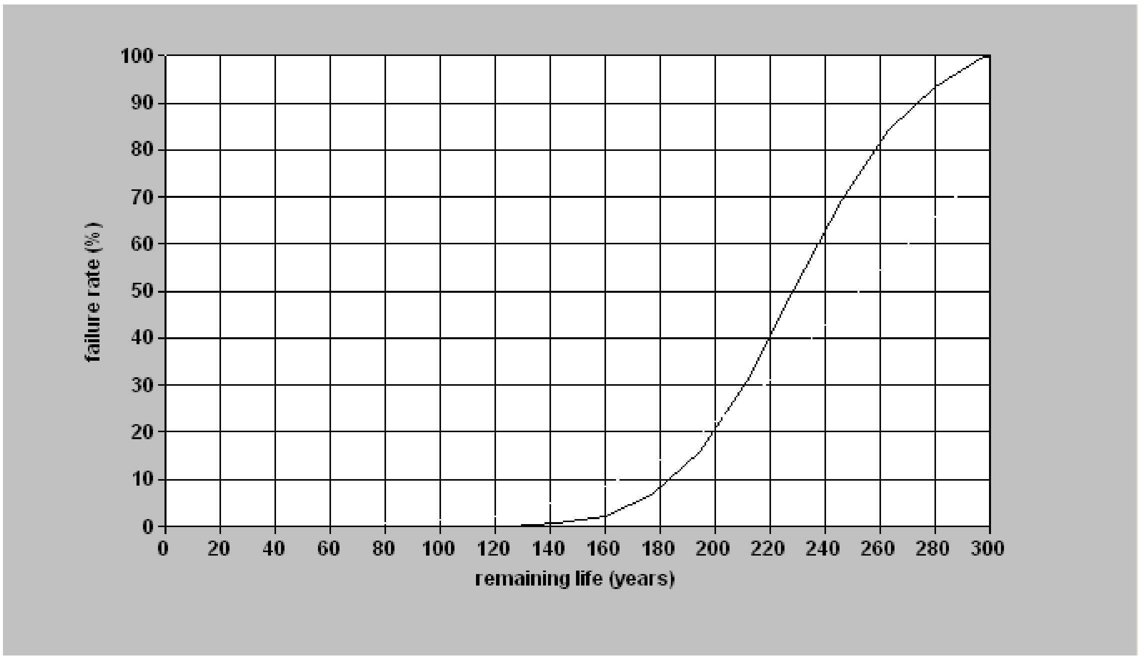


Figure 3.11 Assessed failure rate of transformer St. Andrews T1

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years
- Loading equal to 1: > 30 years.

Conclusion

From the remaining life analysis follows no significant ageing. The different analysis methods indicate a remaining life of 30 years or longer.

4.6 St. Andrews – Transformer 2

4.6.1 Visual inspection

 	Overview pictures of transformer T2 at substation St. Andrews. No severe signs of damage, deterioration and leakage.
	Picture of the tap-changer compartment. No severe signs of damage and deterioration. Some indications for oil sweating.
	Picture of two 33 kV bushings. No signs of damage or deterioration on the 33 kV and 11 kV bushings.

	Rust was found on several locations on the radiators.
	Large spots with rust on the supporting construction of the radiators.
	Rust formation along the bottom plate of the transformer.
	Original 11 kV cables are still in operation. Some wear on the terminations, but no signs of deterioration.

 	Original 33 kV incoming cables are still in operation. No severe signs of damage, leakage and deterioration on bushings and other components.

Conclusion

During the visual inspection, no severe signs of damage, deterioration and leakage have been observed. Some oil sweating on the tap changer compartment. The rust formation on the radiators might need further attention. Cables are the original ones, but no visual signs of damage, leakage and deterioration.

4.6.2 Partial discharge measurements

Frequency spectra

The recorded frequency spectra are shown in figure 3.12.

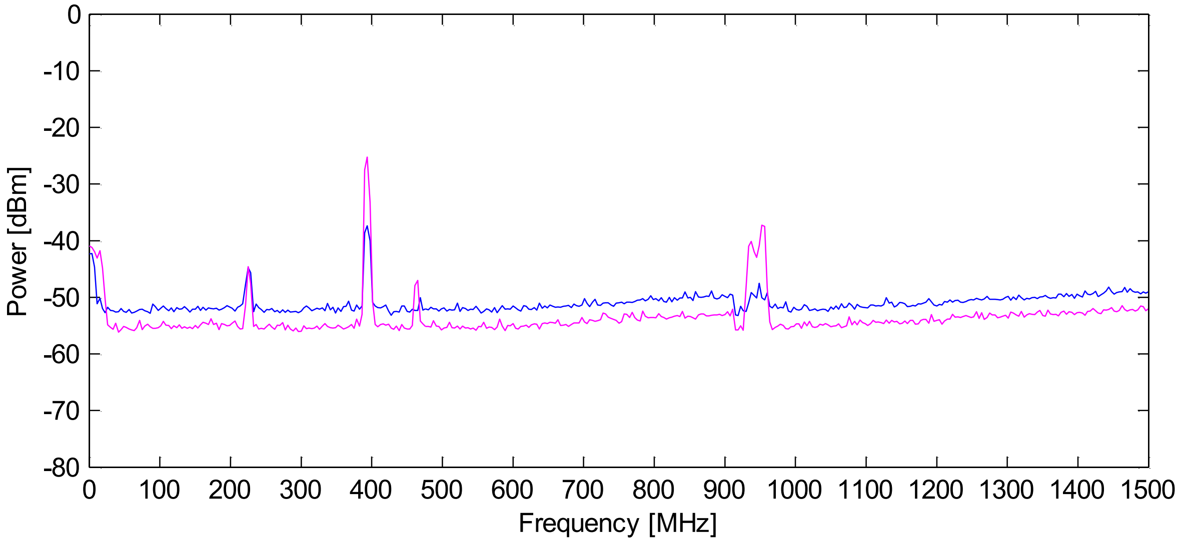


Figure 3.12 Frequency spectra of background (blue) and object (magenta)

Point-on-wave measurements

Based on a comparison between the two frequency spectra shown in figure 3.12, point-on-wave measurements were performed on:

- 20 MHz
- 40 MHz
- 470 MHz.

It was found that the detected signals are not generated by partial discharge activity within the object.

It is noted that in addition to the UHF-methodology, also partial discharge measurements by means of the acoustic methodology were performed. These measurements confirmed the results of the UHF-methodology as no indications of partial discharge activity were found.

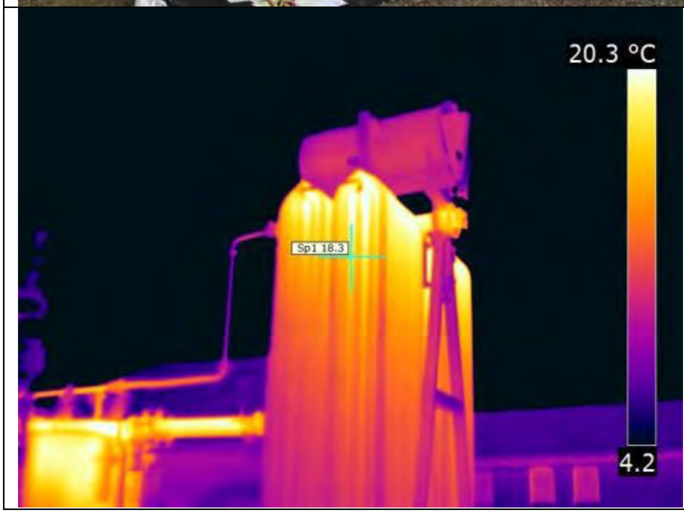
Conclusion

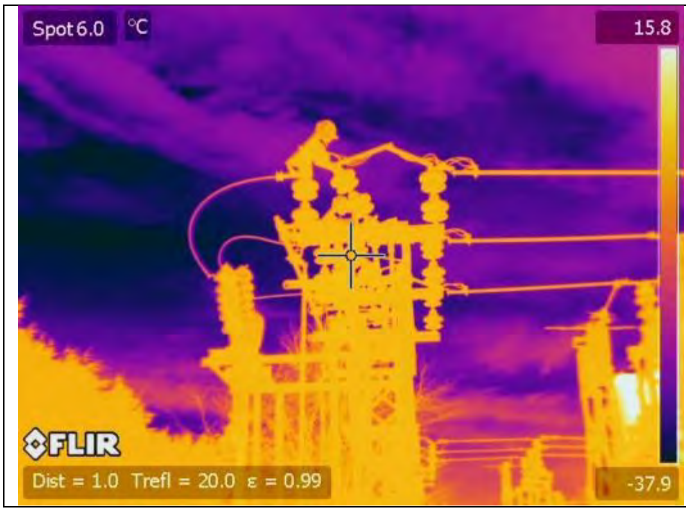
During the partial discharge measurements, no source of partial discharge activity was found within the transformer.

4.6.3 Thermal imaging

	No indication of thermal issues.
	No indication of thermal issues.
	Hot spot on terminal of 33 kV-transformer bushing (left)

<table>
<tr>
<td>


</td>
<td>Hot spot on terminal of 33 kV-transformer bushing</td>
</tr>
<tr>
<td>
</td>
<td>No indication of thermal issues.</td>
</tr>
</table>

	No thermal issues were found in 33 kV-switchyard.

Conclusion

A minor hot spot was found on the terminal a 33 kV- transformer bushing. It is recommended to address this hot spot during the next scheduled maintenance/outage.

4.6.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.11.

Table 3.11 Results dissolved gas analysis

Gas	Date (dd-mm-yyyy)			Unit
	13-10-2009	08-10-2012	**25-02-2014**	
Hydrogen	37.2	7.1	**26.5**	µL/L
Methane	4.1	2.6	**2.6**	µL/L
Ethane	3	2.6	**3.0**	µL/L
Ethylene	3.5	2.6	**3.1**	µL/L
Acetylene	0	0	**< 1**	µL/L
Propane	-	-	**11.0**	µL/L
Propene	-	-	**31.2**	µL/L
Carbon-monoxide	146.1	101.5	**294**	µL/L
Carbon dioxide	2693.3	3487.7	**3340**	µL/L
N-butane	-	-	**22.6**	µL/L
Iso-butane	-	-	**25.9**	µL/L

Results physical properties

The physical properties are presented in table 3.12.

Table 3.12 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	0.63	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	< 0.05	%(m/m)
Corrosive properties	None-corrosive	-
DBDS	< 5	mg/kg
Breakdown voltage	47	kV/2.5 mm
Color	2.0-2.5	-
Specific resistance (@ 90°C)	12.9	GΩ·m
Tan(δ) (@ 90°C)	176	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	None detected	-
Water content	17	mg/kg
Acidity	0.16	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates a normal aging process. DNV GL recommends to collect a new sample in January 2015 for the analysis on the concentration of dissolved gasses.

The physical properties of the oil meet the requirements of IEC 60422. DNV GL recommends to collect a new sample in January 2016 for the analysis of the physical properties.

4.6.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is 0.63 mg/kg and the age is 48 years. The DP value is assessed to be 446 (s.d. 27).

In figure 3.13, the assessment of the remaining life of this transformer is given. From this figure it can be seen that the expected remaining life is very high. At 5% failure rate, the remaining life is 85 years.

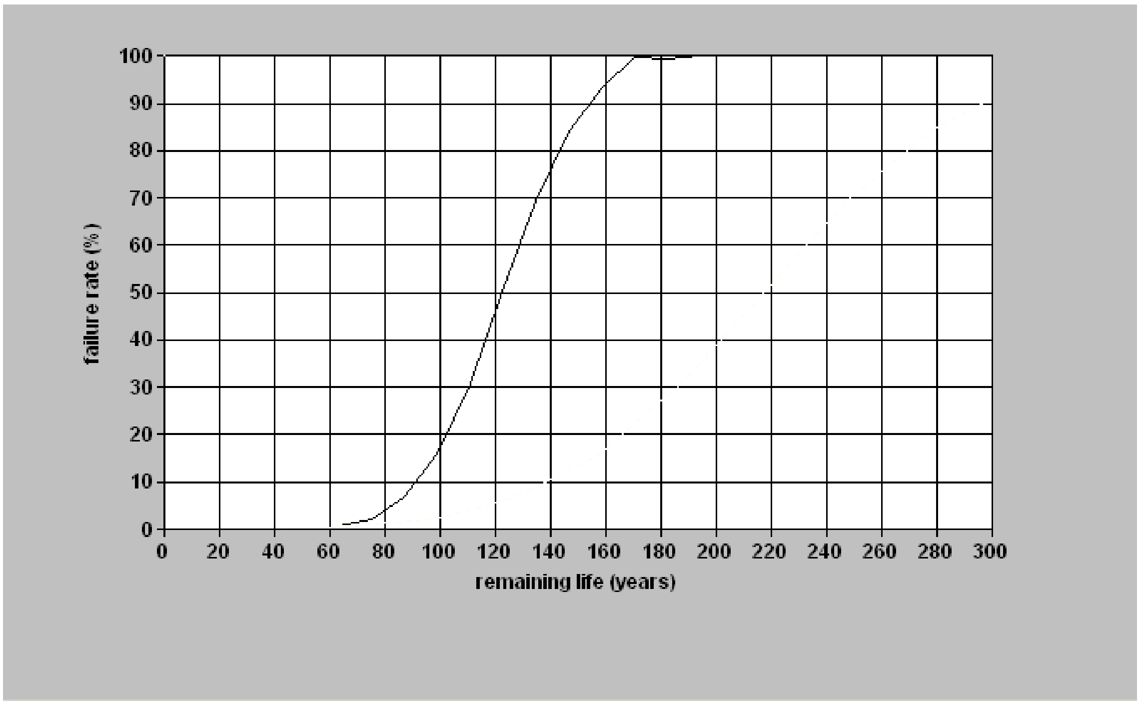


Figure 3.13 Assessed failure rate of transformer St. Andrews T2

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years
- Loading equal to 1: > 30 years.

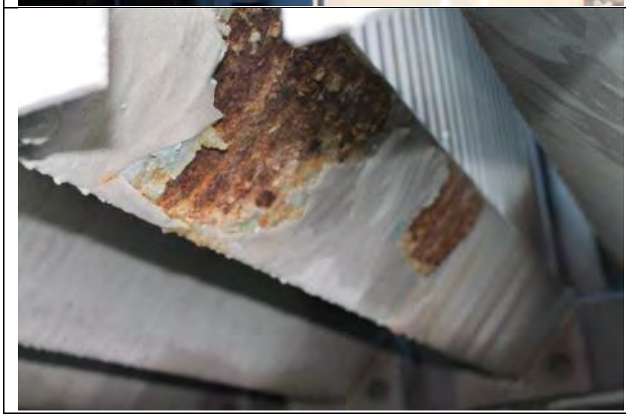
Conclusion

From the remaining life analysis follows no significant ageing. The different analysis methods indicate a remaining life of 30 years or longer.

4.7 Cupar – Transformer 1

4.7.1 Visual inspection

 	Overview pictures of transformer T1 at substation Cupar. No severe signs of damage and deterioration. Oil leakage is observed at different spots.
	
	Picture of hatch cover on the tap-changer compartment. No severe signs of damage and deterioration. Significant indications for oil sweating.

 	Oil sweating at one of the corner tops of the transformer housing and around one of the valves.
	Picture of the 33 kV bushings. No signs of damage or deterioration on the 33 kV and 11 kV bushings.
	Rust was found on several locations on the radiators, in particular large spots at the bottom of the radiators.

	Rust formation along the bottom plate of the transformer.
	Original 11 kV cables are still in operation. Some wear on the terminations, but no signs of deterioration. New 11 kV cables have been jointed to enter the new substation.
	New 33 kV have been installed in 2007. No severe signs of damage, leakage and deterioration on bushings. Direct cable connection to HV transformer so no other bay components present at site.

Conclusion

During the visual inspection, no severe signs of damage and deterioration have been observed. Some oil sweating and leakage has been observed, in particular on the tap-changer compartment, but also at several points of the transformer housing and (oil) valves. The rust formation on the radiators might need further attention.

The silica gel looks saturated and needs to be replaced (action was already taken on-site by the maintenance crew).

4.7.2 Partial discharge measurements

Frequency spectra

The recorded frequency spectra are shown in figure 3.14.

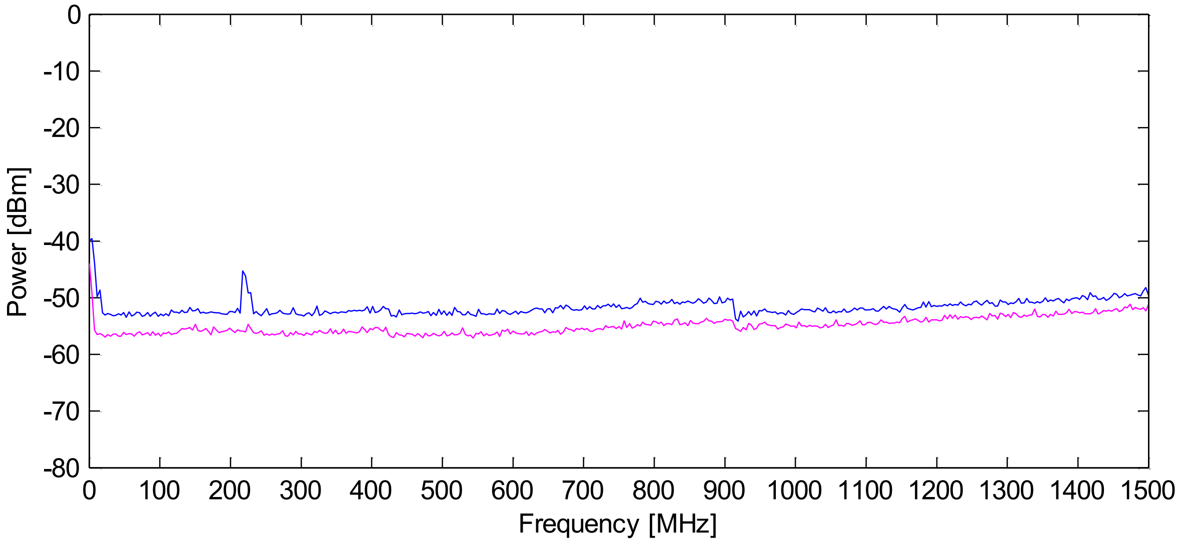


Figure 3.14 Frequency spectra of background (blue) and object (magenta)

Point-on-wave measurements

Based on a comparison between the two frequency spectra shown in figure 3.14, point-on-wave measurements were performed on:

- 20 MHz;
- 240 MHz;
- 550 MHz.

It was found that the detected signals are not generated by partial discharge activity within the object.

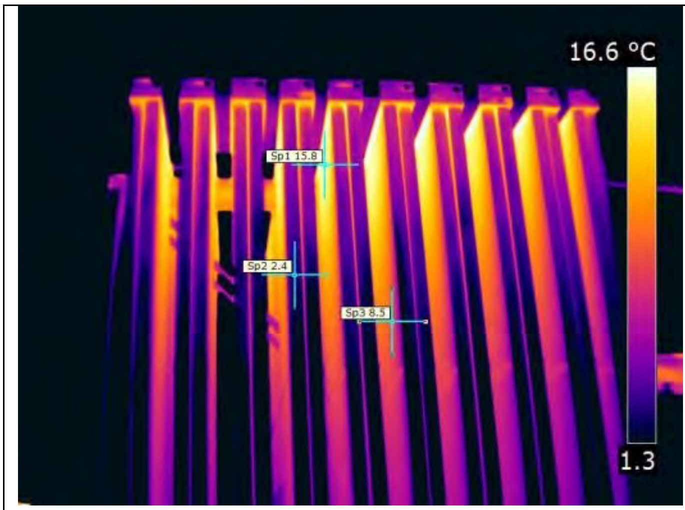
It is noted that in addition to the UHF-methodology, also partial discharge measurements by means of the acoustic methodology were performed. These measurements confirmed the results of the UHF-methodology as no indications of partial discharge activity were found.

Conclusion

During the partial discharge measurements, no source of partial discharge activity was found within the transformer.

4.7.3 Thermal imaging

	No indication of thermal issues.
	No indication of thermal issues.
	No indication of thermal issues.

	No indication of thermal issues.
	No thermal issues were found in 33 kV-cable terminations.

Conclusion

During the thermal imaging of the transformer, no observations were made that would suggest the presence of a thermal issue.

4.7.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.13.

Table 3.13 Results dissolved gas analysis

Gas	Date (dd-mm-yyyy)				Unit
	25-09-2012	08-05-2013	16-07-2013	**25-02-2014**	
Hydrogen	6.3	15.5	12.9	**20.3**	µL/L
Methane	2.3	7.3	3.2	**1.8**	µL/L
Ethane	3.4	5.8	2.9	**3.9**	µL/L
Ethylene	6.6	8.5	6.7	**5.8**	µL/L
Acetylene	0.2	0	0.1	**< 1**	µL/L
Propane	-	-	-	**13.8**	µL/L
Propene	-	-	-	**44.5**	µL/L
Carbon-monoxide	87.2	159.5	140.9	**218**	µL/L
Carbon dioxide	3467.3	4074.8	2803.6	**3180**	µL/L
N-butane	-	-	-	**12.1**	µL/L
Iso-butane	-	-	-	**2.7**	µL/L

Results physical properties

The physical properties are presented in table 3.14.

Table 3.14 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	1.0	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	< 0.05	%(m/m)
Corrosive properties	None-corrosive	-
DBDS	< 5	mg/kg
Breakdown voltage	54	kV/2.5 mm
Color	3.0-3.5	-
Specific resistance (@ 90°C)	2.1	GΩ·m
Tan(δ) (@ 90°C)	636	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	Some detected	-
Water content	28	mg/kg
Acidity	0.17	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates a normal aging process. DNV GL recommends to collect a new sample in January 2015 for the analysis on the concentration of dissolved gasses.

The physical properties of the oil meet the requirements of IEC 60422. DNV GL recommends to collect a new sample in January 2016 for the analysis of the physical properties.

4.7.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is 1.0 mg/kg and the age is 48 years. The DP value is assessed to be 377 (s.d. 27).

In figure 3.15, the assessment of the remaining life of this transformer is given. From this figure it can be seen that the expected remaining life is very high. At a failure rate of 5% the remaining life is estimated to be 38 years.

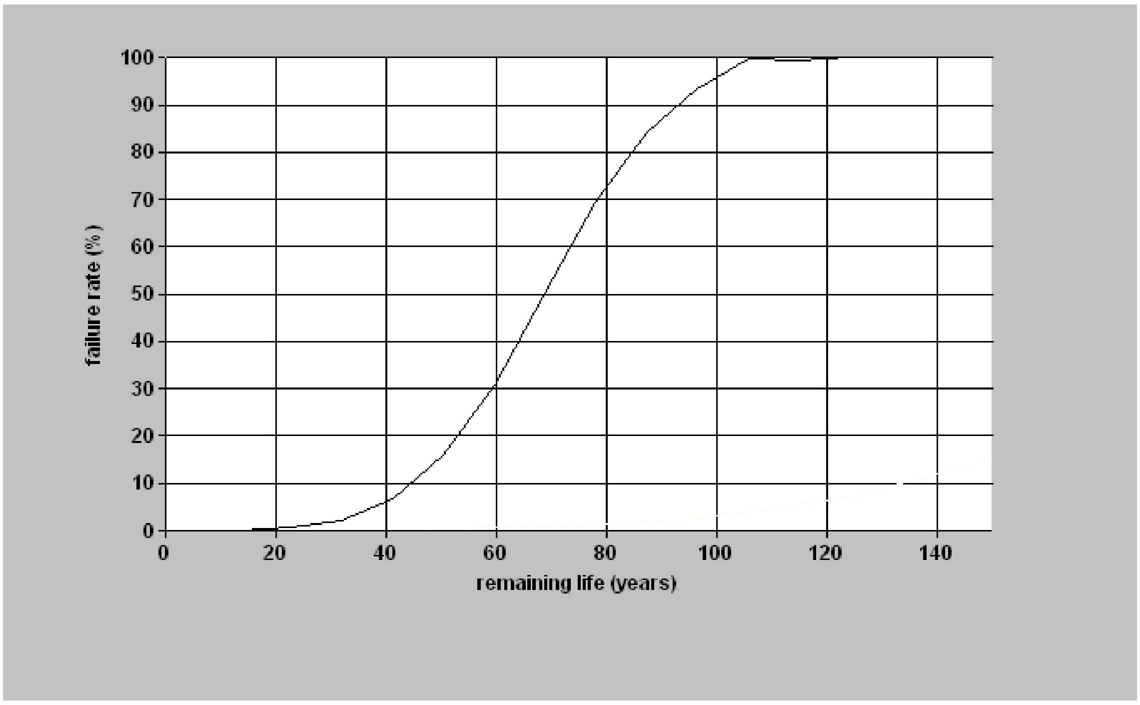


Figure 3.15 Assessed failure rate of transformer Cupar T1

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years;
- Loading equal to 1: > 30 years.

Conclusion

From the remaining life analysis follows no significant ageing. The different analysis methods indicate a remaining life of 30 years or longer.

4.8 Cupar – Transformer 2

4.8.1 Visual inspection

  	Overview pictures of transformer T2 at substation Cupar. No severe signs of damage and deterioration. Oil leakage and sweating is observed at different spots.
	Picture of hatch cover on the tap-changer compartment. No severe signs of damage and deterioration. Significant indications for oil sweating.

	
 	Oil sweating at one of the corner tops of the transformer housing and around one of the valves.

	Picture of two 33 kV bushings. No signs of damage or deterioration on the 33 kV and 11 kV bushings.
	Rust was found on several locations on the radiators.
	Rust formation along the bottom plate of the transformer.
	Original 11 kV cables are still in operation. Some wear on the terminations, but no signs of deterioration.

	New 33 kV have been installed in 2007. No severe signs of damage, leakage and deterioration on bushings. Direct cable connection to HV transformer so no other bay components present at site.

Conclusion

During the visual inspection, no severe signs of damage and deterioration have been observed. Some oil sweating and leakage has been observed, in particular on the tap-changer compartment, but also at several points of the transformer housing and (oil) valves. The rust formation on the radiators might need further attention.

The silica gel looks saturated and needs to be replaced (action was already taken on-site by the maintenance crew).

4.8.2 Partial discharge measurements

Frequency spectra

The recorded frequency spectra are shown in figure 3.16.

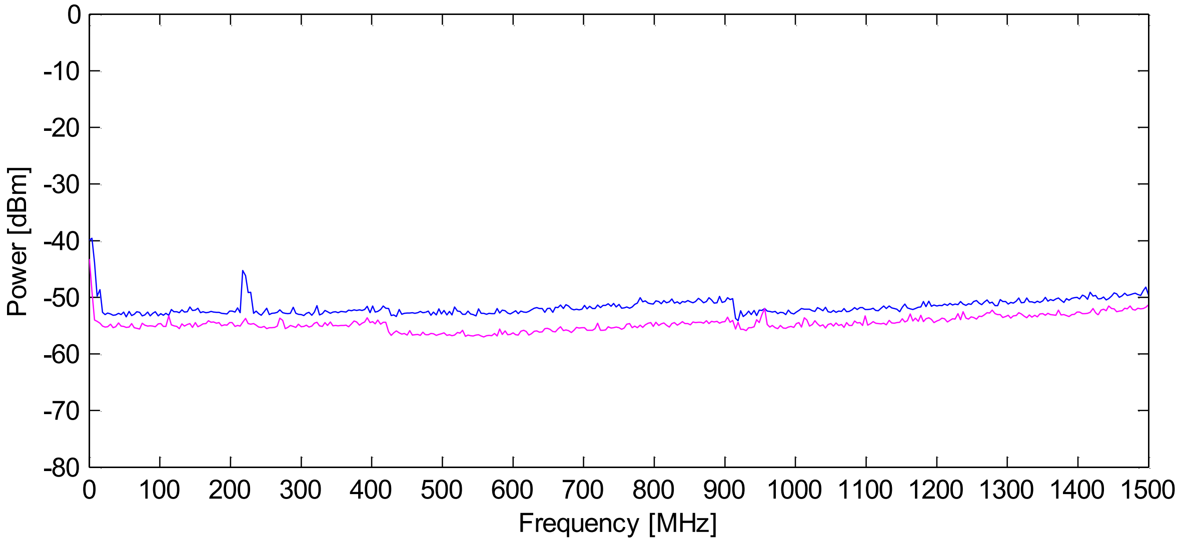


Figure 3.16 Frequency spectra of background (blue) and object (magenta)

Point-on-wave measurements

Based on a comparison between the two frequency spectra shown in figure 3.16, point-on-wave measurements were performed on:

- 20 MHz
- 115 MHz
- 275 MHz
- 600 MHz
- 975 MHz.

It was found that the detected signals are not generated by partial discharge activity within the object.

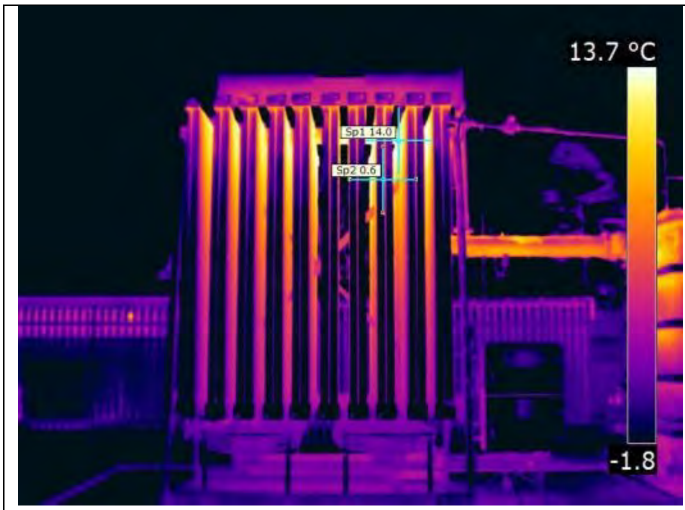
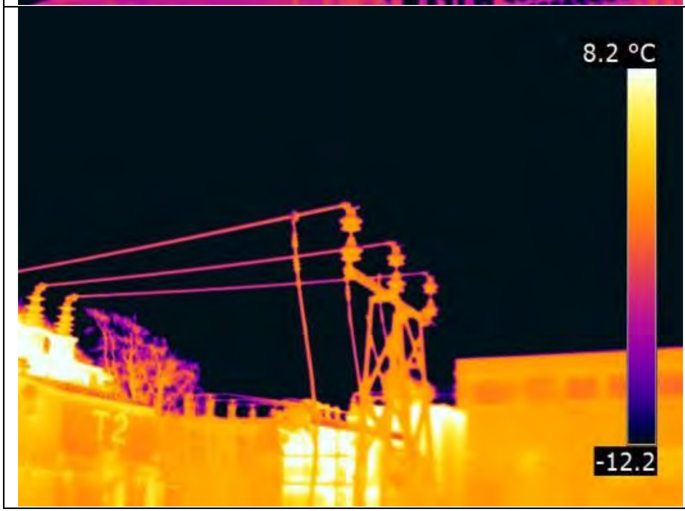
It is noted that in addition to the UHF-methodology, also partial discharge measurements by means of the acoustic methodology were performed. These measurements confirmed the results of the UHF-methodology as no indications of partial discharge activity were found.

Conclusion

During the partial discharge measurements, no source of partial discharge activity was found within the transformer.

4.8.3 Thermal imaging

	No indication of thermal issues.
	No indication of thermal issues.
	No indication of thermal issues.

	No indication of thermal issues.
	No thermal issues were found in 11 kV-cable terminations.
	No thermal issues were found in 33 kV-cable terminations.

Conclusion

During the thermal imaging of the transformer, no observations were made that would suggest the presence of a thermal issue.

4.8.4 Oil analysis

Dissolved gas analysis

The results of the dissolved gas analysis are presented in table 3.15.

Table 3.15 Results dissolved gas analysis

Gas	Date (dd-mm-yyyy)				Unit
	25-09-2012	08-05-2013	16-07-2013	**25-02-2014**	
Hydrogen	4	6.5	8.4	**11.8**	µL/L
Methane	2.2	8.8	3.4	**2.3**	µL/L
Ethane	1.6	13.1	2	**3.8**	µL/L
Ethylene	6.5	9.2	8.1	**8.3**	µL/L
Acetylene	0	0.1	0	**< 1**	µL/L
Propane	-	-	-	**11.6**	µL/L
Propene	-	-	-	**57.2**	µL/L
Carbon-monoxide	101	163	200.4	**293**	µL/L
Carbon dioxide	3463.2	4107.3	3916.3	**4400**	µL/L
N-butane	-	-	-	**13.2**	µL/L
Iso-butane	-	-	-	**2.5**	µL/L

Results physical properties

The physical properties are presented in table 3.16.

Table 3.16 Physical properties

Property	Value	Unit
2-acetylfuran	< 0.1	mg/kg
2-furfural	0.71	mg/kg
2-furfurylalcohol	< 0.1	mg/kg
5-hydroxymethyl-2-furfural	< 0.1	mg/kg
5-methyl-2-furfural	< 0.1	mg/kg
DBPC	< 0.05	%(m/m)
Corrosive properties	None-corrosive	-
DBDS	< 5	mg/kg
Breakdown voltage	68	kV/2.5 mm
Color	3.5-4.0	-
Specific resistance (@ 90°C)	3.3	GΩ·m
Tan(δ) (@ 90°C)	624	$\cdot 10^{-4}$
Appearance	Clear	-
Contaminants	Some detected	-
Water content	30	mg/kg
Acidity	0.22	gKOH/kg

Conclusion

The composition of the dissolved gasses indicates a normal aging process. DNV GL recommends to collect a new sample in January 2015 for the analysis on the concentration of dissolved gasses.

The physical properties of the oil meet the requirements of IEC 60422. DNV GL recommends to collect a new sample in January 2016 for the analysis of the physical properties.

4.8.5 Remaining lifetime assessment

Method 1: Furanic compounds

The 2-furfural concentration in the oil of this transformer is 0.71 mg/kg and the age is 48 years. The DP value is assessed to be 431 (s.d. 27).

In figure 3.17, the assessment of the remaining life of this transformer is given. From this figure it can be seen that the expected remaining life is very high. For a failure rate of 5%, the remaining life is 70 years.

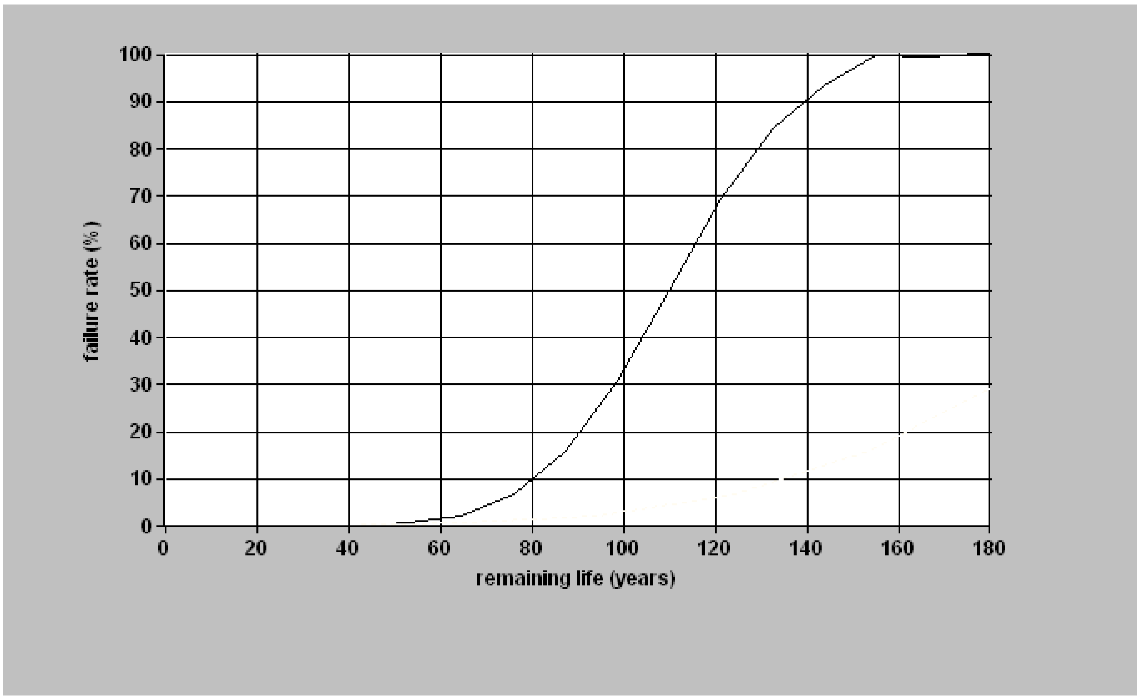


Figure 3.17 Assessed failure rate of transformer Cupar T2

Method 2: Dynamic loading guide calculations

Based on the results of the dynamic loading guide calculations, the calculated remaining lifetime is as follows:

- Loading based on history: >> 30 years
- Loading equal to 1: > 30 years.

Conclusion

From the remaining life analysis follows no significant ageing. The different analysis methods indicate a remaining life of 30 years or longer.

4.9 Summary

The results of the condition assessment of the different transformers are presented in table 3.17. The main conclusion is that 6 transformers are still in good condition and have an expected remaining lifetime of about 30 years or more. Some hotspots have been detected in the connecting equipment to St. Andrews T2 and Whitchurch T1, but these can be solved by proper maintenance and will not affect the loading. Only Ruabon and Whitchurch, which are new transformers, show free water in the oil and failed to pass the IEC 60422 criteria which could impact the loading capacity.

Table 4.17 Summary of the condition assessment

Transformer	Visual	PD	IR	Oil	Remaining lifetime		
					Method 1: Furfural	Method 2: Loading Guide	
						Continuous historical loading	*Continuous nominal loading*
St. Andrews T1	Rust	OK	OK	OK	170 year	>> 30 year	> 30 year
St. Andrews T2	Rust	OK	Hotspot on 33 kV terminal	OK	85 year	>> 30 year	> 30 year
Cupar T1	Rust, sweating	OK	OK	OK	38 year	>> 30 year	> 30 year
Cupar T2	Rust, sweating	OK	OK	OK	70 year	>> 30 year	> 30 year
Ruabon T1	OK	Corona discharge in air	Peculiar temperature profile on radiators	Free water	-[1]	>> 30 year	> 29 year
Whitchurch T1	OK	OK	Hotspot on 33 kV disconnectors	Free water PD-activity	-[2]	>> 30 year	> 29 year
Yockings Gate T1	Leaking cable box	OK	OK	OK	70 year	>> 30 year	> 27 year
Liverpool Road T1	Sweating	OK	OK	PD-activity Corrosive	45 year	>> 30 year	> 28 year

[1] The estimated remaining life that is calculated by the model (4 years) is unrealistically low as the actual 2-furfural concentration can assumed to be lower than of the detection limit of 0.1 mg/kg considered by the model.
[2] The estimated remaining life that is calculated by the model (14 years) is unrealistically low as the actual 2-furfural concentration can assumed to be lower than of the detection limit of 0.1 mg/kg considered by the model.

5 CONCLUSIONS/RECOMMENDATIONS

5.1 Conclusions

Based on the results of the condition assessment presented in this report, the following conclusions can be drawn:

1) the estimated remaining lifetime of all 8 transformers that were part of the condition assessment is over 25 years
2) the observations during the visual inspections, thermo-graphic surveys (IR), online partial discharge measurements (PD) and oil analyses can be summarized as follows:

Transformer	Visual	PD	IR	Oil
St. Andrews T1	Rust	OK	OK	OK
St. Andrews T2	Rust	OK	Hotspot on 33 kV terminal	OK
Cupar T1	Rust, sweating	OK	OK	OK
Cupar T2	Rust, sweating	OK	OK	OK
Ruabon T1	OK	Corona discharge in air	Peculiar temperature profile on radiators	Free water
Whitchurch T1	OK	OK	Hotspot on 33 kV-disconnectors	Free water PD-activity
Yockings Gate T1	Leaking cable box	OK	OK	OK
Liverpool Rd. T1	Sweating	OK	OK	PD-activity Corrosive

3) Pending mitigative measures to be implemented on Ruabon T1 and Whitchurch T1, DNV GL currently qualifies the following six transformers suitable for operating under overloading conditions under careful dynamic loading:
   - St. Andrews T1 and T2
   - Cupar T1 and T2
   - Yockings Gate T1
   - Liverpool Road T1.

5.2 Recommendations

Based on the results of the condition assessment presented in this report, the following recommendations are given:

1) in addition to the normal maintenance regime, perform the following short-term actions (0-12 months):
    - Ruabon T1:
        - collect an oil sample from the main tank for analysis of the concentration of dissolved gasses and quality
        - as the transformer is still under warranty, contact the manufacturer regarding the measured partial discharge activity
    - Whitchurch T1:
        - collect an oil sample from the main tank for analysis of the concentration of dissolved gasses and quality
    - Liverpool Road T1:
        - collect an oil sample from the main tank for analysis of the concentration of dissolved gasses and quality
        - on the basis of a risk assessment study (CIGRÉ Brochure 378, 2009), evaluate the necessity for corrective actions regarding the corrosiveness of the oil
2) in addition to the normal maintenance regime, perform the following medium-term actions (12-24 months):
    - St. Andrews T1:
        - define and implement actions to correct/mitigate the observed rust
    - St. Andrews T2:
        - define and implement actions to correct/mitigate the observed rust
        - define and implement actions to correct the observed hot-spot on a 33 kV-terminal
    - Cupar T1:
        - define and implement actions to correct/mitigate the observed rust
    - Cupar T2:
    - define and implement actions to correct/mitigate the observed rustWhitchurch:
        - define and implement actions to correct the observed hot-spots on 33 kV-disconnectors
    - Yockings Gate T1:
        - define and implement actions to correct the observed mass-leakage from the 33 kV-cable box.

3) In addition to the normal maintenance regime, perform the following long-term actions (24-60 months):
    - Cupar T1:
        - define and implement actions to correct/mitigate the observed sweating
    - Cupar T2:
        - define and implement actions to correct/mitigate the observed sweating
    - Yockings Gate T1:
        - define and implement actions to correct/mitigate the observed sweating.

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.